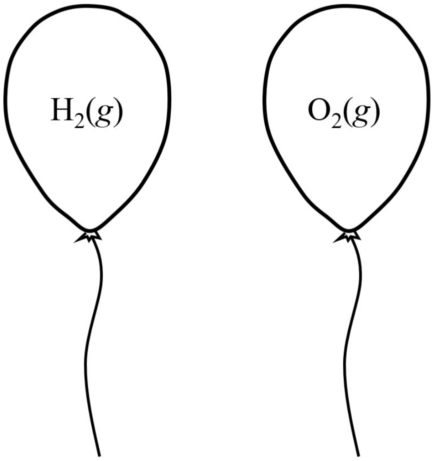
3.5 Kinetic Molecular Theory

Essential knowledge statements from the AP Chemistry CED:

- The kinetic molecular theory (KMT) relates the macroscopic properties of gases to motions of the particles in the gas. The Maxwell–Boltzmann distribution describes the distribution of the kinetic energies of particles at a given temperature.
- All the particles in a sample of matter are in continuous, random motion. The average kinetic energy of a particle is related to its average velocity by the equation: $KE = ½\, mv^2$
- The Kelvin temperature of a sample of matter is proportional to the average kinetic energy of the particles in the sample.
- The Maxwell–Boltzmann distribution provides a graphical representation of the energies/velocities of particles at a given temperature.

The following statements were listed in the previous packet in Topic 3.4 (Ideal Gas Law).
These statements summarize the kinetic molecular theory.

- Gas particles are in constant random, rapid motion.
- Gases expand to fill their container completely.
- Two or more gases will form a homogeneous mixture when they are combined together.
- Gases are highly compressible.
- The volume of the gas particles themselves is negligible compared to the volume occupied by the gas.
- Collisions of gas particles are perfectly elastic, meaning that energy is transferred but not lost during collisions.
- There are no attractive or repulsive forces between the gas particles.



Consider two different samples of gas, $H_2(g)$ and $O_2(g)$, at the same temperature.

The absolute temperature of a gas is a measure of the average kinetic energy of its gas particles.

Since these two gas samples are at the same temperature, the gas particles in each sample have the same average kinetic energy.

Take a closer look at the following equation, in which KE = kinetic energy, m = mass, and v = velocity.

$$KE = \frac{1}{2} mv^2$$

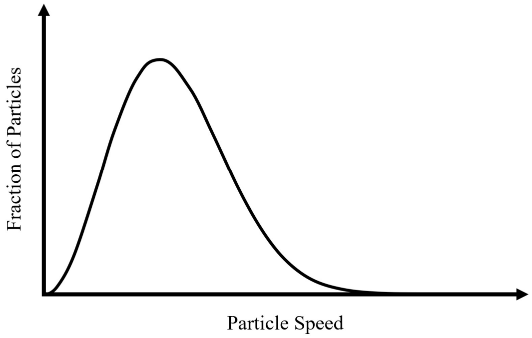
If two different gas samples are at the same temperature…

- …the gas with the smaller molar mass contains particles travelling at a faster average speed.
- …the gas with the larger molar mass contains particles travelling at a slower average speed.

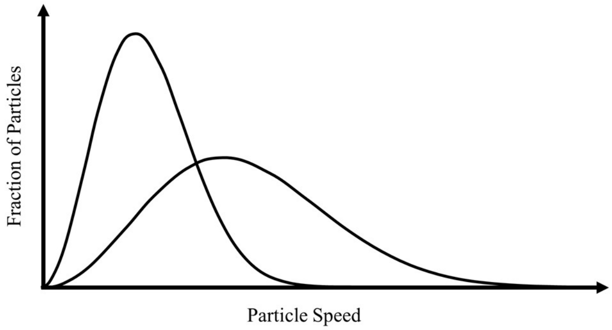
1. $H_2(g)$ particles are (lighter heavier) than $O_2(g)$ particles.

   At a given temperature, the $H_2(g)$ particles travel at a (slower faster) average speed than the $O_2(g)$ particles.

In a sample of gas, each particle is not traveling at the same speed. There is a range of values for speed. This range can be represented graphically by a Maxwell-Boltzmann distribution curve, as shown below. The peak of the curve represents the most probable speed, or the speed of the largest fraction of gas particles.



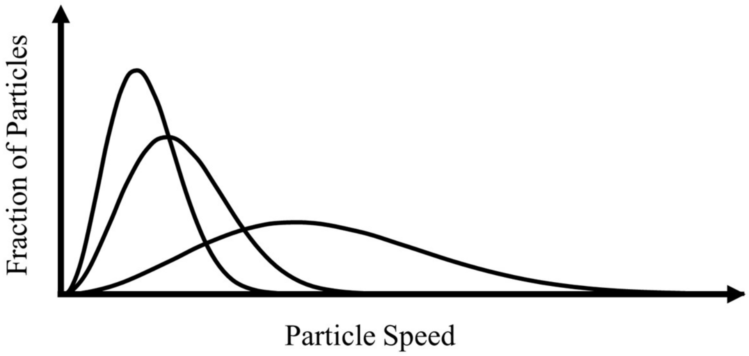
2. The diagram below represents the distribution of particle speed for samples of $H_2(g)$ and $O_2(g)$ at the same temperature. Label each curve as either $H_2(g)$ or $O_2(g)$.



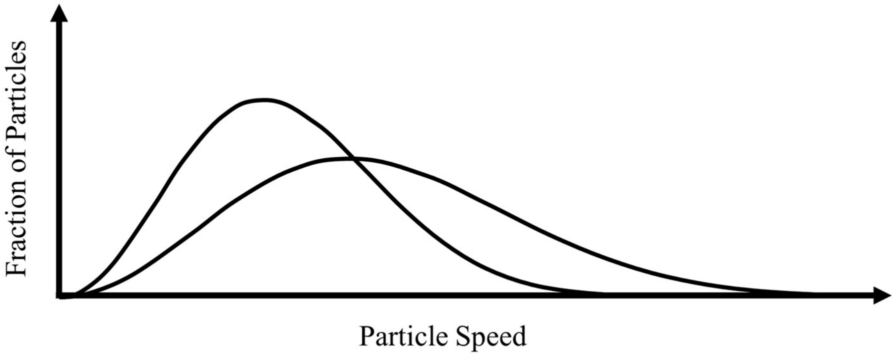
Important observations about these two Maxwell-Boltzmann distribution curves

- The area under each curve is the same, because the total number of particles in each sample is the same.
- As the average speed of the particles increases,
  - there is a wider range of values for particle speed
  - the curve broadens and flattens
  - the peak of the curve moves to the right

3. The diagram below represents the distribution of particle speed for samples of He(*g*), Ne(*g*), and Ar(*g*) at the same temperature. Label each curve as either He(*g*), Ne(*g*), or Ar(*g*).



4. The diagram below represents the distribution of particle speeds for samples of O_2(*g*) at two different temperatures: 300 K and 600 K. Label each curve as either 300 K or 600 K.



Sample #1	Sample #2
N_2 at 400 K	O_2 at 400 K

5. Place a check mark (✓) next to each of the following statements that is <u>true</u> regarding the two gas samples listed in the table above.

__________ The gas particles in samples #1 and #2 have the same average kinetic energy.

__________ The gas particles in sample #1 have greater average kinetic energy than the gas particles in sample #2.

__________ The gas particles in sample #2 have greater average kinetic energy than the gas particles in sample #1.

__________ The gas particles in samples #1 and #2 have the same average speed.

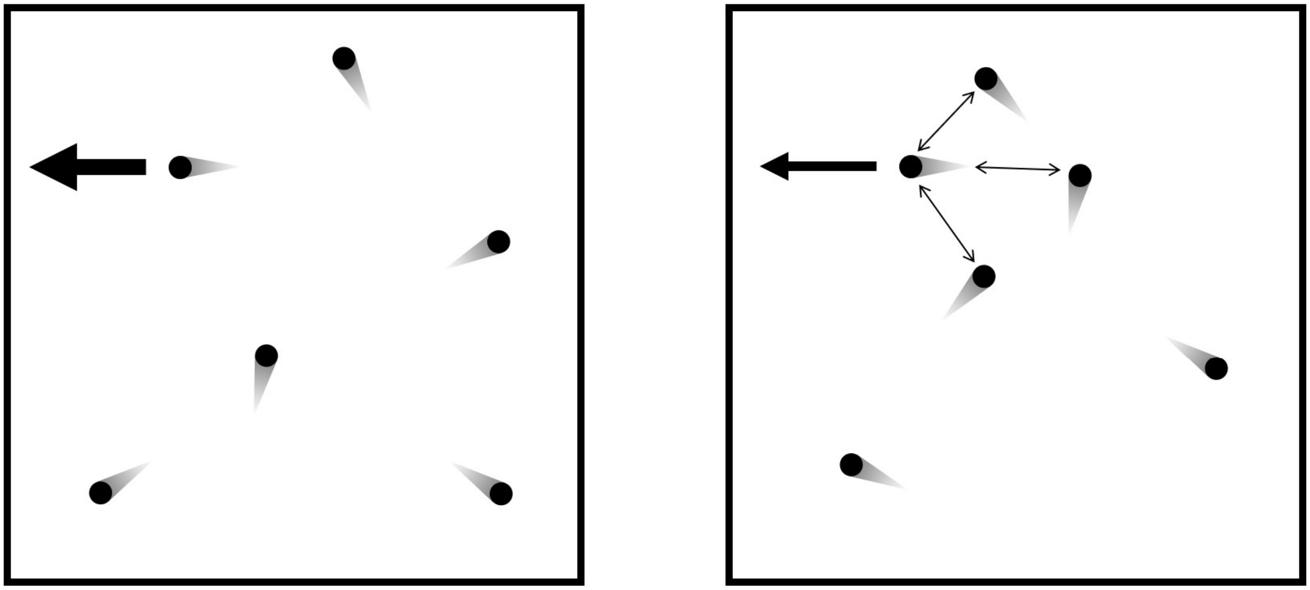
__________ The gas particles in sample #1 have greater average speed than the gas particles in sample #2.

__________ The gas particles in sample #2 have greater average speed than the gas particles in sample #1.

3.6 Deviation from Ideal Gas Law

Essential knowledge statement from the AP Chemistry CED:

- The ideal gas law does not explain the actual behavior of real gases. Deviations from the ideal gas law may result from interparticle attractions among gas molecules, particularly at conditions that are close to those resulting in condensation. Deviations may also arise from particle volumes, particularly at extremely high pressures.

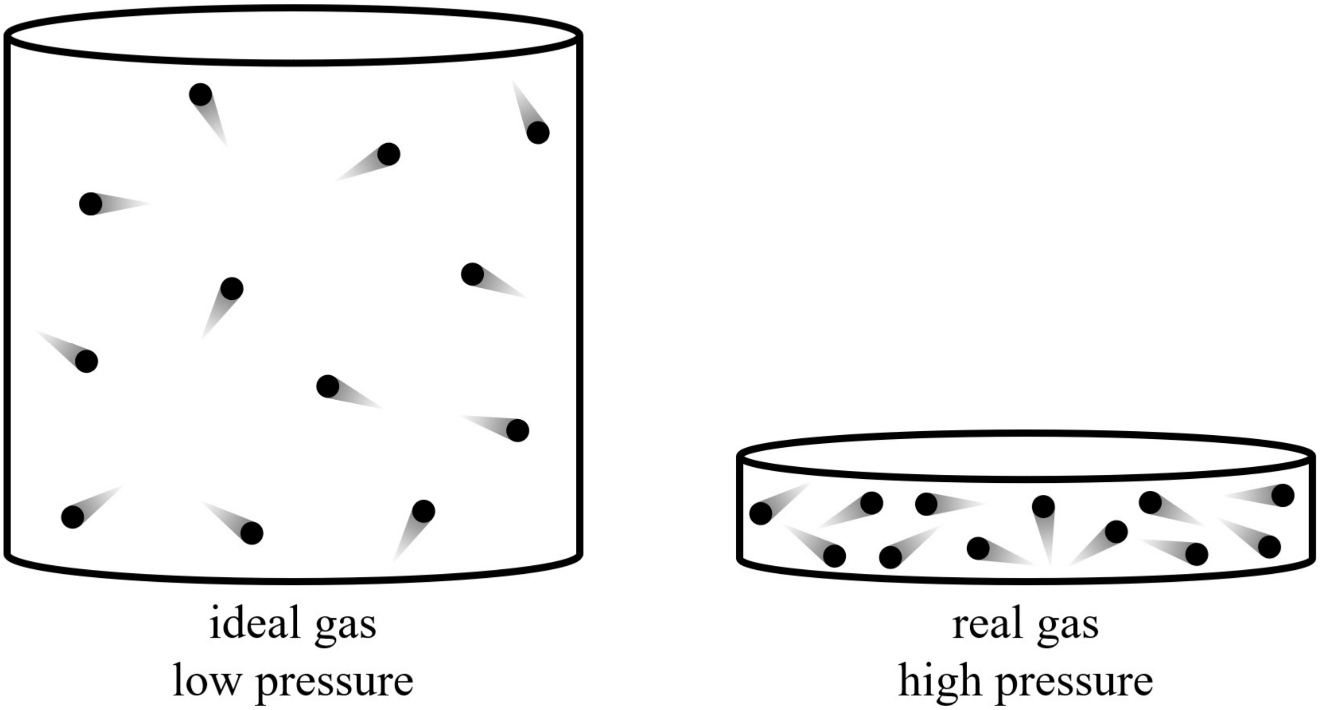


ideal gas
high temperature

real gas
low temperature

The Effect of Interparticle Attractions on the Observed Gas Pressure

6. In an ideal gas, it is assumed that there are no attractive forces between the gas particles. However, the particles of a real gas do experience attractive forces. This effect is especially noticeable when the gas temperature is relatively (low high). The attractive forces between gas particles can (decrease increase) the force with which the particles collide with the container walls, as shown in the diagram above. This causes the observed pressure of a real gas to be (less greater) than the value predicted by the ideal gas law.



The Effect of Particle Volume on the Observed Gas Pressure

7. In an ideal gas, it is assumed that the volume occupied by the gas particles themselves is zero, or negligible. The free space in which the gas particles can move around is equal to the entire volume of the container. However, the particles of a real gas do have volume, and they do occupy space inside the container. This effect is especially noticeable when the gas pressure is very (low high). When the volume of the gas particles themselves becomes a significant fraction of the container volume, the free space in which the gas particles can move around is (decreased increased). This causes the observed pressure of a real gas to be (less greater) than the value predicted by the ideal gas law.

8. A gas sample should exhibit ideal behavior at relatively (low high) temperatures and (low high) pressures.

   A gas is likely to experience deviations from ideal behavior at relatively (low high) temperatures and (low high) pressures.

$CH_4(g)$ $NH_3(g)$

9. Which gas shown above is more likely to experience deviations from ideal behavior at relatively low temperatures? Justify your answer.

$He(g)$ $Xe(g)$

10. Which gas shown above is more likely to experience deviations from ideal behavior at relatively high pressures? Justify your answer.

3.7 Solutions and Mixtures

Essential knowledge statements from the AP Chemistry CED:

- Solutions, also sometimes called homogeneous mixtures, can be solids, liquids, or gases. In a solution, the macroscopic properties do not vary throughout the sample. In a heterogeneous mixture, the macroscopic properties depend on location in the mixture.
- Solution composition can be expressed in a variety of ways; molarity is the most common method used in the laboratory.
  - Equation: molarity (M) = (moles of solute)/(liters of solution)

A solution can involve solids, such as steel or brass. A solution can involve liquids, such as a mixture of ethanol and water. A solution can involve gases, such as the air/atmosphere. A common example of a solution is one in which a substance is dissolved completely in water. This is known as an **aqueous** solution.

There are two main ways to prepare an aqueous solution.

- Dissolve a solid solute in water
- Perform a dilution, in which a concentrated solution is combined with water to make a dilute solution. (Note: A concentrated solution is often referred to as a stock solution.)

Dissolve a solid solute in water

1. Perform a calculation to determine the mass of solid that is needed to prepare a specific volume of solution with a specific concentration.
2. Use weighing paper or a small container to measure the determined mass of solid on a balance.
3. Choose a volumetric flask with a volume that is equal to the desired volume of the solution.
4. Add the weighed sample of solid to the volumetric flask. Rinse the weighing paper or container with distilled water if necessary. Transfer the rinsing solution to the volumetric flask.
5. Add distilled water to the volumetric flask until it is approximately half full.
6. Swirl the solution in the flask until the solid dissolves completely.
7. Fill the volumetric flask with distilled water up to the calibration mark on the neck of the flask.
8. Seal the flask and mix the final solution to ensure that it is homogeneous.

Perform a dilution

1. Perform a calculation to determine the volume of stock solution that is needed to prepare a specific volume of solution with a specific concentration.
2. Use a graduated cylinder, buret, or volumetric pipet to measure the determined volume of stock solution as precisely as possible.
3. Choose a volumetric flask with a volume that is equal to the desired volume of the solution.
4. Transfer the measured amount of stock solution to the volumetric flask.
5. Fill the volumetric flask with distilled water to the calibration mark on the neck of the flask.
6. Seal the flask and mix the final solution to ensure that it is homogeneous.

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11. A student needs to prepare 250.0 mL of 0.0500 *M* $Na_2SO_4(aq)$.

    (a) Determine the mass of $Na_2SO_4(s)$ that is needed to prepare this solution.

    (b) A student makes the claim that the concentration of $Na^+(aq)$ ions in this solution is equal to 0.0500 *M*. Do you agree or disagree with the student's claim? Justify your answer.

Step	Description
1	Used weighing paper to measure 3.03 g KNO_3(*s*) on a balance.
2	Added the KNO_3(*s*) to a 100.0 mL volumetric flask.
3	Added distilled water to the volumetric flask up to the calibration mark on the neck of the flask.
4	Sealed the volumetric flask and mixed the final solution until all of the KNO_3(*s*) dissolved completely.

12. A student was asked to prepare 100.0 mL of 3.00 *M* KNO_3(*aq*). The student wrote down a description of each step that they performed in the laboratory. The list is shown above.
    - Identify two different mistakes that were made in this experiment.
    - Explain what the student should have done in order to correct each mistake.

Step	Description
1	Used weighing paper to measure 50.00 g $CaCl_2$(*s*) on a balance.
2	Added the $CaCl_2$(*s*) to a 500.0 mL volumetric flask.
3	Added distilled water to the volumetric flask until it was approximately half full.
4	Swirled the solution until the solid is completely dissolved.
5	Added distilled water to the volumetric flask up to the calibration mark on the neck of the flask.
6	Sealed the flask and mixed the final solution by inverting the flask several times.

13. A student prepared a solution of $CaCl_2$(*aq*) by following the procedure shown above. Calculate the concentration of the chloride ions, Cl^-(*aq*), in this solution.

14. A student needs to prepare a solution of NaOH(*aq*). Calculate the volume of 6.0 *M* NaOH(*aq*) needed to make 500.0 mL of 0.100 *M* NaOH(*aq*).

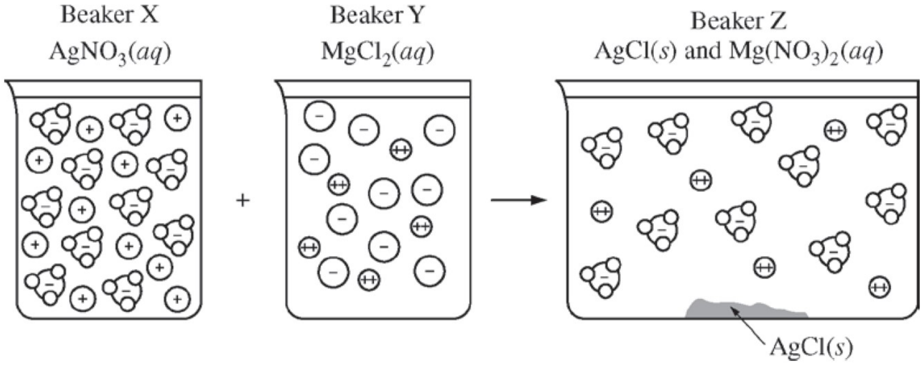
Step	Description
1	Added distilled water to a 200.0 mL volumetric flask until it was approximately half full.
2	Used a volumetric pipet to measure 25.0 mL of 3.00 *M* HNO_3(*aq*) and added the solution to the volumetric flask.
3	Added distilled water to the volumetric flask up to the calibration mark on the neck of the flask.
4	Sealed the flask and mixed the final solution by inverting the flask several times.

15. A student prepared a solution of HNO_3(*aq*) by following the procedure shown above. Calculate the concentration of HNO_3(*aq*) in this solution.

3.8 Representations of Solutions

Essential knowledge statement from the AP Chemistry CED:

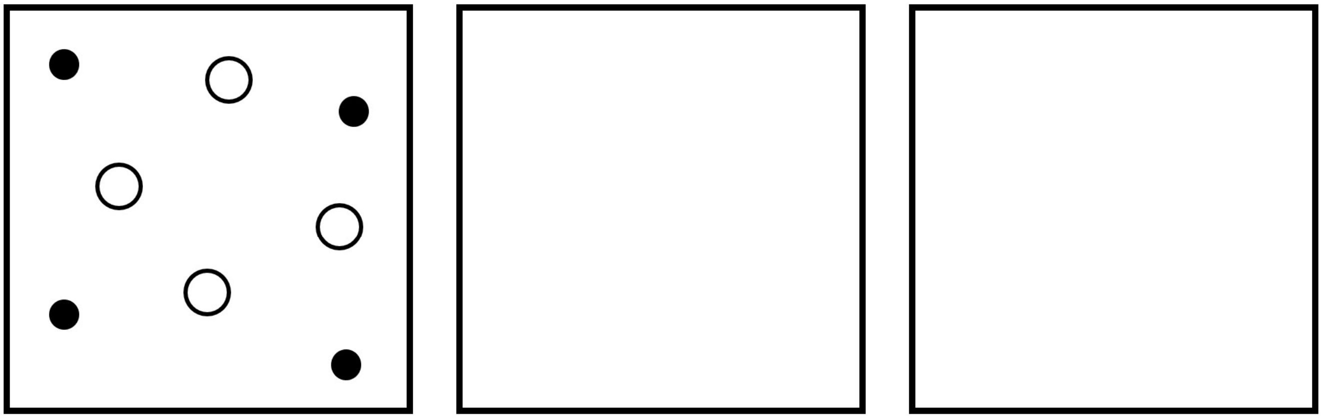
- Particulate representations of solutions communicate the structure and properties of solutions, by illustration of the relative concentrations of the components in the solution and drawings that show interactions among the components.



16. Beaker X contains 1.0 L of 2.0 *M* $AgNO_3$(*aq*). Beaker Y contains 1.0 L of $MgCl_2$(*aq*). A student combines the solutions by pouring them into a larger, previously empty beaker Z. A white precipitate is formed. Assume that the volumes are additive. Use the information in the particle diagrams above to answer the following questions.

(a) Determine the concentration of $MgCl_2$(*aq*) in Beaker Y. ______________________________

(b) Determine the concentration of $Mg(NO_3)_2$(*aq*) in Beaker Z. ____________________________



$1.0\ M\ \mathrm{NaCl}(aq)$ $1.5\ M\ \mathrm{NaCl}(aq)$ $1.0\ M\ \mathrm{MgCl_2}(aq)$

17. The particle diagram shown above on the left represents 1.0 L of $1.0\ M\ \mathrm{NaCl}(aq)$. Water molecules are not shown in the diagram.

    (a) Do the black circles in the diagram above represent $\mathrm{Na^+}(aq)$ ions or $\mathrm{Cl^-}(aq)$ ions? Justify your answer.

    (b) In the boxes above, draw particle diagrams to represent 1.0 L of $1.5\ M\ \mathrm{NaCl}(aq)$ and 1.0 L of $1.0\ M\ \mathrm{MgCl_2}(aq)$.

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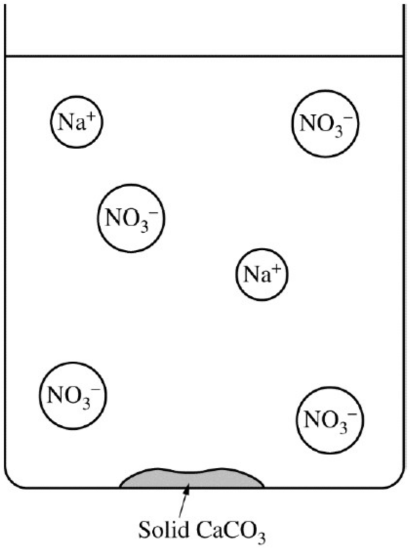
18. A student is given a 50.0 mL sample of a solution of $\mathrm{Na_2CO_3}(aq)$ of unknown concentration. To determine the concentration of $\mathrm{Na_2CO_3}$ in this solution, the student adds an excess amount of $1.0\ M\ \mathrm{Ca(NO_3)_2}(aq)$ to the solution, causing a precipitate to form.

    (a) Write the balanced molecular equation for the precipitation reaction that occurs between $\mathrm{Na_2CO_3}(aq)$ and $\mathrm{Ca(NO_3)_2}(aq)$.

    (b) Write the net ionic equation for the reaction that you wrote in part (a).

18. (continued)

(c) The diagram shown at right is incomplete. Draw in the species needed to accurately represent the major ionic species remaining in solution after the reaction has been completed.



(d) The student filters the solution and dries the solid precipitate. The mass of the precipitate is recorded as 0.93 g. Calculate each of the following.

(i) the number of moles of the precipitate

(ii) the concentration, in mol/L, of Na_2CO_3 in the 50.0 mL sample of solution that was used in this experiment

(e) If the solid precipitate was not completely dry when its mass was recorded, will the calculated value for the concentration of Na_2CO_3 be too low or too high? Justify your answer.

(f) After the precipitate has been filtered from the solution, the liquid that passes through the filter paper is tested to see if it can conduct electricity. What would be observed? Justify your answer.