Charles's Law

Have you ever noticed that on a cold day, a tire on a car might look as if it's low on air? However, after driving the car for awhile, the tire warms up and looks less flat. What made the difference in the tire? When canning vegetables at home, why are they often packed hot in the jars and then sealed? These questions can be answered by applying another of the gas laws, Charles's law. Another example of how gases are affected by temperature is shown in the **problem-solving LAB.** If kelvin temperature is doubled, so is the volume.

How are gas temperature and volume related? The French physicist Jacques Charles (1746–1823) studied the relationship between volume and temperature. In his experiments, he observed that as temperature increases, so does the volume of a gas sample when the pressure is held constant. This property can be explained by the kinetic-molecular theory; at a higher temperature, gas particles move faster, striking each other and the walls of their container more frequently and with greater force. For the pressure to stay constant, volume must increase so that the particles have farther to travel before striking the walls. Having to travel farther decreases the frequency with which the particles strike the walls of the container.

Look at **Figure 14-3**, which includes a graph of volume versus temperature for a gas sample kept at a constant pressure. Note that the resulting plot is a straight line. Note also that you can predict the temperature at which the volume will reach a value of zero liters by extrapolating the line at temperatures below which values were actually measured. The temperature that corresponds to zero volume is −273.15°C, or 0 on the kelvin (K) temperature scale. This temperature is referred to as absolute zero, and it is the lowest possible theoretical temperature. Theoretically, at absolute zero, the kinetic energy of particles is zero, so all motion of gas particles at that point ceases.

Examine the relationship between temperature and volume shown by the cylinders in **Figure 14-3**. In the graph, note that 0°C does not correspond to zero volume. Although the relationship is linear, it is not direct. For example, you can see from the graph that increasing the temperature from 25°C to 50°C does not double the volume of the gas. If the kelvin temperature is plotted instead, a direct proportion is the result. See **Figure 14-4** on the next page.

History CONNECTION

Jacques Charles's interest in the behavior of gases was sparked by his involvement in ballooning. He built the first balloon that was filled with hydrogen instead of hot air. Charles's investigations attracted the attention of King Louis XVI, who allowed Charles to establish a laboratory in the Louvre, which is a museum in Paris.

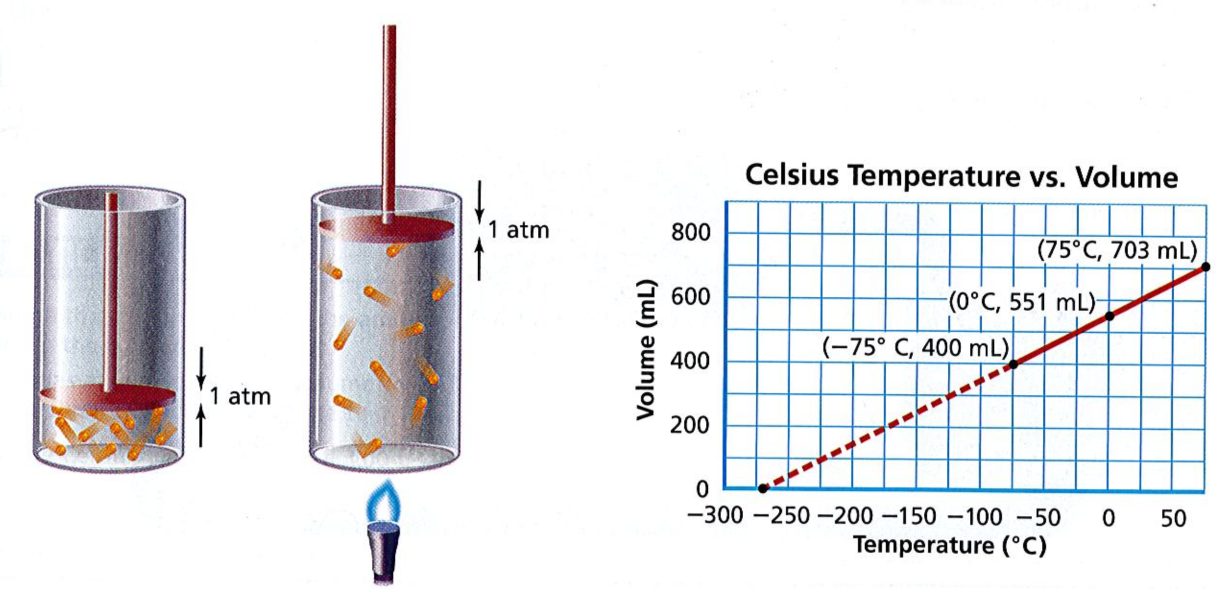


Figure 14-3

The gas particles in this cylinder take up a given volume at a given temperature. When the cylinder is heated, the kinetic energy of the particles increases. The volume of the gas increases, pushing the piston outward. Thus the distance that the piston moves is a measure of the increase in volume of the gas as it is heated. Note that the graph of volume versus temperature extrapolates to −273.15°C, or 0 K.

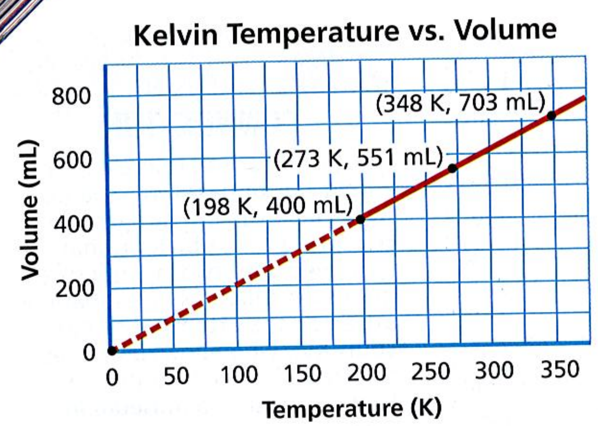


Figure 14-4

This graph illustrates the directly proportional relationship between the volume and the kelvin temperature of a gas held at constant pressure. When the kelvin temperature doubles, the volume doubles.

Charles's law states that the volume of a given mass of gas is directly proportional to its kelvin temperature at constant pressure. For help with understanding direct relationships, see the **Math Handbook,** page 905. So for any two sets of conditions, Charles's law can be expressed as

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

Here V_1 and T_1 represent any initial pair of conditions, while V_2 and T_2 are any new set of conditions. As with Boyle's law, if you know any three of the four values, you can calculate the fourth using the equation.

The temperature must be expressed in kelvin units when using the equation for Charles's law. The kelvin scale starts at absolute zero, which corresponds to –273.15°C and is 0 K. Because a Celsius degree and a kelvin unit are the same size, it is easy to convert a temperature in Celsius to kelvin units. Round 273.15 to 273, and add it to the Celsius temperature.

$$T_K = 273 + T_C$$

problem-solving LAB

How is turbocharging in a car engine maximized?

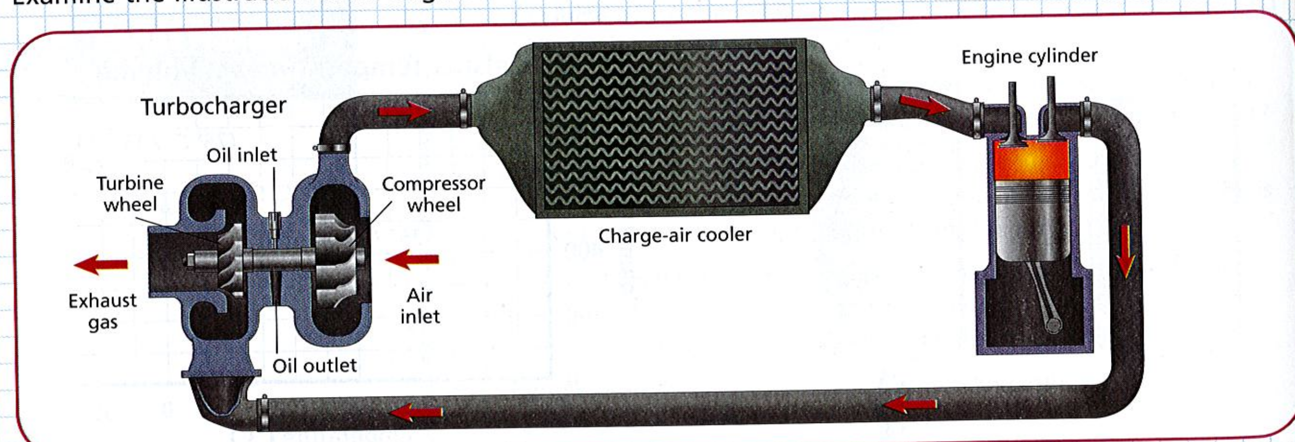
Interpreting Scientific Illustrations After gasoline and air are burned in the combustion chamber of an automobile, the resulting hot gases are exhausted out the tailpipe. The horsepower of an automobile engine can be significantly improved if the energy of these exhaust gases is used to operate a compressor that forces additional air into the combustion chamber. Outside air is then blown over this compressed air to cool it before it enters the engine. Increasing the power of an engine in this manner is known as turbocharging.

Analysis

Examine the illustration of an engine fitted with a turbocharging system. The paths of the exhaust gas, entering combustion air, and the cooling air are shown.

Thinking Critically

1. What property of the exhaust gas is being used to turn the turbine that runs the compressor? Explain.
2. If more power is to be gained from this design, what must also accompany the extra supply of oxygen to the combustion chamber?
3. What property does the compressor alter so that more air can be injected into the combustion chamber? Explain.
4. Why does the air in the compressor get hot, and why does cooling help to improve the power of the engine?



EXAMPLE PROBLEM 14-2

Charles's Law

A gas sample at 40.0°C occupies a volume of 2.32 L. If the temperature is raised to 75.0°C, what will the volume be, assuming the pressure remains constant?

1. Analyze the Problem

You are given the initial temperature and volume of a sample of gas. Charles's law states that as the temperature increases, so does the volume, assuming the pressure is constant. Because the temperature in this problem is increasing, the volume will increase. So the initial volume should be multiplied by a volume ratio greater than one.

Known	Unknown
T_1 = 40.0°C	V_2 = ? L
V_1 = 2.32 L	
T_2 = 75.0°C	

2. Solve for the Unknown

Add 273 to the Celsius temperature to obtain the kelvin temperature.

$T_K = 273 + T_C$

Substitute the known Celsius temperatures for T_1 and T_2 to convert them to kelvin units.

T_1 = 273 + 40.0°C = 313 K

T_2 = 273 + 75.0°C = 348 K

Multiply both sides of the equation for Charles's law by T_2 to solve for V_2.

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

$$V_2 = V_1\left(\frac{T_2}{T_1}\right)$$

Substitute the known values into the rearranged equation.

$$V_2 = 2.32\ \text{L}\left(\frac{348\ \text{K}}{313\ \text{K}}\right)$$

Multiply and divide numbers and units to solve for V_2.

$$V_2 = 2.32\ \text{L}\left(\frac{348\ \cancel{\text{K}}}{313\ \cancel{\text{K}}}\right) = 2.58\ \text{L}$$

3. Evaluate the Answer

The increase in kelvin units is relatively small. Therefore, you expect the volume to show a small increase, which agrees with the answer. The unit of the answer is liters, a volume unit.

Math Handbook

Review using direct relationships in the **Math Handbook** on page 905 of this textbook.

PRACTICE PROBLEMS

Assume that the pressure and the amount of gas present remain constant in the following problems.

6. A gas at 89°C occupies a volume of 0.67 L. At what Celsius temperature will the volume increase to 1.12 L?
7. The Celsius temperature of a 3.00-L sample of gas is lowered from 80.0°C to 30.0°C. What will be the resulting volume of this gas?
8. What is the volume of the air in a balloon that occupies 0.620 L at 25°C if the temperature is lowered to 0.00°C?

Practice!

For more practice with Charles's law problems, go to **Supplemental Practice Problems** in Appendix A.

Kelvin Temperature vs. Pressure

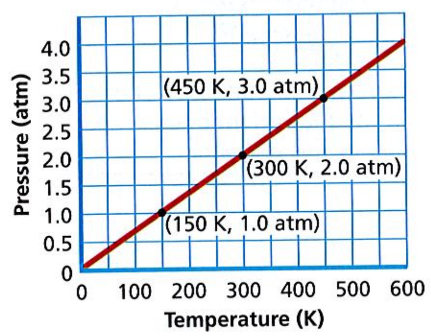
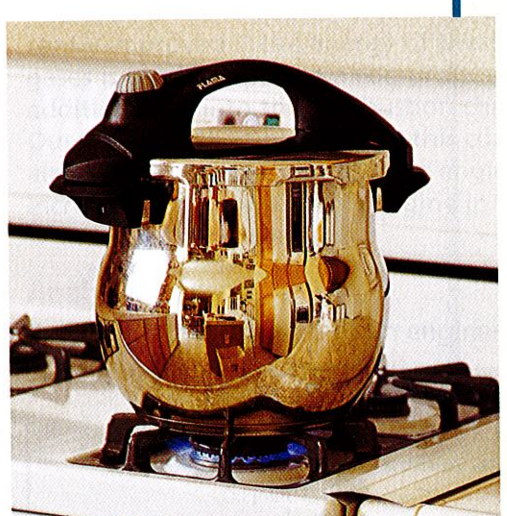


Figure 14-5

Compare the relationship between pressure and kelvin temperature as shown in this graph and the relationship between volume and kelvin temperature as shown in **Figure 14-4**. Notice that both show direct relationships.



This cooker is sealed so that the volume is constant. Pressure increases in the cooker as temperature increases.

Gay-Lussac's Law

Boyle's law relates pressure and volume of a gas, and Charles's law states the relationship between a gas's temperature and volume. What is the relationship between pressure and temperature? Pressure is a result of collisions between gas particles and the walls of their container. An increase in temperature increases collision frequency and energy, so raising the temperature should also raise the pressure if the volume is not changed.

How are temperature and pressure of a gas related? Joseph Gay-Lussac explored the relationship between temperature and pressure of a contained gas at a fixed volume. He found that a direct proportion exists between the kelvin temperature and the pressure, such as that illustrated in **Figure 14-5**. **Gay-Lussac's law** states that the pressure of a given mass of gas varies directly with the kelvin temperature when the volume remains constant. It can be expressed mathematically.

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

As with Boyle's and Charles's laws, if you know any three of the four variables, you can calculate the fourth using this equation. Remember that temperature must be in kelvin units whenever it is used in a gas law equation.

EXAMPLE PROBLEM 14-3

Gay-Lussac's Law

The pressure of a gas in a tank is 3.20 atm at 22.0°C. If the temperature rises to 60.0°C, what will be the gas pressure in the tank?

1. Analyze the Problem

You are given the initial pressure and the initial and final temperatures of a gas sample. Gay-Lussac's law states that if the temperature of a gas increases, so does its pressure. Because the temperature in this problem is increasing, the pressure will increase. So the initial pressure should be multiplied by a volume ratio greater than one.

Known	Unknown
P_1 = 3.20 atm	P_2 = ? atm
T_1 = 22.0°C	
T_2 = 60.0°C	

2. Solve for the Unknown

Add 273 to the Celsius temperature to obtain the kelvin temperature.

$T_K = 273 + T_C$

Substitute the known Celsius temperatures for T_1 and T_2 to convert them to kelvin units.

T_1 = 273 + 22.0°C = 295 K

T_2 = 273 + 60.0°C = 333 K

Multiply both sides of the equation for Gay-Lussac's law by T_2 to solve for P_2.

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

$$P_2 = P_1\left(\frac{T_2}{T_1}\right)$$

Substitute the known values into the rearranged equation.

$$P_2 = 3.20 \text{ atm}\left(\frac{333 \text{ K}}{295 \text{ K}}\right)$$

Multiply and divide numbers and units to solve for P_2.

$$P_2 = 3.20 \text{ atm}\left(\frac{333 \cancel{\text{K}}}{295 \cancel{\text{K}}}\right) = 3.61 \text{ atm}$$

3. Evaluate the Answer

Gay-Lussac's law states that pressure and temperature are directly proportional. Kelvin temperature shows a small increase, so you expect the pressure to show a small increase, which agrees with the answer calculated. The unit is atm, a pressure unit.

PRACTICE PROBLEMS

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

9. A gas in a sealed container has a pressure of 125 kPa at a temperature of 30.0°C. If the pressure in the container is increased to 201 kPa, what is the new temperature?

10. The pressure in an automobile tire is 1.88 atm at 25.0°C. What will be the pressure if the temperature warms up to 37.0°C?

11. Helium gas in a 2.00-L cylinder is under 1.12 atm pressure. At 36.5°C, that same gas sample has a pressure of 2.56 atm. What was the initial temperature of the gas in the cylinder?

12. If a gas sample has a pressure of 30.7 kPa at 0.00°C, by how much does the temperature have to decrease to lower the pressure to 28.4 kPa?

13. A rigid plastic container holds 1.00 L methane gas at 660 torr pressure when the temperature is 22.0°C. How much more pressure will the gas exert if the temperature is raised to 44.6°C?

Practice!

For more practice with Gay-Lussac's law problems, go to **Supplemental Practice Problems** in Appendix A.

You have seen how the variables of temperature, pressure, and volume affect a gas sample. The gas laws covered in this section each relate two of these three variables if the other variable remains constant. What happens when all three of these variables change? You'll investigate this situation in the next section.