

has fallen—that is, the depth of water on flat ground after the rainfall would have equaled one millimeter if none of it had been lost.

Properties of Gases

Before beginning a detailed study of the nature of gases and gas laws, let's review what you already know about gases and their properties.

The four phases of matter are solid, liquid, gas, and plasma. A solid has a definite volume and a definite shape. The molecules which form a solid are tightly bound together, are not easily compressed, and move very little. When a solid is heated, the molecules begin moving faster and farther apart until the solid becomes a liquid. A liquid, which has a definite volume but no definite shape, can be poured and will flow. The molecules of a liquid are bound less tightly together and move more freely than those of a solid.

When a liquid is heated, its molecules begin moving even faster and farther apart until the liquid becomes a gas. The term "gas" normally refers to those substances which are in the gas phase at normal air pressures and temperatures. The term "vapor" normally refers to those substances which are in the liquid phase at normal pressures and temperatures, but which have been heated to form a gas. Since hydrogen is in the gas phase at normal temperatures, it is termed a gas. Water is in the liquid phase at normal temperatures, but when it boils and becomes a gas, it is called a vapor. In this PACE, the term "gas" will be used to refer to both vapors and gases.

A gas, which has neither a definite volume nor shape, will expand in every direction and will continue expanding indefinitely if it is not contained. A gas will expand to fill completely any container in which it is placed and will leak from the container at any opening, no matter how small. Gases are completely mixable and diffuse very rapidly,

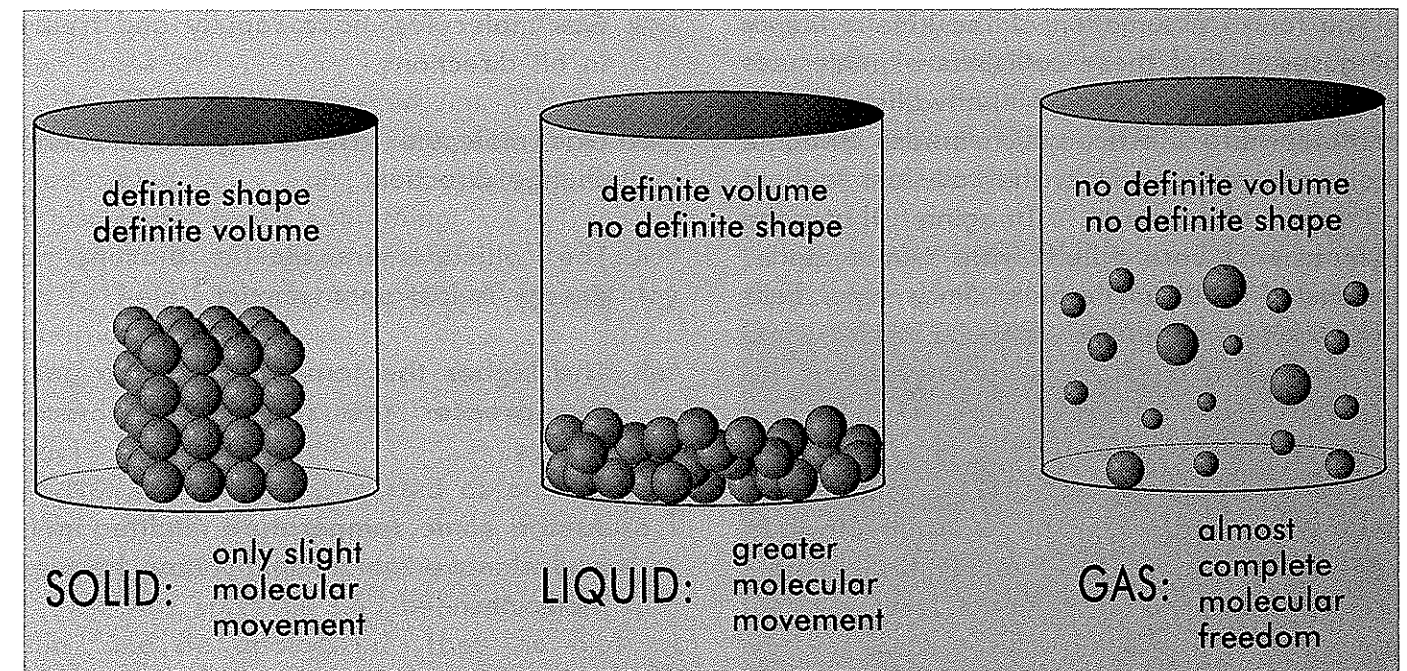
as Jim Bachman discovered at his grandmother's home—the tempting aroma of the warm cinnamon rolls had permeated the entire house. Gases can easily flow from one place to another. Gases have mass, but can be compressed easily because their molecules are so far apart. Gases expand and contract with changes in air temperature and pressure. The force of gravity has a limited, but real, effect on gases. Earth's atmosphere is held in place by the force of gravity.

Most gases are not found as single atoms in the natural state, but as molecules of two or more atoms. The most common forms of oxygen, hydrogen, and nitrogen are composed of two atoms— O_2 , H_2 , and N_2 . Ozone, another form of oxygen, is labeled O_3 . Each ozone molecule contains three oxygen atoms.

Kinetic Theory of Gases

In 1827 Scottish botanist Robert Brown made a startling discovery. As he studied pollen grains in a drop of water under the microscope, he noticed that the grains were moving back and forth in a random, zigzag way. These pollen grains did not seem to be moving of their own accord, but appeared to be moving because they were being bumped by some unseen objects. What Brown observed was evidence of the fact that molecules are constantly in motion. This observable movement of tiny particles of matter as they are bumped by molecules is called the *Brownian movement*, or Brownian motion. As the molecules of water move, they bump the pollen grains and cause the Brownian movement.

Because of Brown's discovery of Brownian movement, scientists developed the kinetic theory of matter—that all matter consists of moving molecules. The word kinetic comes from the Greek word *kīnētikós* which means motion. As men observed and experimented with gases, their combined efforts gradually led to the formulation of the kinetic theory of



Comparison of molecules of solid, liquid, and gas

gases, which is based on the kinetic theory of matter. Like much of science, this theory is only a model—that is, it is not a provable definition, but only serves to help explain the behavior of gases.

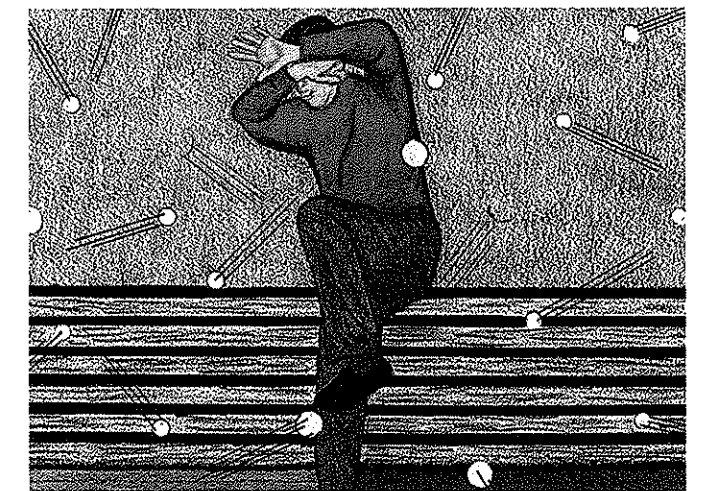
The kinetic theory includes seven basic assumptions. The first assumption is that gases consist of molecules which are much more widely separated than those of solids or liquids. The volume of the molecules in a gas makes up only a small portion of its total volume; the rest is empty space. In air at sea level, for example, the actual volume of the molecules is only about 0.1 percent of the volume of the space which they occupy. The remaining 99.9 percent of the volume occupied by a gas is empty space.

Because of the large amount of empty space in a gas, doubling the size of the molecules does not make a noticeable change in the distance between them. For that reason, many of the properties which apply to one gas apply equally well to another.

The second basic assumption of the kinetic theory of gases is that gas molecules are always in motion. They move rapidly, in all directions, and most of them at a relatively

constant speed. Because the molecules are able to move freely, a gas will expand indefinitely until it fills all the space available to it.

The third assumption of the kinetic theory of gases is that gas molecules collide with each other and with the walls of their container billions of times each second. At room temperature, a typical air molecule moves at a speed of approximately 1,770 km/h. At these tremendous speeds, the collisions cause the molecules to change direction randomly. It is as if hundreds of thousands of table tennis balls were flying about a gymnasium at tremendous speeds.



The fourth assumption of the kinetic theory of gases is that these collisions of molecules with each other or with the walls of their container are elastic, which means that the molecules rebound from the collisions without a loss of energy. Imagine that the gymnasium were filled with "super balls" instead of table tennis balls. Since super balls are much more elastic, their bouncing would continue at a much more rapid rate and for a much longer period of time. If molecular collisions were not elastic, the molecules would lose energy with each impact and eventually settle to the bottom of their container. Since gas molecules remain uniformly distributed, scientists theorize that molecular collisions must be elastic.

The fifth assumption of the kinetic theory of gases is that the molecules gain kinetic energy when the temperature of a gas is increased. Because the kinetic energy increases, scientists conclude that raising the temperature of a gas increases the speed of its molecules.

The sixth assumption is that the size of the molecules also influences their speed. If two gases, one with lighter molecules than another, have the same temperature, the molecules of the lighter gas will move more rapidly than the heavier molecules. Because hydrogen molecules are 1/16 as heavy as oxygen molecules, hydrogen molecules move four times as rapidly as oxygen molecules at the same temperature.

The seventh assumption of the kinetic theory of gases is that the molecules of a gas show little attraction or repulsion for each other. Although they should attract one another, gas molecules are so widely separated and moving so rapidly that their attractive forces are too small to affect calculations.

The kinetic theory of gases can be summarized as follows:

1. Gas molecules are small compared with the space between them.

2. Gas molecules move rapidly and freely in all directions.
3. Gas molecules frequently collide and change direction.
4. The collisions are elastic; that is, no energy is lost upon impact.
5. The higher the temperature of a gas, the greater the speed of its molecules.
6. At the same temperature, lighter molecules move more rapidly than heavier molecules.
7. Gas molecules exert practically no attractive force upon one another.

Pressure and Density of Gases

"It seems as if winter will never end," remarked Jim's best friend, Marty Baker, as he sat down beside Jim in the school cafeteria on Thursday.

"I know," responded Jim. "I enjoy the snow, but it does get tiresome by February."

"Especially by the end of February," added Marty's brother, Rick, who joined the other boys at the table. "I think I know why they made February the shortest month."

A puzzled look on the older boys' faces brought a smile to Rick's. "It's because everyone's so anxious for it to end!" he laughed.

As the boys joined in the laughter, Marty said, "Say, Jim, our dad is taking us to Angel Pass this week end to go skiing. Would you like to go along?"

Jim hesitated for a moment. "Are you going just for Saturday?" he asked. "I don't want to miss church on Sunday."

"Don't you remember, Jim?" asked Rick impatiently. "School is out all day tomorrow for a teachers' meeting. Dad is taking the day off, and we're going for tomorrow and

Saturday. How about it? Do you think you can make it?"

"Sounds great!" answered Jim. "I'll have to check with my parents, but I'm sure they won't mind if . . . uh, wait a minute, fellas. I just remembered something."

"What's that?" asked Marty.

"I help my grandmother on Friday afternoons."

"Oh, come on, Jim, you can let it go for one day. I mean, you go over there every day!" said Rick.

"Not every day," Jim said defensively. "I only go three days a week. I do it because I love my grandmother and she needs my help."

Rick was sorry he had been so short with Jim, and he apologized. Then he had an idea. "Jim, couldn't you go today instead of tomorrow?"

"Yes, or maybe tomorrow morning," suggested Marty. "We're not planning to leave until noon."

That was a thought. "It might work, fellas," said Jim, "but I'll have to talk it over with my folks and with Grandma. She probably wouldn't mind if I didn't come one day, but I still feel responsible for her. Let me see what I can work out, okay?"

Jim's answer satisfied the boys, and the conversation drifted into different channels. Jim's answer hadn't satisfied him, however, and the thought gnawed at his mind that a responsibility was a responsibility, and it should be fulfilled.

Jim was battling with the problem of whether conditions should or should not affect the carrying out of a responsibility. When a chance to have fun came along and his friends pressured him to join them, Jim was tempted to forget his responsibility even though he had determined to remain dependable under all conditions. Commitments are not so easily fulfilled when outside pressures increase.

Gas pressure. Any gas confined in a container exerts pressure on the walls of the

container. If you have ever *inflated* a bicycle tire, you probably noticed that as you pump more air into the tire, the harder it becomes to pump. This is due to the increasing pressure of the air in the tire. As more air is pumped into the tire, the number of molecules in the available space increases and they become more tightly packed together.



Pumping air into a bicycle tire

Because more molecules are bouncing off the inside of the tire walls than off the outside, the tire is kept firmly pushed out in all directions.

Pressure is caused by the kinetic energy of gas molecules. Gas molecules continuously bombard the walls of their container. Although each individual molecule impacts the walls with an extremely small force, collectively these billions of small forces create a relatively large force.

Under normal conditions, the forces of gas molecules inside a container are not noticeable because they are balanced by other molecules outside the container. For example, the gas molecules bombarding the walls of a house from inside are balanced by the gas molecules bombarding the house from outside. If a tornado, which contains an area of extremely low air pressure, passes over the house, the house will explode because of the unbalanced high pressure from inside.

The amount of pressure within a container of gas can be measured with a *manometer*.

Remember: In all activities involving calculations, round only the final answer.

Using the Words to Know on page 1 of the PACE, fill in the blanks with the correct answers.

- (1) If your mother bakes bread, the aroma will soon _____ the entire house.
- (2) The pressure of the oxygen in the experiment was measured with a _____.
- (3) The weatherman pointed out the _____ that indicated a low-pressure area on the map.
- (4) The welder connected new tanks of oxygen and _____ to his equipment before he started the new job.
- (5) An old Gospel song tells us to "_____ it [the message, 'Jesus saves'] on the rolling tide"
- (6) Before the birthday party, his father will _____ the balloons with helium gas.
- (7) The lab technician moved the _____ in the cylinder to decrease the volume.
- (8) A _____ is a unit of measurement which indicates atmospheric pressure.
- (9) The movement of molecules can be observed indirectly by observing _____.

On pages 2-10 of the PACE, study carefully:

I. Nature of Gases

Air, Atmospheric Pressure, and Weather
Properties of Gases

Fill in the blanks. If the activity is a question, answer with a complete sentence.

- (10) Creation is dependable because _____.
- (11) The lowest layer of the atmosphere, called the _____, is a mixture of several gases.
- (12) The lowest level of the _____, which is above the homosphere, contains mostly oxygen.
- (13) When divided by temperature, the layers of the atmosphere (beginning closest to Earth) are the _____, _____, _____, and _____.
- (14) Suction pumps can pump water from the ground because _____.
 - a. they are powerful enough to pull water from the ground
 - b. the soil exerts pressure on the underground water
 - c. the air on the surface of the water has weight and exerts pressure
 - d. water underground is hotter than surface water

- (15) The fact that air has _____ and exerts _____ was proven by the experiments of Galileo Galilei and Evangelista Torricelli.

Match these items.

- | | |
|---|----------------------------------|
| _____ (16) 0.75 mm of mercury | a. isobars |
| _____ (17) Hg | b. high pressure |
| _____ (18) 760 mm Hg | c. standard atmospheric pressure |
| _____ (19) curved lines on weather map indicating areas of equal pressure | d. mercury |
| _____ (20) circle on weather map | e. millibar |
| _____ (21) fair weather | f. falling pressure |
| _____ (22) precipitation ahead | g. high or low center |

Choose the correct answer.

- (23) It would be impossible for you to suck water through a straw longer than 10.4 m because _____.
 - a. you cannot generate enough suction
 - b. at that point, the weight of the water inside the straw is balanced by the atmospheric pressure outside the straw, and the water will rise no higher
 - c. you could not suck for a long enough period of time
 - d. you cannot find a straw longer than 10.4 m
- (24) THINK! You discover that the only ground water supply at your new homesite is 15 m below ground. Since you must have water, you decide to get water from that supply by _____.
 - a. purchasing a "super-duper" hydraulic pump
 - b. building your home 5 m below the surface of the ground
 - c. pumping more air into the well to increase the air pressure and make it possible for the water to rise to a higher level
 - d. using a long rope and a bucket
- (25) THINK! You are unaware of the weight of the atmosphere because _____.
 - a. the atmospheric pressure is the same as the pressure inside your body
 - b. you have a thick skin
 - c. God designed your body to withstand great pressure
 - d. air has no weight

List the six ways of expressing standard atmospheric pressure.

- (26) _____
- (27) _____
- (28) _____
- (29) _____
- (30) _____
- (31) _____

Fill in the blanks.

(32) Pressure in a liquid is _____ at greater depths because of _____.

(33) The atmospheric pressure is less on Mount Everest than in the Sahara Desert because _____.

(34) Describe an aneroid barometer. _____.

(35) What is a front? _____.

Match these items.

- | | |
|------------------------|-----------------------|
| _____ (36) barometer | a. temperature |
| _____ (37) thermometer | b. wind speed |
| _____ (38) hygrometer | c. amount of rainfall |
| _____ (39) anemometer | d. air pressure |
| _____ (40) rain gauge | e. relative humidity |

Put a (✓) beside each property of a gas.

- | | |
|---|--|
| _____ (41) has a definite volume | _____ (46) has a definite mass |
| _____ (42) expands to fill container | _____ (47) can't be compressed easily |
| _____ (43) flows easily | _____ (48) expands and contracts as air pressure changes |
| _____ (44) is greatly affected by gravity | _____ (49) diffuses slowly |
| _____ (45) is completely mixable | _____ (50) has molecules that are far apart |

Fill in the blanks.

(51) A _____ is a substance which is a liquid at normal pressures and temperatures but becomes a gas when heated; a _____ is a substance which is a gas at normal pressures and temperatures.

(52) Most gases in the natural state are _____ of two or more atoms.

(53) THINK! Why is a helium-filled balloon on the ceiling one day and on the floor the next?

(54) THINK! Why does it take longer for a Mylar® balloon (one of those silvery-colored ones) to lose its helium than for a common rubber balloon? _____

(55) O₃ is _____.

Score exercises 1-55.

On pages 10-16 of the PACE, study carefully:
Kinetic Theory of Gases
Pressure and Density of Gases

Fill in the blanks.

(56) Brownian movement is the observable _____ of tiny particles of matter as they are bumped by _____.

(57) State the kinetic theory of matter. _____

(58) The kinetic theory of gases is a _____; it cannot be proven, but only helps explain the _____ of gases.

(59) Many of the properties which apply to one gas also apply to most others because _____

(60) An air molecule moves at a speed of approximately _____.

(61) In an _____ collision, no _____ is lost.

(62) Why do gas molecules have little attraction or repulsion for each other? _____

Summarize the seven assumptions of the kinetic theory of gases.

(63) _____

(64) _____

(65) _____

(66) _____

(67) _____

(68) _____

(69) _____