13.3

1 FOCUS

Objectives

13.3.1 **Evaluate** how the way particles are organized explains the properties of solids.

13.3.2 **Identify** the factors that determine the shape of a crystal.

13.3.3 **Explain** how allotropes of an element are different.

Guide for Reading

Build Vocabulary L2

Word Parts The word *amorphous* comes from the Greek prefix *a-*, meaning "not," and the Greek root *morph*, meaning "form." An amorphous substance has no form. Morphing is a special effect used in films or videos to change the shape or form of an object. The branch of biology that deals with form and structure is morphology.

Reading Strategy L2

Relate Text and Visuals Have students use Figure 13.11 to make a table summarizing the characteristics of the seven crystal systems.

2 INSTRUCT

Connecting to Your World

Explain that for some elements, the atoms can be arranged in more than one way. Ask, **Which form of carbon was discovered in 1985?** *(buckminsterfullerene)*

A Model for Solids

Discuss L2

Check students' knowledge of types of compounds by asking them to compare the structures of molecular and ionic compounds. *(Ionic compounds are composed of ions and are usually formed from a metal and a nonmetal. Molecular compounds are composed of molecules formed from two or more nonmetallic elements.)*

13.3 The Nature of Solids

Guide for Reading

Key Concepts

- How are the structure and properties of solids related?
- What determines the shape of a crystal?

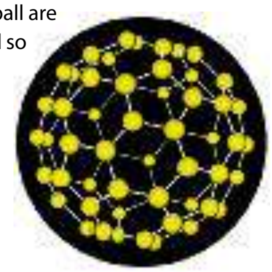
Vocabulary

melting point
crystal
unit cell
allotropes
amorphous solid
glass

Reading Strategy

Building Vocabulary After you have read the section, give an example of a substance that is and one that is not an *amorphous solid.*

Connecting to Your World In 1985, scientists discovered a new form of carbon. They called this form of carbon buckminsterfullerene, or buckyball for short. The molecules in buckyball are hollow spheres. The carbon atoms are arranged so that the pattern on the surface of the sphere resembles the surface of a soccer ball. In this section, you will learn how the arrangement of particles in solids determines some general properties of solids.



A Model for Solids

The general properties of solids reflect the orderly arrangement of their particles and the fixed locations of their particles. In most solids, the atoms, ions, or molecules are packed tightly together. These solids are dense and not easy to compress. Because, the particles in solids tend to vibrate about fixed points, solids do not flow.

When you heat a solid, its particles vibrate more rapidly as their kinetic energy increases. The organization of particles within the solid breaks down, and eventually the solid melts. The **melting point** (mp) is the temperature at which a solid changes into a liquid. At this temperature, the disruptive vibrations of the particles are strong enough to overcome the attractions that hold them in fixed positions. The melting and freezing points of a substance are at the same temperature. At that temperature, the liquid and solid phases are in equilibrium.

Crystal Structure and Unit Cells

Most solid substances are crystalline. In a **crystal** the particles are arranged in an orderly, repeating, three-dimensional pattern called a crystal lattice. Figure 13.10 shows part of the crystal lattice in sodium chloride. **The shape of a crystal reflects the arrangement of the particles within the solid.**

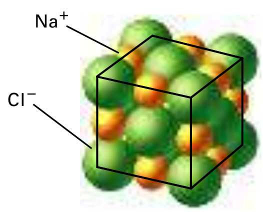


Figure 13.10 The orderly arrangement of sodium and chloride ions within a sodium chloride crystal determines the shape of the crystal. The closely packed ions vibrate about fixed points on the crystal.

Section Resources

Print

- **Guided Reading and Study Workbook,** Section 13.3
- **Core Teaching Resources,** Section 13.3 Review
- **Transparencies,** T145–T147
- **Laboratory Manual,** Lab 21

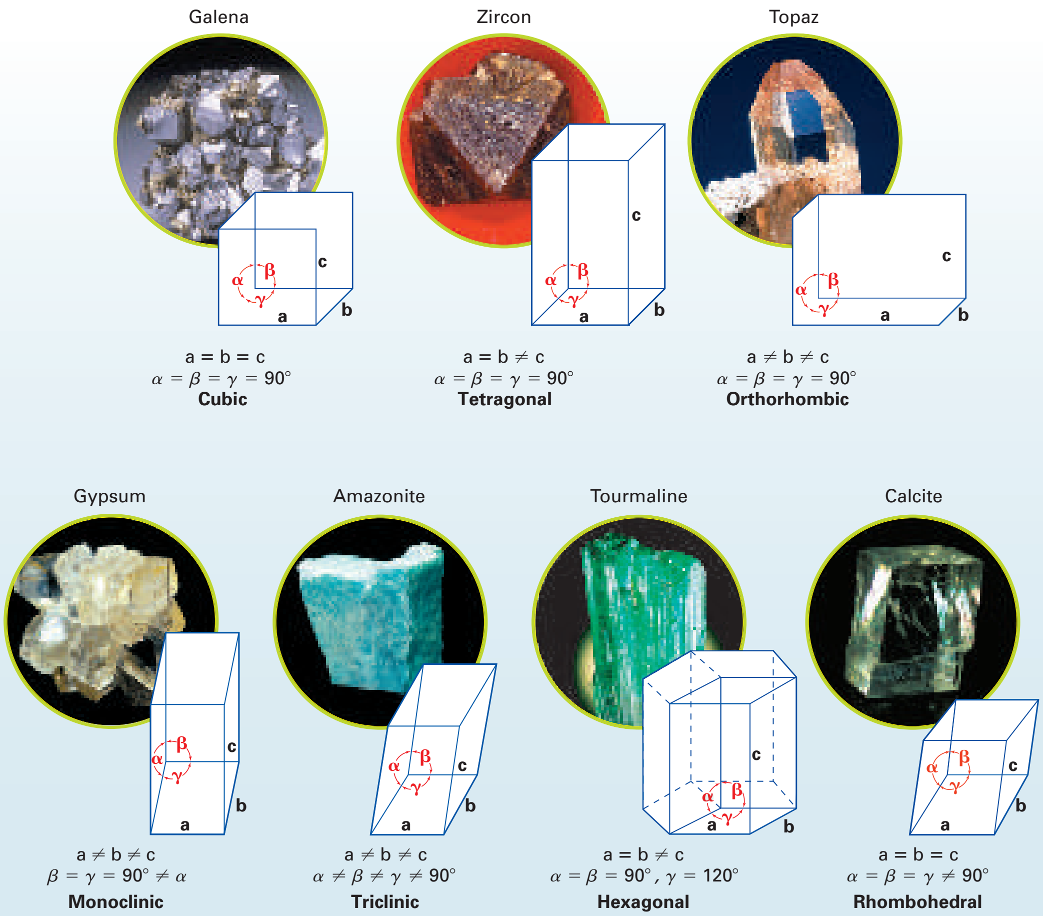
Technology

- **Interactive Textbook with ChemASAP,** Assessment 13.3
- **Go Online,** Section 13.3

The type of bonding that exists between particles in crystals determines their melting points. In general, ionic solids have high melting points because relatively strong forces hold them together. By contrast, molecular solids have relatively low melting points. Not all solids melt, however. Wood and cane sugar, for example, decompose when heated.

Crystal Systems A crystal has sides, or faces. The angles at which the faces of a crystal intersect are always the same for a given substance and are characteristic of that substance. Crystals are classified into seven groups, or crystal systems, which have the characteristic shapes shown in Figure 13.11. The edges are labeled a, b, and c. The angles are labeled α, β, and γ. The seven crystal systems differ in terms of the angles between the faces and in the number of edges of equal length on each face.

Figure 13.11 Crystals are classified into seven crystal systems. **Classifying** ***In which of the systems are all three angles equal to 90°?***



Crystal Structure and Unit Cells

CLASS Activity

Wallpaper Lattices L2

Purpose Students explore an analogy for the crystal lattices in solids.

Materials samples of wallpaper with repeating patterns

Procedure Explain that wallpaper patterns often consist of a small group of images that are repeated to obtain the overall effect. The group of images is like a unit cell in a crystal lattice. Ask students to identify the "unit cells" in wallpaper samples. Show students how to obtain a set of "lattice points" by choosing the same point in each unit of the repeating pattern. The collection of lattice points shows the fundamental arrangement of the units in the pattern. Ask students if they could arrange the components of each unit differently to produce a different "unit cell."

Expected Outcome Students observe two-dimensional arrangements at the macroscopic level that are analogous to the three-dimensional arrangements in crystal lattices.

Differentiated Instruction

Gifted and Talented L3

Have students do research on the crystalline structure and formation of natural, synthetic, and simulated diamonds. Simulated diamonds are known as YAGs (yttrium aluminum garnet). Have students write a short paper comparing the three kinds of crystalline structures.

Answers to...

Figure 13.11 cubic, tetragonal, and orthorhombic

TEACHER Demo

Crystalline Solid Model L2

Materials dishwashing detergent, watch glass, overhead projector, drinking straw

Procedure You can use an aqueous solution of detergent to make a model of a crystalline solid. Place the solution in a watch glass on an overhead projector and use a straw to blow bubbles into the solution. The bubbles form a regular, repeating pattern that is analogous to the arrangement of unit cells in a crystalline solid.

Go Online NSTA SCILINKS

Download a worksheet on **Allotropes** for students to complete, and find additional teacher support from NSTA SciLinks.

The shape of a crystal depends on the arrangement of the particles within it. The smallest group of particles within a crystal that retains the geometric shape of the crystal is known as a **unit cell.** A crystal lattice is a repeating array of any one of fourteen kinds of unit cells. There are from one to four types of unit cells that can be associated with each crystal system. Figure 13.12 shows the three kinds of unit cells that can make up a cubic crystal system.

Go Online NSTA SCILINKS
For: Links on Allotropes
Visit: www.SciLinks.org
Web Code: cdn-1133

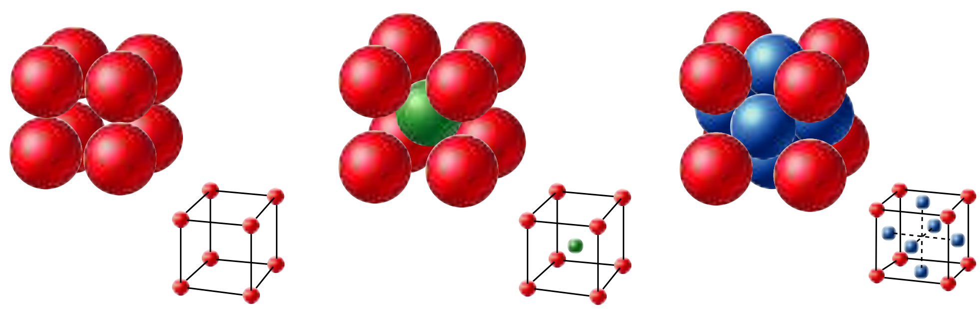
Allotropes Some solid substances can exist in more than one form. A good example is the element carbon. Diamond is one crystalline form of carbon. It forms when carbon crystallizes under tremendous pressure (thousands of atmospheres). A different crystalline form of carbon is graphite. The lead in a pencil is not the element lead; it is graphite. In graphite, the carbon atoms are packed in sheets rather than in the extended three-dimensional array characteristic of diamond.

In 1985, a third form of carbon was discovered in ordinary soot. This form of carbon is called buckminsterfullerene, or buckyball. The 60 carbon atoms in molecules of buckyball are bonded together to form a hollow sphere, or cage. The atoms are arranged in a pattern of hexagons and pentagons on the surface of the cage, similar to the pattern on the surface of a soccer ball. Since 1985, other molecules of carbon with hollow cages have been discovered. The one with 70 carbon atoms is shaped like a football. As a group, these forms of carbon are called fullerenes.

The physical properties of diamond, graphite, and fullerenes are quite different. Diamond has a high density and is very hard. Graphite has a relatively low density and is soft and slippery. The hollow cages in fullerenes give them great strength and rigidity. Diamond, graphite, and buckyballs are allotropes of carbon. **Allotropes** are two or more different molecular forms of the same element in the same physical state. Although allotropes are composed of atoms of the same element, they have different properties because their structures are different. Figure 13.13 compares the structures of carbon allotropes. Only a few elements have allotropes. In addition to carbon, these include the nonmetals phosphorus, sulfur, and oxygen (O_2 and O_3), and the metalloids boron and antimony.

Figure 13.12 The unit cell in a cubic crystal system may be simple cubic, body-centered cubic, or face-centered cubic. In the space-filling models and line drawings, the spheres represent atoms or ions.

Simple cubic | Body-centered | Face-centered



In a simple cubic unit cell, the atoms or ions are arranged at the corners of an imaginary cube.

In a body-centered cubic unit cell, the atoms or ions are at the corners and in the center of an imaginary cube.

In a face-centered cubic unit cell, there are atoms or ions at the corners and in the center of each face of the imaginary cube.

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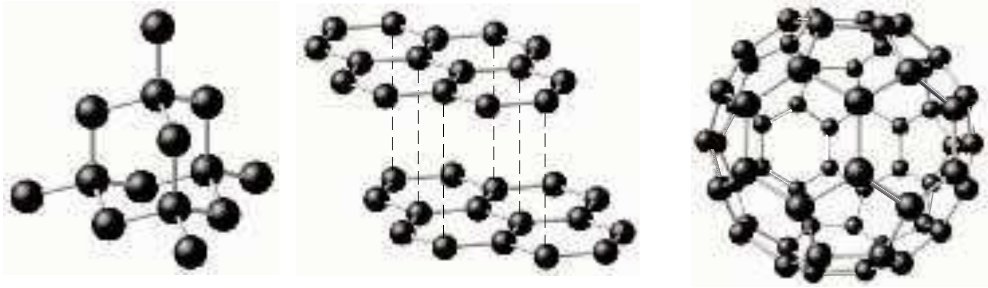
Facts and Figures

LCDs

Liquid-crystal displays (LCDs) are used in calculators and wristwatches. Liquid crystals exhibit properties both of liquids and solids. Interested students may want to find out how liquid crystal displays work, with emphasis on their physical properties.

Diamond   Graphite   Fullerene



In diamond, each carbon atom in the interior of the diamond is strongly bonded to four others. The array is rigid and compact.

In graphite, the carbon atoms are linked in widely spaced layers of hexagonal (six-sided) arrays.

In buckminsterfullerene, 60 carbon atoms form a hollow sphere. The carbons are arranged in pentagons and hexagons.

Figure 13.13 Diamond, graphite, and fullerenes are allotropes of carbon. **Classifying** ***Based on the arrangements of their atoms, explain why the properties of fullerenes are closer to those of diamond than of graphite?***

Non-Crystalline Solids Not all solids are crystalline in form; some solids are amorphous. An **amorphous solid** lacks an ordered internal structure. Rubber, plastic, and asphalt are amorphous solids. Their atoms are randomly arranged. Other examples of amorphous solids are glasses. A **glass** is a transparent fusion product of inorganic substances that have cooled to a rigid state without crystallizing. Glasses are sometimes called supercooled liquids. The irregular internal structures of glasses are intermediate between those of a crystalline solid and those of a free-flowing liquid. Glasses do not melt at a definite temperature. Instead, they gradually soften when heated. This softening with temperature is critical to the glassblower's art. When a crystalline solid is shattered, the fragments tend to have the same surface angles as the original solid. By contrast, when an amorphous solid, such as glass, is shattered, the fragments have irregular angles and jagged edges.

Checkpoint ***What property of glass is important to glassblowers?***

13.3 Section Assessment

15. **Key Concept** In general, how are the particles arranged in solids?
16. **Key Concept** What does the shape of a crystal tell you about the structure of a crystal?
17. How do allotropes of an element differ?
18. What phases are in equilibrium at a substance's melting point?
19. How do the melting points of ionic solids generally compare with those of molecular solids?
20. What is the difference between a crystal lattice and a unit cell?

Elements Handbook

Glass Read about optical glass on page R20. What are the general physical properties of glass? How does optical glass differ from other types of glass? What are some uses of optical glass?

Interactive Textbook

Assessment 13.3 Test yourself on the concepts in Section 13.3.

with ChemASAP

Section 13.3 Assessment

15. Particles in solids are packed tightly together in an orderly arrangement. The locations of the particles are fixed.
16. The shape of a crystal reflects the arrangement of the particles within the solid.
17. Allotropes are different molecular forms of the same element in the same physical state.
18. The liquid and solid states are in equilibrium.
19. Ionic solids generally have higher melting points than do molecular solids.
20. A crystal lattice is a repeating array of unit cells.

Discuss L2

Ask students if they know of any elements besides carbon that exist in different allotropic forms. *(Elemental oxygen occurs as O_2 and O_3, both of which are gases; sulfur can exist as monoclinic or orthorhombic crystals; phosphorus can exist as red or white phosphorus, which are solids at room temperature.)*

3 ASSESS

Evaluate Understanding L2

Ask students to describe the distinguishing characteristics of crystalline solids and amorphous solids. *(Crystalline solids are characterized by an orderly, repeating three-dimensional arrangement of atoms, ions, or molecules. All crystals have a regular shape that reflects the arrangement of particles in the solid. Amorphous solids lack a well-defined arrangement of particles.)*

Reteach L1

Describe how a higher degree of organization and stronger intermolecular attractions between particles distinguish solids from gases and liquids.

Elements Handbook

Glass has the disordered structure of a liquid, but the hardness of a solid. Optical glass is purer than window glass and transmits more light. Optical glass is used in eyeglasses, lenses, and optical fibers.

Interactive Textbook

If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 13.3.

with ChemASAP

Answers to...

Figure 13.13 The hollow cages have a structure that is closer to diamond's rigid structure than to the widely spaced layers in graphite.

Checkpoint Glass gradually softens when heated.

Small-Scale LAB

The Behavior of Liquids and Solids L2

Objective After completing this activity, students will be able to:
- explain some behaviors of liquids and solids.

Skills Focus Observing, inferring, drawing conclusions

Prep Time 20 minutes

Materials plastic Petri dish, water, ice, rubbing alcohol, calcium chloride, graph paper (1-cm), bromothymol blue solution (BTB), vinegar, aqueous ammonia

Advance Prep

- Purchase vinegar, aqueous ammonia, and rubbing alcohol.
- If you purchase BTB as a powder, prepare a 0.04% solution by dissolving 100 mg BTB powder in 16.0 mL 0.01*M* NaOH. Dilute to 250 mL.

Class Time 40 minutes

Safety Be sure students wear goggles and aprons. BTB can stain clothing and skin. The room should be well ventilated and there should be no flames.

Expected Outcomes The answers to the Analyze questions include a description of the expected outcome for each experiment.

Analyze

1. Water in the dish evaporates and condenses into a cloud when it contacts the cold surface under the ice.
2. The drop of water on top of the dish provides enough cooling to cause cloud formation.
3. Water beads up and alcohol spreads because the intermolecular attractions in water are stronger.
4. Calcium chloride absorbs water from the environment in the dish.
5. The many pieces of calcium chloride effectively dry the atmosphere, leaving no water vapor in the dish.

Small-Scale LAB

The Behavior of Liquids and Solids

Purpose

To explore and explain some behaviors of liquids and solids.

Materials

- plastic Petri dish
- water
- ice
- rubbing alcohol
- graph paper, 1-cm
- calcium chloride

Procedure

1. In your notebook, make a copy of the table shown below. Add a column for your observations. In the experiments, you will place substances labeled A and B inside the Petri dish and substances labeled C on top of the dish.
2. For Experiment 1, place one drop of water in the Petri dish. Replace the cover and place a small piece of ice on top of the cover.
3. After a few minutes, observe the interior surface of the Petri dish cover and the contents of the dish. Record your observations. Clean and dry the Petri dish and cover.
4. Repeat Steps 2 and 3 for Experiments 2–5, using the materials listed in the table. For Experiment 4, place the Petri dish on the graph paper so that you can place the water and the calcium chloride about 3 cm apart.

Experiment	Substance A	Substance B	Substance C
1	drop of water		ice cube
2	drop of water		drop of water
3	drop of rubbing alcohol		drop of water
4	drop of water	piece of $CaCl_2$	
5		several pieces of $CaCl_2$	ice cube

Analyze

Using your experimental data, record the answers to the following questions beneath your data table.

1. Explain your observations in Experiment 1 in terms of the behavior of liquids.
2. Why is ice not needed for cloud formation in Experiment 2?
3. What differences do you observe about the behavior of rubbing alcohol in Experiment 3 and the behavior of water in the previous experiments? Explain.
4. What happens to solid calcium chloride in a humid environment?
5. Propose an explanation for no cloud formation in Experiment 5.

You're The Chemist

1. **Analyze It!** Place a drop of water and a drop of rubbing alcohol about 3 cm apart in a Petri dish. Cover the dish and place it on a piece of graph paper. Be careful not to mix the contents. Observe what happens to the size of the water drop over time.
2. **Analyze It!** Add a drop of bromthymol blue (BTB) to a drop of vinegar. What happens?
3. **Design It!** Vinegar is a solution of water and ethanoic acid, CH_3COOH. Design and carry out an experiment to see if ethanoic acid will evaporate from a drop of vinegar. Does ethanoic acid evaporate?
4. **Design It!** Design and carry out an experiment to see if ammonia will evaporate from a drop of aqueous ammonia.

You're the Chemist

1. The water drop increases in diameter over time as the alcohol evaporates and is "captured" by the water drop. The attractions in the resulting mixture are weaker overall.
2. The BTB turns from green to yellow in the presence of vinegar.
3. Place a drop of vinegar and a drop of BTB about 3 cm apart in a Petri dish. Cover and observe. The BTB slowly changes from green to yellow. Ethanoic acid that evaporates is "captured" by the BTB.
4. Place a drop of ammonia and a drop of BTB about 3 cm apart in a Petri dish. Cover and observe. The BTB slowly changes from green to blue. Ammonia that evaporates is "captured" by the BTB.