the flask and quickly place a balloon over its mouth as illustrated in Figure BB. It may be necessary to have a student hold the flask with insulated gloves while you put the balloon on. *Be cautious for the flask is hot!* As water vapor cools, it condenses, resulting in approximately a 1000-fold reduction in volume. Air pressure forces the balloon into the flask so that it almost fills it (Figure CC). Place the flask in a prominent location before students enter the room and then ask if they can determine how this was accomplished. You may also wish to see if they can replicate what you have done by allowing them to implement their ideas. Provide a variety of resources including such things as straws, vacuum pumps, glass rods, scoopulas, bicycle pumps, hot plates, and other equipment of your choosing. Students may try to inflate the balloon while it is in the flask with their breath or a tire pump, but to no avail. They may also try to draw air out from around the balloon using a straw or vacuum pump. Hopefully they will eventually realize that they need to use the same principle employed in the three activities mentioned in part 5. *Make certain students abide by all safety regulations while experimenting.*

The popcorn activity (part 5) provides an excellent opportunity for introducing the concept of indirect measurement (see section 1.3). You may wish to have students test kernels that have been sandpapered or scratched. They will note that the kernels do not pop because the coating has been broken, allowing steam to escape before expansive pressures can build.

**Answers:** (1) Pressure on the trapped air increases as the container is pushed deeper, resulting in compression and a reduction in volume. (2) Student answers will vary. (3) Carbon dioxide flows over and around burning objects, displacing oxygen and thereby extinguishing fires. (4) Unconfined gases expand indefinitely. The gravitational field of Earth is sufficient to prevent gaseous molecules from escaping in large numbers, while the gravitational field of Mercury is too small to retain them. (5) In the liquid state, a substance occupies only one thousandth the volume it occupies in a gaseous state. Thus, it requires much less space to ship materials as liquids. (6) Student answers will vary. Not all of the water is lost when popcorn pops. Some water remains trapped in pockets within the starch-cellulose structure of the popped popcorn kernel.

### 5.1.2 PRESSURE-VOLUME RELATIONSHIP OF GASES

**Discussion:** A plot of pressure versus volume shows the familiar inverse relationship, $PV = k$. As pressure increases, volume decreases (Figure DD). If we rearrange this equation, we get: $V = k (1/P)$, which is the equation of a straight line with slope $k$. You may wish to have students plot $V$ versus $1/P$ to obtain a straight line plot with slope $k$.

The Cartesian “diver” is useful in illustrating several laws and principles of science. The “diver” is not just the dropper, but rather the dropper and the air and water contained within it. When the plastic bottle is squeezed, pressure is transmitted undiminished throughout the water according to
5.1 Gases

Pascal's principle. Air within the diver is compressed and water enters to fill space this air once occupied. Due to the compression of air and the entrance of water in the diver, the composite density of the diver (eyedropper, air and water) may eventually exceed the density of the surrounding water, causing the diver to descend. When pressure is released all processes work in reverse and the diver ascends. With just the right amount of pressure, the diver can be made to remain at any position in the bottle.

Archimedes' principle may be used to explain the diver. When floating, the diver displaces its own weight of water, the buoyant force of water is equal to the gravitational force and the diver is in equilibrium. When the container is squeezed, more water enters the diver, and at some point the weight of water displaced by the diver is less than the composite weight of the diver and it descends.

Answers: (1) See discussion. (2) When the bottle is squeezed, water enters the eyedropper, increasing the composite density of the diver, and causing it to sink. In a similar manner, submarines take on water in their ballast tanks, increasing their composite density and causing them to dive. When pressure is released from the bottle, water escapes from the dropper, lowering the composite density of the diver, and allowing the diver to rise. In a similar manner, the crew in a submarine may release compressed air into the ballast tanks, causing them to displace water. As water is displaced, the composite density of the submarine decreases, causing it to rise. (3) The balloon returns to its original size, but the shaving cream and marshmallows shrink smaller than their original sizes. The number of gas molecules within the balloon remains relatively constant because the walls allow few gaseous molecules across. By contrast, the air pockets in the shaving cream and marshmallow expand and eventually burst in the evacuated bell jar. When air is allowed to re-enter the jar, shaving cream and marshmallows shrivel under atmospheric pressure because of the lack of trapped air. (4) An increase in pressure on the gas forced the molecules closer together, increasing the density and decreasing the volume. (5) Student answers vary, but should express this concept: At constant temperature, the volume of a gas is inversely proportional to the pressure exerted on it. The volume vs. pressure graph should resemble Figure DD. (6) Increased pressure on a gas decreases the volume of the gas and increases its density. (7) According to Boyle's Law, the product of the initial volume and pressure is equal to the product of the final volume and pressure: \( P_1 V_1 = P_2 V_2 \). So \((1 \text{ atm}) \times (? \text{ L}) = (2.5 \text{ atm}) \times (10 \text{ L}) \). 25 L of air will be required.

5.1.3 TEMPERATURE-VOLUME RELATIONSHIP OF GASES: CHARLES'S LAW

Discussion: Jacques Charles showed that, at constant pressure, the volume of a gas expands when heated and contracts when cooled, and that the relationship varies linearly with temperature expressed in degrees Celsius. At any given pressure, the plot of volume versus temperature yields a straight line according to the equation:

\[ V = c + kT_C \]

where \( T_C \) is the temperature in degrees Celsius and \( c \) and \( k \) are constants. The extrapolation of student graphs to zero volume should yield a temperature of \(-273.15^\circ\text{C}\), but student values may vary significantly because the techniques employed are relatively crude.