Thermal Physics Theory
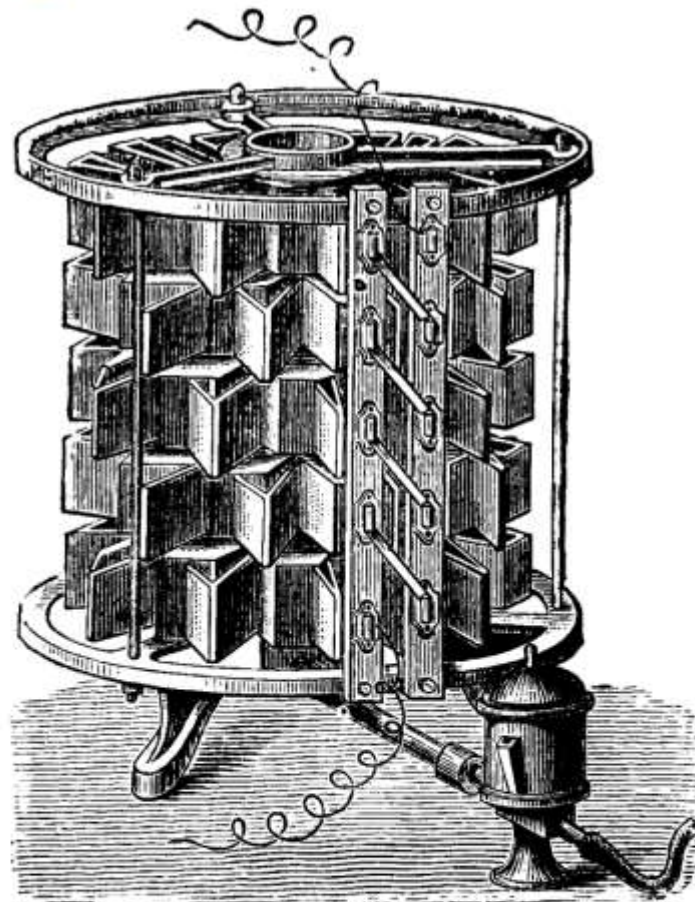
Temperature And Energy Transfer

Heat:

Heat is a form of energy related to the kinetic energy of molecules.

Temperature And Thermal Equilibrium:

Temperature is the degree of hotness or coldness of a body. It is the gradient which decides the direction of heat flow.

- It is a scalar.
- SI unit is kelvin(K). More generally centigrade or Fahrenheit is used.

Two objects are said to be in **thermal equilibrium** if the two bodies are of the same temperature. Then, no heat flows between them.

Absolute Temperature:

The temperature in kelvin scale is absolute temperature. At absolute zero temperature (0K), the molecular motion stops completely.

$$T(K) = T(°C) - 273.15$$

Heat Transfer:

Heat transfer can happen in three ways

1. Conduction: Conduction happens when the bodies are in contact. The vibrating molecules of a higher temperature body pass on the energy to lower temperature molecules. Metals are good conductors and gases are poor conductors of heat.
2. Convection: This occurs in fluid. When heat is being supplied to a fluid, the density of the hotter part decreases (due to expansion) and moves to the upper part forcing the cooler part downwards. This flow of fluid is called convection current.
3. Radiation: Through this process, the heat can directly be transferred without any medium or contact. This occurs by emission and absorption of infrared radiation.

Thermal Capacity:

Thermal capacity of a body is the amount of heat required to raise its temperature by 1°C.

Unit: $J°C^{-1}$ or JK^{-1}.
If the temperature of a body changes by ΔT when Q amount of heat is supplied, its thermal capacity is s $C = Q/\Delta T$.

E.g.: How much heat is required to raise the temperature of a quantity of water from 20°C to 100°C if its thermal capacity is 5000JK^{-1}.
Answer.
Rearranging the definition of thermal capacity
$Q = C \times \Delta T = 5000 \times (100 - 20) = 400kJ$

E.g.: How much heat is lost from a block of metal if its temperature drops from 60° to 20°C if its thermal capacity is 800JK^{-1}.
Answer.
Heat lost $= -C\Delta T = 800 \times (60 - 20) = 32kJ$

Specific Heat Capacity:

The specific heat capacity of a material if the amount of heat required to raise the temperature of unit mass of substance by 1°C.
Unit is $Jkg^{-1}K^{-1}$ or $Jkg^{-1}°C^{-1}$.
If the temperature of a body of mass m changes by ΔT when Q amount of heat is supplied, its thermal capacity is $c = Q/m\Delta T$

Understand the difference between thermal capacity and specific heat capacity by understanding the factors on which the quantities depend.

E.g.: How much heat will be required to heat 300g of water from 20°
to 60°C if the specific heat of water is 4200 $Jkg^{-1}K^{-1}$.

Answer.
$c = Q/m\Delta T$
$Q = mc\Delta T = 0.3 \times 4200 \times (60 - 20) = 50.4kJ$

E.g.: A car of mass 1500 kg travelling at 20 ms^{-1} brakes suddenly
and comes to a stop.
a) How much KE does the car lose?
b) If 75% of the energy is given to the front brakes, how much
energy will they receive?
c) The brakes are made out of steel and have a total mass of 10 kg.
By how much will their temperature rise if the specific heat of steel
is 440 $Jkg^{-1}K^{-1}$?

Answer.
a) The KE of the car is s $(1/2)mv^2 =(1/2)\times 1500 \times 20^2 = 300kJ$
b) 75% of 300 kJ is 225kJ.
c) From the definition of specific heat capacity,
Raise in temperature of brakes $\Delta T = Q/mc = 225000 /440\times10 =$
51.13K

E.g.: A piece of iron of mass 0.133kg at temperature θ is transferred
to 0.476kg of water at 16°C. The temperature of water rises to 45°C.
The specific heat capacities of water and iron are 4200 $Jkg^{-1}K^{-1}$ and
540 $Jkg^{-1}K^{-1}$ respectively.
a) Find the energy transfer in terms of θ from iron.
b) Find the energy transferred to water.
c) Using your answers, determine θ.

Answer.
a) Energy lost by iron block = $mc\Delta T = 0.133 \times 540 \times (θ - 45) = 60 \times (θ - 45)$
b) Energy gained by water = $0.476 \times 4200 \times (45-16) = 5.8 \times 10^4 J$

c) Assuming that no energy is lost,

$60 \times (\theta - 45) = 58000$

$\theta = 1000°C$

Phase Change:

Phase change takes place at constant temperature. The heat transferred during this process deals with changing potential energy of molecules. The energy transferred per unit mass of substance to change its phase is called specific latent heat.

- **Specific latent heat of vaporisation** is the amount of heat required to convert unit mass of substance from liquid to gas at constant temperature.
- **Specific latent heat of fusion** is the amount of heat required to convert unit mass of substance from solid to liquid at constant temperature.
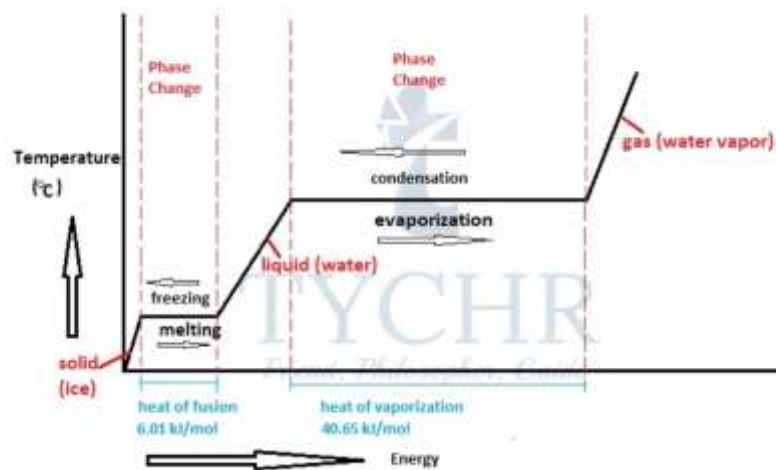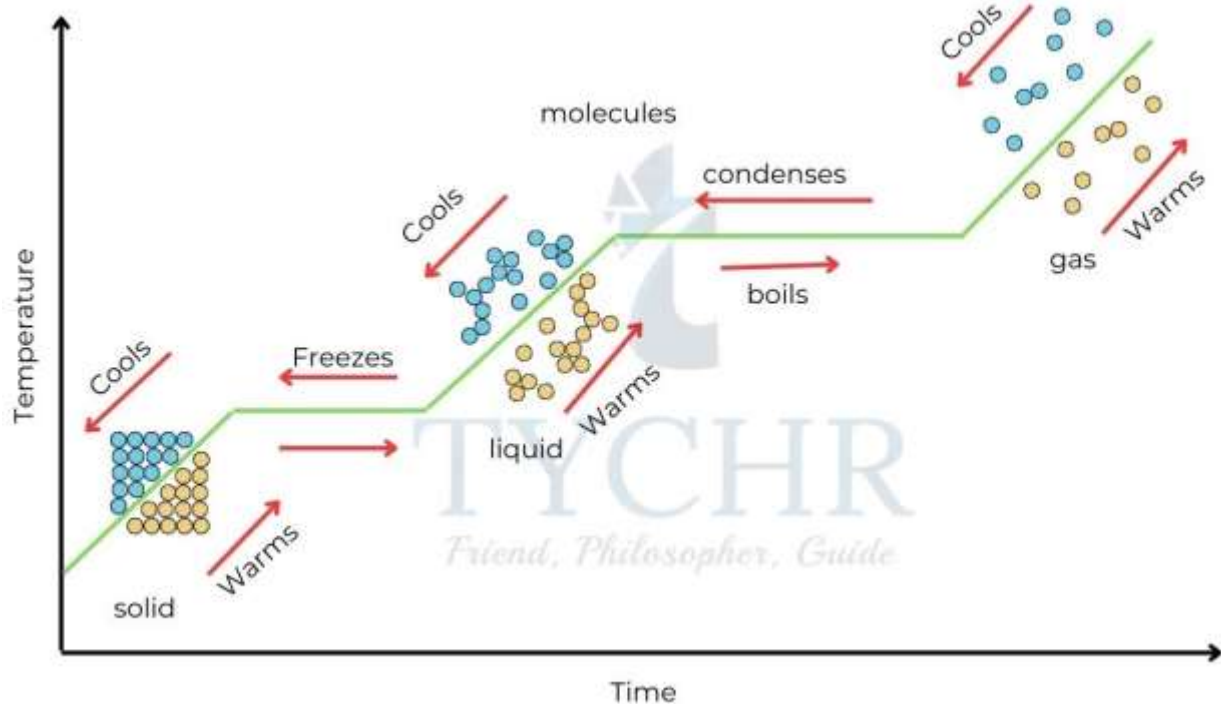

If Q is the amount of heat required for a substance of mass m for phase change,

Latent heat at $L = Q/m$.

Graphical Representation Of Phase Change:

Consider a substance initially in solid state. Heat is supplied to the substance at a constant rate and the temperature of the substance is plotted against time.

Graph showing Phase Change

The regions of non-horizontal lines represent temperature change at corresponding states.
Horizontal lines represent phase change. They are horizontal because temperature does not change even though heat is supplied during phase change.

E.g.: How much energy is released when 500g of water is converted into ice at constant temperature if specific latent heat of fusion of water is 3.35×10^5 Jkg^{-1}.

Answer.
From the definition of latent heat,
$Q = mL = 0.5 \times 3.35 \times 10^5 = 1.675 \times 10^5$J

E.g.: A heater is used to boil a liquid in a pan for a measured time. The following data are available.

Power rating of heater = 25 W

Time for which liquid is boiled = 6.2×10^2 s

Mass of liquid boiled away = 4.1×10^{-2} kg

Use the data to determine the specific latent heat of vaporization of the liquid.

Answer.

The amount of heat supplied to water is $25 \times 6.2 \times 10^{-2} = 15.5 kJ$

Latent heat of vaporisation = $Q/m = (15.5 \times 10^3)/(4.1 \times 10^{-2}) = 3.8 \times 10^5 Jkg^{-1}$

Modelling A Gas
Avogadro's Hypothesis And Mole:

Avogadro's hypothesis states that equal volumes of all gases contain equal number of molecules at same temperature and pressure.

Mole is a unit for quantity of substance. It is equal to the number of atoms present in 12g of carbon-12 isotope. It is equal to 6.022×10^{23}. **Molar mass** of a substance is the mass of 1 mole of substance.

E.g.: 1 mole of carbon has a mass of 12g. How many atoms are present in 2g?

Answer.

One mole contains 6.022×10^{23} atoms.

2 grams is $(1/6)^{th}$ of a mole. So, it contains $(1/6) \times 6.022 \times 10^{23} = 1.003 \times 10^{23}$ atoms.

E.g.: The density of iron is $7874 kgm^{-3}$. What is the volume occupied by one mole of iron if its molar mass is 55.85g?

Answer.

$Volume = mass/density = 0.05585 / 7874 = 7.093 cm^3$

Ideal Gas:

Few assumptions are made in developing theories for gases. These are

- The molecules are perfectly elastic.
- The molecules are perfect spheres.
- Molecules are identical.
- There are no forces between molecules. This implies that internal energy of gases is only due to kinetic energy and not due to potential energy.
- The molecules are very small. The volume occupied by molecules is negligible compared to the volume occupied by the gas.

Defining The State Of Gas:

Three variables are necessary and sufficient to completely describe the state of gas.

Volume: Volume of a gas is the volume of the container in which it is held.

Temperature: The temperature of gas is directly proportional to the average kinetic energy of gas molecules.

The **total kinetic energy** of N molecules of gas at temperature T is $(3/2)NkT$. Here k is the **Boltzmann constant** and has a value of $1.38 \times 10^{-23} JK^{-1}$.
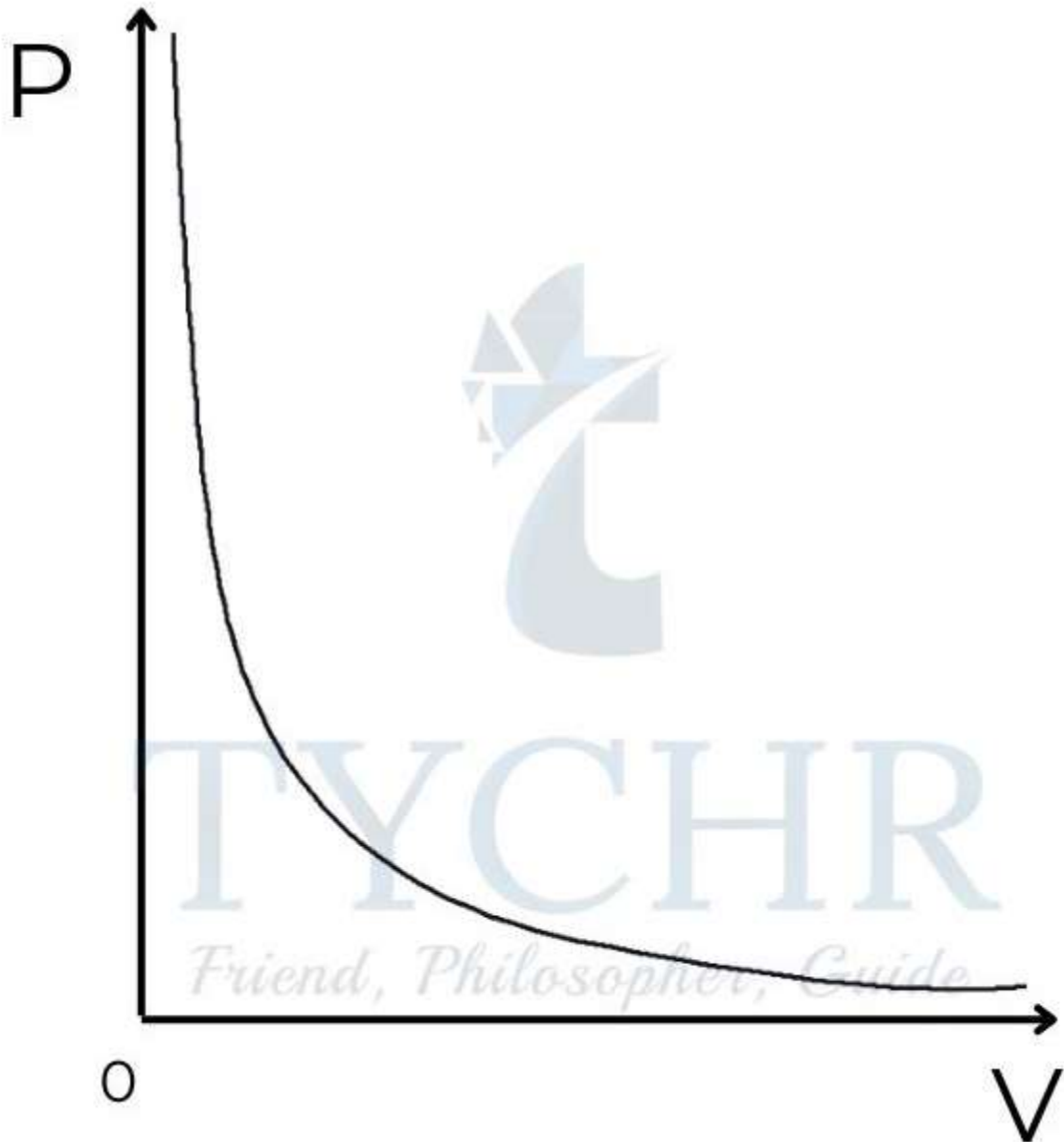
Pressure: The pressure of a gas is the force exerted per unit area. It is a scalar and is uniform through the gas.

Gas laws:

Boyle's law:

The pressure of a fixed amount of gas at constant temperature is inversely proportional to its volume.

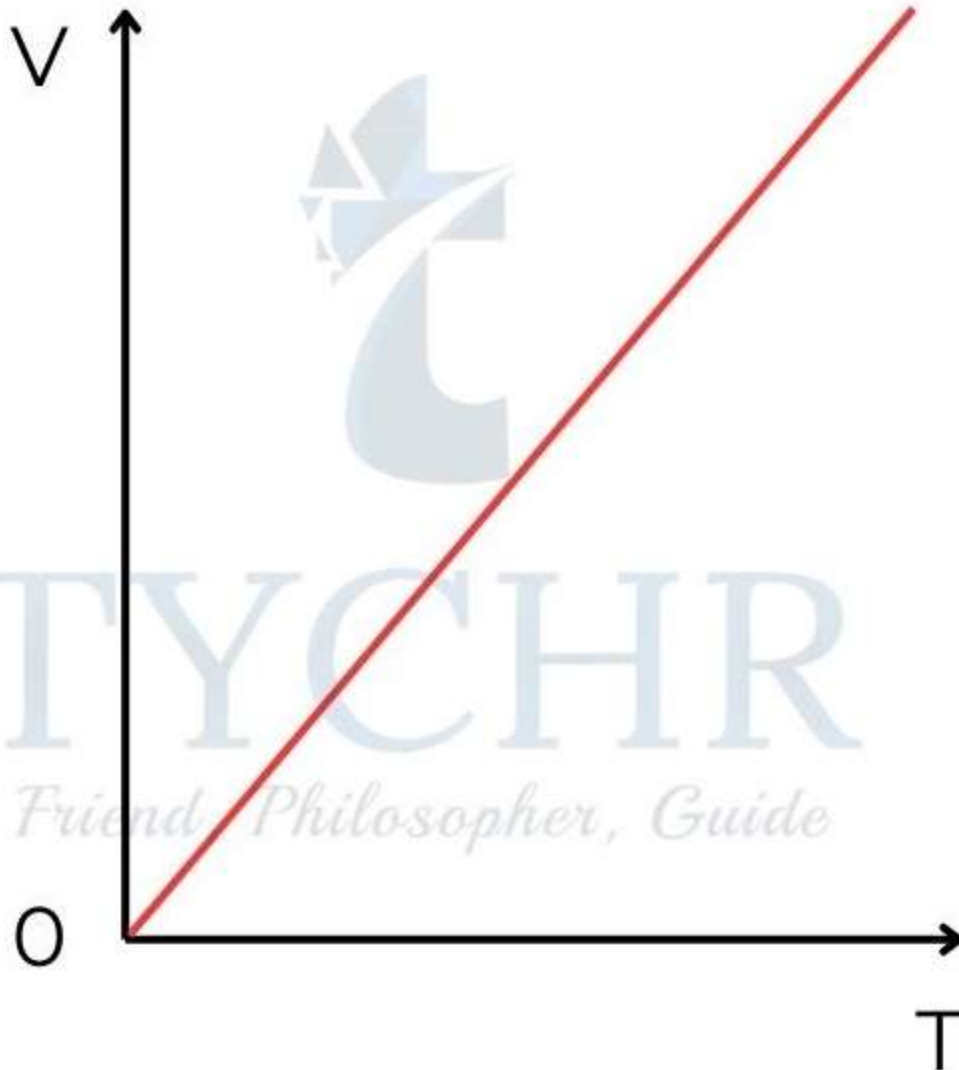$P \alpha \left(1/V\right)$ *at constant* T

Boyle's Law

Graph of pressure against volume for a gas at constant temperature.

Charles law:
For a fixed amount of mass at constant pressure, the volume occupied by a gas is directly proportional to absolute temperature.
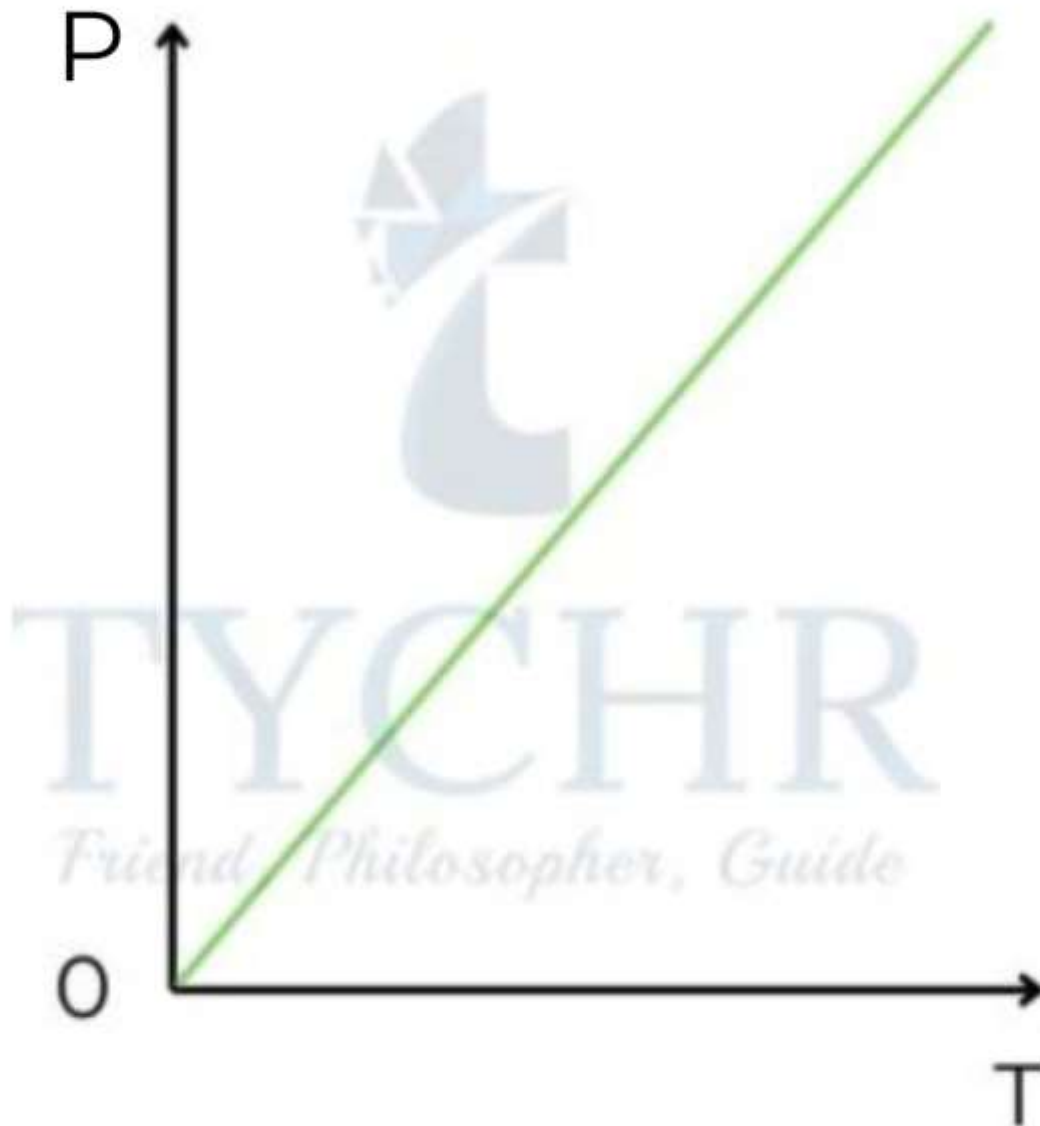*V α T at constant pressure*

Charles Law
Graph of volume against temperature at constant pressure

Gay-Lussac's law:

The pressure of a constant amount of gas contained with constant volume is directly proportional to the absolute temperature of gas.

$P \propto T$ *at constant volume*

Graph of pressure against temperature at constant volume

Combining the three laws and Avogadro's hypothesis, we get the ideal gas equation.

$PV/nT = constant = R$

$PV = nRT$

R is called **universal gas constant** and has a value of 8.314 J mol^{-1} K^{-1}.

E.g.: The pressure of a gas inside a cylinder is 300 kPa. If the gas is compressed to half its original volume and the temperature rises from 27 °C to 327 °C, what will its new pressure be?

Answer.
Using the ideal gas equation, PV = nRT
$(P \times 0.5V)/(327 + 273) = (300 \times V)(27 + 273)$
$P = 1200 kPa$

E.g.: Calculate the percentage change in volume of a fixed mass of an ideal gas when its pressure is increased by a factor of 2 and its temperature increases from 30 °C to 120 °C.
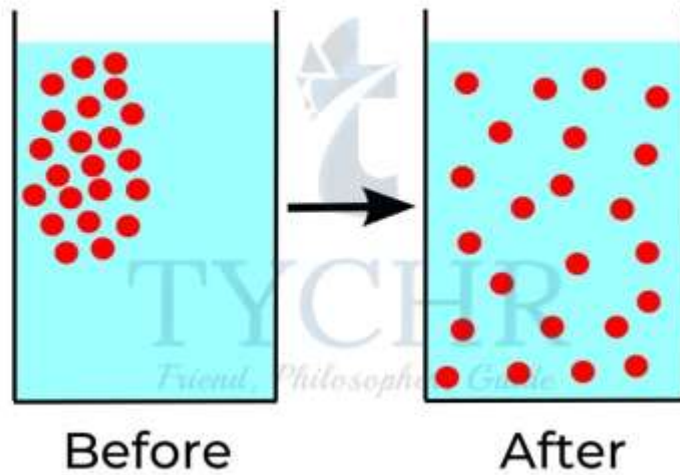**Answer.**

$$\frac{P_1 V_1}{T_1} = \frac{P_2 V_2}{T_2}$$

$PV/T = constant$ $\quad \frac{V_2}{V_1} = \frac{P_1}{P_2}\frac{T_2}{T_1} = \frac{1}{2}\frac{393}{293} = 0.65$

The volume of gas decreases by 35%.

Microscopic Interpretation Of Gases:

Diffusion: It is the process through which gases from one place to another. The gas molecules collide with surrounding air molecules and move through out air.

Before   After

Brownian movement: Small particles like smoke or pollen grains move in shot straight lines of irregular pattern which can be observed through a microscope. This is due to bombardment of smoke particles by air molecules.
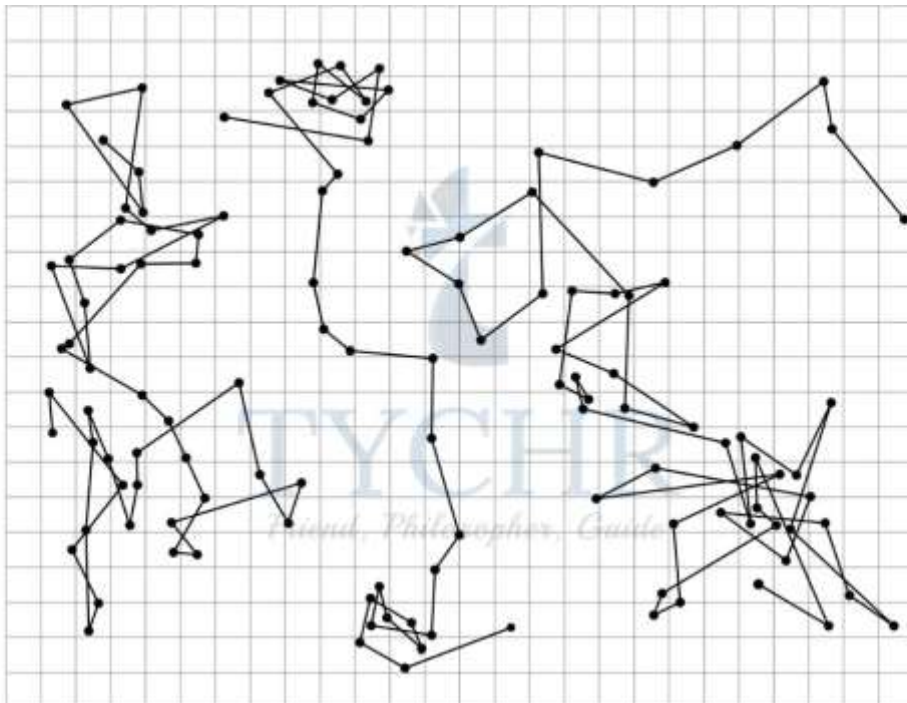
instead of motion, write movement

Root mean square speed of a gas: The root mean square is the mean velocity of the gas as a whole. For a group of n molecules,

$c = \sqrt{(\sum_{i=1}^{n} c_i^2 n)/n}$

The pressure of a gas is related to the root mean square speed as

$P = (1/3)\rho c^2$

E.g.: Nitrogen gas is sealed in a container at a temperature of 320 K and a pressure of 1.01×10^5 Pa.

a) Calculate the mean square speed of the molecules.

b) Calculate the temperature at which the mean square speed of the molecules reduces to 50% of that in a). Mean density of nitrogen gas over the temperatures considered = 2 kgm^{-3}

Answer.

a) $c = (3P/\rho) = (3 \times 1.01 \times 10^5)/1.2 = 25.3 \times 10^5 m^2 s^{-2}$

b) $c^2 \alpha$ So, the mean square speed reduces to 50% at 50% of temperature − at 160K.

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WWW.TYCHR.COM

+91 9540653900