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NEW JERSEY CENTER
FOR TEACHING & LEARNING

# Gases

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## The Kinetic Molecular Theory


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## The Kinetic-Molecular Theory

This revolutionary theory was developed by Ludwig Boltzmann in the late 1800's. It was based on the idea that matter is made up of atoms and molecules too small to be seen... ideas that were rejected by most scientists until the early 1900's...only a 100 years ago.

This theory connects the microscopic world of atoms and molecules with the macroscopic world around us and helps us greatly understand the behavior of gases.

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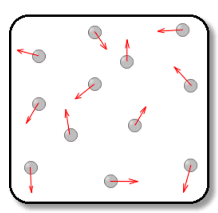
## Kinetic Molecular Theory

In order to understand the behavior of gases, we work with some key premises.



PREMISE 1
Gas molecules are in constant motion and therefore possess kinetic energy. The faster the speed, the higher the kinetic energy.

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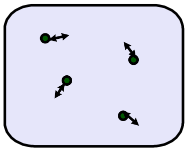
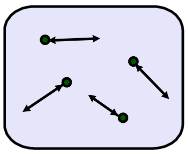
## Kinetic Molecular Theory



Low Temperature



PREMISE 2

The average kinetic energy of a sample of a gas is proportional to the temperature.

The higher the temperature, the higher the average kinetic energy.

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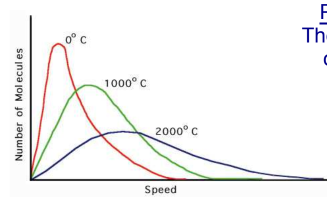
## Kinetic Molecular Theory




PREMISE 2 (continued)

The *average* kinetic energy of a sample of a gas is proportional to the temperature.

*Notice that at any given temperature, there is a wide range of speeds yet the average speed is clearly greater at the higher temperatures.*

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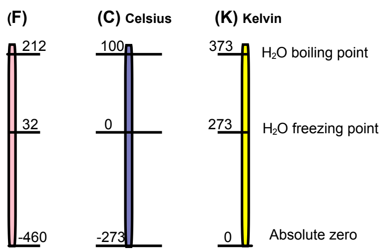
## Temperature

There are 3 scales used for measuring temperature.




**Absolute zero is the lowest theoretical temperature.*

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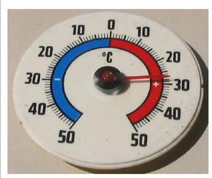
## Temperature



It is important that we can convert between the two scientific units used to measure temperature (K and C)

C + 273 = K or K - 273 = C

So... a temperature of 16 C = 289 K

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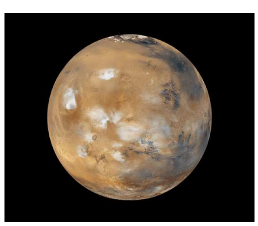
1 **At the equator of Mars, the temperature can be quite balmly during the summer, reaching about 70 Fahrenheit or 20 Celsius. What would this be in Kelvin?**

- A 253 K
- B -253 K
- C 293 K
- D -293 K
- E 32 K



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1 **At the equator of Mars, the temperature can be quite balmly during the summer, reaching about 70 Fahrenheit Kelvin?**

- A 253
- B -253
- C 293
- D -293
- E 32 K

Answer

C

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2 **Standard temperature is considered 273 K. What is this temperature in Celsius?**

- A 273 C
- B 0 C
- C -273 C
- D 32 C
- E 546 C

Slide 12 (Answer) / 140

2 **Standard temperature is considered 273 K. What is this temperature in Celsius?**

- A 273 C
- B 0 C
- C -273 C
- D 32 C
- E 546 C

Answer

B

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3 **Water freezes at about 0 degrees Celsius. At what absolute temperature does water freeze?**

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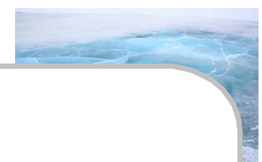
3 **Water freezes at about 0 degrees Celsius. At what absolute temperature does water freeze?**



Answer

273 K

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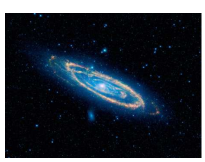
4 **The average temperature of the universe is thought to be roughly -270.5 Celsius. What is that temperature in Kelvin?**



Slide 14 (Answer) / 140

4 **The average temperature of the universe is thought to be roughly -270.5 Celsius. What is that temperature in Kelvin?**

Answer

2.5 K

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**5** **Room temperature is about 20 degrees Celsius. What temperature is that in Kelvin?**

Slide 15 (Answer) / 140

**5** **Room temperature is about 20 degrees Celsius. What temperature is that in Kelvin?**

**Answer**

293 K

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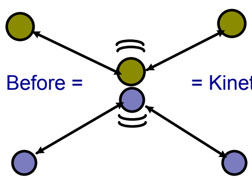
## Kinetic Molecular Theory

Kinetic Energy Before =



= Kinetic Energy After

PREMISE 3
Collisions between gas molecules are perfectly elastic, meaning that there is not net loss in kinetic energy over the course of the collision.

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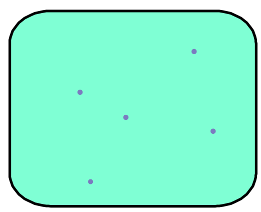
## Kinetic Molecular Theory



PREMISE 4
Because of their extremely low density, we assume that the gas molecules occupy a negligible amount of space in a container. Therefore the volume of the container is essentially the volume occupied by the gas.

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## Kinetic Molecular Theory

| Premise | Summary Statement |
|---|---|
| 1 | Gas molecules are in constant motion and therefore possess kinetic energy |
| 2 | Average kinetic energy of gases is proportional to the temperature |
| 3 | Collisions between gas molecules are elastic |
| 4 | Gases occupy a negligible amount of space in the container |

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# Properties of Gases

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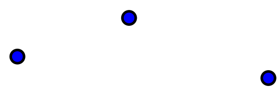
## Characteristics of Gases

The gaseous state is characterized by extremely weak interactions between the atoms, ions, and molecules.



Gases (essentially no bonds)

Solids (strong bonds) Liquids (weak bonds)

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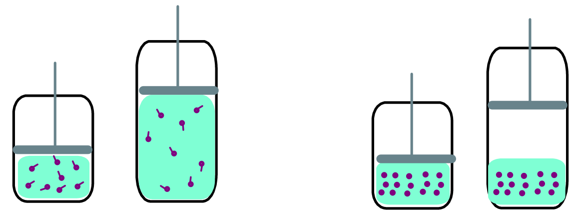
## Characteristics of Gases

Since there are very few attractions between gas molecules....

Gas molecules are free to move and will expand to fill their containers



gas molecules

same group of gas molecules

liquid molecules

same group of liquid molecules

*liquids do not expand to fit their containers.*

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## Characteristics of Gases

Since there are very few attractions between gas molecules....

A small number of molecules can occupy a large volume resulting in very low densities

| Physical State of Water | Density (g/mL) |
|---|---|
| Ice | 0.91 g/mL |
| Liquid | 0.98 g/mL |
| Vapor (gas) | 0.00052 g/mL |

*Note the gas is over 1800 times less dense than the liquid!*

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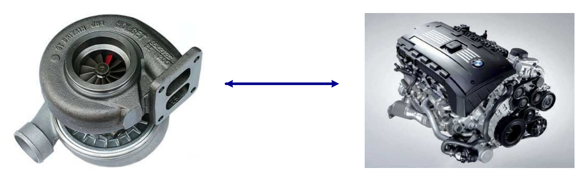
## Characteristics of Gases

Since gases have such low densities, meaning very few molecules in a very large space, they can be compressed into a much smaller volume!



A turbocharger compresses the air before it enters the car or jet engine.

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**6 Which of the following would NOT describe the gaseous state of matter?**

- ○ A High compressibility
- ○ B Strong intermolecular attractions
- ○ C Low Density
- ○ D Will expand to fill container
- ○ E Particles are in motion

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**6 Which of the following would NOT describe the gaseous state**

- ○ A High co
- ○ B Strong i
- ○ C Low De
- ○ D Will exp
- ○ E Particle

Answer

B

7 **Which of the following would be TRUE regarding the gaseous state?**

- A Gases are slightly less dense than the liquid state
- B Gases have attractive forces similar to that of the other states
- C The volume of a gas can change far more than that of a solid or liquid
- D Gas molecules weigh less than molecules in the liquid or solid state
- E None of these are true



7 **Which of the the gaseous**

- A Gases are s
- B Gases have
- C The volume or liquid
- D Gas molecu state
- E None of these

Answer

C



8 **Which of the following is NOT true of gases?**

- A Gas molecules are in motion
- B At a given temperature, all of the gas molecules are moving at the same speed
- C Gas molecules take up very little space in a container
- D The higher the temperature, the higher the average kinetic energy of the gas molecules
- E The kinetic energy of a gas molecule before and after a collision is the same



8 **Which of the following is NOT true of gases?**

- A Gas mole
- B At a give moving a
- C Gas mol contai
- D The hig kinetic e
- E The kin after a c

Answer

B



# Measuring Pressure

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## Measuring Gases

In order to understand gases, we measure four variables

| | |
|---|---|
| Pressure | Temperature |
| Volume | Number of moles |

We will focus first in describing how we measure pressure and temperature before discussing the relationships between these four variables

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## Pressure

A key characteristic of gases is their pressure; how much force they exert on their container.

Pressure is the amount of force applied per unit area.

The magnitude of pressure is given by:

$$\textbf{Pressure} = \frac{\textbf{Force}}{\textbf{Area}}$$

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## Pressure

The SI units of pressure can be found from this formula:

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

Since Force is measured in Newtons and Area is measured in square meters ($m^2$);

the SI units of Pressure are Newtons/meter$^2$ ($N/m^2$)

1 $N/m^2$ is also called a Pascal (Pa)

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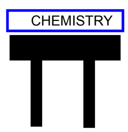
## Pressure and Forces

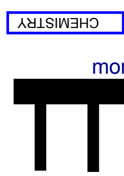
The same force can result in very different pressures.

If a book is placed on a table in a flat position, its weight exerts a pressure over a greater area than if it is placed on its edge.

So a book on its side exerts less pressure than a book on its edge.




less pressure



more pressure

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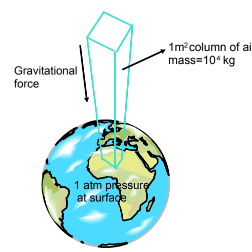
## Atmospheric Pressure

Atmospheric pressure is the weight of air per unit area.

A 1.0 m column of air extending to outer space has a weight of about 101,000 N, or 101 kN.

As a result, it exerts a pressure of about 101,000 Pa, or 101 kPa.

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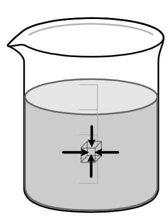
## Pressure

The pressure exerted by any fluid, including gases, is always perpendicular to any surface. As there is no direction associated with pressure, it is a scalar quantity.

If you change the orientation of the element applying the force, the pressure will stay the same.



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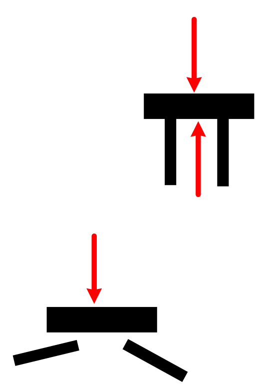
## Atmospheric Pressure

*A force of 300,000 Newtons is equivalent to about 13,000 pounds. Why doesn't the table collapse?*

Move to see answer

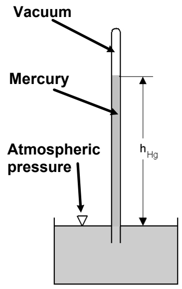


## The Barometer

The barometer is a device for measuring atmospheric pressure at a particular time and place.

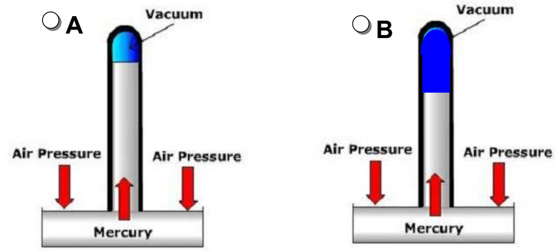
A tube filled with mercury is turned upside down in a container of mercury.

The mercury falls until the net force on it is zero.






**9 Which barometer indicates higher air pressure?**






**9 Which barom...?**


Answer

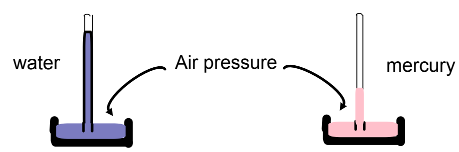
A



## The Barometer

Any substance could be used to build a barometer. But the greater the density of the liquid (D) the smaller the height required.

| Substance | Density (g/mL) | Height of column |
|---|---|---|
| water | 0.99 | 9100 mm Hg (30 ft) |
| mercury | 5.4 | 760 mm Hg (2.5 ft) |





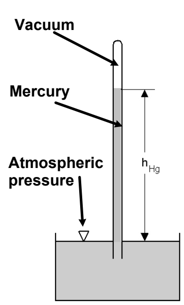

## The Barometer

As weather systems move through, the mercury rises and falls as the local atmospheric pressure changes.

However, standard atmospheric pressure of 1 atm or 101 kPa supports a column of Hg which is 760 mm tall.

So another unit of pressure is mm of Hg (also called a torr).

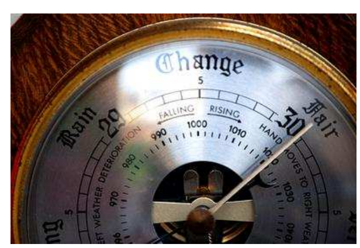
1 atm = 760 mm Hg = 760 torr






## The Barometer and Changing Weather

Click here for a video on how barometers work.



## The Barometer in Aviation

Aircraft altimeters measures the altitude of the aircraft. As the air pressure will be decreased at altitudes above sea level, the actual reading of the instrument will be dependent upon its location.

This pressure is then converted to an equivalent sea-level pressure for purposes of reporting and adjusting altitude.

Since aircraft may fly between regions of varying normalized atmospheric pressure (due to the presence of weather systems), pilots are constantly getting updates on the barometer as they fly.



## Standard Pressure

Normal atmospheric pressure at sea level is referred to as standard pressure.

It is equal to all of the values below....

1.00 atm = 1.01 bar = 760 mm Hg = 760 torr = 101 kPa



## Units of Pressure: Question

The storm pressure of superstorm Sandy was recorded as 940 millibars or 0.940 bars.
Convert this to the unit atm, mm Hg, and torr.

move for answer



**10 An average tornado has a pressure of around 639 torr. Which of the following would be equivalent?**

- A 639 atm
- B 760 mm Hg
- C 0.84 atm
- D 0.84 mm Hg
- E 101 KPa



**10 An average tornado has a pressure of around 639 torr. Which of the following would be equivalent?**

- A 639 atm
- B 760 mm
- C 0.84 a
- D 0.84 m
- E 101 KP

Answer

C



**11 What is the pressure and temperature (in K) at standard conditions (STP)?**

- A 1 atm, 273 K
- B 273 atm, 1 K
- C 1 mm Hg, 298 K
- D 1.01 bar, 298 K
- E 1 atm, 0 K

Slide 44 (Answer) / 140

11 **What is the pressure and temperature (in K) at standard con**

- A 1 atm, 2
- B 273 atm
- C 1 mm
- D 1.01 Pa
- E 1 atm, 0

Answer

A

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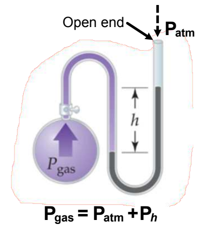
## Manometer




This device is used to measure the difference in pressure between atmospheric pressure and that of a gas in a vessel.

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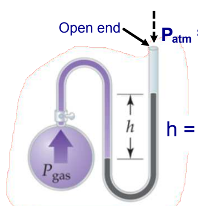
## Manometer

What would be the pressure of the gas in the container?




move for answer

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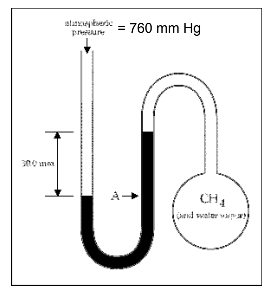
12 **What is the pressure of the methane and water vapor gas mixture in the manometer pictured?**

- A 30 mm Hg
- B 760 mm Hg
- C 730 mm Hg
- D 790 mm Hg
- E 700 mm Hg

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12 **What is the pressure of the methane and water vapor gas mixture in**

- A 30 mm
- B 760 mm
- C 730 mm
- D 790 mm
- E 700 mm

Answer

C

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# Gas Laws

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## The Gas Laws

We will now look at the relationships between the four variables of a gas

| | |
|---|---|
| Pressure | Temperature |
| Volume | Number of moles |

In order to study the effect of one variable on another, we must keep the others variables constant.



## The Gas Laws

Four laws were eventually combined to create the Ideal Gas Law. These four laws show the relationship between the four variables under different conditions.

**Boyle's Law**

**Charles's Law**

**Avogadro's Law**

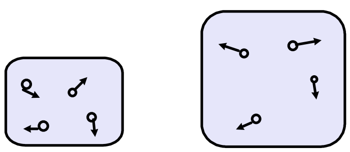
**Gay Lussac's Law**



## Pressure and Volume

If the volume of a container is increased at a constant temperature, a fixed quantity of gas molecules will collide less often with the container resulting in a proportional drop in pressure.

This is an inverse relationship. $P \propto \frac{1}{V}$ $V \propto \frac{1}{P}$

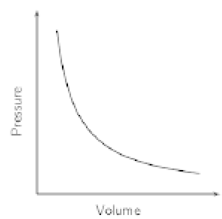


| | |
|---|---|
| V = 2 L | V = 4 L |
| P = 32 mm Hg | P = 16 mm Hg |
| more collisions | fewer collisions |



## Pressure and Volume

The inverse relationship between pressure and volume is known as Boyle's Law.




Plot of Pressure vs. Volume



Sorry, this element requires Flash, which is not currently supported in PDFs.

Please refer to the original Notebook file.

*Credit goes to Professor Tom Greenbowe chemical education research group at Iowa State University*



**13 If the volume of a gas is decreased, the pressure will also decrease.**

- ○ True
- ○ False

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**13 If the volume of a gas is decreased, the pressure will also dec**

- True
- False

Answer

False

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## Application

In order for air to enter the lungs, the pressure inside the lungs must be less than the pressure outside. Try to explain how this happens.

move for answer

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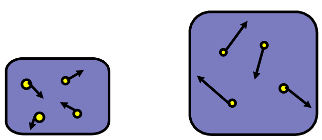
## Volume and Temperature

A fixed quantity of a gas under constant pressure will occupy more space as the temperature is increased. The change in volume is directly proportional to the change in the Kelvin temperature.



V = 2 L     V = 4 L

T = 200 K     T = 400 K

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**14 If the temperature of a gas increases, the volume will also increase.**

- True
- False

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**14 If the temperature of a gas increases, the volume will also incre**

- True
- False

Answer

True

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15 Which of the following correctly expresses the relationship between temperature and volume (Charle's Law)?

A $T \propto \frac{1}{V}$

B $T \propto V$

Slide 59 (Answer) / 140

15 Which of the following correctly expresses the relationship between temperature and volume (Charle's Law)?

A $T \propto \frac{1}{V}$

B $T \propto V$

Answer

B

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Sorry, this element requires Flash, which is not currently supported in PDFs.

Please refer to the original Notebook file.

*Credit goes to Professor Tom Greenbowe chemical education research group at Iowa State University*

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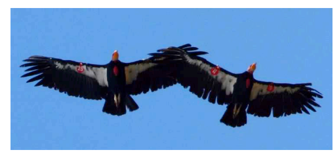
## Application

Soaring birds like the California Condor rely on hot air rising in order to stay airborne for long periods of time without using much energy. Can you explain why hot air rises using Charles' Law and the concept of Density?



move for answer

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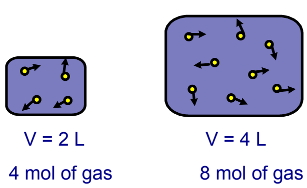
## Volume and Moles

The volume of a gas at constant temperature and pressure is directly proportional to the number of moles of the gas. Simply put, the more molecules that are present, the more room they will need to move around if the pressure is to stay the same.

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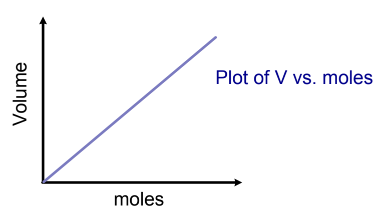
## Volume and Moles

The direct relationship between the volume of a gas and the moles of a gas is called Avogadro's Law

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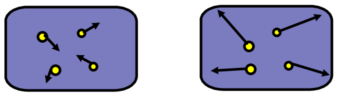
## Pressure and Temperature

The pressure of a gas kept at a constant temperature and volume will increase proportionally with the temperature. In essence, the faster the molecules move, the greater the force of each collision, which increases the pressure.



P = 32 mm Hg
T = 200 K
less energetic collisions

P = 64 mm Hg
T = 400 K
more energetic collisions

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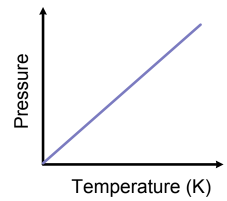
## Pressure and Temperature

The direct relationship between the pressure and the Kelvin temperature of a gas is known as Gay-Lussac's Law.




Plot of P vs T

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## Application

In car racing, the mechanics have to be very careful in adjusting the pressure of the car tires. Using the concept of friction and Gay-Lussac's law, what do you think happens to the air pressure in a car tire over the course of a long car race?

move for answer

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Slide 68 / 140

## Calculating Changes in Gas Variables

Quite often, one or more of the variables we use to describe a gas change as a result of a chemical reaction or due to some environmental change. We can use the relationships developed to accomplish this.

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## Calculating Changes in Gas Variables

QUESTION: A 13 mL balloon at 34 C is heated to 78 C at a constant pressure. Assuming no molecules escaped or entered the balloon, what is the new volume of the balloon?

PROCEDURE

1. Identify quantities given and determine what is changing and by how much.
2. Using your knowledge of gas laws, predict what impact this change will have on the other variable.
3. Multiply the original variable by this change.

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## Calculating Changes in Gas Variables

QUESTION: A 13 mL balloon at 34 C is heated to 78 C at a constant pressure. Assuming no molecules escaped or entered the balloon, what is the new volume of the balloon?

1. Identify quantities given and determine what is changing and by how much.

V = 13 mL
$T_i$ = 34 C (34+273) = 307 K
$T_f$ = 78 C (78+273) = 351 K

Temperature is increasing by a factor of 351/307

2. Using gas laws, predict what impact this change will have on the other variable.

Since the relationship between V and T is direct, the V will also increase by a factor of 351/307

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## Calculating Changes in Gas Variables

QUESTION: A 13 mL balloon at 34 C is heated to 78 C at a constant pressure. Assuming no molecules escaped or entered the balloon, what is the new volume of the balloon?

3. Multiply the original variable by the change

$$13\text{ mL} \times \frac{351\text{ K}}{307\text{ K}} = 14.9\text{ mL}$$

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## Calculating Changes in Gas Variables

QUESTION: A rigid gas canister has a volume of 18.5 L at 13 C and the pressure gauge reads 45 atm. To what temperature would the gas need to be decreased to cause the pressure to read only 30 atm?

move for answer

Slide 73 / 140

**16 The volume of a gas at a pressure of 400 mm Hg doubles, what will be the new pressure if the process occurred isothermally in a closed container ?**

- A 400 mm Hg
- B 600 mm Hg
- C 800 mm Hg
- D 300 mm Hg
- E 200 mm Hg

Slide 73 (Answer) / 140

**16 The volume of a gas at a pressure of 400 mm Hg doubles, wh process o container**

- A 400 m
- B 600 m
- C 800 m
- D 300 m
- E 200 m

Answer

E

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**17 A 6.0 liter volume of gas is at a temperature of 200 K. The temperature of the gas is reduced to 100 K while holding its quantity and pressure fixed. What is the new volume of the gas?**

17 A 6.0 liter volume of gas is at a temperature of 200 K. The temperature of the gas is reduced to 100 K while h... fixed. What...

Answer

3L



18 A 6.0 liter volume of gas is at a pressure of 21 kPa. The volume of gas is reduced to 2.0 L while holding its quantity and temperature fixed. What is the new pressure of the gas?



18 A 6.0 liter volume of gas is at a pressure of 21 kPa. The volume of gas is reduced to 2.0 L while holding its quantity ... ew pressure o...

Answer

63 kPa



19 A gas is at a temperature of 200 K and a pressure of 0.80 atm. What must be the new temperature if the pressure of the gas was found to be 1.6 atm after heating. The quantity and volume of the gas were fixed.



19 A gas is at a temperature of 200 K and a pressure of 0.80 atm. Wh... he pressure of... heating. Th... fixed.

Answer

400 K



20 Bear mace can be sprayed to deter a bear attack! The pressure of the gas in the rigid canister is 1900 torr at 30 C. If there were originally 10 moles of gas in the canister before using and 6.8 moles after using, what must be the new pressure in the canister at 30 C? (Hint: Think about what the relationship would be between pressure and moles)

- A 2794 torr
- B 1896.2 torr
- C 1534 torr
- D 1292 torr
- E The pressure would not be affected

20 Bear mace can be sprayed to deter a bear attack! The pressure of the gas in the rigid canister is 1900 torr at 30 C. If there w... canister befo... at must be the... (Hint: Think... between pre...

Answer

D

- A 2794 to...
- B 1896.2...
- C 1534 to...
- D 1292 to...
- E The pressure would not be affected



## Calculating Changes in Gas Variables

Question: If a flexible balloon with a volume of 200 mL at sea level (pressure 0.97 atm) and a temperature of 15 C is held underwater so that the new pressure was 1.8 atm and the temperature cooled to 5 C, what would be the new volume?

**Since multiple variables are changing, each be addressed**

**V = 200 mL $T_i$ = (15 + 273) = 288 K $T_f$ = (5+273) = 278 K**

**$P_i$ = 0.97 atm $P_f$ = 1.8 atm**

The temperature is decreased by a factor of 278/288

The pressure increased by a factor of 1.8/0.97

V and T are direct so the V will also decrease by 278/288

V and P are inverse so the V will decrease by 0.97/1.8

so.... $200\text{ mL} \times \frac{278\text{ K}}{288\text{ K}} \times \frac{0.97\text{ atm}}{1.8\text{ atm}} = 104\text{ mL}$



21 A gas in a closed flexible 3.4 L container is heated from 150 K to 300 K and the pressure is decreased from 600 mm Hg to 400 mm Hg. What is the new volume?



21 A gas in a closed flexible 3.4 L container is heated from 150 K to 300 K and the pressure is decreased from 600 mm ... volume?

Answer

10.2 L



# Ideal Gas Law

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## Ideal Gas Law

(Boyle's law) PV = constant

(Charles's law) V/T = constant

(Avogadro's law) V/n = constant

(Gay Lussac's Law) P/T = constant

Combining these yields the ideal gas law

$$\frac{PV}{nT} = R \text{ (a constant)} \qquad PV = nRT$$

where "R" is the gas constant.
This is the only formula you'll need for ideal gas problems!

## Ideal Gas Law

The value of the Ideal Gas Constant (R) depends on the units chosen for P and V.

| Units | Numerical value |
|---|---|
| L-atm/mol-K | 0.08206 |
| J/mol-K* | 8.314 |
| cal/mol-K | 1.987 |
| m3-Pa/mol-K* | 8.314 |
| L-torr/mol-K | 62.36 |

*** SI units**



## Working with the Ideal Gas Law

Any variable within the Ideal Gas Law can be solved for so long the other three are given.

Question: What is the temperature of 32 grams of $N_2$ gas that occupies 200 mL at a pressure of 450 mm Hg.

PROCEDURE

1. Write down known variables. Make sure V is written in liters and P in atmospheres and convert grams to moles.

2. Rearrange the Ideal Gas Law (PV=nRT) to solve for the unknown variable.

3. Put in numbers and solve.



## Working with the Ideal Gas Law

Question: What is the temperature of 32 grams of $N_2$ gas that occupies 200 mL at a pressure of 450 mm Hg.

Write down known variables. Make sure V is in Liters, P in atm, and grams in moles

V = 200 mL = 2 L     P = 450 mm Hg = 0.59 atm

32 grams of $N_2$ = 1.14 moles $N_2$

Rearrange the Ideal Gas Law to solve for unknown variable

PV = nRT --> T = PV/nR



## Working with the Ideal Gas Law

Question: What is the temperature of 32 grams of $N_2$ gas that occupies 200 mL at a pressure of 450 mm Hg.

Input numbers and solve

T = PV/nR

$$T = \frac{0.59 \text{ atm} \times 0.20 \text{ L}}{1.14 \text{ moles} \times 0.0821 \text{ L*atm/mol*K}}$$

T = 1.26 K *(wow, that's cold!!)*



**22 A sample of a gas occupies 7.5L at 0.975atm and at 28⁰C.The number of moles present in the gas is _________?**



**22 A sample of a gas occupies 7.5L at 0.975atm and at 28⁰C.The number of moles present in the gas is _________?**

Answer

0.296 moles

Slide 87 / 140

23 **The pressure of 1.55 mols of a gas is _________ if it has a volume of 3.2 L at 27$^0$C.**

Slide 87 (Answer) / 140

23 **The pressure of 1.55 mols of a gas is _________ if it has a volu**

**Answer**

11.9 atm

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## Gases and Chemical Reactions

The number of moles of gas molecules often change during a chemical reaction.

$C_3H_8(g) + 5O_2(g) \rightarrow 3CO_2(g) + 4CO_2(g)$

6 moles 7 moles

This change in moles will cause a proportional change in volume and pressure.
The volume would increase by 7/6 (direct relationship)
The pressure would also increase by 7/6(direct relationship)

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## Gases and Chemical Reactions

Example: A reaction occurs in a flexible container with an initial volume of 12 L. What is the new volume after the reaction below goes to completion?

$PCl_5(g) \rightarrow PCl_3(g) + Cl_2(g)$

move for answer

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24 **The below reaction occurs at constant temperature and volume. The initial pressure was 110 kPa; what would the final pressure be after the reaction?**

**$Cl_2$ (g) + $C_2H_4$ (g) # $C_2H_4Cl_2$ (g)**

Slide 90 (Answer) / 140

24 **The below reaction occurs at constant temperature and volume. The initial pressure was 110 kPa; what would the fi**

**Answer**

55 kPa

Slide 91 / 140

25 **This reaction occurs at constant pressure and temperature. The initial volume was 2.8L; what would the final volume be?**

$Cl_2$ (g) + $C_2H_4$ (g) # $C_2H_4Cl_2$ (g)

Slide 91 (Answer) / 140

25 **This reaction occurs at constant pressure and temperature. The initial volume was 2.8L; what would the final volume be?**

Answer

1.4 L

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## STP

Data is often provided assuming that a gas is at *standard temperature and pressure* (STP)

STP is defined as:

P = 1atm

T = 273K (0°C)

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26 **What volume does one mole of gas occupy at 1 atm and 0 C?**

Slide 93 (Answer) / 140

26 **What volume does one mole of gas occupy at 1 atm and 0 C?**

Answer

22.4 L

Slide 94 / 140

## Molar Volume at STP

We learned earlier this year that one mole of gas has a volume of 22.4 L at STP.Now we can see why.

$$PV=nRT$$

$$V=\frac{nRT}{P}$$

$$V = \frac{(1.00 \text{ mol})(0.0821 \text{ L-atm/mol-K})(273 \text{ K})}{1.00 \text{ atm}}$$

**V = 22.4 L** For one mole of gas at STP.

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# Gas Density

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## Densities of Gases

Density is the ratio of mass to volume. $D = \frac{m}{V}$

As we just learned:

1 mole of any gas occupies 22.4 L @ STP.

However, each gas has a different mass and therefore a different density.

| Gas | Density (g/L) @STP |
|---|---|
| Helium | 0.1785 |
| Oxygen | 1.430 |
| Carbon dioxide | 1.970 |

*Note: The density is directly proportional to the molar mass of the gas*

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**27 The density of oxygen gas is 1.430 g/L @STP. What would you expect the density of Argon gas to be at the same conditions?**

Slide 97 (Answer) / 140

**27 The density of oxygen gas is 1.430 g/L @STP. What would you expect the density of Argon gas to be at the same conditions?**

Answer

1.79 g/L

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**28 Which of the following gases would have the smallest density @STP?**

- A Kr
- B $N_2$
- C $C_3H_8$
- D $CCl_4$
- E $CH_4$

Slide 98 (Answer) / 140

**28 Which of the following gases would have the smallest density @STP?**

- A Kr
- B $N_2$
- C $C_3H_8$
- D $CCl_4$
- E $CH_4$

Answer

E

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## Calculating the Density of a Gas

$PV = nRT \rightarrow PV = \frac{m}{M}RT$

Substitute $n = \frac{m}{M}$ for n; m is the mass of the sample and M is the molecular mass of the gas.

$MPV = mRT$

$\frac{MP}{RT} = \frac{m}{V}$

Cross multiply

$\frac{m}{V} = \frac{MP}{RT}$

Solve for the density: $\frac{m}{V}$

$D = \frac{MP}{RT}$

This formula yields the density (D) of a gas if we know its molecular mass, pressure and temperature.

Slide 100 / 140

**29** **What is the density (in g/L) of $H_2$ gas at 1.4 atm and 300K?**

Slide 100 (Answer) / 140

**29** **What is the density (in g/L) of $H_2$ gas at 1.4 atm and 300K?**

Answer

0.11 g/L

Slide 101 / 140

**30** **What is the density of oxygen gas at the top of Mt. Everest at a pressure of 600 mm Hg and a temperature of -18 C?**

Slide 101 (Answer) / 140

**30** **What is the density of oxygen gas at the top of Mt. Everest at a pressure of 600 mm Hg and a temperature**

Answer

1.21 g/L

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**31** **What is the density (in g/L) of $N_2$ gas at 1.6 atm and 320K?**

Slide 102 (Answer) / 140

31 **What is the density (in g/L) of $N_2$ gas at 1.6 atm and 320K?**

Answer

1.70 g/L

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## Application

In World War I, toxic gases like chlorine gas were used to sink into the trenches and do harm to opposing soldiers. Knowing the composition of air and the concept of density, explain why chlorine gas ($Cl_2$) was effective.

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## Molecular Masses of Gases

$$D = \frac{MP}{RT}$$

$$DRT = MP$$

$$MP = DRT$$

$$M = \frac{DRT}{P}$$

We can rearrange the density formula for M, so that we can determine the molecular mass of a gas if we know its density, temperature and pressure... all things we can easily find in a lab.

From this formula we can find the molecular mass of a gas by measuring its density, temperature and pressure.

Slide 105 / 140

32 **Of the following gases, _______ has a density of 2.104 g/L at 303 K and 1.31 atm.**

- A He
- B Ne
- C Ar
- D Kr
- E Xe

Slide 105 (Answer) / 140

32 **Of the following gases, _______ has a density of 2.104 g/L at 303 K and 1.31 atm.**

- A He
- B Ne
- C Ar
- D Kr
- E Xe

Answer

C

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33 **The density of ____ is 0.900 g/L at STP.**

- A $CH_4$
- B Ne
- C CO
- D $N_2$
- E NO

Slide 106 (Answer) / 140

**33 The density of ____ is 0.900 g/L at STP.**

- A $CH_4$
- B Ne
- C CO
- D $N_2$
- E NO

Answer

B

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## Partial Pressure

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## Dalton's Law of Partial Pressures

The total pressure of a mixture of gases is equal to the sum of the pressure of each gas.

$$P_{tot} = P_A + P_B + P_C \ .....$$

So, in a sample of air, the total pressure is equal to the sum of the partial pressures of nitrogen, oxygen, water vapor, etc.

$$n_{red} \times P_{average} = P_{red}$$

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**34 In a mixture of Ne, Ar, and Kr gases at STP, what is the partial pressure of Ne gas if the partial pressure of Ar = 56 mm Hg and the partial pressure of Kr = 190 mm Hg?**

Slide 109 (Answer) / 140

**34 In a mixture of Ne, Ar, and Kr gases at STP, what is the partial pressure of Ne gas if the partial pressure of Ar = 56 mm Hg and the partial pressure of Kr = 190 mm Hg?**

Answer

514 mmHg

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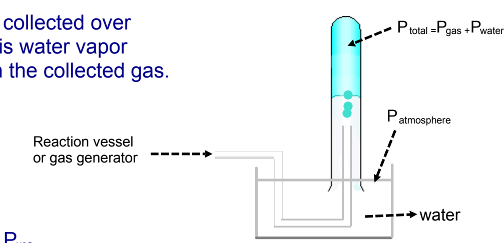
## Partial Pressures

When gas is collected over water, there is water vapor mixed in with the collected gas.




$P_{total} = P_{gas} + P_{H2O}$

To find the partial pressure of the desired gas, on must subtract the vapor pressure of water from the total pressure.

$P_{gas} = P_{total} - P_{H2O}$

The vapor pressure of water depends on the temperature.

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## Water Vapor Pressure Chart

| Temperature (°C) | Pressure (mm Hg) | Pressure (mbar) |
|---|---|---|
| 0 | 4.58 | 6.11 |
| 5 | 6.54 | 8.72 |
| 10 | 9.21 | 12.28 |
| 12 | 10.52 | 14.03 |
| 14 | 11.99 | 15.99 |
| 16 | 13.63 | 18.17 |
| 17 | 14.53 | 19.37 |
| 18 | 15.48 | 20.64 |
| 19 | 16.48 | 21.97 |
| 20 | 17.54 | 23.38 |
| 21 | 18.65 | 24.86 |
| 22 | 19.83 | 26.44 |
| 23 | 21.07 | 28.09 |
| 24 | 22.38 | 29.84 |
| 25 | 23.76 | 31.68 |

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**35** **$N_2$ gas is collected over water ($H_2O$). The total pressure of the gas is 1 atm, 760 mm Hg. Water vapor ($H_2O$ gas) has a partial pressure of 25 mm Hg at that temperature. What is the partial pressure of the $N_2$ component of the gas?**

Slide 112 (Answer) / 140

**35** **$N_2$ gas is collected over water ($H_2O$). The total pressure of the ... vapor ($H_2O$ ... at that temp... pressure of...**

Answer

735 mmHg

Slide 113 / 140

**36** **$O_2$ gas is collected over water ($H_2O$). The total pressure of the gas is 1 atm, 760 mm Hg. Water vapor ($H_2O$ gas) has a partial pressure of 35 torr mm Hg at that temperature. What is the partial pressure of the $O_2$ component of the gas?**

Slide 113 (Answer) / 140

**36** **$O_2$ gas is collected over water ($H_2O$). The total pressure of th... vapor ($H_2O$... mm Hg at... pressure ...**

Answer

725 mmHg

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## Dalton's Law of Partial Pressures

The partial pressure of a gas in a mixture is directly proportional to the number of moles of that gas.

$$\frac{\text{moles gas A}}{\text{moles gas total}} = \frac{P_A}{P_{tot}}$$

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## Dalton's Law of Partial Pressures

If a gas mixture were made up of 3 moles of $N_2$ and 1 mole of $O_2$.

The composition of the mixture would be...

3 mol $N_2$: 1 mol $O_2$

75% $N_2$ and 25% $O_2$.

If the total pressure of the gas mixture was 1.0 atm, then the partial pressures would be...

$1.0 \text{ atm} \times \frac{3 \text{ mol } N_2}{4 \text{ mol tot}} = 0.75 \text{ atm } N_2$

$1.0 \text{ atm} \times \frac{1 \text{ mol } O_2}{4 \text{ mol tot}} = 0.25 \text{ atm } O_2$

Slide 116 / 140

37 A gas mixture is made up of 2 moles of $H_2$ and 6 moles of $N_2$. It has a total pressure of 1.6 atm. What is the partial pressure of $H_2$?

Slide 116 (Answer) / 140

37 A gas mixture is made up of 2 moles of $H_2$ and 6 moles of $N_2$. It has a total pressure of 1.6 atm. What is the partial

Answer

0.4 atm

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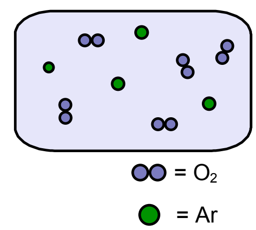
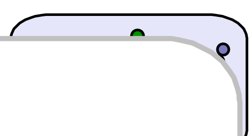
38 What is the partial pressure of oxygen gas in the mixture below assuming the total pressure in the container is 670 mm Hg?




Slide 117 (Answer) / 140

38 What is the partial pressure of oxygen gas in the mixture below assuming the total pressure in the container is 670 mm Hg?



Answer

0.3

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## Graham's Law of Effusion

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## Molecular Velocity of Gases

If a gas is composed of two different molecules, they will both be at the same temperature, therefore they will have the same kinetic energy.

$$KE_1 = KE_2$$

$$1/2\ m_1v_1^2 = 1/2\ m_2v_2^2$$

$$m_1v_1^2 = m_2v_2^2$$

*Notice that this is an inverse relationship between mass and velocity. The heavier the mass, the smaller the velocity.*

Slide 120 / 140

## Molecular Velocity of Gases

| Gas | Avg. Velocity @ 27 C |
|---|---|
| Helium (4 g/mol) | 1369 m/s |
| Oxygen (32 g/mol) | 484 m/s |
| Carbon dioxide (44 g/mol) | 412.8 m/s |

*Note: This is not a linear relationship. Helium is 1/8 the mass of oxygen but travels at only 4x the speed.*

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**39 Which of the following gases would have the highest average velocity at a given temperature?**

- A $C_3H_8$
- B $CH_3Cl$
- C $CH_4$
- D $N_2$
- E Xe

Slide 121 (Answer) / 140

**39 Which of the following gases would have the highest average velocity at a given temperature?**

- A $C_3H_8$
- B $CH_3Cl$
- C $CH_4$
- D $N_2$
- E Xe

Answer

C

Slide 122 / 140

**40 Which of the following pairs of gases would be most difficult to separate based on molecular speed?**

- A $H_2$ and $O_2$
- B $O_2$ and $CH_4$
- C $C_3H_8$ and $CO_2$
- D $CO_2$ and $CF_4$
- E He and Kr

Slide 122 (Answer) / 140

**40 Which of the following pairs of gases would be most difficult to separate based on molecular speed?**

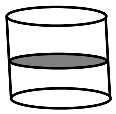
- A $H_2$ an
- B $O_2$ an
- C $C_3H$
- D $CO_2$
- E He a

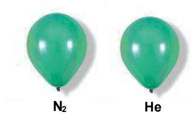
Answer

C

## Graham's Law of Effusion

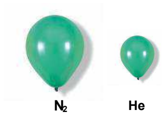
Effusion is the escape of gas molecules through a tiny hole into an evacuated space.






The two balloons are filled to the same volume

The difference in the rates of effusion for helium and nitrogen ($N_2$ is more massive than He ) explains why helium balloons deflate faster.




**after 48 hrs**

The He balloon was smaller



## Graham's Law of Effusion

$$\left(\frac{V1}{V2}\right)^2 = \frac{M2}{M1}$$

This equation illustrates Graham's Law of Effusion. The rates at which two gases will effuse is inversely proportional to the square root of their molar masses.

$$\frac{v_1}{v_2} = \frac{\#M_2}{\#M_1} \quad \textbf{or} \quad \frac{v_1}{v_2} = \#M_2/M_1$$



## Graham's Law of Effusion

How much faster would we expect hydrogen gas ($H_2$) to move compared to nitrogen gas ($N_2$)?

move for answer



**41 Of the following gases, _______ will have the greatest rate of effusion at a given temperature.**

- A $NH_3$
- B $CH_4$
- C Ar
- D HBr
- E HCl



**41 Of the following gases, _______ will have the greatest rate of effusion at a given temperature.**

- A $NH_3$
- B $CH_4$
- C Ar
- D HBr
- E HCl

**Answer**

B



**42 A gas mixture consists of oxygen and helium. What is the ratio of the average velocity of oxygen to helium?**

Slide 127 (Answer) / 140

42 A gas mixture consists of oxygen and helium. What is the ratio of the average velocity of

Answer

0.35x

Slide 128 / 140

43 A gas mixture consists of nitrogen and helium. What is the ratio of the average velocity of helium to nitrogen?

Slide 128 (Answer) / 140

43 A gas mixture consists of nitrogen and helium. What is the ratio of the average velocity of h

Answer

2.65 x

Slide 129 / 140

## Graham's Law of Effusion

An unknown gas travels at a rate that is 1.17 x slower than oxygen gas. What is the molar mass of the unknown gas?

move for answer

Slide 130 / 140

44 A mixture of carbon dioxide and an unknown gas was allowed to effuse from a container. The carbon dioxide took 1.25 times as long to escape as the unknown gas. Which one could be the unknown gas?

- A $Cl_2$
- B CO
- C HCl
- D $H_2$
- E $SO_2$

Slide 130 (Answer) / 140

44 A mixture of carbon dioxide and an unknown gas was allowed to effuse from a container. The carbon di escape as th be the unkn

- A $Cl_2$
- B CO
- C HCl
- D $H_2$
- E $SO_2$

Answer

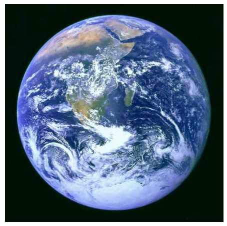
B

## Application

The escape velocity (velocity a molecule needs to escape from the earth) is equal to **11,100 meters per second** in the upper atmosphere. The average speed of hydrogen gas is 1,832 meters per second. Explain, with what you know about the definition of temperature and Graham's Law...

1. Why does some hydrogen gas can escape the Earth's atmosphere?

2. Why is our atmosphere composed of more nitrogen and oxygen than than hydrogen?





# Real versus Ideal Gases

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## Real Gases

Until now, we have been assuming that gases behave ideally, ie.. that they behave according to our assumptions.

| Assumptions |
|---|
| Gases molecules occupy no volume |
| All collisions between molecules are elastic |

In reality, gases do occupy a tiny amount of space and do experience a small degree of attractions which make some collisions inelastic.



## Real Gases

The temperature, pressure, and type of gas can influence how ideal or real a gas behaves.

What kind of temperature you would want to have in order for the gas to behave ideally?

move for answer

What kind of pressure you would want to have gases behave most ideally?

move for answer



## Real Gases

The temperature, pressure, and type of gas can influence how ideal or real a gas behaves.

In terms of size, what kind of gas molecule would behave most ideally?

move for answer

In terms of intermolecular forces, what kind of gas molecule would behave most ideally?

move for answer



## Real vs. Ideal Gases

| Property | Ideal Gas | Real Gas |
|---|---|---|
| Volume | none | small |
| Intermolecular forces | none | weak |
| Required Temperature | High | Low |
| Required Pressure | Low | High |

Note: All gases behave non-ideally at most temperatures and pressures. So, although a gas never behaves completely ideally, a small gas at a high temperature and low pressure will behave most ideally. *Think about what conditions would most likely lead to perfectly elastic collisions.

**45** **Which of the following gases would behave most ideally?**

- A Xe
- B Kr
- C Ar
- D Ne
- E He



**45** **Which of the following gases would behave most ideally?**

- A Xe
- B Kr
- C Ar
- D Ne
- E He

**Answer**

E



**46** **Under what conditions would a gas behave LEAST ideally?**

- A 300 K and 1 atm
- B @STP
- C 400 K and 0.5 atm
- D 100 K and 0.01 atm
- E 100 K and 1 atm



**46** **Under what conditions would a gas behave LEAST ideally?**

- A 300 K a
- B @STP
- C 400 K a
- D 100 K a
- E 100 K a

**Answer**

E



## Some Common Gases

**This chart could save your life!**

| Name | Formula | Characteristics |
|---|---|---|
| Hydrogen cyanide | $HCN$ | Very toxic, slight odor of bitter almonds |
| hydrogen sulfide | $H_2S$ | Very toxic, rotten egg smell |
| carbon monoxide | $CO$ | colorless, odorless, toxic |
| carbon dioxide | $CO_2$ | colorless, odorless |
| methane | $CH_4$ | colorless, odorless, flammable |
| oxygen | $O_2$ | colorless, odorless |
| ethylene | $C_2H_4$ | ripens fruit |
| nitrous oxide | $N_2O$ | Laughing gas, oxidizer for cars |
| ammonia | $NH_3$ | strong smell |