

## Chapter 5

# States of Matter

Imagine a liquid substance that can harden rapidly and form an exact replica of any container that holds it. The material does not burn, boil, melt, or dissolve in any commonly available acid or solvent. Once it hardens, it won't change under normal circumstances. What sort of material is this? This substance was created in 1907 by a chemist named Leo Baekeland. He called the substance *Bakelite*, and it was the first useful plastic. Since then, many more plastics have been developed for many different uses. It is hard to imagine life today without plastic! Read this chapter to learn about interesting properties of plastics and other matter.



### Key Questions

1. *How are liquids and gases alike, and how are they different?*
2. *Why does a frozen pond have ice on the top and not the bottom?*
3. *Why are solids solid?*



## 5.1 Liquids and Gases

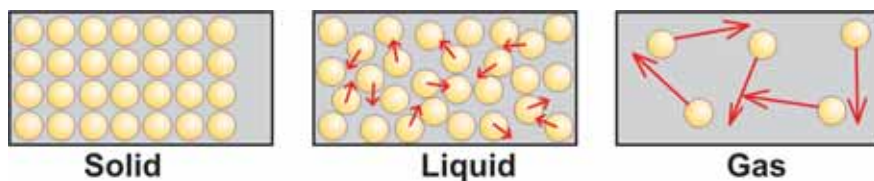
A **fluid** is a form of matter that flows when any force is applied, no matter how small. Liquids are one kind of fluid, gases are another. You have seen water flow from a faucet (or overflow a sink) and felt cool air flow through an open window (or carry the aroma of cooking food into your room). What are some other properties of fluids?

### Atoms and molecules in liquids and gases

**Molecules in a liquid** The molecules in liquid water have more energy and move around much more than do the molecules in ice. In a **liquid**, molecules can slide over and around each other. This is how liquids flow and change shape. But the atoms do not have enough energy to completely break their bonds with one another. That is why liquids have constant volume even though the shape may change.

**Molecules in a gas** As in liquids, molecules in a **gas** are free to move around and so gas flows. However, molecules in a gas have much more energy than molecules in a liquid. On average, each molecule has enough energy to completely break away from its neighbors. That is why gas expands to fill any container (Figure 5.1).

**Density of liquids and gases** In general, a liquid material is a little less dense than the same material in a solid form. This is because the molecules in a liquid move around more and take up a little more space. A gas is usually much less dense than either a liquid or solid. This is because the molecules in a gas are spread out with comparatively large spaces between them.

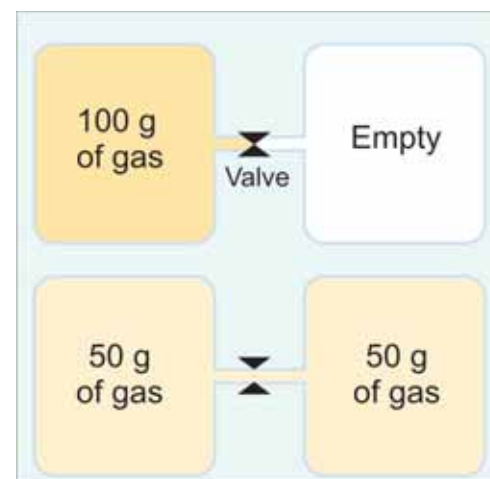


### VOCABULARY

**fluid** - a form of matter that flows when any force is applied, no matter how small. Liquids and gases are fluids.

**liquid** - phase of matter that can flow and change shape but has constant volume.

**gas** - phase of matter with high energy molecules that can expand to fill a container.

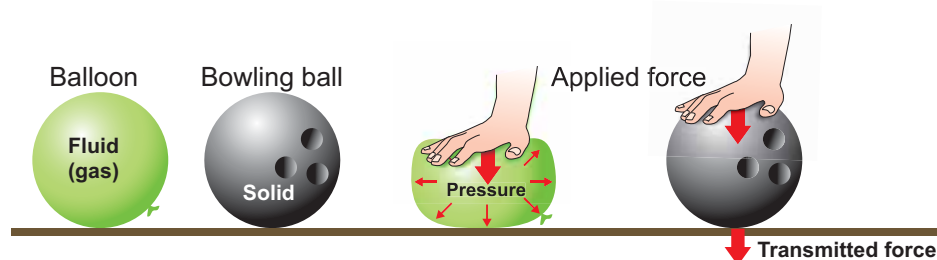


**Figure 5.1:** Gases flow like liquids, but they also may expand or contract to completely fill any container.



## Pressure

**Forces in fluids** Think about what happens when you push down on an inflated balloon. The downward force you apply creates forces that act sideways as well as down. This is very different from what happens when you push down on a bowling ball. The ball transmits the force directly down. Because fluids change shape, forces in fluids are more complicated than forces in solids.

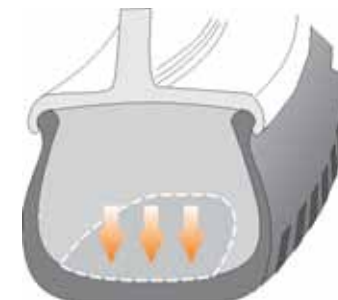


**Pressure** A force applied to a fluid creates **pressure**. Pressure acts in all directions, not just the direction of the applied force. When you inflate a car tire, you are increasing the pressure in the tire. A pressure of 40 pounds per square inch means every square inch of the inside of the tire feels a force of 40 pounds. This force acts up, down, and sideways in all directions inside the tire. The downward portion of the pressure force is what holds the body of the car up (Figure 5.2).

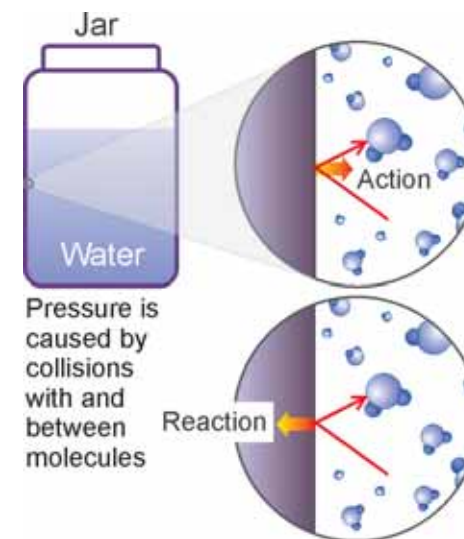
**The molecular explanation** What causes pressure? On the microscopic level, pressure comes from collisions between atoms. If you had a jar of water, and if there were such as thing as an atomic-magnification video camera, you would see trillions of atoms bounce off each other and the walls of the jar every second (Figure 5.3). Every square centimeter of the inside surface of the jar feels a force from the constant impact of atoms. That force is what we feel as pressure. Pressure comes from the constant collisions of many, many atoms.

### VOCABULARY

**pressure** - a distributed force per unit area that acts within a fluid.



**Figure 5.2:** The pressure inside your tire is what holds your car up.



**Figure 5.3:** The molecular explanation of pressure.

## Intermolecular forces

**What intermolecular forces do** There are two types of forces that act between atoms. The strongest forces are between atoms that are bonded together into molecules and compounds. These forces act *within* molecules, such as the forces that hold the hydrogen and oxygen atoms together in a water molecule. A weaker type of force acts *between* molecules, or between atoms that are not bound together in molecules. These in-between forces are called **intermolecular forces**. For example, intermolecular forces hold water molecules together in liquid water and in ice.

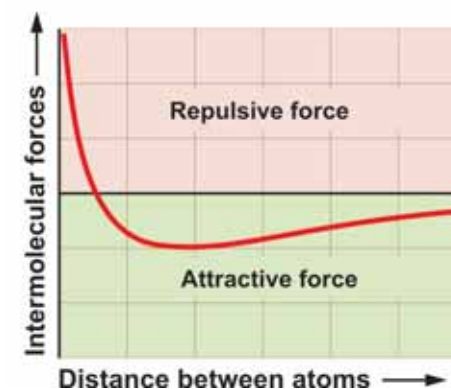
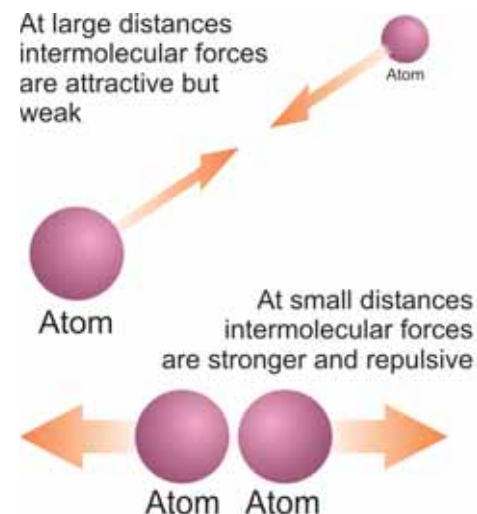
**Properties of intermolecular forces** At distances greater than the size of the molecule, intermolecular forces are attractive and pull molecules together. Once molecules become close enough to touch, intermolecular forces become repulsive. This is what prevents one molecule from overlapping another. Intermolecular forces pull molecules together at long range and hold them apart at short range.

**The role of thermal energy** The phases of matter — solid, liquid, gas — exist because of competition between thermal energy and intermolecular forces. Intermolecular forces always try to bring molecules close. Thermal energy causes molecules to vibrate and spread apart.

**Explaining the phases of matter** When molecules have a lot of thermal energy (high temperature), intermolecular forces are completely overcome and the molecules spread apart, as in a gas. When molecules have a medium amount of thermal energy, they come together to form a liquid. In a liquid, the molecules have enough thermal energy to partially overcome intermolecular forces and move around, but not enough energy to completely escape. When molecules have a low amount of thermal energy, the intermolecular forces dominate and molecules become fixed in place as a solid.

### VOCABULARY

**intermolecular forces** - forces between separate atoms and molecules that are attractive at a distance but repulsive at close range.



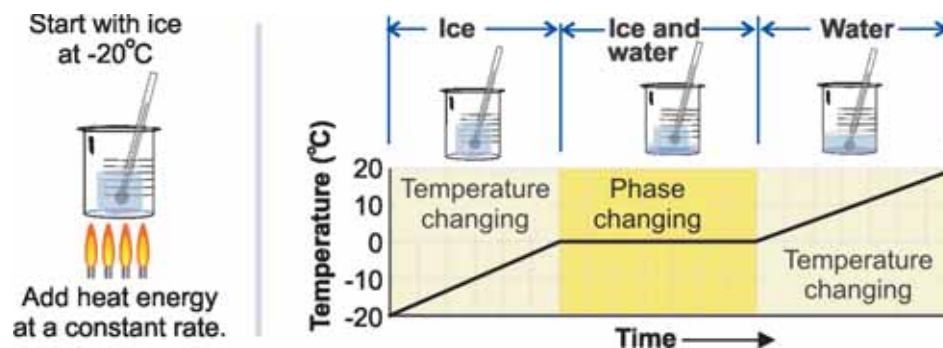


## Melting and boiling

**Melting point** The **melting point** is the temperature at which a substance changes from a solid to a liquid. For example, the melting point of water is zero degrees Celsius. Different substances have different melting points because intermolecular forces have different strengths in different substances. Stronger forces require more energy to break. For example, iron melts at a much higher temperature than water, about  $1,500^{\circ}\text{C}$ . The difference in melting points tells us that the intermolecular forces in iron are stronger than they are in water.

**Boiling** When enough thermal energy is added, intermolecular forces are completely overcome and a liquid becomes a gas. The temperature at which a liquid becomes a gas is called the **boiling point**. For water, the boiling point is 100 degrees Celsius. That is the temperature at which liquid water becomes a gas (steam). Boiling takes place within a liquid as bubbles of gas particles form and rise to the surface (Figure 5.4).

**Changes in state require energy** It takes energy to overcome intermolecular forces. This explains a peculiar thing that happens when a substance melts or boils. As heat energy is added to ice, the temperature increases until it reaches  $0^{\circ}\text{C}$ . Then *the temperature stops increasing*. As you add more heat, more ice becomes liquid water but the temperature stays the same. This is because the added energy is being used to break the intermolecular forces and change solid into liquid. Once all the ice has become liquid, the temperature starts to rise again if more energy is added.



### VOCABULARY

**melting point** - the temperature at which a substance changes from a solid to a liquid.

**boiling point** - the temperature at which a substance changes from a liquid to a gas.



Water melts at  $0^{\circ}\text{C}$  ( $32^{\circ}\text{F}$ )



Water boils at  $100^{\circ}\text{C}$  ( $212^{\circ}\text{F}$ )

Figure 5.4: Melting and boiling.

## Melting and boiling points of common substances

### Range of melting and boiling points

Materials have a wide range of melting and boiling points. This is essential for life because we need some materials to be solid at room temperature, others to be liquid, and still others to be gas. Table 5.1 gives the melting and boiling points for some ordinary materials.

### Water is less dense in solid form



Most materials have a higher density as a solid than as a liquid. Water is a notable exception. Solid water has an open crystal structure that resembles a honeycomb, where each water molecule forms intermolecular bonds with four other water molecules. This creates a six-sided arrangement of molecules. The six-sided crystal form explains the six-way symmetry you see when you examine snowflakes with a magnifying lens.

### Decreasing density

As water freezes, molecules of water separate slightly from each other because of the honeycomb structure. This causes the volume to increase slightly, while the mass stays the same. As a result the density decreases. This explains why water expands when it is frozen and also floats. The density of ice is about  $0.92 \text{ g/cm}^3$  whereas the density of water is about  $1.0 \text{ g/cm}^3$ .

### Water's density and living organisms

Because ice is less dense than liquid water, it floats on the surface of lakes and ponds when they freeze over in winter. When this occurs, the temperature of the water below the ice layer remains above freezing. This is one factor that helps fish and other aquatic organisms to survive over long, cold winters (Figure 5.5).

Oxygen and nitrogen are ordinarily gases at room temperature. If the temperature gets low enough, however, these materials become liquid and even solid. Liquid nitrogen at  $-196^\circ\text{C}$  is used to rapidly freeze or cool materials. Liquid oxygen is used in rockets because in outer space there is no gaseous oxygen for burning rocket fuel.

Table 5.1:

Material	Melting point ( $^\circ\text{C}$ )	Boiling point ( $^\circ\text{C}$ )
Tungsten	3,422	5,555
Iron	1,538	2,861
Copper	1,085	2,562
Aluminum	660	2,519
Lead	327	1,749
Hard plastic	240	300
Candle wax	50	400
Water	0	100
Alcohol	-108	78
Nitrogen	-210	-196
Oxygen	-219	-183
Helium	none	-269

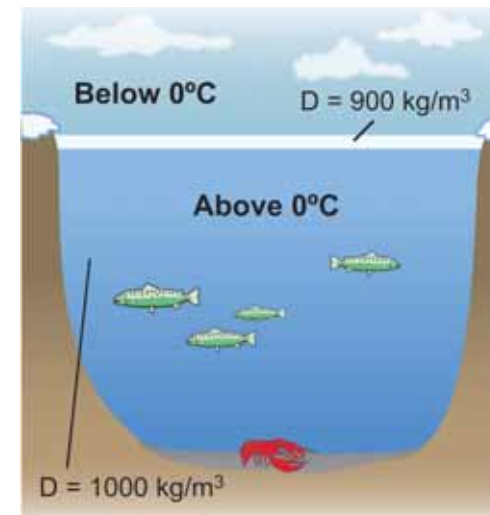


Figure 5.5: Ice floats on the surface of a pond, keeping the water beneath it from reaching freezing temperatures.



## Evaporation and condensation

**Evaporation** **Evaporation** occurs when molecules go from liquid to gas at temperatures *below* the boiling point. Evaporation happens because temperature measures the *average* kinetic energy of molecules. Some have energy above the average and some below the average. Some of the highest-energy molecules have enough energy to break bonds with their neighbors and become a gas if they are near the surface. These high-energy molecules are the source of evaporation.

**Evaporation cools liquids** Evaporation takes energy away from a liquid because the molecules that escape are the ones with the most energy. The average energy of the molecules left behind is lowered. That is why your body sweats on a hot day. The evaporation of sweat from your skin cools your body by carrying away energy (Figure 5.6).

**Condensation** **Condensation** occurs when molecules go from gas to liquid at temperatures below the boiling point (Figure 5.7). Condensation occurs because water vapor molecules with less than the average energy stick to a cool surface forming drops of liquid water. Condensation raises the temperature of a gas because atoms in a gas have more energy than atoms in a liquid. Low-energy atoms condense into liquid, leaving the higher-energy (warmer) atoms in the gas.

**Relative humidity** Ordinary air contains some water vapor. Evaporation adds water vapor to the air. Condensation removes water vapor. The percentage of water vapor in the air is a balance between evaporation and condensation. When air is *saturated*, it means evaporation and condensation are exactly balanced. If you try to add more water vapor to saturated air, it condenses immediately back into liquid again. The *relative humidity* tells how close the air is to saturation. When the relative humidity is 100 percent, the air is completely saturated. That means any water vapor that evaporates from your skin is immediately condensed again, which is why you feel hot and sticky when the humidity is high.

### VOCABULARY

**evaporation** - change from liquid to gas at a temperature below the boiling point.

**condensation** - change from gas to liquid at a temperature below the boiling point.



**Figure 5.6:** *Sweat evaporating from skin removes energy and cools the body.*



**Figure 5.7:** *Dew forms when water vapor in air condenses into droplets.*

## Convection

### What is convection?

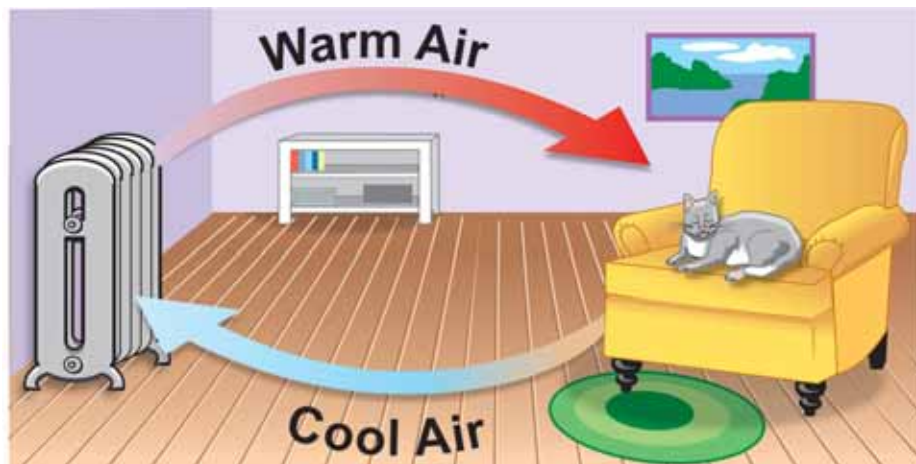
**Convection** is the transfer of heat through the motion of fluids such as air and water. If you have warmed your hands over a fire, you have felt convection. Heat from the flame was transferred to your hand by the upward movement of air.

### Natural convection

Convection occurs because fluids expand when they heat up. Since expansion increases volume, but not mass, the density of a warm fluid becomes lower than the density of surrounding cooler fluid, causing the warmer fluid to float upward. In a pot on the stove, hot water circulates to the top and cooler water sinks to the bottom. This circulating flow is called *natural convection*.

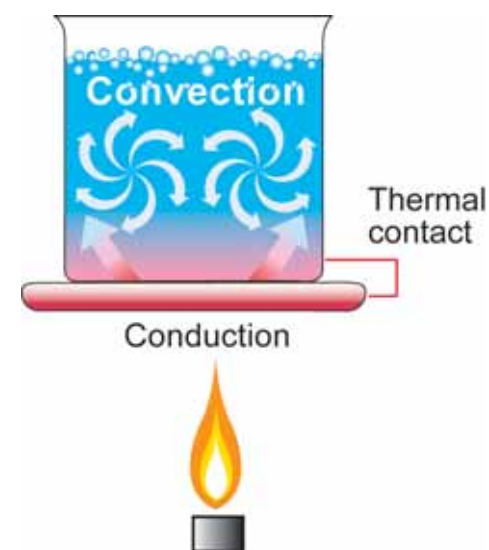
### Forced convection

In many buildings and houses, a boiler heats water that is then pumped throughout the structure to distribute the heat. Since the heat is being carried by a moving fluid, this is another example of convection. However, the flow is created by pumps, which makes this an example of *forced convection*. Natural convection also occurs in the same system. The heat from a hot radiator warms the air in a room by natural convection. The warmer air rises and cooler air is drawn from the far side of the room. The cooler air is then warmed and rises, creating circulation that spreads heat through the room.



## VOCABULARY

**convection** - the transfer of heat through the motion of fluids such as air and water.



**Figure 5.8:** Convection currents in water. The hot water at the bottom of the pot rises to the top and replaces the cold water.





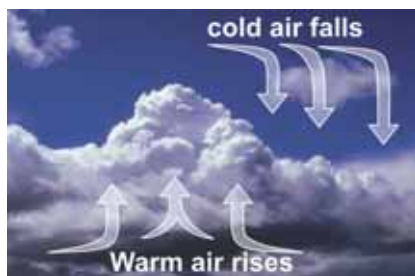
## The atmosphere of Earth

**Air is not “nothing”** Air feels “light” because it is 1,000 times less dense than water. Air may seem like “nothing” but all the oxygen our bodies need and all the carbon needed by plants comes from air. As a tree grows, you will not see soil disappear to provide mass for the tree. After oxygen and hydrogen (from water), the most abundant element in a tree is carbon. All of those carbon atoms come from carbon dioxide ( $\text{CO}_2$ ) in the air.

**Air is a mixture of gases** Air is the most important gas to living things on the Earth. The atmosphere of Earth is a mixture of gases (Figure 5.9). Molecular nitrogen ( $\text{N}_2$ ) and oxygen ( $\text{O}_2$ ) account for 97.2 percent of the mass of air. Argon and water vapor make up most of the rest.

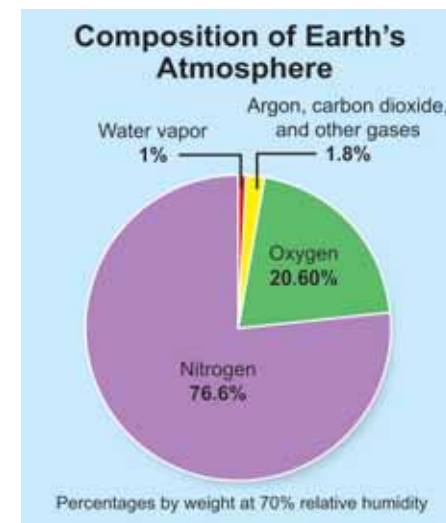
**Atmospheric pressure** Gravity creates pressure because fluids have mass and therefore weight. The Earth’s atmosphere has a pressure due to the weight of air. The density of air is low, but then the atmosphere is more than 80,000 meters deep (Figure 5.10).

### Weather

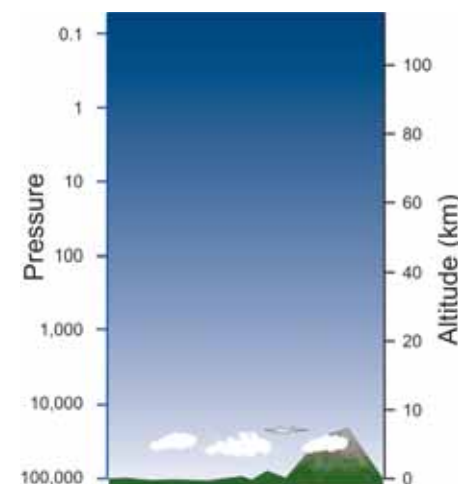


Earth’s weather is created by gigantic convection currents in the atmosphere. Energy from the sun mostly passes through the atmosphere to warm the ground. Air near the ground becomes warm and expands. Warmer air is less dense than cold air and therefore the warm air near the ground rises.

**How rain forms** Over the oceans, the warm air may be nearly saturated with water vapor. At high altitude, the temperature of the atmosphere drops rapidly. As the temperature drops, the ability of the air to hold water vapor also decreases. That excess water vapor condenses to create rain and other forms of precipitation.



**Figure 5.9:** Air is a mixture of gases.



**Figure 5.10:** The change in pressure with altitude in the atmosphere.

## 5.1 Section Review

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1. Describe the movement of the atoms or molecules in a gas.
2. A liquid takes the shape of its container, but why doesn't a liquid expand to fill the container completely?
3. When you push *down* on a confined fluid, you create pressure. In what direction does the pressure act?
4. What happens to the temperature of ice at its melting point while you add heat? While it is melting, does it gain or lose energy?
5. What is evaporation? How is it different from boiling?
6. You place 1 liter of a substance into a 2-liter bottle and tightly cover the bottle. The substance expands until it completely fills the bottle. What state is the substance in?
7. Describe how the density of ice affects our daily lives. Explain why ice forms on the top of ponds and lakes, and not the bottom. Use the following terms in your explanation: density, organized structure, and water molecules. How does this property of water help support life in lakes and ponds?
8. Why doesn't convection occur in a solid material?
9. Why is it more comfortable to exercise on a day when the relative humidity is low?
10. Convection creates circulating currents in a pot of boiling water because \_\_\_\_ water rises and \_\_\_\_ water sinks.
11. Describe how water can be present in all three states at the same time in the atmosphere?
12. Would you expect a higher atmospheric pressure at the top of a mountain in Alaska's Denali national park or near sea level in Florida's Everglades national park?



### CHALLENGE

Visitors to high-altitude regions may suffer from Acute Mountain Sickness (AMS) if they do not allow their bodies to acclimate to the new surroundings. Do some research to find a set of guidelines for preventing this condition. Design a brochure for travelers that describes symptoms of AMS and provides recommendations for preventing and/or treating them.



## 5.2 Solid Matter

You have learned that matter is made up of atoms and molecules. In a solid the atoms or molecules are closely packed and stay in place, which is why solids hold their shape. In this section you will learn how the properties of solids result from the behavior of atoms and molecules.

### The molecular structure of solids

**Why solids are solid** In a **solid**, thermal energy is not enough to overcome intermolecular forces of attraction. Individual molecules are bound together tightly enough that they do not change their positions as they do in liquids and gases. Imagine that the molecules in a solid are connected by springs (Figure 5.11) that represent the intermolecular forces. Thermal energy keeps the molecules moving, but because of those intermolecular forces, they only “spring” back and forth around the same average position. That is why solid materials hold their shape.

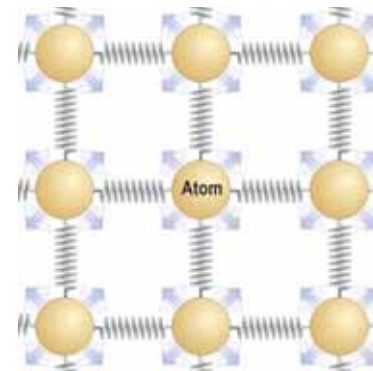
**Solids hold their shape** Because the molecules are bound to each other, all solids have some ability to hold their shape when forces are applied. Some solids, like steel, can hold their shape under much greater forces than others, like rubber (Figure 5.12). Many solids, like plastic, have properties between the softness of rubber and the hardness of steel. Engineers design the molecular structures of solids to have the properties that are needed for given applications.

**Physical properties of solids** Some important physical properties of solids are:

- Density: mass per-unit volume.
- Strength: the ability to maintain shape under great force.
- Elasticity: the ability to stretch and return to the same shape.
- Ductility: the ability to bend without breaking.
- Thermal conductivity: the ability to transmit heat energy.
- Electrical conductivity: the ability to allow electricity to flow.

### VOCABULARY

**solid** - a phase of matter with a definite shape and constant volume.



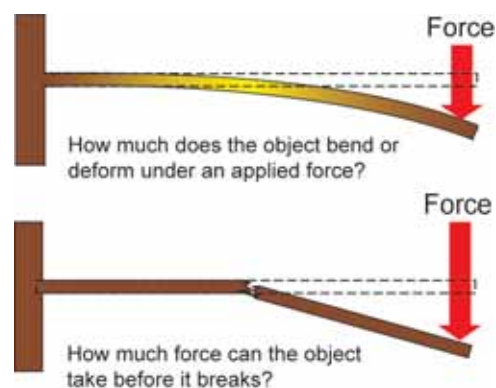
**Figure 5.11:** Atoms in a solid are connected by bonds that act like springs. The atoms still vibrate but stay in the same average position relative to each other.



**Figure 5.12:** Steel and rubber are both solids but they have different strengths, or abilities to hold their shape under force.

## Mechanical properties

### The meaning of “strength”



When you apply a force to an object, the object may change its size, shape, or both. The concept of “strength” describes the ability of a solid object to maintain its shape even when force is applied. The **strength** of an object depends on the answers to the two questions in the diagram.

**Elasticity** If you pull on a rubber band, its shape changes. If you let it go, the rubber band returns to its original shape. Rubber bands can stretch many times their original length before breaking, a property called elasticity. **Elasticity** describes a solid’s ability to be stretched and then return to its original size. This property also gives objects the ability to bounce and to withstand impact without breaking.

**Brittleness** **Brittleness** is defined as the tendency of a solid to crack or break before stretching very much. Glass is a good example of a brittle material. You cannot stretch glass even one-tenth of a percent (0.001) before it breaks. To stretch or shape glass you need to heat the glass until it is almost melted. Heating causes molecules to move faster, temporarily breaking the forces that hold them together.

**Ductility** One of the most useful properties of metals is that they are ductile. A ductile material can be bent a relatively large amount without breaking. For example, a steel fork can be bent in half and the steel does not break. A plastic fork cracks when it is bent only a small amount. Steel’s high **ductility** means steel can be formed into useful shapes by pounding, rolling, and bending. These processes would destroy a brittle material like glass.

### VOCABULARY

**strength** - the ability to maintain shape under the application of forces.

**elasticity** - the ability to be stretched or compressed and then return to original size.

**brittleness** - the tendency to crack or break; the opposite of elasticity.

**ductility** - the ability to bend without breaking.



**BRITTLINESS**

**Figure 5.13:** *Brittleness is the tendency of a solid to crack when force is applied.*



## Crystalline solids

### Crystalline solids

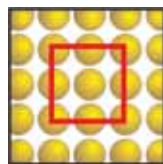


Almost everyone would recognize this solid as a crystal. In science, however, *crystal* has a broader meaning. The atoms (or molecules) in a solid can be arranged in two fundamentally different ways. If the atoms are in an orderly, repeating pattern, the solid is called **crystalline**. Examples of crystalline solids include salts, minerals, and metals. The geode in the picture is a mineral crystal.

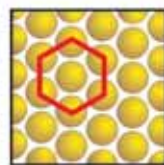
### Many solids are crystalline

*Most naturally occurring solids on Earth are crystalline.* This is most evident when materials exist as single crystals, like salt, for instance. If you look at a crystal of table salt under a microscope, you see it is cubic in shape. If you could examine the arrangement of atoms, you would see the shape of the crystal comes from the cubic arrangement of sodium and chlorine atoms (Figure 5.14). The external shape of a crystal reflects the internal arrangement of atoms and molecules.

### Multicrystalline solids



Cubic crystal



Hexagonal crystal

Metals like steel are also crystalline. They don't look like "crystals" because solid metal is made from very tiny crystals fused together in a jumble of different orientations (Figure 5.14). But on the microscopic level, atoms in a metal are arranged in regular crystalline patterns. The diagram shows two common patterns, cubic and hexagonal.

### Crystal silicon

One of the most important crystalline elements is silicon. Silicon crystals are the foundation of microelectronics. Almost all the electronic circuits in cell phones, computers, and innumerable other devices are made from pure silicon crystals that have been sliced into wafers. Microscopic electric circuits are printed on the silicon wafers. The regularity of the silicon atoms in the crystal is what allows millions of tiny circuits on a computer "chip" to function identically.

## VOCABULARY

**crystalline** - solids that have an orderly, repeating pattern of molecules or atoms.



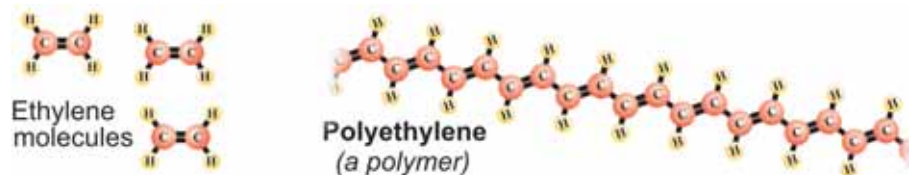
**Figure 5.14:** The shape of a salt crystal is due to the arrangement of sodium and chlorine atoms at the submicroscopic level.

## Polymers

**Plastics** You can probably look around you and see a dozen objects made of plastic. Because plastic can be created with an extremely wide range of physical properties, this material is used for many things. Some plastics are soft, like the polyurethane wheels on in-line skates. Other plastics are hard, like the polycarbonate used to make safety glasses. Still other plastics are slippery, like the nonstick surfaces on cooking pans.

**Amorphous solids** Most plastics are examples of **amorphous** solids. The word amorphous comes from the Greek for “without shape.” Unlike crystalline solids, amorphous solids do not have a repeating pattern of molecules or atoms (Figure 5.15). Other examples of amorphous solids include rubber, wax, and glass.

**Polymers** Plastics belong to a family of materials called **polymers**. The prefix “poly” means many. Polymers are materials in which individual molecules are made of long chains of repeating units. For example, ethylene is a molecule with two carbon and four hydrogen atoms. Polyethylene is a polymer made by joining ethylene molecules together in a long chain. Pure ethylene is a gas at room temperature. Polyethylene is a solid plastic that is used in containers, sandwich bags, and innumerable other applications.

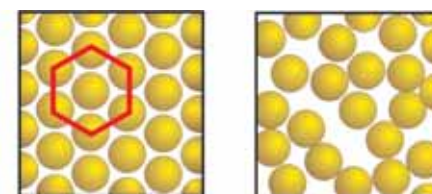


**Why polymers are so useful** Polymers are useful because they have melting points that are well above room temperature but much lower than most metals. In their liquid state, polymers (plastics) can be easily formed using molds (Figure 5.16). When the liquid cools and solidifies, the plastic object has good strength and elasticity. By altering the recipe and molecular structure it is possible to design polymers that have an incredible variety of physical properties.

### VOCABULARY

**amorphous** - solids that do not have a repeating pattern of molecules or atoms.

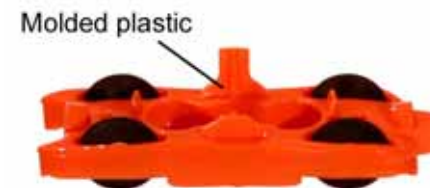
**polymer** - material in which individual molecules are made of long chains of repeating units



**Crystalline**  
(repeating pattern)

**Amorphous**  
(no pattern)

**Figure 5.15:** The difference between crystalline solids and amorphous solids.



**Figure 5.16:** Making a molded plastic part.



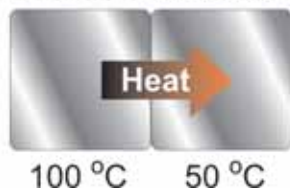
## Heat conduction in solids

**What is conduction?** **Heat conduction** is the transfer of heat by the direct contact of particles of matter. When you hold a warm mug of tea or cocoa, you experience conduction. Heat is transferred from the mug to your hand. Conduction occurs between two materials at different temperatures when they are touching each other. Heat can also be transferred by conduction *through* materials. If you stir hot cocoa with a metal spoon, heat is transferred *from* the cocoa *through* the spoon and *to* your hand.

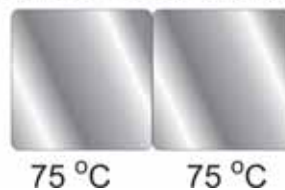
**How does conduction work?** Picture yourself placing a spoon into a mug of hot cocoa. The molecules in the cocoa have a higher average kinetic energy than those of the spoon. The molecules in the spoon exchange energy with the molecules in the cocoa through collisions. The molecules in the spoon spread the energy up the handle of the spoon through the intermolecular forces between them. Conduction works through collisions and through the intermolecular forces between molecules.

**Thermal equilibrium** As the collisions continue, the molecules of the hotter material (the cocoa) lose energy and the molecules of the cooler material (the spoon) gain energy. The kinetic energy of the hotter material is transferred, one collision at a time, to the cooler material. Eventually, both materials are at the same temperature. When this happens, they are in thermal equilibrium. **Thermal equilibrium** occurs when two bodies have the same temperature. No heat flows in thermal equilibrium because the temperature is the same in the two materials.

Heat flows as long as there are temperature differences



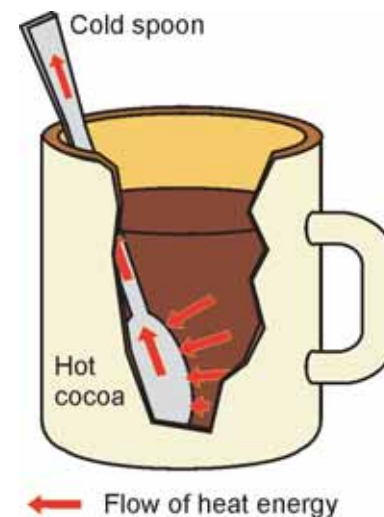
Two objects are in **thermal equilibrium** when they have the same temperature



### VOCABULARY

**heat conduction** - the transfer of heat by the direct contact of particles of matter.

**thermal equilibrium** - a condition where temperatures are the same and no heat flows.



**Figure 5.17:** Heat flows by conduction from the hot cocoa into the spoon and up its handle.

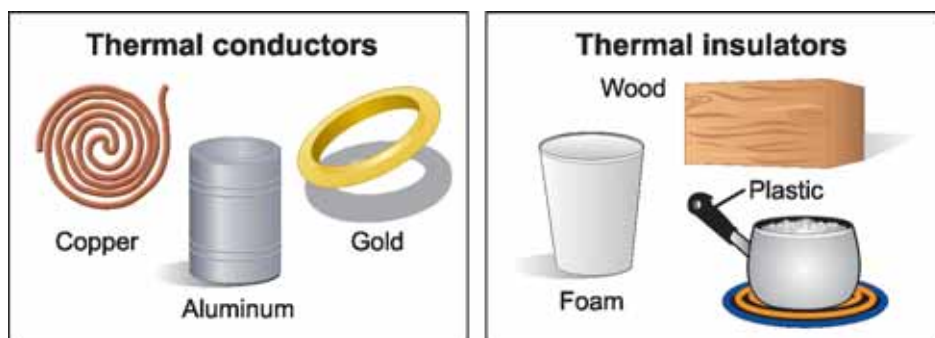
## Thermal conductors and insulators

**Which state of matter conducts best?**

Although conduction also occurs in liquids and gases, solids make the best conductors because the molecules in a solid are packed close together. Because molecules in a gas are spread so far apart, relatively few collisions occur, making air, for instance, a poor conductor of heat. This explains why materials used to keep things warm, such as fiberglass insulation and down jackets, have thousands of air tiny spaces inside (Figure 5.18).

**Thermal conductors and insulators**

Materials that conduct heat easily are called thermal conductors and those that conduct heat poorly are called thermal insulators. For example, metal is a thermal conductor, and a foam cup is a thermal insulator. The words *conductor* and *insulator* are also used to describe a material's ability to conduct electrical current. In general, good electrical conductors like silver, copper, gold, and aluminum are also good thermal conductors.

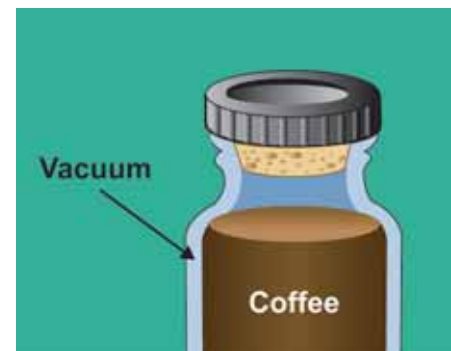


**Heat conduction cannot occur through a vacuum**

Conduction cannot occur in the vacuum of space where there is no matter. A thermos bottle keeps liquids hot for hours using a vacuum. A thermos is a container consisting of a bottle surrounded by a slightly larger bottle. Air molecules have been removed from the space between the bottles to create a vacuum. This prevents heat transfer by conduction. A small amount of heat is conducted through the cap and the glass where the two walls meet, so eventually the contents will cool off (Figure 5.19).



**Figure 5.18:** Because air is a poor conductor of heat, a down jacket keeps you warm in cold winter.



**Figure 5.19:** A thermos bottle uses a vacuum to prevent heat transfer by conduction or convection.





## 5.2 Section Review

1. Observe the world around you and find a useful object made of an elastic material. Would this object work if it was made of a brittle material? Why does the elasticity of the material allow this object to work so well?
2. Golf balls are made with a rubber core. Why does it make no sense to make the core of glass?
3. What property of copper allows it to be pulled into thin wire?
4. Rubber and steel are both elastic, yet engineers do not design bridges out of rubber. Explain why.
5. Name one example of a material for each set of properties:
  - a. high elasticity and ductile.
  - b. amorphous and brittle.
  - c. crystalline and brittle.
  - d. crystalline and elastic.
6. Describe how the arrangement of the atoms and molecules in a sugar crystal differ from those in a piece of plastic.
7. You are an engineer who must choose a type of plastic to use for the infant car seat you are designing. Name two properties of solids that would help you decide, and explain why each is important.
8. In nature, heat will always flow from a:
  - a. cold object to a warm object.
  - b. small object to a large object.
  - c. warm object to a cold object.
9. Why do you think pots and pans for cooking are made out of metal?
10. What properties make a material a good thermal insulator? Give three examples of good thermal insulator.
11. Air spaces between the feathers of a down-filled coat cause the coat to be a good thermal \_\_\_\_.
12. Name one example of heat transfer through conduction.

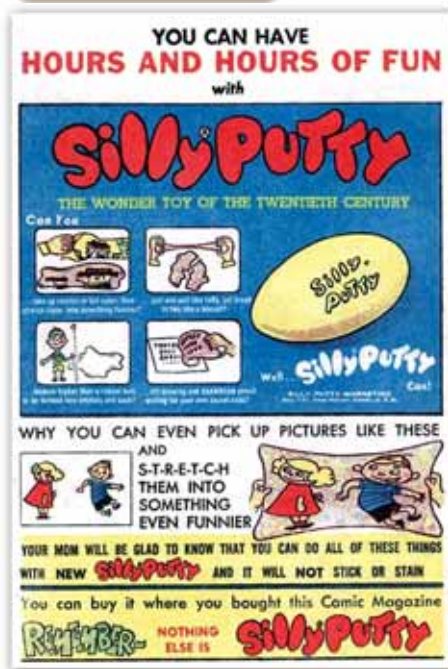


### CHALLENGE

Find out how much insulation is recommended for homes in your community. Where is the most insulation recommended: in the ceiling, walls, or floors? Using what you know about heat transfer, explain why.

CHEMISTRY  
CONNECTION

## Silly Putty®: Solid or Liquid?



Silly Putty—it’s been a popular party favor for more than fifty years. Your parents probably played with it when they were kids. Some people call it America’s longest lasting fad.

It’s easy to understand why people like Silly Putty. Roll it into a ball, and you can bounce it around the room. Pull on it slowly and it will stretch out like a long lazy snake. Give it a quick yank and it will break with a satisfying *snap*.

Have you ever tried to smash a ball of Silly Putty with a hammer? It keeps its shape every time. However, if you gently press on it with your thumb, you can flatten it easily. If you leave a ball of Silly Putty on your dresser overnight, in the morning you’ll see that it flattened out by itself while you were sleeping.

### What’s going on here?

Silly Putty isn’t easy to categorize. It holds its shape when hammered, yet flows into a puddle when left alone overnight. No wonder the people who make Silly Putty call it “a real solid liquid.”

Rheologists (scientists who study how matter flows and/or deforms) have another term for Silly Putty: it’s a *viscoelastic* liquid.

*Viscoelastic* is a compound word (like *snowman*). The *visco-* part comes from the word *viscous*, which means “resistant to flow.”

Thick, goeey, slow-flowing liquids like hot fudge sauce are *viscous*. Silly Putty is like that.

You’re probably already familiar with the second half of the word. *Elastic*, in physics terms, describes a material that returns to its original shape when deformed.

So, rheologists describe Silly Putty as a slow-flowing, elastic liquid.

### How did it get that way?

It’s not too surprising that Silly Putty bounces, because it was accidentally invented by a chemist looking for a substitute for rubber. In 1943, James Wright, a researcher for General Electric, dropped some boric acid into silicone oil, creating a goeey compound.

This compound, first called “nutty putty,” was sent to engineers around the world—but no practical uses were found. In 1949, a man named Peter Hodgson decided to sell it as a toy. He borrowed \$147 to buy a batch from General Electric, divided the batch into one-ounce lumps, and placed each lump into a plastic egg. He renamed the compound “Silly Putty” after the main ingredient, silicone.

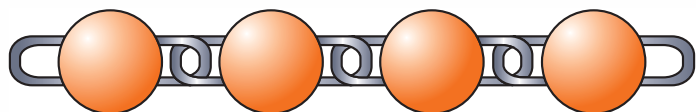
A *New Yorker* magazine reporter wrote an article about Silly Putty in 1950, and afterward Hodgson received 250,000 orders in three days. Silly Putty was a hit!

### Inside Silly Putty

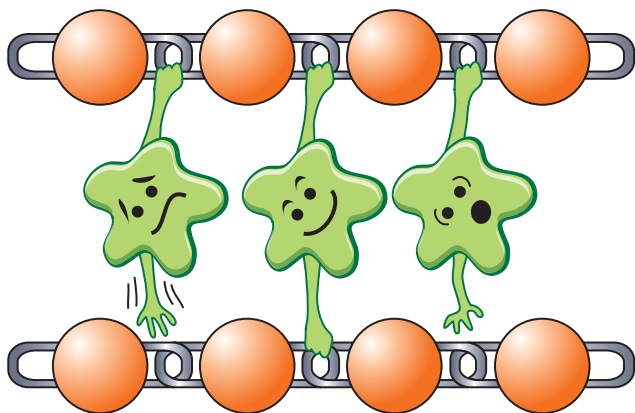
The silicone oil used to make Silly Putty is known to chemists as polydimethylsiloxane, or PDMS. PDMS is a



polymer, which means each molecule is made up of long chain of identical smaller molecules.



When boric acid is added to the long chains of PDMS, boron crosslinks begin to form. This means that the boron hooks chains of PDMS molecules together like this:



These boron crosslinks are not very strong. Remember that molecules in solids and liquids are always in motion. This motion breaks boron crosslinks, but over time new crosslinks form. This action is called *dynamic* (changing) *crosslinking*.

Because of this dynamic crosslinking, Silly Putty reacts one way to quick forces and another way to long-acting forces.

When you strike Silly Putty with a hammer, the Silly Putty reacts like an elastic solid: it bounces back. That's because most of the boron crosslinks remain in place during the split second of the hammer's strike.

When you leave a ball of Silly Putty untouched overnight, the boron crosslinks that help Silly Putty hold its shape have about eight hours to break down. Over that time, molecular motion

breaks many of the original crosslinks. Gravitational force constantly pulls the PDMS molecules downward, and in the morning you're left with a Silly Putty puddle.



#### Questions:

1. Silly Putty does have some practical uses, despite the fact that engineers in the 1940's couldn't think of any. Find out about these using the Internet, or come up with one on your own.
2. Use the Internet to find out about a man named Earl Warrick. What was his role in the invention of Silly Putty?
3. The crew of Apollo 8 took some Silly Putty to the moon. Use the Internet to find out how the astronauts used it.

\*Permission granted by Binney and Smith to publish trademark named Silly Putty.


**CHAPTER  
ACTIVITY**

## Make Your Own Viscoelastic Liquid

The exact recipe for Silly Putty is kept secret, but you can make your own viscoelastic liquid with ingredients you may have around the house. The homemade compound uses different molecules to form the polymer chains, but the boron crosslinks work the same way.



### What you will need

White glue and water solution made in a 1:1 ratio  
 Borax and water solution: mix 5 mL of Borax in 60 mL of water (Borax powder is found in supermarket laundry detergent aisles)  
 8-ounce paper cup  
 Stirring stick (A tongue depressor works well)

### What you will do

1. Pour 60 mL of the white glue solution into the cup.
2. Add 30 mL of the borax solution.
3. Stir the mixture for 2-3 minutes.
4. Remove the mixture from the cup and knead it with your hands. It will be sticky at first. Keep kneading until it is easy to pull the Putty away from your hands in a single lump.

### Applying your knowledge

- a. Develop a class procedure for measuring the Putty's bounciness and stretchiness. Compare your results with your classmates'. Was every batch of Putty the same? If not, can you suggest reasons for the differences?
- b. There are lots of experiments you could do with your home-made Putty. Here are a few examples:
  - a. How does temperature affect bounciness?
  - b. Does stretchiness change over time?
 Choose one of these questions or make up your own question to answer about your Putty.
- c. State your hypothesis.
- d. Develop a procedure for testing your hypothesis. Remember, only one variable can be changed!
- e. Create a data table to record your results. Here's a sample:

Temperature	Bounce height when dropped 50 cm
-10°C	
5°C	
20°C	
35°C	
50°C	

- f. Carry out your experiment and record your results. What conclusion(s) can you draw?
- g. Share your results with your classmates.

# Chapter 5 Assessment

## Vocabulary

Select the correct term to complete the sentences.

melting point	boiling point	evaporation
intermolecular forces	convection	pressure
condensation	fluid	strength
heat conduction	thermal equilibrium	ductility
crystalline	amorphous	brittleness
elasticity		

### Section 5.1

- When a substance changes from gas to liquid at a temperature below its boiling point, \_\_\_\_ has taken place.
- The temperature at which a substance changes from liquid to gas is its \_\_\_\_.
- The transfer of heat through the motion of fluids such as water or air is known as \_\_\_\_.
- A scientist would call the change of a substance from liquid to gas at a temperature below its boiling point \_\_\_\_.
- The temperature at which a substance changes from solid to liquid is its \_\_\_\_.
- A form of matter that flows when any force is applied to it is called a(n) \_\_\_\_.
- A force that acts in all directions and comes from the constant collisions of many atoms is \_\_\_\_.
- \_\_\_\_ are what hold water molecules together in liquid water and in ice.

### Section 5.2

- Transfer of heat by direct contact between particles of matter is called \_\_\_\_.

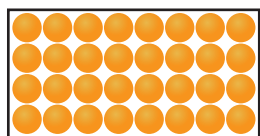
- A solid whose atoms are arranged in an orderly, repeating pattern would be called a \_\_\_\_ solid.
- When heat does not transfer from one object to another because both objects are at the same temperature, the condition is called \_\_\_\_.
- The ability to bend without breaking is known as \_\_\_\_.
- Solids whose atoms or molecules have **no** orderly, repeating pattern are called \_\_\_\_ solids.
- \_\_\_\_ is a solid's ability to be stretched and then return to its original size.
- The tendency of a solid to crack or break before stretching very much is known as \_\_\_\_.
- The ability of an object to maintain its shape even when force is applied is \_\_\_\_.

## Concepts

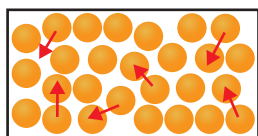
### Section 5.1

- For each phase or form, identify the matter as liquid (**L**), gas (**G**), or both (**B**):
  - \_\_\_\_ definite volume but changes shape to fit the shape of the container.
  - \_\_\_\_ generally has the lower density of the two forms.
  - \_\_\_\_ expands to completely fill any container.
  - \_\_\_\_ bonds between atoms are not completely broken.
  - \_\_\_\_ may be called a fluid.
  - \_\_\_\_ molecules of this form have more energy.
  - \_\_\_\_ force exerted on this form is transmitted as pressure in all directions.
- Explain what causes pressure in a fluid on a microscopic level. In what direction does the pressure act on the fluid?

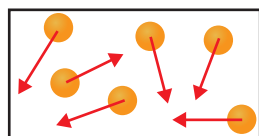
3. Describe the two types of forces that act between atoms.
4. Use the words *attractive* and *repulsive* to make the following statements true:
  - a. At distances greater than the size of the molecules, intermolecular forces are \_\_\_\_.
  - b. Once molecules are close enough to touch, intermolecular forces become \_\_\_\_.
5. What is the result of intermolecular forces being repulsive and attractive at varying distances?
6. How do thermal energy and intermolecular forces behave with each other?
7. What phase of matter has a low amount of thermal energy, which allows the intermolecular forces to dominate?
8. The solid, liquid, and gaseous phases of a material each have different strengths of intermolecular force compared to the amount of thermal energy. For each diagram below, rank as low, medium, or high:
  - a. the amount of intermolecular force, and
  - b. the amount of thermal energy



**Solid**



**Liquid**



**Gas**

9. Name one factor that causes iron to have a higher boiling point than water.
10. As heat energy is added to ice, the temperature increases until it reaches 0°C. What happens at this point and why?
11. Why is ice less dense than water?

12. Why is oxygen transported as a liquid in rocket ships instead of as a gas?
13. How does the evaporation of sweat on a hot day help to cool your body?
14. If a meteorologist describes the air as saturated, what does he or she mean?
15. Give one example of natural convection.
16. What type of heat transfer is represented in the diagram below?



17. From where does the carbon in a tree come from?
18. What two gases make up the majority of the atmosphere?
19. How does rain form?

### Section 5.2

20. Why can solid materials hold their shape?
21. How does glass behave differently when it is solid versus when it is heated? Why?
22. What crystal forms the basis for much of the microelectronics industry? What makes it so valuable?
23. What physical properties make plastics such a valuable material for manufacturing goods?

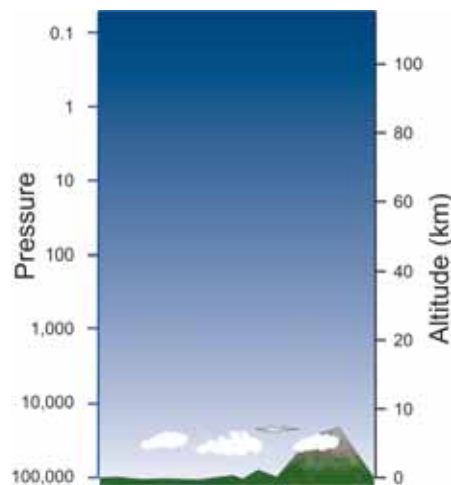


24. Describe an example using the terms *conduction* and *thermal equilibrium*. Identify each of the following as a thermal conductor or insulator:
- copper pipe
  - styrofoam cup
  - wooden spoon
  - a vacuum space
  - aluminum pot

## Problems

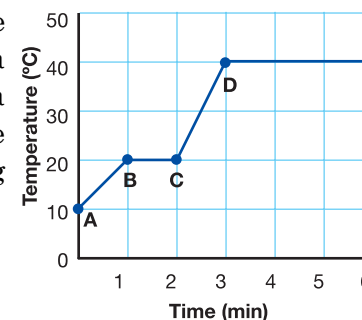
### Section 5.1

- According to the diagram, most of our weather occurs below what altitude?



- The air in your school can hold  $20 \text{ g/m}^3$  of water when it is saturated at  $70^\circ\text{F}$ . What is the *relative humidity* of the air in your school at  $70^\circ\text{F}$  if the moisture content is  $5 \text{ g/m}^3$ ?

- The diagram to the right shows a graph of temperature vs. time for a material which starts as a solid. Heat is added at a constant rate. Using the diagram, answer the following questions:



- During which time interval does the solid melt?
- During which time interval is the material all liquid?
- What is the boiling point of the substance?
- Does it take more heat energy to melt the solid or boil the liquid?

### Section 5.2

- Based on the definition of a vacuum, if you were to put an alarm clock inside a vacuum and set it to ring, what would happen when the alarm went off?
- The diagram shows a cup of cocoa at  $65^\circ\text{C}$ . The arrows show the direction of heat conduction as a cold spoon is placed into the cup. What could the temperature of the spoon be?
  - $75^\circ\text{C}$
  - $65^\circ\text{C}$
  - $55^\circ\text{C}$
- Which make the best thermal conductor: solids, liquids, or gases? Why?

