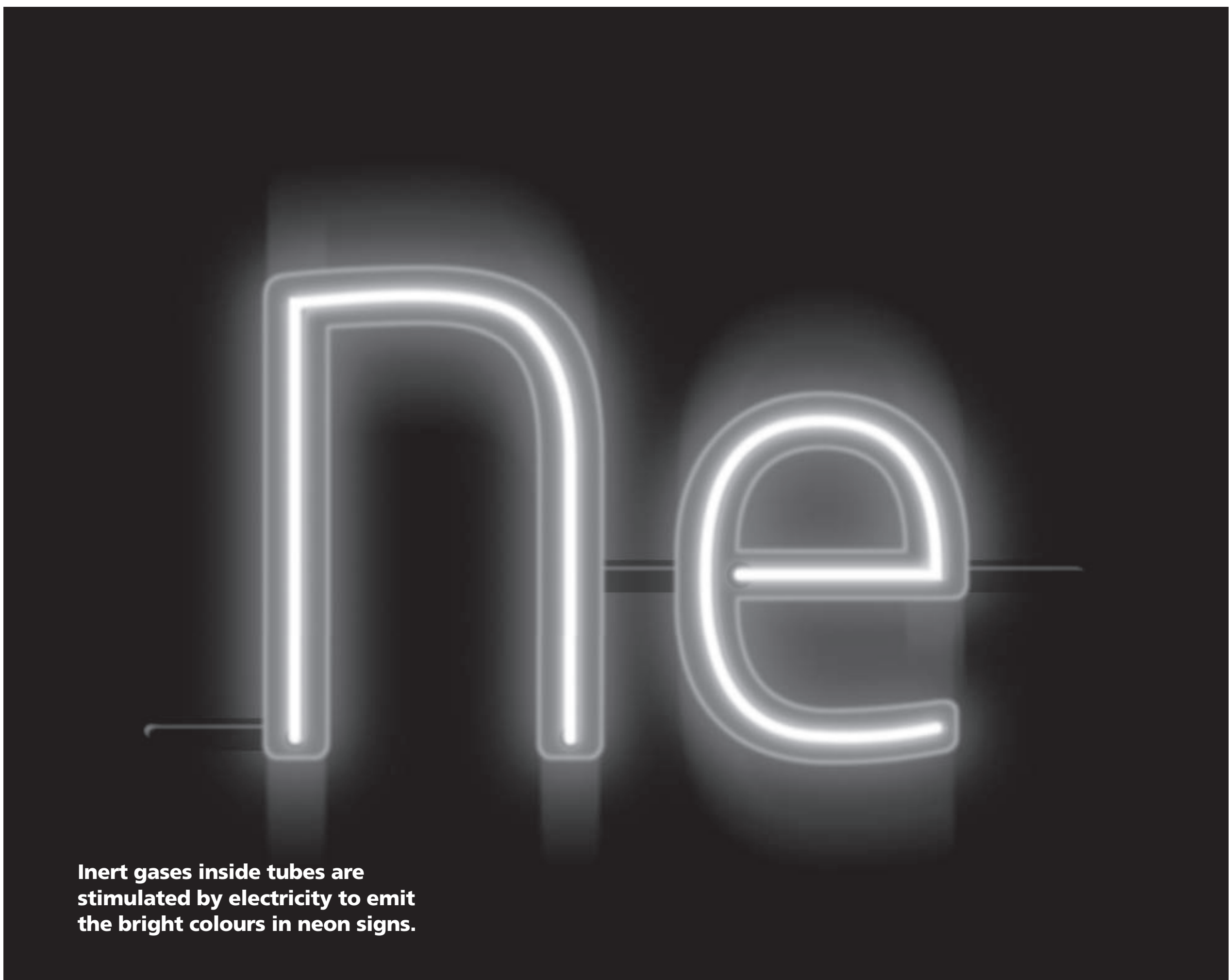
Gases

Everyone knows that you need air to survive. But what part of air keeps you alive? Air is a mixture of many different gases. One of those gases is oxygen, the gas our bodies need to obtain energy from food through cellular respiration. What makes oxygen different from the other gases in air? How are oxygen and all gases similar?

In this chapter, you will learn about gases and their behaviour. To help us understand how gases behave, scientists make generalizations about what most gases do, even though all gases are different. As you read this chapter, keep an eye open for these generalizations, and think about why they are necessary.



Inert gases inside tubes are stimulated by electricity to emit the bright colours in neon signs.

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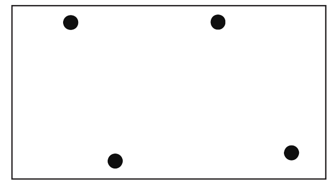
13.1 Temperature, Pressure, and Avogadro's Theory

13.1.A What Is an "Ideal" Gas?

Every gas is a bit different. To make a model that applies to any gas, we need to invent the concept of a "perfect" gas, a substance that behaves like a gas under all conditions. Scientists call this an **ideal gas**.

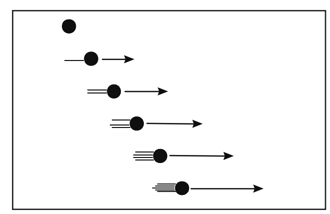
Every real gas falls short of ideal gas behaviour in one or more ways. Still, at room temperature, the ideal gas model describes most gases very well. To build our ideal gas model, we will make five assumptions.

1. **Gas molecules are very small and far apart.** Real gas molecules are very small, and are usually far enough apart that this generalization applies. However, this ideal gas assumption fails if the gas molecules are large.



In your classroom, the distance between gas molecules is about 11 times the diameter of a molecule.

2. **No forces of attraction exist between gas molecules.** At high temperatures, real gas molecules move quickly and behave like ideal gas molecules. At lower temperatures, real gas particles slow down and begin to stick together, and this ideal gas assumption fails.
3. **Gas molecules collide with each other without losing energy.** All real gas molecules jiggle, vibrate, and emit heat radiation during their collisions. They gradually lose energy to their surroundings. This ideal gas assumption fails for complex molecules with many parts, over long periods of time.
4. **Between collisions, gas molecules are in constant straight-line motion.** Real gases do move in straight lines between collisions. While this ideal gas assumption is very reliable, it does fail if molecules are extremely large or complex.
5. **Gas molecules within a sample have a range of kinetic energies, from zero to very high values.** This assumption is usually true for real gas molecules. At any instant, a few molecules have near zero kinetic energy, and a few molecules have extremely high kinetic energy. Between those two extremes, most of the molecules have kinetic energies near the average. This assumption fails only at extremely cold temperatures, very close to –273°C.



In this diagram, the short lines represent the amount of kinetic energy each molecule has. The arrows represent each molecule's speed.

Check Your Understanding

1. Describe a single molecule of an ideal gas. Is it large or small, simple or complex, etc.? Explain.

____

2. Xenon molecules are three times larger than helium molecules. Which gas will behave most like an ideal gas? Explain. ____

3. Which gas, methane (CH_4) or butane (C_4H_{10}), will behave most like an ideal gas? Explain.

____

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13.1.B Avogadro's Hypothesis

WARM UPS AND STRETCHES

Fill in each blank below with one of these words: theory, model, observation, explanation, hypothesis, science.

_________ A story of an event, which is told in terms of things that are simpler and more permanent than the event itself.

A __________ is a representation that behaves like observed reality in some way.

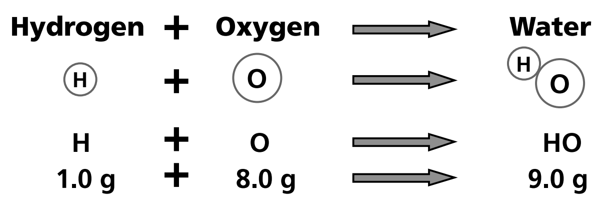
_________ is not the study of nature; it is the study of human representations of nature.

A __________ uses a set of simple, permanent things and behaviours to explain a large variety of events.

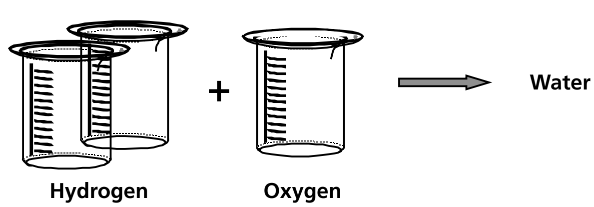
Amadeo Avogadro (1776–1856), spent most of his life in Italy. During his investigations, he exchanged letters with both John Dalton (England) and Joseph Louis Gay-Lussac (France). Their letters contained two important things.

First, they described their experiments, so that they could repeat each others' experiments. This is an important part of science, but only a part. Cooks exchange recipes, and cooking isn't science. Second, they exchanged *representations* of what they believed was occurring, in order to explain their experiments. This is the characteristic that makes science different from other kinds of knowledge.

Let's review how Dalton represented the reaction between hydrogen and oxygen to make water. Dalton assigned hydrogen atoms a relative mass of 1, and oxygen atoms a relative mass of 8. Thus, Dalton could explain why hydrogen always combined with oxygen in a mass ratio of 1 : 8.



Gay-Lussac was interested in the volumes of the reacting gases. He found that gases always reacted in whole number ratios, such as 1:1 or 3:2. Hydrogen and oxygen, for example, always reacted in a ratio of two volumes of hydrogen to one volume of oxygen.



How could both things be true at the same time? Why would gases always combine in a ratio that reflected the atomic masses, *and also* react in a whole number ratio of volumes?

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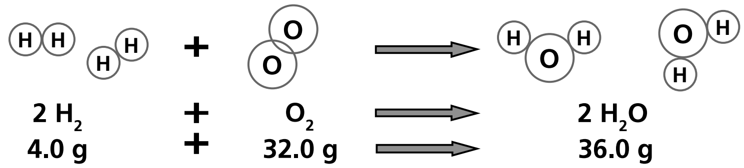
Avogadro invented two new ideas to explain these results.

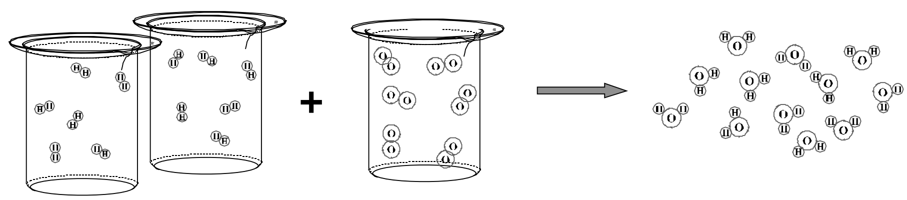
Dalton used the words *atom* and *molecule* interchangeably. Gay-Lussac used both words to explain gas behavior. Avogadro was the first to make a distinction between the two terms. He suggested that oxygen gas consisted of molecules; and that each molecule was made of two atoms.

Avogadro changed Dalton's representation of the reaction to the following.



Avogadro's second new idea was to combine the representations of Dalton and Gay-Lussac. The only way to make both the mass ratios and the volume ratios work out was to draw equal numbers of molecules in each volume. Equal volumes of gases must contain equal numbers of molecules.

Count the molecules in the diagrams below to confirm Avogadro's conclusion.



Avogadro's volume: What volume is occupied by one mole of oxygen molecules? In a warm room, at 27°C, one mole of gas occupies 25 L. This is sometimes known as the molar volume. This number is not exact, but it is a very good approximation. We will use this number in the following pages, as we continue to build our model of an ideal gas. Finally, we will make any necessary small corrections at the end of this section.

Avogadro's number: We learned earlier that Avogadro's constant is a kind of conversion factor between the system of atomic mass units, and the metric system of grams. When describing reactions between gases, Avogadro's number has other uses as well. Read the statements below. Then write additional labels on the diagrams to indicate the number of mols, the number of molecules, and the volume of each gas.

One mole of any gas contains 6.02×10^{23} molecules.
At 27°C, one mole of any gas occupies 25 L.
32.0 g of oxygen molecules = 1.00 mols of O_2 molecules = 6.02×10^{23} molecules of O_2
2.00 g of hydrogen molecules = 1.00 mols of H_2 molecules = 6.02×10^{23} molecules of H_2

Check Your Understanding

1. What distinguishes science from other kinds of study?

2. How would Dalton have finished this sentence? "Whenever two gases combine in a chemical reaction, they always combine ____________."

3. How would Gay-Lussac have finished this sentence? "Whenever two gases combine in a chemical reaction, they always combine ____________."

4. You have one litre of methane gas (mass of 16.0 u). What volume of oxygen gas (mass of 32.0 u) would contain the same number of molecules?

5. What is Avogadro's number?

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13.1.C Temperature Is the Average Kinetic Energy of an Ideal Gas

WARM UPS AND STRETCHES

Kinetic energy, E_k, is the *energy of moving matter*. Consider a shot put with mass 2 kg, and velocity 2 m/s. Its kinetic energy is calculated using the equation $E_k = ½\, mv^2$ as shown at right. (Units have been left off.)

$$E_k = \frac{1}{2}mv^2$$
$$= \frac{1}{2}(2)(2)^2$$
$$= 4$$

How is kinetic energy dependent upon mass and velocity? Let's explore this by changing one variable at a time, and observing the effect upon E_k.

What is E_k if you double the mass to 4, and leave velocity the same at 2?

$$E_k = \frac{1}{2}mv^2$$
$$= \frac{1}{2}(4)(2)^2$$
$$=$$

What happens to E_k if you keep the mass at 2 and double the velocity to 4?

$$E_k = \frac{1}{2}mv^2$$
$$= \frac{1}{2}(2)(4)^2$$
$$=$$

Temperature Is Related to Particle Velocity

At 20°C, air particles hit your skin at an average velocity of 460 m/s, much faster than sound! The air particles around you have a range of velocities and kinetic energies. At room temperature, a very few particles move at zero velocity, and a very few move at 2000 m/s. Most of the particles are close to the average of 460 m/s.

Because each particle has such tiny mass, you cannot feel the impact of the individual particles. However, you *can* feel the kinetic energy of the air particles as *temperature*. In fact, temperature T is the *average kinetic energy* of the particles.

When you sit down in a cool room, your skin is able to sense the loss of your body heat to the surrounding air. If you turn up the thermostat, you cause the air particles to speed up, which is the same thing as heating them. Your skin can sense the difference, and you soon begin to feel more comfortable.

In a pizza oven at 230°C, the air particles move at an average of 620 m/s. If you were to touch the door of the oven, the rapidly moving particles in the door would transfer kinetic energy to your skin, causing a burn. The kinetic energy would cause cells to burst, and proteins to break apart, giving you a serious burn.

Your freezer is at −18°C, and the air particles inside move at about 430 m/s. If you were to expose your skin to that temperature, the particles in your body would transfer kinetic energy to the slower particles in the cold air. Eventually, water particles in your skin would move so slowly that they would begin to stick together, forming ice crystals. The ice crystals would pierce cell membranes, causing damage similar to a burn.

How cold can it get? As the particles slow, the temperature of the whole collection gets colder. If the particles stop moving, then the average kinetic energy is zero. This temperature is called *absolute zero*. Nothing can be colder than absolute zero, because particles cannot have less than zero motion, or less than zero kinetic energy.

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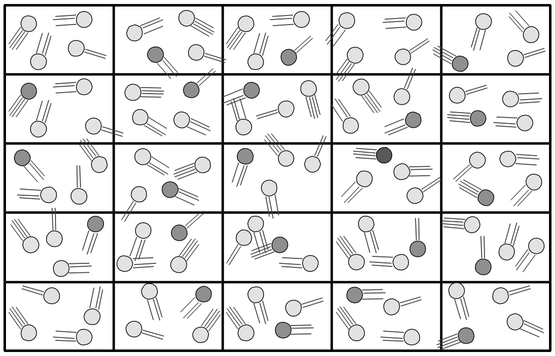
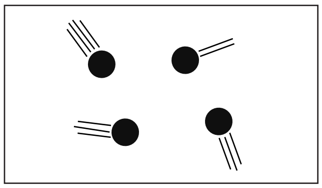


Each particle represents 1% of one mole.

Representing Kinetic Energy in a Gas

How should we represent a gas? The number of particles in one mole is too large to draw. So...let each "particle" we draw represent "one one-hundredth" of a mole, that is, 1% of one mole.

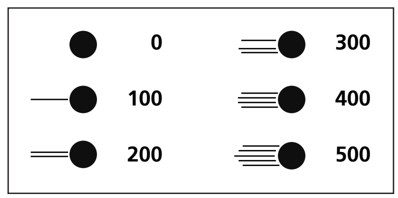
In the last section, we found that one mole of gas at 27°C occupied 25 L. If we represent 100% of one mole as 100 "particles," then 25 L of gas would contain 100 particles. The diagram at right is still too much to draw.

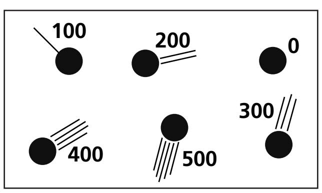


A single box represents a 1 L container, usually at 27°C and normal pressure.

For the rest of this section, we will represent a one-litre container as a single box. Inside that one-litre box, there would normally be 4% of one mole, represented by four "particles." Unless stated otherwise, you can assume that the pressure will be normal, and the temperature will be 27°C.

How should we represent the kinetic energy of molecules in a gas? Let's represent the E_k of air particles as "energy bars." Each bar represents 100 "units of E_k." A circle with four energy bars represents a particle with 400 units of E_k.





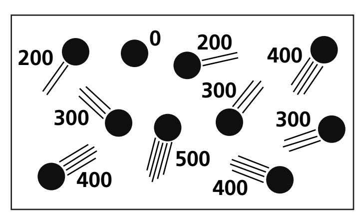
What is the temperature of the gas?

In any real gas, the particles would have a wide range of kinetic energies. The representation at left shows a box containing six particles of a gas (6% of a mole), with a variety of kinetic energies. The distribution of E_k is indicated by both the "energy bars" and by the numbers

The temperature is the *average kinetic energy* of the particles. Calculate the average of the six numbers. The average kinetic energy is 250 (check the math yourself), so $T = 250$.

SAMPLE PROBLEM

10 gas particles trapped inside a box represent 10% of one mole contained in a one-litre box. The "particles" have the individual kinetic energies as shown.



What is the temperature of the gas?

Solution

Find the *average* kinetic energy of the particles.

1. Count the energy bars, and label each particle with its E_k.
2. Calculate the total E_k. (E_{kT} = 3000).
3. Find the average E_k of the particles. (Divide the total kinetic energy by the number of particles.)

$E_k = E_{kT} / n_T$
$= (3000) / (10)$
$= 300$
$T = 300$
The gas temperature 300.

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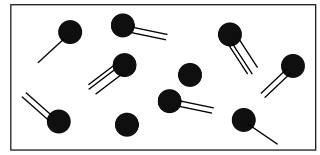
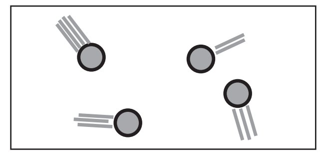
PRACTICE PROBLEMS

1. Is this collection of particles hotter, or colder, than $T = 200$? Show your work.



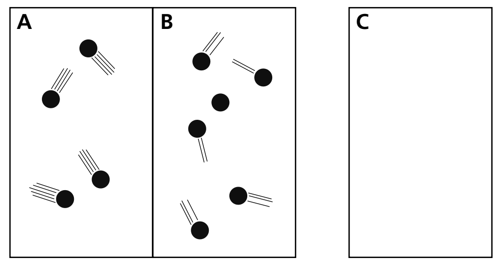
2. Add four more particles, so that the *average* kinetic energy is 170.



3. Find the average kinetic energy:

a) in box *A* **b)** in box *B*

Boxes *A* and *B* are mixed in box *C*. Draw the particles, and find the temperature of Box *C*.



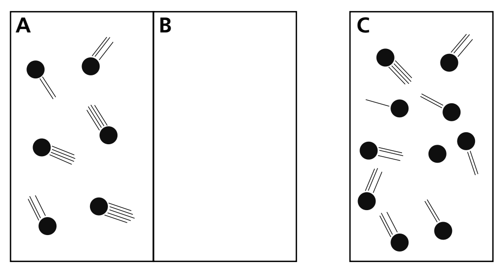
4. Find the temperature:

a) in box *A* **b)** in box *C*

Boxes *A* and *B* were mixed in box *C*.

a) Draw the particles in *B*, including energy bars.

b) Calculate the temperature of *B*.



Check Your Understanding

1. Write a definition for *temperature*. ______________________

2. What is the coldest possible temperature? Explain.

____

3. Which factor, particle *mass* or particle *velocity*, has the greatest effect on kinetic energy?

____

4. When you mix air at $T = 400$ with air at $T = 200$, is the final temperature always 300? Explain.

____

13.1.D How Do Scientists Measure Temperature?

WARM UPS AND STRETCHES

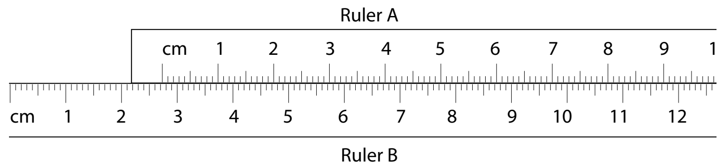
Compare ruler A with ruler B. The "zeros" of the rulers are in different places. Read rulers to find:

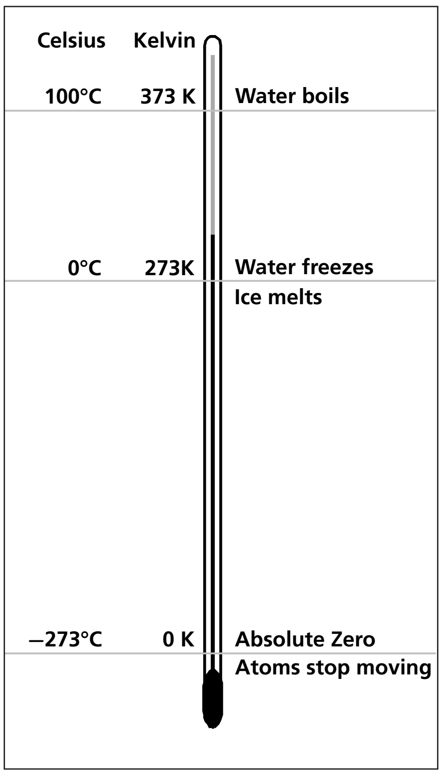
Ruler A 0.00 cm = _____cm Ruler B

Ruler A ____ cm = 5.00 cm Ruler B

Ruler A ____ cm = 5.46 cm Ruler B

Ruler A 8.37 cm = _____cm Ruler B





This thermometer shows both Celsius and Kelvin temperature scales.

Thermometers and Temperature Scales

Over the centuries, people have used several different temperature scales. The Fahrenheit scale is gradually being phased out. The Celsius scale is the most commonly used in the world. The Kelvin scale is used by scientists.

Suppose that you made a thermometer with no markings. How would you calibrate the thermometer to measure Celsius temperatures? You would need to mark the thermometer at two temperatures that are easy to reproduce. If you put the thermometer into an insulated cup containing pure water and ice, you could mark that temperature 0°C. If you then put the thermometer into pure boiling water, you could mark that temperature 100°C. The temperature of melting ice and boiling water are known as "fixed points."

The Celsius Scale is used for everyday temperatures, such as weather, home heating, and cooking.

The melting point of water is taken as 0°C. The boiling point of water at sea level would be marked 100°C. The interval between those two temperatures was divided into 100 equal parts, called *degrees* of temperature.

The Kelvin scale is used by scientists. Zero on the Kelvin scale is set at absolute zero, the temperature at which particles of matter have zero kinetic energy. Absolute 0 K = –273°C. One Kelvin degree of temperature is the same size as the Celsius degree, so there are 100 Kelvin degrees between the melting and boiling points of water. The melting point of water is 273 K. The boiling point of water is 373 K. The Kelvin scale is the only scale that reflects the actual kinetic energy of the particles.

No one has made a cooling device that can reach 0 K (absolute zero). In fact, 0 K cannot be reached, because particles cannot be completely stopped. The lowest temperature that scientists have ever reached is about 5×10^{-10} K. While scientists agree that 0 K equals –273.15°C, in this course, we will round off to –273°C.

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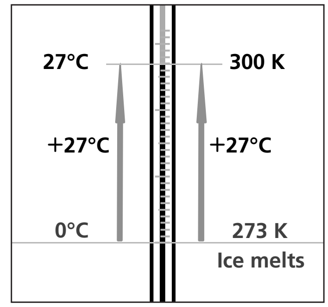
SAMPLE PROBLEM

What is 27°C in Kelvin?

Solution

Draw a simple sketch of a thermometer. Then:

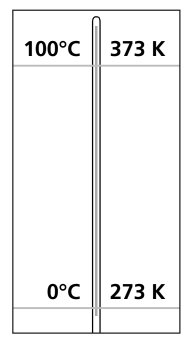
1. Draw a line across the thermometer at the known temperature, 27 Celsius degrees higher than the melting point of ice, 0°C.
2. Find the same fixed point on the Kelvin scale, 273 K.
3. Add the same number of degrees to the same fixed point on the Kelvin scale.



The room has T = 300 K

PRACTICE PROBLEMS

1. **a)** Your normal body temperature averages around 37°C. What is that temperature in Kelvin?
   b) The temperature 298 K is very important for chemists. What is that temperature in Celsius?



2. **a)** Methane melts at −183°C and boils at −164°C. What are these temperatures in K?
   b) The surface temperatures of Venus, Mars and Saturn are 730 K, 210 K, and 133 K respectively. What are these temperatures in Celsius?

Check Your Understanding

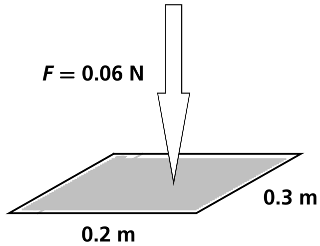
1. What change of state is used to define 0°C? What is used to define 0 K?

2. What is a "fixed point?"

13.1.E Gas Pressure is Caused by Motion of Particles

WARM UPS AND STRETCHES

Pressure is defined as the *force exerted per unit area*. The SI unit of force is the **pascal (Pa)**. One pascal is one **newton** of force exerted on a surface of one square metre. Calculate the pressure exerted by one packet of sugar scattered over one sheet of loose-leaf paper.



$$P = \frac{F}{A}$$

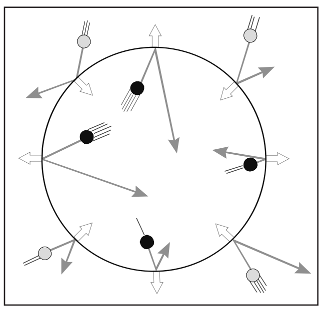
$$= \frac{(\quad)}{(\quad)(\quad)}$$

$$= \frac{N}{m^2} \text{ or } \quad Pa$$

The Pressure in a Bubble

Soap bubbles have walls that are only a few molecules thick. How does air keep the soapy film from collapsing?

A bubble 12.4 cm in diameter has a volume of 1.0 L. The air molecules inside strike the soap film at about 460 m/s, bouncing off the delicate walls. Each collision with the soap bubble pushes the walls of the bubble outward. We call that push **pressure**.



The long arrows represent the particle's path as it strikes the bubble. The boxed arrows indicate the impact on the bubble at the point of collision. Note that the impacts inside and outside the bubble are balanced.

Outside the bubble, air molecules are doing exactly the same thing, pushing the bubble inward. Even though the bubble is completely free to bend, stretch, and shrink, the bubble neither expands nor collapses.

The pressure exerted by the gas inside the soap film precisely balances the atmospheric pressure from outside the bubble, plus a small amount of surface tension in the soap film itself.

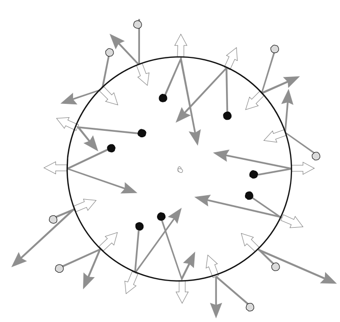
In other words, gas pressure is a consequence of particles having motion, mass, and space to move.

Representing Gas Pressure

The large circle in the margin represents a bubble with a volume $V = 1.0$ L. Recall that each "particle" represents 1% of one mole of air molecules. This bubble contains 0.04 mols of air molecules.

SAMPLE PROBLEM

The diagram at right represents a bubble with volume 2.0 L. Draw eight particles of air inside, and eight particles outside the bubble. Then draw arrows to indicate the path of each particle, and the impact that it gives the bubble.



Solution

The particles both inside and outside the bubble move in random directions, colliding with the walls of the bubble.

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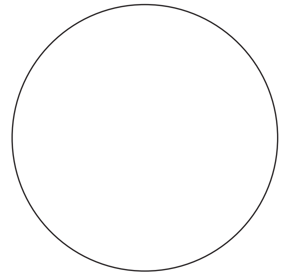
PRACTICE PROBLEMS

Each bubble has a volume of 1.0 L, and initially contains four particles. Complete each diagram, and answer the questions. *The air outside the bubble affects each situation. Draw air particles outside the bubble!*

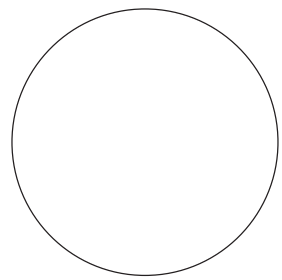
1. Imagine that the four particles inside the bubble have stopped moving. Complete the diagram to represent this situation.



What would happen to the gas pressure inside the bubble?

What would happen to the bubble? (Don't forget air outside the bubble.)

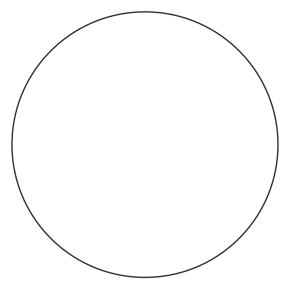
2. What would happen if you added four more gas particles inside the bubble? Draw a picture to show this new situation.



What would happen to gas pressure inside the bubble?

What would happen to the bubble?

3. Start with four particles inside the bubble. Now increase the speed of the four particles inside the bubble.



Draw a picture to show this new situation.

What would happen to gas pressure inside the bubble?

What would happen to the volume of the bubble?

Check Your Understanding

1. Define pressure. ____________________

2. Describe how a gas exerts pressure. ____________________

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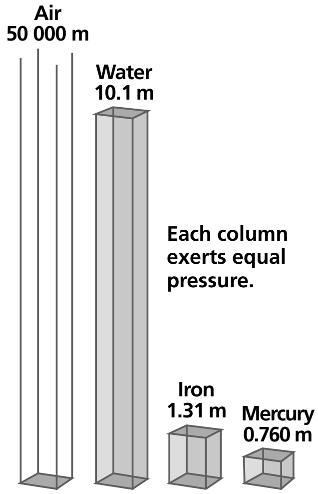
13.1.F How Do Scientists Measure Pressure?



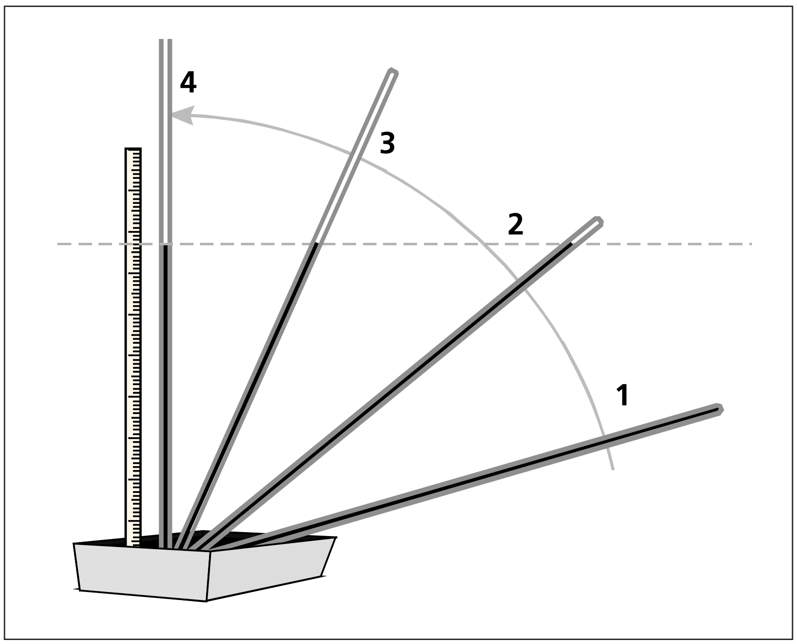
An Ocean of Air

You live at the bottom of a vast ocean of air, 50 km deep. If you draw a 1 m × 1 m square on the floor, the column of air rising 50 km above it contains a little more than ten tonnes (actually 10 340 kg) of air. The force of gravity on that air is 101 300 N. The atmospheric pressure on the floor is 101.3 kPa.

Just as a fish is unaware of the pressure exerted by the water, you are probably unaware of the pressure exerted by the air. Here are some surprising comparisons:

- Imagine a slab of iron, 1 m × 1 m × 1.31 m high. That slab of iron exerts the same pressure on the floor as atmospheric pressure.
- Imagine diving to the bottom of a swimming pool, 10 m deep. The water pressure that you experience there is equivalent to one atmosphere.

Atmospheric pressure was not measured until Torricelli performed a series of experiments around 1643. He melted one end of a long glass tube until it sealed. Then he filled the tube with mercury, and covered the open end of the tube with his thumb. He carefully dunked that end of the tube into a pan of mercury, removed his thumb, and gradually raised the other end of the tube to a vertical position. Imagine Torricelli's surprise when the mercury rose to a height of 760 mm and no higher! The space above the mercury column was found to be empty (a vacuum).



Torricelli proposed that the pressure of the air on the surface of the mercury was equal to the pressure exerted by the mercury column inside the tube. Above the mercury was a vacuum. The pressure of the atmosphere was equal to the pressure of the mercury column.

Check Your Understanding

Label the diagram above to indicate:

(a) the vacuum above the mercury column inside the tube.

(b) the force exerted by the atmosphere on the surface of the mercury in the pan

(c) the height of the mercury column.

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Representing Pressure Scales

A barometer is an instrument that measures atmospheric pressure. In the diagram at right, atmospheric pressure is indicated with three different scales. Only a vacuum exerts zero pressure, and $P = 0$ is the same in all three scales.

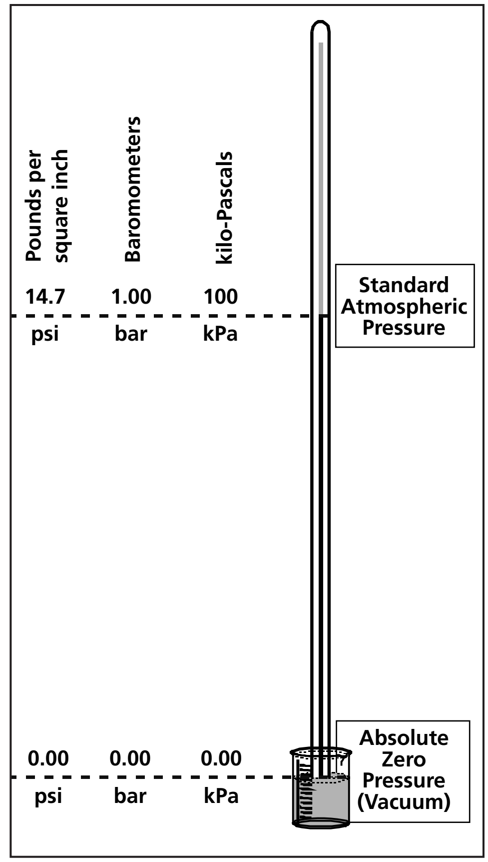
Standard Atmospheric Pressure: Atmospheric pressure averages 101.3 kPa at sea level. Chemists have defined the standard atmospheric pressure as 100 kPa, equal to 1.00 bar. It is also equal to 14.7 psi (pounds per square inch).

Chemists define Standard Temperature and Pressure (STP) as 0°C and 100 kPa.

Gauge Pressure: If you were to use a pressure gauge or electronic pressure probe to measure atmospheric pressure in your classroom, your instrument is likely to read zero. Pressure gauges and probes usually don't measure the surrounding atmospheric pressure. If your electronic pressure probe measures $P = 25$ kPa, it is measuring "25 kPa greater than atmospheric pressure." The *real* pressure is:

$$P = 25 \text{ kPa} + 100 \text{ kPa}$$
$$= 125 \text{ kPa}$$

Mark this pressure on the barometer at right.



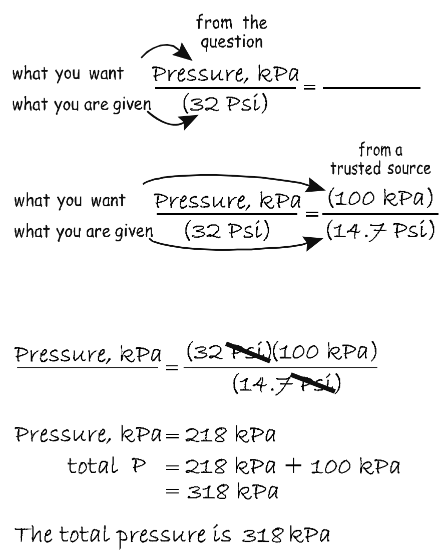
Torricelli's mercury barometer, with a column of mercury 760 mm high

SAMPLE PROBLEM

The pressure gauge at the service station measures the air pressure inside your tires as 32 psi. What is the *real* air pressure inside the tire, in kilopascals?

Solution

1. Set up two quotient lines, with an equal sign.
2. From the question, write "what you want" over the *left* quotient line, and "what you're given" under the *left* quotient line.
3. Write the same ratio above and below the *right* quotient line. Atmospheric pressure is *defined* as these two numbers in the two scales, so you can trust that ratio. It is a trusted source.
4. Simplify the left hand side. Factor out the common units on the right hand side.
5. Do the math. Add one atmosphere to the gauge pressure to measure the real pressure.
6. Round off, and write a sentence.



PRACTICE PROBLEMS

1. A pressure gauge reads the gas pressure inside the cylinder of a diesel motor as 2000 kPa. What is the *real* pressure inside the cylinder?

2. Your bicycle tire is rated to a maximum pressure of 70 psi. What is that pressure in kilopascals?

3. When you are flying in a passenger plane, the pressure outside is only 50 kPa. What pressure is that in psi?

4. At 4.4°C, the pressure gauge on a cylinder of butane reads 3.1 psi. What is the *real* pressure inside the cylinder, in kPa and in bar?

Check Your Understanding

1. Why does the atmosphere exert pressure? ____________________

____

2. The air pressure on your desk top is 101 000 N/m^2 . What force is air exerting on the top of your desk? ____________________

3. List three measures of atmospheric pressure that are equivalent to 760 mm of mercury.

____

4. Measured in mm Hg, an athlete's blood pressure is $\frac{105}{78}$. What are these pressures in kPa?

____

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LAB 13.1G AVOGADRO'S HYPOTHESIS

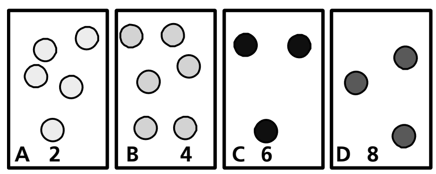
Focus Question

Do equal volumes of different gases contain the same numbers of particles?

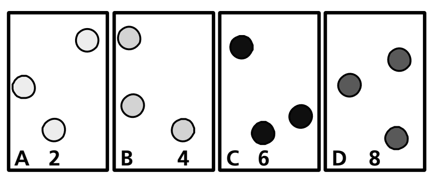
CONCEPTS AND THEORIES

Avogadro postulated that equal volumes of ideal gases, at the same temperature and pressure, contain the same number of particles. Consider four different kinds of gas particles *A*, *B*, *C* and *D* having masses 2, 4, 6 and 8 respectively (units have been ignored). We have no way to count the particles directly, but we can compare the total mass of the gas contained within equal volumes at the same *P* and *T*.

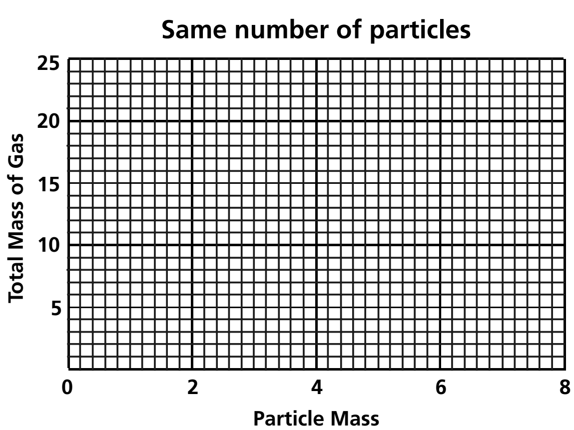
If Avogadro is wrong, each volume of gas has a different number of particles. Find the total mass of gas *A*, and plot the total mass of *A* against the mass of one particle of *A*. Plot gases *B*, *C* and *D* in the same way, and draw the best smooth line through the points.

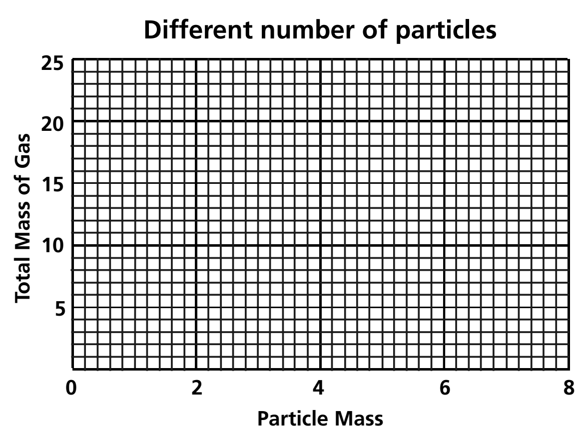


If Avogadro is right, each volume of gas has exactly the same number of particles. Repeat the calculations, plot the points and draw the best smooth line through the points.



If Avogadro is correct, which graph should your measurements resemble?



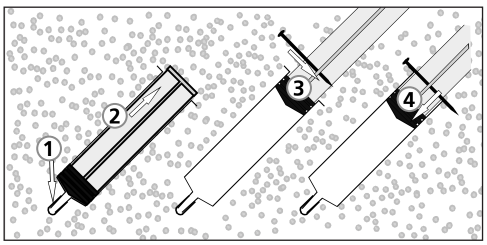


EVENTS AND OBJECTS *(including safety)*

Suggested gases: hydrogen, helium, argon, methane, propane, butane, oxygen, carbon dioxide.

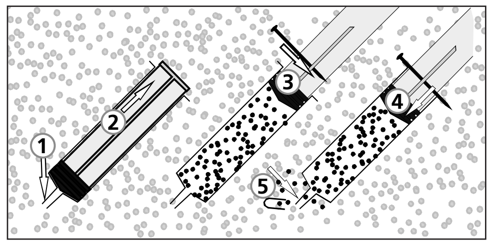
To measure the mass of a truly empty syringe:

1. Expel the air, and place a cap on the syringe.
2. Draw the piston back, creating vacuum conditions.
3. Insert a small nail into the hole in the piston.
4. Gently let the piston down until it is stopped by the nail.
5. Measure the mass of the empty syringe, cap and nail.



To measure the mass of a gas:

1. Empty the syringe, and attach to a gas source.
2. Draw enough gas to fill the syringe.
3. Insert the nail.
4. Expel the excess gas until stopped by the nail.
5. Cap the syringe, and measure the mass of the syringe, the cap and the nail and the gas.



RECORDS AND TRANSFORMATIONS

Design a table to record all of the information that you intend to gather in the experiment. Design a graph to plot and analyze the data as described above.

DISCUSSION

Interpret your findings. Did you answer the question? Is Avogadro correct? Have you changed any of your initial concepts? Would you improve any of your methods or actions?

Focus Question

Write the question in your own words.

THEORY THINKING

1. Concepts and Theories

Describe your thinking as you planned the experiment to answer the question.

4. Discussion

Did you answer the focus question? Were your original concepts and theories adequate? Were your methods effective?

ACTION/METHOD

2. Events and Objects

Describe how you used the syringes, balance, etc. to test your hypothesis.

3. Records and Transformations

Present your records in a table and in a graph. Add comments.

MODEL BUILDING

ACTION/METHOD

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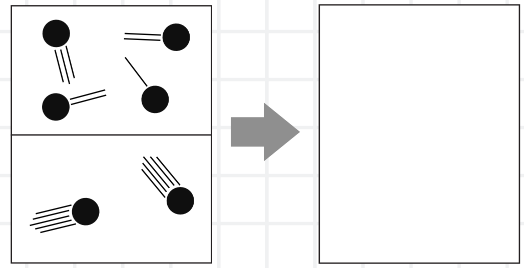
Questions & Quizzes

1. A 2 L box is divided into two sections, *A* and *B*. Each section contains different amounts of the same gas, at two different temperatures.

a) Use the "energy bars" to calculate the temperature of each section.

b) Predict the final temperature, after the dividing wall is removed.

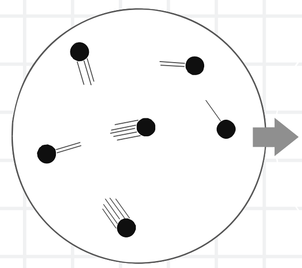


2. A bubble contains sticky-gas particles as shown.

a) Draw air particles outside the bubble.

b) In the next instant, these gas particles stick to the bubble membrane. Draw a new diagram to show the bubble and the particles a few seconds later.

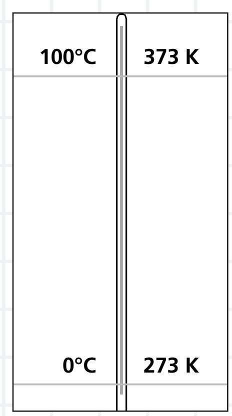
c) Explain your answer.



3. When we are active and awake, our body temperature averages around 37°C.

a) What is human body temperature in Kelvin? Show your work.

b) Suppose you were running a fever, 3°C above your Celsius temperature. What is the Kelvin temperature of your fever?



4. When a pressure gauge is placed on a fresh CO_2 cylinder for a paintball gun, the pressure gauge reads 850 psi.

Calculate the *real* gas pressure inside the cylinder, in kPa.

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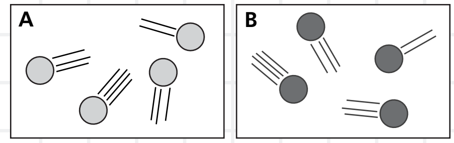
Questions & Quizzes

5. Consider gas *A* (mass = 4) and gas *B* (mass = 16) at the same temperature. Avogadro hypothesized that equal volumes of these different gases must contain equal numbers of particles. Are the gas pressures in A and B the same, or different? Write 3 – 4 sentences to explain why your answer must be true.



6. A student measures out 44 g of dry ice (solid CO_2). She puts the dry ice into a clear plastic garbage bag, presses out the air, and seals the bag. An hour later, the dry ice has turned to gas at 27°C, and 100 kPa.

a) What is the volume of one mole of CO_2 at 27°C, and 100 kPa?

b) How many moles of CO_2 are in one litre of gas?

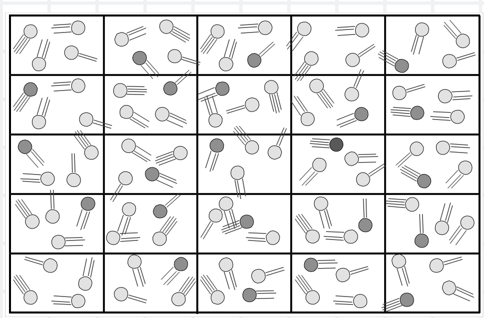
c) Explain your answer.

7. In an experiment, a student traps 25 mL of CO_2 gas in a syringe at 27°C and 100 kPa.

a) How many moles of gas would that be?

b) What mass of CO_2 gas would you expect to find in the syringe?

8. Air is approximately 78% nitrogen, 21% oxygen and 1% argon. The diagram at right represents 100 air molecules (100% of a mole) in 25 L. If this mixture was replaced with 100 nitrogen molecules, would the pressure increase, decrease, or remain the same? Explain your thinking, using the particle theory.



13.2 The Gas Laws Are an Algebraic Model of Gas Behaviour

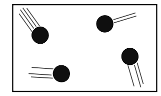
13.2.A Gas Pressure Relates to Particle Number and Volume

WARM UPS AND STRETCHES

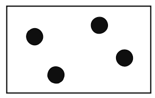
In the previous section, we developed a set of diagrams to represent a gas.

What volume is represented by a single box like the one at right?

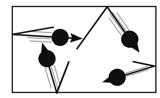
What gas temperature is represented in this diagram?



How many moles of gas are represented by four particles?



What is ordinary atmospheric pressure in your classroom in kilopascals?



Representing *P*, *V*, *n*, and *T*

In everyday experience, we think of pressure as a *cause* of events. In chemistry, it is more useful to think of pressure as the *effect* caused by other factors. What are those factors?

Imagine a clean, dry, open milk carton, sitting on your desk in your classroom at 27°C. The volume of the carton is $V = 1$ L. Inside the carton is $n = 0.040$ mols of gas. In a warm room, the temperature could be 27°C or $T = 300$ K. Atmospheric pressure in your classroom is $P = 100$ kPa. At any given temperature, the gas pressure inside the box depends on the number of moles of gas and the volume in which they are confined. The greater the number of particles per volume, the greater the pressure.

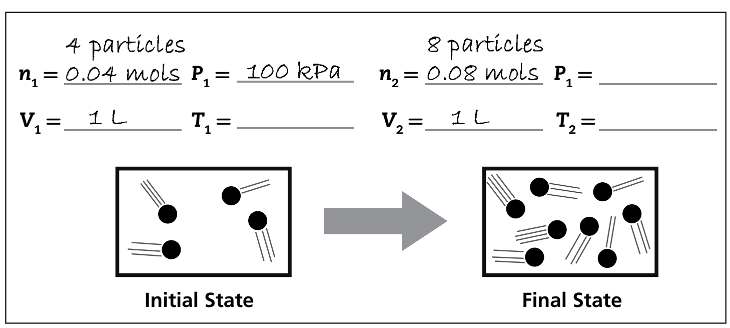
SAMPLE PROBLEM

A vessel with $V_1 = 1$ L contains $n_1 = 4$ particles or 0.04 mol. You double the number of particles. What is the final pressure P_2?

Solution

In the initial state, 4 particles in a 1 L box cause an initial pressure of $P_1 = 100$ kPa, or 1 bar .

In the final state, $n_2 = 8$ particles = 0.08 mol. With twice as many particles pounding on the walls of the same container, the final pressure will be twice as great. $P_2 = 200$ kPa.



What happens to P if you double the volume of each box? In both cases, there would be half as many particles per litre, half as many collisions, and half as much pressure. We can summarize our solution in two statements.

1. Doubling the number of particles in the container will cause the pressure to double. In other words, *pressure is directly proportional to the number of particles in the container*.
2. Doubling the volume of a container will cause the pressure to be reduced by one half. *Pressure is inversely proportional to the volume of the container.*

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PRACTICE PROBLEMS

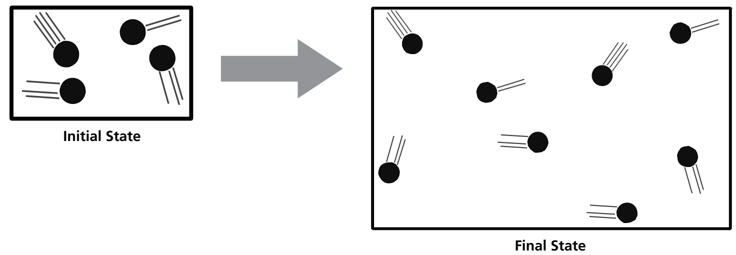
Temperature is 300 K in every case. Determine *V*, *n*, and *P* using the particle model.

1. Double the number of particles and quadruple the volume.

What is the final pressure, in kPa?

n_1= ________ P_1= ________ n_2= ________ P_2= ________

V_1= ________ T_1= ________ V_2= ________ T_2= ________



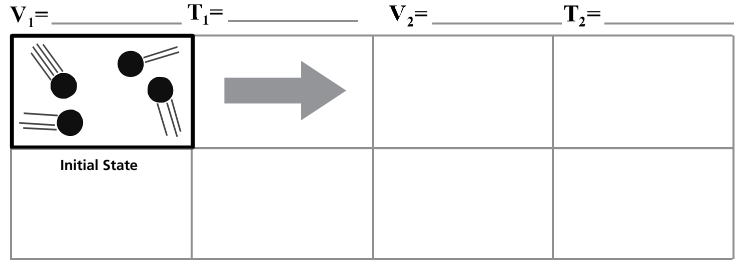
2. The initial state of a gas is shown. In the final state, $n_2 = 4\ n_1$, and $V_2 = 2\ V_1$.

Draw the final state.

What is the final pressure?

n_1= ________ P_1= ________ n_2= ________ P_2= ________

V_1= ________ T_1= ________ V_2= ________ T_2= ________



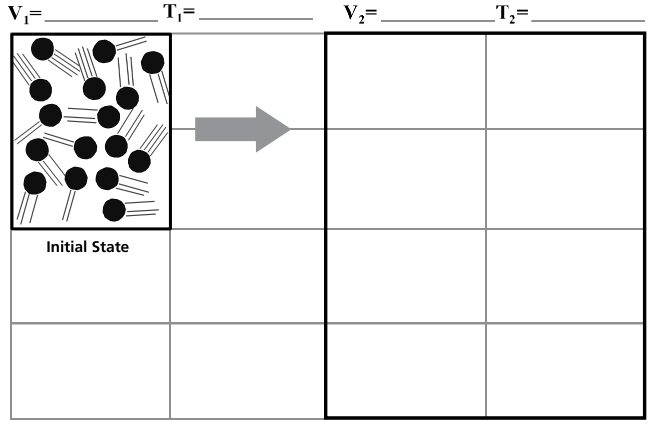
3. A bottle contains 0.16 mols of a gas.

a) What is the initial pressure of the gas, in kPa?

b) Predict the final state of the gas if it is allowed to expand as shown.

n_1= ________ P_1= ________ n_2= ________ P_2= ________

V_1= ________ T_1= ________ V_2= ________ T_2= ________



4. Calculate (*PV*/*n*) for all eight boxes in the sample problem and practice problems. What pattern do you see?

Check Your Understanding

1. Imagine a clean, dry empty 1.0 L water bottle sitting on your desk. Describe the air inside it.

2. What is the average kinetic energy of the air in a warm 27°C room? Use the Kelvin scale.

3. State the relationship between the number of air particles inside a volleyball and the pressure.

4. State the relationship between *V* and *P* of a gas. Use the particle theory to explain.

5. What does "inversely proportional" mean? Name two quantities that are inversely proportional.

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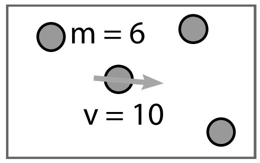
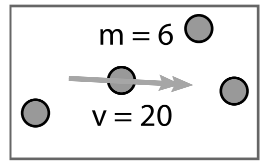
13.2.B Pressure is Related to the Temperature of a Gas

WARM UPS AND STRETCHES

A 1.0 L vessel contains 0.04 mols of gas. All of the particles have mass = 6. Before heating, the particle velocity is 10 ⟶. After heating, v = 20 ↠. Calculate the kinetic energy of each particle, and the temperature of the gas, before and after heating.

$$E_k = \frac{mv^2}{2}$$





$$E_k = \frac{mv^2}{2}$$

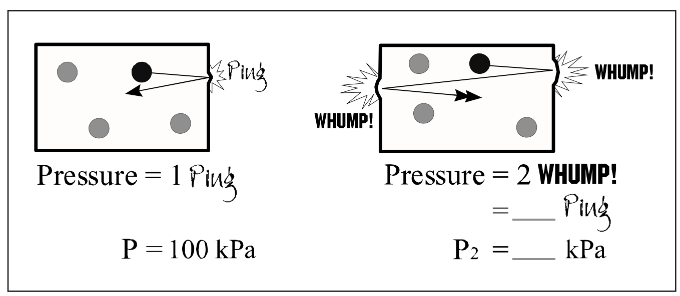
Particles, Kinetic Energy, and Pressure

Heating a sealed container of gas can cause the container to burst. Why does that happen? In these pages, we will extend the particle theory to explain this behaviour.

In our model, remember that one box represents $V = 1$ L. Four particles represent $n = 0.04$ mol.

Kinetic energy E_k is related to the *square* of the velocity of each particle. As you found in the warm-up exercise above, if the gas particles are moving twice as fast, they have four times the kinetic energy. Twice as fast: the final temperature is *four times the initial temperature*!

When a particle is moving twice as fast, it will hit the walls of the container *twice as hard*. (One Whump = two pings). If a particle is moving twice as fast, it will hit the container *twice as often*. When the particles hit 2× as hard, 2× as often, the final pressure is *four times the initial pressure*!



When the temperature was quadrupled, the pressure in the gas was quadrupled at the same time. *The pressure and temperature of a gas are directly proportional to each other*.

SAMPLE PROBLEM

Incandescent light bulbs are filled with argon gas. At $T = 300K$, the gas pressure $P = 80$ kPa.

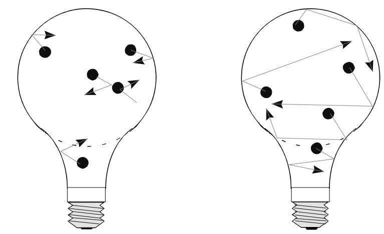
When the light bulb is turned on, the argon is heated to 600 K. What is the new gas pressure?

Solution.

The temperature was increased by a factor of two.

The pressure will increase by the same factor. (80 kPa × 2) = 160 kPa.

The pressure at 600 K will be 160 kPa.



$T_1 = 300$ K ×2 = $T_2 = 600$ K

$P_1 = 80$ kPa ×2 = $P_2 = 160$ kPa

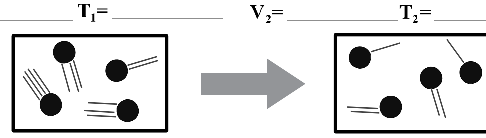
PRACTICE PROBLEMS

1. If a 1.0 L vessel contained 0.040 mols of gas at 27°C, the gas pressure would be 100 kPa.

What would the pressure be if the gas was cooled to −123°C? *(Hint: Convert T to Kelvin)*

n_1= ______ P_1= ______ n_2= ______ P_2= ______

V_1= ______ T_1= ______ V_2= ______ T_2= ______

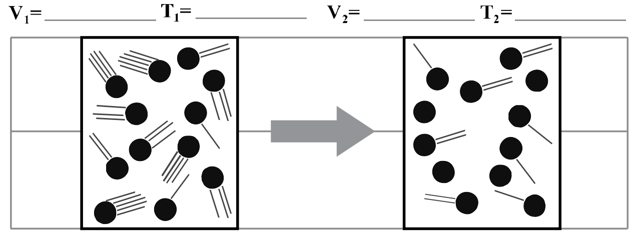


2. A 2.0 L cylinder contains 0.12 mols of gas at 300 K, and 150 kPa.

If the gas in the cylinder is cooled to 100 K, what is the new pressure?

12 "Particles"
n_1= 0.12 mols P_1= 100 kPa n_2= ______ P_2= ______

V_1= ______ T_1= ______ V_2= ______ T_2= ______

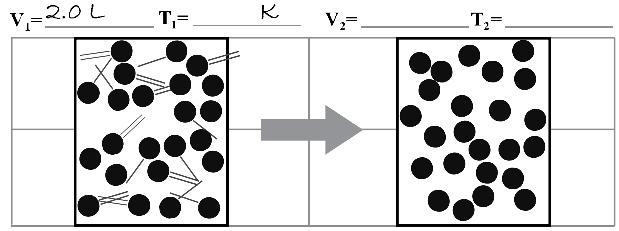


3. A 2.0 L bottle of cold gas at $T = -173$°C contains $n = 0.24$ mols, and $P = 100$ kPa.

What is the new pressure if the bottle is heated to −23°C?

24 "Particles"
n_1= 0.24 mols P_1= 100 kPa n_2= ______ P_2= ______

V_1= 2.0 L T_1= ______ K V_2= ______ T_2= ______



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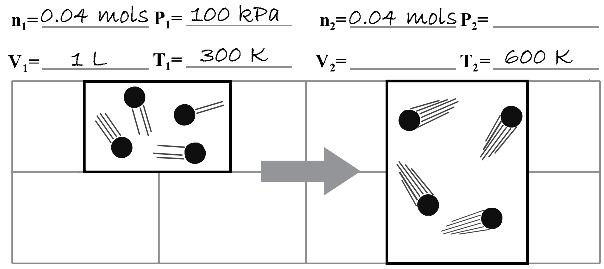
PRACTICE PROBLEMS *Continued*

4. A 1.0 L vessel contains 0.04 mols of gas at 300 K and 100 kPa.

a) The gas is heated to 600 K, and allowed to expand to 2 L. What is the new pressure?

b) If *n* and *P* are held constant, how does *V* appear to change with *T*?



5. Calculate (PV/nT) for all eight gas models in the problems above. What pattern do you see?

Check Your Understanding

1. If you double the velocity v of gas particles, what happens to the temperature T? Explain.

2. If you double the velocity v of the particles, what happens to the pressure P? Explain.

3. What relationship exists between the temperature of a gas and the pressure in the gas?

4. A certain gas is at $T = 300$ K and $P = 150$ kPa. What is the final pressure if T is changed to 600 K?

13.2.C The Complete Gas Law

Relating *P*, *V*, *n* and *T*

We have studied how changes in volume, temperature and number of particles causes pressure to change. How can we gather all of these factors into one simple relationship?

We know that P and V are inversely proportional: PV = constant for any sample of gas, as long as n and T of the gas don't change.

We also know that n and T are inversely proportional. The product nT = constant, as long as P and V of the gas don't change.

Are PV and nT related to each other?

For each question in the table below, calculate PV and nT. Then calculate the ratio PV/nT in the last column to two significant figures. (These values are from Practice Problems 13.2.A and 13.2.B.)

Question	P (kPa)	V (L)	PV	n (mols)	T (k)	nT	$\frac{PV}{nT}$
1	100	1		0.04	300		
2	50	4		0.08	300		
3	200	2		0.16	300		
4	50	8		0.16	300		
5	50	1		0.04	150		
6	150	2		0.12	300		
7	100	2		0.24	100		
8	500	2		0.24	500		

It appears that the *ratio PV/nT is a constant*. In fact, it is a famous constant, known to chemists as R, the gas constant. If we measure P in kPa, V in L, n in mols and T in Kelvin, the standard value of R is 8.314 (L•kPa/mol•K)

$$\frac{PV}{nT} = R$$

***R* is the gas constant.**

Our pencil-and-paper representation of gas behaviour has been very accurate!

Rearranging the relationship, we obtain the Ideal Gas Equation. This equation can be used to find any quantity related to gases in chemical reactions.

$$PV = nRT$$

The Ideal Gas Equation

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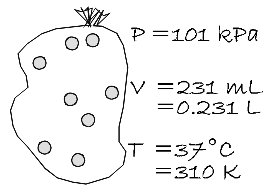
SAMPLE PROBLEM

Solving Ideal Gas Problems

A student chugs a can of ginger ale, and a few minutes later burps into a plastic bag. The volume of the burp-gas is measured at 231 mL at 37°C and 101 kPa. How many mols of burp-gas are there?

Solution	
1. Write the question in your own words	Find mols of gas, if P=101 kPa, V=231 mL, T=37°C
2. Underline relevant quantities and units.	
3. Draw a diagram, and label it.	
4. Do all unit conversions on the diagram.	
5. Write the appropriate equation.	$PV = nRT$
6. Rearrange the equation to find what you want.	$nRT = PV$ $n = \frac{PV}{RT}$
7. Substitute. Use brackets, include units.	$n = \frac{(101\ \text{kPa})(0.231\ \text{L})}{(8.314\ \frac{\text{L}\bullet\text{kPa}}{\text{mol}\bullet\text{K}})(310\ \text{K})}$
8. Solve. Check that units are what you want.	$= 0.0090523$ mol
9. Round off to the lowest precision in the data.	$= 0.0091$ mol
10. Write a sentence	The burp contained 0.0091 mols of gas.

You will do your best if you *write a complete solution in the same format each and every time.*

PRACTICE PROBLEMS

Solve each problem, using the scaffold from the sample problem.

1. Chemists define Standard Temperature and Pressure (STP) as 0°C and 100 kPa. What volume would 0.040 mols of gas occupy at STP?

2. A fully inflated tire contains 26 L of air at 35°C. The pressure gauge reads 33 psi. How many moles of gas would the tire contain? (*Hint: what is the real pressure on the gas?*)

Check Your Understanding

1. What is STP?

2. Write the ideal gas equation.

3. What is *R*? State its value, and explain its significance.

4. What is the volume of 2.0 g of oxygen, O_2, at STP? (*Hint: how many mols of oxygen?*)

5. An aquatic plant produces a 1.0 mL bubble of O_2, at 110 kPa and 28°C. How many mols of O_2 is this?

6. At what temperature would 0.25 mols of carbon dioxide occupy 3.0 L at 90 kPa pressure?

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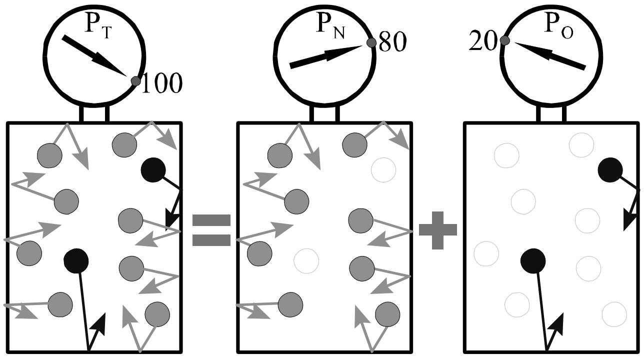
13.2.D The History of the Gas Laws

Dalton's Law

John Dalton (1766–1844) investigated the pressure in mixtures of gases. Dalton showed that each gas in a mixture of gases exerts its own pressure. For example, air is approximately 20% O_2 and 80% N_2. If the total air pressure is 100 kPa, then O_2 molecules exert a pressure of 20 kPa, and N_2 molecules exert P_N = 80 kPa.



Dalton showed that the sum of the pressures of each gas in a mixture equals the total pressure of the mixture.

Dalton's Law of Partial Pressures:

The total pressure in a mixture of gases is equal to the sum of the partial pressures of each individual component gas.

$P_{Total} = P_1 + P_2 + P_3$ **(etc.)**

Explain why Dalton's law is true, based upon the particle model in this chapter.

____

____

Boyle's Law

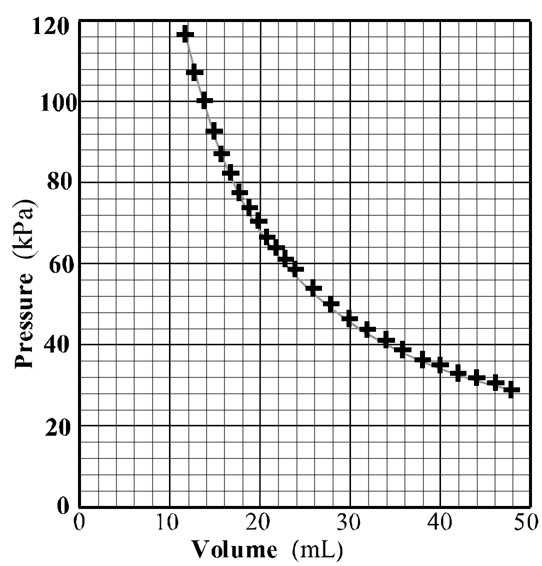
Robert Boyle (1627–1691) was a great investigator of chemistry and physics. He believed that gases were made of particles, held in place by little forces, something like springs. Boyle published his investigations into the "springiness of air" in 1662.

Notice in the graph to the right how reducing the volume increases pressure. Conversely, as volume increases, gas pressure decreases.

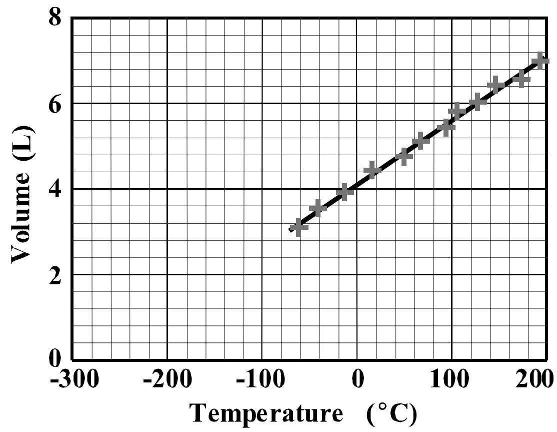
Boyle's Law:

For a fixed amount of gas at constant temperature, pressure and volume are inversely proportional.

$P_1V_1 = P_2V_2$



This graph demonstrates Boyle's Law relating pressure and volume.



This graph demonstrates Charles' Law relating volume and temperature.

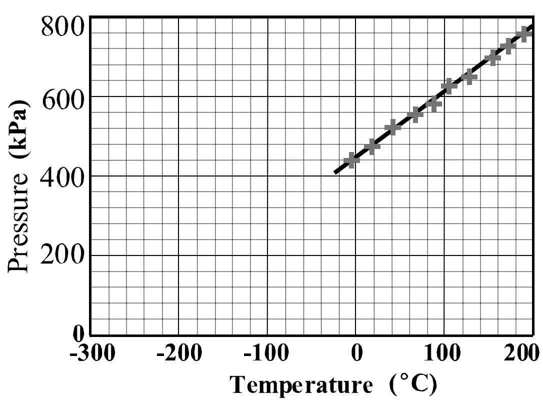
Charles' Law

Jacques Charles (1746-1823) was a French scientist and balloonist. He was interested in the volume of gas in a balloon, which he knew would affect the altitude at which a balloon would fly. Charles filled 5 balloons to the same volume with different gases. When he raised the temperature of each balloon to 80°C, all gases increased in volume by the same amount. (See graph at left)

Charles' Law:

For a given quantity of gas at a fixed pressure, the volume is directly proportional to the temperature.

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



This graph demonstrates Gay Lussac's Law relating pressure and temperature.

Gay-Lussac's Law

Joseph Gay-Lussac (1778–1850) was an atmospheric scientist, who like Charles, was an avid balloonist. It is said that he ascended more than six kilometres into the atmosphere to obtain samples of air at different altitudes. Guy-Lussac extended Charles' law, to relate temperature, pressure, and volume for a given quantity of gas. (See graph at left)

Guy Lussac's Law:

For a given quantity of gas at constant pressure, volume and temperature are directly proportional.

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

The Combined Gas Law

Boyle, Charles, and Guy-Lussac all worked with fixed masses of gas. They sealed the gas into a container, and then changed only P, V and T. In their experiments, no gas particles were added or removed. We would say that n was held constant in all of their experiments.

Changing P, V and T of one sample allows us to combine all three gas laws. Suppose a sample of gas at P_1, V_1 and T_1, was changed to P_2, V_2 and T_2, without changing n. In that case, n and R would be constants. If you factored out the constant nR, then P, V and T are related as shown.

$$P_1V_1 = nRT_1 \qquad\qquad P_2V_2 = nRT_2$$

$$\frac{P_1V_1}{T_1} = nR \qquad = \qquad nR = \frac{P_2V_2}{T_2}$$

$$\frac{P_1V_1}{T_1} = \frac{P_2V_2}{T_2}$$

This last equation is known as the **Combined Gas Law**.

Check Your Understanding

1. "Pressure and volume are inversely proportional." Who first published that law?

2. On a warm day, the pressure inside your tires increases. Which gas law predicts that behaviour?

3. One kilogram of air occupies less volume when it is cold. Whose law does this exemplify?

4. In the graph that accompanies Charles' law, extend the graph to find the temperature at which the pressure of a gas becomes zero. What is the significance of this temperature?

5. In the graph of Guy-Lussac's law, at what temperature would the volume of a gas become zero? Why is this temperature important?

6. Why is it true that the gas laws only work if you use the Kelvin scale?

7. You are at the bottom of a swimming pool, and you exhale a few bubbles of air. Why do the bubbles expand as they rise to the surface?

8. You are at street level, with a plastic bag containing 500 mL of gas at 100 kPa and 25°C. You get on an elevator, and feel your ears popping as you rise. When you step out of the elevator, the pressure is 95 kPa and temperature is 18°C. What is the new volume of the bag?

9. You are in your kitchen with a plastic bag containing 500 mL of gas 20°C. What is the volume of gas if you cool it in your freezer to −18°C?

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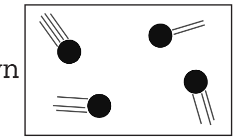
LAB 13.2E DESIGN EXPERIMENTS TO TEST THE PARTICLE MODEL



We have developed a particle model that describes the behaviour of a gas in terms of a fixed number of particles, moving with a known average kinetic energy, confined to a fixed volume, and exerting a known pressure.

The corresponding algebraic model is the ideal gas law, consisting of four variables (*P*, *V*, *n* and *T*), and one constant, *R*, related to each other in a simple equation.

$$PV = nRT$$

Does this model reflect the behaviour of real gases?

Your task is to design an investigation to test one aspect of the model. You will choose one independent variable from either *V*, *n* or *T*. You must also choose one dependent variable, either P or *V*. All other variables must be *controlled*, that is, held constant. Your experiment must generate 10–20 measurements. That will be enough data for you to create a graph. Finally, you must judge whether the model accurately predicts the real behaviour of your gas.

Focus Question

Write a focus question that clearly states what you are trying to find out. You may revise this question as new ideas come to you. You might choose to replicate an experiment of Boyle, Charles, or Guy-Lussac. What focus question did each of those scientists ask?

CONCEPTS AND THEORIES

Use both the particle pictures and the algebraic equation to describe how your experiment should work. As you develop your experimental plans, you will come back to this section to make changes. You may wish to add new details, remove old ideas, or clarify your thinking.

EVENTS AND OBJECTS *(including safety)*

Choose the materials and equipment for your experiment. Here are a few ideas to consider.

1. Are you going to use a rigid vessel to hold your gas, such as a flask and stopper?
2. Will you need a vessel with changeable volume, such as a syringe or a bicycle pump?
3. What instruments, probes, and software will you require to measure temperature?
4. What probes or instruments do you need to measure pressure?
5. How will you determine the number of moles of particles your experiment contains?
6. How do you plan to either vary or control the temperature? Will you use a water bath?
7. Will you need a source of heat, such as a hot water faucet or a hot plate?
8. What pressures will develop in your experiment? Are they safe?
9. How will you accurately measure volume?
10. What gas will you use? How will you know if it is pure?

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Before proceeding with any experiment, check the design with your teacher. Do not attempt any unauthorized experiment.

RECORDS AND TRANSFORMATIONS

What kinds of information will you be recording? Design a table to record all of the information that you intend to gather in the experiment. Design any graphs you will need to plot and analyze the data you collect.

DISCUSSION

Interpret your findings. Did you answer the question? Was your experiment reliable? Did your experiment create errors? Would you improve any of your methods or actions? You may write about any aspect of your experiment in the discussion.

Most students find that the planning process does not take place smoothly. You may have to go through all five steps several times, before you have a plan that you feel confident will be successful.

Focus Question

Write the question in your own words.

THEORY THINKING

1. Concepts and Theories

4. Discussion

ACTION/METHOD

2. Events and Objects

3. Records and Transformations

MODEL BUILDING

ACTION/METHOD

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Questions & Quizzes

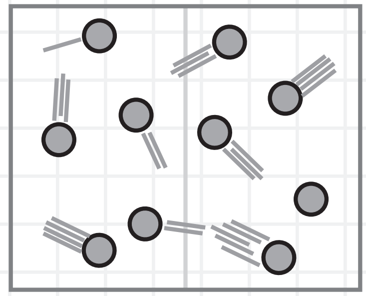
1. From the representations of the particles and the container in the diagram, determine:

V (L) ________

T (K) ________

n (mols) _______

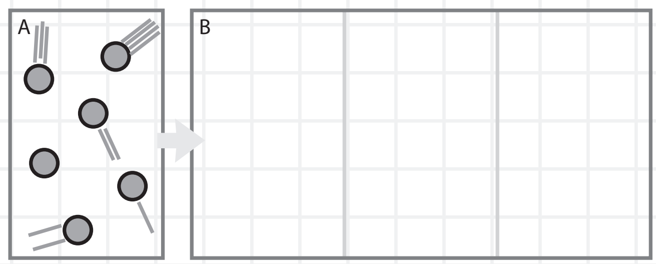
P (kPa) _______



2. The gas pressure in box A is 100 kPa. Box A is allowed to expand to the volume shown in box B.

Draw the particles in box B.

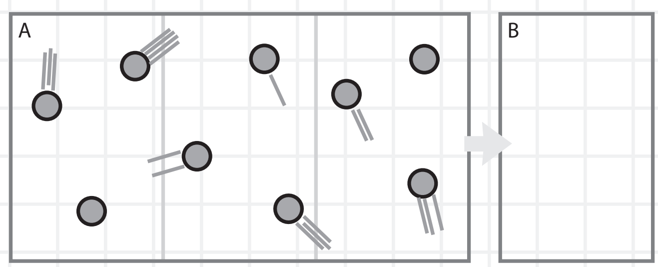
What is the new pressure in box B, if *T* is the same?



3. From the diagram, determine volume *V*, amount *n*, and temperature *T* in box A.

What is the pressure in box A?

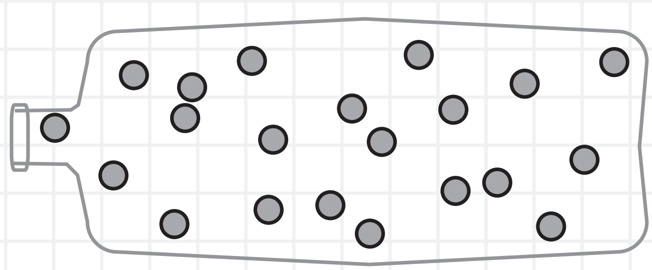
If box A is compressed into box B at constant temperature, what is the new pressure in box B?



4. A student attaches a bicycle pump to an empty 2.0 L plastic pop bottle. After the student pumped for a minute, the bottle was at 300 K as shown.

Add "energy bars" to the particles to correctly represent the average kinetic energy.

Calculate the pressure in the bottle.



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Questions & Quizzes

5. A balloon contains 5.0 L of helium at 115 kPa and 15°C. How many mols of He are in the balloon?

6. Carbon monoxide is deadly. As little as 0.020 mols of CO per cubic metre of air will cause death in one hour. How many litres of carbon monoxide is 0.020 mols, at STP?

7. Hydrogen peroxide decomposes as: $2\ H_2O_2 \rightarrow O_2 + 2\ H_2O$

How many litres of oxygen gas would form at STP, if 3.4 g of hydrogen peroxide decomposed?

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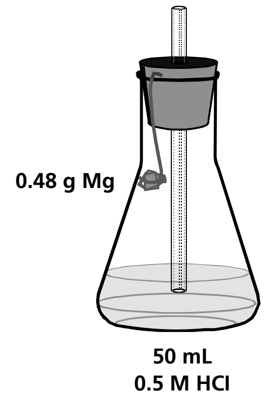
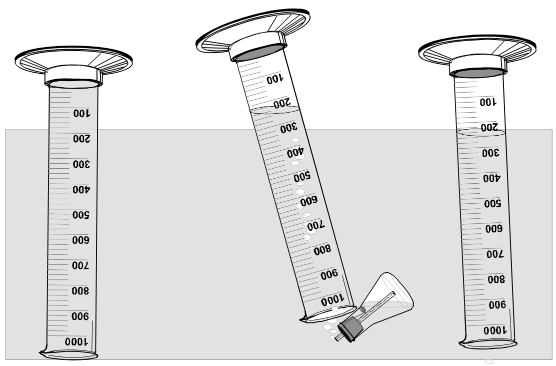
13.3 Gases and Chemical Reactions

13.3.A Reactions that produce gases



A teacher prepared a stopper and tube as shown, fitted to a 100 mL flask containing 50 mL of 0.50 M HCl. She measured 0.48 g Mg metal, and secured it in a copper wire as shown, so the Mg was above the liquid where no reaction could occur.

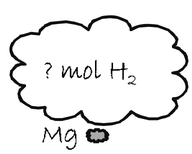
She then filled a 1000 mL graduated cylinder to overflowing with water, sealed the top with the palm of her hand, and inverted it into a large tub of water so that the cylinder contained no air bubbles.



When she inverted the flask under the cylinder, she collected the H_2 produced as the Mg reacted with the HCl. Finally, she equalized the water levels, and then measured the volume of H_2 at 20°C and 100 kPa.

SAMPLE PROBLEM

Predict the volume of hydrogen gas, H_2, produced by the reaction. described above. You will need to: **(a)** work out the chemical reaction calculations using stoichiometry, and **(b)** use the gas law calculations.

Solution	
1. Rewrite question **2.** Underline relevant parts	What volume of hydrogen gas would be produced when 0.48 g of Mg react with excess HCl?
3. Draw diagram **4.** Convert units	 $T = 20°C = 293\ K$ $P = 100\ kPa$ $m_{Mg} = 0.48\ g$
5. Write equation **6.** Rearrange equation	$\frac{0.48\ g}{24.3\ g}\ Mg + 2\ HCl \longrightarrow \frac{?\ mol}{1\ mol}\ H_2 + MgCl_2$

	(Calculating mols)	(Calculating volume)
7. Substitute into equation **8.** Solve equation	$\frac{Mols\ H_2}{(0.48\ g\ Mg)} = \frac{(1\ mol\ H_2)}{(24.3\ g\ Mg)}$ $Mols\ H_2 = \frac{(1\ mol\ H_2)(0.48)}{(24.3)}$	$PV = nRT$ $V = \frac{nRT}{P}$ $= \frac{(0.0198\ mol\ H_2)(8.31\ \frac{L\cdot kPa}{mol\cdot K})(293\ K)}{(100\ kPa)}$
9. Round off answer	$Mols\ H_2 = (0.0198\ mol\ H_2)$	$V = (0.4812\ L\ H_2)$
10. Write a sentence	The reaction will produce 0.00988 mols, or ($0.48\ L\ H_2$)	

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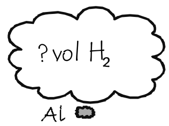
PRACTICE PROBLEMS

1.

① Rewrite question	The teacher repeated the procedure in the sample problem but used 0.54 g of Al foil, and 50 mL of 5.0 M HCl. What volume of H_2 was produced?	
② Underline relevant parts		
③ Draw diagram	T =	
④ Convert units	P = m_{Al} =	
⑤ Write equation	$2\,Al + 3\,HCl \longrightarrow 3\,H_2 + 2\,AlCl_3$	
⑥ Rearrange equation		
⑦ Substitute into equation	______ = ______	
⑧ Solve equation	= ______	
⑨ Round off answer	=	
⑩ Write a sentence		

2.

① Rewrite question	When solid ammonium carbonate is heated, it decompos If 0.50 g of $(NH_4)_2CO_3$ was placed in an empty 2.0 L cylinder, and decomposed at 500 °C, what pressure woul develop?	
② Underline relevant parts		
③ Draw diagram		
④ Convert units	T =	
⑤ Write equation	$(NH_4)_2CO_{3(s)} \longrightarrow 2\,NH_{3(g)} + H_2O_{(g)} + CO_{2(g)}$	
⑥ Rearrange equation		
⑦ Substitute into equation	______ = ______	$PV = nRT$
⑧ Solve equation	=	
⑨ Round off answer	=	
⑩ Write a sentence		

Check Your Understanding

1. A student puts 100 mL of vinegar into a 1.0 L champagne bottle. He then adds 10.0 g of baking soda, $NaHCO_3$, and corks the bottle. What pressure would develop at 18°C ?
2. Wine makers use yeast to turn sugar, $C_6H_{12}O_6$ into two moles each of ethanol C_2H_5OH and CO_2. What volume of carbon dioxide would be produced from 1.5 kg of sugar at 16ºC and 98.0 kPa?

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13.3.B Reactions that Consume Gases

In photosynthesis, green plants use light energy to turn $CO_{2(g)}$ and $H_2O_{(l)}$ into glucose $C_6H_{12}O_{6(s)}$, and $O_{2(g)}$. In cellular respiration, many living organisms use enzymes to reverse the reaction, releasing the energy that is needed for life.

A tree is a large photosynthesis reactor that changes carbon dioxide gas into cellulose, the stuff of plant fibres. Cellulose, like starch, is made of long chains of sugar molecules. Trees are made of sugar molecules! We can use the chemical formula for sugar, $C_6H_{12}O_6$, to represent the chemical formula of most sugars, starches, and cellulose.

Fortunately for us, there are very few organisms on Earth that are capable of taking cellulose apart into sugar. Wood is only broken down by fungi, and a few kinds of bacteria. The sugar molecules in starch, however, can be easily detached from each other. If trees were made of starch, even you and I could eat them!

SAMPLE PROBLEM

Consider a maple tree, recently cut down in Toronto, with a total mass of dry wood of 6.00 tonnes. What volume of carbon dioxide would that tree have fixed into cellulose over its eighty-year life span? Assume the average T in Toronto is 7°C, and the *P* is 102 kPa. Assume the mass of the tree is pure cellulose.

Solution		
1. Rewrite question **2.** Underline relevant parts **3.** Draw diagram **4.** Convert units	What volume of CO_2 would have to react in order to make 6.00 tonnes of cellulose? Assume average temperature T = 7°C and barometric pressure P = 102 kPa. ? vol CO_2 T = 7°C = 280 K m = 6.00 T = 6.00 Mg P = 102 kPa	
5. Write equation **6.** Rearrange equation	? mol / 6 mol: $6\,CO_2 + 6\,H_2O \longrightarrow C_6H_{12}O_6 + 6\,O_2$ (6.00×10^6 g / 180 g for $C_6H_{12}O_6$)	
	(Calculating mols)	**(Calculating volume)**
7. Substitute into equation **8.** Solve equation	$\frac{\text{mols } CO_2}{(6.00 \times 10^6 \text{ g } C_6H_{12}O_6)} = \frac{(6 \text{ mol } CO_2)}{(180 \text{ g } C_6H_{12}O_6)}$ $\text{mols } CO_2 = \frac{(6 \text{ mol } CO_2)(6.00 \times 10^6)}{(180)}$	$PV = nRT$ $V = \frac{nRT}{P}$ $= \frac{(2.00 \times 10^5 \text{ mol } CO_2)(8.31 \frac{L \bullet kPa}{mol \bullet K})(280 \text{ K})}{(102 \text{ kPa})}$
9. Round off answer	mols CO_2 = $(2.00 \times 10^5$ mol $CO_2)$	$V = 4.5645 \times 10^6$ L CO_2
10. Write a sentence	To make a 6.00 T tree requires 4.56 million litres of CO_2	

One million litres is equivalent to a cube, 10 m × 10 m × 10 m. Are you surprised at this volume of carbon dioxide? Write a sentence or two to say why.

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PRACTICE PROBLEMS

1.

<table>
<tr><td>1 Rewrite question</td><td rowspan="4">An empty 5.00 L steel can contains a few mL of water at 21°C and 112 kPa. The rest is air, 20% oxygen. What mass of rust could form inside the can?

[20% of 5.00 L is 1.00 L of O_2]

T = 21°C
=
V =
P = 112 kPa</td></tr>
<tr><td>2 Underline relevant parts</td></tr>
<tr><td>3 Draw diagram</td></tr>
<tr><td>4 Convert units</td></tr>
<tr><td>5 Write equation</td><td rowspan="2">$$\underset{}{4\,Fe} + 4\,H_2O + \overset{1.00\,L}{3\,O_2} \longrightarrow \overset{?\,g}{2\,Fe_2O_3{\bullet}2\,H_2O}$$</td></tr>
<tr><td>6 Rearrange equation</td></tr>
<tr><td>7 Substitute into equation</td><td rowspan="3">$PV = nRT$

$n = \frac{PV}{RT}$</td><td rowspan="3">____ = ______
= ______
=</td></tr>
<tr><td>8 Solve equation</td></tr>
<tr><td>9 Round off answer</td></tr>
<tr><td>10 Write a sentence</td><td colspan="2"></td></tr>
</table>

2.

<table>
<tr><td>1 Rewrite question</td><td rowspan="4">One molecule of carbon monoxide gas can poison one Fe^{2+} ion. Jackie has about 5.9 mg of iron in her blood. What volume of CO gas would poison all of that iron? 15°C and 100 kPa.

T =</td></tr>
<tr><td>2 Underline relevant parts</td></tr>
<tr><td>3 Draw diagram</td></tr>
<tr><td>4 Convert units</td></tr>
<tr><td>5 Write equation</td><td rowspan="2">$CO + Fe^{2+} \longrightarrow CO : Fe^{2+}$ complex (Poisoned)</td></tr>
<tr><td>6 Rearrange equation</td></tr>
<tr><td>7 Substitute into equation</td><td rowspan="3"></td><td rowspan="3"></td></tr>
<tr><td>8 Solve equation</td></tr>
<tr><td>9 Round off answer</td></tr>
<tr><td>10 Write a sentence</td><td colspan="2"></td></tr>
</table>

Check Your Understanding

1. Anhydrous copper (II) sulphate, $CuSO_4$, slowly absorbs water vapour from the air to form $CuSO_4{\bullet}5H_2O$. What volume of water vapour would be absorbed by 5.00 g of $CuSO_4$?
2. When leaves compost, the reaction is the opposite of photosynthesis. What volume of oxygen gas would react as 1.00 tonne of dry leaves slowly rot into CO_2 and H_2O? Assume 12°C and 101 kPa.

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13.3.C Reactions Between Gases

Many important chemical reactions occur between gases. For example, natural gas that we use to heat our homes (methane, CH_4) is a gas; oxygen is a gas; the products carbon dioxide and water are all gases at combustion temperatures.

Natural gas is sold by the cubic metre, at a price that varies between 25 cents and 50 cents per cubic metre. The volume of gas is measured as it passes through the gas meter outside your house. Gas companies use gas law calculations to adjust all metered readings to STP, in order to compensate for changes in temperature and pressure. One cubic metre is 1000 L.

SAMPLE PROBLEM

In one evening you burn one cubic metre of natural gas, measured at 101 kPa and 17°C. That's enough for three showers, the dishes, and one load of laundry. What mass of carbon dioxide gas does that produce? You must calculate the number of moles of methane before inserting it into the balanced chemical equation.

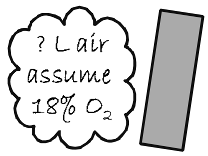
	Solution
1. Rewrite question **2.** Underline relevant parts	What mass of CO2 is produced by burning 1.00 m³ of CH_4, measured at 17°C and 101 kPa?
3. Draw diagram **4.** Convert units	(1.00 m³ CH_4) → (? g CO_2) T = 17°C = 290 K V = 1.00 m³ = 1000 L P = 101 kPa
5. Write equation **6.** Rearrange equation	$\underset{1\ \text{mol}}{\overset{41.890\ \text{mols}}{CH_4}} + 2\,O_2 \rightarrow \underset{44.0\ \text{g}}{\overset{?\ \text{g}}{CO_2}} + 2\,H_2O$

	(Calculating mols)	(Calculating volume)
7. Substitute into equation **8.** Solve equation	$PV = nRT$ $n = \frac{PV}{RT}$ $= \frac{(101\ \text{kPa})(1000\ \text{L}\ CH_4)}{(8.31\frac{\text{L•kPa}}{\text{mol•K}})(290\ \text{K})}$	$\frac{\text{mass } CO_2}{(41.890\ \text{mols } CH_4)} = \frac{(44.0\ \text{g } CO_2)}{(1\ \text{mol } CH_4)}$ $\text{mass } CO_2 = \frac{(41.890)(44.0\ \text{g } CO_2)}{(1)}$
9. Round off answer	= 41.890 mols CH_4	= 1843 g CO_2) = 1.8 kg of CO_2
10. Write a sentence	Burning one cubic metre of natural gas will produce 1.8 kg of CO_2.	

In the next page, you will work with other fuels under different sets of conditions.

PRACTICE PROBLEMS

1.

① Rewrite question	A small utility cylinder of propane contains 400 g of C What volume of air at STP is needed to support complete combustion of the C_3H_8?	
② Underline relevant parts		
③ Draw diagram	 T = 0°C = P = m =	
④ Convert units		
⑤ Write equation	$C_3H_{8(g)} + 5\ O_{2(g)} \rightarrow 4\ H_2O_{(g)} + 3\ CO_{2(g)}$	
⑥ Rearrange equation		
⑦ Substitute into equation	——— = ———	$PV = nRT$
⑧ Solve equation	=	
⑨ Round off answer	=	
⑩ Write a sentence		

2.

① Rewrite question	If you block the air flow in a gas stove, H_2CO formaldehyde will form. Only 0.80 g of H_2CO in a typical kitchen is toxic. What volume of CH_4 at STP would produce 0.80 g of H_2CO?	
② Underline relevant parts		
③ Draw diagram		
④ Convert units		
⑤ Write equation	$CH4 + O_2 \rightarrow H_2CO + H_2O$	
⑥ Rearrange equation		
⑦ Substitute into equation		
⑧ Solve equation		
⑨ Round off answer		
⑩ Write a sentence		

Check Your Understanding

1. Ammonia, $NH_{3(g)}$ is manufactured by reacting $H_{2(g)}$ and $N_{2(g)}$ at 150 bar and 400°C . What volumes of $H_{2(g)}$ and $N_{2(g)}$ would have to combine under those conditions to make 1.00 kg of ammonia?
2. A sugar cube contains 2.0 g of $C_6H_{12}O_{6(s)}$. What volume of $O_{2(g)}$ at STP is required to completely oxidize the sugar via respiration? (Hint: respiration is the opposite of photosynthesis.)

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LAB 13.3D MOLAR VOLUME OF A GAS

Focus Question

How accurately can I measure the molar volume of hydrogen gas at STP?

CONCEPTS AND THEORIES

When a one mole of Mg reacts with excess hydrochloric acid, one mole of hydrogen is produced.

$M_{g\,(s)} + 2\,HCl_{\,(aq)} \rightarrow H_{2\,(g)} + MgCl_{2\,(aq)}$

T (°C)	P_v (kPa)
18	2.1
19	2.2
20	2.3
21	2.5
22	2.6
23	2.8
24	3.0
25	3.2
26	3.4
27	3.6
28	3.8

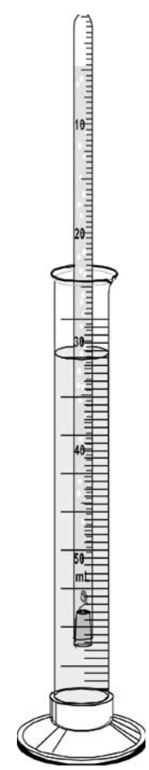
If you react a known mass of magnesium, you can predict the number of moles of hydrogen produced. How closely will your experiment agree with your prediction? What kinds of experimental errors could contribute to a discrepancy between prediction and measurement?

Here are two potential errors in the measurement of the pressure of the hydrogen gas inside the tube. Water will evaporate and contribute part of the pressure of the gas inside the tube. The partial pressure of the water vapour must be subtracted from the total pressure to measure the partial pressure of the hydrogen gas. The table at left shows the partial pressure contributed by water vapour at each temperature.

You can accurately measure atmospheric pressure in the classroom. The pressure inside the gas tube is affected by the height of the water. To minimize errors in the measurement of pressure inside the tube, raise or lower the tube in the larger graduated cylinder, so that the water levels inside and outside are the same.

EVENTS AND OBJECTS *(including safety)*

Carefully pour 10 mL of 5 M HCl into the gas measuring tube. Then pour water slowly down the side of the tube to prevent mixing, until the tube is filled to the brim.



Measure the mass of 1 cm of Mg ribbon as precisely as possible. Trap the Mg in a copper wire, and then fix the wire in place with a two-hole rubber stopper. When you invert the tube into the beaker, you will see the dense HCl solution descend, and the reaction will begin. After the reaction is finished, measure the temperature, pressure, and volume of the hydrogen gas as accurately as possible.

RECORDS AND TRANSFORMATIONS

Design a table to record all of the information that you intend to gather in the experiment. Plan all of your calculations before you do the experiment.

DISCUSSION

Interpret your findings. Did you answer the question? Was your experiment reliable? Did your experiment create errors? Would you improve any of your methods or actions? You may write about any aspect of your experiment in the discussion.

Don't worry if your planning process does not take place smoothly. You may have to go through all five steps several times to decide on a successful plan.

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Focus Question

Write the question in your own words.

1. Concepts and Theories

4. Discussion

2. Events and Objects

3. Records and Transformations

THEORY THINKING

ACTION/METHOD

MODEL BUILDING

ACTION/METHOD

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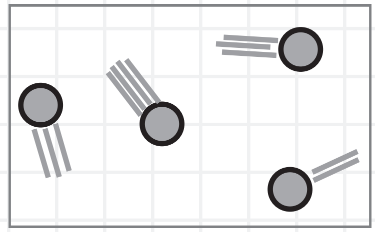
Questions & Quizzes

1. How many grams of CaC_2 are needed to produce 1.00 L of acetylene gas at 27°C and 100 kPa?

   $CaC_{2(s)} + 2\ H_2O_{(l)} \rightarrow C_2H_{2(g)} + Ca(OH)_{2(aq)}$



2. A pressure gauge was inserted through the cap of a ginger ale bottle, and measured a pressure of 150 kPa at 20°C. The bottle was shaken, and the pressure gauge then read 250 kPa. What mass of carbonic acid decomposed? The volume of gas above the liquid was 27 mL.

   $H_2CO_{3(aq)} \rightarrow CO_{2(g)} + H_2O_{(l)}$

3. A student is demonstrating how "scrubbing" technology can remove sulfur dioxide from industrial smokestacks. Adrian starts with 1.00 L of $SO_{2(g)}$ at 18°C and 96.7 kPa. What mass of powdered limestone does Adrian need to completely consume the sulfur dioxide gas?

   $SO_{2(g)} + CaCO_{3(s)} \rightarrow CaSO_{3(aq)} + CO_{2(g)}$

4. A chemist mixed 1.00 L of acetylene with 5.00 L of air at 100 kPa and 27°C. If the chemist ignited the mixture, would the reaction burn cleanly (complete combustion), or would it produce a cloud of black smoke (incomplete combustion)?

   $2\ C_2H_{2(g)} + 5\ O_{2(g)} \rightarrow 4\ CO_{2(g)} + 2\ H_2O_{(g)}$

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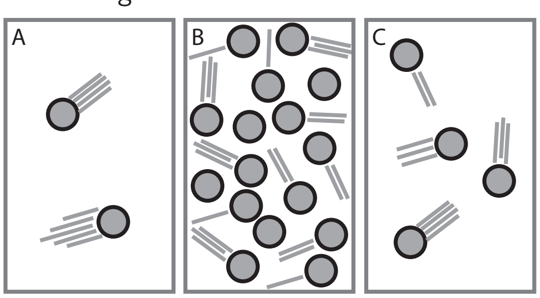
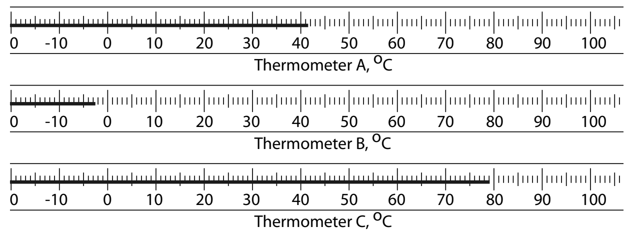
13.1 Review Questions

1. An ideal gas is a "perfect" gas that is used to model the behaviour of all real gases. List the five characteristics of an ideal gas.
2. Explain how constant motion and collisions between ideal gas molecules and with their container cause pressure and volume phenomena.
3. What effect does increasing temperature have on the motion of ideal gas molecules?
4. Butane, C_4H_{10}, is liquified in lighters, but turns to a gas when released at room temperature.
   - **(a)** What is the mass of one mole of butane?
   - **(b)** How many butane molecules are in one mole of C_4H_{10}?
   - **(c)** Approximately what volume is occupied by 44 g of butane gas at STP?
   - **(d)** What is the mass of 1 L of butane gas at 25°C and 100 kPa?
5. How many gas molecules are present in a 22.4 L sample of a mixture of gases containing nitrogen, oxygen, and hydrogen at standard temperature and pressure?
6. To two significant figures, the relative atomic mass of Ar, argon gas is 40, and that of Ne, neon, is 20. A 25 L plastic bag holds 40 g of argon gas. What volume would 20 g of neon occupy, under the same conditions?
7. Define "temperature."
8. Below are three boxes, each of which contains gas molecules as shown.



   - **(a)** Which of these boxes has the highest temperature?
   - **(b)** Which of these boxes contains the greatest amount of kinetic energy?
   - **(c)** Which of these boxes has the greatest pressure? Explain.
9. Below are three pictures of a Celsius thermometer. Read the temperature to the nearest one-tenth of one degree. Then convert each temperature to Kelvin.



10. In two or three sentences, explain the concept of "atmospheric pressure."
11. Convert each of these pressure readings into the indicated units.
    - **(a)** 72 psi to kPa
    - **(b)** 84 kPa to bar
    - **(c)** 3.6 bar to kPa
12. In a chemistry experiment, a student produced some carbon dioxide inside a sealed container. With an electronic pressure probe, she measured the pressure of carbon dioxide as 14.78 kPa. Using a barometer, she found that the atmospheric pressure in the classroom was 1.01 bar. What was the actual gas pressure exerted by the CO_2 inside the container?

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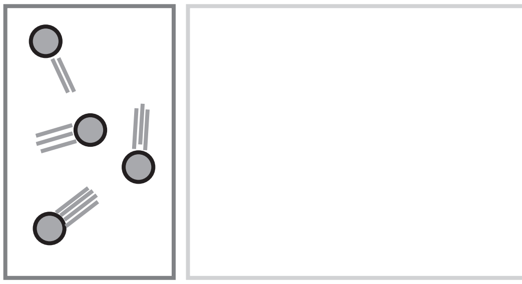
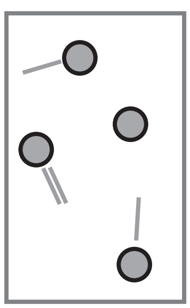
13.2 Review Questions

13. Examine the diagram below. Draw another diagram to indicate 0.12 mols of gas in a 2.0 L container at the same temperature. What is the pressure in the new container.

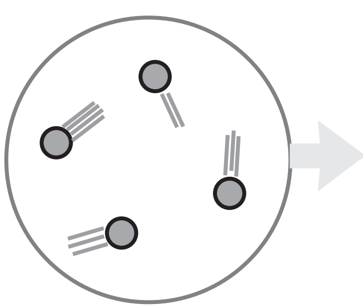


14. Draw a diagram on the grid below to show a 3.0 L container at $P = 200$ kPa. Determine how many moles of gas the container holds, and draw particles to represent those particles.

15. In the diagram below, $n = 0.04$, $T = 100$ and $P = 33$. Add four particles to the diagram, so that the pressure is increased to 100 kPa.



16. A gas bubble occupies 1.00 L at 27°C.



The bubble is heated at constant to 177°C. Calculate the new volume of the bubble, and draw a new labelled diagram.

17. An official volleyball has a volume of 4.7 L, and a pressure of 31kPa when tested with a pressure gauge at 300 K. How many mols of air molecules must be inside the ball?

18. Dalton using particle picture. The real pressure inside a bicycle tire is 400 kPa. The air is made up of 21% oxygen, 78% nitrogen, and 1% argon. What is the partial pressure of each gas?

19. Use the diagrams at right to explain why Boyle's Law describes an inverse relationship between temperature and volume.

20. When 75 mL of air is drawn into a syringe, its pressure is 105.0 kPa. What will be the pressure when the volume is decreased to 60.0 mL?

21. Combined gas law using particle picture At a certain temperature, one mole of hydrogen gas has a volume of 25.4 L and pressure of 100.00 kPa. What pressure will be required to confine this quantity of gas to 10.0 L?

22. Combined using particle picture. One mole of hydrogen at 25°C occupies a volume of 25.0 L. If the temperature of the gas is increased to 50°C at constant pressure, what volume will be occupied by the hydrogen?

23. A 0.5 mol sample of a gas is found to occupy 15.0 L at a pressure of 100.0 kPa and temperature of 20.0°C. What volume will the gas occupy if the temperature is increased to 35°C and the pressure is increased to 125.0 kPa?

24. At the same pressure, the volume of a sample of gas shrinks when it is cooled, from 10.0 L to 5.0 L. If the starting temperature was 50°C, what is the final Celsius temperature?

25. A bag is filled with 5.0 L of helium at 20.5°C and 101.5 kPa. What volume will the gas occupy if the temperature increases to 30.0°C and the pressure decreases to 98.5 kPa?

13.3 Review Questions

26. Potassium chlorate decomposes when heated.

$$2\ KClO_{3(s)} \rightarrow 3\ O_{2(g)} + 2\ KCl_{(s)}$$

What volume of oxygen would be produced if 5.0 g of potassium chlorate was decomposed at 150°C and 100 kPa?

27. Ammonium carbonate decomposes when heated to 200°C.

$$(NH_4)_2CO_{3(s)} \rightarrow 2\ NH_{3(g)} + H_2O_{(g)} + CO_{2(g)}$$

A researcher adds 6.89 g of $(NH_4)_2CO_3$ to a dry 1.5 L bottle at 98.0 kPa, and seals the bottle. Predict the pressure inside the bottle if it is placed inside an oven at 250°C.

28. When you buy hydrogen peroxide in a drug store, the concentration of $H_2O_{2(l)}$ is 3.0% by mass. A student put a sealed bottle containing 159 mL (161 g) of solution into the refrigerator at 6.0°C. Unfortunately, he had contaminated the solution, causing the peroxide to completely decompose. What pressure would be exerted by the oxygen plus original air inside the bottle, if the empty space above the liquid is 111 mL?

$$2\ H_2O_{2(l)} \rightarrow 2\ H_2O_{(l)} + O_{2(g)}$$

29. Electrolysis of water produces hydrogen and oxygen gas in separate chambers. Determine the mass of 25.0 mL of oxygen collected at 22.0°C and 101.3 kPa.

30. How much magnesium metal must react with hydrochloric acid to produce 1.0 L of hydrogen gas at 21.5°C and 101.3 kPa?

31. During photosynthesis, oxygen is produced by green plants according to the chemical equation below. What volume of oxygen(20°C and 101.3 kPa) is released by a green plant as it produces 12.0 g of glucose ($C_6H_{12}O_6$)?

32. A driver-side airbag contains about 180 g of sodium azide, NaN3, which decomposes explosively to produce hot nitrogen gas.

$$2\ NaN_{3\ (s)} \rightarrow 2\ Na + 3\ N_{2\ (g)}.$$

Calculate the pressure inside an expanding airbag if the volume is 30 L and gas temperature is 220°C?

13.4 Putting It All Together

33. Working at 98 kPa, a student puts 5.0 g of baking soda, $NaHCO_{3\ (s)}$, into a small plastic bag and folds it closed. He inserts it into a 750 mL champagne bottle that contains an excess of vinegar, firmly stoppers the bottle, and then shakes it to mix the vinegar and baking soda.

$$NaHCO_{3\ (s)} + HC_2H_3O_{2\ (aq)} \rightarrow CO_{2\ (g)} + H_2O_{(l)} + NaC_2H_3O_{2\ (aq)}$$

If all of the baking soda reacts, what will be the total pressure inside the bottle at 15°C?

34. Calcium carbide reacts with water to produce acetylene gas.

$$CaC_{2\ (s)} + H_2O_{(l)} \rightarrow H_2C_{2\ (g)} + Ca(OH)_{2\ (s)}$$

A chemist in a quality control lab is testing the purity of calcium carbide. She measures 9.37 g of grey solid from a tin labeled “calcium carbide”, and reacts it with water to collect 935 mL of acetylene gas at 99.5 kPa and 17.0°C. What percentage of her original grey solid was calcium carbide?

35. The chemical reaction for the complete combustion of gasoline is presented below.

$$2\ C_8H_{18\ (l)} + 25\ O_{2\ (g)} \rightarrow 16\ CO_{2\ (g)} + 18\ H_2O_{\ (g)}$$

What volume of gasoline, C_8H_{18} (density = 0.70 g/mL) must be burned in air, assuming complete combustion, to produce 2.0 L (the size of a soft drink bottle) of carbon dioxide at 25°C and 101.3 kPa?

34. When hydrogen peroxide decomposes, oxygen and water are produced.

$$2\ H_2O_{2\ (aq)} \rightarrow O_{2\ (g)} + H_2O_{\ (l)}$$

The resulting gas is a mixture of oxygen and water vapour. A 43.8 mL sample of O_2 gas is collected at 20°C and 101.5 kPa. The partial pressure of water vapour is 2.0 kPa. What mass of hydrogen peroxide decomposed?

35. Ammonia gas is very soluble in water. A volume of 1.02 L of dry ammonia gas at 27°C and 100 kPa is passed over 25.00 mL of water, and 100% of the ammonia dissolves in the water. What is the concentration of $NH_{3\ (aq)}$ in the water?

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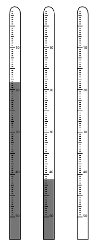
36. A teacher puts 18.44 mL of $O_{2\,(g)}$ into a glass measuring tube at 21.0°C and 98.6 kPa. The teacher then adds hydrogen gas, $H_{2\,(g)}$, so that the total volume of mixed gases is 41.29 mL. The teacher then ignites the mixture of gases with a spark. Assuming that the limiting reagent is completely consumed, which gas is left over? What volume of gas remains after everything returns to its initial conditions?



37. The complete combustion of gasoline in air follows the equation:

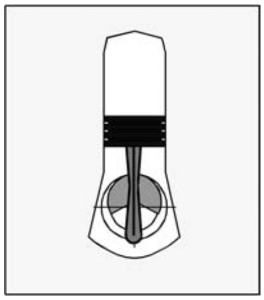
$$2\ C_8H_{18\,(l)} + 25\ O_{2\,(g)} \rightarrow 16\ CO_{2\,(g)} + 18\ H_2O_{\,(g)}$$

Air is a mixture of gases, containing 21% oxygen. What is the maximum mass of gasoline, $C_8H_{18\,(l)}$, that could be burned in exactly 1.00 L of air, at 100 kPa and 20°C?

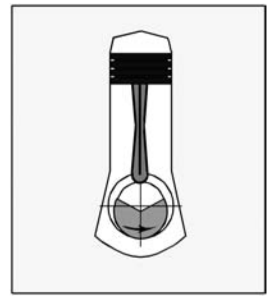
Questions 38–40 concern the workings of one cylinder in a 4-cylinder 2.4 L automobile engine. When the piston is at the lowest point, each cylinder has a capacity of 0.667 L. When the piston is at the highest point, the volume of trapped gas is 0.067 L. The difference in volumes, 0.60 L, is the displacement of each cylinder; the total displacement of the motor is 2.4 L. The compression ratio is the ratio of the largest capacity to the smallest volume; in this case, the compression ratio is 10:1.

38. Each cylinder of a 3.8 L 4-cylinder has a total capacity of 0.667 L.

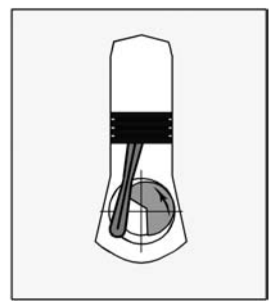
What mass of gasoline, $C_8H_{18\,(l)}$, could be burned in the oxygen this cylinder contains? (Hint: see your answer to (37) above.)



39. When the piston is at the top, it has compressed the 0.024 mols of air to 0.067 L. Compressing the gas has heated it to 205°C. What is the new pressure in the cylinder?



40. When the gasoline burns, the combustion products increases the amount of gas molecules to 0.026 mols. The temperature increases to 780°C, and the piston has slid downward so that the volume is 0.122 L. What is the new pressure?



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