11.3 Gases and Temperature Changes

Section Preview/ Specific Expectations

In this section, you will

- **perform** laboratory experiments investigating the effects of temperature changes on the volume of gases
- **solve** problems using Charles' law and Gay-Lussac's law
- **convert** units between the Celsius and Kelvin temperature scales
- **communicate** your understanding of the following terms: *Kelvin scale, absolute zero, Charles' law, Gay-Lussac's law, pressure-relief valve, fusible plugs*

CHECKPOINT

As you perform Investigation 11-B, keep in mind the ratio of 1/273 discovered by Charles. Can you recall from your previous studies a special significance for the number 273?

As you learned in Section 11.1, the average kinetic energy of gas molecules is directly related to the temperature. The greater the temperature, the greater the average motion of the molecules and the greater their average kinetic energy. In other words, the temperature of a substance is defined as the measure of the average kinetic energy of the molecules in that substance.

When substances are cooled, they lose kinetic energy. How does this affect their volume? Remember, for an ideal gas, we can think of its particles as having mass but no volume. When you perform Investigation 11-B on page 438, imagine air behaving as an ideal gas. How do you think air, in an expandable container will react to temperature changes?

Temperature and Volume

Sometimes, scientific discoveries are made well before any technological application of them can be envisioned. At other times, the desire to develop new technologies leads to experiments from which discoveries are made.

Jacques Charles (1746–1823), a French scientist, was the first to fill a balloon with hydrogen. He was also interested in hot-air balloons, which were being developed in France at the time. Charles investigated the expansion rates of nitrogen, oxygen, hydrogen, and carbon dioxide. He found that these gases all expanded by the same ratio. For each degree Celsius increase in temperature, all of these gases would expand by a certain fraction. This fraction was $1/273^{rd}$ of their volume at 0°C. For each degree Celsius decrease in temperature, their volume would decrease by the same fraction. Thus, if a gas at 0°C were to be heated to 273°C, its volume would double. This held true when the pressure and the amount of gas remained constant. Figure 11.16 shows the expansion of the volume of gas in a hot-air balloon as the air inside the balloon is heated.

Figure 11.16 **These photographs show the gradual expansion of a hot air balloon. Since hot air is less dense than cooler air, the balloon rises.**

Chemistry Bulletin

Science | Technology | Society | Environment

Gas Temperature and Cryogenics

Some people wish to be frozen when they die, trusting that future technologies will be able to revive them. This untested process is called *cryonics*. It was first suggested by Robert C.W. Ettinger in 1962. Ettinger has since set up his own Cryonics Institute in Michigan, where people can have their bodies frozen and stored. We still cannot freeze and re-animate higher animals, such as people. Cryogenic freezing, however, can suspend the life of tissues and organs used for transplants. Cryogenics has also made many other technologies possible. It has proven that science and science fiction are often closer than we think!

The term *cryogenics* can be applied to all temperatures below the normal boiling point of oxygen, or –183°C.

When substances encounter temperatures this low, they often behave strangely. Liquid helium, for example, becomes a "superfluid" at temperatures below –270.97°C. The principle of "superconductivity" is just as interesting Cryogenically cooled rings made out of metals such as lead and aluminum become "superconductors." They can keep currents travelling in circles for hours even after scientists have removed the original source of electricity.

Scientists have made use of the strange things that happen to matter at low temperatures. Superconductors have been used to make huge electromagnets, like the one at the Argonne National Laboratory near Chicago. Argonne's electromagnet can produce a magnetic field 134 000 times as strong as Earth's. It operates on relatively little power because of its superconducting capabilities. Such magnets are used in nuclear power research to find new nuclear particles. And while cryogenics has advanced nuclear science, it also helps scientists to study the effects of nuclear radiation. Scientists study cryogenically frozen atoms suspended in an irradiated state to understand how nuclear radiation can harm human health.

Cryogenically cooled magnets are used in MRI technology.

Cryogenics produces large-scale amounts of nitrogen and oxygen. Scuba divers and astronauts use compressed oxygen tanks that provide a six to eight hour supply of oxygen. Rocket engines use liquid oxygen as fuel. We use liquid nitrogen to make ammonia for fertilizers, to keep frozen foods cold during transport, and to fast-freeze these foods.

The list of applications of cryogenics is long and varied, and research continues. Maybe Ettinger is right and one day all of the occupants of the Cryonics Institute will live again!

Making Connections

1. What do you think might be some possible future applications of cryogenics?
2. Scientists use Dewar Flasks to contain cryogenic fluids. How do these flasks work? Do some research to find out.

Investigation 11-B

SKILL FOCUS
- Performing and recording
- Analyzing and interpreting
- Identifying variables

The Relationship Between Temperature and Volume of a Gas

As you learned in Investigation 11-A, the length of a column of trapped air is directly proportional to its volume. In this investigation, you will see the effect of temperature changes on the volume of a gas, also measured in terms of the length of a column of trapped air.

Question

What is the relationship between the temperature and volume of a fixed amount of gas at a constant external pressure?

Materials

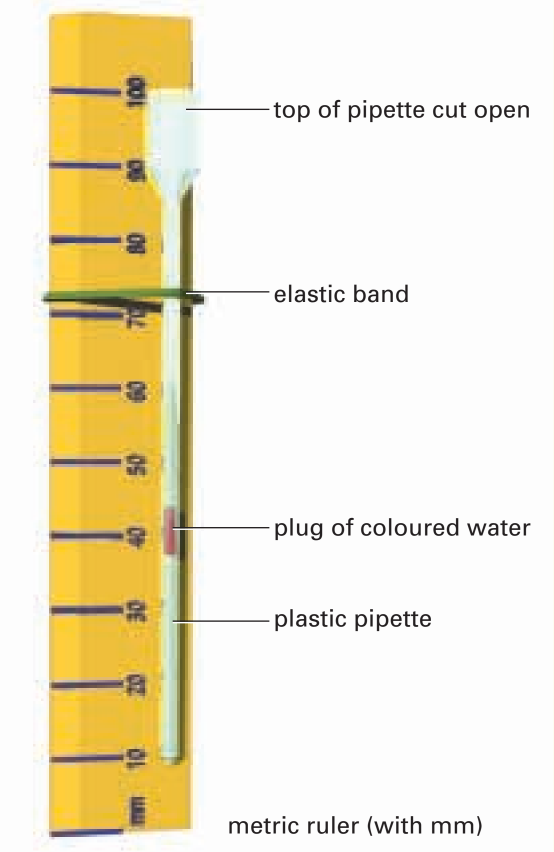
thin stem plastic pipette
metric ruler (with mm)
Celsius thermometer
400 mL beaker
ice
hot plate
match or Bunsen burner
2 elastics
scissors
coloured water
tap water

Safety Precautions

- Be very careful when sealing the end of the plastic pipette with a flame. The plastic will melt and may begin to burn. Hot, molten plastic can burn your skin.
- Do not inhale any of the fumes from the plastic.
- Before lighting the Bunsen burner, check that there are no flammable solvents nearby.

Procedure

1. Squeezing the pipette bulb, draw enough water into the pipette to form a small plug. The rest of the pipette should contain air.
2. Using a flame from a match or Bunsen burner, carefully seal the open end of the pipette completely. Allow the pipette to cool for at least 3 min before carrying on with the rest of the procedure.
3. Using scissors, cut off the tip of the bulb of the pipette.
4. Carefully attach the pipette to the ruler, using a rubber band, so that the bottom of the tube is even with the 1.0 cm mark of the ruler.
5. Fill a 400 mL beaker about two thirds full of tap water and add 3 or 4 ice cubes. Place the thermometer in the water. Then put the ruler with attached pipette into the water. Allow the ruler and pipette to sit for 5 min.



6. Copy the data table into your notebook. Your table should have at least eight rows for data.

Temp. (°C)	V (length of trapped air in mm)

7. After 5 min, measure the length (or "volume") of the trapped gas in mm. Remember that the bottom of the pipette stem is set at the 1.0 cm mark. Record these values in your data table.
8. Place the beaker on the hot plate and **slowly** heat the water in the beaker. Measure the length ("V") and temperature of the trapped gas at every 10°C to 15°C. Measure the length and temperature to a maximum of 60°C.
9. Clean the apparatus and dispose of the pipette as directed.
10. Complete the data table. Find the average of the V/T column.
11. Plot a graph of V (mm) versus T. The horizontal axis (temperature) must extend from –300°C to 100°C.
12. Draw a line of best fit. Extrapolate this line to the x-intercept.

Analysis

1. What is the independent variable in this investigation? What is the dependent variable?
2. What relationship did you notice between temperature and volume?
3. When Jacques Charles did an activity similar to this one, he obtained an x-intercept of –273°C. What is significant about this value?
4. If the value obtained by Charles was correct, what is the percentage error in your x-intercept?

Conclusion

5. In your own words, state the qualitative relationship that exists between the temperature and volume of a fixed amount of gas at constant pressure.

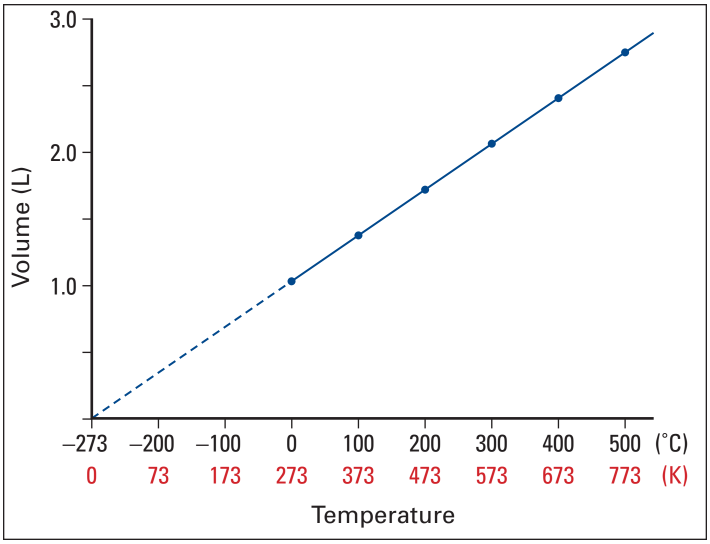


Figure 11.17 Absolute zero for an ideal gas is –273.15˚C or 0 K, the point at which all molecular motion theoretically ceases.

The Kelvin Scale and Absolute Zero

Charles found that, regardless of the gas tested, the *x*-intercept on a graph would always be –273˚C. In 1848, Lord Kelvin (1824–1907), a Scottish scientist, realised the significance of this finding. He reasoned that at –273˚C, molecular motion would cease. At this temperature, kinetic energy would be zero. The volume of a gas would, hypothetically, also be zero.

Of course, real gas molecules do have volume. Also, at low temperatures all gases will condense and change state. Still, Kelvin used this reasoning as the basis for a new temperature scale, the **Kelvin scale**. The starting point for the scale, 0 K, is called **absolute zero**. Figure 11.17 shows how absolute zero can be hypothesized, based on data from experiments. The modern accepted value for 0 K, derived with equipment more sophisticated than that available to Charles, is –273.15˚C. Each unit in the Kelvin scale is exactly the same as a unit in the Celsius scale.

There are no degree signs used in the Kelvin scale. More importantly, there are no negative values. What would happen if you tried to calculate a temperature twice as warm as –5˚C? Mathematically, the answer would be –10˚C, but this is a *colder* temperature. When mathematical manipulations are involved in studying gas behaviour, you need to convert degree Celsius temperatures into kelvins. This is done using the relationship

$$T_K = {^\circ}\mathrm{C} + 273.15 \textbf{ or } {^\circ}\mathrm{C} + 273$$

Most often, you will round off and use 273 as the conversion factor relating K and ˚C.

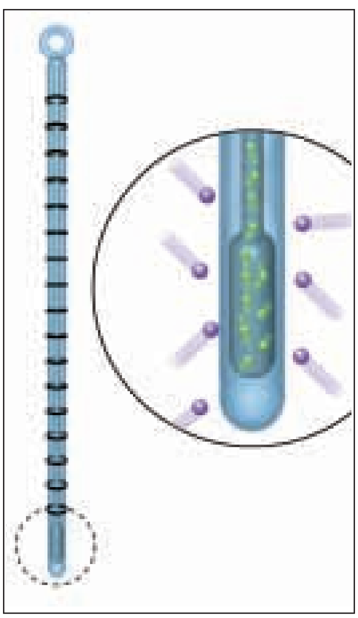


Figure 11.18 As temperature increases, particles move more rapidly, striking the outside of the thermometer with greater force and frequency. The kinetic energy of the particles is transferred to the particles inside the tube of the thermometer. The volume of the liquid inside the tube (usually mercury or coloured alcohol) expands.

Charles' Law

Although Charles discovered that the volume of a fixed amount of gas at constant pressure was proportional to its temperature, he never published this finding. In 1802, Joseph Louis Gay-Lussac (1778–1850), a French scientist, made reference to Charles' work in a published paper. The relationship between temperature and volume has since become known as **Charles' law**. Charles' law states that *the volume of a fixed mass of gas is proportional to its temperature when the pressure is kept constant*.

As you can see from Figure 11.19 on page 442, the volume of a gas increases or decreases by a fixed increment when subjected to a change in temperature. The algebraic statement of Charles' law depends on using absolute, or Kelvin, temperatures. This law is stated as $V \propto T$, where T is measured in kelvins. (Figure 11.18 uses Charles' law to explain how a thermometer works.)

Introducing a proportionality constant (k_1), this relationship can be restated as

$$V = k_1T \qquad \text{or} \qquad \frac{V}{T} = k_1$$

This relationship only applies if pressure is kept constant and temperature is given in kelvins. If a sample of gas is collected at initial conditions (i), this relationship can be rewritten as

$$\frac{V_i}{T_i} = k_1$$

Suppose the gas sample is subjected to a change in temperature. Under the final conditions (f), there will be a volume change such that

$$\frac{V_f}{T_f} = k_1$$

Since both initial and final conditions are equal to the proportionality constant, Charles' law can be written as

$$\frac{V_i}{T_i} = \frac{V_f}{T_f}$$

Thus, Charles' law can be restated as: *the volume of a fixed mass of gas at constant pressure is directly proportional to its Kelvin temperature.* In the next ThoughtLab, you will convert your temperature findings from Investigation 11-B into kelvins and see why you must use Kelvin temperature when performing calculations with gases.

Electronic Learning Partner

Go to the Chemistry 11 Electronic Learning Partner for a demonstration of Charles' law.

ThoughtLab Charles' Law and Kelvin Temperature

As you have learned, when making calculations involving temperature in gas samples, Kelvin temperatures must be used. You will see why for yourself in this ThoughtLab.

Materials

data table from Investigation 11-B
graph paper

Procedure

1. Make a new data table like the one below. You should include at least eight rows for data.

Temp (°C)	Temp (K)	V (mm)	$\frac{V\text{ (mm)}}{T\text{ (°C)}}$	$\frac{V\text{ (mm)}}{T\text{ (K)}}$

2. Fill in columns 1, 3, and 4 with your data from Investigation 11-B.
3. Convert temperature data in column 1 from °C to kelvins. Enter the new values in columns 2 and 5.
4. Plot a graph of V (mm) versus T (K). The horizontal axis (T) must extend from 0 K to 400 K.
5. Draw a line of best fit. Extrapolate this line to the x-intercept.

Analysis

1. What did you notice about the values of V/T (K) in the data table?
2. How do the values of V/T (K) compare to the values of V/T (°C) in the data table? Explain the significance of these two sets of data.
3. What mathematical relationship seems to exist between volume and temperature when temperature is recorded in °C? In kelvins?

Extension

4. Make a new data table like the one below. Include at least eight rows for data.

At 100 kPa | At 163 kPa | At 346 kPa

T (K)	V (mm)	T (K)	V (mm)	T (K)	V (mm)

In columns 1 and 2, enter your data from columns 2 and 3 of the data table you made above. Carry the data from column 1 into columns 3 and 5.

5. Using the Boyle's law formula ($P_iV_i = P_fV_f$ at constant T and n), calculate the "volume" of the gas sample at 163 kPa and at 346 kPa.
6. Plot a graph of your new data table. Use a different colour for each line. Extrapolate each line to the x-intercept.
7. Of what significance are the results obtained from this graph?

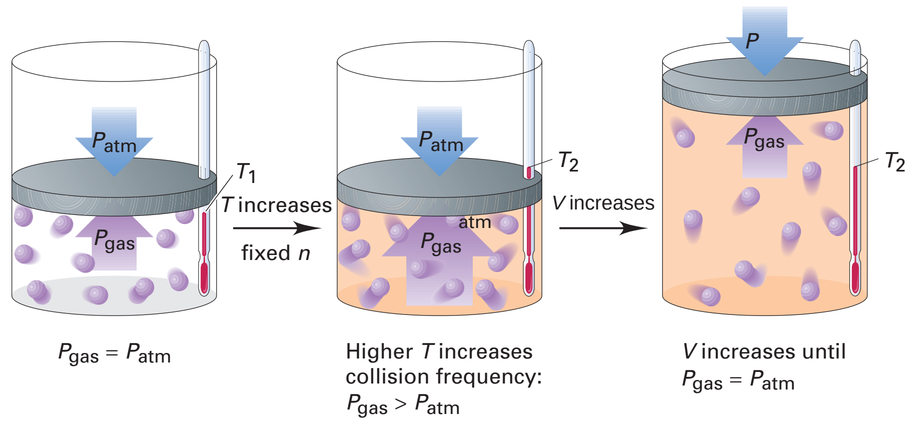


Figure 11.19 **As a gas is heated from T_i to T_f, the molecules move faster and collide with the container walls more frequently, increasing the pressure applied by the gas (P_{gas}). This added pressure increases the volume of the container until the pressure exerted by the gas is equal to the pressure exerted by the atmosphere.**

CHEM FACT

As helium gas is cooled below −268.95°C, it forms a liquid. At −270.97°C, helium still looks like a liquid, but a liquid with unusual properties. Suddenly, liquid density drops and this "liquid" gains the ability to move through very small holes that helium gas cannot pass through. It flows up the walls of its container defying gravity, and has zero viscosity. Below −270.97°C, helium becomes a superfluid, the only one discovered so far. Helium never changes to a solid.

Sample Problem

Charles' Law: Calculating Volume

Problem

Using a glass syringe, a scientist draws exactly 25.5 cm^3 of dry oxygen at 20.0°C from a metal cylinder. She needs to heat the oxygen for an experiment, so she places the syringe in an oven at 65.0°C and leaves it there for 30 min. Assuming the atmospheric pressure remains the same, what volume will the oxygen occupy?

What Is Required?

You need to find the volume of the oxygen in the syringe after it has been heated for 30 min. (V_f = ?)

What Is Given?

- You know the initial volume and temperature.
  Initial volume (V_i) = 25.5 cm^3
  Initial temperature (T_i) = 20.0°C
- You know the final temperature.
  Final temperature (T_f) = 65.0°C
- You know that the pressure does not change.

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Plan Your Strategy

Algebraic method

- Since the pressure is constant and the temperature of the gas increases, you will need to use the Charles' law formula to find the final volume of the gas sample.
- Since T is given in °C, you will need to convert it to kelvins.
- You can substitute numbers and units for the variables in the formula to solve for the unknown (V_f).

Ratio method

- Since the pressure is constant and the gas is subjected to an increase in temperature, you know that, according to Charles' law, the volume will increase.
- Since T is given in °C, you will need to convert it to kelvins.
- To find the final volume, you can multiply the initial volume by a ratio of the kelvin temperatures that is greater than one.

Act on Your Strategy

Algebraic method

$$T_i = (20.0^\circ\text{C} + 273) = 293\ \text{K} \qquad T_f = (65.0^\circ\text{C} + 273) = 338\ \text{K}$$

$$\frac{V_i}{T_i} = \frac{V_f}{T_f}$$

$$\frac{25.5\ \text{cm}^3}{293\ \text{K}} = \frac{V_f}{338\ \text{K}}$$

To isolate V_f, you need to multiply both sides of the equation by 338 K.

$$\frac{25.5\ \text{cm}^3}{293\ \text{K}} \times 338\ \text{K} = \frac{V_f}{\cancel{338\ \text{K}}} \times \cancel{338\ \text{K}}$$

$$\frac{(25.5\ \text{cm}^3)(338\ \cancel{\text{K}})}{(293\ \cancel{\text{K}})} = V_f$$

$$V_f = 29.42\ \text{cm}^3$$

Ratio method

$$T_i = (20.0^\circ\text{C} + 273) = 293\ \text{K} \qquad T_f = (65.0^\circ\text{C} + 273) = 338\ \text{K}$$

$$V_f = V_i \times \text{ temperature ratio}$$
$$= 25.5^\circ\text{C} \times \frac{338\ \cancel{\text{K}}}{293\ \cancel{\text{K}}}$$
$$= 29.42\ \text{cm}^3$$

Continued ...

PROBLEM TIP

In these Sample Problems, you will see two different methods of solving the problem: the algebraic method and the ratio method. Choose the method you prefer to solve this type of problem.

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Since the least number of significant digits in the question is three, the final volume will be reported to three significant digits.

$$V_f = 29.4\ \text{cm}^3$$

Check Your Solution

- The units for the answer are in cubic centimetres.
- When the units cancel out, cm^3 remains.
- The volume of the oxygen gas increased due to an increase in temperature.

Sample Problem

Charles' Law: Calculating Temperature

Problem

A balloon is filled with 2.50 L of dry helium at 23.5°C. The balloon is placed in a freezer overnight. The next morning, the balloon is removed and the volume is found to be 2.15 L. What was the temperature (in °C) inside the freezer if the pressure remained constant?

What Is Required?

You need to find the temperature of the freezer in °C. (T_f = ?)

What Is Given?

- You know the initial volume and temperature.
  Initial volume (V_i) = 2.50 L
  Initial temperature (T_i) = 23.5°C
- You know the final volume.
  Final volume (V_f) = 2.15 L
- You know that the pressure does not change.

Plan Your Strategy

Algebraic method

- Since pressure is constant and the volume and temperature change, you will need to use the Charles' law formula to find the final temperature of the gas sample.
- Since T is given in °C, you need to convert it to kelvins.
- You can substitute numbers and units for the variables in the formula to solve for the unknown (T_f).

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Ratio method

- Since pressure remains constant and the volume of the balloon decreases, you know that according to Charles' law, the temperature of the gas must also decrease.
- Since T is given in °C, you need to convert it to kelvins.
- To find the final temperature inside the freezer, you can multiply the initial temperature by a volume ratio that is less than one.

Act on Your Strategy

Algebraic method

$$T_i = (23.5^\circ\text{C} + 273)$$
$$= 297 \text{ K}$$

$$\frac{V_i}{T_i} = \frac{V_f}{T_f}$$

$$\frac{2.50 \text{ L}}{297 \text{ K}} = \frac{2.15 \text{ L}}{T_f}$$

To simplify the equation and make it easier to solve, you can first cross-multiply the above equation.

$$(2.50 \text{ L})(T_f) = (296.5 \text{ K})(2.15 \text{ L})$$

To isolate T_f, you need to divide both sides of the equation by 2.50 L.

$$\frac{(\cancel{2.50 \text{ L}})(T_f)}{(\cancel{2.50 \text{ L}})} = \frac{(297 \text{ K})(2.15 \text{ L})}{(2.50 \text{ L})}$$

$$T_f = \frac{(297 \text{ K})(2.15 \cancel{\text{L}})}{(2.50 \cancel{\text{L}})}$$
$$= 255.42 \text{ K}$$

Since the question asks for the temperature in °C, you need to convert kelvins to °C. To do this, subtract 273 from the answer.

$$T_f = (255.42 \text{ K} - 273)$$
$$= -17.6^\circ\text{C}$$

Ratio method

$$T_i = (23.5^\circ\text{C} + 273)$$
$$= 297 \text{ K}$$

$$T_f = 297 \text{ K} \times \text{volume ratio}$$
$$= 297 \text{ K} \times \frac{2.15 \cancel{\text{L}}}{2.50 \cancel{\text{L}}}$$
$$= 255.42 \text{ K}$$

Since the question asks for the temperature in °C, you need to convert kelvins to °C. To do this, subtract 273 from the answer.

$$T_f = (255.42 \text{ K} - 273)$$
$$= -17.6^\circ\text{C}$$

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mind STRETCH

Using the formula $y = mx + b$, see if you can derive the Charles' law formula from the graph that you produced in the ThoughtLab on page 441. For help in deriving equations from graphs, see Appendix E.

Since the least number of significant digits in the question is three significant digits, the final temperature will be reported to the same significant digits.

$T_f = -17.6°C$

Check Your Solution

- The unit for the answer is in kelvins.
- When the units cancel out, kelvins remain.
- Kelvins have been converted to °C.
- The temperature of the balloon has decreased, which is reflected in its decrease in volume.

Practice Problems

5. Convert the following temperatures to the Kelvin scale.

(a) 25°C

(b) 37°C

(c) 150°C

6. Convert the following temperatures to degrees Celcius.

(a) 373 K

(b) 98 K

(c) 425 K

7. Give an example of something that might be at each temperature in question 5.

8. A sample of nitrogen gas surrounding a circuit board occupies a volume of 300 mL at 17°C and 100 kPa. What volume will the nitrogen occupy at 100.0°C if the pressure remains constant?

9. A 2.5 L balloon is completely filled with helium indoors at a temperature of 24.2°C. The balloon is taken out on a cold winter day (–17.5°C). What will the volume of the balloon become, assuming a constant pressure?

10. 10.0 L of neon at 20.0°C is expanded to a volume of 30.0 L. If the pressure remains constant, what must the final temperature be (in °C)?

11. A 14.5 cm^3 sample of oxygen gas at 24.3°C is drawn into a syringe with a maximum volume of 60 cm^3. What is the maximum change in temperature that the oxygen can be subjected to before the plunger pops out of the syringe?

12. Methane gas can be condensed by cooling and increasing the pressure. A 600 L sample of methane gas at 25°C and 100 kPa is cooled to –20°C. In a second step, the gas is compressed until the pressure is quadrupled. What will the final volume be? (**Hint:** Use both Boyle's law and Charles' law to answer this question.)

PROBLEM TIP

In question 8, the smallest number of significant digits is two (17°C). However, before doing your calculations, you must convert this value to kelvins (290 K). This value now has *three* significant digits. Round off your final answer to *three* significant digits.

Gay-Lussac's Law

Aside from balloons and syringes, most containers that are used to store gases have a fixed volume. You know that temperature is a measure of the average kinetic energy of the molecules making up a substance. If the temperature of a gas increases, but the volume of its container cannot increase, what happens to the pressure of the gas inside?

Extending the work of Charles, Joseph Louis Gay-Lussac discovered the relationship between temperature and pressure acting on a fixed volume of a gas. (Remember that for gases, V_{gas} = volume of container holding the gas.) As you will learn later in this section, this relationship is very important for the safe handling of gases under pressure in steel tanks or aerosol cans. **Gay-Lussac's law** states that *the pressure of a fixed amount of gas, at constant volume, is directly proportional to its Kelvin temperature*. (See Figure 11.20.)

$P \propto T$
(if T is given in kelvins and volume and amount of gas is constant)

Introducing a new proportionality constant (k_2), this relationship can be restated as

$$P = k_2 T \qquad \text{or} \qquad \frac{P}{T} = k_2$$

If we assign P_i and T_i as the initial conditions, and P_f and T_f for the final conditions, the above relationship can be rewritten as

$$\frac{P_i}{T_i} = \frac{P_f}{T_f}$$

As you will notice, this mathematical relationship is very similar to that of Charles' law.

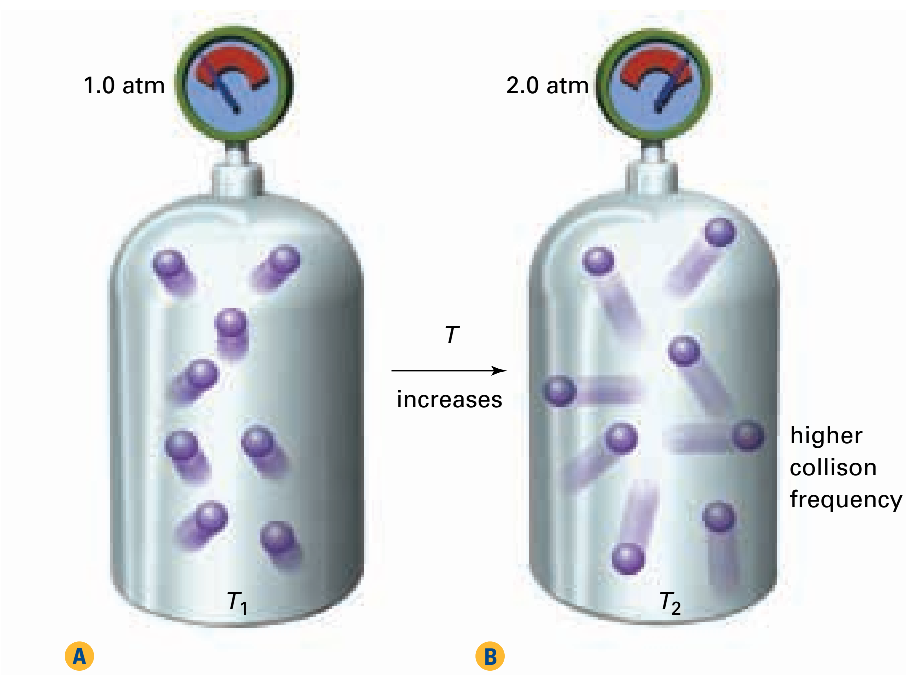

Figure 11.20 **When temperature increases from T_i to T_f in a rigid container with a constant volume, the average speed of the gas molecules increases. Since the molecules move faster, they collide with each other and with the walls of the container more forcefully and more frequently. The gas pressure increases.**

Technology LINK

Underinflated vehicle tires contribute to unsafe road handling and to lower fuel economy. Based on what you know about Gay-Lussac's law, why should you measure the pressure in vehicle tires before driving the vehicle for a long distance?

Web LINK

www.school.mcgrawhill.ca/resources/
Refrigerators and air conditioners function because of the relationship between pressure and temperature. Research the Joule-Thomson Effect. Go to the web site above. Go to **Science Resources**, then to **Chemistry 11** to find out where to go next.

Sample Problem

Gay-Lussac's Law: Calculating Pressure

Problem

A cylinder of chlorine gas (Cl_2) is stored in a concrete-lined room for safety. The cylinder is designed to withstand 50 atm of pressure. The pressure gauge reads 35.0 atm at 23.2˚C. An accidental fire in the room next door causes the temperature in the storage room to increase to 87.5˚C. What will the pressure gauge read at this temperature?

What Is Required?

You need to find the pressure of the oxygen once the temperature has been increased. (T_f = ?)

What Is Given?

- You know the initial pressure and temperature.
  Initial pressure (P_i) = 35.0 atm
  Initial temperature (T_i) = 23.2˚C
- You know the final temperature.
  Final temperature (T_f) = 87.5˚C
- You know that the volume of the rigid metal tank will not change appreciably.

PROBLEM TIP

In these Sample Problems, you will see two different methods of solving the problem: the algebraic method and the ratio method. Choose the method you prefer to solve this type of problem.

Plan Your Strategy

Algebraic method

- Since the volume of the cylinder is essentially constant, and the temperature increases, you will need to use the Gay-Lussac's law formula to find the final pressure of the gas sample.
- Since T is given in ˚C, you need to convert it to kelvins.
- You can substitute numbers and units for the variables in the formula to solve for the unknown. (P_f = ?)

Ratio method

- Since the volume of the cylinder is essentially constant, and the temperature increases, you know that according to Gay-Lussac's law, the pressure exerted by the gas increases as well.
- Since T is given in ˚C, you need to convert it to kelvins.
- To find the final pressure of the gas, you can multiply the initial pressure by a temperature ratio that is greater than one.

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Act on Your Strategy

Algebraic method

$T_i = (23.2°\text{C} + 273) = 296 \text{ K}$ $\quad$ $T_f = (87.5°\text{C} + 273) = 360 \text{ K}$

$$\frac{P_i}{T_i} = \frac{P_f}{T_f}$$

$$\frac{35.0 \text{ atm}}{296 \text{ K}} = \frac{P_f}{361 \text{ K}}$$

To simplify the equation and make it easier to solve, you can first cross-multiply the above equation.

$$(35.0 \text{ atm})(361 \text{ K}) = (P_f)(296 \text{ K})$$

To isolate P_f, you need to divide both sides of the equation by 296 K.

$$\frac{(35.0 \text{ atm})(361 \text{ K})}{(296 \text{ K})} = \frac{(P_f)\cancel{(296 \text{ K})}}{\cancel{(296 \text{ K})}}$$

$$\frac{(35.0 \text{ atm})(361 \cancel{\text{K}})}{(296 \cancel{\text{K}})} = P_f$$

$$P_f = 42.69 \text{ atm}$$

Ratio method

$T_i = (23.2°\text{C} + 273) = 296 \text{ K}$ $\quad$ $T_f = (87.5°\text{C} + 273) = 361 \text{ K}$

$$\begin{aligned} P_f &= 35.0 \text{ atm} \times \text{temperature ratio} \\ &= 35.0 \text{ atm} \times \frac{361 \cancel{\text{K}}}{296 \cancel{\text{K}}} \\ &= 42.69 \text{ atm} \end{aligned}$$

Since the least number of significant digits in the question is three, the final pressure will be rounded off to the same number of significant digits.

$$P_f = 42.7 \text{ atm}$$

Check Your Solution

- The unit for the answer is in atmospheres.
- When the units cancel out, atm remains.
- Kelvins have been converted to °C.
- The pressure inside the cylinder has increased, as would be expected when the temperature increases.

Practice Problems

13. An unknown gas is collected in a 250.0 mL flask and sealed. Using electronic devices, it is found that the gas inside the flask exerts a pressure of 135.5 kPa at 15°C. What pressure will the gas exert if the temperature (in Kelvins) is doubled?

Continued ...

Continued ...
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14. At 18°C, a sample of helium gas stored in a metal cylinder exerts a pressure of 17.5 atm. What will the pressure become if the tank is placed in a closed room where the temperature increases to 40°C?

15. A gaseous refrigerant, enclosed in copper tubes, surrounds the freezer in a small refrigerator. The gas is found to exert a pressure of 110 kPa at 45°C. The refrigerant is allowed to expand through a nozzle into an expansion chamber such that the exerted pressure decreases to 89 kPa. What is the temperature inside the freezer?

16. Before leaving on a trip to Florida, you measure the pressure inside the tires of your car at a gas station. At −7.5°C the tire pressure is found to be 206.5 kPa. When you arrive in Florida, you stop for dinner. Before leaving, you once again measure the tire pressure at a gas station beside the restaurant. Most pressure gauges in the United States are calibrated in psi. You find the tire pressure to be 34.3 psi. What is the approximate temperature in Florida? (**Hint:** See the MathLink on page 428 to find out how to convert psi to kPa.)

Compressed Gases and Safety Concerns

The Gay-Lussac's law Sample Problem in this section indicates how carefully gases under pressure must be handled. Chlorine gas can cause serious respiratory problems and irritate the skin and mucous membranes. In extreme cases, death from suffocation could result from exposure to this gas. Yet chlorine is an important industrial product. Compounds of chlorine are used in bleaches, oxidizing agents, and solvents, and as intermediates in the manufacture of other substances.

Compressed gases are commonly stored in thick-walled metal cylinders designed especially for this purpose. All cylinders must comply with Canadian Transport Commission (CTC) regulations. Containers must be permanently marked with a serial number and specifications for the volume of the cylinder and the maximum pressure it can withstand. Containers must be tested every five to ten years, with the date of the test stamped on the cylinder.

Figure 11.22 on the next page shows a typical compressed gas cylinder. You can see that it is built to withstand high pressures. There are other safety precautions as well, however.

Most cylinders used to store gases have safety devices regulating the internal gas pressure. The most common of these is a **pressure relief valve**. If the pressure inside the cylinder increases to a dangerous level, a spring allows the valve to open and release excess gas until the internal pressure returns to a safe level. Some pressure relief valves will close once excess gas is released. These valves are relatively expensive compared to non-reclosing valves. Non-reclosing valves are found on common household products such as aerosol hairsprays.

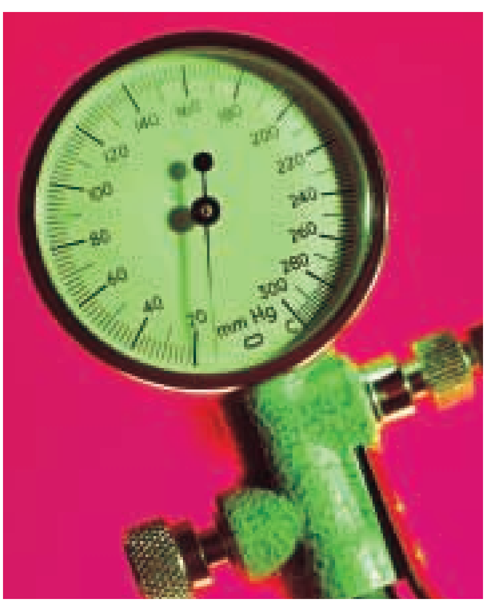

Figure 11.21 Gas cylinders have pressure valves to help the user regulate the amount of gas escaping when the cylinder is opened.

Cylinders used to store gases such as acetylene (C_2H_2), that could cause an explosive chemical reaction at high temperatures, are fitted with **fusible plugs**. These plugs are designed to melt and allow gas to escape at temperatures lower than those at which hazardous reactions can start. Fusible plugs for acetylene cylinders are made of a metal alloy that melts at 100°C.

Not all compressed gas cylinders are fitted with pressure-relief valves or fusible plugs. Cylinders containing toxic gases such as chlorine or phosgene ($COCl_2$) are one example. These gases could cause serious harm to health if released into the air in sufficient quantities. Therefore, these gases, like all compressed gases, must be handled with great care. They must be stored in a well-ventilated, dry area. The surrounding storage area must be fire-resistant, and proper fire-fighting equipment must be immediately available. Gas cylinders should never be stored near electrical circuits that might spark or near other ignition sources such as open flames. Material Data Safety Sheets must be available, and all cylinders must be clearly labelled with WHMIS warning signs.

Figure 11.22 **Pressure relief valves prevent a compressed gas cylinder from exploding if the temperature, and thus the pressure increases.**

Section Wrap-up

In this section, you learned about the relationship between volume and temperature (Charles' law). You also learned about the relationship between pressure and temperature (Gay-Lussac's law). In the next section, you will see how these relationships can be combined with Boyle's law to produce one equation that works in all three situations.

Section Review

1. K/U What safety concerns and precautions should be taken with compressed gases? Use what you know about the movement of particles to explain these precautions.

2. (a) I A gas at 107 kPa and 300 K is cooled to 146 K at the same volume. What is the new pressure?
   (b) I 17 L of gas at 300 K are cooled to 146 K at the same pressure. What is the new volume?

3. MC Describe the relationship between your answers in parts (a) and (b) of question 2.

4. C Explain in terms of molecular motion why, when the temperature is increased:
   (a) a gas increases in volume
   (b) the pressure of a gas increases

5. K/U A balloon at a party drifts above a hot stove, and explodes. Why did this happen?