SECTION
11.3 Gases and Temperature Changes

Key Terms

absolute zero
Charles's law
Gay-Lussac's law

So far, you have studied gas laws in terms of a fixed amount of gas at a constant temperature. However, you know that gas behaviour is affected by changes in temperature as well as changes in pressure. Scientific inquiries conducted in the late 1700s and early 1800s demonstrated connections between the temperature of a gas and its pressure and volume. These inquiries led to the development of two gas laws that complement Boyle's law. One of these laws describes the relationship between the temperature and volume of a gas at constant pressure. The other law describes the relationship between temperature and pressure when the volume of the gas is fixed.

The Relationship between Gas Volume and Temperature

During the last two decades of the 1700s, ballooning became a popular pursuit among inventors and scientists in France. Both the hot-air balloon and the hydrogen balloon were invented during this time. Two prominent French scientists, Jacques Charles (1746–1823) and Joseph Louis Gay-Lussac (1778–1850), were especially interested in ballooning. These scientists realized that there was a connection between the behaviour of the balloons and the properties and behaviour of gases in general.

Working independently, both Charles and Gay-Lussac discovered the same principle: As long as the amount of gas and the pressure on the gas are constant for a specific experiment, there is an increase in volume of a gas with an increase in temperature. Thus, the volume of a gas is proportional to the temperature of a gas. You can see this idea represented in **Figure 11.13**. The graphs show that plotting volume versus temperature results in a straight-line graph, when pressure and amount of gas are constant.

These graphs also show another consistent result that Charles and Gay-Lussac obtained in their studies. When linear plots of volume versus temperature are extrapolated to zero volume, all the lines converge at one value of temperature: −273.15°C. Using more recent technology to collect data than was available to either Charles or Gay-Lussac, scientists have found that the temperature for zero volume of a gas is, in fact, −273.15°C. In actual circumstances, no real gas can have a volume of zero, but experimental data do in fact show that volume approaches zero as temperature approaches −273.15°C.

Extrapolated Volume versus Temperature Data at Four Different Pressures

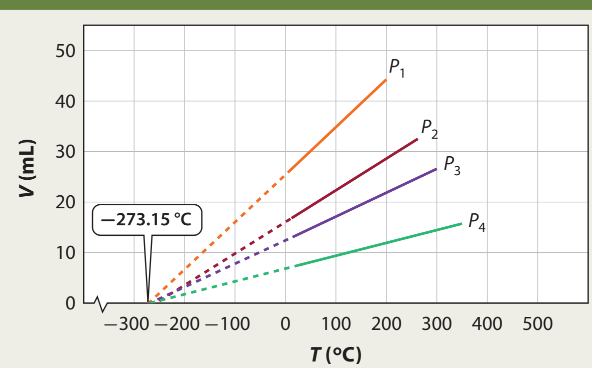

Figure 11.13 These graphs represent four experiments in which the same amount of gas was used and data were collected at four different pressures (P_1 to P_4). The solid portions of the lines represent the temperatures at which data were taken. The dashed portions represent the extrapolation of the volume versus temperature plots. All of the plots intersect at −273.15°C.

The Kelvin Temperature Scale and Absolute Zero

In 1848, twenty-five years after the death of Jacques Charles, Scottish physicist Lord Kelvin (William Thomson, 1824–1907) interpreted the significance of the extrapolated temperature at zero volume of a gas. Kelvin suggested that −273.15°C was the lowest possible temperature, or **absolute zero**. He then established a new temperature scale based on absolute zero as the starting point on the scale. The temperature scale was named the Kelvin scale in his honour.

absolute zero the lowest theoretical temperature, equivalent to −273.15°C; the temperature at which the volume of a gas approaches zero

Figure 11.14 compares the Celsius and Kelvin temperature scales. The name of a unit in the Kelvin scale is the kelvin (K). The size of the kelvin is the same as the size of a Celsius degree, but the term "degree" is not used when reporting temperatures on the Kelvin scale. As well, the starting points for these two temperature scales are different. Notice that there are no negative values on the Kelvin scale. What would happen if you tried to calculate a temperature that is 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 temperatures from the Celsius scale to the Kelvin scale.

For converting Celsius to kelvin: $K = °C + 273.15$
For converting kelvin to Celsius: $°C = K - 273.15$

The rounded-off value of 273 is often used as the conversion factor relating K and °C.

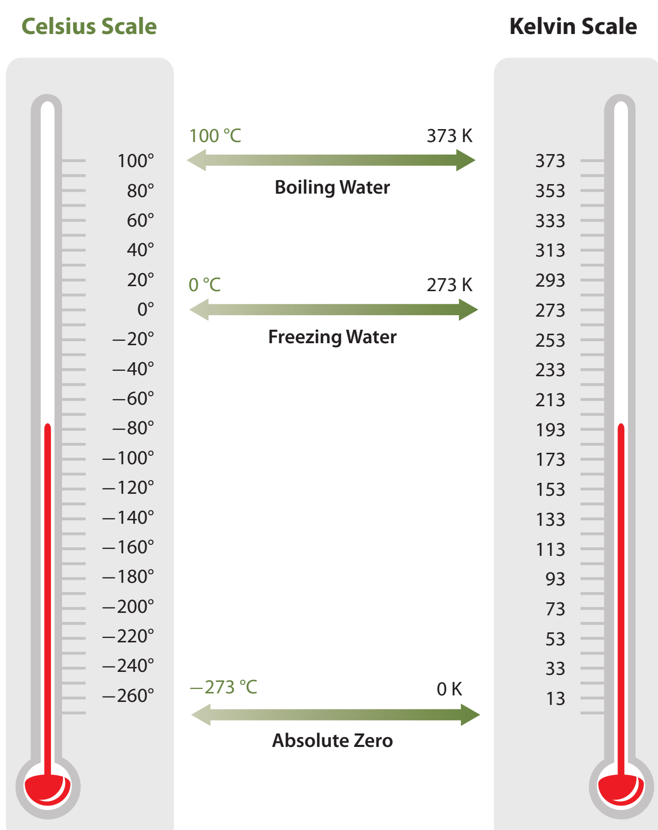

Figure 11.14 There are 273 temperature units between absolute zero and the freezing temperature of water on the Celsius and Kelvin scales. There are also 100 temperature units between the freezing and boiling temperatures of water on both scales.

Apply *If you double a Celsius temperature, by how much does the Kelvin temperature increase?*

Learning Check

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

14. What is absolute zero, and what is its significance?

15. Examine the graph in **Figure 11.14**. What do all the graph lines have in common?

16. Make the following temperature conversions.
- **a.** 27.3°C to K
- **b.** −25°C to K
- **c.** 373.2 K to °C
- **d.** 23.5 K to °C

17. Why is it necessary to keep the pressure of a gas constant when studying the relationship between temperature and volume of a gas?

18. A teacher pours liquid nitrogen at a temperature of 77 K over a balloon. Predict the changes that would occur to the balloon.

Activity 11.2 Analyzing the Temperature-Volume Relationship of a Gas

In this activity, you will use data from the table below and the graph that you construct from them to analyze the relationship between the temperature of a gas and its volume and to infer the importance of the Kelvin temperature scale.

Volume versus Temperature Data

Temperature (°C)	Temperature (K)	Volume (cm^3)	$\frac{\text{Volume } (cm^3)}{\text{Temperature } (°C)}$	$\frac{\text{Volume } (cm^3)}{\text{Temperature } (K)}$
8		29.5		
20		30.8		
30		32.1		
40		34		
50		37		
60		42		
70		49		

Materials
- graph paper
- ruler

Procedure
1. Copy and complete the data table. For the second column, you must calculate the Kelvin equivalent. For the last two columns, you must calculate the quotient of volume divided by temperature.
2. Draw one graph using the data from columns 1 and 4. Draw a second graph using the data from columns 2 and 5.

Questions
1. Use a Venn diagram to describe how the two graphs that you drew are similar and how they are different.
2. What is the *x*-intercept on each graph? What does each represent?
3. Analyze your calculated values of $\frac{V}{T}$ (°C) and $\frac{V}{T}$ (K) in the data table. What do you notice about the values?
4. How do the values of $\frac{V}{T}$ (°C) compare to the values of $\frac{V}{T}$ (K)? Explain the significance of these sets of data.
5. Based on the data in this activity, what relationship seems to exist between the volume and temperature of a gas, when pressure and amount of gas remain constant? How is that relationship affected by the temperature scale that is used?

Charles's Law and the Kelvin Temperature Scale

Charles's law a gas law stating that the volume of a fixed amount of gas at a constant pressure is directly proportional to the Kelvin temperature of the gas: $V \propto T$

You learned at the start of this section that the volume of a gas is proportional to its temperature, when pressure and amount of gas are constant. This relationship between temperature and volume has become known as **Charles's law**. This law is often stated in terms of a *directly* proportional relationship between temperature and volume. This statement only holds true, however, if the temperature is expressed in Kelvin units. To understand why, examine the graphs in **Figure 11.5**.

Both graphs show that the plot of temperature versus volume is a straight line, but notice that Graph A—in which temperature is in degrees Celsius—does *not* show a direct proportion. The graph of the line does not pass through the origin, and doubling the temperature does not double the volume. Graph B *does* show a direct proportion; temperature is in kelvins, and the graph of the line passes through the origin. A temperature of 0 K corresponds to 0 mL. Doubling the temperature doubles the volume.

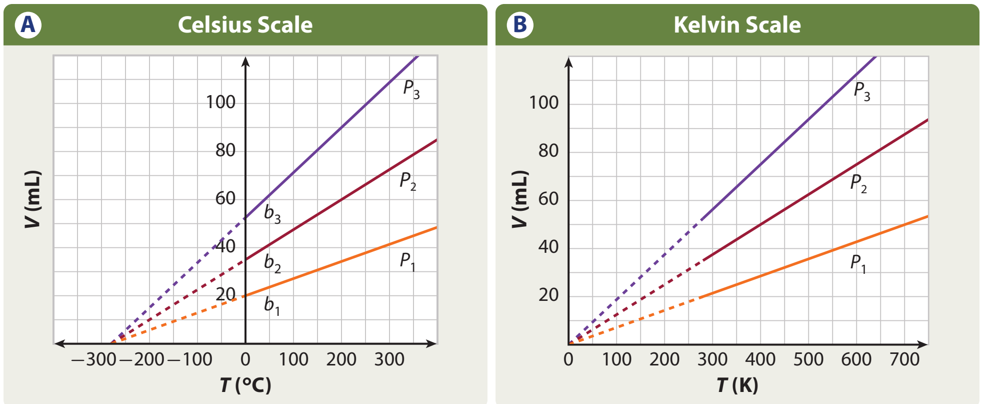

Figure 11.15 **(A)** Using the Celsius temperature scale produces straight-line graphs that have three different *y*-intercepts. **(B)** Using the Kelvin temperature scale produces straight-line graphs with the same *y*-intercept.

Analyze *Identify the x- and y-intercepts for each graph.*

Suggested Investigation

Inquiry Investigation 11-B, Studying Charles's Law

Developing a Mathematical Expression of Charles's Law

If temperature is expressed in Kelvin, the mathematical expression of Charles's law can be derived easily. The steps are similar to the method you used to create the mathematical expression for Boyle's law.

Begin with the general expression for a straight line.	$y = mx + b$
In a graph of volume versus temperature, let the *y*-axis represent volume, *V*, and let the *x*-axis represent temperature, *T*, in kelvins. Use these values to rewrite the expression.	$V = mT + b$
The symbol *m* represents the slope of the line and *b* is the *y*-intercept. Because temperature is expressed in kelvins, the line representing volume and temperature passes through the origin. Thus, $b = 0$.	$V = mT$
Divide both sides of the equation by *T*. This shows that $\frac{V}{T}$ is equal to a constant, *m*, which is the slope of the line.	$\frac{V}{T} = \frac{m\cancel{T}}{\cancel{T}}$ $\frac{V}{T} = m$
Let $\frac{V_1}{T_1}$ represent the volume and temperature at one data point on the graph and let $\frac{V_2}{T_2}$ represent volume and temperature at a second data point. The quotient of volume divided by temperature at each point equals the constant, *m*.	$\frac{V_1}{T_1} = m$ and $\frac{V_2}{T_2} = m$
Because the quotients of $\frac{V_1}{T_1}$ and $\frac{V_2}{T_2}$ are equal to the same constant, they are equal to each other.	$\frac{V_1}{T_1} = \frac{V_2}{T_2}$

Charles's law is expressed mathematically as

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}$$

This relationship only applies if the pressure and amount of gas are kept constant and if temperature is in kelvin units. The following Sample Problems and Practice Problems will reinforce your understanding of Charles's law.

Sample Problem

Using Charles's Law to Calculate Volume of a Gas

Problem

A balloon inflated with air in a room in which the temperature of the air is 295 K has a volume of 650 mL. The balloon is put into a refrigerator at 277 K and left long enough for the air in the balloon to reach the same temperature as the air in the refrigerator. Predict the volume of the balloon, assuming that the amount of air has not changed and the air pressure in the room and in the refrigerator are the same.

What Is Required?

You need to find the volume, V_2, of the balloon after it has been cooled to 277 K.

What Is Given?

You know the volume and temperature of the air sample for the first set of conditions and the temperature for the second set of conditions:

$V_1 = 650$ mL

$T_1 = 295$ K

$T_2 = 277$ K

Plan Your Strategy	Act on Your Strategy
Temperature and volume are changing at constant pressure and amount of gas. Therefore, use the equation for Charles's law.	$\frac{V_1}{T_1} = \frac{V_2}{T_2}$
Isolate the variable V_2 by multiplying each side of the equation by T_2 and rearranging the equation.	$\frac{V_1}{T_1}(T_2) = \frac{V_2}{\cancel{T_2}}(\cancel{T_2})$ $\frac{V_1 T_2}{T_1} = V_2$
Substitute numbers and units for the known variables in the formula and solve. Since the lowest number of significant digits in values in the question is two, the final volume is reported to two significant digits.	$V_2 = \frac{V_1 T_2}{T_1}$ $= \frac{(650 \text{ mL})(277 \cancel{\text{K}})}{(295 \cancel{\text{K}})}$ $= 610$ mL

According to Charles's law, when the amount and pressure of a gas are constant, there is a directly proportional relationship between the volume of the gas and its Kelvin temperature:
$V \propto T$

Alternative Solution

Plan Your Strategy	Act on Your Strategy
According to Charles's law, a decrease in temperature will cause a decrease in volume. Determine the ratio of the initial temperature and the final temperature that is less than 1.	$T_2 = 277$ K $T_1 = 295$ K temperature ratio < 1 is $\frac{277 \text{ K}}{295 \text{ K}}$
To find the final volume, multiply the initial volume of the balloon by the ratio of the two Kelvin temperatures that is less than 1.	$V_2 = V_1 \times$ temperature ratio $= (650 \text{ mL}) \times \frac{277 \cancel{\text{K}}}{295 \cancel{\text{K}}}$ $= 610$ mL

Check Your Solution

Volume units remain when the other units cancel out. Because the temperature decreases, the volume is expected to decrease. The answer represents a lower value for the volume.

Sample Problem

Using Charles's Law to Calculate Temperature of a Gas

Problem

A birthday balloon is filled to a volume of 1.50 L of helium gas in an air-conditioned room at 294 K. The balloon is then taken outdoors on a warm sunny day and left to float as a decoration. The volume of the balloon expands to 1.55 L. Assuming that the pressure and amount of gas remain constant, what is the air temperature outdoors in kelvins?

What Is Required?

You need to find the outdoor air temperature, T_2, in K.

What Is Given?

You know the volume and temperature of the air sample for the initial set of conditions and the volume for the final set of conditions:

$V_1 = 1.50$ L

$T_1 = 294$ K

$V_2 = 1.55$ L

Plan Your Strategy	Act on Your Strategy
Temperature and volume are changing at constant pressure and amount of gas. Therefore, use the equation for Charles's law.	$\frac{V_1}{T_1} = \frac{V_2}{T_2}$
Isolate the variable T_2 by multiplying each side of the equation first by T_2 and then by $\frac{T_1}{V_1}$.	$\left(\frac{V_1}{T_1}\right)(T_2) = \left(\frac{V_2}{\cancel{T_2}}\right)(\cancel{T_2})$ $\left(\frac{\cancel{V_1}}{\cancel{T_1}}\right)\left(\frac{\cancel{T_1}}{\cancel{V_1}}\right)T_2 = V_2\left(\frac{T_1}{V_1}\right)$ $T_2 = \frac{V_2T_1}{V_1}$
Substitute numbers and units for the known variables in the formula and solve. Since the number of significant digits in values in the question is three, the final volume is reported to three significant digits.	$T_2 = \frac{V_2T_1}{V_1}$ $= \frac{(1.55\ \cancel{L})(294\ K)}{(1.50\ \cancel{L})}$ $= 304$ K

Alternative Solution

Plan Your Strategy	Act on Your Strategy
According to Charles's law, a decrease in temperature will cause a decrease in volume. Determine the ratio of the initial volume and the final volume that is greater than 1.	$V_1 = 1.50$ L $V_2 = 1.55$ L volume ratio > 1 is $\frac{1.55\ L}{1.50\ L}$
To find the final temperature, multiply the initial temperature of the balloon by the ratio of the two volumes that is greater than 1.	$T_2 = T_1 \times$ volume ratio $= (294\ K) \times \frac{1.55\ \cancel{L}}{1.50\ \cancel{L}}$ $= 304$ K

Check Your Solution

The unit for the answer is kelvins. When the other units cancel out, kelvins remain. Because the volume of the balloon had increased, you would expect that the temperature had increased. The answer represents an increase in temperature.

Practice Problems

Note: Assume that the pressure and amount of gas are constant in all of the problems except question 20.

11. A gas has a volume of 6.0 L at a temperature of 250 K. What volume will the gas have at 450 K?

12. A syringe is filled with 30.0 mL of air at 298.15 K. If the temperature is raised to 353.25 K, what volume will the syringe indicate?

13. The temperature of a 2.25 L sample of gas decreases from 35.0°C to 20.0°C. What is the new volume?

14. A balloon is inflated with air in a room in which the air temperature is 27°C. When the balloon is placed in a freezer at −20.0°C, the volume is 80.0 L. What was the original volume of the balloon?

15. At a summer outdoor air temperature of 30.0°C, a particular size of bicycle tire has an interior volume of 685 cm^3. The bicycle has been left outside in the winter and the outdoor air temperature drops to −25.0°C. Assuming the tire had been filled with air in the summer, to what volume would the tire be reduced at the winter air temperature?

16. At 275 K, a gas has a volume of 25.5 mL. What is its temperature if its volume increases to 50.0 mL?

17. A sealed syringe contains 37.0 mL of trapped air. The temperature of the air in the syringe is 295 K. The sun shines on the syringe, causing the temperature of the air inside it to increase. If the volume increases to 38.6 mL, what is the new temperature of the air in the syringe?

18. A beach ball is inflated to a volume of 25 L of air in the cool of the morning at 15°C. During the afternoon, the volume changes to 26 L. What was the Celsius air temperature in the afternoon?

19. The volume of a 1.50 L balloon at room temperature increases by 25.0 percent when placed in a hot-water bath. How does the temperature of the water bath compare with room temperature?

20. Compressed gases can be condensed when they are cooled. A 5.00×10^2 mL sample of carbon dioxide gas at room temperature (assume 25.0°C) is compressed by a factor of four, and then is cooled so that its volume is reduced to 25.0 mL. What must the final temperature be (in °C)? (**Hint:** Use both Boyle's law and Charles's law to answer the question.)

Kinetic Molecular Theory and Charles's Law

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Applying the kinetic molecular theory to Charles's law is shown in **Figure 11.16**. The Kelvin temperature of a gas is directly proportional to the average kinetic energy of the gas molecules. An object's kinetic energy is related to its speed ($E_k = \frac{1}{2}mv^2$). As the temperature of a gas increases, the molecules move at higher speeds. As a result, they collide with the walls of the container and with one another more frequently and with greater force. Therefore, they exert a greater pressure on the walls of the container. If, however, the external pressure on the gas stays the same, the gas pressure causes the container to increase in size. As the volume of the container gets larger, the gas molecules must travel farther to collide with the walls of the container and with one another. As the collisions become less frequent, the pressure drops. The process continues until the pressure inside the container is once again equal to the external pressure.

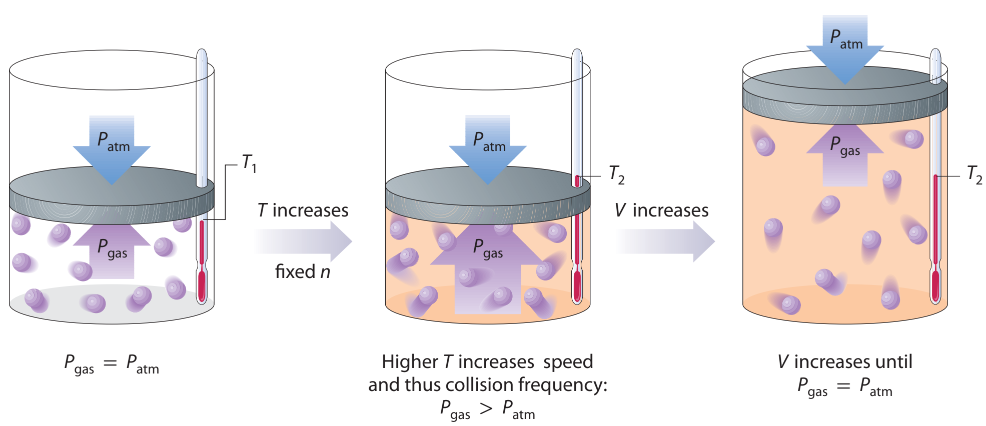

Figure 11.16 When the temperature of a gas increases, the speed of the gas molecules increases. The gas molecules collide with the walls of the container more frequently, thus increasing the pressure. If the external pressure remains the same, the gas pushes the piston up and increases the volume of the container.

Gay-Lussac's Law: The Relationship between Temperature and Pressure

Most gases, such as those used for many industrial, commercial, and medical purposes, are stored in containers that have a fixed volume. Compressed gases such as oxygen and nitrogen are usually stored in rigid cylinders and tanks, often with gauges such as the one shown in **Figure 11.17**. 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, Louis Gay-Lussac discovered the relationship between temperature and pressure acting on a fixed volume of a gas. As the temperature of the gas increases, so does the pressure. In fact, when temperature is expressed in kelvins, the relationship between temperature and pressure is directly proportional. This relationship is now referred to as **Gay-Lussac's law**.

Gay-Lussac's law a gas law stating that the pressure of a fixed amount of gas at a constant volume is directly proportional to its Kelvin temperature: $P \propto T$

Figure 11.17 Many gases are stored at high pressure in tanks such as this one. These tanks typically have gauges that monitor the pressure of the gas.

Explain *Why do compressed gas cylinders often have a pressure relief valve, which causes the release of gas when the temperature increases?*

Activity 11.3 Egg in a Bottle (Teacher Demonstration)

This activity shows the relationship between gas pressure and temperature when gas volume is constant. Your teacher will demonstrate it in order to avoid wasting food.

Materials

- peeled, hard-boiled egg
- heat-proof glass bottle (neck opening should be just a little too small for the peeled hard-boiled egg to go through)
- ice-water bath
- hot-water bath

Procedure

1. Observe as a cooled, peeled, hard-boiled egg is placed in the opening of a bottle. The egg should have its tapered-side down and be sitting on the rim of the bottle.
2. The bottle will be placed in a hot-water bath for 5 to 10 min and then transferred to a cold-water bath. Observe what happens to the egg.

Questions

1. Describe what happened to the egg when the bottle was transferred to the cold-water bath.
2. Describe the change in pressure and temperature of the air in the bottle when the bottle is in the hot-water bath and then in the cold-water bath.
3. Explain why the result you observed occurred.
4. How would the result change if a flexible container had been used instead of a bottle?

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Developing a Mathematical Expression for Gay-Lussac's Law

Gay-Lussac's law states that the pressure of a fixed amount of gas, at constant volume, is directly proportional to its Kelvin temperature. The relationship can be expressed as $P \propto T$, where T is given in kelvins.

Using the general expression for a straight line ($y = mx + b$) and applying the same mathematical treatment used for Charles's law, a mathematical expression for Gay-Lussac's law is

$$\frac{P_1}{T_1} = \frac{P_2}{T_2}$$

For this equation, P_1 and T_1 represent the initial pressure and temperature conditions and P_2 and T_2 represent the final pressure and temperature conditions. The relationship applies as long as the volume and amount of a gas are constant and the temperature is expressed in kelvins.

The following Sample Problem and Practice Problems will reinforce your understanding of Gay-Lussac's law.

Sample Problem

Using Gay-Lussac's Law To Calculate Pressure of a Gas

Problem

The pressure of the oxygen gas inside a canister with a fixed volume is 5.0 atm at 298 K. What is the pressure of the oxygen gas inside the canister if the temperature changes to 263 K? Assume the amount of gas remains constant.

What is Required?

You need to find the new pressure, P_2, of the oxygen gas inside the canister resulting from a decrease in temperature:

What is Given?

You know the initial pressure of the oxygen gas in the canister, as well as the initial and final air temperatures:

$P_1 = 5.0$ atm

$T_1 = 298$ K

$T_2 = 263$ K

Plan Your Strategy	Act on Your Strategy
Temperature and pressure are changing at constant volume and amount of gas. Therefore, use the equation for Gay-Lussac's law.	$\frac{P_1}{T_1} = \frac{P_2}{T_2}$
Isolate the variable P_2 by multiplying each side of the equation by T_2	$\frac{P_1}{T_1}(T_2) = \frac{P_2}{\cancel{T_2}}(\cancel{T_2})$ $\frac{P_1 T_2}{T_1} = P_2$
Substitute numbers and units for the known variables in the formula and solve. Since the lowest number of significant digits in values in the question is two, the final pressure is reported to two significant digits.	$P_2 = \frac{P_1 T_2}{T_1}$ $= \frac{(5.0\text{ atm})(263\ \cancel{\text{K}})}{298\ \cancel{\text{K}}}$ $= 4.4$ atm

According to Gay-Lussac's law, when the amount and volume of a gas are constant, there is a directly proportional relationship between the pressure of the gas and its Kelvin temperature:

$$P \propto T$$

Alternative Solution

Plan Your Strategy	Act on Your Strategy
According to Gay-Lussac's law, a decrease in temperature will cause a decrease in pressure. Determine the ratio of the initial temperature and the final temperature that is less than 1.	$T_1 = 298$ K $T_2 = 263$ K temperature ratio < 1 is $\frac{263\text{ K}}{298\text{ K}}$
To find the final pressure, multiply the initial pressure of the gas by the ratio of the two temperatures that is less than 1.	$P_2 = P_1 \times$ temperature ratio $= (5.0\text{ atm}) \times \frac{263\text{ K}}{298\text{ K}}$ $= 4.4$ atm

Check Your Solution

The result shows the expected decrease in pressure. With kelvin units cancelling out, the remaining unit, atm, is a pressure unit.

Practice Problems

Note: Assume that the volume and amount of gas are constant in all of the following problems.

21. A gas is at 105 kPa and 300.0 K. What is the pressure of the gas at 120.0 K?

22. The pressure of a gas in a sealed canister is 350.0 kPa at a room temperature of 298 K. The canister is placed in a refrigerator and the temperature of the gas is reduced to 278 K. What is the new pressure of the gas in the canister?

23. A propane barbeque tank is filled in the winter at −15.0°C to a pressure of 2500 kPa. What will the pressure of the propane become in the summer when the air temperature rises to 20.0°C?

24. A rubber automobile tire contains air at a pressure of 370 kPa at 15.0°C. As the tire heats up, the temperature of the air inside the tire rises to 60.0°C. What would the new pressure in the tire be?

25. A partially filled aerosol can has an internal pressure of 14.8 psi when the temperature is 20.0°C.

a. What would the pressure in the can be, in kPa, if it were placed into an incinerator for disposal, which would have the effect of raising the temperature inside the can to 1800°C?

b. Approximately how many times higher is that new pressure compared to standard atmospheric pressure?

26. A sealed can of gas is left near a heater, which causes the pressure of the gas to increase to 1.4 atm. What was the original pressure of the gas if its temperature change was from 20.0°C to 90.0°C?

27. Helium gas in a 2.00 L cylinder has a pressure of 1.12 atm. When the temperature is changed to 310.0 K, that same gas sample has a pressure of 2.56 atm. What was the initial temperature of the gas in the cylinder?

28. A sample of neon gas is contained in a bulb at 150°C and 350 kPa. If the pressure drops to 103 kPa, find the new temperature, in °C.

29. A storage tank is designed to hold a fixed volume of butane gas at 2.00×10^2 kPa and 39.0°C. To prevent dangerous pressure buildup, the tank has a relief valve that opens at 3.50×10^2 kPa. At what Celsius temperature does the valve open?

30. If a gas sample has a pressure of 30.7 kPa at 0.00°C, by how many degrees Celsius does the temperature have to increase to cause the pressure to double?

STSE

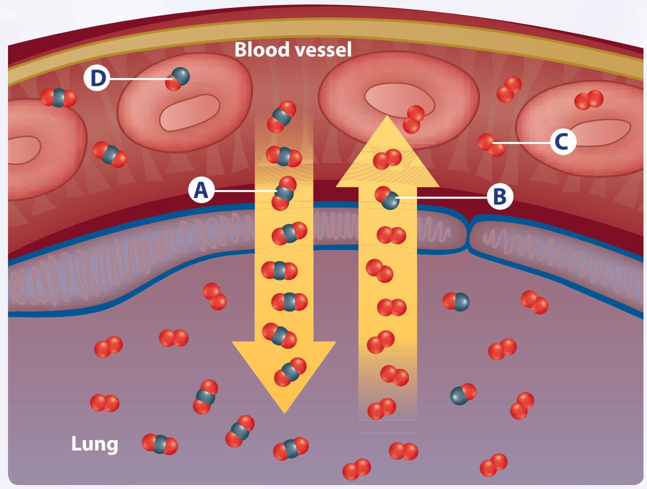
CHEMISTRY Connections

Health Under Pressure

You live, work, and play in air that is generally about 1 atm in pressure and contains 21% oxygen. Have you ever wondered what might happen if the pressure and the oxygen content of the air were greater? Would you recover from illness or injury more quickly? These questions are at the heart of hyperbaric medicine.

HYPERBARIC MEDICINE The prefix *hyper-* means above or excessive, and a bar is a unit of pressure equal to 100 kPa, which is roughly normal atmospheric pressure. Thus, the term hyperbaric refers to pressure that is greater than normal. Patients receiving hyperbaric therapy are exposed to pressures greater than the pressure of the atmosphere at sea level.

THE OXYGEN CONNECTION Greater pressure is most often combined with an increase in the concentration of oxygen that a patient receives. The phrase *hyperbaric oxygen therapy* (HBOT) refers to treatment with 100% oxygen. A chamber that might be used for HBOT is shown below. Inside the hyperbaric chamber, pressures can reach five to six times normal atmospheric pressure. At hyperbaric therapy centres across the country, HBOT is used to treat a wide range of conditions, including burns, decompression sickness, slow-healing wounds, anemia, and some infections.



Gases are exchanged between the lungs and the circulatory system.

CARBON MONOXIDE POISONING Use the diagram above to help you understand how HBOT aids in the treatment of carbon monoxide poisoning.

NORMAL GAS EXCHANGE Oxygen O_2(g), moves from the lungs to the blood and binds to the hemoglobin in red blood cells. Carbon dioxide, CO_2(g) is released, as shown by **(A)**.

ABNORMAL GAS EXCHANGE If carbon monoxide CO(g), enters the blood, as shown by **(B)**, it, instead of oxygen, binds to the hemoglobin and enters blood cells (D). Cells in the body begin to die from oxygen deprivation.

OXYGEN IN BLOOD PLASMA In addition to the oxygen carried by hemoglobin, oxygen is dissolved in the blood plasma, as shown by **(C)**. HBOT increases the concentration of dissolved oxygen to an amount that can sustain the body.

ELIMINATING CARBON MONOXIDE Pressurized oxygen also helps to remove any carbon monoxide

Connect to the Environment

The engines of idling cars emit carbon monoxide. Write an email to a friend or relative who likes to let his or her car idle for many minutes in the winter to warm it up. Explain why carbon monoxide is a dangerous pollutant. Do research to strengthen your argument. Find out the connection between ground-level ozone and carbon monoxide and why that connection might harm the environment.

Section 11.3 REVIEW

Section Summary

- The Kelvin temperature scale is based on a temperature of 0 K at absolute zero. The size of a kelvin on the Kelvin scale is the same as the size of a degree on the Celsius scale.
- Charles's law states that the volume of a fixed amount of gas at a constant pressure is directly proportional to the Kelvin temperature of the gas: $V \propto T$.
- The mathematical equation for Charles's law is $\frac{V_1}{T_1} = \frac{V_2}{T_2}$, where T is temperature in kelvin.
- Gay-Lussac's law states that the pressure of a fixed amount of gas at a constant volume is directly proportional to the Kelvin temperature of the gas: $P \propto T$
- The mathematical equation for Gay-Lussac's law is $\frac{P_1}{T_1} = \frac{P_2}{T_2}$, where T is temperature in kelvin.

Review Questions

1. K/U Explain why it is theoretically possible for an ideal gas to have a volume of zero but it is not possible for a real gas to have a volume of zero.
2. C Using a table or a graphic organizer such as a Venn diagram, summarize the similarities and differences between the Celsius and Kelvin scales.
3. K/U Convert each of the following to K or °C.
   - **a.** 37.8°C
   - **b.** 122.4°C
   - **c.** −40.0°C
   - **d.** 275 K
   - **e.** 173.6 K
   - **f.** 873 K
4. K/U If the amount and pressure of a gas remain constant, what happens to the volume of a gas as the temperature decreases? Name the law that describes this relationship.
5. C Draw a graph that represents the behaviour of a gas according to Charles's law. Provide an explanation for why your graph represents that particular law.
6. A Describe an example from everyday life that illustrates the principle of Charles's law.
7. C Imagine that a classmate was absent when you studied Charles's law in class. Explain to this classmate why it is necessary to use Kelvin temperatures and not Celsius temperatures when doing problems involving this law.
8. T/I A sample of gas has a volume of 0.4 L at 293 K. What is the volume of the gas at 523 K, assuming that the pressure and amount of gas remain constant?
9. T/I A sample of gas is originally at 30°C. What temperature increase in degrees Celsius will produce a 10 percent increase in the volume of the gas? Assume the pressure and amount of gas are constant.
10. C An experiment was conducted to investigate Gay-Lussac's law. The pressure was measured with an increase in temperature. The volume and amount of gas were kept constant.The data from the experiment are listed in the table below. Construct a graph using the data in the table to determine if Gay-Lussac's law is validated. Based on the graph, explain why the law is or is not supported by the data.

Temperature and Pressure of a Gas

Temperature Reading (°C)	Pressure Reading (kPa)
10.0	101
20.0	105
30.0	109
50.0	116
60.0	119
75.0	125
100.0	134

11. T/I At 277.0 K, a gas has a pressure of 99.5 kPa. What is the pressure of the gas at 210.0 K, if the volume and amount of gas are constant?
12. A In a fire, gas cylinders containing combustible gases are at risk of exploding, because the amount of gas and volume are fixed. If a tank of propane gas has an internal pressure of 1500 kPa at 20.0°C, what will the internal tank pressure become at 1000.0°C?
13. T/I A squash ball has an internal air pressure of 14.8 psi at a temperature of 18.0°C. During play, the internal temperature of the air inside the ball rises to 70.0°C. Assuming that the volume and amount of air inside the ball do not change, what is the new air pressure inside the ball?
14. A Assume you are in charge of designing a container that would hold and deliver a combustible gas at high pressure. Given your knowledge of Gay-Lussac's and Charles's laws, what are some of the features you would incorporate in your design?