observe that when many liquids are combined—such as coffee and cream in a cup—they eventually mix together. If they happen to be insoluble in each other—such as oil and vinegar—they instead form two distinct layers. However, we can also conclude that the particles must remain close to other particles as they move, since, for a given mass of a substance, the liquid occupies a volume not much greater than the solid form would. Liquids and solids are called the **condensed states of matter** because they are much denser than gases; that is, their mass-to-volume ratio is much greater.

1.11 Most of a gas is empty space

The temperature of a substance is a measure of the average energy of the motion of its constituent particles.

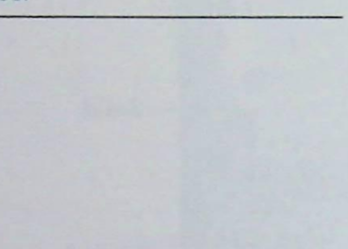
At low temperatures, matter exists in the liquid or solid state, where, as we have seen, the particles are close together. Therefore, some force of attraction must operate between the particles to keep them from moving very far from each other. At some point, as the temperature of a liquid is raised, the substance becomes a gas, a state in which each particle lies on average at a relatively great distance from all others. Therefore, the particles must have enough energy to overcome the forces of attraction that occur between them. Although other factors are also involved, in general the greater the attractive force between its particles, the higher the temperature required for a substance to boil (convert to a gas).

The volume occupied by a given sample of matter is much greater when it exists as a gas rather than as a liquid or solid, because *most of the space in a gas is completely empty* at any instant (see Figure 1.10). The volume occupied by liquid water, for example, expands by a factor of about 1000 when it is converted, by boiling, into a gas at everyday pressure. The atoms themselves do *not* change in size when they become part of a gas rather than a liquid or solid; they remain the same size, but they are much farther apart from one another.

1.12 The scientific model for a gas is separated particles in rapid motion

Perhaps you have had the unpleasant experience of walking down the street and being accosted by the noxious smell of rotten eggs emanating from a nearby sewer. The odor, which is produced by the gaseous compound hydrogen sulfide, will reach your nose even if there is no wind. This experience confirms the theory that the particles in a gas are constantly in motion. If they were not, odors would not carry unless there was a wind current present. As the Roman poet Lucretius said 2000 years ago in his epic poem *The Nature of Things:*

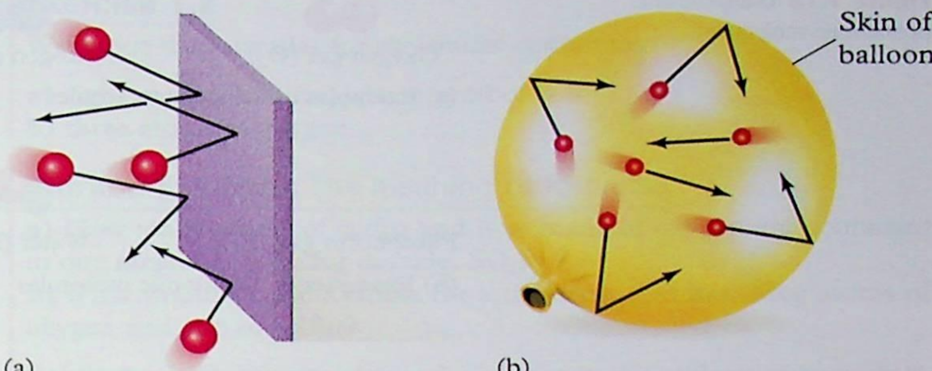
> We can perceive the various scents of things
> Yet never see them coming to our nostrils



View gas particles hitting a surface at Visualizations: Chapter 1: Media Link 7

The scientific model for gases is that of independent, tiny particles traveling rapidly in straight-line motion through empty space, as a rocket ship travels through outer space. Owing to the rapid motion of its

Figure 1.11 Gas particles in motion and exerting pressure on (a) a wall and (b) the inside surface of a balloon.



constituent particles, a gas quickly expands to fill completely whatever space is accessible to it. As a given gas particle travels through space, it occasionally collides with other gas particles or with the walls of its container if it is in one. These collisions result in a change in direction for the particles—much as a billiard ball changes direction when it hits another ball or hits the side of the pool table (see Figure 1.10).

One of the many pieces of evidence that led to the scientific model for gases is that gases are much easier to compress to a smaller volume than are liquids or solids. Compressing a gas corresponds only to reducing the amount of empty space that lies between the independent particles.

A piece of evidence that led to the notion that the particles in a gas are in constant motion is the fact that a gas exerts a force on the walls of whatever container it occupies. Technically, the **pressure** exerted by a gas is the amount of force that it exerts on a specified area of surface, say one square centimeter (see Figure 1.11a). For example, the helium gas atoms in a helium-filled balloon are in constant motion. As a consequence of their movements, they often collide with the inside skin of the balloon (see Figure 1.11b). The pressure exerted on the balloon walls by this constant bombardment is sufficient to keep the balloon "blown up," even though the stretched elastic of the balloon's material is trying to contract and thereby collapse the interior. Indeed, the balloon collapses only when some of the helium leaks into the air outside the balloon.

Taking It Further with Math

For information and problems on gas laws, go to Taking It Further with Math at www.whfreeman.com/chemistryinyourlife.

1.13 Molecules are groups of atoms that are tightly bound together

The particles that undergo independent motion in certain gases, such as neon and argon, are individual atoms. However, the nitrogen particles that travel in air are *not* individual atoms, but rather are *pairs* of nitrogen atoms that are strongly connected to each other. These pairs of atoms travel through space as intact units, even surviving collisions with other particles and with the container's walls. The same is true for oxygen, which also occurs as pairs of atoms (see Figure 1.12).

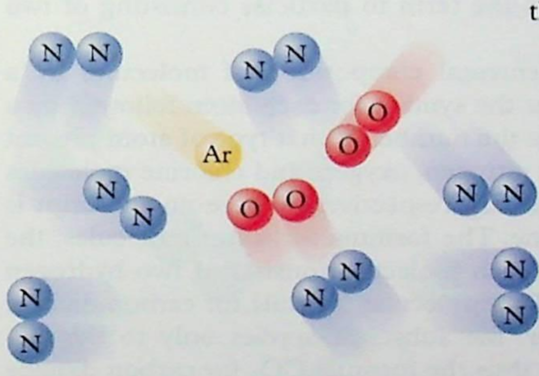
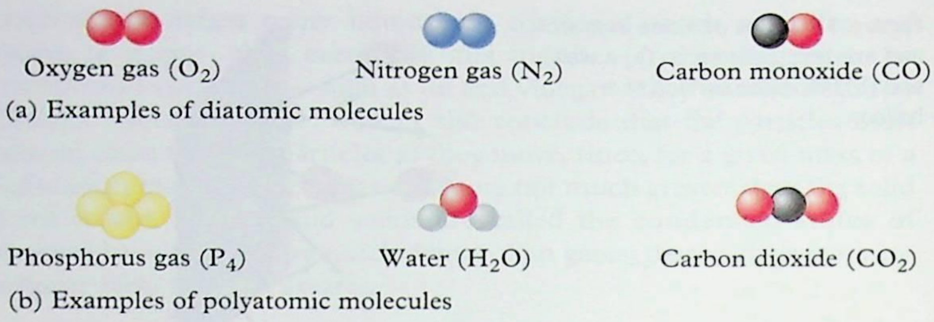


Figure 1.12 Some of the atomic (Ar) and molecular (N_2 and O_2) components of air. Notice that there is a lot of space between gas particles, but no space between atoms bound together as molecules.

Figure 1.13 Diatomic and polyatomic molecules.

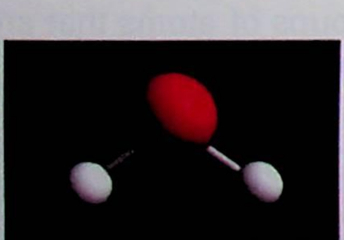


Indeed, a great many substances exist as **molecules**, collections of a relatively small number of atoms that are strongly bound to each other and that remain as intact units even when the material is melted or boiled. The elements hydrogen, fluorine, chlorine, bromine, and iodine, as well as nitrogen and oxygen, all consist of two-atom, or **diatomic,** molecules (see Figure 1.13a). Other substances are made up of diatomic molecules containing two different types of atom. For example, the substance carbon monoxide consists of diatomic molecules, each made up of one atom of carbon and one atom of oxygen.

Molecules that contain *more* than two atoms, whether the atoms are all the same or of more than one type, are called **polyatomic** molecules (see Figure 1.13b). Molecules of gaseous phosphorus consist of four phosphorus atoms. Carbon dioxide exists as polyatomic molecules having one carbon atom and two oxygen atoms each. Water consists of molecules containing two hydrogen atoms and one oxygen atom each. Substances that exist as independent atomic units, such as helium, should presumably be called "molecules" as well; however, conventional chemical usage restricts the term to particles consisting of two or more atoms.

The alternative of listing the atom's symbol as a repetitive list—for example, NN—is cumbersome with large molecules and never used.

Chemists indicate the elemental composition of molecules by a **molecular formula** that gives the symbol for each atom followed by a numerical subscript to indicate the number of that type of atom present in *one molecule*. Thus diatomic nitrogen, oxygen, and chlorine molecules are represented as N_2, O_2, and Cl_2, respectively. Where no subscript is shown, the implied value is one. The formula for water molecules, the well-known H_2O, means that each molecule consists of two hydrogen atoms and one oxygen atom. The molecular formula for carbon dioxide molecules is CO_2. Remember, the subscript applies only to the element that directly precedes it; thus the formula CO_2 for carbon dioxide specifies that there are two oxygen atoms, but only one carbon atom, in each molecule. Some compounds consist of molecules that have quite a large number of atoms. For example, a molecule of common table sugar (sucrose) is $C_{12}H_{22}O_{11}$, so there are 45 atoms per molecule! Notice that the atoms are written as a continuous string with no punctuation marks.



View representations of the molecular structures of water, oxygen, and sugar at Chapter 1: Visualizations: Media Link 8.

Exercise 1.2

Write out the formulas for molecules containing:

a) eight atoms of sulfur, whose symbol is S
b) three atoms of oxygen

Worked Example: The meaning of formulas

a) How many atoms of sulfur and how many of oxygen are contained in one molecule of sulfur dioxide, SO_2?
b) What would be the formula for a molecule that has three atoms of oxygen and one of sulfur?

Solution: **a)** The symbol for each element in the molecular formula is followed by a subscript, unless the number of atoms is one, in which case no subscript is shown. There is one atom of sulfur and two of oxygen in SO_2, since the subscript 2 refers only to the element whose symbol precedes it. **b)** If a molecule had three atoms of oxygen and one of sulfur, the formula would be SO_3 since, as in SO_2, the implied subscript to sulfur is one.

Exercise 1.3

a) How many atoms of nitrogen and how many of oxygen are contained in one molecule of the substance called nitrous oxide, the formula for which is N_2O? **b)** Each molecule of the gas called ammonia has one nitrogen atom and three hydrogen atoms. What is the formula for ammonia?

Molecules occur not only in the gas phase, but in liquids and solids as well. Liquid nitrogen consists of intact, individual N_2 molecules. The same is true for the other diatomic molecular gases O_2, H_2, F_2, Cl_2, Br_2, and I_2 when they are liquefied. Freezing these liquids produces solids that contain diatomic molecules that are clearly separated from each other. This is illustrated in Figure 1.14 for the case of solid chlorine.

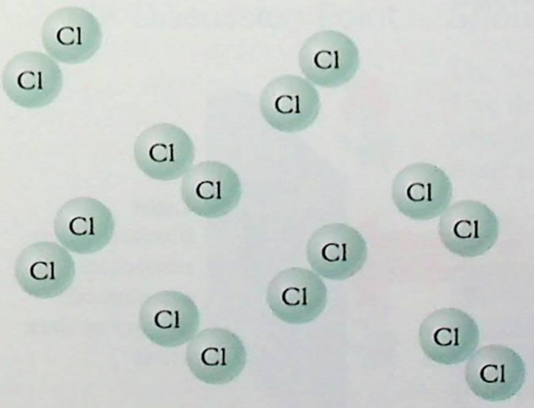


Figure 1.14 Position of the atoms in solid chlorine, Cl_2.

1.14 Liquid crystal is an intermediate state for molecules, between liquid and solid

Looking up from your laptop computer, you glance at the digital clock and see you have two hours before meeting friends for dinner. Deciding that you need some stimulation for the task at hand, you heat a cup of coffee in the microwave and set the CD player to your favorite track. As you use each of these devices, you see what is happening on an LCD, or *liquid crystal display.* LCDs are all around us in electronic devices that display information. LCDs have advantages over other display technologies in that they are thinner, lighter, and use much less power.

The substance used in the screen is a molecular substance in the **liquid crystal state,** a form of matter that is intermediate between the liquid and solid states and that occurs for a few materials. In the liquid crystal state, the substance flows like a viscous liquid—one that flows somewhat but not very readily—even though its molecules exist in highly ordered patterns, as in a crystalline solid. The molecules of substances that form liquid crystals are usually long and rod shaped. The rod shape makes them stack together so that they lie in a parallel fashion (see Figure 1.15, bottom), but they are able to slide past each other (like freight trains on parallel tracks).

Because all the molecules in a liquid crystal are aligned in one direction, some of the properties of the substance depend upon the direction in which they are aligned. For example, light can be either transmitted through the substance or reflected by it, depending on whether the light beam is directed parallel to or perpendicular to the direction of the molecules. Furthermore, the orientation of the molecules changes direction if an electric field is applied to the substance. Consequently, the pattern of spots—whether transparent or opaque—that a huge number of liquid crystals display on a screen depends upon the orientation of the molecules, and therefore upon whether or not a field is applied, at each position (see Figure 1.16). Using this phenomenon, letters and numbers and pictures can be displayed on a screen.

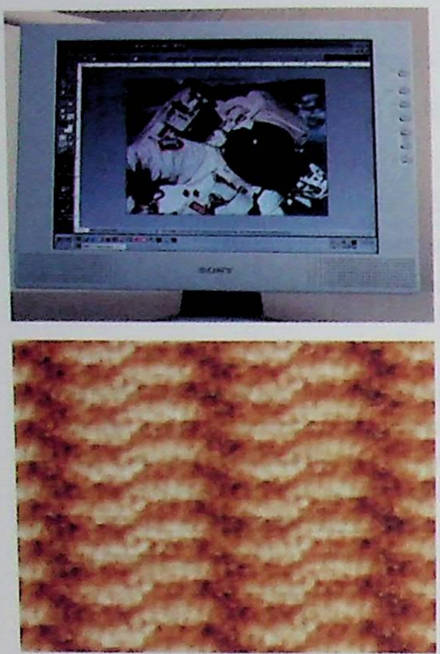


Figure 1.15 Liquid crystal. *(Top, George Semple for W. H. Freeman and Company; bottom, Chip Clark, from L. L. Jones and P. W. Atkins,* Chemistry, *4th ed. © 2000 by L. L. Jones and P. W. Atkins. W. H. Freeman and Company, 2000.)*

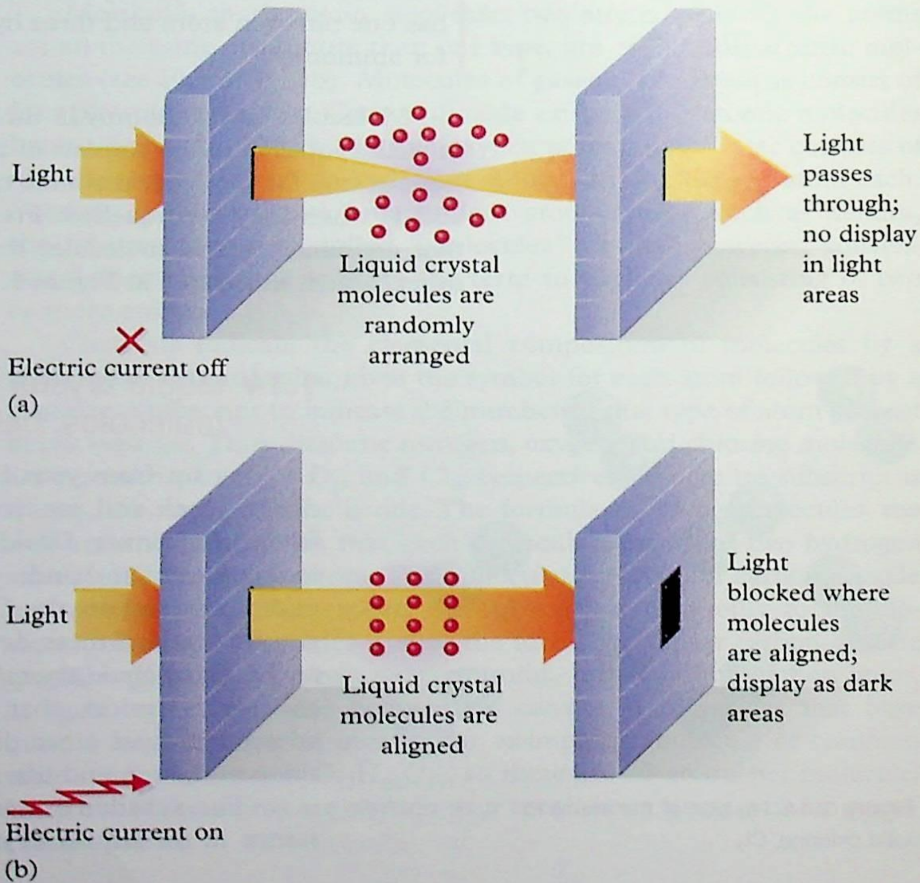


Figure 1.16 Rearrangement of molecules in a liquid crystal when an electric field is applied.