Lecture 2

Spring 2022

General Chemistry II

Chem 102

- Significant Figures
- Dimensional Analysis
- Limiting Reactant
- Ideal Gases

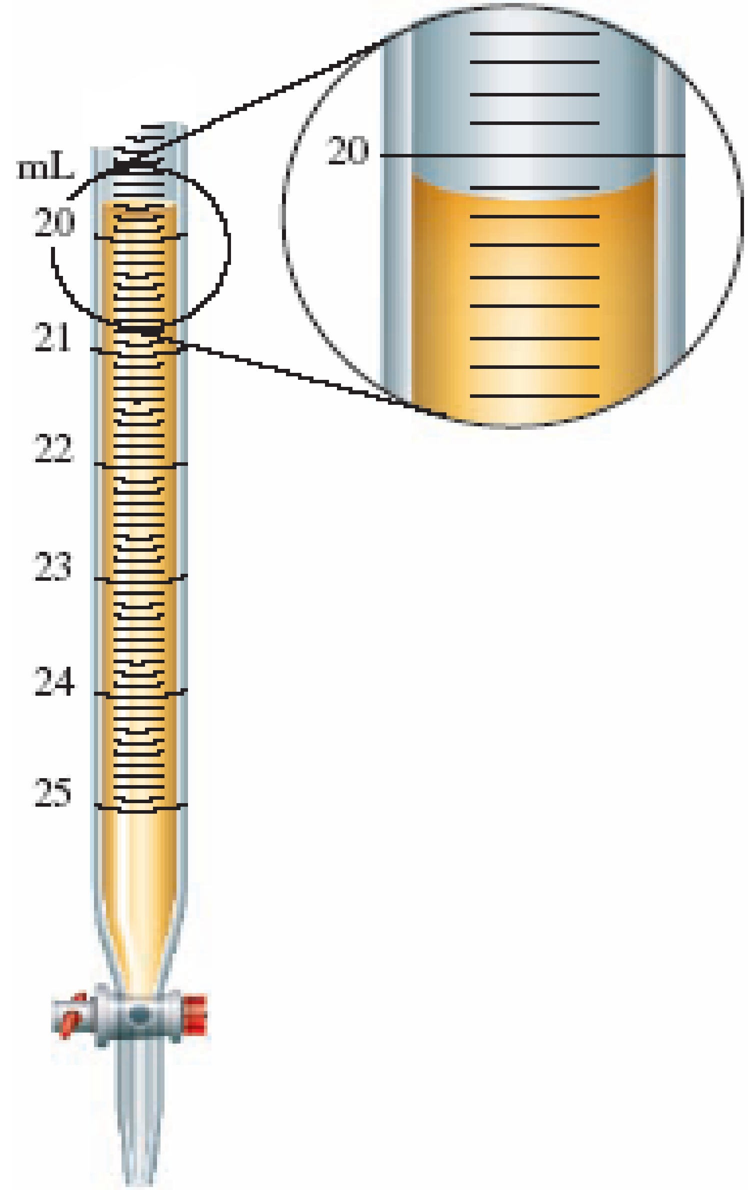
Ahmad Alakraa

Uncertainty in Measurement

- If five different people read same volume, the results **in mL** might be

20.16, 20.14, 20.16, 20.17, 20.15

- 20.1 are certain digits but the last digit is estimated (**uncertain, doubtful**) digit

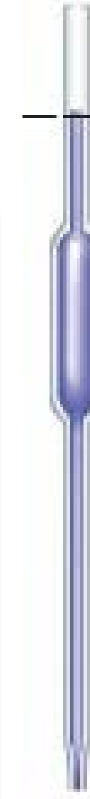


Significant Figures, SF

- Any measurement is reported by recording only **SF** (all certain digits + 1st uncertain digit).

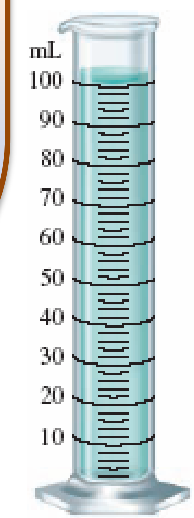
- For a burette, it would not make any sense to record the volume of thousandths of a milliliter (0.004) (insignificant) because the value for hundredths of a milliliter must be estimated.

- In analyzing a sample of polluted water, a chemist measured out a 25.00-mL water sample with a pipette. Another chemist used a graduated cylinder to measure 25 mL of a solution. What is the difference between the measurements?



Solution

- The quantity 25 mL means that the volume is between 24 mL and 26 mL, whereas the quantity 25.00 mL means that the volume is between 24.99 mL and 25.01 mL.



A pipette measures volume with much greater precision

Counting SF: Rules

- **Nonzero** → always SF
- **Zeros**: three types

A- **Leading zeros** (zeros precede nonzero digits)

→ do not count as SF

0.0025 → has only two SF

B- **Captive zeros** (zeros between nonzero digits)

→ always count as SF

1.008 → has four SF

C- **Trailing zeros** (zeros at the right end of the number)

→ are SF only if the number contains a decimal point.

100 → has only one SF

1.00×10^2 → has three SF

Exact numbers: numbers obtained by **counting** or **definitions** & not measured by devices.

These have an **infinite number** of SF.

Examples

- 10 experiments, 3 apples, 8 molecules.
- 2 in $2\pi r$ (circumference of a circle) and 4/3 in $4/3\ r^3$ (volume of a sphere).
- **1 inch = 2.54 cm**.

⇒Neither 2.54 nor 1 limits the number of SF when used in a calculation.

Exercise

Counting No. of SF

- A student's extraction on tea yields 0.0105 g of caffeine.

  2 leading zeros **(not SF)**, 1 captive zero **(SF)**, 2 nonzeros **(SF)**.

  → Overall: 3 SF

- 0.050080 g in a measurement.

  2 leading zeros **(not SF)**, 2 captive zero **(SF)**, 1 trailing zero **(SF)**, 2 nonzeros **(SF)**.

  → Overall: 5 SF

- 8.050×10^{-3} s → Overall: 4 SF

Rules in calculations

Multiplication and division

- Count No. of **SF** in each No. being multiplied or divided and limit the answer to the least of them

$$4.56 \times 1.4 = 6.38 \xrightarrow{\textit{Corrected}} 6.4$$

Limiting: 2 SF → 2 SF

Rules in calculations

Addition and subtraction

- The result should have the same number of decimal places as the least precise measurement in the calculation.

No. of **SF**, is not considered

$$12.11 +$$
$$18.0 +$$
$$1.013$$
$$\overline{}$$
$$31.123 \xrightarrow{\textit{Corrected}} 31.1$$

Rounding

- Carry extra digits through to the final result, then round.
- If the digit to be removed
  - < 5, preceding digit stays the same.

    1.33 → 1.3

  - ≥ 5, preceding digit is increased by 1.

    1.36 → 1.4

- Use only the first number to the right of the last significant figure.
  - Do not round **sequentially**. Rounding 6.834 to 3 SF

    6.8347 → 6.83 √ 6.84 ×

Calculate and count SF

$$1.05\times10^{-3}\div6.135=1.711491\times10^{-4}$$

$$\xrightarrow{\text{Corrected to 3 SF}}1.71\times10^{-4}$$

$$21-13.8=7 \quad \textit{no DP } 1\text{ SF}$$

Determine the value of the gas constant (R) for a gas with a pressure (P = 2.560 atm), molar volume (V =8.8 L/mol), and temperature (T = 275.15 K)?

$$R=\frac{PV}{T}=\frac{(2.560)(8.8)}{275.15}=\frac{22.528}{275.15}=$$

$$0.081875321=0.082=8.2\times10^{-2} \quad 2\text{ SF}$$

Dimensional Analysis (unit factor method)

It is a method used to convert a given result from one system of units to another.

Apples and oranges do not add

- Calculate in inches the length of a 2.85 cm pen knowing that 2.54 cm = 1 in?

$$1 = \frac{1\ in}{2.54\ cm}$$

is called a unit factor which does not affect SF

$$2.85\ cm \times \frac{1\ in}{2.54\ cm} = \frac{2.85}{2.54}\ in = 1.12\ in \quad 3\ SF$$

Exercises

- How many mL are in 1.63 L?

$$1.63\ L \times \frac{1000\ mL}{1\ L} = 1630\ mL = 1.63 \times 10^{3}\ mL$$

- The speed of sound in air is about 343 m/s. What is this speed in miles per hour?

$$343\ \frac{m}{s} \times \frac{3600\ s}{1\ h} \times \frac{1\ mi}{1609\ m} = 767\ \frac{mi}{h}$$

Concept of the limiting reactant

- ***You have a part-time job in a sandwich shop.***
- ***One popular sandwich is always made:***

2 slices bread
3 slices meat
1 slice cheese
→ ***Sandwich***

Test your performance

- ***You have these ingredients. How many sandwiches can you make?***
- ***What will be left over?***

8 slices Bread

9 slices Meat

5 slices Cheese

Remember

Bread + Meat + Cheese → Sandwich

Bread	Meat	Cheese	→	Sandwich
2	3	1		1

Approaches

1: How many sand. that each ingredient can make?

	Bread	+ Meat	+ Cheese	→ Sand.
Stoichiometry	2	3	1	1
Available	8	9	5	?
Sand.	4	3	5	3

Limiting reactant: is the reactant giving the lowest ratio of moles available/coefficient in the balanced equation (stoichiometry)

Approaches

2: Find the reactant having a deficiency :

	Bread +	Meat +	Cheese →	Sand.
Stoichiometry	2	3	1	1
Available	8	9	5	?

Sand. 4

Can Meat make 4 Sand.? No

Can Cheese make 4 Sand.? Yes

Limiting reactant: *is the reactant having deficiency relatively to other reactants in view of their stoichiometries*

Approaches

3: Compare the moles ratios of required and available moles:

	Bread +	Meat +	Cheese →	Sand.
Stoichiometry	2	3	1	1
$\frac{\text{coefficient}}{\text{Bread coefficient}}$	1	1.5	0.5	
Available	8	9	5	
$\frac{\text{coefficient}}{\text{Bread coefficient}}$	1	1.125	0.625	

Limiting reactant: is the reactant that can not provide the quantity required to consume the whole materials of other reactant (s)

How many sandwiches each component can make?

Bread

$$8 \text{ slices } bread \times \frac{1\ sand}{2 \text{ slices } bread} = 4\ sand$$

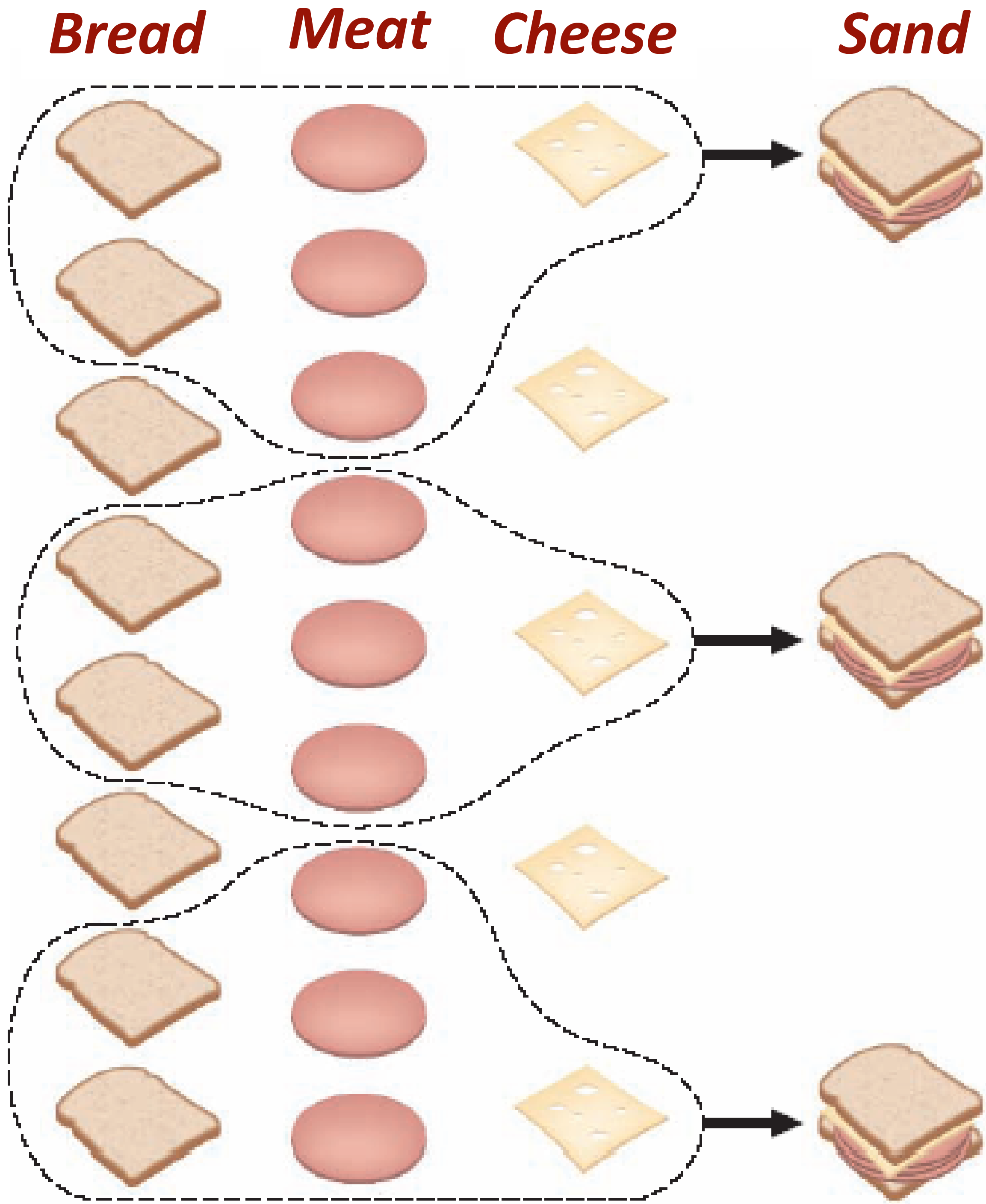
Meat

$$9 \text{ slices } meat \times \frac{1\ sand}{3 \text{ slices } meat} = 3\ sand$$

Cheese

$$5 \text{ slices } cheese \times \frac{1\ sand}{1 \text{ slices } cheese} = 5\ sand$$

- ***Overall, how many sandwiches can you make? 3***
- ***When you run out of meat, you must stop making sandwiches. The meat is the limiting ingredient.***
- ***What do you have left over? 2 slices of bread + 2 pieces of cheese***



The Limiting reactant (meat) is the component that limits the number of products (sandwiches) you can make.

Exercise

Nitrogen gas can be prepared by passing gaseous ammonia over solid copper (II) oxide at high temperatures. The other products of the reaction are solid copper and water vapor. If a sample containing 18.1 g of NH_3 is reacted with 90.4 g of CuO, which is the limiting reactant? Find the mass of N_2 that will be formed?

Solution: Find limiting reactant

$$NH_3\,(g) + CuO\,(s) \rightarrow N_2\,(g) + Cu\,(s) + H_2O\,(g)$$

- 18.1 g NH_3
- 90.4 g CuO

Balancing

$$2NH_3\ (g) + 3CuO\ (s) \rightarrow N_2\ (g) + 3Cu\ (s) + 3H_2O\ (g)$$

What are the moles of NH_3 and CuO?

Molar masses NH_3 =17.03 g/mol CuO =79.55 g/mol

$$18.1\ \cancel{g\ NH_3} \times \frac{1\ mol\ NH_3}{17.03\ \cancel{g\ NH_3}} = 1.06\ mol\ NH_3$$

$$90.4\ \cancel{g\ CuO} \times \frac{1\ mol\ CuO}{79.55\ \cancel{g\ CuO}} = 1.14\ mol\ CuO$$

Moles of CuO required to react with 1.06 mol NH_3

$$1.06\ \cancel{mol\ NH_3} \times \frac{3\ mol\ CuO}{2\ \cancel{mol\ NH_3}} = 1.59\ mol\ CuO$$

Only 1.14 mol CuO is available. CuO is limiting (CuO will run out before NH_3).

Verification: Compare the required and actual mole ratios of CuO and NH_3 in the balanced equation:

$$Required = \frac{mol\ CuO}{mol\ NH_3} = \frac{3}{2} = 1.5$$

$$Actual = \frac{mol\ CuO}{mol\ NH_3} = \frac{1.14}{1.06} = 1.08$$

Since the actual ratio is smaller than required (1.5), CuO is the limiting reactant.

A second verification: the limiting reactant should have the lowest ratio of moles available/coefficient in the balanced equation.

$$For\ NH_3 = \frac{Moles\ available}{Stoichiometry} = \frac{1.06}{2} = 0.535$$

$$For\ CuO = \frac{Moles\ available}{Stoichiometry} = \frac{1.14}{3} = 0.38$$

Since the ratio of CuO is smaller, CuO is the limiting reactant.

Find the mass of N_2 produced:

We must use the amount of limiting reactant (CuO) to calculate the amount of N_2 formed.

First calculate the moles of N_2

$$1.14\ \cancel{mol}\ CuO \times \frac{1\ mol\ N_2}{3\ \cancel{mol}\ CuO} = 0.38\ mol\ N_2$$

Next calculate the mass of N_2

✓ Using the molar mass of N_2 (28.02 g/mol)

$$0.38\ \cancel{mol}\ N_2 \times \frac{28.02\ g\ N_2}{1\ \cancel{mol}\ N_2} = 10.6\ g\ N_2$$

Percent yield

- **Theoretical yield:** the amount of a product that is expected by calculations to be obtained assuming the limiting reactant is completely consumed.
  - Side reactions usually reduce the yield than calculations.

- **Actual yield:** the amount of a product that is obtained actually.

$$\textit{Percent Yield}, \% = \frac{\textit{Actual Yield}}{\textit{Theoritical Yield}} \times 100$$

Exercise

- Methanol (CH_3OH) is the simplest alcohol. It is used as a fuel in race cars and is a potential replacement for gasoline. Methanol can be manufactured by combining gaseous carbon monoxide and hydrogen. Suppose 68.5 kg CO(g) is reacted with 8.60 kg H_2(g).
  - Calculate the theoretical yield of methanol?
  - If 3.57×10^4 g CH_3OH is actually produced, what is the percent yield of methanol?

Solution

Balanced equation

$$2H_2\,(g) + CO\,(g) \rightarrow CH_3OH\,(l)$$

Convert mass to moles

$$68.5\,kg\,CO \times \frac{1000\,g\,CO}{1\,kg\,CO} \times \frac{1\,mol\,CO}{28.02\,g\,CO} = 2.44 \times 10^{3}\ mol\,CO$$

$$8.60\,kg\,H_2 \times \frac{1000\,g\,H_2}{1\,kg\,H_2} \times \frac{1\,mol\,H_2}{2.016\,g\,H_2} = 4.27 \times 10^{3}\ mol\,H_2$$

Which is limiting

$$For\ H_2 = \frac{Moles\ available}{Stoichiometry} = \frac{4.27 \times 10^{3}}{2} = 2.135 \times 10^{3}$$

$$For\ CO = \frac{Moles\ available}{Stoichiometry} = \frac{2.44 \times 10^3}{1} = 2.44 \times 10^3$$

H_2 *is limiting*

The theoretical Yield

$H_2 : CH_3OH = 2:1$

$$2.135 \times 10^3\ \text{mol}\ CH_3OH \times \frac{32.04\ g\ CH_3OH}{1\ \text{mol}\ CH_3OH}$$

$$= 6.86 \times 10^4\ g\ CH_3OH$$

$$Percent\ Yield, \% = \frac{Actual\ Yield}{Theoritical\ Yield} \times 100$$

$$= \frac{3.57 \times 10^4\ g}{6.86 \times 10^4\ g} \times 100 = 52\%$$

Exercise

Consider the equation

$$2A + B \rightarrow A_2B$$

If you mix 1.0 mole of A with 2.0 mole of B, the number of moles of A_2B produced if the reaction is 100 % complete is -------

A is the limiting reactant

⇒ 0.5 mole A_2B produced

Exercise

Consider the following equation

$$2A + B \rightarrow AC$$

Which of the following formula for molar masses can be correct?

- ❑ ***C = A + B*** ➡ √ ***For Balanced eqn.***
- ❑ ***B = 2C*** ➡ √ ***Unbalanced eqn.***
- ❑ ***2A + B = AC*** ➡ √ ***For Balanced eqn.***
- ☑ ***All of them***

Exercise

A limiting reactant in a chemical reaction

- ❑ has the lowest coefficient in a balanced equation. ×
- ❑ has the lowest ratio of moles available/coefficient in the balanced equation. √
- ❑ has the lowest ratio of coefficient in the balanced equation/moles available. ×

Ideal Gases

The state of a gas can be fully described in terms of 4 variables (Mass, Volume, Pressure, Temperature). By knowing 3 of them, the fourth can be calculated

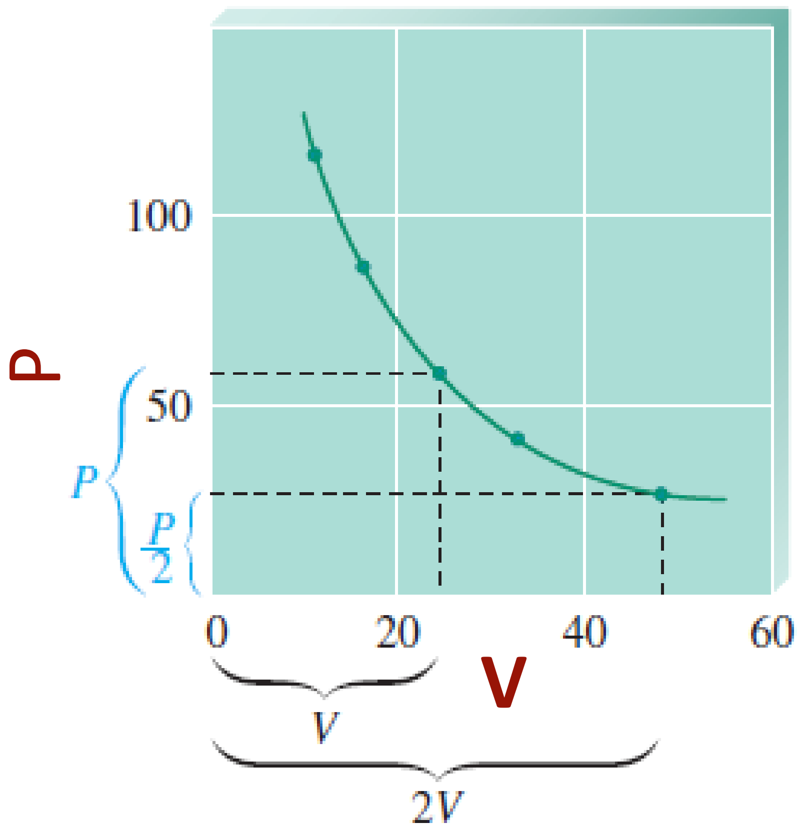
Boyle's Law

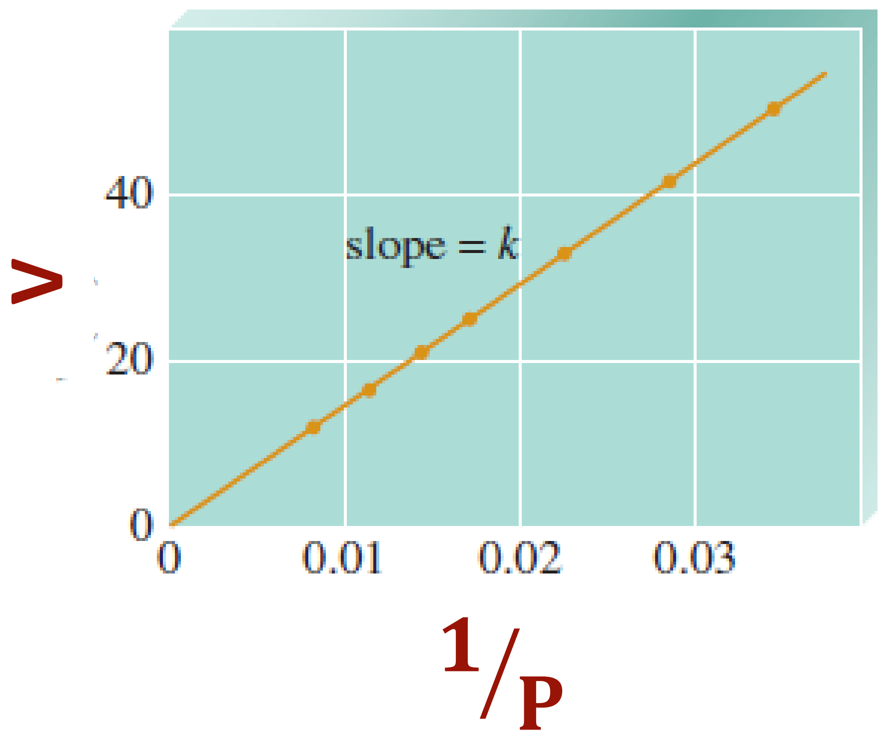
$$V \propto \frac{1}{P}$$

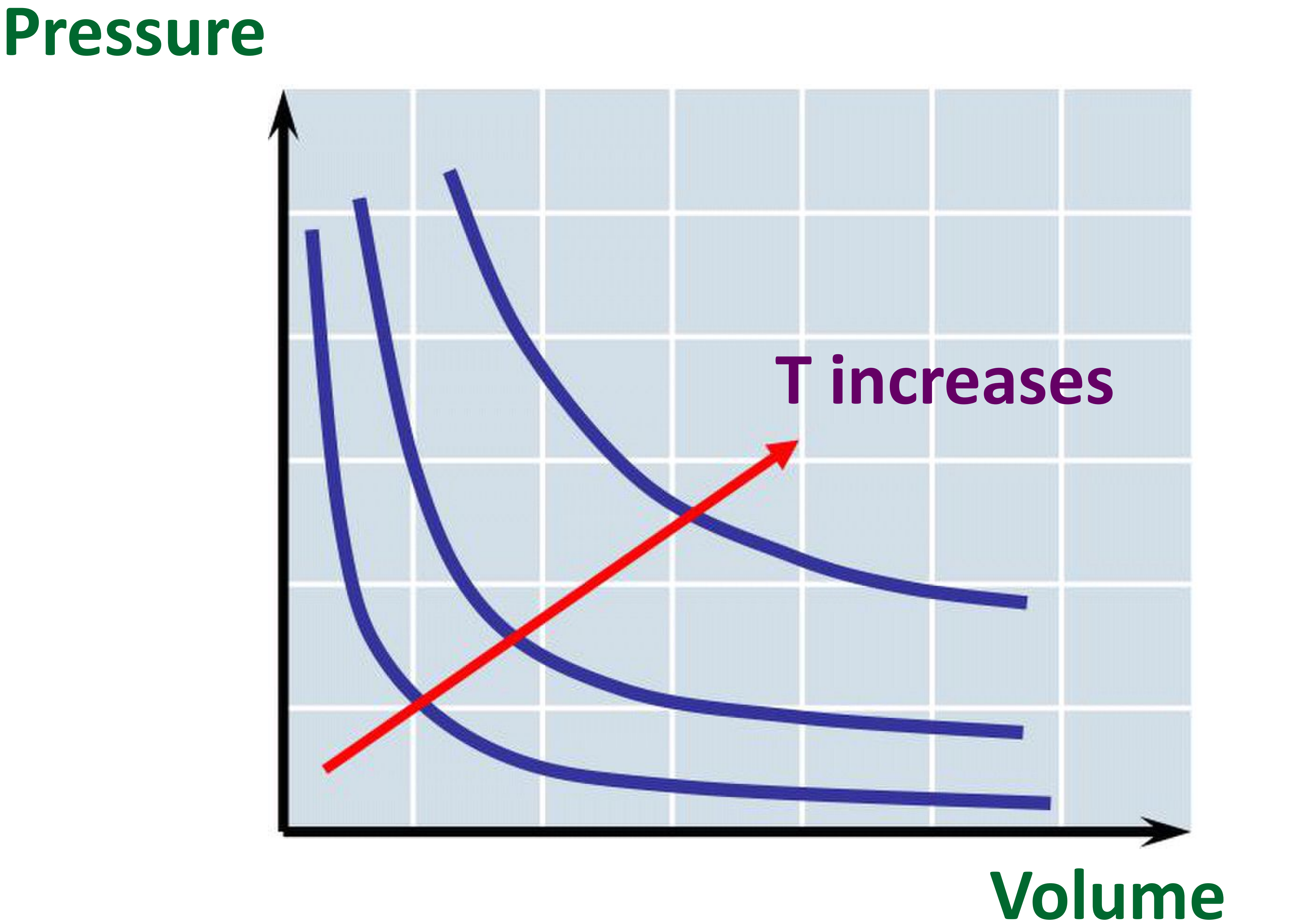
$$PV = \text{const. } (k)$$

$$P_1V_1 = P_2V_2$$

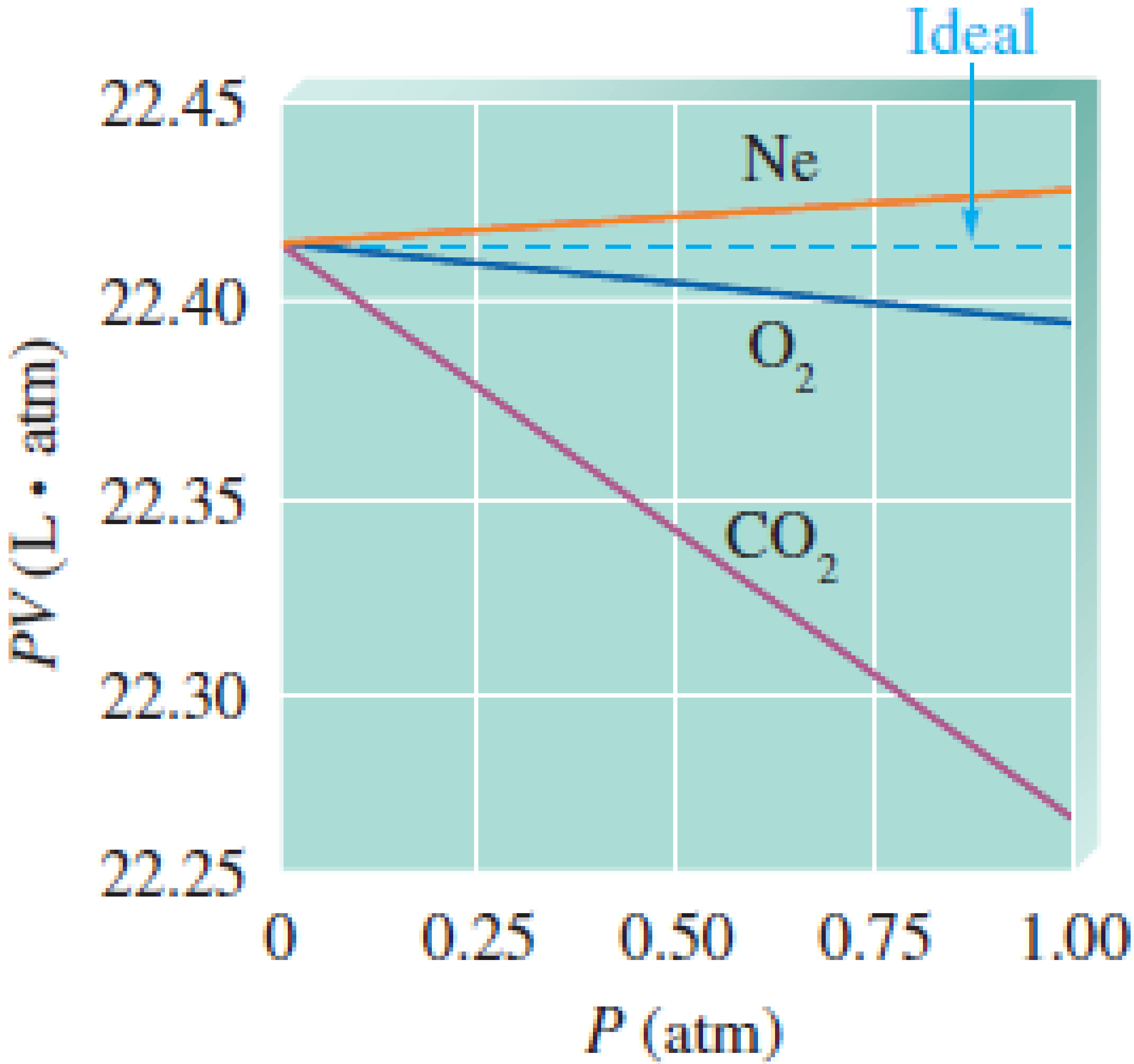
At a constant temperature, the volume of a fixed amount of gas is inversely proportional to its pressure.






Pressure
T increases
Volume

Boyle's Law holds precisely only at very **low P**



Exercise

Sulfur dioxide (SO_2), a gas that plays a central role in the formation of acid rain, is found in the exhaust of automobiles and power plants. Consider a 1.53 L sample of gaseous SO_2 at a pressure of 5.6×10^3 Pa. If the pressure is changed to 1.5×10^4 Pa at a constant temperature, what will be the new volume of the gas?

$P_1 = 5.6 \times 10^3 Pa$ → $V_1 = 1.53 L$

$P_2 = 1.5 \times 10^4 Pa$ → $V_2 = ? L$

$$P_1V_1 = P_2V_2$$

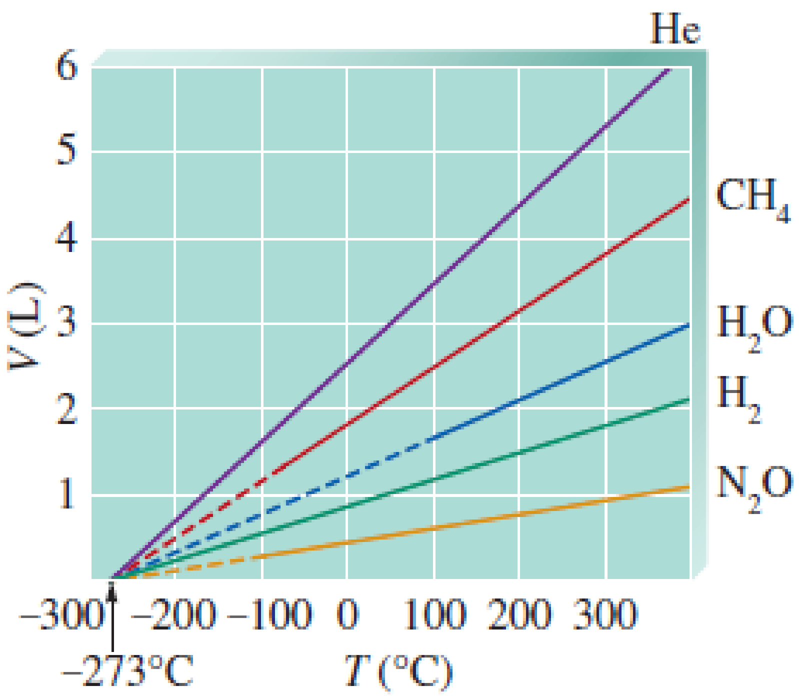
$$V_2 = \frac{P_1V_1}{P_2} = \frac{5.6 \times 10^3 \, \cancel{Pa} \times 1.53 L}{1.5 \times 10^4 \, \cancel{Pa}} = 0.57 L$$

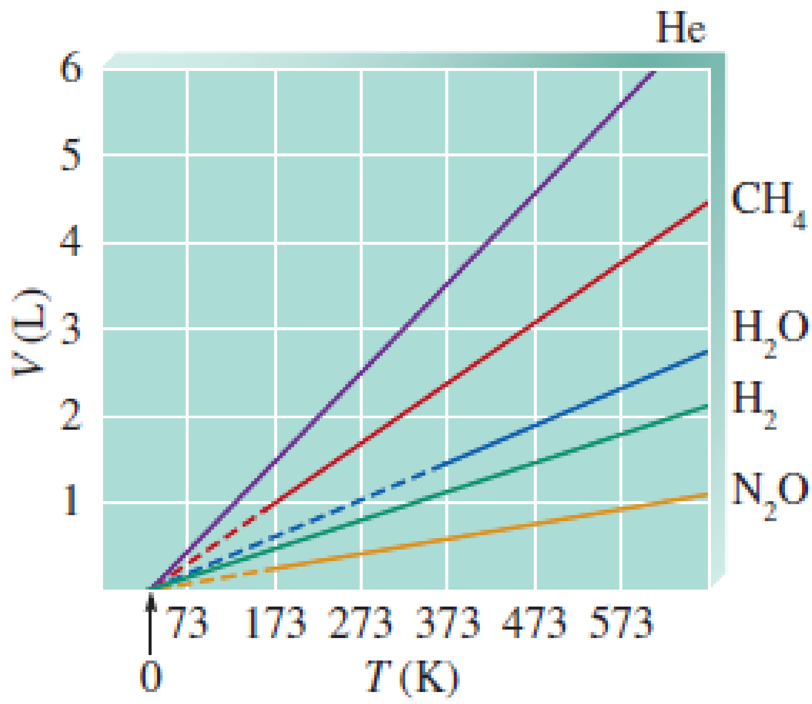
V decreases √

Charles's Law

$$V \propto T \qquad \frac{V}{T} = k \qquad \frac{V_1}{T_1} = \frac{V_2}{T_2}$$

The volume of a fixed amount of a gas at a constant pressure increases linearly with the gas temperature





- **Different Slopes**: because of different numbers of moles of gas.
- Volumes of gases extrapolate to **ZERO** at –273°C = 0 K (absolute Zero)

Exercise

A sample of gas at 15°C and 1 atm has a volume of 2.58 L. What volume will this gas occupy at 38°C and 1 atm?

Solution

P and n = constant

$V_1 = 2.58L$ → $T_1 = 15^{o}C + 273 = 288K$

$V_2 = ?L$ → $T_2 = 38^{o}C + 273 = 311K$

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

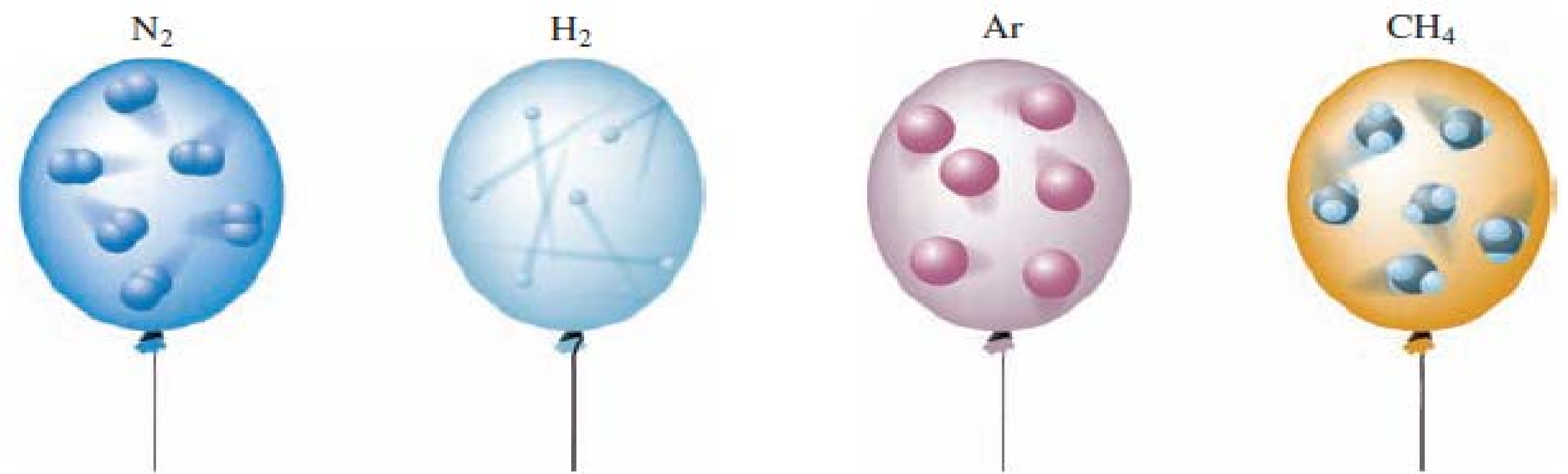
$$V_2 = \frac{V_1 T_2}{T_1} = \frac{2.58L \times 311\cancel{K}}{288\cancel{K}} = 2.79L$$

V increases √

Avogadro's Law

$V \propto n$ $\frac{V}{n} = k$ $\frac{V_1}{n_1} = \frac{V_2}{n_2}$

- Equal volumes of gases at the same temperature and pressure contain the same number of "particles".
- For a gas at constant T and P, the volume is directly proportional to its number of moles.



Exercise

P and T = constant

Suppose we have a 12.2 L sample containing 0.50 mole of oxygen gas (O_2) at a pressure of 1 atm and a temperature of 25°C. If all this O_2 were converted to 0.33 mole of ozone (O_3) at the same temperature and pressure, what would be the volume of the ozone?

Solution

$V_1 = 12.2L$ → $n_1 = 0.5\,\text{mol}\,O_2$

$V_2 = ?L$ → $n_2 = 0.33\,\text{mol}\,O_3$

$$\frac{V_1}{n_1} = \frac{V_2}{n_2}$$

$$V_2 = \frac{V_1 n_2}{n_1} = \frac{12.2L \times 0.33\,\text{mol}}{0.5\,\text{mol}} = 8.1L$$

V decreases √

Exercise

Ammonia burns in oxygen to form nitric oxide (NO) and water vapor. How many volumes of NO are obtained from one volume of ammonia at the same temperature and pressure?

Solution

$$4NH_3 + 5O_2 \longrightarrow 4NO + 6H_2O$$

$$1 \text{ mole } NH_3 \longrightarrow 1 \text{ mole } NO$$

$$P \text{ and } T = \text{constant}$$

$$1 \text{ volume } NH_3 \longrightarrow 1 \text{ volume } NO$$

The Ideal Gas Law

Boyle's law: $V = \frac{k}{P} \quad (constant\ T, n)$

Charles's law: $V = bT \quad (constant\ P, n)$

Avogadro's law: $V = an \quad (constant\ T, P)$

$$V = R\left(\frac{Tn}{P}\right)$$

$$PV = nRT$$

Equation of state for gases

R : Universal gas constant

$$R = \frac{0.08206\ L\ atm}{K\ mol}$$

This equation is mostly obeyed at low pressures and high temperatures

Universal Gas Constant

$$R = \frac{PV}{nT} = \frac{1\ \text{atm} \times 22.414\ \text{L}}{1\ \text{mol} \times 273.15\ \text{K}} =$$

$$0.082057\ \text{L atm K}^{-1}\ \text{mol}^{-1}$$

$$= 82\ \text{mL atm K}^{-1}\ \text{mol}^{-1}$$

$$= 8.314\ \text{J K}^{-1}\ \text{mol}^{-1}$$

$$= 2.0\ \text{cal K}^{-1}\ \text{mol}^{-1}$$