Name: ______________________________________ Date: ________________________

Guided Learning: Molecular Structure and Properties

Learning goals
After completing this activity, you will be able to …

- Explain how atomic structure relates to properties of crystals.
- Understand how solutes dissolve in solutions.
- Explain how electrolytes work to transmit currents.
- Distinguish between polar and nonpolar solutions.
- Relate ignition temperatures to molecular structure.
- Relate molecular structures in food to energy content and digestibility.
- Describe how molecular structure affects the function of proteins.

Vocabulary: alkanes, autoignition temperature, carbohydrate, combustion, crystal, dissociation, electrolyte, enzyme, hydrogen bond, lipid, melting point, molecule, nucleic acid, polarity, protein, solute, solution, solvent

Warm-up questions
While many properties are determined by the electron configurations of the atoms that are bonded together, others depend on the arrangement of atoms in larger structures. In this activity, you will discover how physical and chemical properties such as melting point, solubility, and flammability are related to these larger structures.

1. What does an ice cube have in common with a quartz crystal? _______________________

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2. Suppose you heat up a quartz crystal and an ice cube in a frying pan. What would happen?

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3. Which do you think is held together by stronger chemical bonds, a quartz crystal or an ice cube? Explain. ____

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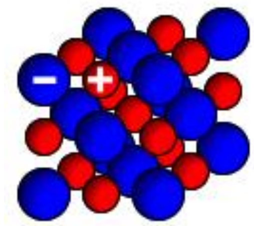
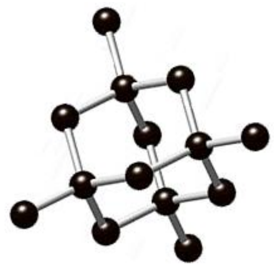
Activity A: Crystals

When two atoms form an ionic bond, one of the atoms has a net positive charge and the other has a net negative charge. The positive ion will attract negative ions, and the negative ion will attract positive ions. This may result in the formation of a **crystal**, a regularly repeating pattern of atoms. The simple crystalline structure of sodium chloride (NaCl) is shown at right, with red sodium ions (Na^+) and blue chlorine ions (Cl^-).



Sodium chloride crystal

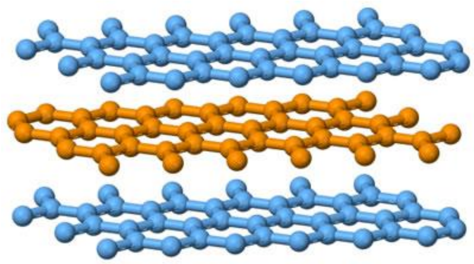


Diamond crystal

Crystals can also form from covalent bonds. For example, diamonds are made of pure carbon. Each carbon atom has a valence of 4 and forms 4 bonds with other carbon atoms. The resulting crystalline structure is shown at left.

The bonds holding carbon atoms together in diamonds are extremely strong. Diamonds are the hardest known natural substance and have very high **melting points**. Diamonds form at extreme high pressures deep below Earth's surface.

In general, the hardness of a crystal is related to the strength of its chemical bonds and to its crystal structure. For example, one reason that diamonds are so hard is that their crystal structure does not include any planes of atoms that can easily slide past one another. Graphite, another mineral made of pure carbon, is much softer than diamond because its crystal structure consists of an array of flat planes that are loosely bonded together, as shown at right.



Graphite crystal structure

Sodium chloride

Diamond

In addition to hardness, the crystalline structure often determines the shape of the resulting crystals. Sodium chloride crystals (left) are usually square, diamond crystals (left) are octahedral, and graphite crystals consist of thousands of small, flat flakes. All three of these crystal shapes reflect their molecular structures.

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1. What holds ionic crystals together? ____

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2. What holds covalent crystals together? ____

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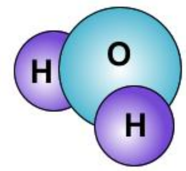
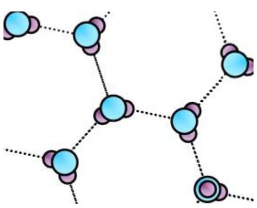
Activity B: Water and polarity

Of all the compounds on Earth, perhaps the most important to living things is water. Water freezes at 0° C and boils at 100° C. Earth's surface has an average temperature of 15° C, which means that water is liquid most places on Earth. This is important to living things because many nutrients dissolve in liquid water. Also, liquid water helps to transport nutrients both within and between cells. Water also helps to promote chemical reactions vital to living things. Water is a direct participant in chemical reactions such as photosynthesis. Finally, liquid water provides a living environment for aquatic organisms.

A water **molecule** (below) consists of two hydrogen atoms covalently bonded to an oxygen atom. The hydrogen atoms form an angle of about 104 degrees with the central oxygen atom.

In the covalent bonds between the hydrogen and oxygen atoms, the sharing of the electron pair is not perfectly symmetrical. The oxygen atom exerts a stronger pull on the electrons than the hydrogen atom. As a result, the average position of the electrons is closer to the nucleus of the oxygen atom than to the nuclei of the hydrogen atoms. This causes the hydrogen atoms to maintain a partial positive charge while the oxygen atom has a partial negative charge. This unequal distribution of charge is called **polarity**.

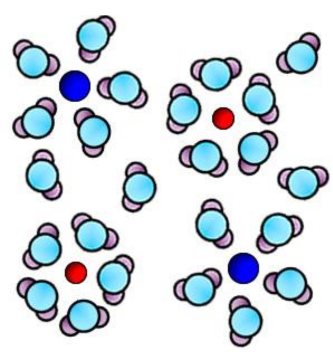




The polarity of water molecules results in a small attraction between the hydrogen atoms of one water molecule and the oxygen atom of another water molecule. If the water molecules are moving slowly enough, this attraction can lead to the formation of solid crystals of ice or snow (left). Because the **hydrogen bonds** holding the molecules of water are relatively weak, ice crystals have a low melting point and a low density.

Although hydrogen bonds are not as strong as ionic or covalent bonds, they are strong enough to give water molecules a certain "stickiness" that makes water difficult to melt or boil. Compared to nonpolar gases such as carbon dioxide and nitrogen, water has a very high melting point (0 °C) and a high boiling point (100 °C). Carbon dioxide, for exmple, transforms from a solid to a gas at -78 °C. It also requires a lot of energy to melt ice, boil water, or raise the temperature of liquid water. It requires 4.18 joules to raise the temperature of a gram of water by one degree Celsius; this is one of the highest specific heat capacities found in nature.

Another useful property of water is its ability to act as a **solvent**. When a **solute** such as sodium chloride (NaCl) is added to water, the hydrogen atoms on water molecules are attracted to the negatively charged chloride ions, while the oxygen atoms are attracted to the positively charged sodium ions.



Eventually the sodium and chlorine ions are pulled apart, a process called **dissociation**. The result is a **solution** of sodium and chloride ions dissolved in water. In the diagram at right, the sodium ions are shown in red and the chlorine ions are shown in blue.

When an ionic compound dissociates in a solvent (such as water), the positive and negative ions are free to move around. Solutions with free ions are known as **electrolytes** and can conduct electricity.

Not all substances can be dissolved in other substances. In general, polar solvents (such as water) will dissolve polar solutes (such as sodium chloride and other salts), while nonpolar solvents (such as oil) can dissolve nonpolar solutes. This principle is summed up by the aphorism "like dissolves like."

Polarity also explains why water does not dissolve oil. When a droplet of water is added to oil, the polar water molecules are attracted to one another and tend to clump together rather than mix with the oil. Water *can* be mixed with oil when a third type of molecule is added that contains both a polar and a nonpolar end. Detergent molecules have this structure and are effective at removing grease and oil from skin, hair, clothing, or dishes. (If you've ever tried to wash your greasy hands without soap, you understand how effective soap can be!)

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1. What properties of water make it essential for living things? ___________________________

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2. How do the freezing and boiling points of water relate to its usefulness as a solvent on

Earth? ____

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3. What makes water a polar molecule? ____

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4. Do you think molecules such as O_2, Cl_2, or F_2 are polar? Explain why or why not.

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5. Suppose you dropped calcium chloride ($CaCl_2$) into water and stirred. Describe what would happen at an atomic level. (Hint: $CaCl_2$ is an ionic salt.)

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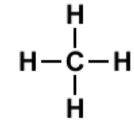
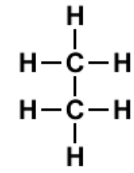
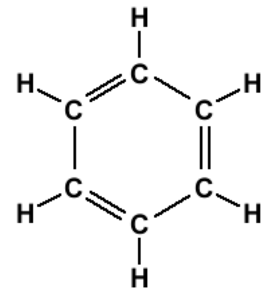
Activity C: Organic compounds


Methane


Ethane


Benzene

Organic compounds are compounds that contain carbon and are mostly produced by living things. (Note: Some carbon-based compounds such as carbon dioxide and calcium carbonate are not considered organic.) Many organic compounds contain a central "spine" of carbon atoms that are bound to hydrogen or hydroxide ions. Several simple organic compounds are shown at right.

Carbon provides an excellent basis for organic molecules because it can form up to four bonds. In comparison, hydrogen and hydroxide (OH^-) can form one bond, while oxygen can form two. Organic molecules can exist as chains, rings, chains of rings, or large branched structures. Some of the largest and most complex organic molecules are the proteins and nucleic acids that form the basis of living things.

Most organic molecules react with oxygen gas to produce carbon dioxide and water. These reactions, called **combustion** reactions, release a great deal of heat energy in the form of heat. Combustion occurs when gasoline is burned in a car engine, when wood is burned in a fireplace, and when sugars are converted to energy inside cells. For example, the balanced equation for the combustion of glucose (a simple sugar) is:

$$C_6H_{12}O_6 + 6O_2 \rightarrow 6H_2O + 6CO_2$$

Most combustion reactions do not occur spontaneously at room temperature. (This is a good thing!) A certain amount of energy is required to break the bonds of the original molecules and enable the molecules of water and carbon dioxide to form. The minimum temperature required for a substance to begin to burn is called the **autoignition temperature** for the substance. Once the reaction has started, the heat produced by the reaction is usually enough to keep the reaction going until all or most of the fuel has burned.

Many of the organic molecules used for energy in industry and transportation are **alkanes**: simple combinations of carbon and hydrogen that are derived from petroleum and natural gas. A group of alkanes called *linear alkanes* consist of a "backbone" of carbon atoms attached to hydrogen atoms. As the chart at right shows, there is a strong relationship between the ignition temperature of a linear alkane, its heat yield, and the length of the carbon backbone.

Alkane	Formula	Ignition temp.	Heat yield per mole
Methane	CH_4	537 °C	802 kJ
Ethane	C_2H_6	515 °C	1,437 kJ
Propane	C_3H_8	450 °C	2,044 kJ
n-Butane	C_4H_{10}	405 °C	2,659 kJ
n-Pentane	C_5H_{12}	309 °C	3,272 kJ
n-Hexane	C_6H_{14}	225 °C	3,856 kJ

Quick check: How does the ignition temperature and heat yield of an alkane depend on its structure? ____

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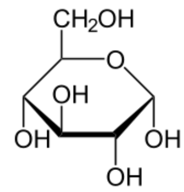
Living organisms produce four main types of organic compounds: **carbohydrates** (sugars and starches), **lipids** (fats), **proteins**, and **nucleic acids** (DNA and RNA). Many of these molecules are very large, containing millions and even billions of atoms. For each of these types of molecules, their structure plays an interesting role in how they are used by living things.

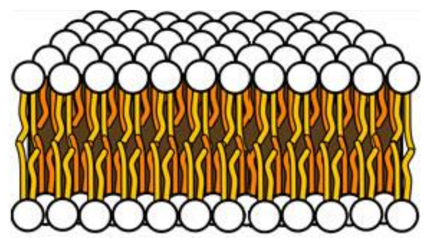
- Carbohydrates are used to provide energy and are also used as structural elements, especially by plants. The simplest carbohydrate is glucose, which has a ring-like structure shown at right. Other sugars consist of either one or two ring units. Complex carbohydrates, such as starches and cellulose, are composed of many of these basic ring units.



  Simple carbohydrates can be digested very quickly, giving you a burst of energy. This energy is quickly used up, which often leads to fatigue. Complex carbohydrates take longer to digest and thus supply a steadier, longer-term energy supply than the energy provided by simple sugars.

- Lipids are used for energy and as the main structural element in cell membranes. The lipids involved in cell membranes, called phospholipids, contain a “head” that is polar and two “tails” that are not. When placed in water, the polar heads are attracted to the water molecules and tend to point outward toward the water molecules, while the tails cluster together away from the water.

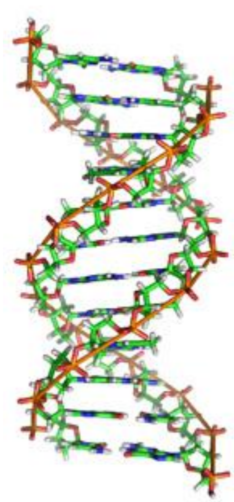
  This can result in a membrane composed of a double layer of phospholipids, or a “phospholipid bilayer,” shown at right. Most biological membranes, including cell membranes, organelle membranes, and the membranes that surround vacuoles and vesicles are composed of phospholipid bilayers.



- Proteins are complex molecules that perform a myriad of functions in the body. Proteins are primary structural elements of muscles, cartilage, and other tissues. **Enzymes** are proteins that catalyze most of the chemical reactions in the body. Many cell organelles are composes mainly of proteins.

  An essential component of a protein’s function is its shape. Proteins are composed of long chains of building blocks called amino acids. These chains fold into a wide variety of complex three-dimensional shapes. The surface of these shapes interacts with other molecules and can provide a substrate for other molecules to interact in a chemical reaction. The surface of hemoglobin contains several sites that bind to oxygen molecules, thus allowing oxygen to be transported to cells in the body.

- Perhaps the most remarkable molecules in living things are the nucleic acids DNA and RNA. DNA molecules, which look like twisted ladders, have two unique properties. First, DNA molecules can encode genetic information in the “rungs” of the ladder structure. Second, DNA molecules have the ability to split apart and form two identical copies of their structure. This ability to replicate allows DNA to be the hereditary material for all life on Earth.



DNA

1. Why is it a good thing that autoignition temperatures tend to be very high? _______________

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2. Carbon is often called "the backbone of life."

   A. Other than being a common element, what property of carbon allows it to be the basis of so many molecules essential to living things? __________________________

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   B. Look at the periodic table. What other elements share this property? ______________

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3. Look at the chemical equation for the combustion of glucose. How does this equation relate to the things that animals must take into their bodies to live?

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4. How does the structure of simple and complex carbohydrates relate to the rate at which they deliver energy when they are digested?

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5. How does the structure of lipids relate to their ability to form membranes? _______________

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6. How does the structure of proteins influence their ability to act as enzymes? ____________

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7. How are the fundamental characteristics of living things related to the structure of the DNA molecule? If possible, discuss your answer with your classmates and teacher.

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