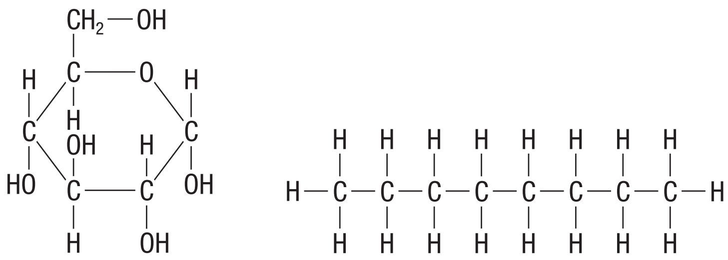
Food as Fuel

What do gasoline and glucose have in common? What is it about the chemical makeup of gasoline and glucose that provides the energy needed to run a car or a cell? The one thing that glucose and gasoline have in common that makes them both good fuel molecules is an abundance of hydrogen in the form of carbon-hydrogen (C–H) bonds (**Figure 1**). As a result of their structure and bond type, there is a great deal of potential energy in both glucose and gasoline.



(a) glucose **(b)** octane

Figure 1 (a) Glucose and (b) octane (a component of gasoline) are valuable fuels due to the presence of easily accessible carbon-hydrogen (C–H) bonds.

Electrons in C–H bonds are a good source of energy because of their position and proximity to the relatively small atomic nuclei of carbon and hydrogen atoms. For any atom, an electron that is farther away from the nucleus contains more potential energy than an electron that is more closely held by the nucleus (**Figure 2**).

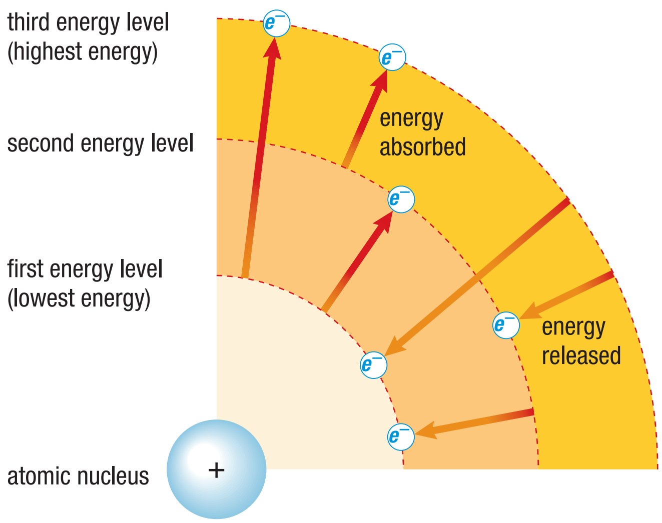


Figure 2 Electrons that absorb energy move to a higher energy level, which is farther away from the nucleus. Electrons that release energy move closer to the nucleus. Electrons can only exist in discrete energy states.

In addition to distance from the nucleus, the size of the nucleus influences the potential energy of an electron. An electron is more strongly attracted to a large nucleus than to a small nucleus. Therefore, at the same distance away, an electron has more potential energy relative to a large nucleus than relative to a smaller nucleus. As a result, an electron releases energy if it moves closer to a large nucleus and must gain energy to be pulled away.

The electrons associated with a C–H bond are approximately equidistant from two relatively small nuclei. As a result, the electrons in C–H bonds contain high energy. This is because they can be readily pulled closer to larger and more attractive nuclei—a process that releases energy. In contrast, molecules that already have an abundance of oxygen contain less potential energy because many of their bonding electrons are close to oxygen, which is strongly electronegative. The more electronegative an atom is, the greater the force of attraction it has to an additional electron (or electrons). In the case of an oxygen atom, two additional electrons from the atoms of other elements are able to get very close to the oxygen nucleus and are held very strongly. As the electrons in other atoms are attracted to the oxygen nucleus, they lose potential energy—releasing this energy during bond formation. After the additional electrons are in position close to the oxygen nucleus, the equivalent amount of energy would be required to remove them.

These fundamental principles of chemistry are relevant to everyday life. For example, they explain why fat contains more potential energy per unit of weight compared to proteins and carbohydrates. A fat molecule consists almost entirely of C–H bonds. Foods with a high fat content that are known to be high in energy include fatty fish (tuna or salmon), eggs, avocados, nuts, and meats. When cooking a high-energy food such as bacon, liquefied fat drains from the meat. This fat is highly flammable because of its high energy content, and it can cause a grease fire in your kitchen.

Energy Changes during Oxidation

Oxidation occurs when an atom or molecule loses electrons to another atom. The term "oxidation" comes from the fact that in many chemical reactions, the electrons within molecules, particularly those referred to as fuels, become bonded to an oxygen atom. Since O_2 has very high electronegativity, it is an ideal electron acceptor atom in the process of cellular respiration. The opposite of oxidation—known as reduction—occurs when an atom or molecule gains electrons. In a chemical reaction, the atom or molecule that gains electrons is called the oxidizing agent (that is, it oxidizes the other substance). The substance that loses electrons is known as the reducing agent (that is, it reduces the other substance).

As you learned in Chapter 1, in some redox reactions, electrons transfer completely from one molecule to another, while in other redox reactions, electrons remain shared between two atoms. The reaction between methane and oxygen illustrates a redox reaction in which the degree of electron sharing changes (**Figure 3**). Methane and oxygen are the reactants, and carbon dioxide and water are the products.

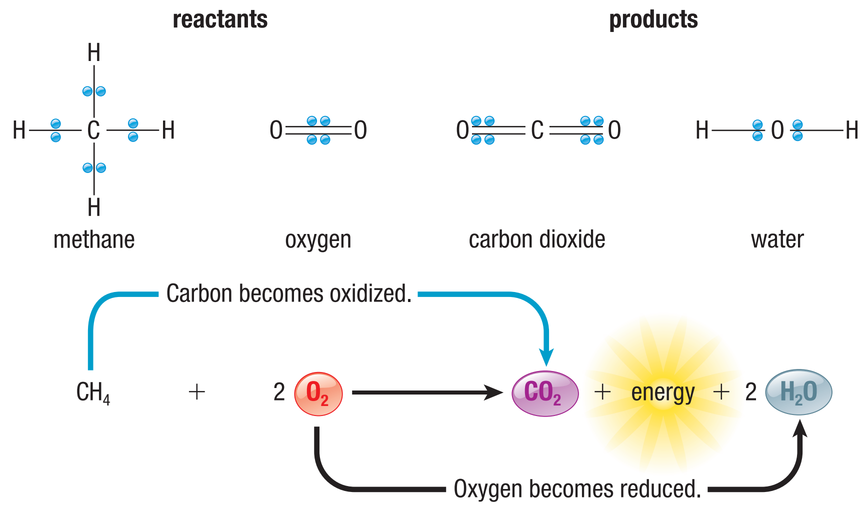


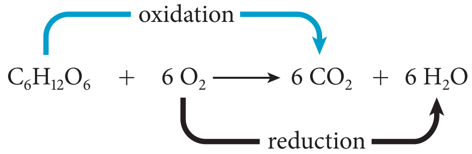
Figure 3 This diagram shows the relative loss and gain of electrons in a redox reaction in which methane reacts with oxygen. The carbon in the methane molecule is oxidized, and the oxygen is reduced. The dots indicate the positions of the electrons that are involved in the covalent bonds of the reactants and products.

In methane, the electrons are shared equally between bonded C–H atoms because C and H have almost the same electronegativity. Consider what happens to the electrons with respect to the carbon atoms. In the product CO_2, the electrons are drawn closer to the O atoms than to the C atoms because the O atoms are much more electronegative than the C atoms. Overall, this bond configuration means that C has partially lost its shared electrons in the reaction. The carbon atom within methane has been oxidized in this reaction.

Now look at the reactant oxygen and the product water. In the oxygen molecule, the two oxygen atoms share their electrons equally. The O_2 reacts with a hydrogen atom from methane. In the water molecule that is produced, the electrons are closer to the O atom than to the H atoms, due to the O atom's greater electronegativity. Therefore, the oxygen molecule has been reduced. The reaction releases a lot of energy because of the redox reaction that takes place between methane and oxygen. Energy is released when the electrons associated with the C–H bonds in methane move closer to the electronegative oxygen atoms that form CO_2 and H_2O.

The oxidation of fuel molecules, such as those in food, releases some of the potential energy stored within the molecule and allows it to be used for cellular processes. Redox reactions often involve the movement of electrons associated with hydrogen and oxygen atoms. Therefore, by convention, the removal of hydrogen atoms from, or the addition of oxygen atoms to, a molecule or atom is also called oxidation. Conversely, the addition of hydrogen or the removal of oxygen is called a reduction.

The following redox reaction describes the complete oxidation of glucose:



Note that the carbons in the original glucose have lost their hydrogen atoms (along with the hydrogen atoms' electrons) and gained oxygen—they have been oxidized. In contrast, the oxygen atoms that were in the form of O_2 have now formed bonds with hydrogen and carbon—these oxygen atoms have been reduced. Energy is released from the glucose molecule as the high-energy carbon, and hydrogen electrons transfer to carbon dioxide and water, forming bonds with oxygen.

Rapid Combustion and Controlled Oxidation

Recall that during rapid oxidation, or the burning of fuels such as gasoline, it is oxygen gas itself that does the oxidizing. Glucose molecules can also undergo combustion and burn (**Figure 4(a)**, next page). Like all combustion reactions, the oxidation of glucose results in the transfer of electrons to O_2. The reaction produces CO_2 and H_2O and releases energy. CO_2 and H_2O are produced during the complete oxidation of all organic molecules. Since CO_2 and H_2O are both fully oxidized, they contain no more available chemical energy. When glucose burns, a large amount of waste thermal energy is released after an initial large energy of activation is overcome by a spark or flame.

An alternative to using rapid oxidation is to use the same overall reaction, resulting in similar end products, but with a series of steps. This is what happens inside cells, where the energy contained in food molecules is released through controlled oxidation. During controlled oxidation, cells are able to capture more free energy and produce less waste thermal energy. The energy contained in all the electrons in the C–H bonds is not liberated suddenly to produce a lot of thermal energy. In cells, the oxidation of glucose occurs through a series of enzyme-catalyzed reactions (**Figure 4(b)**, next page). Each step in these reactions releases a modest amount of energy following the absorption of a small amount of activation energy, which is provided by the thermal energy of the surroundings. The energy released transfers to energy-carrying molecules for the next step.

Thermodynamically, the net energy changes that occur in rapid combustion and controlled oxidation are identical. They are both exergonic reactions that have the same overall change in free energy. The difference is that, in the rapid combustion reaction, all of the energy is given off at once and cannot be as efficiently harnessed to drive metabolic reactions in the cell.

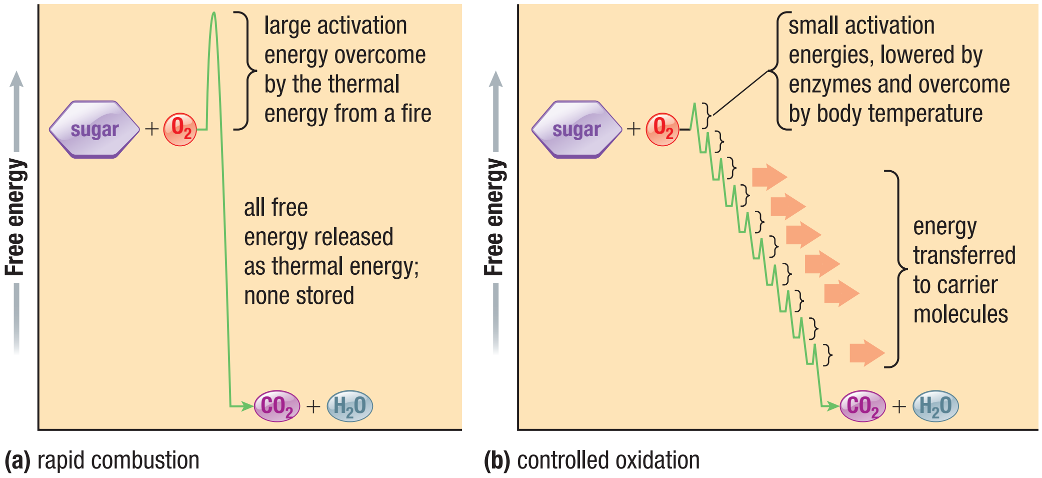


Figure 4 A comparison of the oxidation of glucose by (a) rapid combustion (burning) and (b) controlled oxidation

Energy Carriers

dehydrogenase an enzyme that oxidizes a substrate and transfers hydrogen ions to an acceptor

NADH the reduced form of the coenzyme nicotinamide adenine dinucleotide

The most important redox reactions in eukaryotic cells occur when glucose is oxidized by oxygen to form carbon dioxide and water. The oxidation of food molecules often uses enzymes called **dehydrogenases**, which facilitate the transfer of high-energy electrons from food to molecules that act as energy carriers or shuttles. The most common energy carrier molecule in cells is a positively charged coenzyme called nicotinamide adenine dinucleotide (NAD^+) (**Figure 5**). At various points during cellular respiration, dehydrogenases remove two hydrogen atoms from a substrate molecule, transferring the two high-energy electrons and only one of the protons (H^+) to NAD^+. The other H^+ is released into the cytosol. This process results in the full reduction to **NADH**. The efficiency of the transfer of energy between food molecules and NAD^+ is high, and very little energy is lost as waste thermal energy. As you will see later, the potential energy carried in NADH and other reduced molecules facilitates the synthesis of ATP. The next chapter examines these processes and related chemical pathways in more detail.

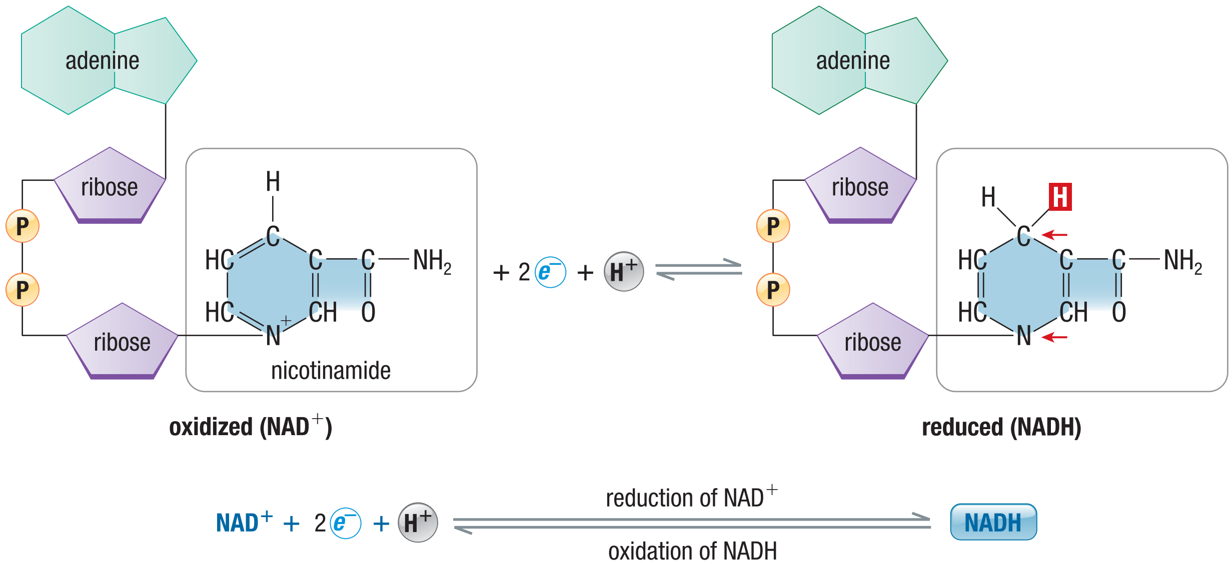


Figure 5 Structure of the electron carrier NAD^+ and its fully reduced form, NADH

3.4 Review

Summary

- Molecules with a large number of C–H bonds are high-energy molecules. Fat molecules have many C–H bonds and are a high-energy food source.
- Oxidation refers to the loss of electrons, and reduction refers to the gain of electrons.
- Potential energy that is stored in food molecules is released during oxidation reactions.
- Rapid oxidation reactions lead to a rapid loss of energy in the form of waste thermal energy. Controlled oxidation reactions involve many steps. There is less waste energy because more released energy can be captured effectively.
- During many cellular redox reactions, dehydrogenases facilitate the transfer of electrons from food to energy-carrier molecules.
- NAD^+ is a common high-energy electron carrier molecule in cellular processes, which is reduced to the form NADH. NADH provides a source of energy to drive ATP synthesis.

Questions

1. Explain, in your own words, why both gasoline and glucose make good fuels. K/U C
2. (a) Write the chemical equation for the complete combustion of glucose.
   (b) Which is the oxidizing agent?
   (c) Which is the reducing agent? K/U C
3. Use diagrams to explain how the relative positions of electrons change during a redox reaction, and how these positions are related to energy changes during the reaction. T/I C
4. Suggest a benefit provided by some of the waste energy that is released during cellular redox reactions. T/I A
5. Explain the gaining and releasing of energy by electrons, as related to changes in position relative to one or more atomic nuclei. T/I
6. In pairs, brainstorm examples of oxidation in everyday life that illustrate how reactive oxygen can be. A
7. List two examples of slow oxidation events and two examples of rapid oxidation events. T/I
8. Carefully examine Figure 5 on page 154. K/U T/I
   (a) What atom is reduced by gaining an electron during the reduction of NAD^+?
   (b) What atom is reduced by bonding to an added hydrogen atom?
   (c) Does this reaction influence any other atoms in the nicotinamide structure?
9. How is it beneficial for organisms to use controlled oxidation rather than rapid combustion to release energy from their food? Provide at least two benefits. K/U
10. You may have heard of antioxidants that aid in removing harmful oxidizing agents from the body. Many fresh fruits and vegetables are high in antioxidants (**Figure 6**). Conduct online research to find out how these antioxidizing agents do this. Why might this be important for proper cell functioning? K/U T/I

Figure 6 Antioxidant-containing foods

WEB LINK