# SCIENTIFIC AND HISTORICAL BACKGROUND

Picture a warm day at the beach. You are standing on firm sand, knee-deep in the surf, with a soft breeze cooling your face and arms. You are having a direct, tangible experience with matter in its three common states: *solid* sand, *liquid* water, and *gas* air.

The sand is composed of several substances—perhaps some quartz, feldspar, and olivine. The seawater is also composed of several substances—primarily water with a lot of dissolved salts. The air is composed of substances, principally nitrogen and oxygen gas, with a lot of other gases in small quantities. So all matter, in any state, is made of one or more substances.

Substances are made of elements. Elements are the basic kinds of matter from which all other kinds of matter are made. The smallest bit of an element is the atom of that element. Because we are deferring the introduction of the atom, we will refer to the smallest bit of an element as the particle of that element. ***Particle*** is the word we will use to refer to the fundamental unit of a substance.

Quartz in the sand is made of silicon and oxygen; water in the ocean is made of hydrogen and oxygen; nitrogen gas in the air is made of nitrogen.

Quartz, like all substances, is defined by a chemical formula. Quartz is silicon dioxide ($SiO_2$). $SiO_2$ is the basic unit of quartz—the quartz **particle**. The quartz particle is made of one silicon particle (atom) and two oxygen particles. A chunk of pure quartz is made of quartz particles only.

In a similar way, water is defined by the formula $H_2O$. $H_2O$ is the water particle. And nitrogen is defined by the formula $N_2$. $N_2$ is the nitrogen gas particle.

## WHAT IS STATE?

Substances assume one of three common states, or phases, as a result of the relationships between their particles. If particles of a substance are locked in place with respect to one another, due to attractive forces between the particles, the substance is in a condition we call **solid**.

If the particles are not locked in place and can slide past, around, and over one another, but are still held in contact with one another by attractive forces, the substance is in a condition we call **liquid**.

If, however, the particles of a substance are not held in contact with one another by attractive forces, they will fly off into space as individual particles. When particles are unencumbered by attachments to others of their kind, the substance is in a condition we call **gas**.

## GAS IS MATTER

Air is matter in its gas phase. So all the matter that occupies the huge volume of space surrounding Earth from the planet's surface to an elevation of some 500–600 kilometers exists as independent particles—matter's rugged individualists.

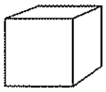
When a blast of wind turns your umbrella inside out or sends your trash can tumbling down the street, you are reminded that air is real stuff. It has mass, it occupies space, and when it is in motion, like any mass, it has momentum. Most of the time, however, air goes unnoticed. Air is the medium in which we live. Being surrounded by air is our default condition—air is largely not perceived as substantial.

Air is, in fact, not a gas, but a mixture of many gases. Many are familiar, including oxygen, nitrogen, helium, hydrogen, carbon dioxide, and water. The whole lot constitutes Earth's precious atmosphere. The particular composition and concentration of our atmospheric gases is one of the defining characteristics of Earth. But that story is told in the **Weather and Water Course**.

## A CLOSER LOOK AT AIR

One of the challenges in the study of chemistry is scale. All the really interesting things happen between objects that are way too small to observe directly. The scale is difficult to convey to students, but adopting a mental model for the size, density, and activity of gas particles is critically important in the understanding of gas as matter and its properties.

Let's look at air on the human scale. Consider a cubic centimeter of air (cm$^3$), a volume just this size.



To represent each particle of oxygen, nitrogen, and all the others in that 1 cm$^3$ of air as people, we would have to assemble everyone on Earth (6 billion in round figures) and replicate each individual 4.5 billion times. Once done, we'd have a mob of folks roughly equal to the number of particles in that 1 cm$^3$ of air—27 quintillion (27,000,000,000,000,000,000) individuals.

Gas particles are relatively far apart. If we space the human hoard at about the right distances to represent the spacing of gas particles in air, the people would be about 5 meters (m) apart.

Gas particles are in constant motion, moving in straight lines until they collide with something. Collisions transfer energy. The sum of the kinetic energy before a collision is equal to the sum of the kinetic energy after the collision. However, the kinetic energy (speed) of the individuals may change. If a runner going at high speed runs into a person out for a walk, the runner's speed will decrease and the walker's speed will increase as a result of the collision. Energy transfer.

The average speed at which air particles travel is outlandish—300 meters per second (m/s, or 670 miles per hour, mph). This activity results in a lot of collisions. A typical particle may experience 10 billion collisions every second!

Is it safe to go out into this violent environment filled with air particles careening out of control, crashing into everything in sight? Sure. Remember, when an air particle crashes into you, it is actually crashing into a single particle in your epidermis. If the impact transfers energy to that particle, it will increase in kinetic energy. If enough particles increase in kinetic energy, they may stimulate a nerve, which in turn may send a message to the brain that says, "Hey, it's getting warm over here."

## INTERACTING WITH GAS

If you put a wall, like a plastic jar with a lid, around a volume of gas, the particles hit not only each other, but also the walls of the jar. The unrelenting onslaught of impacts exerts a force on the inside wall of the jar. If the jar is exposed to the atmosphere, the force exerted on the outside of the jar is exactly equal. There is no net force on the walls of the jar.

If you place the sealed jar in a vacuum chamber and remove the air particles from the environment around the jar, the external force will disappear. The air particles inside, however, will continue to push on the inside surface of the jar. The jar walls may not be able to withstand the force, called air pressure, exerted on the inside of the jar. The jar may experience a catastrophic structural failure.

Gas is mostly space. The average distance between particles at standard atmospheric pressure is about 15 molecule diameters. The reason the distance isn't even larger is gravity. Earth's gravity applies a force of attraction on every nearby mass. Air particles have mass, so they are pulled toward Earth's center. If Earth's gravity were greater, the particles would be pulled toward Earth with greater force, and the distance between particles would be smaller.

Because of all the available space in a mass of gas, it can be forced into a smaller volume. This is what happens when students push on the plunger of a sealed syringe full of air. At first the plunger goes in pretty easily, as if nothing were in the syringe. Then students become aware that there is definitely something there—something almost spongy or resilient. Then they hit the limit. The plunger won't go any farther. Why?

Reducing the distance between particles by force is called **compression**. When additional force is applied to a mass of gas, the particles come closer together by virtue of the fact that the same number of particles has less space in which to operate. This results in even more collisions per unit of time, including collisions with the wall of the container (including the plunger).

As more and more force is applied to the plunger, the distance continues to decrease and the frequency of collisions continues to increase. The gas will always reflect the force applied to it. Eventually even the most enthusiastic student will reach a limit. The gas will feel solid. It will not compress any more because the pusher cannot bring any more force to bear.

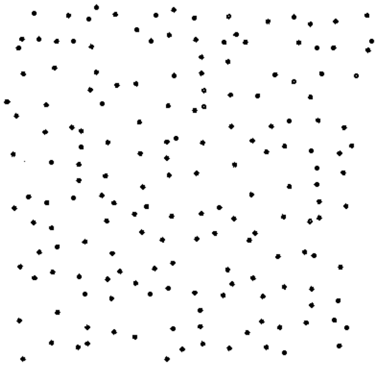
What's different about the compressed gas? Not much except its density. Students may have a little difficulty sorting out the changes.

- Are there more particles in a volume of gas when it is compressed? No.
- Does a volume of compressed gas weigh more? No.
- Does a volume of compressed gas weigh more than an equal volume of uncompressed gas? Yes.
- Are there more particles in a volume of compressed gas than in an equal volume of uncompressed gas? Yes.
- Do the particles get smaller as the volume of gas gets smaller? No.
- Does the space between particles get smaller as gas compresses? Yes.

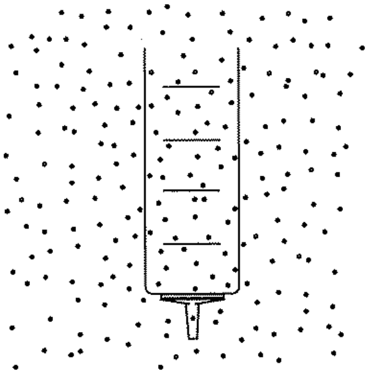
And why is it so hard to pull up on the plunger in a sealed syringe when the plunger starts all the way down? The reason is there is very little air in the syringe to start with. There just aren't many particles in there to push up on the plunger. The farther up students pull the plunger, the fewer impacts there are per unit of time on the rubber tip of the plunger. The particles on the outside, however, are pushing with their usual zeal. The resistance students feel is the force of atmospheric pressure pushing the plunger down to the bottom of the syringe barrel. Pretty impressive.

### REPRESENTING GAS

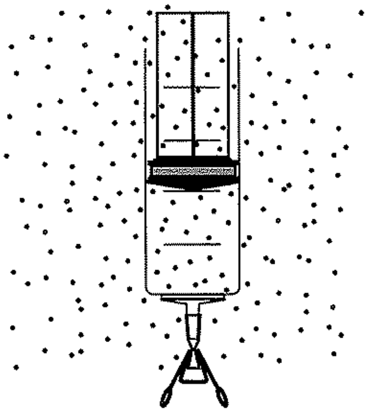
Gas particles are a colorful lot, everything from helium atoms to some fairly complex organic particles composed of dozens or hundreds of atoms. Nonetheless, we ask students to think of them generically and to represent individual particles as little circles or dots. And, of course, a dot in a diagram might stand in for several hundreds of trillions of actual air particles. Thus, a sample of air might be represented like this.



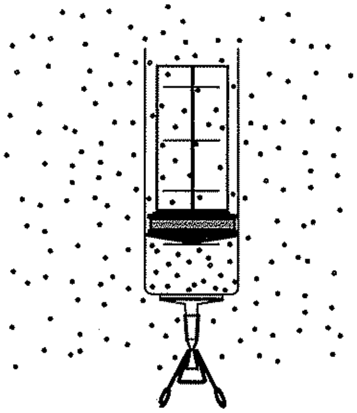
If students remove the plunger from a syringe barrel and place the barrel in the air sample, the air particles would invade the space at a concentration equal to the ambient concentration. It would look like this.



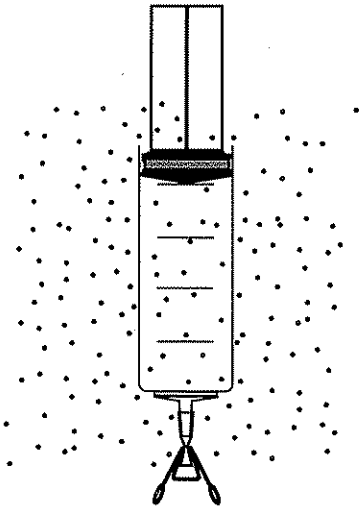
If the plunger were inserted, the concentration of air particles would remain unchanged, and if students then clamped the tip shut, the concentration of air particles would still remain at the ambient concentration.



If a force were applied to the plunger now that the syringe is sealed with a volume of air trapped inside, the air in the syringe would be compressed. The 20 trapped "particles " in the illustration would now be concentrated in a smaller space, looking like this.



And finally, if the plunger were drawn up to the top of the barrel, the 20 particles in the syringe will disperse throughout a much larger volume. The density would drop to a concentration less than the ambient concentration.



Another important point is that the particles would be uniformly (but randomly) distributed in the space available at all times. Added pressure would not force all the air particles down to the bottom of the syringe, nor would raising the plunger pull the particles to the top of the syringe.