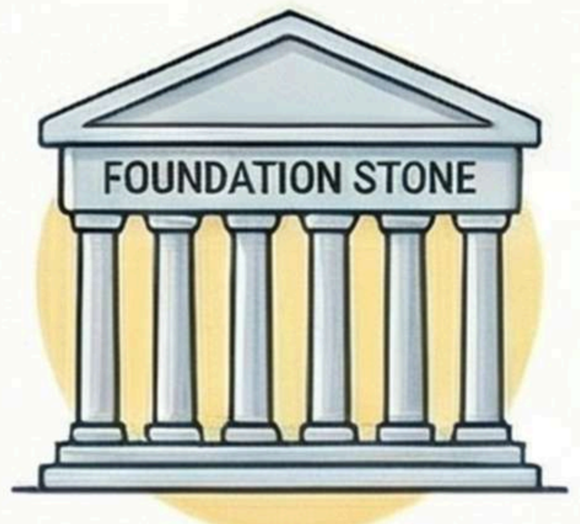
Excellency
The Experience

Subject Expo

Units, Measurement & Motion

The International System of Units (SI)



A Universal Language for Measurement

The SI is the internationally accepted system of units for scientific, technical, and commercial work, based on seven fundamental quantities.

Units are categorized as Base or Derived.

Base units are the fundamental units (e.g., metre). Derived units are combinations of base units (e.g., metre/second).

BASE QUANTITY	SI UNIT NAME	SYMBOL
Length	metre	m
Mass	kilogram	kg
Time	second	s
Electric Current	ampere	A
Thermodynamic Temperature	kelvin	K
Amount of Substance	mole	mol
Luminous Intensity	candela	cd

Mastering Significant Figures

What Are Significant Figures?

They are the digits in a measurement that are known reliably plus the first uncertain digit, indicating the measurement's precision.

Rules for Identifying Significant Figures

Non-zero digits are always significant.	45.2 has 3
Zeros between non-zero digits are significant.	10.2 has 3
Leading zeros are NOT significant.	0.005 has 1
Trailing zeros are significant ONLY if there is a decimal point.	5.300, 0.070

The Scientific Notation Solution

To avoid ambiguity, express as a x 10^b.
All digits in 'a' are significant
(e.g., 1.2500 x 103 has 5).

The Rule for Multiplication & Division

result has SAME significant figures as the number with the LEAST significant figures.

The Rule for Addition & Subtraction

result has SAME decimal places as the number with the LEAST decimal places.

Rounding Off Rules

- If digit > 5, increase preceding by 1.
- If < 5, leave unchanged.
- If IT IS 5, round preceding to nearest even number (e.g., 2.745 → 2.74; 2.735 → 2.74).

Dimensional Analysis

The 'Dimensions' of a Quantity

The dimensions are the base quantities [M], [L], [T], [A], [K], [mol], [cd] raised to powers representing a physical quantity.
Example: Velocity is [LT-1].

Principle of Homogeneity

An equation is dimensionally correct only if the dimensions of all terms on both sides are the same.

Application 1: Checking Equation Consistency

Use to verify plausibility, dimensionally inconsistent must be wrong.

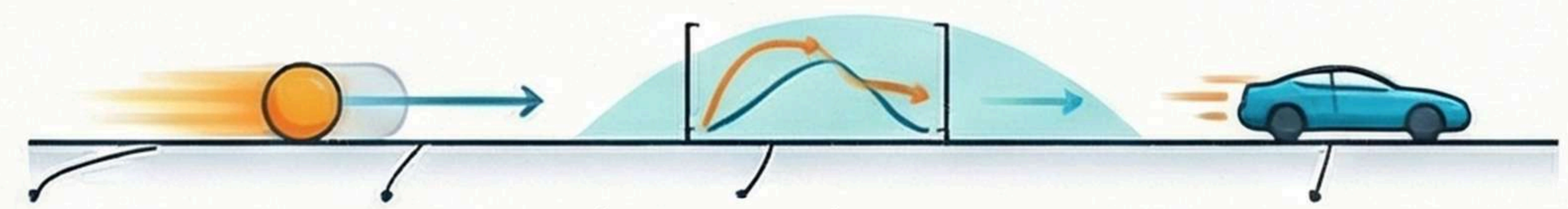
Application 2: Deducing Relationships

Derive a formula assuming product-type dependence.

Important Limitation

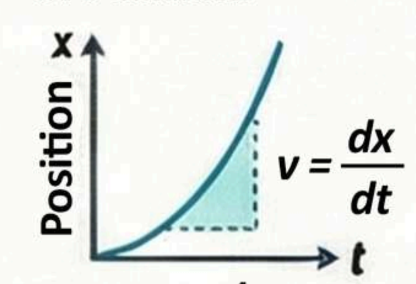
Cannot determine value of dimensionless constants like 2, π.

Describing Motion in a Straight Line



Velocity:

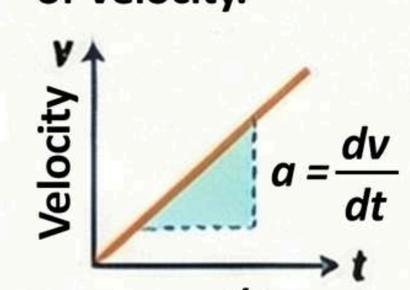
The Rate of Change of Position.



$v = \frac{dx}{dt}$

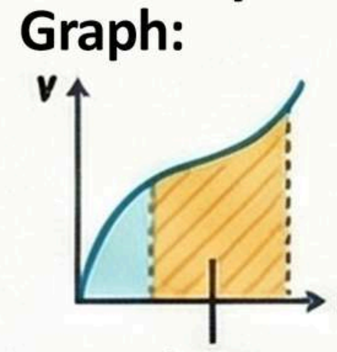
Acceleration:

The Rate of Change of Velocity.



$a = \frac{dv}{dt}$

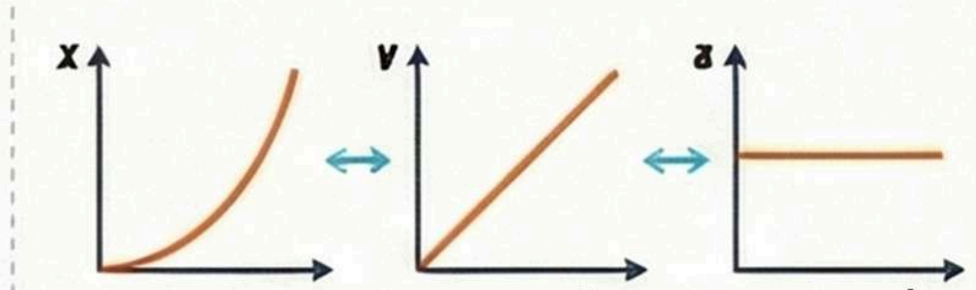
The Area Under a Velocity-Time Graph:



Displacement during interval.

Interpreting Motion Graphs

For uniform acceleration:



x-t graph: (parabola) v-t graph: (straight inclined line) a-t graph: (horizontal line)

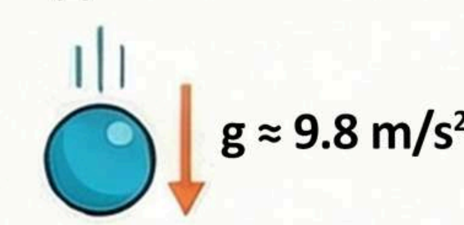
Key Equations for Uniform Acceleration

The Kinematic Equations of Motion

These five equations relate displacement (s), time (t), initial velocity (V_2), final velocity (v), and constant acceleration (a).

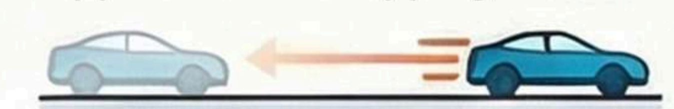
1. $V = V_0 + at$
2. $x = V_0t + 1/2at^2$
3. $v^2 = v_0^2 + 2ax$

Application 1: Free Fall



Constant acceleration downward.

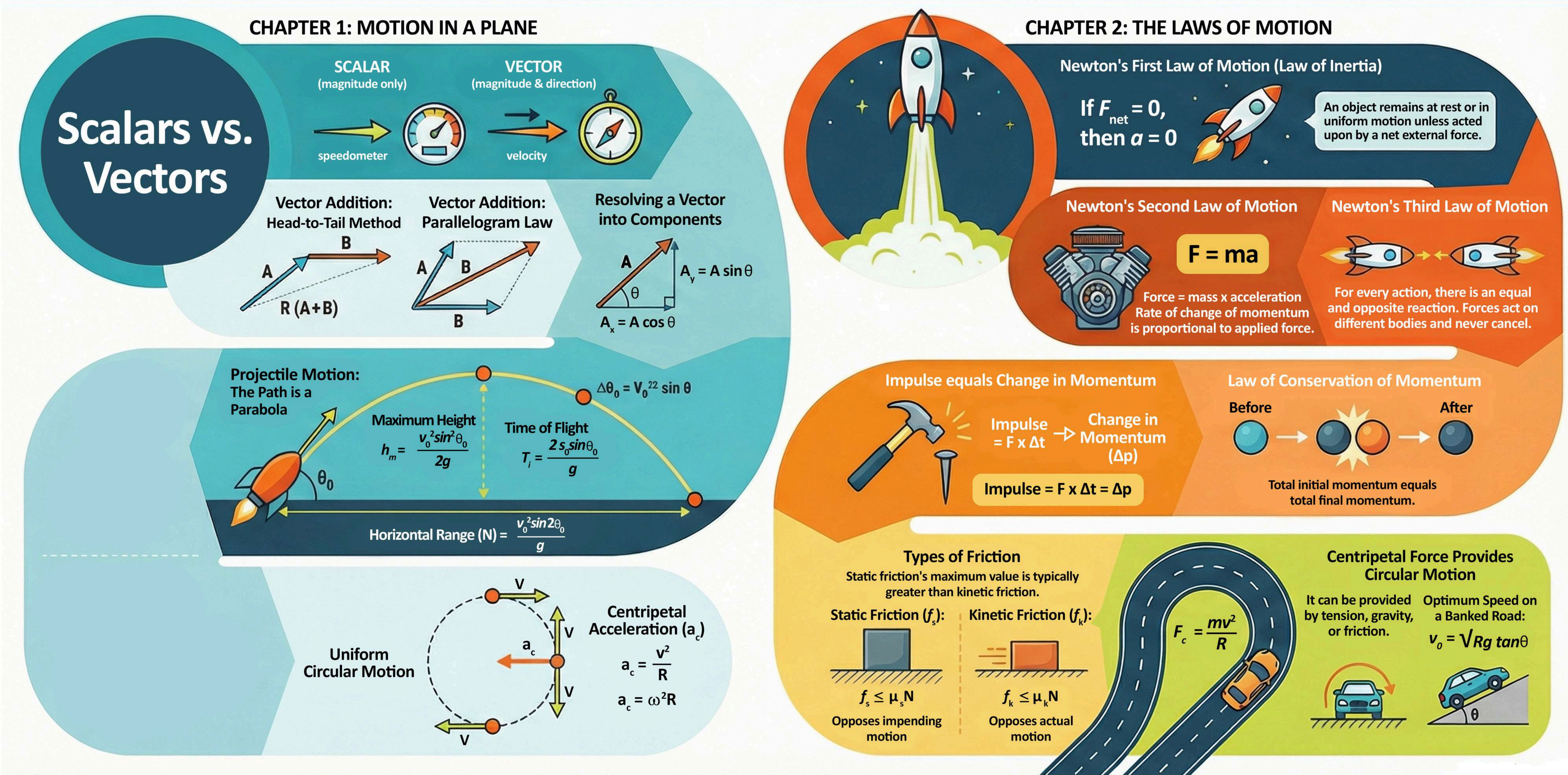
Application 2: Stopping Distance



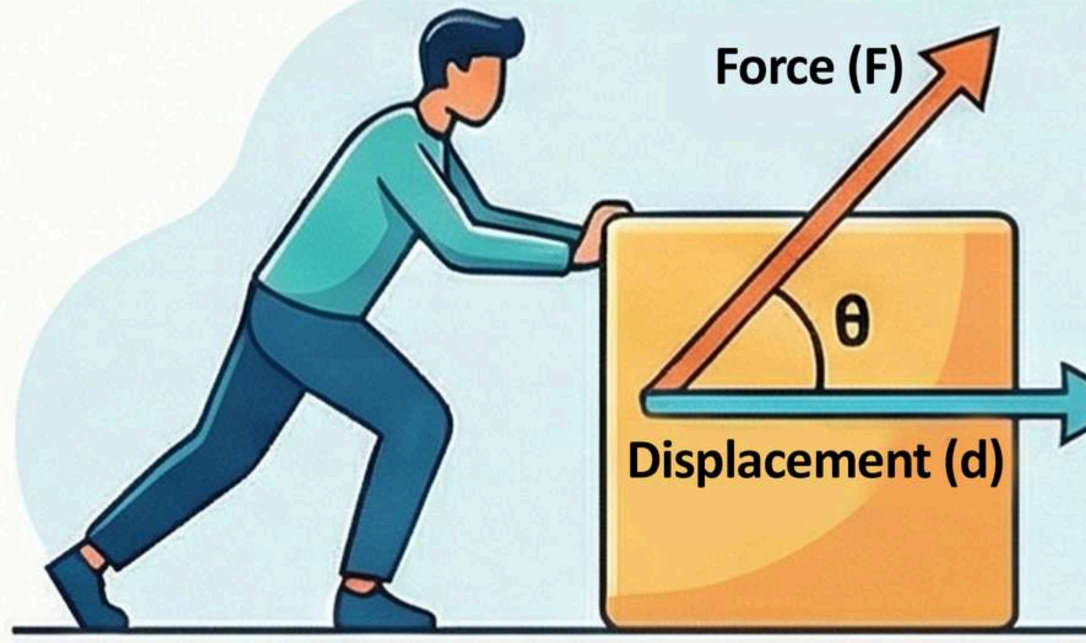
$d = -\frac{v_0^2}{2a}$

Distance is proportional to the square of initial speed.

Motion in a Plane



Work, Energy, and Power



1. THE PHYSICS OF WORK

What is Work?

Work is done by a force on an object when the object undergoes a displacement. It is the product of the component of the force in the direction of displacement and the magnitude of the displacement.

Calculating Work Done

$W = F.d = Fd\cos(\theta)$

When is No Work Done?

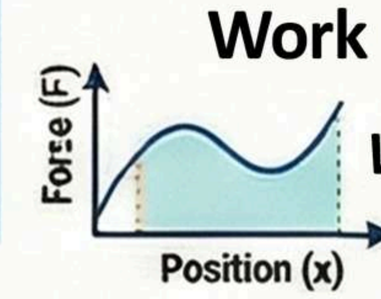
1) Displacement is zero (e.g., pushing a wall).
2) The net force is zero.
3) The force is perpendicular to the displacement (0 = 90°, cos 90° = 0).

Positive vs. Negative Work

Positive: $0° \leq \theta \leq 90°$

Negative: $90° < \theta \leq 180°$ (eg., friction)

Work Done by a Variable Force



$W = \int F(x)dx$

Unit of Work & Energy: The SI unit is the Joule (J)

2. FORMS OF MECHANICAL ENERGY

Kinetic Energy (K)

The energy an object possesses due to its motion. It is a scalar quantity.

$K = 1/2mv^2$

Potential Energy (V)

Gravitational Potential Energy

$V(h) = mgh$

For an object of mass m at a height h near the Earth's surface

Elastic Potential Energy of a Spring

$V(x) = 1/2kx^2$

Stored in a spring that is compressed or stretched by a distance x from its equilibrium position

3. KEY ENERGY PRINCIPLES

Conservative vs. Non-Conservative Forces

Conservative
Work done depends only on initial and final positions (e.g., gravity, spring).

Non-Conservative
Work done depends on the ipath taken (e.g., friction).

The Work-Energy Theorem

The net work done by all forces acting on a body is equal to the change in its kinetic energy.

$W_{net} = K_{final} - K_{initial} = \Delta K$

Conservation of Mechanical Energy

If forces doing work are conservative, total mechanical energy (E = K + V) remains constant.

$E_{initial} = E_{final}$ or $K_{initial} + V_{initial} = K_{final} + V_{final}$

With non-conservative forces: $\Delta E = W_{nc}$

4. POWER: THE RATE OF WORK

Power is the time rate at which work is done or energy is transferred.

Calculating Power of the formula:

Average Power: $P_{avg} = W/t$

Instantaneous Power: $P = dW/dt = F.v$

Units of Power:

SI unit is the watt (W),
1 W = 1 J/s
1hp ≈ 746W

Kilowatt-hour (kWh) is Energy, Not Power

A unit of energy in billing (1kW = 3.6 x 10^6J).

5. COLLISIONS

Momentum is Always Conserved

In any collision, the total linear momentum of the system is conserved.

Types of Collisions

Elastic: Total kinetic energy is conserved.

Inelastic: Total kinetic energy is not conserved (lost as heat, sound).

Completely Inelastic: Objects stick together, maximum loss of kinetic energy.

One-Dimensional Elastic Collisions:

Two equal mass objects collide head-on (one at rest), moving object stops, resting object moves with initial velocity.

Two-Dimensional Elastic Collisions:

Two equal mass objects, glancing collision (one at rest), they move off at right angles (90°).

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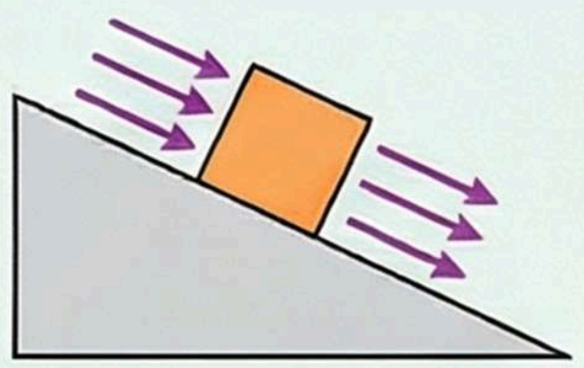
Rotational Motion

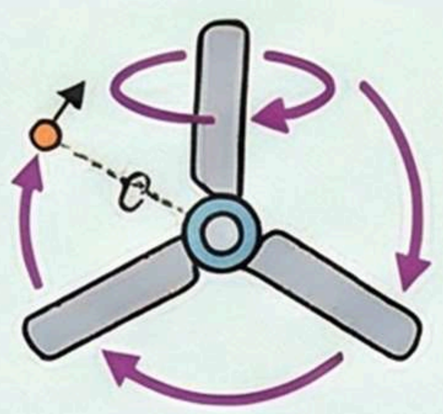
1. TYPES OF RIGID BODY MOTION

Pure Translational Motion



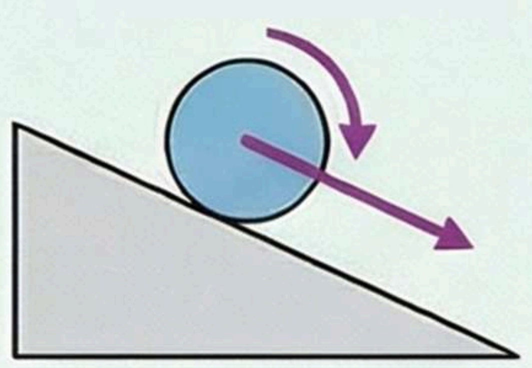
All particles move with the same velocity at any instant.
Example: Block on an inclined plane.

Pure Rotational Motion



Body rotates about a fixed axis. Every particle moves in a circle. Example: Spinning ceiling fan.

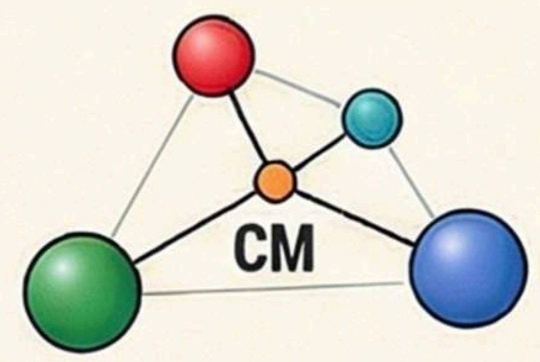
Combined Motion



Body both translates and rotates simultaneously.
Example: Rolling cylinder.

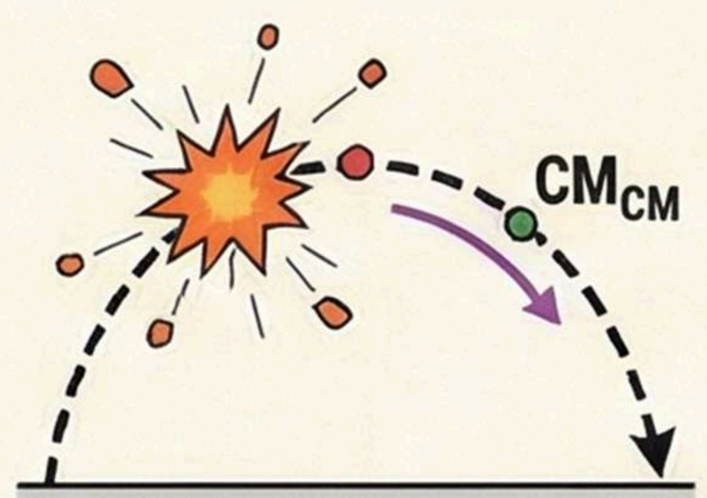
2. THE CENTER OF MASS (CM)

Definition: Mass-Weighted Average Position



Conceptual point representing the average location of the total mass.

Motion of the CM



$$M\vec{A}_{cm} = \vec{F}_{ext}$$

An Exploding Projectile: After a projectile explodes mid-air, its fragments fly apart due to internal forces. However, the center of mass of the fragments continues along the original parabolic path, governed only by the external force of gravity.

Calculating CM (Position Vector R):

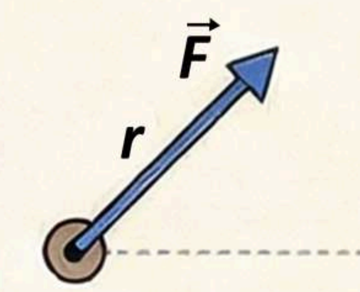
$$\vec{R} = \frac{\sum M_i \vec{r}_i}{M}$$

3. TRANSLATIONAL VS. ROTATIONAL MOTION: THE ANALOGIES

Linear Motion (Translation)	Concept	Rotational Motion (Fixed Axis)
x	Displacement	Angular Displacement (θ)
$v = \frac{dx}{dt}$	Velocity	Angular Velocity ($\omega = d\theta/dt$)
$a = \frac{dv}{dt}$	Acceleration	Angular Acceleration ($\alpha = d\omega/dt$)
Mass (M)	Inertia	Moment of Inertia ($I = \Sigma m_i r_i^2$)
$F = Ma$	Newton's 2nd Law	$\tau = I\alpha$
Linear Momentum ($p = Mv$)	Momentum	Angular Momentum ($L = I\omega$)
$W = \int \vec{F}\, ds$	Work Done	$W = \int \vec{\tau}\, d\theta$
$K = 1/2\, Mv^2$	Kinetic Energy	$K = 1/2\, I\omega^2$
$P = F.v$	Power	$P = \tau\omega$

4. TORQUE & ANGULAR MOMENTUM

Torque (τ): Rotational Force Equivalent

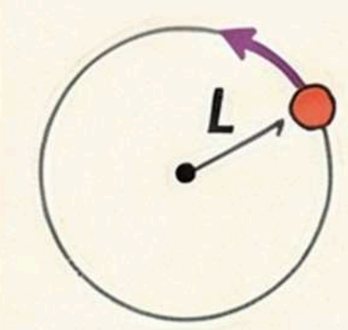


$\vec{\tau} = \vec{r} \times \vec{F}$

Turning effect of a force.

Angular Momentum (L): Rotational Momentum Equivalent

For a particle, it's $l = rp$



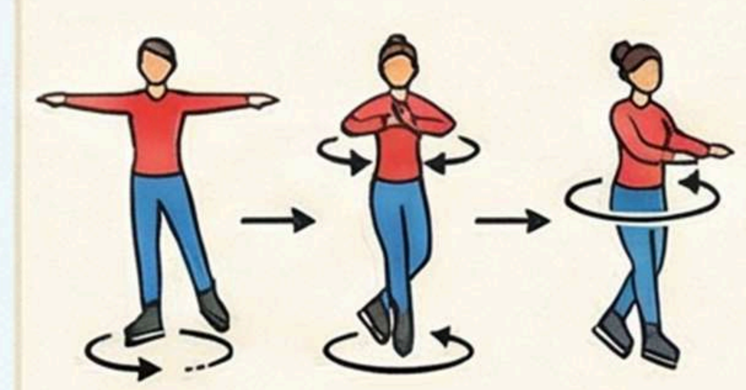
$L = I\omega$

Magnitude $L = I\omega$ for a rigid body.

Newton's Second Law for Rotation

$$\tau_{ext} = dL/dt$$

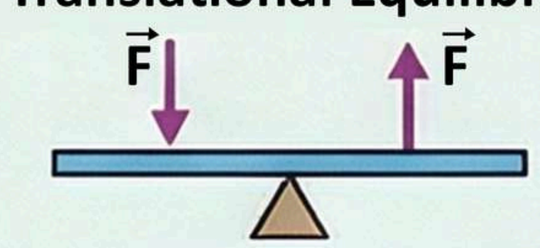
Conservation of Angular Momentum: Skater's Spin



Large I, Small ω → Small I, Large ω → L is constant.

5. CONDITIONS FOR MECHANICAL EQUILIBRIUM

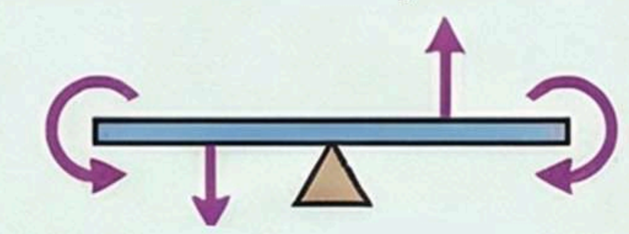
1. Translational Equilibrium



$$\sum F_{ext} = 0$$

Net external force is zero (prevents linear acceleration).

2. Rotational Equilibrium



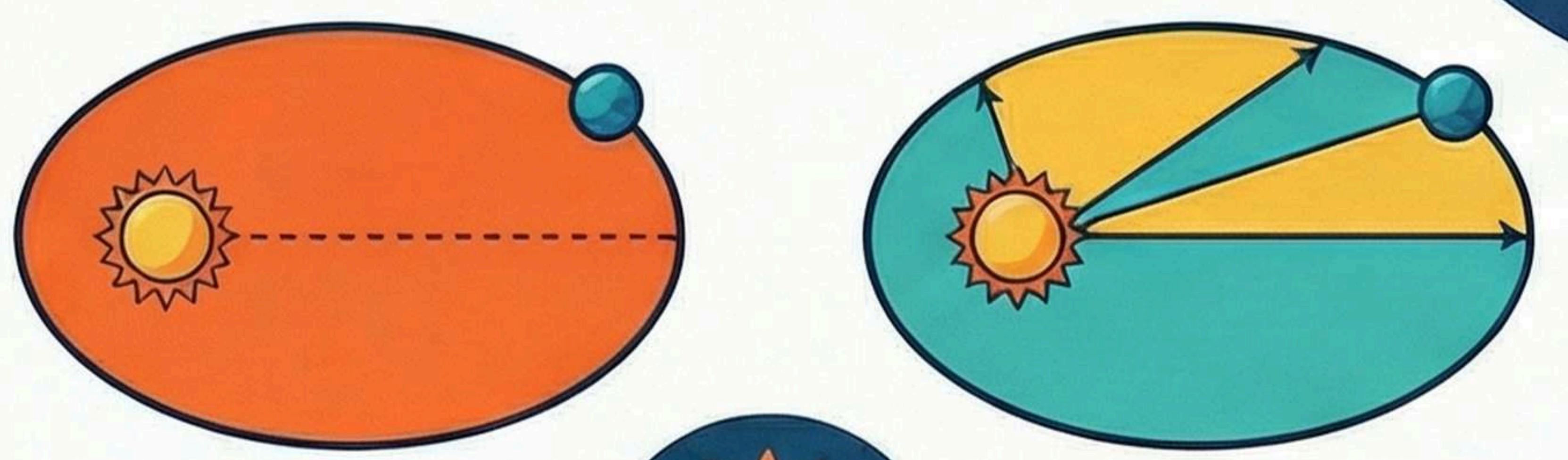
$$\sum \tau_{ext} = 0$$

Net external torque is zero (prevents angular acceleration).

Both conditions must be met for complete equilibrium.

Gravitation

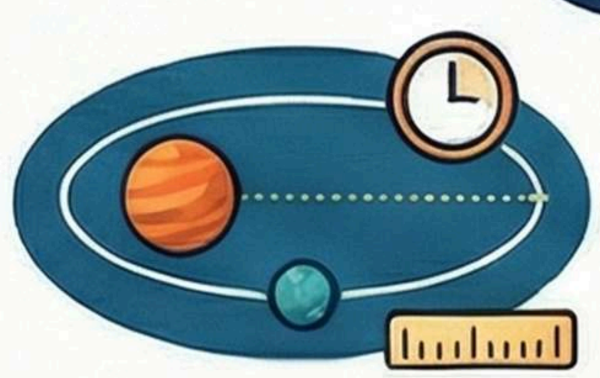
KEPLER'S LAWS OF PLANETARY MOTION



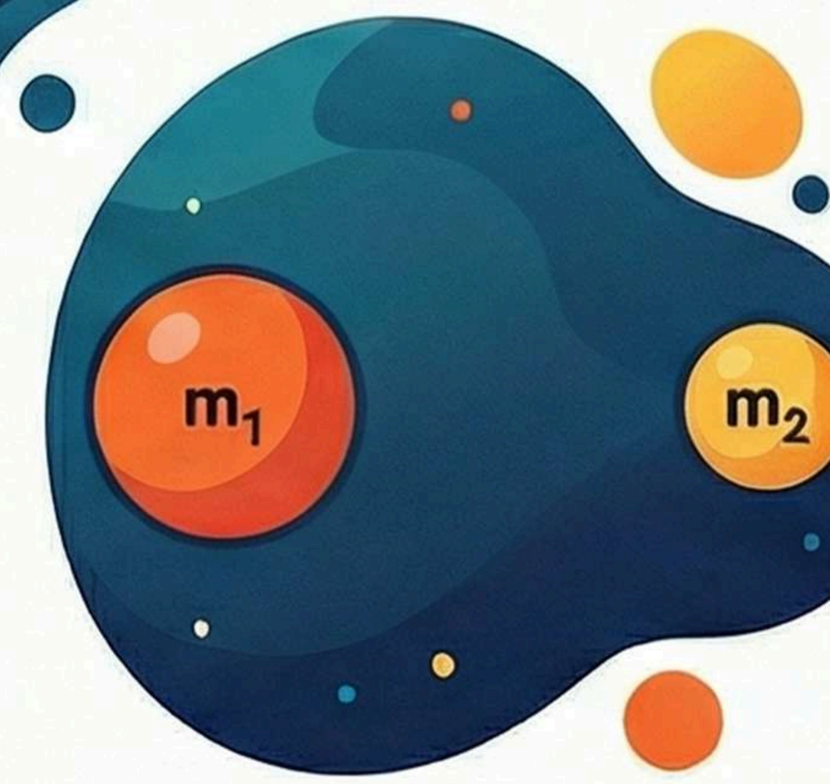
1. Law of Orbits
All planets move in elliptical orbits with the Sun situated at one of the foci of the ellipse.

2. Law of Areas
The line joining any planet to the sun sweeps out equal areas in equal intervals of time. This is a consequence of the conservation of angular momentum.

3. Law of Periods
The square of the time period of a planet's revolution (T) is proportional to the cube of the semi-major axis (s) of its orbit.
($T^2 \alpha\ a^3$)



NEWTON'S UNIVERSAL LAW OF GRAVITATION



Every body in the universe attracts every other body.

The force is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

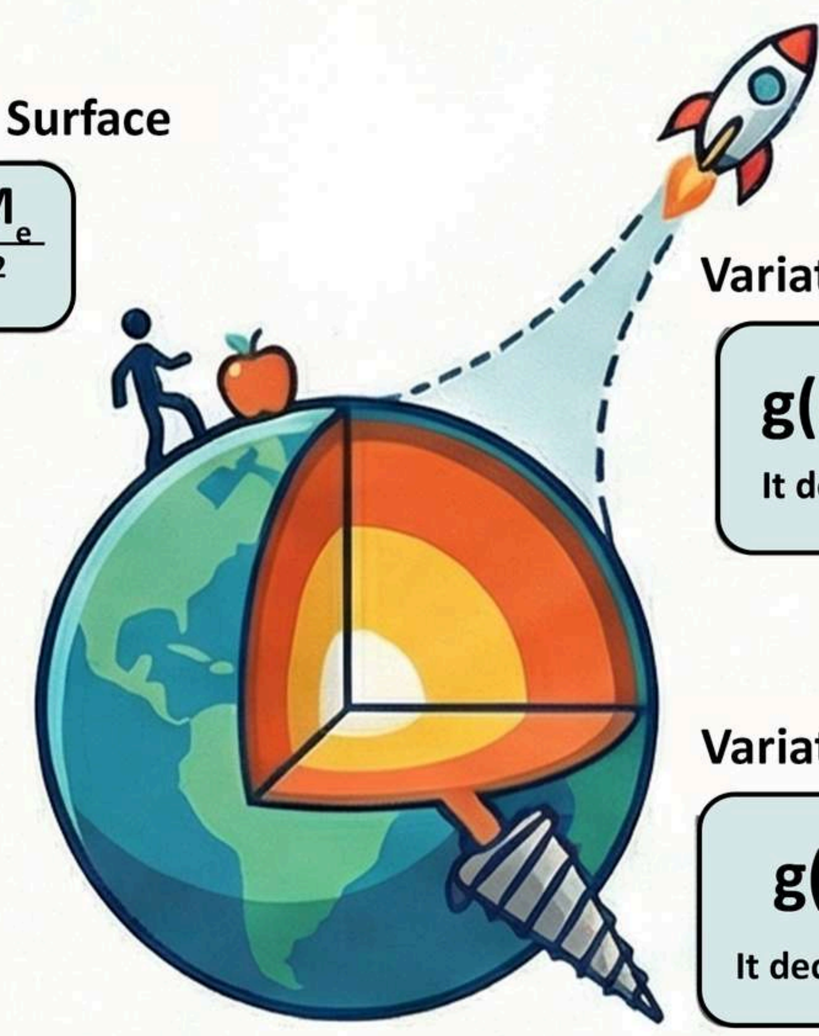
$$F \quad G \frac{(m_1 m_2)}{r^2}$$

Gravitational Constant (G): 6.67×10^{-11}Nm2/Kg2

ACCELERATION DUE TO GRAVITY (g)

'g' on Earth's Surface

$$g = \frac{GM_e}{R_e^{\ 2}}$$



Variation with Height (h)

$$g(h) \approx g(1- \text{—})$$

It decreases as you go up.

Variation with Depth (d)

$$g(h) \approx g(1- \frac{d}{R_e})$$

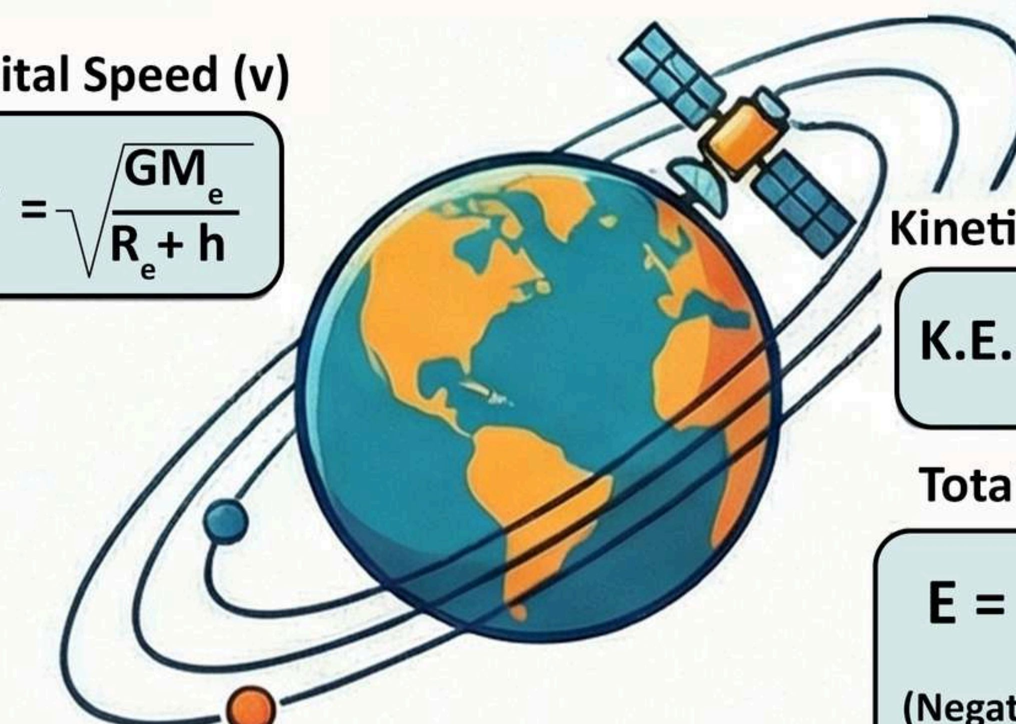
It decreases as you go down.

Maximum at the Surface:
The acceleration due to Earth's gravity is maximum on its surface and decreases with both increasing altitude and depth.

EARTH SATELLITES

Orbital Speed (v)

$$V = \sqrt{\frac{GM_e}{R_e + h}}$$



Kinetic Energy (K.E.)

$$K.E. = \frac{GM_e m}{2(R_e + h)}$$

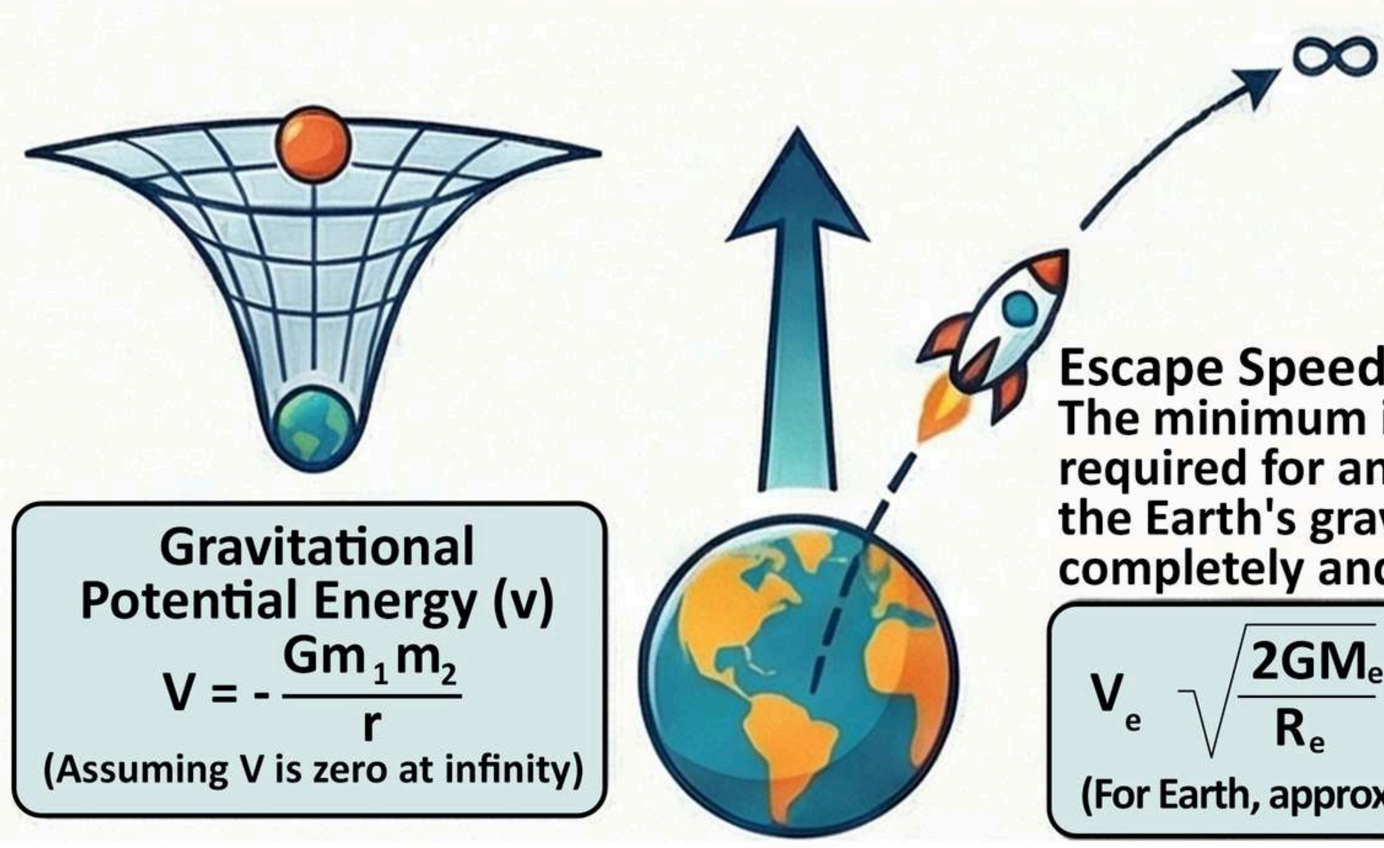
Total Energy (E)

$$E = \frac{GM_e\, m}{2(R_e + h)}$$

(Negative, indicates a bound system).

Energy Relationship
For a circular orbit, the total energy is the negative of the kinetic energy (E = -K.E.) and half of the potential energy (E = P.E./2).

ENERGY AND ESCAPE SPEED



Gravitational Potential Energy (v)

$$V = -\frac{Gm_1 m_2}{r}$$

(Assuming V is zero at infinity)

Escape Speed (v_e)
The minimum initial speed required for an object to escape the Earth's gravitational pull completely and reach infinity.

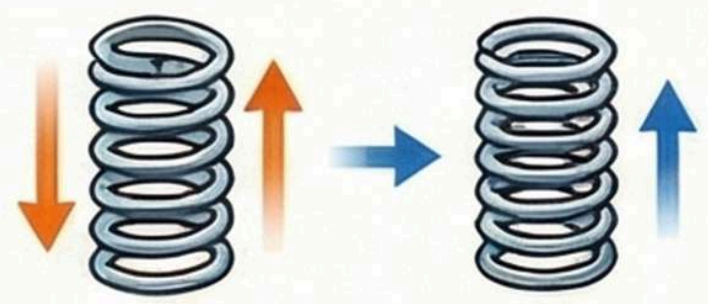
$$V_e \sqrt{\frac{2GM_e}{R_e}} = \sqrt{2gR_e}$$

(For Earth, approx. 11.2 km/s)

Mechanical Properties of Solids

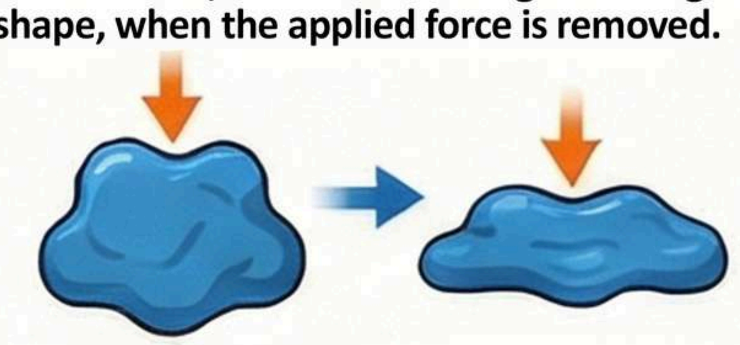
Fundamental Material Properties

Elasticity
The property of a body to regain its original size and shape when the applied deforming force is removed.



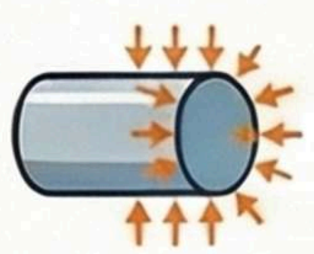
Elastic Material: Helical Spring
When you stretch a spring and release it, it returns to its original length due to its elastic properties.

Plasticity
The property of a body to undergo permanent deformation, without returning to its original shape, when the applied force is removed.



Plastic Material: Putty or Mud
If you apply force to a lump of putty, it changes shape permanently and shows no tendency to return to its previous form.

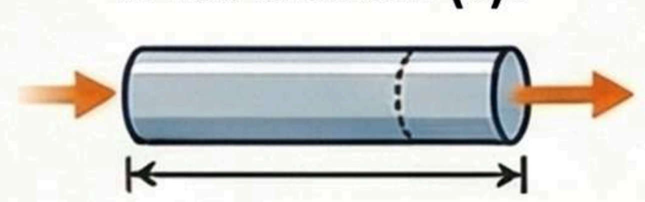
Understanding Stress and Strain



What is Stress (σ)?
The internal restoring force developed per unit area of a body when it is deformed. Its SI unit is Nm^{-2} or Pascal (Pa).

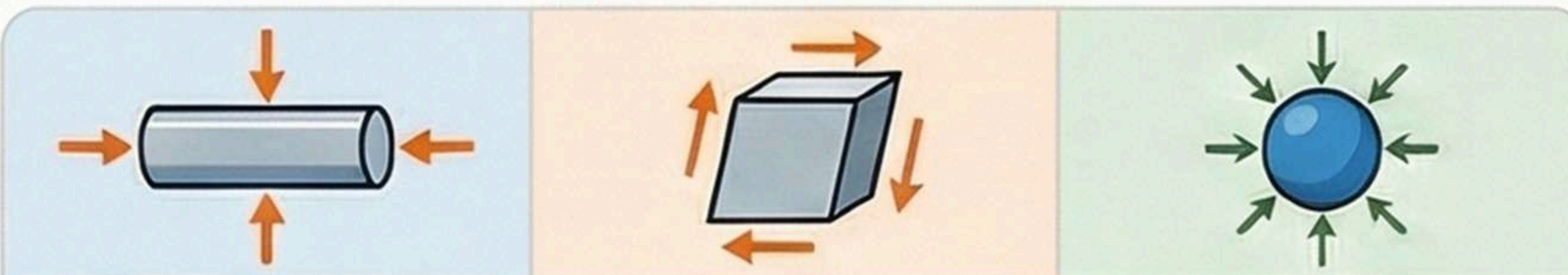
Stress = Force/Area, $\sigma = F/A$

What is Strain (δ)?



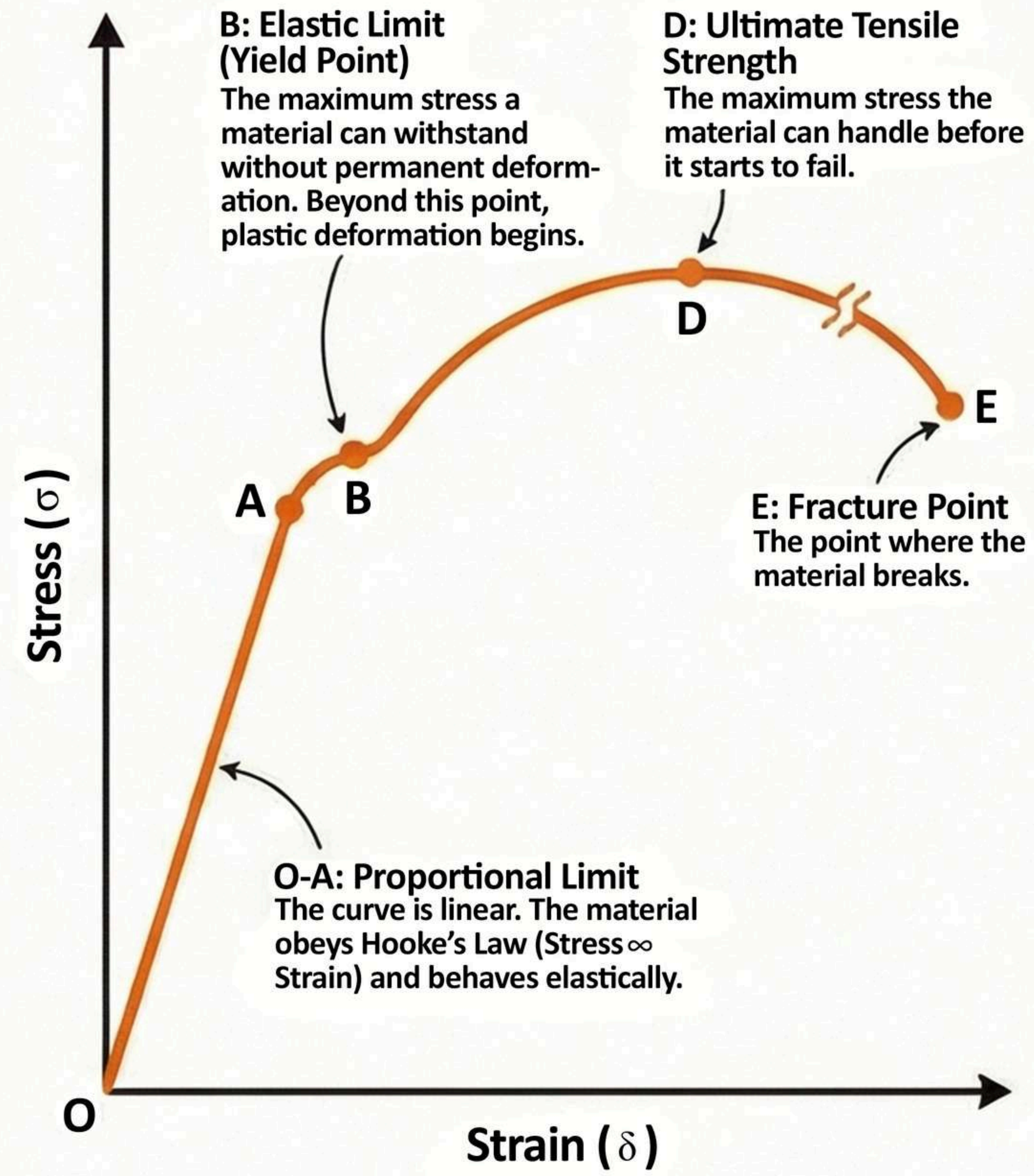
The ratio of the change in dimension of the body to its original dimension. It has no units or dimensional formula.

Types of Stress and Strain



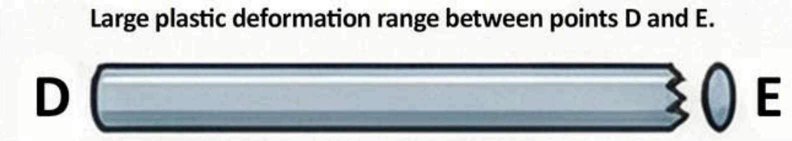
Longitudinal	Shearing	Hydraulic
Force is applied normally to the cross-sectional area, causing stretching (tensile) or compression.	Force is applied parallel (tangential) to the cross-sectional area.	Force is applied uniformly from all sides, perpendicular to the surface (e.g., an object in a fluid under pressure).
Longitudinal Strain = $\frac{\text{Change in length}}{\text{Original length}}$ = ($\Delta L/L$)	Shearing Strain = $\frac{\text{Relative displacement}}{\text{Length}}$ = ($\Delta x/L = \tan\theta$)	Volume Strain = $\frac{\text{Change in volume}}{\text{Original volume}}$ = ($\Delta V/V$)
Changes the length of the object.	Tilts or twists the object's shape.	Decreases the volume without changing the shape.

The Stress-Strain Curve for a Metal: A Visual Map of Material Behavior



Ductile vs. Brittle Materials

Ductile (can be stretched)
Large plastic deformation range between points D and E.



Brittle (breaks suddenly)
Small plastic deformation range; points D and E are close.

Elastic Moduli & Key Formulas & Applications

Hooke's Law

Stress = k x Strain

For small deformations, stress is directly proportional to strain.
Where 'k' is the constant of proportionality, known as the Modulus of Elasticity.

Young's Modulus (Y)
Measures resistance to change in length. It is the ratio of longitudinal stress to longitudinal strain. Applies to solids.

$$Y = \frac{F \times L}{A \times \Delta L}$$

A higher Y value means the material is stiffer and more elastic (e.g., Steel).

Shear Modulus (G)
Measures resistance to change in shape (shearing). Also called the Modulus of Rigidity. Applies to solids.

$$G = \frac{\text{Shearing Stress}}{\text{Shearing Strain}}$$

$$G = \frac{F/A}{\theta}$$

Bulk Modulus (B)
Measures resistance to change in volume. It is the ratio of hydraulic stress to volume strain. Applies to solids, liquids, and gases.

$$B = \frac{-P}{\Delta V/V}$$

Solids are the least compressible (high B), while gases are the most compressible (low B).

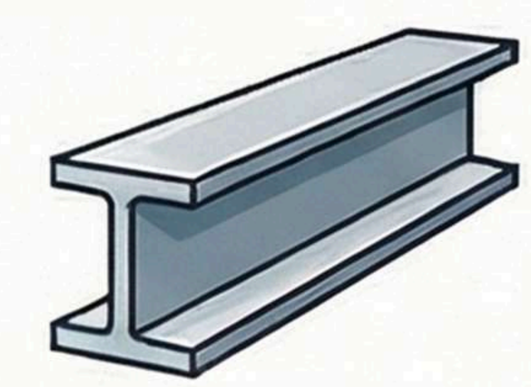
Elastic Potential Energy

The work done to stretch a wire is stored as potential energy.
Energy per unit volume is:

u = 1/2 Stress x Strain

Engineering Applications

Designing Crane Ropes:
The rope's cross-sectional area (A) must be large enough so the stress (W/A) does not exceed the material's yield strength (δ).

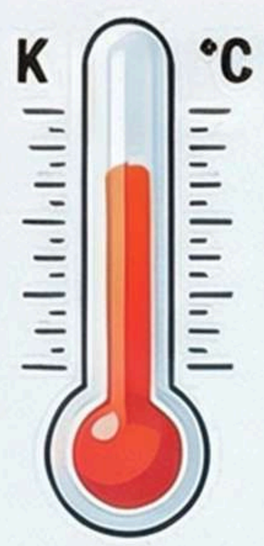


Beams in Bridges and Buildings:
Beams are designed with an I-shaped cross-section. This shape increases depth to prevent bending (sag) without adding excessive weight or cost.

Minimizing Bending: To reduce sag in a beam, it is more effective to increase its depth (d) than its breadth (b), since sag is proportional to $1/d^3$ but only 1/d.

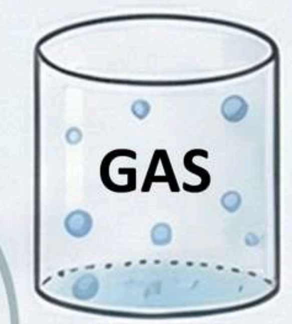
Thermal Properties of Matter

TEMPERATURE & HEAT FUNDAMENTALS



TEMPERATURE:
- Measure of hotness/coldness.
- Relative measure indicating direction of heat flow.
- SI unit: Kelvin (K); Celsius (°C) common.

ABSOLUTE ZERO (0 K):
- Lowest possible temperature.
- Ideal gas pressure is zero.
- Foundation of Kelvin scale.



OK

TEMPERATURE SCALES REFERENCE POINTS

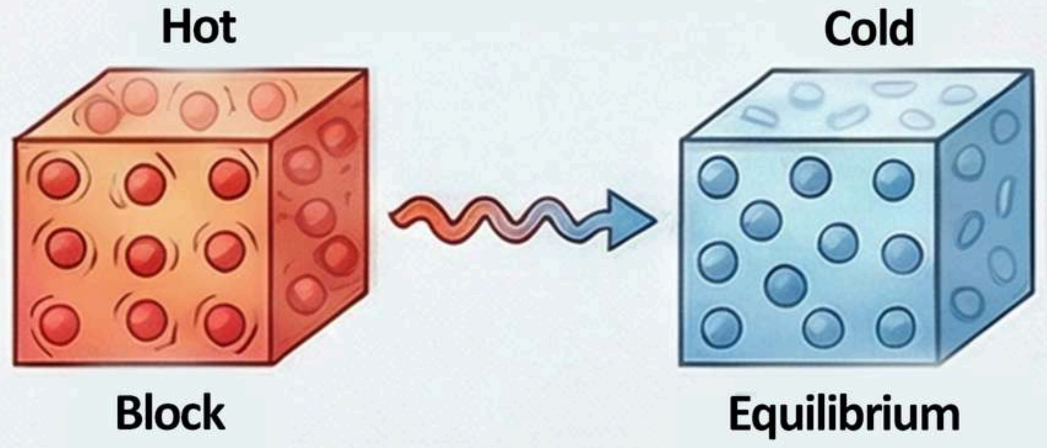
	CELSIUS (°C)	Fahrenheit (°F)	KELVIN (K)
Absolute Zero	-273.15	-459.67	0
Freezing Point of Water	0	32	273.15
Triple Point of Water	0.01	32.02	273.16
Boiling Point of Water	100	212	373.15

Scale Conversions:

$$\frac{t_F - 32}{180} = \frac{t_C}{100}$$

$$T\,(K) = t_C + 273.15$$

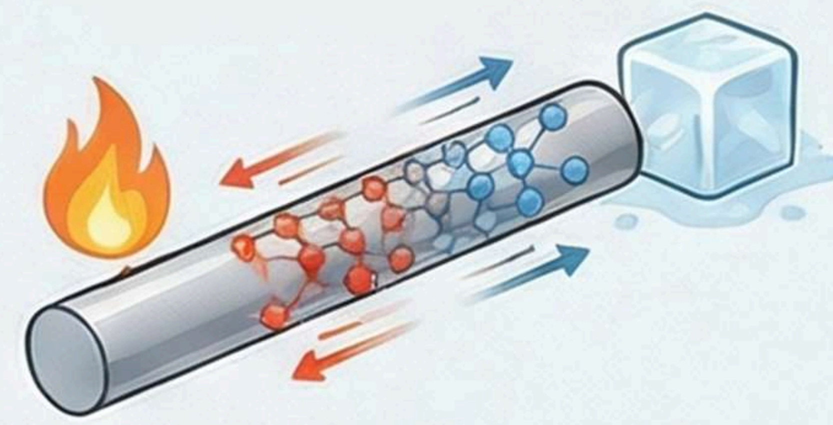
HEAT
Energy transferred due to a temperature difference. Flows from higher temperature to lower temperature until thermal equilibrium.
SI unit: Joule (J).



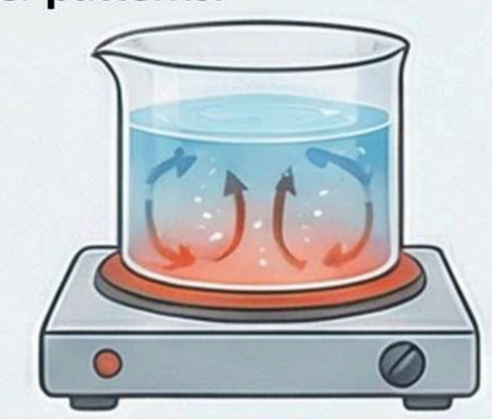
MODES OF HEAT TRANSFER

CONDUCTION
Heat transfer through direct molecular collision. Requires medium. Metals good, gases poor conductors.

$H = KA(T_h - T_c)/L$

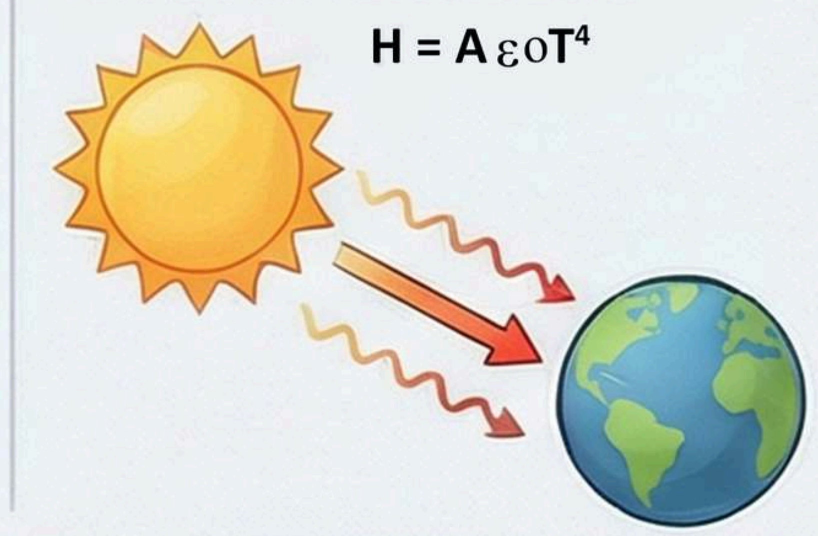


CONVECTION
Heat transfer by actual motion of matter. Fluids only (liquids & gases).
Natural (buoyancy) or forced (pump).
Responsible for sea breezes and weather patterns.



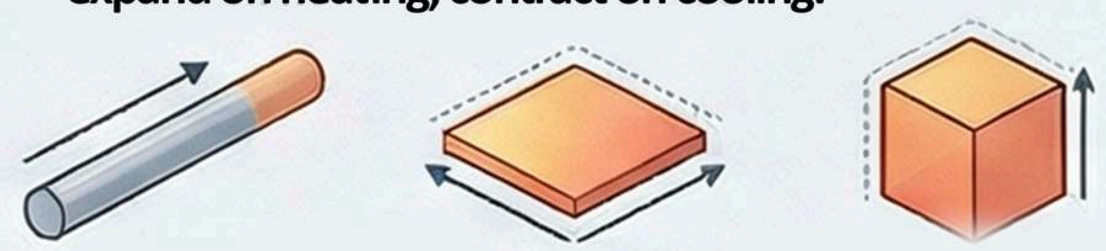
RADIATION
Heat transfer via electromagnetic waves. Requires no medium, travels through vacuum. The sun heats Earth.

$H = A\varepsilon\sigma T^4$



THERMAL EXPANSION & CHANGE OF STATE

THERMAL EXPANSION
Matter changes dimensions with temperature. Most expand on heating, contract on cooling.



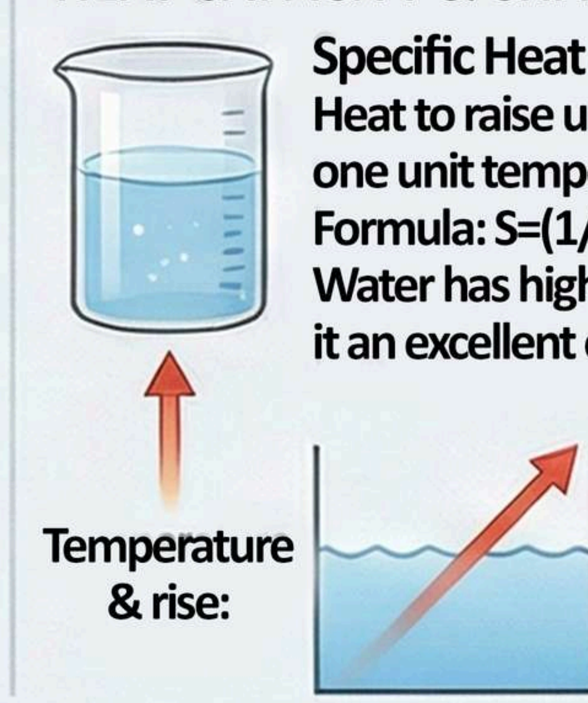
Linear Expansion: $\frac{\Delta l}{l_D} = a_L\,\Delta T$

Area Expansion: $\frac{\Delta A}{A_D} = a_A\,\Delta T$

Volume Expansion: $\frac{\Delta V}{V_B} = a_V\,\Delta T$

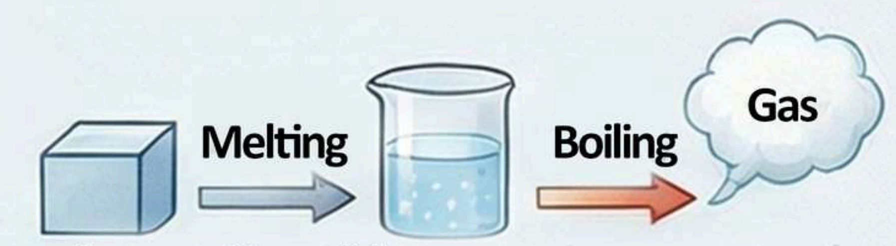
Water's Anomalous Expansion: Contracts from 0°C to 4°C, max density at 4°C. Lakes freeze top down.

HEAT CAPACITY & CHANGE OF STATE



Specific Heat Capacity (s):
Heat to raise unit mass by one unit temperature.
Formula: $S = (1/m)(\Delta Q/\Delta T)$
Water has high s making it an excellent coolant.

CHANGE OF STATE
Occurs at constant temperature.



Latent Heat (L): Heat to change state of unit mass. Latent Heat of Fusion (Lf) is for solid-liquid transition, and Latent Heat of Vaporization (LV) is for liquid-gas transition.

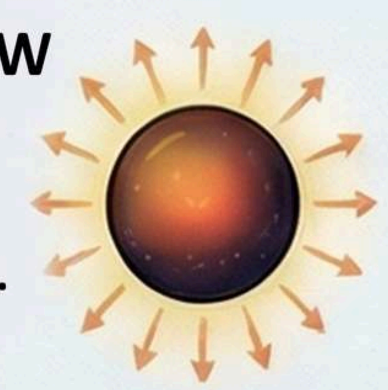
Heat Transfer during Phase Change:

$$Q = mL$$

KEY LAWS OF THERMAL RADIATION & COOLING

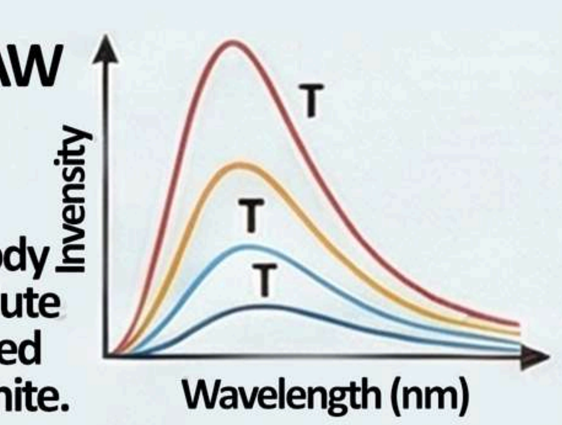
STEFAN-BOLTZMANN LAW
'e' is emissivity (1 for a perfect blackbody), '' is the Stefan Boltzmann constant, A is area and T is absolute temperature.

$H = A\varepsilon\sigma T^4$



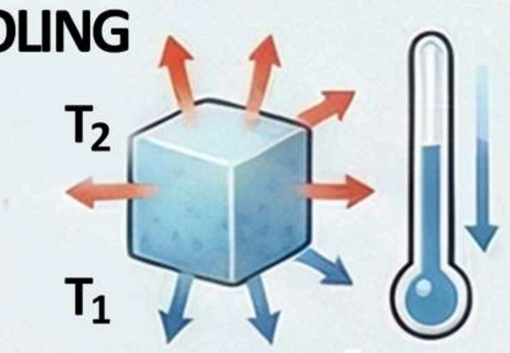
WIEN'S DISPLACEMENT LAW
$\lambda_m T = \text{constant}$

States that the wavelength (λ_m) of maximum emission from a blackbody is inversely proportional to its absolute temperature (T). Explains why heated objects change color from red to white.

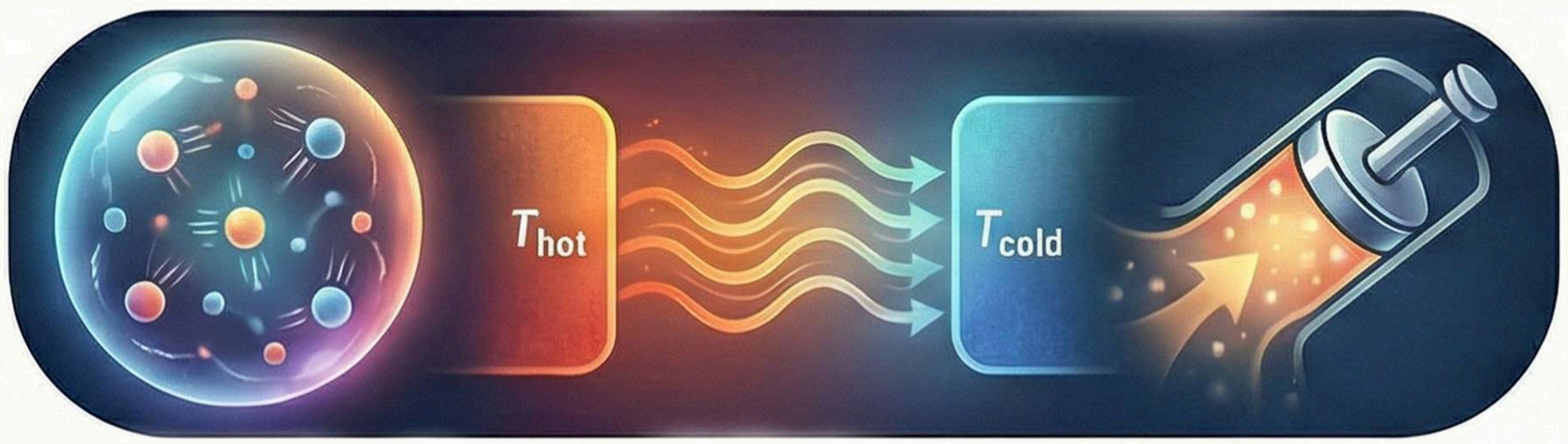


NEWTON'S LAW OF COOLING
$$\frac{dQ}{dt} = -k(T_2 - T_1)$$

Rate of heat loss proportional to temperature difference (small differences).



Thermodynamics



INTERNAL ENERGY (U)
State Variable: Sum of kinetic & potential energies. Value depends only on the current state.

HEAT (Q)
Energy in Transit: Transferred due to temperature difference. Not a property a system has.

WORK (W)
Energy in Transit: Transferred by means other than temperature difference (e.g., piston moving). Not a state variable.

FIRST LAW:

$$\Delta Q = \Delta U + \Delta W$$

Heat supplied (ΔQ) eguals chage in internal energy (ΔU) plus work done (ΔW)

STATE VARIABLES DESCRIBE EQUILIBRIUM

KELVIN-PLANCK STATEMENT

Gas → Volume

Pressure (P), Volume (V), Temperature (T), Internal Energy (U) describe macroscopic equilibrium.

CLAUSIUS STATEMENT

COLDER BODY → HOTTER BODY

No process can solely transfer heat from a colder to a hotter body **without external work being dong**

Describe Equilibrium States:

EXTENSIVE VS. INTENSIVE VARIABLES

System VS. Small

Extensive (e.g , u, v) depend on size. Intensive (e.g., p,t) do not.

EQUATION OF STATE

$$PV = \mu RT$$

Relation between state variables describing behavior (e.g., Ideal Gas).

ZEROTH LAW: THE BASIS OF TEMPERATURE

A — B — C

If two systems are in thermal equilibrium with a third, they are in thermal equilibrium with each other. Establishes temperature as a fundamental property.

KELVIN-PLANCK STATEMENT

HEAT RESERVOIR → WORK

No engine can absorb heat from a single reservoir & convert it completely into work. Perfect efficiency is impossible.

CLAUSIUS STATEMENT

COLDER BODY → HOTTER BODY

No process can solely transfer heat from a colder to a hotter body without external work being done.

THERMODYNAMIC PROCESSES AT A GLANCE

Quasi-Static Process
Idealized, infinitely slow process where system remains in equilibrium at every stage.

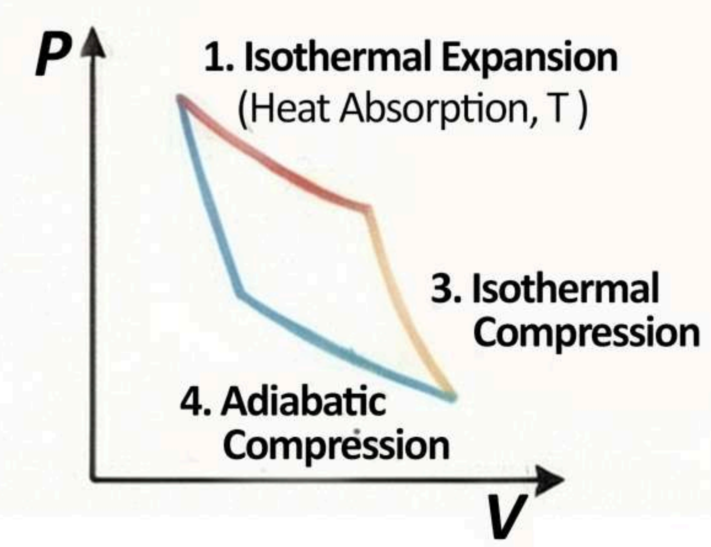
ISOTHERMAL
Condition: Constant Temperature (ΔT=0)
Work Done: $W = \mu RT \ln \frac{V_2}{V_1}$
First Law Implication: Heat absorbed equals work done (ΔQ=W).

ADIABATIC
Condition: No Heat Exchange (ΔQ=0)
Work Done: $W = \frac{\mu B(T_1 - T_2)}{T - 1}$
First Law Implication: Work is done at the expense of internal energy (ΔU=W).

ISOCHORIC
Condition: Constant Volume (ΔV=0)
Work Done: $W = 0$
First Law Implication: Heat absorbed equals change in internal energy (ΔQ = ΔU).

ISOBARIC
Condition: Constant Pressure (ΔP= 0)
Work Done: $W = P(V_2 - V_1)$
First Law Implication: Heat absorbed increases internal energy and does work

THE IDEAL ENGINE: THE CARNOT CYCLE



The Most Efficient Engine Possible

The Carnot engine is an idealized, reversible engine that operates between two temperatures, a hot source (T_1) and a cold sink (T_2).

CARNOT EFFICIENCY FORMULA

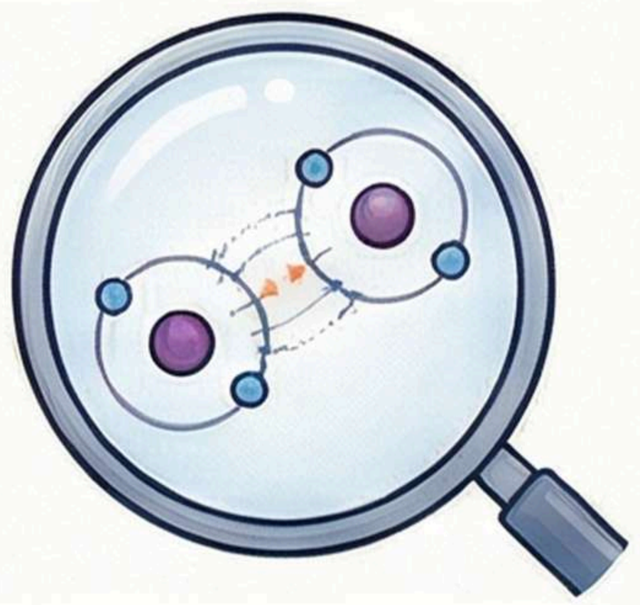
$$\eta = 1 - \left(\frac{T_2}{T_1}\right)$$

The maximum possible efficiency of any heat engine depends only on the absolute temperatures of the hot (T_1) and cold (T_2) reservoirs.

Kinetic Theory of Gases

1. The Molecular Nature of Matter

The Atomic Hypothesis



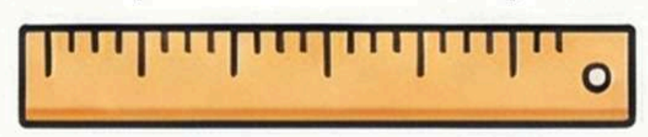
All matter is composed of tiny particles (atoms) in perpetual motion, attracting each other at small distances and repelling when squeezed together.

Fundamental Gas Laws

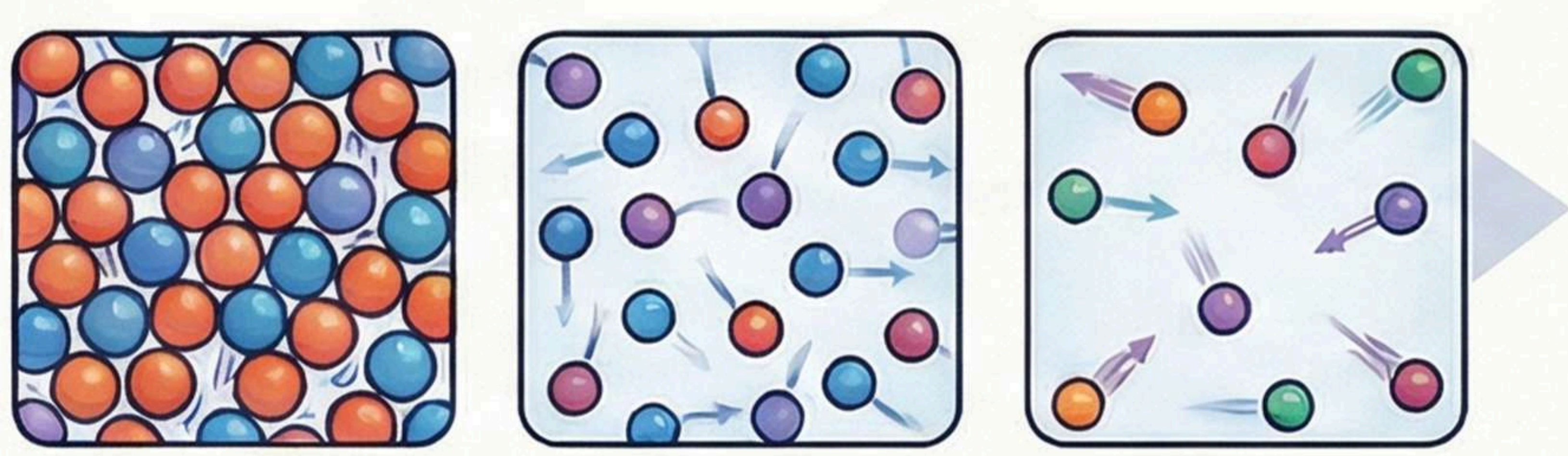
Boyle's Law ($P \propto 1/V$ at constant T), Charles' Law ($V \propto T$ at constant P), and Dalton's Law of Partial Pressures ($P_{total} = P1 + P2 + ...$) are all described by the ideal gas equation.

Scale of an Atom

Approx. size: -1 angstrom ($1Å = 10^{-10}$meters).



Molecular Spacing & States



Solids (~2 Å, fixed)

Liquids (~2 Å, mobile)

Gases (tens of Å, free-moving)

2. Behavior of Gases & The Ideal Gas Laws

What is an Ideal Gas?

A theoretical model of a gas where intermolecular forces are negligible. Real gases approximate this behavior at low pressures and high temperatures.

The Ideal Gas Equation (Moles)

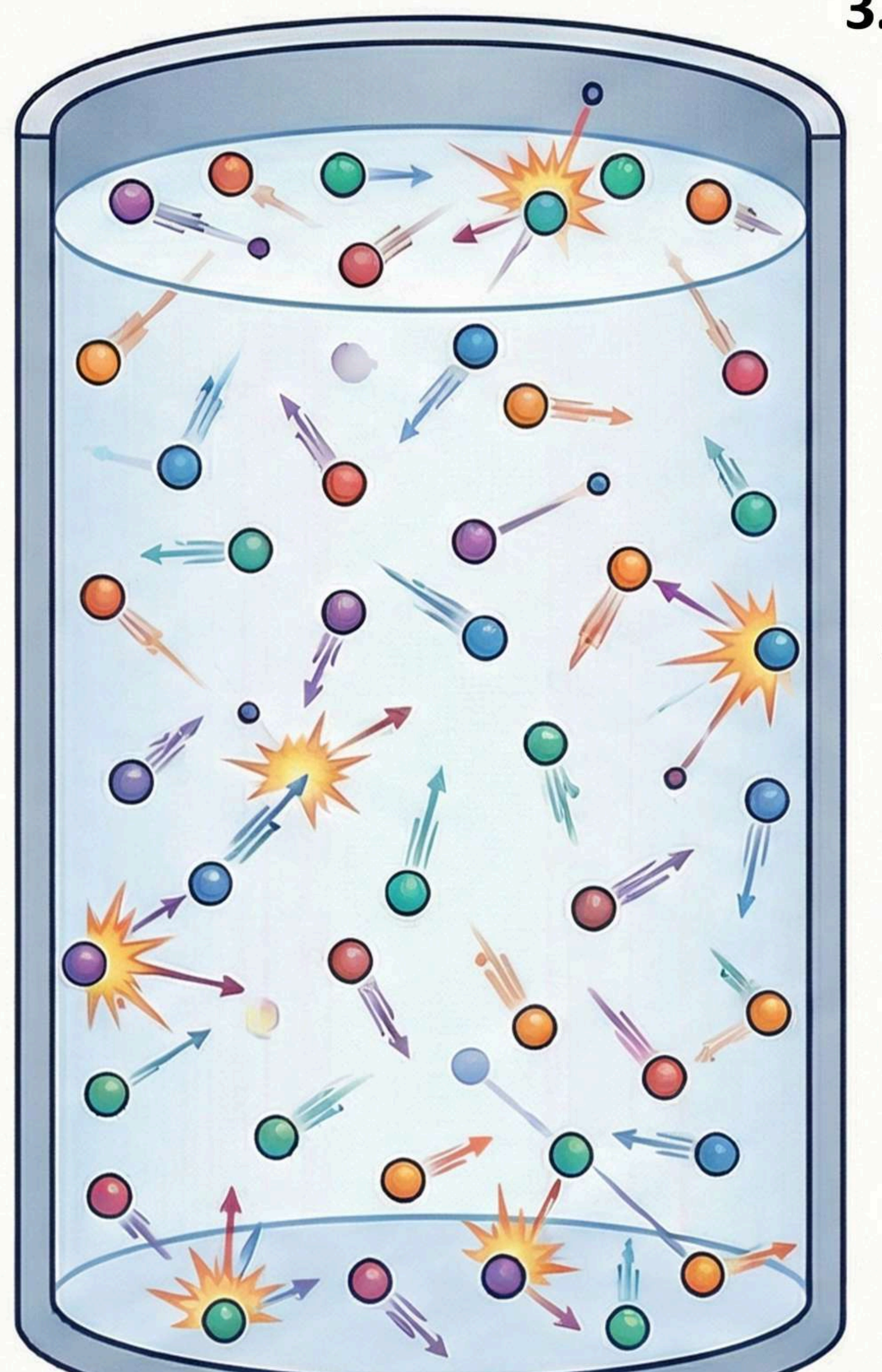
$$PV = \mu RT$$

P is pressure, V is volume, is the number of moles, R is the universal gas constant ($8.314\ J\ mol^{-1}k^{-1}$), and T is the absolute temperature in Kelvin.

The Ideal Gas Equation (Molecules)

$$PV = Nk_BT$$

N is the total number of molecules and k_B is the Boltzmann constant ($1.38 \times 10^{-23}\ Jk^{-1}$).



The Microscopic World: Perpetual Motion & Collisions

3. Kinetic Theory: Linking Motion to Temperature & Pressure

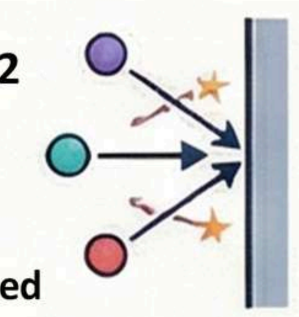
Core Assumptions

Gas made of many molecules in random motion. All collisions are perfectly elastic.

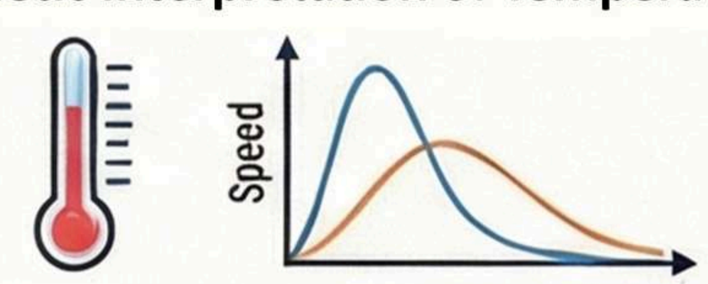
Pressure from Molecular Motion

$$P = 1/3nmv^2$$

n = number density
m = mass
v^2 = mean squared speed



Kinetic Interpretation of Temperature



Absolute temperature is directly proportional to average translational kinetic energy.

Average Kinetic Energy Per Molecule

$$\frac{E}{N} = \frac{1}{2}mv^2 = \frac{3}{2}k_BT$$

This fundamental result connects the macroscopic property of temperature (T) to the microscopic property of molecular motion.

Root-Mean-Square (rms) Speed

$$V_{rms} = \sqrt{\frac{3k_BT}{m}}$$

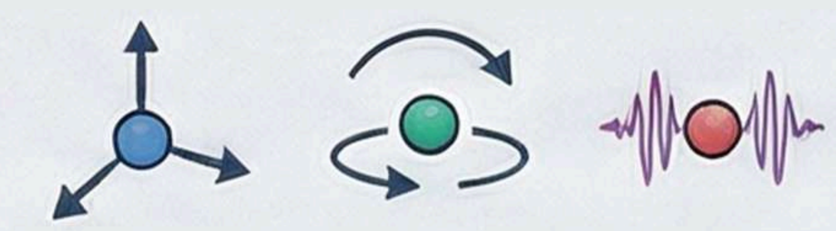
At the same T, lighter molecules have higher average speed.

4. The Law of Equipartition of Energy & Specific Heat

Law of Equipartition of Energy

In thermal equilibrium, the total energy of a system is shared equally among all its possible energy modes, or degrees of freedom.

Energy per Degree of Freedom



Each vibrational mode contributes k_BT ($1/2k_BT$ for kinetic and $1/2k_BT$ for potential energy).

Predicted Molar Specific Heats

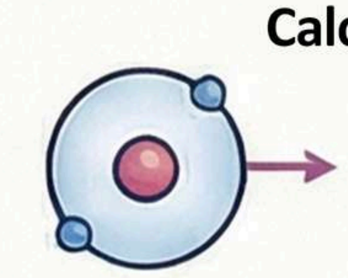
Type of Gas	Degree of Freedom (f)	Internal Energy (U) per mole	Molar Specific Heat C_v	Ratio $\gamma = \frac{C_B}{C_V}$
Monatomic	3 (Trans)	3/2 RT	3/2 R	5/3 = 1.67
Diatomic (Rigid)	5 (3 Trans x 2 Rot)	5/2 RT	5/2 R	7/5 = 1.40
Diatomic (Vibrating)	7 (2 Trans x 2 Rot + 1 Vib)	7/2 RT	7/2 R	9/7 = 1.29

5. Mean Free Path

Mean Free Path (*l*)

The average distance a molecule travels between two successive collisions.

Calculating Mean Free Path



$$l = \frac{1}{\sqrt{2}\, n \pi d^2}$$

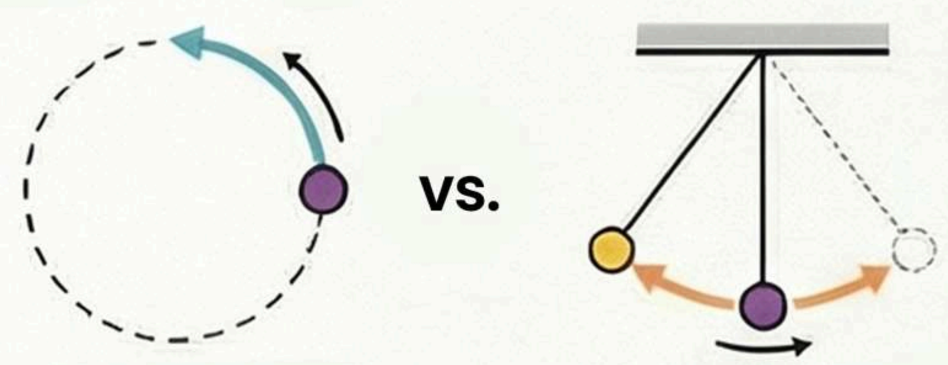
n = number density
d = molecular diameter

Reason for Slow Diffusion

High speeds, but short mean free path and constant deflection cause slow diffusion.

Oscillations and Waves

THE FUNDAMENTALS OF MOTION



Periodic Motion
Repeats at regular intervals (e.g., circular motion).

Oscillatory Motion
Moves to-and-fro about a mean position.

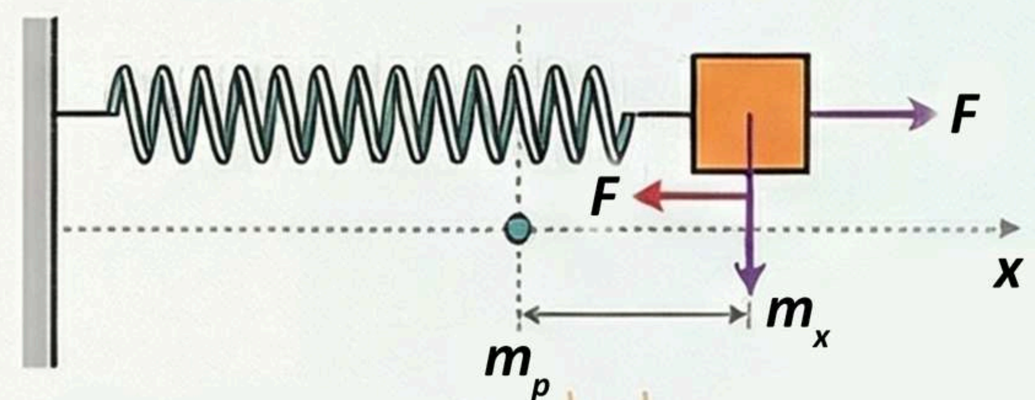
All oscillatory motion is periodic, but not all periodic motion is oscillatory.

Period (T)
Smallest time interval for repetition; Unit: second (s).

Frequency (ν)
Repetitions per unit time. $\nu = 1/T$
Unit: Hertz (Hz) = 1 oscillation/s.

Displacement (x or y)
Change in physical property from equilibrium position.

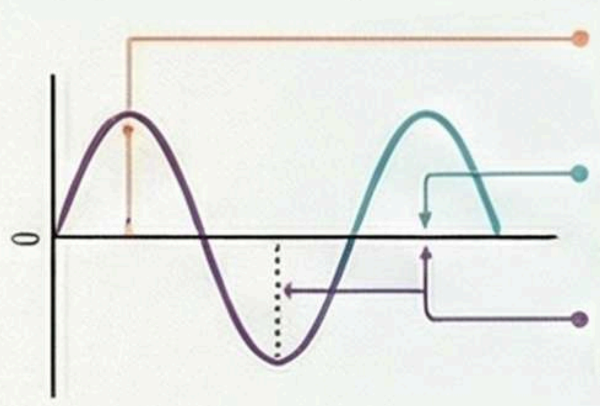
SIMPLE HARMONIC MOTION (SHM)



Defining Condition
Restoring force is directly proportional to displacement & directed towards mean position.

Force Law
$F = -kx$
k: force constant
x: displacement

Displacement Equation
$x(t) = A\cos(\omega t + \phi)$



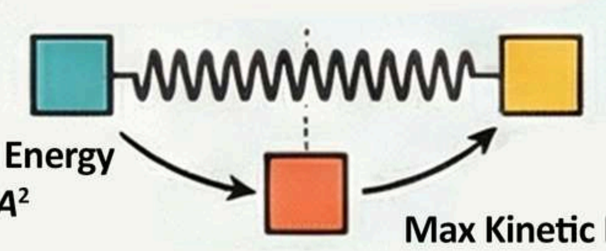
Amplitude (A)
Max displacement.

Angular Frequency (ω)
$\omega = 2x/T$

Phase ($\omega t + \phi$)
State of motion at time t.

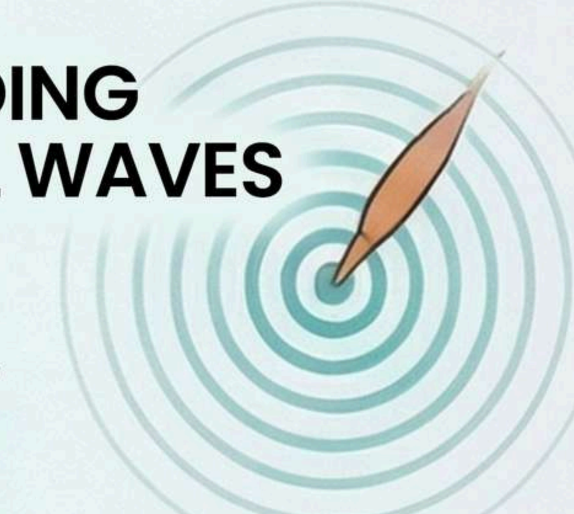
Velocity & Acceleration
$v(t) = -\omega A\sin(\omega t + \phi)$
$a(t) = -\omega^2 A\cos(\omega t + \phi) = -\omega^2 x(t)$
Acceleration is proportional to displacement.

Energy Conservation

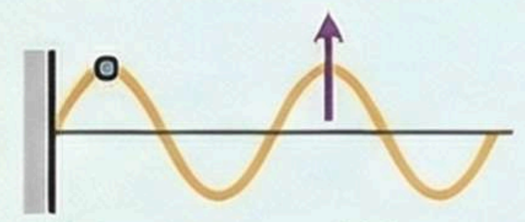


Total Energy
$E = K + U = 1/2kA^2$

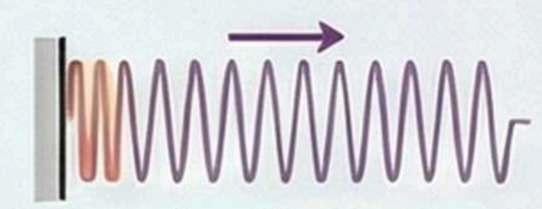
UNDERSTANDING MECHANICAL WAVES



What is a Wave?
Disturbance propagating, transporting energy & information without matter transfer.



Transverse Wave
Particle oscillation perpendicular to wave travel (e.g., wave on a string).



Longitudinal Wave
Particle oscillation parallel to wave travel (e.g., sound wave in air).

Travelling Wave Equation
$y(x,t) = \alpha\sin(kx - \omega t + \Phi)$
Describing sinusoidal waves in + x direction.

Wave Speed (v)

General
$v = \nu\lambda$
$v = \omega/k$

Speed on Stretched String
$v = \sqrt{\dfrac{T}{\mu}}$
T: tension
μ: linear mass density

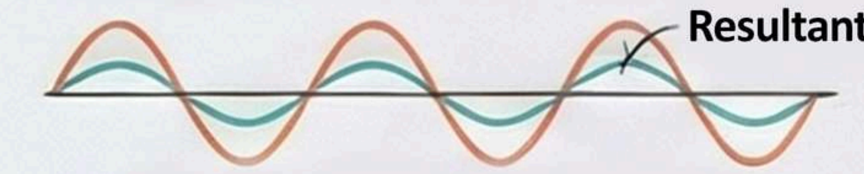
Speed of Sound (Longitudinal)
$v = \sqrt{\dfrac{B}{\rho}}$ or $v = \sqrt{\dfrac{\gamma P}{\rho}}$
B: bulk modulus
ρ: density
γ: heat capacity ratio
P: pressure

DATA TABLE: HARMONICS

System	Fundamental Frequency (1st Harmonic)	General Formula for Harmonics
1 String (fixed at both ends)	$\nu_1 = \dfrac{v}{2L}$	$\nu_n = n\dfrac{v}{2L}$, for $n = 1, 2, 3, \ldots$ (All harmonics)
2 Pipe (open at both ends)	$\nu_1 = \dfrac{v}{2L}$	$\nu_n = n\dfrac{v}{2L}$, for $n = 1, 2, 3, \ldots$ (All harmonics)
3 Pipe (closed at both ends)	$\nu_1 = \dfrac{v}{4L}$	$\nu_n = n\dfrac{v}{4L}$, for $n = 1, 3, 5, \ldots$ (Odd harmonics only)

WAVE BEHAVIOR & PHENOMENA

Principle of Superposition



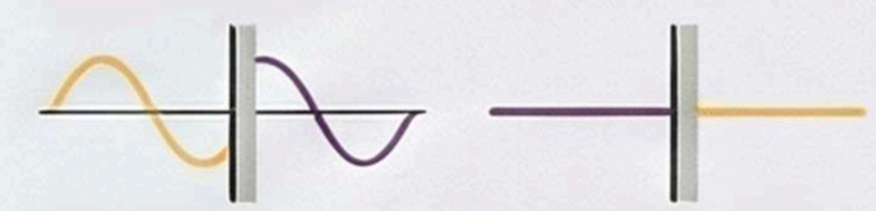
Resultant as the algebraic sum

Interference

Constructive
Waves in phase add up; ($A_{result} = 2a$)

Destructive
Waves out of phase by n cancel; ($A_{result} = 0$)

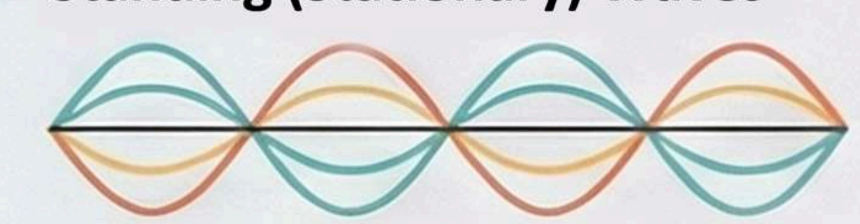
Reflection



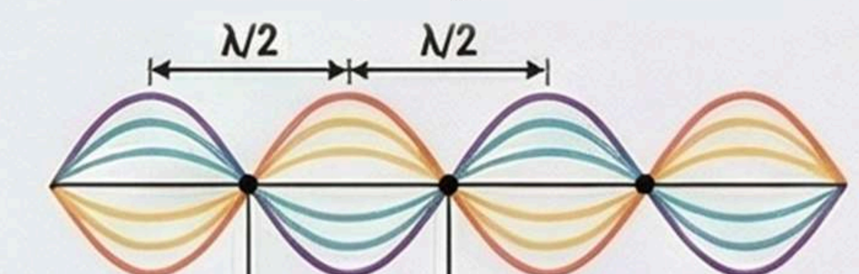
Rigid Boundary
Phase change of 180°/π

Open Boundary
No Phase change

Standing (Stationary) Waves



Formed by the superposition of two identical waves traveling in opposite directions.



Nodes
Point of zero amplitude, no motion

Antinodes
Point of maximum amplitude