❶ FOCUS

Objectives

14.4.1 Relate the total pressure of a mixture of gases to the partial pressures of the component gases.

14.4.2 Explain how the molar mass of a gas affects the rate at which the gas diffuses and effuses.

Guide for Reading

Build Vocabulary **L2**

Imagine a Picture As students learn about *effusion* and *diffusion,* have them visualize each process at the microscopic level. Then have them describe what is happening.

Reading Strategy **L2**

Monitor Your Understanding If students are having difficulty reading *Graham's Law,* have them think about how they are reading and how they might deal with the difficulty.

❷ INSTRUCT

Have students study the photograph and read the text that opens the section. Ask students to try to explain why high-altitude climbers carry a supply of oxygen. *(Students may recall that atmospheric pressure decreases with altitude. They may conclude that the drop in pressure is related to a decrease in the concentration of the gases in air, including oxygen.)*

Dalton's Law
Discuss **L2**

Assess students' knowledge about gases by asking them to compare the number of particles in two identical, sealed containers of propane and helium gas at the same temperature and pressure. *(Equal volumes of gases at the same temperature and pressure contain equal numbers of particles.)*

14.4 Gases: Mixtures and Movements

Guide for Reading

➤ Key Concepts
- How is the total pressure of a mixture of gases related to the partial pressures of the component gases?
- How does the molar mass of a gas affect the rate at which the gas effuses or diffuses?

Vocabulary
partial pressure
Dalton's law of partial pressures
diffusion
effusion
Graham's law of effusion

Reading Strategy
Previewing Before you read, look at the equation on this page that is highlighted in yellow. In your own words, describe the relationship that the equation is expressing.

Interactive Textbook

Animation 17 Observe the behavior of a mixture of nonreacting gases.

—with **ChemASAP**

Connecting to Your World
The top of Mount Everest is more than 29,000 feet above sea level. A list of gear for an expedition to Mount Everest includes climbing equipment such as an ice axe and a climbing harness. It includes ski goggles and a down parka with a hood. All the items on the list are important, but none is as important as the compressed-gas cylinders of oxygen. In this section, you will find out why a supply of oxygen is essential at higher altitudes.

Dalton's Law

Gas pressure results from collisions of particles in a gas with an object. If the number of particles increases in a given volume, more collisions occur. If the average kinetic energy of the particles increases, more collisions occur. In both cases, the pressure increases. Gas pressure depends only on the number of particles in a given volume and on their average kinetic energy. Particles in a mixture of gases at the same temperature have the same average kinetic energy. So the kind of particle is not important.

Table 14.1 shows the composition of dry air, air that does not contain any water vapor. The contribution each gas in a mixture makes to the total pressure is called the **partial pressure** exerted by that gas. In dry air, the partial pressure of nitrogen is 79.11 kPa. **In a mixture of gases, the total pressure is the sum of the partial pressures of the gases.**

$$P_{total} = P_1 + P_2 + P_3 + \ldots$$

This equation is a mathematical expression of a law proposed by Dalton. **Dalton's law of partial pressures** states that, at constant volume and temperature, the total pressure exerted by a mixture of gases is equal to the sum of the partial pressures of the component gases.

Table 14.1

Composition of Dry Air		
Component	**Volume (%)**	**Partial pressure (kPa)**
Nitrogen	78.08	79.11
Oxygen	20.95	21.22
Carbon dioxide	0.04	0.04
Argon and others	0.93	0.95
Total	100.00	101.32

Section Resources

Print
- **Guided Reading and Study Workbook,** Section 14.4
- **Core Teaching Resources,** Section 14.4 Review
- **Transparencies,** T158–T159
- **Laboratory Manual,** Lab 25
- **Small-Scale Chemistry Laboratory Manual,** Lab 21

Technology
- **Interactive Textbook with ChemASAP,** Animation 17, 18; Problem-Solving 14.32; Assessment 14.4
- **Go Online,** Section 14.4

100 kPa   250 kPa   200 kPa   550 kPa

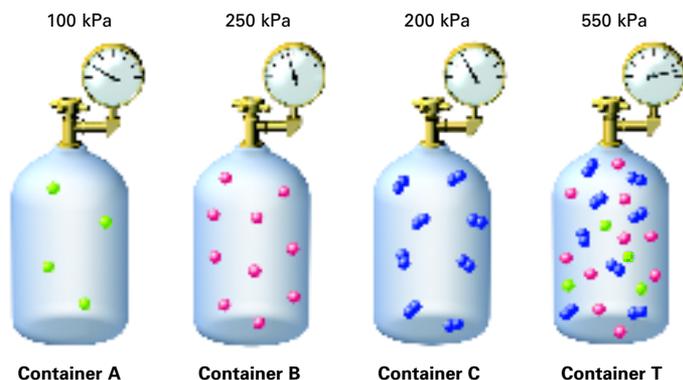Container A   Container B   Container C   Container T

Figure 14.16 Three gases are combined in container T. The pressure that each gas exerts is independent of the pressure exerted by the other two gases. The pressure in container T is the sum of the pressures in containers A, B, and C. **Interpreting Diagrams** *What is the relationship between the number of particles in containers A and C and the partial pressures of the gases in A and C?*

Look at Figure 14.16. Containers A, B, C, and T (for total) have the same volume and are at the same temperature. The gases in containers A, B, and C are combined in container T. Because the volumes are identical, each gas in the mixture exerts the pressure it exerted before the gases were mixed in container T. So the pressure in container T (550 kPa) is the sum of the pressures in containers A, B, and C (100 + 250 + 200 kPa).

If the percent composition of a mixture of gases does not change, the fraction of the pressure exerted by a gas does not change as the total pressure changes. This fact is important for people who must operate at high altitudes. For example, at the top of Mount Everest, the total atmospheric pressure is 33.73 kPa. This is about one-third of its value at sea level. The partial pressure of oxygen is also reduced by one third, to 7.06 kPa. The partial pressure of oxygen must be 10.67 kPa or higher to support respiration in humans. The climber in Figure 14.17 needs an oxygen mask and a cylinder of compressed oxygen to survive.

Figure 14.17 This climber is using a tank of compressed gas to supplement the supply of oxygen available at high altitudes.

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Sample Problem 14.6

Answers

31. 20.0 kPa + 46.7 kPa + 26.7 kPa = 93.4 kPa or 9.34×10^1 kPa
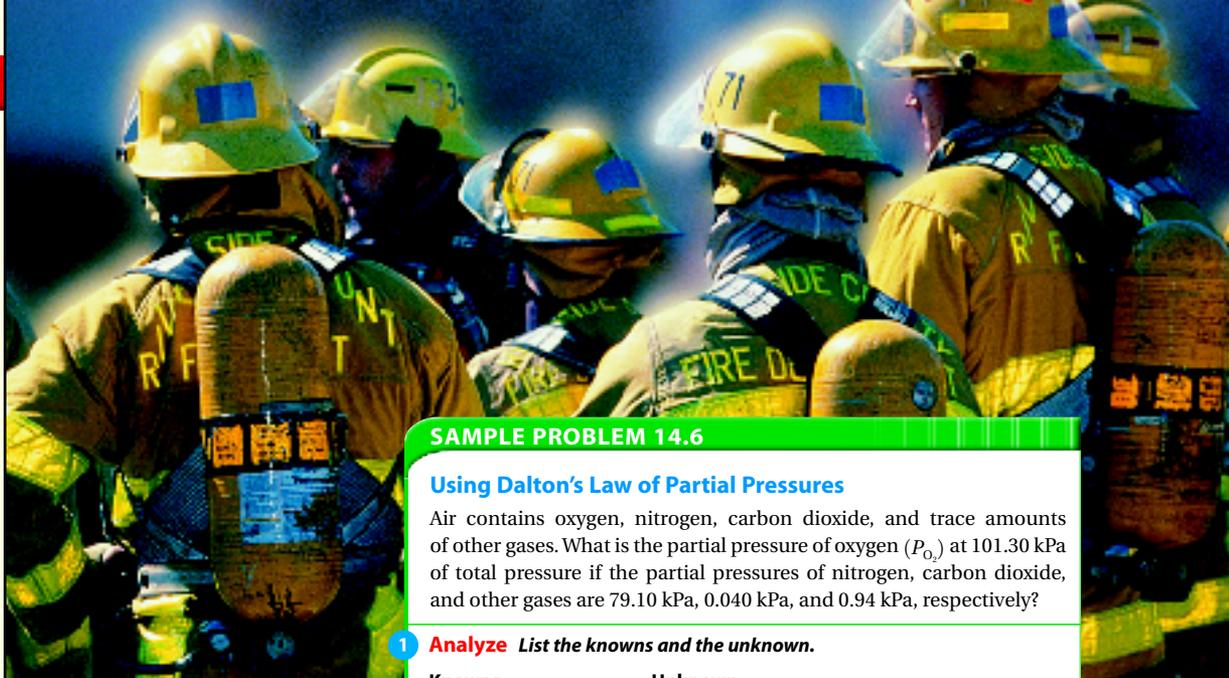
32. 32.9 kPa − 6.6 kPa − 23.0 kPa = 3.3 kPa

Practice Problems Plus L2

The pressure in an automobile tire filled with air is 245.0 kPa. The P_{O_2} = 51.3 kPa, P_{CO_2} = 0.10 kPa, and P_{others} = 2.3 kPa. **What is the P_{N2}?** (191.3 kPa)

Use Visuals L1

Have students examine the visual on this page and read the caption. Ask, **How does the amount of oxygen in the tank of compressed air compare to the amount of oxygen in the air you normally breathe?** *(Air is usually about 21% oxygen, so the air in the tanks contains about the same percentage of oxygen.)*

Firefighters carry tanks of compressed air. The tanks contain from 19.5% to 23.5% oxygen by volume.

Interactive Textbook

Problem Solving 14.32
Solve Problem 32 with the help of an interactive guided tutorial.

—— with **ChemASAP**

SAMPLE PROBLEM 14.6

Using Dalton's Law of Partial Pressures

Air contains oxygen, nitrogen, carbon dioxide, and trace amounts of other gases. What is the partial pressure of oxygen (P_{O_2}) at 101.30 kPa of total pressure if the partial pressures of nitrogen, carbon dioxide, and other gases are 79.10 kPa, 0.040 kPa, and 0.94 kPa, respectively?

1 Analyze *List the knowns and the unknown.*

Knowns
- P_{N_2} = 79.10 kPa
- P_{CO_2} = 0.040 kPa
- P_{others} = 0.94 kPa
- P_{total} = 101.30 kPa

Unknown
- P_{O_2} = ? kPa

Use Dalton's law of partial pressures $(P_{total} = P_{O_2} + P_{N_2} + P_{CO_2} + P_{others})$ to calculate the unknown value (P_{O_2}).

2 Calculate *Solve for the unknown.*

Rearrange Dalton's law to isolate P_{O_2}. Substitute the values for the partial pressures and solve the equation.

$$P_{O_2} = P_{total} - (P_{N_2} + P_{CO_2} + P_{others})$$
$$= 101.30 \text{ kPa} - (79.10 \text{ kPa} + 0.040 \text{ kPa} + 0.94 \text{ kPa})$$
$$= 21.22 \text{ kPa}$$

3 Evaluate *Does the result make sense?*

The partial pressure of oxygen must be smaller than that of nitrogen because P_{total} is only 101.30 kPa. The other partial pressures are small, so an answer of 21.22 kPa seems reasonable.

Practice Problems

31. Determine the total pressure of a gas mixture that contains oxygen, nitrogen, and helium. The partial pressures are: P_{O_2} = 20.0 kPa, P_{N_2} = 46.7 kPa, and P_{He} = 26.7 kPa.

32. A gas mixture containing oxygen, nitrogen, and carbon dioxide has a total pressure of 32.9 kPa. If P_{O_2} = 6.6 kPa and P_{N_2} = 23.0 kPa, what is P_{CO_2}?

Graham's Law

Suppose you open a perfume bottle in one corner of a room. At some point a person standing in the opposite corner will be able to smell the perfume. Molecules in the perfume evaporate and diffuse, or spread out, through the air in the room. **Diffusion** is the tendency of molecules to move toward areas of lower concentration until the concentration is uniform throughout. In Figure 14.18A, bromine vapor is diffusing through the air in a graduated cylinder. The bromine vapor in the bottom of the cylinder has started to move upward toward the area where there is a lower concentration of bromine. In Figure 14.18B, the bromine has diffused almost to the top of the cylinder. If the process is allowed to continue, the bromine vapor will spill out of the cylinder.

There is another process that involves the movement of molecules in a gas. This process is called effusion. During **effusion**, a gas escapes through a tiny hole in its container. With effusion and diffusion, the type of particle is important. 🔑 **Gases of lower molar mass diffuse and effuse faster than gases of higher molar mass.**

Thomas Graham's Contribution The Scottish chemist Thomas Graham studied rates of effusion during the 1840s. From his observations, he proposed a law. **Graham's law of effusion** states that the rate of effusion of a gas is inversely proportional to the square root of the gas's molar mass. This law can also be applied to the diffusion of gases.

Graham's law makes sense if you know how the mass, velocity, and kinetic energy of a moving object are related. The expression that relates the mass (m) and the velocity (v) of an object to its kinetic energy (KE) is KE $= 1/2mv^2$. For the kinetic energy to be constant, any increase in mass must be balanced by a decrease in velocity. For example, a ball with a mass of 2 g must travel at 5 m/s to have the same kinetic energy as a ball with a mass of 1 g traveling at 7 m/s. There is an important principle here. If two objects with different masses have the same kinetic energy, the lighter object must move faster.
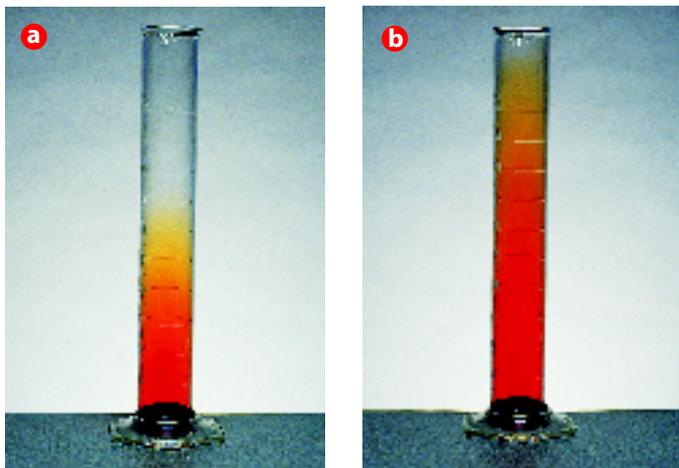
Go Online

SC*i*LINKS

For: Links on Diffusion/Effusion
Visit: www.SciLinks.org
Web Code: cdn-1144

Figure 14.18 The diffusion of one substance through another is a relatively slow process. **a** Bromine vapor is diffusing upward through the air in a graduated cylinder. **b** After several hours, bromine vapors are near the top of the cylinder. **Predicting** *What will happen as the bromine continues to diffuse?*

Differentiated Instruction

Less Proficient Readers   L1

Have students work in groups to rank the relative rates of diffusion at a constant temperature for carbon dioxide, helium, and nitrogen. *(helium > nitrogen > carbon dioxide)*

Graham's Law

Word *Origins*   L2

During diffusion, the particles move apart. During effusion, the particles move out of a tiny hole. (Students may have trouble with the scientific definitions of *effusion* and *diffusion* because of the multiple, often overlapping, meanings of these terms in common usage. For example, in many dictionaries one definition of *effuse* is "to spread out; diffuse; radiate.")

Use Visuals   L1

Figure 14.18 Have students study the photograph. Explain that diffusion is a relatively slow process whose rate is inversely proportional to the square root of the molar mass of the gas.

CLASS   Activity

Effusion   L1

Purpose Students compare effusion rates of helium and air.

Materials 2 round, identical balloons; helium; metric tape measure.

Safety Wear safety goggles when handling balloons.

Procedure Fill two identical, round non-latex balloons with equal volumes of helium and air. Have volunteers measure the circumference of the balloons. One day later, measure the circumferences again.

Expected Outcome Helium effused from the balloon at a faster rate.

Go Online

SC*i*LINKS

Download a worksheet on **Diffusion/Effusion** for students to complete, and find additional teacher support from NSTA SciLinks.

Answers to...
Figure 14.18 The bromine will spill out of the container.

❸ ASSESS

Evaluate Understanding   L2

Tell students that the partial pressures of oxygen and hydrogen gases in a container are both 100 kPa. Ask, **In which sample are there more molecules? In which sample do the molecules have greater average kinetic energy?** *(Both gases have the same number of molecules and same average kinetic energy.)* Ask, **About how much faster does helium diffuse compared to oxygen?** *(Helium diffuses almost three times faster than oxygen.)*

Reteach   L1

Remind students that *diffusion* is a general term that applies to molecules moving away from a region of high concentration. Effusion is a specific example of diffusion in which molecules pass through a narrow opening. Graham's law applies to both.

Elements ➤ Handbook

Both tables report data for dry air. Both show that air is mainly nitrogen and oxygen. Table 14.1 uses percents and includes a compound. The table on R4 uses ppm and provides specific data for more elements .

Interactive Textbook

If your class subscribes to the Interactive Textbook, use it to review key concepts in Section 14.4.

with ChemASAP

Figure 14.19 The character balloons used in parades are filled with helium gas so that they will float.

Comparing Effusion Rates The balloon in Figure 14.19 is used in holiday parades. It is filled with helium so that it will float above the crowd along the parade route. There is a drawback to using helium in a balloon. Both helium atoms and the molecules in air can pass freely through the tiny pores in a balloon. But a helium-filled balloon will deflate sooner than an air-filled balloon. Kinetic theory can explain this difference.

If the balloons are at the same temperature, the particles in each balloon have the same average kinetic energy. But helium atoms are less massive than oxygen or nitrogen molecules. So the molecules in air move more slowly than helium atoms with the same kinetic energy. Because the rate of effusion is related only to a particle's speed, Graham's law can be written as follows for two gases, A and B.

Interactive Textbook

Animation 18 Observe the processes of gas effusion and diffusion.

with ChemASAP

$$\frac{Rate_A}{Rate_B} = \sqrt{\frac{molar\ mass_B}{molar\ mass_A}}$$

The rates of effusion of two gases are inversely proportional to the square roots of their molar masses. You can use the expression to compare the rates of effusion of nitrogen (molar mass = 28.0 g) and helium (molar mass = 4.0 g). Helium effuses (and diffuses) nearly three times faster than nitrogen at the same temperature.

$$\frac{Rate_{He}}{Rate_{N_2}} = \sqrt{\frac{28.0\ g}{4.0\ g}} = \sqrt{7.0} = 2.7$$

14.4 Section Assessment

33. 🔑 **Key Concept** In a mixture of gases, how is the total pressure determined?

34. 🔑 **Key Concept** What is the effect of molar mass on rates of diffusion and effusion?

35. How is the partial pressure of a gas in a mixture calculated?

36. What distinguishes effusion from diffusion? How are these processes similar?

37. How can you compare the rates of effusion of two gases in a mixture?

38. Explain why the rates of diffusion of nitrogen gas and carbon monoxide are almost identical at the same temperature.

Elements ➤ Handbook

Table 14.1 on page 432 and the *Elements in the Atmosphere* table on page R4 provide data on the composition of air. Look at the data included in each table. Identify two ways in which the tables are similar. Describe at least three differences.

Interactive Textbook

Assessment 14.4 Test yourself on the concepts in Section 14.4.

with ChemASAP

Section 14.4 Assessment

33. Total pressure is equal to the sum of the partial pressures of the components.
34. Gases with lower molar masses diffuse and effuse faster than gases with higher molar masses.
35. Subtract the partial pressures of the other gases from the total pressure.
36. During effusion, a gas escapes through a tiny hole in its container. In both cases, the rate depends on the molar mass.
37. The rate of effusion of two gases in a mixture is inversely proportional to the square roots of their molar masses.
38. Carbon monoxide and nitrogen have almost identical molar masses when the masses are rounded to two significant figures (28 g).

Diffusion

Purpose
To infer diffusion of a gas by observing color changes during chemical reactions.
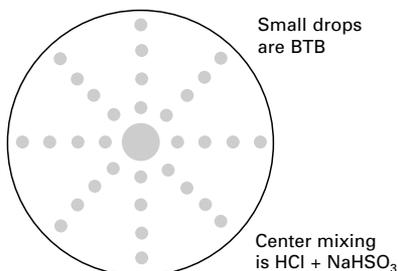
Materials
- clear plastic cup or Petri dish
- reaction surface
- dropper bottles containing bromthymol blue, hydrochloric acid, and sodium hydrogen sulfite
- ruler
- cotton swab
- NaOH, NH_4Cl, KI, and $NaNO_2$ (optional)

Procedure
1. Use the plastic cup or Petri dish to draw the large circle shown below on a sheet of paper.

Small drops are BTB

Center mixing is HCl + $NaHSO_3$

2. Place a reaction surface over the grid and add small drops of bromthymol blue (BTB) in the pattern shown by the small circles. Make sure the drops do not touch one another.
3. Mix one drop each of hydrochloric acid (HCl) and sodium hydrogen sulfite ($NaHSO_3$) in the center of the pattern.
4. Place the cup or Petri dish over the grid and observe what happens.
5. If you plan to do You're The Chemist Activity 1, don't dispose of your materials yet.

Analyze and Conclude
Using your experimental data, record the answers to the following questions below your data table.
1. Describe in detail the changes you observed in the drops of BTB over time. Draw pictures to illustrate the changes.

2. Draw a series of pictures showing how one of the BTB drops might look over time if you could view the drop from the side.
3. The BTB changed even though you added nothing to it. If the mixture in the center circle produced a gas, would this explain the change in the drops of BTB? Use kinetic theory to explain your answer.
4. Translate the following word equation into a balanced chemical equation: Sodium hydrogen sulfite reacts with hydrochloric acid to produce sulfur dioxide gas, water, and sodium chloride.

You're The Chemist
The following small-scale activities allow you to develop your own procedures and analyze the results.
1. **Analyze It!** Carefully absorb the center mixture of the original experiment onto a cotton swab and replace it with one drop of NaOH and one drop of NH_4Cl. Describe what happens and explain in terms of kinetic theory. Ammonium chloride reacts with sodium hydroxide to produce ammonia gas, water, and sodium chloride. Write and balance a chemical equation to describe this reaction.
2. **Design It!** Design an experiment to observe the effect of the size of the BTB drops on the rate at which they change. Explain your results in terms of kinetic theory.
3. **Analyze It!** Repeat the original experiment, using KI in place of BTB and mixing sodium nitrite ($NaNO_2$) with hydrochloric acid at the center. Record your results. Write and balance an equation for the reaction. $NaNO_2$ reacts with HCl to produce nitrogen monoxide gas, water, sodium nitrate, and sodium chloride.

Analyze and Conclude
1. The drops near the center change immediately. As the gas diffuses, all the drops change color. The color change begins at the outer edge of each drop.

center

yellow

green

2.

green

yellow
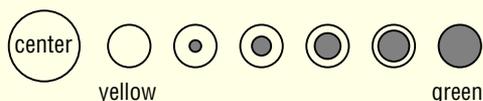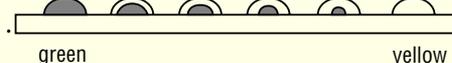
3. The particles of gas produced are in motion. As the particles diffuse from the center, they collide and react with molecules of BTB.
4. $NaHSO_3 + HCl \rightarrow SO_2 + H_2O + NaCl$

Diffusion　L2
Objective After completing this activity, students will be able to:
- infer diffusion of a gas by observing color changes during reactions.

Skills Focus Inferring, Drawing Conclusions

Prep Time 30 minutes
Class Time 40 minutes

Advance Preparation

Solution	Preparation
1.0M HCl	82 mL of 12M in 1.0 L
0.04% BTB	100 mg in 16.0 mL 0.01M NaOH, dilute to 250 mL
0.5M NaOH	20.0 g in 1.0 L
1.0M NH_4Cl	13.4 g in 250 mL
0.4M $NaNO_2$	6.9 g in 250 mL
0.1M KI	4.2 g in 250 mL
1.0M $NaHSO_3$	26 g in 250 mL

Safety Always slowly add acid to water.

Teaching Tips
- Before class, add a drop of BTB to the paper to be sure the paper is not acidic. The BTB should remain blue.

Expected Outcome
The drops of BTB turn yellow, starting with those closest to the center.

You're the Chemist!
1. As ammonia diffuses, BTB changes from yellow to blue.

   $NH_4Cl + NaOH \rightarrow NH_3 + H_2O + NaCl$
2. Vary the size of the BTB drops from "pin-heads" to "puddles." Tiny drops are better able to detect small quantities of gases.
3. The KI turned orange in the same manner as the BTB turned yellow.

   $3NaNO_2 + 2HCl \rightarrow$
 $2NO + H_2O + NaNO_3 + 2NaCl$

For Enrichment　L3
Have students design an experiment that shows the effect of temperature on rate of diffusion. The drops change color more quickly at higher temperatures.