The Gas Laws—Absolute Temperature and Charles' Law

11.8

Everyone loves the light, fluffy taste of popcorn while watching a good movie. Popcorn is thought to have been discovered by the Native Americans thousands of years ago (**Figure 1**). Archaeologists believe that popcorn was originally popped by placing it on extremely hot stones. As it popped, it shot off this way and that. Popcorn behaves as it does because of the behaviour of gases. The study of gases and their application has a long history in chemistry.

Figure 1 Popcorn is a tasty application of the gas laws.

While you may not be aware of it, you have quite a bit of experience with the properties of gases. When the weather turns cool in the fall, you might notice that you need to pump up your bicycle tires. During air travel or when diving deep into a swimming pool you have probably felt a strange sensation in your ears. While we can easily see and feel the effects of gases in such examples as popcorn and painful ears, studying gases is a bit more of a challenge. We cannot see most gases. They are not easy to touch and feel. Too often, we think of a container being empty if it "only" has air in it.

Curious people often make observations of phenomena, and then search for patterns and explanations. Observations of how gases behave preceded the laws that now help us predict and explain gas behaviour. Many of the gas laws are named after the scientists who made the observations. Before discussing the properties of gases and the laws that describe these properties, we will consider the two temperature scales that scientists most often use when conducting investigations with gases.

Absolute Zero and Temperature Scales

How can a temperature have a negative value? Why does water boil at 100 °C? Is 30 °C twice as hot as 15 °C? The Celsius scale, developed by the Swedish scientist Anders Celsius in 1742, is convenient for most everyday situations. Celsius devised the scale by taking a thin, closed glass tube of a pure liquid, such as mercury, and recording the height of the liquid when the tube was placed in ice water. He called this height "100 degrees." He then repeated the process placing the tube in boiling water to find the height that he called "zero degrees." Celsius then divided the distance between the two marks evenly into 100 divisions. Each of these divisions is one degree Celsius. The scale was later reversed to make it a more practical unit of measure (**Figure 2**). (The Celsius scale is also known as the centigrade scale. Centigrade simply means "divided into 100 degrees.")

Figure 2 The Celsius scale is convenient for daily applications.

Later, another temperature scale was developed that proved to be more useful. Examine **Figure 3**, which is a volume versus temperature graph for several different gases. We can extend the lines to the left of the measured values to find the theoretical volumes of gases as their temperatures decrease.

WEB LINK

Anders Celsius was primarily an astronomer. To find out more about the life and achievements of Anders Celsius,

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Temperature and Volume of Several Gases

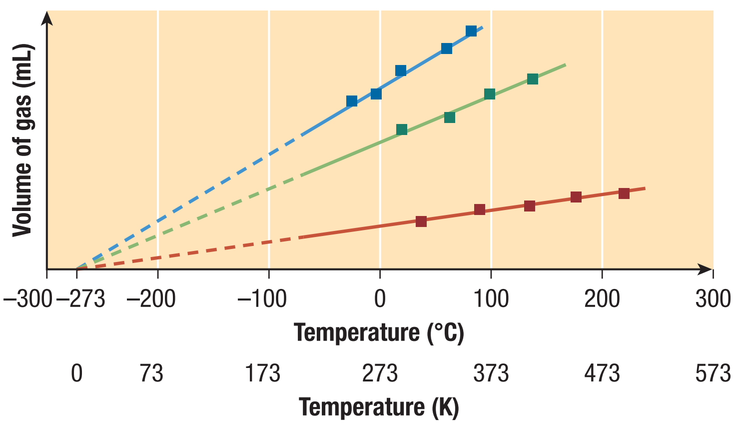

Figure 3 The solid lines represent actual measurements. When the graphs of several volume–temperature experiments are extrapolated (dashed lines), all the lines meet at absolute zero, –273.15 °C or 0 K.

What happens when we reach a theoretical volume of zero? If we extrapolate the data shown on the graph, we see that the lines will all intersect the temperature axis at −273.15 °C. Lord Kelvin was the first scientist to notice this. He experimented with a variety of gases, graphing their volumes at various temperatures, and noticed that the graphs of all gases intercept the temperature axis at the same point. This implied that the volume of every gas would become zero at a temperature of −273.15 °C.

This temperature, at which a gas theoretically has no volume, is now known as **absolute zero**. It is the lowest possible temperature. There is some controversy over which scientist is responsible for this term. (See Section 12.3, The Science of Cold.)

Lord Kelvin developed a new temperature scale based on the value of −273.15 °C. He decided that this measurement would be equivalent to 0 on the new scale. By setting a value of zero for the lowest temperature that matter can achieve, Lord Kelvin ensured that the new scale would have no negative values. This is the scale that we now call the **Kelvin temperature scale** or the **absolute temperature** scale. It has the unit symbol "K." Chemists and others studying gases routinely use this scale for their measurements and calculations. We will also use it throughout this unit. **Figure 4** shows some typical values of Celsius temperatures and the corresponding values in kelvins. In theory, at 0 K, entities should have no motion and therefore no kinetic energy. Scientists ever since have been striving to slow the motion of entities, in a race to achieve absolute zero.

absolute zero the theoretical temperature at which the entities of a material contain no kinetic energy and therefore transmit no thermal energy; equal to −273.15 °C

Kelvin temperature scale a temperature scale that includes absolute zero and the same-sized unit divisions as the Celsius temperature scale

absolute temperature a measurement of the average kinetic energy of the entities in a substance; unit symbol K

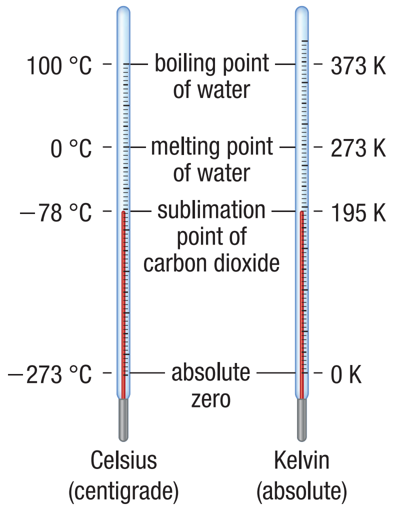

Figure 4 Various freezing and boiling points on the Celsius scale and the Kelvin scale

Tutorial 1 Temperature Conversions

To convert temperatures from degrees Celsius to kelvins (absolute temperature) or vice versa, use the following conversion equation, in which t represents the temperature in degrees Celsius and T represents the temperature in kelvins:

$$T = t + 273.15$$

You will notice that most temperature readings are taken in degrees Celsius and are whole numbers. After converting these values to kelvins you will always round to the nearest whole number. For this reason, the value of 273 is adequate for temperature conversions involving whole numbers. When converting temperatures, use your common sense. You have a great deal of experience with temperatures between –20 °C and 40 °C.

Sample Problem 1: Converting from Celsius to Kelvin

Standard ambient temperature is defined as 25 °C. Convert this temperature to absolute temperature.

Given: $t = 25$ °C

Required: T

Analysis: $T = t + 273$

Solution: $T = 25 + 273$

$T = 298$ K

Statement: Standard ambient temperature is 298 K.

Sample Problem 2: Converting from Kelvin to Celsius

Convert 150 K to degrees Celsius.

Given: $T = 150$ K

Required: t

Analysis: $T = t + 273$

$t = T - 273$

Solution: $t = 150 - 273$

$t = -123$ °C

Statement: A temperature of 150 K is equivalent to −123 °C.

LEARNING TIP

°C vs. K
Note that the unit for centigrade is degree Celsius (°C) whereas the unit for absolute temperature is kelvin (K). There is no degree symbol.

Practice

SKILLS HANDBOOK A6.1, A6.3

1. Convert the following temperatures from degrees Celsius to absolute temperature: K/U
   (a) Dry ice sublimes into a gas at −78 °C. [ans: 195 K]
   (b) The hottest temperature recorded in Canada is 45 °C (in Saskatchewan, 1937). [ans: 318 K]
2. Convert the following temperatures from absolute temperature to degrees Celsius: K/U
   (a) Pure gold melts at 1337 K. [ans: 1064 °C]
   (b) The coldest temperature recorded in Canada is 210 K (in Snag, Yukon, 1947). [ans: –63 °C]

Charles' Law—The Relationship between Volume and Temperature

What causes a kernel of popping corn to pop? Popping corn has two unusual features: a rigid, non-porous shell and a small quantity of water (8 % to 20 % by mass) trapped inside. As the kernel is heated the water becomes a gas: water vapour. This vapour expands as much as it can within the non-porous shell. Eventually the expanding water vapour bursts the shell, causing the kernel to "pop." This relationship between the temperature and volume of the water vapour in popcorn is an illustration of a gas law.

WEB LINK

To find out more about the science of popcorn,

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An understanding of the relationship between the volume of gas and temperature has been attributed to French scientist Jacques Charles (1746–1823). Charles investigated the expansion of a variety of gases by placing a sample of gas in a closed, expandable container. For example, a container might be sealed by a piston that was free to move. In such a container, the amount of gas (in moles) and the pressure were kept constant.

Charles found that the volume of a gas increases as its temperature increases. Graphing volume against Celsius temperature produces a straight line. Figure 3 on page 547 shows this type of relationship for three gases. As each gas is cooled, it eventually condenses into a liquid. Hence, we cannot measure the temperatures of gases below this point.

The relationship between the volume and temperature of a gas is called **Charles' law.** This law states that the volume of a gas is directly proportional to its temperature, in kelvins, provided that pressure and the amount of gas are constant. Mathematically, we can represent Charles' law by the equation

Charles' law the statement that as the temperature of a gas is increased, the volume of the gas increases proportionally, provided that the pressure and amount of gas remain constant; the volume and temperature of a gas are directly proportional

$$V = aT$$

In this equation a is a constant and T is the absolute temperature (in kelvins). The equation for Charles' law suggests that doubling the absolute temperature, for example from 273 K to 546 K, results in a doubling of the volume (**Table 1**.) Note, however, that doubling the Celsius temperature, for example from 20 °C to 40 °C, does not result in a doubling of volume. This is why absolute temperature is used in mathematical problems.

LEARNING TIP

Temperature in Kelvin—Absolutely Always!

The Celsius scale is convenient for everyday use. When we confront mathematical problems with multiplication and division, however, it becomes problematic. A temperature rise from 20 °C to 40 °C is not a 100 % increase in temperature because the absolute temperature is only rising from 293 K to 313 K. If temperature is a variable in a calculation, the Kelvin scale must be used.

Table 1 The Effect of Increasing Temperature on the Volume of a Gas

Temperature, t (°C)	Temperature, T (K)	Volume, V (mL)
0	273	100
20	293	107
40	313	115
80	353	129
273	546	200

> **LEARNING TIP**
>
> **Direct Relationship**
> When one variable is changed (increased or decreased) and the other responds in a similar manner, the two variables are said to be directly related (or directly proportional) to each other. For example, if everyone in your class increased the time they spent preparing for a test and the marks for the class increased, the two variables would be directly proportional.

Since $V = aT$, then $\frac{V}{T} = a$ (a is a constant)

This suggests that any two sets of volume and temperature values for the same gas under the same experimental conditions, should give the same ratio. We can check this prediction with two sets of values from Table 1, such as (273, 100) and (353, 129):

$$\frac{100 \text{ mL}}{273 \text{ K}} = 0.37 \text{ mL/K} \qquad \frac{129 \text{ mL}}{353 \text{ K}} = 0.37 \text{ mL/K}$$

Using the fact that the ratios are the same, we can also express Charles's law in terms of an initial set of measurements V_1, T_1 and a final set of measurements V_2, T_2:

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

We can therefore express Charles' law both mathematically and in words:

> **Charles' Law**
>
> $$\frac{V_1}{T_1} = \frac{V_2}{T_2}, \quad \text{or} \quad \frac{V}{T} = a \text{ (constant)}$$
>
> The volume of a gas is directly proportional to its temperature in kelvins, provided the pressure and the amount of gas remain constant.

To explain Charles' law, consider what happens at the molecular level (**Figure 5**). As the temperature of the gas is increased, the kinetic energy of the gas entities also increases. Entities move more quickly and the number of collisions between entities increases. The number of collisions between the entities and the walls of the container also increases, making the container expand and increasing the volume of the gas.

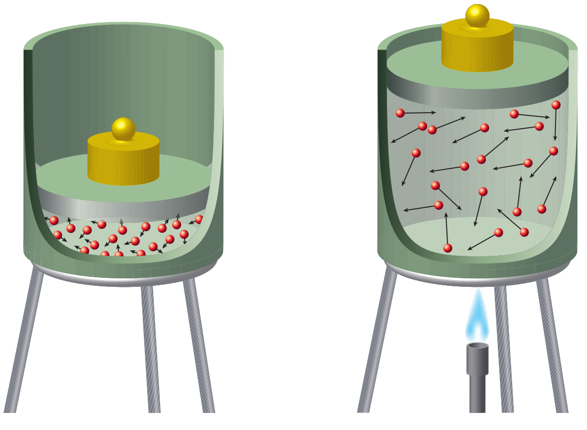

Figure 5 The volume of a gas increases as its temperature is increased. In this case, the container has a movable piston so that volume can change. The pressure of the gas remains constant in this situation.

Figure 6 Jacques Charles (1746–1823) designed and flew the first hydrogen balloon in 1783. His experiences and experiments led to the formulation of Charles' law.

Interestingly, Jacques Charles was a balloon enthusiast. Most balloonists at the time used hot air to lift their balloons. Charles experimented with using hydrogen gas instead (**Figure 6**). He most likely generated the hydrogen by reacting large quantities of acid with iron. In 1783, one of his hydrogen balloons reportedly travelled from Paris to the outskirts of the city in 45 minutes. When it landed, local residents—not knowing what the balloon was—attacked and destroyed it!

Mini Investigation

Soap in the Microwave (Teacher Demonstration)

Skills: Observing, Analyzing, Communicating

SKILLS HANDBOOK **A1.2, A2.4**

The strange white blob in **Figure 7** is not ice cream or mashed potato, but soap! This activity involves observing the effects of microwaves on a piece of Ivory soap. This soap is well known for floating in the bathtub. During the production of Ivory soap, air pockets are created within the bar itself. This makes it behave in a predictably wild way.

Figure 7 Do not do this at home!

Equipment and Materials: microwave oven; microwave-safe dish; 400 mL beaker; oven mitts; water; half a bar of Ivory soap cut into 2 pieces; a piece of another brand of soap

This activity involves heating substances in a microwave oven. Allow all heated objects to cool completely before touching them.

1. Your teacher will place one piece of Ivory soap in a dish and heat it in the microwave oven at medium to high power for approximately 90 s.
2. Your teacher will circulate a small piece of Ivory soap and a small piece of regular soap. Record any interesting observations.
3. While the microwave is running, your teacher will place a small piece of Ivory soap and a small piece of another brand of soap into a beaker of water. Record your observations.
4. When the microwave has finished running, your teacher will remove the soap using oven mitts. Observe and record any changes.
5. When it has cooled, use the microwaved soap to wash your hands. Record your observations.
6. Your teacher may now heat a piece of the other, regular soap in the microwave as a control.

A. How do the properties of the two soaps differ? T/I

B. Suggest an explanation for the unusual properties of Ivory soap. T/I

C. How does the behaviour of Ivory soap demonstrate Charles' law? K/U

Research This

Evaluating the Use of Nitrogen in Car Tires

Skills: Researching, Analyzing, Evaluating, Identifying Alternatives, Defending a Decision

SKILLS HANDBOOK **A5.1**

Good tire maintenance is necessary to optimize car performance, reduce gasoline consumption, and minimize environmental impacts. Proper maintenance includes keeping tires inflated to the specifications of the car. Traditionally, nitrogen gas has been used in race car tires. It is now available in some regions for use by everyday consumers in car tires (**Figure 8**).

1. Research the importance of good tire maintenance.
2. Research the benefits and drawbacks of using nitrogen gas in tires.

A. How can underinflated or overinflated tires affect how long tires last? A

B. What is the effect of underinflation and overinflation of tires on gas consumption and on the environment? T/I A

C. Why is nitrogen gas used in race car tires? K/U

D. In your opinion, is using nitrogen in everyday applications beneficial? Explain your answer. A

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Figure 8 Should nitrogen be used in car tires?

Tutorial 2 Using Charles' Law

The mathematical form of Charles' law is very useful for predicting new values of volume and/or temperature when changes have occurred to a sample of gas. Remember that the amount of gas and the pressure do not change in situations where we apply Charles' law.

Sample Problem 1: Temperature and Volume

A sample of gas is drawn into a piston. If the sample occupies 0.255 L at 25 °C, what volume will the gas occupy if it is heated to 80 °C? The pressure and amount of gas are kept constant throughout the process.

Given: initial Celsius temperature, $t_1 = 25$ °C

final Celsius temperature, $t_2 = 80$ °C

volume, $V_1 = 0.255$ L

The amount of the gas and the gas pressure remain constant.

Required: final volume, V_2

Analysis: Apply Charles' law to the situation.

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

Solution:

Step 1. Convert temperature values to kelvins.

$$T = t + 273$$
$$T_1 = t_1 + 273$$
$$= 25 + 273$$
$$T_1 = 298 \text{ K}$$
$$T_2 = t_2 + 273$$
$$= 80 + 273$$
$$T_2 = 353 \text{ K}$$

Step 2. Rearrange the Charles' law equation to isolate the unknown variable.

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

Step 3. Substitute given values (including units) into the equations and solve.

$$V_2 = \frac{0.255 \text{ L} \times 353 \cancel{\text{K}}}{298 \cancel{\text{K}}}$$
$$= 0.300 \text{ L}$$

Statement: The volume of the gas at 80 °C is 0.300 L.

Check your answer. Does it make sense? Are the units appropriate?

Practice

SKILLS HANDBOOK A6

1. A sample of methane gas occupies an initial volume of 5.25 L at an initial temperature of 200 K. The gas is heated to 300 K while the pressure and the amount of gas remain constant. Determine the new volume. [ans: 7.88 L]
2. A sample of carbon dioxide is placed in a piston. The initial temperature of the gas is 35 °C and it occupies a volume of 2.2 L. Calculate the temperature at which it will occupy 4.4 L. Pressure and the amount of gas remain constant. [ans: 620 K]

11.8 Summary

- Absolute zero on the Kelvin scale (0 K or –273.15 °C) is the theoretical temperature at which entities have no kinetic energy so a gas exerts no pressure and has no volume.
- The absolute temperature scale starts at absolute zero.
- Charles' law states that the volume of a gas is directly proportional to its temperature in kelvins, provided the pressure and amount of gas remain constant.

$$\frac{V_1}{T_1} = \frac{V_2}{T_2}, \text{ or } \frac{V}{T} = \text{constant}$$

11.8 Questions

1. Describe what theoretically happens to a sample of matter cooled to absolute zero. K/U
2. Convert the following temperatures to degrees Celsius or kelvins as required: K/U
   (a) A flame from a match can have temperatures in the range of 1700 K.
   (b) A household incandescent light bulb has a tungsten filament that can reach over 2327 °C.
   (c) Helium becomes a liquid below −268 °C.
   (d) Oxygen was first made into a solid at a temperature near 54 K.
3. A balloon has a volume of 0.57 L at 22 °C. If it is plunged into a container of liquid nitrogen at 77 K, what will be the volume of the balloon? T/I
4. A 0.300 L sample of argon is collected at 50.0 °C. What is the volume of this gas at standard ambient temperature? T/I
5. Carbon dioxide gas sublimes directly to the solid state at −110 °C. If 25 cm^3 of carbon dioxide is cooled from −20 °C to −110 °C, what will the volume of the gas be just before it sublimes? T/I
6. Molten lava from a volcano includes pockets of gases. A sample of lava contains 0.45 L of water vapour at 1170 °C. What volume will the water vapour occupy when it cools to 120 °C? T/I
7. A sample of argon gas at constant pressure is heated and its volume is measured (**Table 2**). K/U T/I C
   (a) Plot a volume vs. temperature graph of the data in Table 2. Include a title, label your axes, and show the appropriate units.
   (b) Extrapolate the data to find the experimental value of absolute zero in degrees Celsius.
   (c) Compare your experimental value to the actual value of absolute zero. Suggest why these values might not agree perfectly.

Table 2 Experimental Data on a Sample of Argon

Temperature (°C)	Volume (mL)
11	95.3
25	100.0
47	107.4
73	116.1
159	145.0
233	169.8
258	178.1

8. We have discussed a lower limit to temperature: absolute zero. Is there an upper limit? Research to find out. A
9. Jacques Charles used the reaction between metal and acid to produce hydrogen for his balloons. Other people, including the Montgolfier brothers, were experimenting with balloons at the same time. Research another method that was used to provide lift for balloons. T/I
10. When you dive deep into a swimming pool you experience a large pressure change that might cause you some discomfort. Divers run into this situation all the time and are taught a technique, known as the Valsalva manoeuvre, that works well to equalize the pressures. Research the cause of this discomfort and how to perform the Valsalva manoeuvre. A
11. Canadian Mandy-Rae Cruickshank is one of the world's best free divers. In "constant weight" free-diving competitions, she swims as far down as she can (as far as 90 m!) using weights for ballast. Research the extreme sport of free diving and its effects on the human body. A

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