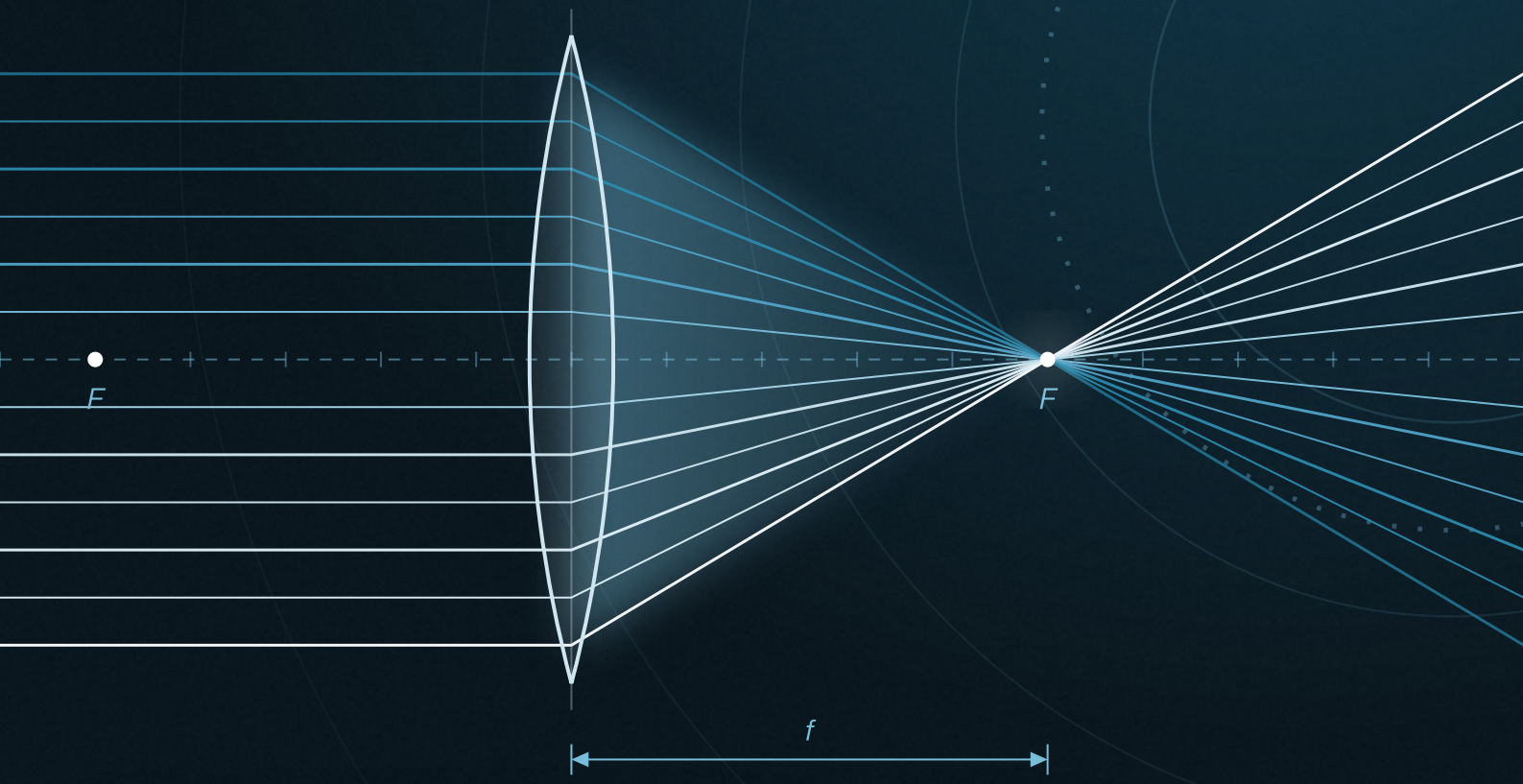
XamAgent

PRELIMS 2027

ED. 2027 · 15 CH · PYQ-PROOF · 189 FIG · 400 ★★★ · 183 MCQ



PRELIMS NOTES

Physics

The night before Prelims, you'll want just one book.

PYQ-PROOF

Every UPSC & BPSC question since 2011 is answerable from these notes.

16 · YEARS

UPSC CSE · BPSC · UPPCS · SSC CGL

Also in हिन्दी

Physics · Prelims Notes
Prelims 2027 Edition. Facts that change over time are current to November 2026.
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- Every effort has been made to keep each fact correct and current. Values, counts, records and policies change; facts of that kind are stated as of November 2026. Where an official notification, syllabus or answer key differs, the official document prevails.
- Answers to past questions follow the commissions' final keys where published; otherwise they follow the standard accepted answer.
- Examination patterns and syllabi are decided by the conducting bodies and may change. Results depend on the reader's own preparation; the author and publisher accept no liability for any loss arising from the use of this book.

Typeset

Set in Mona Sans and Noto Sans Devanagari. Diagrams drawn as vector graphics for this edition.

Why these notes are different

1051	134	103	183
key points	comparison tables	past questions solved	practice MCQs

Tested against real papers

All 103 Physics questions asked in UPSC 2011–2026 and BPSC 56th–71st were put to a reader who saw only these notes, with no answers. Every one can be answered from the text, and each is printed at the end of its chapter with the answer.

Built from the syllabus, not from one book

Chapters follow the combined Prelims syllabi of UPSC CSE, BPSC, UPPCS and SSC CGL, filled out to NCERT depth so nothing an examiner can reach is missing.

Know what to revise first

Every point carries a star. 400 ★★★ points are the facts asked again and again; revise them three times and the rest once.

Made to be remembered on the first reading

Concept before fact, then 105 memory tricks, 22 everyday examples and 189 diagrams drawn for this book, so each idea has a picture and a hook.

Trained on the examiner's tricks

122 exam-trap boxes show how options are twisted: look-alike terms, reversed statements and popular wrong beliefs.

Current, not copied from old editions

Facts that change (records, missions, standards, counts, prizes) were checked against official sources and are stated as of November 2026.

Revision built in

Two speeds: one full reading takes about 12 hours; the revision cards (193 points) and every ★★★ fact take about 2 hours the night before. Each chapter closes with practice questions (183 in all) with one-line explanations.

Clean, exam-ready facts

One fact per line, keyword in bold, numbers with their units and conditions. No filler, no padding, nothing to unlearn later.

	Usual notes	These notes
Coverage	One book's chapter list	Four exams' syllabi, checked against every past question
Priority	Everything looks equally important	Stars on every point; 400 ★★★ facts flagged
Memory	Lists to cram	Hooks, stories, everyday examples and diagrams
Traps	Learnt in the exam hall	Shown in red beside the fact
Freshness	Reprinted old facts	Changing facts current to November 2026
Practice	Separate book	Past questions and practice MCQs in every chapter

Acknowledgements

Our thanks go first to the teachers who showed that physics is not a list of formulas but a way of seeing the world: why a steel ship floats, why the sky is blue, why a pressure cooker cooks faster.

We are grateful to the Union Public Service Commission, the state public service commissions and the Staff Selection Commission, whose published question papers set the standard that every line here was tested against.

Thanks also to the public institutions whose open records keep the facts honest and current: the International Bureau of Weights and Measures, CSIR–National Physical Laboratory, the Indian Space Research Organisation, the Department of Atomic Energy, the Press Information Bureau and the Nobel Foundation.

Above all, this book is for the aspirant reading it after a long day: the one who revises in the bus, studies by a dim lamp, and keeps going after a bad mock test. May these pages make your preparation lighter and your exam day calmer.

The XamAgent team

A note to the reader

Most short notes are short for a reason. Forty or fifty pages, small type, every page full to the edge. One page takes twenty minutes to read and is forgotten by the next. After the exam, they count the questions that “came from” them.

This book does not work that way.

- **Readable type.** Set to be read, not squeezed.
- **Two to three minutes a page.** Measured, not estimated.
- **Built for recall.** Every idea has a diagram, a memory hook, an everyday example and the trap examiners set around it.

It is longer than short notes because memory needs room. The extra pages hold no extra facts to cram.

You will like this book if you value:

- understanding an idea before memorising it;
- knowing which facts to revise first, and which can wait;
- pages that are easy to read and quick to revise;
- notes tested against real papers before the exam, not credited with them after it.

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Contents

1	Units, Measurement and Measuring Instruments	★★★	7
2	Motion, Force and Newton's Laws	★★★	33
3	Work, Energy, Power and Simple Machines	★★	51
4	Gravitation and Satellites	★★★	63
5	Properties of Matter: Solids and Fluids	★★★	81
6	Heat and Thermodynamics	★★★	99
7	Waves and Sound	★★★	125
8	Light I: Reflection, Refraction and Optical Phenomena	★★★	145
9	Light II: Lenses, the Human Eye and Optical Instruments	★★	165
10	Electromagnetic Spectrum and Wave Optics	★★★	182
11	Electricity: Charge, Current and Circuits	★★★	197
12	Magnetism and Electromagnetism	★★	222
13	Atoms, Nuclei and Radioactivity	★★★	241
14	Semiconductors, Electronics and Modern Devices	★★	272
15	Scientists, Discoveries, Laws and Constants: Quick Tables	★★	294
★	**Night-before revision**: Every ★★★ fact in one place		312
	Facts that change: Where to check them		324

How to read: ★★★ asked again and again, ★★ asked sometimes, ★ good to know. Read the whole chapter once, then revise only the revision card and ★★★ points. Green boxes are memory tricks, red boxes are the traps examiners set, orange boxes show the idea in daily life.

CHAPTER 1

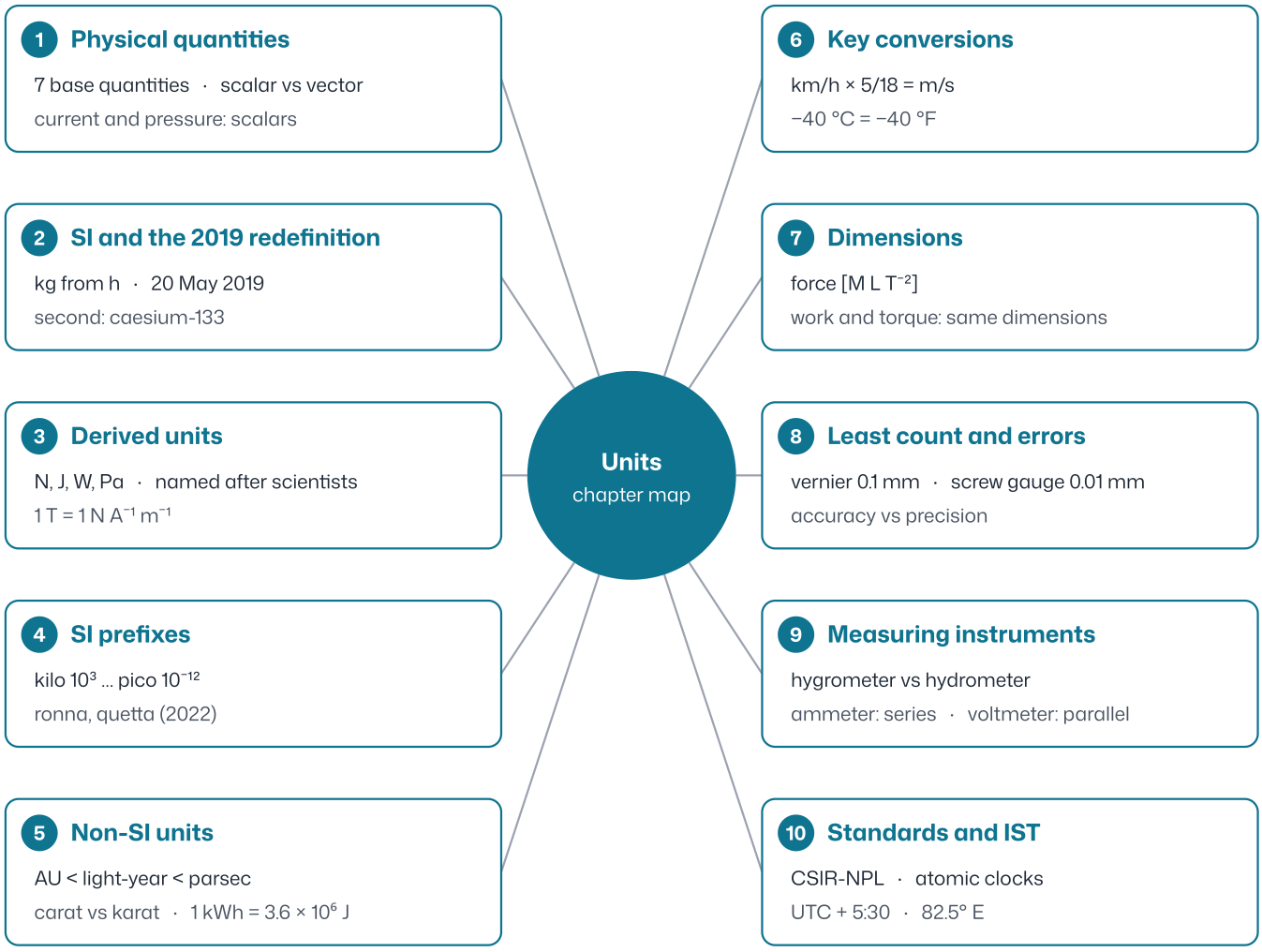
Units, Measurement and Measuring Instruments

BPSC asks two to four questions from here almost every year: which unit measures what, scalar or vector, light-year, kWh to joule, and which '-meter' measures what. SSC and UPPCS repeat the same unit and instrument lists.

Asked 16 times in past papers: UPSC 1 · BPSC 15

≈ 58 min to read ≈ 7 min to revise ★★★

Revise on: Day 1 | Day 3 | Day 7 | Day 21



Revision card

1. Seven SI base units: metre, kilogram, second, ampere, kelvin, mole, candela. Hook: King Mohan Sells Apples, Keeps Mangoes, Candies (kg, m, s, A, K, mol, cd).
2. Since 20 May 2019 all SI units rest on fixed constants: kilogram on Planck constant h, ampere on charge e, kelvin on Boltzmann k, mole on Avogadro N_A.
3. Light-year is a distance (≈ 9.46×10^{12} km). Parsec ≈ 3.26 light-years. AU ≈ 1.5×10^8 km (Earth–Sun).
4. 1 unit of electricity = 1 kWh = 3.6×10^6 J. So 250 units = 9×10^8 J.
5. 1 hp ≈ 746 W; 1 cal ≈ 4.186 J; 1 eV = 1.6×10^{-19} J; 1 atm = 1.013×10^5 Pa = 760 mm Hg.
6. Ångström = 10^{-10} m (wavelength, atom size); fermi = 10^{-15} m (nucleus); micron = 10^{-6} m.
7. Tesla = magnetic field = Wb/m² = N A^{-1} m^{-1} = 10^4 gauss. Hertz = frequency. Watt = power. Pascal = pressure.
8. Scalars: speed, pressure, current, work, energy. Vectors: displacement, velocity, force, torque, current density.
9. No unit at all: strain, refractive index, relative density, Mach number, coefficient of friction.
10. Hygrometer = humidity; hydrometer = liquid density; lactometer = milk; odometer = distance; speedometer = speed; tachometer = rpm.
11. Dynamo makes electricity; dynamometer measures force or engine power. Thermostat keeps temperature steady, it does not measure it.
12. Carat = 0.2 g for gems; karat = gold purity (24K pure, 22K ≈ 91.6%). Knot = a speed (1.852 km/h).
13. Newest prefixes (2022): ronna 10^{27}, quetta 10^{30}, ronto 10^{-27}, quecto 10^{-30}.
14. CSIR-NPL, New Delhi keeps India's national standards and IST (UTC + 5:30, 82.5° E); 2026 rules make IST the single legal time.

Physical quantities: base, derived, scalar, vector

7 base quantities

scalar vs vector

current: scalar

pressure: scalar

speed vs velocity

Anything we can measure is a **physical quantity**: a number plus a unit (5 kg, 20 m/s). A handful of quantities are chosen as **base (fundamental)** quantities; every other quantity is **derived** from them by multiplying or dividing. Speed is length ÷ time, so it needs no unit of its own.

★★★ **Base quantities (7)**: length, mass, time, electric current, temperature, amount of substance, luminous intensity. Force, velocity, work and pressure are derived.

★★ **Derived quantity** = built from base ones, e.g. force = mass × acceleration (kg m s^{-2}), density = mass ÷ volume (kg m^{-3}).

★★★ **Scalar**: has only size (magnitude). Mass, length, time, speed, distance, temperature, work, energy, power, pressure, density, volume, charge, potential, frequency.

★★★ **Vector**: has size and direction and adds by the triangle (parallelogram) rule. Displacement, velocity, acceleration, force, weight, momentum, impulse, torque, angular momentum, electric field, magnetic field.

★★★ **Electric current is a scalar** even though it 'flows' in a direction: two currents meeting at a junction simply add, they do not follow vector addition.

★★★ **Current density** (current per unit area) **is a vector**; it points along the flow at each point.

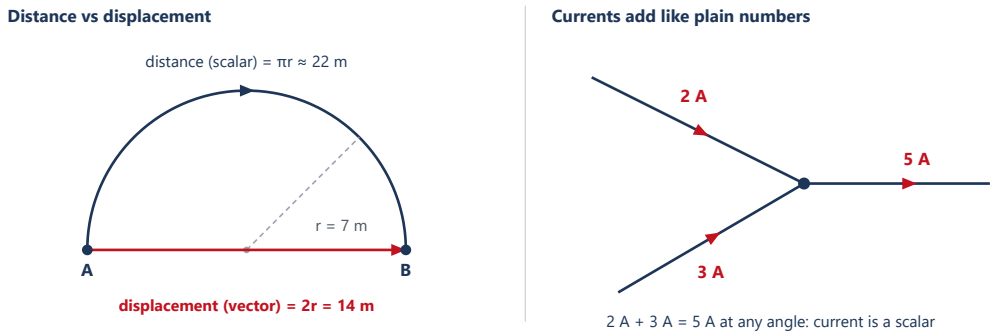
★★★ **Pressure is a scalar**: at a point in a fluid it acts equally in all directions. The force it produces on a surface is a vector.

★★ **Speed vs velocity**: speed = distance ÷ time (scalar); velocity = displacement ÷ time (vector). A runner finishing one full lap has zero displacement and zero average velocity but non-zero average speed.

★ **Tensors**: stress and moment of inertia are neither simple scalars nor vectors; prelims usually lists stress with pressure because both are force per area.

Scalar or vector: the ones examiners pick ★★★

Scalar	Vector
Distance	Displacement
Speed	Velocity
Mass	Weight (a force)
Work, energy, power	Force, torque
Pressure	Thrust (force on a surface)
Electric current	Current density
Electric potential, charge	Electric field
Magnetic flux	Magnetic field (flux density) B
Temperature, heat	Momentum, impulse
Time, volume, density	Acceleration, angular velocity



Left: going from A to B round a semicircle of radius 7 m covers a distance of πr ≈ 22 m, but the displacement is only the straight line AB = 14 m (drawn to scale). Right: 2 A and 3 A meeting at a junction always give 5 A, whatever the angle between the wires, so current is a scalar.

Remember it: Ask: 'Does it point somewhere?' A push (force), a twist (torque) and a shift in place (displacement) all point. A price tag (mass, energy, temperature) does not. Current is the odd one: it flows but obeys plain addition, like water from two taps filling one bucket.

⚠ Exam trap: 'Which is NOT a vector?' with options displacement, speed, velocity, torque: the answer is speed. 'Current is a vector' is false; 'current density is a vector' is true. 'Pressure is a vector' is false.

Quick check

1. How many base quantities does SI have? Is force one of them?
2. Current flows in a direction. Why is it still a scalar?
3. After one full lap of a track, which is zero: average speed or average velocity?

Answer: 1. seven; no, force is derived · 2. currents at a junction add as plain numbers, not by vector rules · 3. average velocity (displacement is zero)

The SI system and the 2019 redefinition

7 base units

kg from h

20 May 2019

caesium-133

metre from c

Kibble balance

Different regions once used feet, seers and tolas, so trade and science needed one common language of measurement. The **Metre Convention (20 May 1875)** set up the **BIPM** near Paris, and the **11th CGPM (1960)** named the modern metric system the **SI (Système International d'Unités)**. In 2019 every base unit was tied to a fixed constant of nature, so a unit can be made anywhere and never drifts.

The seven SI base units ★★★

Base quantity	SI unit	Symbol	Named after
Length	metre	m	Greek 'metron', measure
Mass	kilogram	kg	Greek 'gramma'
Time	second	s	second division of the hour
Electric current	ampere	A	André-Marie Ampère
Thermodynamic temperature	kelvin	K	Lord Kelvin (William Thomson)
Amount of substance	mole	mol	German 'Molekül'
Luminous intensity	candela	cd	Latin 'candle'

Remember it: King Mohan Sells Apples, Keeps Mangoes, Candies → kg, m, s, A, K, mol, cd. Only two base units carry a person's name: Ampère and Kelvin (A and K are the capital letters).

The 7 SI base units and the constant that fixes each (since 20 May 2019)

Quantity	Unit (symbol)	Fixed constant	Defined so since
Time	second (s)	Cs-133 frequency = 9 192 631 770 Hz	1967
Length	metre (m)	speed of light c = 299 792 458 m/s	1983
Mass	kilogram (kg)	Planck constant h	**2019 (new)**
Electric current	ampere (A)	elementary charge e	**2019 (new)**
Temperature	kelvin (K)	Boltzmann constant k	**2019 (new)**
Amount of substance	mole (mol)	Avogadro constant N_a	**2019 (new)**
Luminous intensity	candela (cd)	luminous efficacy K = 683 lm/W	1979

Red rows changed in 2019: the metal kilogram cylinder in France was retired.

Each base unit is now fixed by a constant. The four red rows (kg, A, K, mol) changed on 20 May 2019.

★★★ **2019 redefinition**: agreed by the 26th CGPM in November 2018, in force from **20 May 2019** (World Metrology Day). The values of h, e, k and N_A were fixed exactly.

★★★ **Kilogram** is now defined by the **Planck constant h = 6.626 070 15 × 10^{-34} J s**. The old platinum–iridium cylinder (International Prototype Kilogram, 1889) kept at Sèvres near Paris was retired.

★★ **Ampere** fixed by the **elementary charge e = 1.602 176 634 × 10^{-19} C**; **kelvin** by the **Boltzmann constant k = 1.380 649 × 10^{-23} J/K**; **mole** by the **Avogadro constant N_A = 6.022 140 76 × 10^{23} mol^{-1}**.

★★★ **Second** = time of **9 192 631 770** oscillations of the radiation from the **caesium-133** atom (atomic clock definition since 1967).

★★ **Metre** = distance light travels in vacuum in **1/299 792 458 of a second** (since 1983), so the speed of light is exactly 299 792 458 m/s.

★ **Candela** fixed by the luminous efficacy of 540 THz green light, 683 lm/W (since 1979).

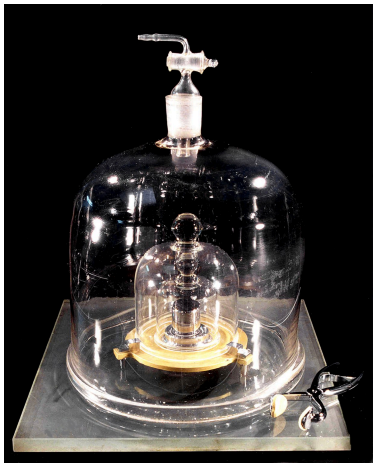
★ **Kibble balance**: the machine that balances the weight of a mass against an electromagnetic force, linking the kilogram to h.

★★ **28th CGPM (October 2026)**: the second is still defined by the **caesium-133** clock; a proposal for a new definition, expected to rest on **optical clocks**, is due at the **29th CGPM (2030)**.

★★ **Leap seconds end**: the 2026 CGPM made **UTC continuous from 20 May 2027**, so no more leap seconds will be added; UT1 and UTC may drift apart by up to one hour.

★ **Supplementary units** (old term): **radian** (plane angle) and **steradian** (solid angle); since 1995 they count as dimensionless derived units. 1 rad ≈ 57.3°.

★ **Older systems**: CGS (centimetre–gram–second), FPS (foot–pound–second, British), MKS (metre–kilogram–second, the parent of SI).



The International Prototype Kilogram ('Le Grand K'): a platinum–iridium cylinder kept under two glass bell jars near Paris. It defined the kilogram from 1889 until 20 May 2019; now the Planck constant does. Image: BIPM, Wikimedia Commons, CC BY-SA 3.0 IGO

⚠ **Exam trap:** 'The kilogram is still defined by a metal cylinder in France' is false since 2019. 'Mass, length and time are the only fundamental quantities' is false: SI has seven. Force and velocity are never base quantities.

☑ Quick check

1. Since 20 May 2019 the kilogram is fixed by which constant?
2. Radiation from which atom defines the second?
3. Which two SI base units are named after people?

Answer: 1. the Planck constant h · 2. caesium-133 (9 192 631 770 oscillations) · 3. ampere and kelvin

Derived units and units named after scientists

newton = kg m s^{-2}

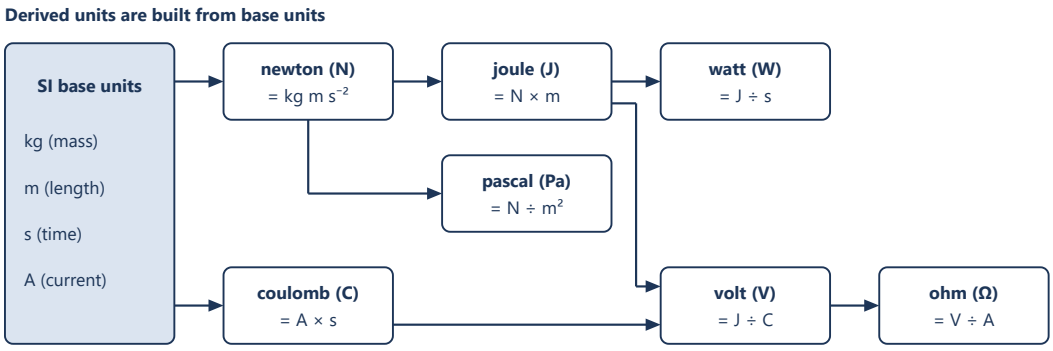
tesla = N A^{-1} m^{-1}

gray vs sievert

lumen vs lux

strain: no unit

A derived unit is a short name for a bundle of base units. The newton is just kg m s^{-2}; the watt is just a joule per second. Twenty-two derived units have special names, and most honour a scientist. Written in full the name is lower case (newton, watt); the symbol takes a capital letter when it comes from a person (N, W, Pa).



Derived units are short names for bundles of base units: the newton is kg m s^{-2}; the joule is a newton-metre and the watt a joule per second; the volt is a joule per coulomb and the ohm a volt per ampere.

SI derived units with special names ★★★

Quantity	Unit (symbol)	In other units	Named after
Force	newton (N)	kg m s^{-2}	Isaac Newton
Work, energy, heat	joule (J)	N m	James Prescott Joule
Power (incl. electric power)	watt (W)	J/s	James Watt
Pressure, stress	pascal (Pa)	N/m^2	Blaise Pascal
Frequency	hertz (Hz)	s^{-1} (cycles per second)	Heinrich Hertz
Electric charge	coulomb (C)	A s	Charles-Augustin de Coulomb
Potential difference, emf	volt (V)	J/C = W/A	Alessandro Volta
Resistance	ohm (Ω)	V/A	Georg Simon Ohm
Conductance	siemens (S)	$Ω^{-1}$ (old name mho)	Werner von Siemens
Capacitance	farad (F)	C/V	Michael Faraday
Magnetic flux	weber (Wb)	V s	Wilhelm Weber
Magnetic field (flux density)	tesla (T)	Wb/m^2 = N A^{-1} m^{-1}	Nikola Tesla
Inductance	henry (H)	Wb/A	Joseph Henry
Celsius temperature	degree Celsius (°C)	K − 273.15	Anders Celsius
Radioactivity (activity)	becquerel (Bq)	one decay per second	Henri Becquerel
Absorbed radiation dose	gray (Gy)	J/kg	Louis Harold Gray
Dose equivalent (biological effect)	sievert (Sv)	J/kg	Rolf Sievert
Luminous flux	lumen (lm)	cd sr	Latin 'light'
Illuminance	lux (lx)	lm/m^2	Latin 'light'
Catalytic activity	katal (kat)	mol/s	Greek 'dissolve'
Plane angle / solid angle	radian (rad) / steradian (sr)	dimensionless	-

★★★ **Tesla from F = BIL**: force on a wire = field × current × length, so B = F/(IL) and **1 T = 1 N A^{-1} m^{-1}** (newton per ampere-metre). Also 1 T = 1 Wb/m^2 = **10^4 gauss**.

★★★ **Watt** is the unit of all power, electric power included: P = VI, so 1 W = 1 V × 1 A.

★★★ **Hertz** = one cycle per second; it measures frequency of any wave or vibration (sound, AC mains at 50 Hz in India, radio).

★★ **Gray vs sievert**: both are J/kg. Gray is the raw energy absorbed; sievert weights it for harm to living tissue.

★★ **Lumen vs lux**: lumen = total light given out by a source; lux = light falling on each square metre (illuminance). LED bulbs are rated in lumens; a lux meter checks room lighting.

★★ **Coulomb** = charge passed by 1 ampere in 1 second; one coulomb ≈ 6.25×10^{18} electrons.

Common quantities whose units have no special name ★★

Quantity	SI unit
Velocity, speed	m/s
Acceleration	m/s^2
Momentum, impulse	kg m/s = N s
Torque (moment of force)	N m (never written J)
Surface tension	N/m
Viscosity (coefficient)	Pa s (CGS: poise; 1 Pa s = 10 poise)
Density	kg/m^3
Specific heat capacity	$J\ kg^{-1}\ K^{-1}$
Latent heat	J/kg
Thermal conductivity	$W\ m^{-1}\ K^{-1}$
Resistivity	Ω m (ohm-metre)
Electric field	N/C = V/m
Angular velocity	rad/s
Moment of inertia	$kg\ m^2$
Power of a lens	dioptre (D) = m^{-1}
Young's modulus	Pa (N/m^2)
Sound intensity	W/m^2 (level in decibels)

★★★ **Quantities with no unit (dimensionless)**: **strain** (change in length ÷ original length), refractive index, relative density (specific gravity), coefficient of friction, Poisson's ratio, relative permittivity (dielectric constant), Mach number, efficiency.

★★★ **Stress and pressure** are both force per area, so both are measured in **pascal**. Strain has no unit because it is a ratio of two lengths.

Remember it: Light units (candela, lumen, lux) are the 'no-name' family: none is named after a person. Electric units read like a roll call of 19th-century electricity pioneers: Volta (volt), Ohm (ohm), Faraday (farad), Henry (henry), and Weber and Tesla for the magnetic units.

⚠ **Exam trap:** Torque and work share N m, but torque is never written in joules. 'Ohm-metre is the unit of resistance' is wrong: ohm-metre is resistivity. 'Siemens measures resistance' is wrong: it measures conductance (the reverse of resistance).

Quick check

1. Write the tesla in newton, ampere and metre.
2. Is ohm-metre the unit of resistance or of resistivity?
3. Name a quantity that has no unit at all.

Answer: 1. 1 T = 1 N A^{-1} m^{-1} (from F = BIL) · 2. resistivity · 3. strain (also refractive index, relative density)

SI prefixes

kilo to tera

milli to pico

ronna, quetta (2022)

M vs m

Prefixes let one unit cover atoms and galaxies without long strings of zeros. Above kilo and below milli, each step is a factor of 1000. The 27th CGPM in **November 2022** added four new prefixes because data storage was heading past yotta.

SI prefixes: each step is ×1000

BIG: names end in -a		SMALL: names end in -o	
quetta (Q)	10^{30} (2022)	**quecto (q)**	10^{-30} (2022)
ronna (R)	10^{27} (2022)	**ronto (r)**	10^{-27} (2022)
yotta (Y)	10^{24}	yocto (y)	10^{-24}
zetta (Z)	10^{21}	zepto (z)	10^{-21}
exa (E)	10^{18}	atto (a)	10^{-18}
peta (P)	10^{15}	femto (f)	10^{-15}
tera (T)	10^{12}	pico (p)	10^{-12}
giga (G)	10^{9}	nano (n)	10^{-9}
mega (M)	10^{6}	micro (μ)	10^{-6}
kilo (k)	10^{3}	milli (m)	10^{-3}

In between: hecto (h) 10^{2} · deca (da) 10^{1} · deci (d) 10^{-1} · centi (c) 10^{-2}

Symbols are capital from mega upward; kilo is small k

Big prefixes end in -a, small ones end in -o. The four in red were added in 2022.

★★★ **Everyday prefixes**: kilo 10^{3}, mega 10^{6}, giga 10^{9}, tera 10^{12}; milli 10^{-3}, micro 10^{-6}, nano 10^{-9}, pico 10^{-12}.

★★ **Next ones**: peta 10^{15}, exa 10^{18}, zetta 10^{21}, yotta 10^{24}; femto 10^{-15}, atto 10^{-18}, zepto 10^{-21}, yocto 10^{-24}.

★★ **Added in 2022**: **ronna (R) 10^{27}, quetta (Q) 10^{30}, ronto (r) 10^{-27}, quecto (q) 10^{-30}**. Earth's mass is about 6 ronnagrams; an electron's mass is about 1 rontogram.

★ **hecto 10^{2}, deca 10^{1}, deci 10^{-1}, centi 10^{-2}**: the only prefixes that are not powers of 1000 (hectare, decibel, centimetre).

★ **Symbol case matters**: M (mega) vs m (milli); P (peta) vs p (pico). 1 mW is a thousandth of a watt; 1 MW is a million watts.

Remember it: Big ladder: Kind Men Give Tea, People Enjoy Zesty Yellow Rich Quality (kilo, mega, giga, tera, peta, exa, zetta, yotta, ronna, quetta). Small ladder: My Mother Never Prepares Food After Zero Yoga, Really Quickly (milli, micro, nano, pico, femto, atto, zepto, yocto, ronto, quecto).

⚠ **Exam trap:** Micro is 10^{-6} (one millionth), not 10^{-9}; nano is 10^{-9}. Femto (10^{-15}) is the 'fermi' size of a nucleus. A 'giga' byte is 10^{9}, a 'tera' 10^{12}.

Quick check

1. Micro or nano: which is 10^{-6}?
2. Which four prefixes were added in 2022?
3. 1 MW is how many times 1 mW?

Answer: 1. micro (nano is 10^{-9}) · 2. ronna, quetta, ronto, quecto · 3. 10^{9} times

Non-SI and traditional units exams love

light-year: distance

AU < ly < parsec

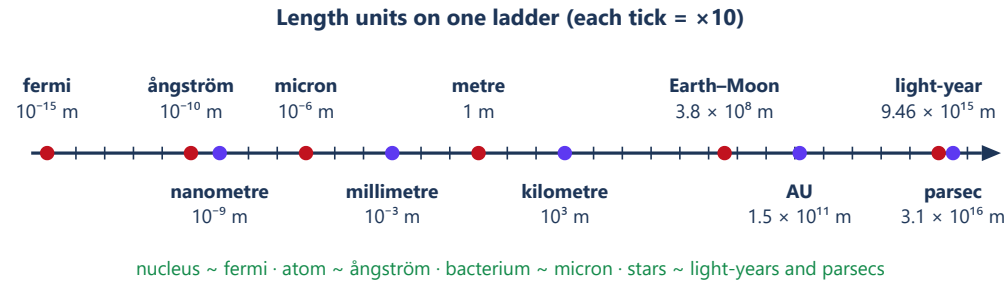
carat vs karat

kWh = 3.6 × 10^6 J

knot: speed

decibel

Many old or specialist units survive because they fit their job: astronomers need huge lengths, jewellers need tiny masses, sailors measure by the Earth's own curve. Exams test what each unit measures, so learn them by family.



From nucleus to stars: fermi < ångström < nanometre < micron < … < AU < light-year < parsec.

Length and distance ★★★

Unit	Value	Used for
Light-year (ly)	distance light travels in one year ≈ 9.46 × 10^{15} m ≈ 9.46 × 10^{12} km	distances to stars
Astronomical unit (AU)	mean Earth–Sun distance ≈ 1.496 × 10^{11} m ≈ 150 million km	solar-system distances
Parsec (pc)	≈ 3.26 ly ≈ 3.09 × 10^{16} m ≈ 206 265 AU	distances to stars and galaxies
Ångström (Å)	10^{-10} m = 0.1 nm	wavelength of light, X-rays; size of atoms
Fermi (femtometre, fm)	10^{-15} m	size of nucleus
Micron (micrometre, µm)	10^{-6} m	cells, bacteria, dust (PM2.5 = particles ≤ 2.5 µm)
Nanometre (nm)	10^{-9} m = 10 Å	visible light 400–700 nm; chip technology
Nautical mile	1852 m exactly (1.852 km)	sea and air navigation; one minute of latitude
Mile (statute)	≈ 1.609 km	road distance (UK, USA)
Fathom	6 feet ≈ 1.83 m	depth of water
Foot / inch / yard	1 ft = 12 in = 30.48 cm; 1 in = 2.54 cm; 1 yd = 3 ft = 0.9144 m	everyday length

★★★ **Light-year measures distance, not time.** Light covers about 3 × 10^5 km every second; in a year that adds up to about 9.46 × 10^{12} km.

★★★ **Why astronomers use light-years**: the **speed of light in vacuum is the same everywhere and always**, so it makes a perfect, unchanging yardstick for huge distances.

★★★ **Order of size**: AU < light-year < parsec. 1 ly ≈ 63 000 AU; 1 pc ≈ 3.26 ly.

★★ **Parsec** = 'parallax of one arc-second': the distance at which 1 AU would look only 1 arc-second wide.

★★ **Nearest star** after the Sun, Proxima Centauri, is about 4.2 ly away; sunlight takes about 8 minutes 20 seconds to reach Earth (1 AU).

⚠ **Exam trap:** 'Light-year is a unit of time' and 'light-year is a unit of speed' are both wrong: it is distance. In UPSC 2021 the reason asked was the constancy of the speed of light, not that stars stay fixed: stellar distances do change, and light does bend near massive bodies.

Mass, volume, area ★★

Unit	Value	Note
Carat (ct)	200 mg = 0.2 g	mass of diamonds and gems
Karat (K)	parts of gold out of 24	purity of gold: 24K pure, 22K ≈ 91.6%, 18K = 75%
Quintal / tonne	100 kg / 1000 kg	crops (quintal), freight (tonne)
Atomic mass unit (u, dalton)	≈ 1.66×10^{-27} kg	1/12 of a carbon-12 atom
Tola	≈ 11.66 g	traditional Indian unit for gold and silver
Pound (lb)	≈ 0.4536 kg	British mass
Litre (L)	1 dm^3 = 1000 cm^3; 1 m^3 = 1000 L	1 mL = 1 cm^3 (cc)
Barrel (oil)	42 US gallons ≈ 159 litres	crude oil trade
Gallon	US ≈ 3.785 L; imperial ≈ 4.546 L	fuel in USA/UK
Hectare (ha)	10 000 m^2	land; 1 ha ≈ 2.47 acres
Acre	≈ 4047 m^2	land

Remember it: Carat with a C is for the Crystal (diamond, a mass). Karat with a K is for the Kangan (gold bangle, a purity out of 24). 22K hallmarked jewellery is marked 916: 22 ÷ 24 = 0.916.

Energy, power and pressure ★★★

Unit	Value in SI	Note
Kilowatt-hour (kWh) = 1 'unit' of electricity	3.6×10^6 J	1000 W for 3600 s; your electricity bill
Calorie (cal)	≈ 4.186 J (≈ 4.2 J)	heat; food 'Calorie' (kcal) = 1000 cal
Electron-volt (eV)	1.602×10^{-19} J	atomic and nuclear energy; MeV, GeV
Erg (CGS)	10^{-7} J	1 J = 10^7 erg
British thermal unit (BTU)	≈ 1055 J	heating, air conditioners
Horsepower (hp)	≈ 746 W	engines, motors, pumps
Ton of refrigeration	≈ 3.5 kW of cooling	AC capacity ('1.5-ton AC')
Dyne (CGS force)	10^{-5} N	1 N = 10^5 dyne
Kilogram-force (kgf)	≈ 9.8 N	pressure unit kgf/cm² ≈ 0.98 bar
Bar	10^5 Pa	weather: 1 millibar = 1 hPa = 100 Pa
Standard atmosphere (atm)	101 325 Pa ≈ 1.013 bar	= 760 mm of mercury
Torr	1/760 atm ≈ 133 Pa	≈ 1 mm Hg; vacuum work
mm of Hg	≈ 133 Pa	blood pressure (120/80 mm Hg)
psi (pound per square inch)	≈ 6.9 kPa	tyre pressure (30–35 psi)

★★★ **kWh to joule**: 1 kWh = 1000 W × 3600 s = **3.6×10^6 J**. Example: 250 units = 250 × 3.6 × 10^6 = **9×10^8 J**.

★★★ **kWh is energy, kW is power.** The meter counts energy used; the rating on a heater (2 kW) is its power.

★★★ **Pressure** = force ÷ area; SI unit **pascal (N/m²)**. 'kg/cm²' is strictly mass per area; the pressure unit is **kgf/cm²** (kilogram-force per square centimetre). So if the options are only kg/cm², kg/cm, kg/mm and kg/cm³, the answer is **none of these**: each is a mass unit over a length, area or volume.

★★ **Electron-volt** is energy, not charge or voltage: the energy one electron gains across 1 volt.

See it around you: A 1.5 kW geyser run for 2 hours uses 1.5 × 2 = 3 kWh = 3 units = 3 × 3.6 × 10^6 = 1.08 × 10^7 J.

Electricity, magnetism, radiation, sound, speed ★★

Unit	Measures	Value / note
Gauss (G)	magnetic field (CGS)	1 T = 10^4 G; Earth's field ≈ 0.25–0.65 G
Maxwell	magnetic flux (CGS)	1 Wb = 10^8 maxwell
Curie (Ci)	radioactivity	3.7 × 10^{10} Bq (activity of 1 g of radium)
Rad / rem	absorbed dose / dose equivalent	1 rad = 0.01 Gy; 1 rem = 0.01 Sv
Röntgen (R)	X-ray and gamma exposure (ionisation of air)	old unit
Decibel (dB)	loudness (sound level)	logarithmic; +10 dB = 10 × intensity
Mach number	speed ÷ speed of sound	no unit; Mach 1 ≈ 343 m/s ≈ 1235 km/h in air at 20 °C
Knot	speed of ships and aircraft	1 nautical mile per hour = 1.852 km/h
rpm	rotational speed	revolutions per minute (read on a tachometer)
Dobson unit (DU)	thickness of ozone column	1 DU = 0.01 mm of pure ozone at 0 °C and 1 atm
Cusec / cumec	river or canal flow	cubic foot per second (≈ 28.3 L/s) / cubic metre per second
Barn	nuclear cross-section (area)	10^{-28} m²

★★★ **Decibel** (one-tenth of a **bel**, after Alexander Graham Bell): 0 dB = faintest audible sound; whisper ≈ 30 dB; talk ≈ 60 dB; long exposure above ≈ 85 dB damages hearing; pain around 120–130 dB.

★★ **Mach**: subsonic < Mach 1 < supersonic; above Mach 5 is hypersonic. Mach number has no unit.

★★ **Knot is a speed**, not a distance and not a length of rope: 20 knots ≈ 37 km/h.

⚠ **Exam trap:** Pairs that get swapped: carat (mass) vs karat (purity); knot (speed) vs nautical mile (distance); kWh (energy) vs kW (power); eV (energy) vs volt (potential); gauss vs tesla (same quantity, 1 T = 10 000 G); decibel measures loudness, hertz measures pitch (frequency).

☑ **Quick check**

1. A light-year is a unit of _____ .
2. Why does the light-year make a good yardstick for stars?
3. 1 kWh is how many joules?

Answer: 1. distance (≈ 9.46 × 10^{15} m) · 2. light's speed in vacuum is the same everywhere and always · 3. 3.6 × 10^6 J

Key conversions at a glance

km/h × 5/18

K = °C + 273

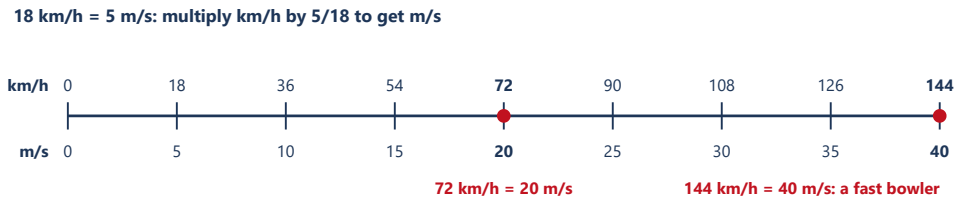
°F = 9/5 °C + 32

−40 °C = −40 °F

37 °C = 98.6 °F

Conversions worth memorising ★★★

From	To	Rule
km/h	m/s	multiply by 5/18 (72 km/h = 20 m/s)
Celsius	Kelvin	K = °C + 273.15 (often 273)
Celsius	Fahrenheit	°F = (9/5) °C + 32
Body temperature	-	37 °C = 98.6 °F ≈ 310 K
Water boils / freezes (1 atm)	-	100 °C = 212 °F = 373 K / 0 °C = 32 °F = 273 K
Same reading on °C and °F	-	−40 °C = −40 °F
1 N	dyne	10^5 dyne
1 J	erg	10^7 erg
1 kWh	J	3.6×10^6 J
1 hp	W	≈ 746 W
1 cal	J	≈ 4.186 J
1 atm	Pa / mm Hg	1.013×10^5 Pa / 760 mm Hg
1 T	gauss	10^4 G
1 inch / 1 foot	cm	2.54 cm / 30.48 cm
1 mile / 1 nautical mile	km	1.609 km / 1.852 km
1 rad	degree	≈ 57.3°



A speed line drawn to scale: each km/h mark sits exactly above its m/s value. Every 18 km/h is 5 m/s, so 72 km/h = 20 m/s and a 144 km/h delivery is 40 m/s.

Remember it: Speed trick: '18 km/h = 5 m/s'. Cricket bowlers at 144 km/h are bowling 40 m/s. And −40 is the one temperature where Celsius and Fahrenheit 'shake hands'.

Quick check

1. 72 km/h in m/s?
2. At which temperature do Celsius and Fahrenheit read the same?
3. Body temperature 37 °C is about how many kelvin?

Answer: 1. 20 m/s (× 5/18) · 2. −40 · 3. ≈ 310 K

Dimensions in brief

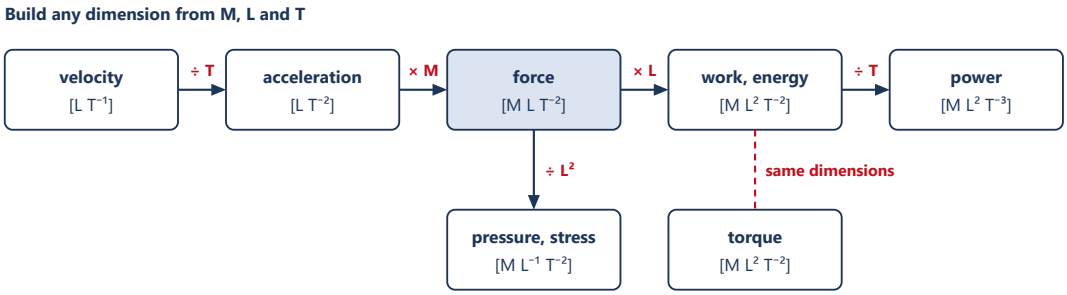
[M L T]

force [M L T⁻²]

work and torque alike

homogeneity

Writing a quantity in powers of mass [M], length [L] and time [T] shows what it is really made of. Two sides of a correct equation must have the same dimensions (principle of homogeneity), which lets us check formulas and convert units quickly.



Each step multiplies or divides by one base dimension. Work and torque end with the same dimensions [M L² T⁻²], though work is a scalar and torque a vector.

Dimensional formulas ★★

Quantity	Dimensions	SI unit
Velocity	[L T⁻¹]	m/s
Acceleration	[L T⁻²]	m/s²
Force	[M L T⁻²]	N
Momentum, impulse	[M L T⁻¹]	N s
Work, energy, torque	[M L² T⁻²]	J (torque: N m)
Power	[M L² T⁻³]	W
Pressure, stress, Young's modulus	[M L⁻¹ T⁻²]	Pa
Surface tension, spring constant	[M T⁻²]	N/m
Frequency, angular velocity	[T⁻¹]	Hz, rad/s
Planck constant, angular momentum	[M L² T⁻¹]	J s
Gravitational constant G	[M⁻¹ L³ T⁻²]	N m² kg⁻²
Strain, refractive index, angle	[M⁰ L⁰ T⁰]	none

★★ **Same dimensions, different quantities**: work and torque; pressure and stress (and energy per volume); impulse and momentum; Planck constant and angular momentum; light-year and wavelength (both length).

★ **Limits of dimensional analysis**: it cannot give pure-number constants (the ½ in ½mv²) and cannot handle formulas with sine, log or exponentials.

⚠ **Exam trap:** 'Quantities with the same dimensions must be the same physical quantity' is false: work (scalar) and torque (vector) share [M L² T⁻²].

Quick check

1. Dimensional formula of force?
2. Which two different quantities share the dimensions [M L² T⁻²]?
3. Why can dimensions not give the ½ in ½mv²?

Answer: 1. [M L T⁻²] · 2. work (energy) and torque · 3. pure numbers have no dimensions

Measuring: least count, vernier, screw gauge, errors

least count

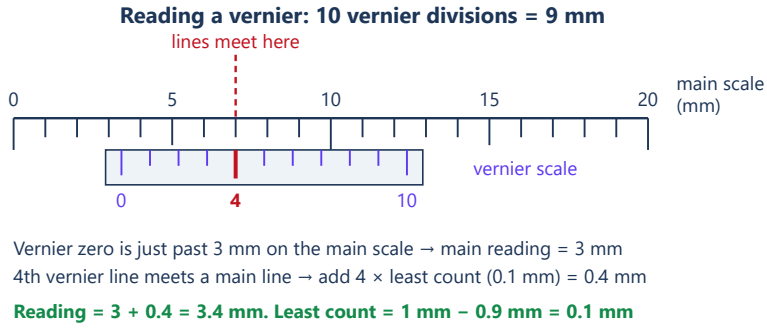
vernier 0.1 mm

screw gauge 0.01 mm

accuracy vs precision

systematic vs random

No instrument reads finer than its smallest division. That smallest reading is its **least count**; the smaller the least count, the more precise the instrument. A vernier and a screw gauge both use a clever second scale to read a fraction of the main division.



Find the vernier line that meets a main-scale line; its number × 0.1 mm is added to the main reading.

Least count of common instruments ★★

Instrument	Least count	Typical use
Metre scale	1 mm	lengths in cm and m
Vernier callipers	0.1 mm (0.01 cm)	inner and outer diameter, depth of a tube
Screw gauge (micrometer)	0.01 mm (0.001 cm)	thickness of wire or sheet
Spherometer	0.01 mm	curvature (radius) of lens or spherical surface
Clinical thermometer	0.1 °C	body temperature, 35–42 °C
Digital stopwatch	0.01 s	short time intervals

★★ **Vernier callipers**: least count = 1 main-scale division − 1 vernier division = 1 mm − 0.9 mm = **0.1 mm**. Named after **Pierre Vernier** (1631).

★★ **Screw gauge**: least count = pitch ÷ number of circular-scale divisions, e.g. 0.5 mm ÷ 50 = **0.01 mm**; ten times finer than a vernier.

★★ **Accuracy** = how close a reading is to the true value; **precision** = how close repeated readings are to each other (and how fine the least count is).

★ **Systematic error** (same direction every time, e.g. zero error, faulty calibration) is removed by adjusting each reading for it; **random error** (unpredictable scatter) is reduced by averaging many readings.

★ **Parallax error**: reading a scale from an angle; avoid by keeping the eye straight above the mark.

★ **Significant figures**: the reliable digits plus the first doubtful one; 2.50 m claims more precision than 2.5 m.

Remember it: Dartboard picture: darts clustered tightly but far from the bull = precise, not accurate. Darts scattered evenly around the bull = accurate on average, not precise. Clustered on the bull = both.

Quick check

1. Least count of vernier callipers, and of a screw gauge?
2. Darts tightly grouped but far from the bull: accurate or precise?
3. Which error shrinks when you average many readings?

Answer: 1. 0.1 mm; 0.01 mm · 2. precise, not accurate · 3. random error

Measuring instruments: what each one measures

-meter, -scope, -graph

hygrometer vs hydrometer

lactometer: milk

odometer vs speedometer

ammeter: series

dynamo vs dynamometer

Most instrument names are Greek or Latin roots plus '-meter' (measure), '-scope' (see) or '-graph' (write/record). Learn about twenty roots and you can decode almost any option an examiner sets.

Decode the name from its root ★★

Root	Meaning	Instrument
hygro-	moisture	hygrometer: humidity
hydro-	water	hydrometer: density of liquids
lacto-	milk	lactometer: purity of milk
pyro-	fire	pyrometer: very high temperature
baro-	weight, pressure	barometer: air pressure
mano-	thin (gas)	manometer: gas pressure
anemo-	wind	anemometer: wind speed
alti-	height	altimeter: altitude
audio-	hearing	audiometer: hearing / sound level
chrono-	time	chronometer: exact time at sea
tacho-	speed	tachometer: rotation speed (rpm)
odo-	road, way	odometer: distance travelled
seismo-	shaking	seismograph: earthquake waves
sphygmo-	pulse	sphygmomanometer: blood pressure
cresco-	I grow (Latin)	crescograph: plant growth
sacchari-	sugar	saccharimeter: sugar in solution
onde (French)	wave	ondometer: frequency of radio waves
tele-	far	telemeter: measuring at a distance
dynamo-	power, force	dynamometer: force, torque, engine power

Weather, earth, sea and navigation ★★★

Instrument	Measures / does	Remember
Barometer	atmospheric pressure	Torricelli, 1643; sudden fall = storm coming, slow rise = fair weather
Barograph	continuous record of air pressure	a recording barometer
Altimeter	height (altitude) of aircraft	works like an aneroid barometer: pressure falls with height
Anemometer	wind speed	spinning cups; a wind vane gives direction
Hygrometer	humidity of air	wet-and-dry-bulb type is a psychrometer
Hygroscope	shows change in humidity	indicates only, does not measure
Rain gauge (udometer)	rainfall	mm of rain
Pyrheliometer	intensity of direct solar radiation	not a furnace thermometer
Seismograph	records earthquake waves	Richter scale = magnitude; Mercalli scale = intensity (damage)
Fathometer (echo sounder)	depth of the sea	times an echo of a sound pulse (SONAR idea)
Hypsometer	height above sea level	from the boiling point of water
Gravimeter	small changes in g	oil and mineral prospecting
Sextant	angle of the Sun or a star above the horizon	finds latitude at sea; heights of distant objects
Chronometer	very accurate time, especially on ships	John Harrison; accurate time gives longitude
Compass / gyrocompass	direction	magnetic needle / spinning gyroscope

Liquids, pressure and matter ★★★

Instrument	Measures / does	Remember
Hydrometer	density (relative density) of liquids	floats deeper in lighter liquids
Lactometer	purity of milk (its density)	a special hydrometer; water lowers milk's density
Manometer	pressure of gases (in a pipe or vessel)	U-tube of liquid
Saccharimeter	concentration of sugar in solution	uses rotation of polarised light
Salinometer	salinity (salt content) of water	seawater, boiler water
Viscometer	viscosity of liquids	engine oil, paints
Refractometer	refractive index	sugar in fruit juice, gems
Spherometer	curvature of spherical surfaces	lenses, mirrors
Venturimeter	rate of flow of liquid in a pipe	Bernoulli's principle
Pitot tube	speed of fluid flow; airspeed of aircraft	Bernoulli's principle

Heat, light and radiation ★★

Instrument	Measures / does	Remember
Thermometer	temperature	mercury, alcohol, digital
Pyrometer	very high temperature (furnaces, molten metal)	reads the heat radiation from a distance
Cryometer	very low temperature	cryo = cold
Bolometer	heat (infrared) radiation	tiny change in resistance
Calorimeter	quantity of heat	specific heat and latent heat experiments
Thermostat	keeps temperature constant	fridge, iron, geyser; regulates, does not measure
Photometer	luminous intensity of a light source	compares two lamps
Lux meter	illuminance (light falling on a surface)	reads in lux
Radiometer	intensity of radiant energy	Crookes radiometer spins in light
Spectroscope / spectrometer	spectrum: splits light into wavelengths	identifies elements in stars
Ondometer (wavemeter)	frequency of electromagnetic (radio) waves	onde = wave
Geiger counter (Geiger–Müller counter)	detects and counts ionising radiation (α, β, γ)	clicks on each particle
Dosimeter	radiation dose received by a person	worn by X-ray and nuclear workers

Electricity and magnetism ★★★

Instrument	Measures / does	Remember
Ammeter	electric current	low resistance; joined in series
Voltmeter	potential difference (voltage)	high resistance; joined in parallel
Galvanometer	detects and measures very small currents	becomes an ammeter with a shunt, a voltmeter with a series resistance
Potentiometer	emf and potential difference very accurately; compares emfs	draws no current at balance, so more accurate than a voltmeter
Ohmmeter / megger	resistance / very high (insulation) resistance	-
Multimeter (AVO meter)	current, voltage and resistance	A-V-O = amps, volts, ohms
Wattmeter	electric power	watts
Energy meter	electrical energy used	kWh ('units') on your bill
Electroscope	detects electric charge	gold-leaf electroscope
Electrometer	charge or potential difference	-
Oscilloscope (CRO)	displays the waveform of a signal	cathode-ray oscilloscope
Dynamo	converts mechanical energy into electrical energy	a generator, not a measuring device
Dynamometer	force, torque or power of an engine	a measuring device

Vehicles, machines and distance ★★★

Instrument	Measures / does	Remember
Odometer	total distance travelled by a vehicle	the 'km reading' on the dashboard
Speedometer	instantaneous speed of a vehicle	the needle
Tachometer	rotational speed of an engine or shaft (rpm)	the rev counter
Telemeter	records readings at a distant place and sends them; range-finder in surveying	satellites send telemetry
Stroboscope	makes fast-rotating or vibrating objects look still	measures their speed
Pedometer	steps walked	fitness bands
Gyroscope	keeps direction / measures rotation	aircraft, ships, phones

Medicine and biology ★★★

Instrument	Measures / does	Remember
Sphygmomanometer	blood pressure	normal about 120/80 mm Hg
Stethoscope	hears heart and lung sounds	René Laennec, 1816
Cardiograph (electrocardiograph, ECG)	records electrical activity of the heart	ECG = electrocardiogram (the graph)
Audiometer	sharpness of hearing; sound intensity	hearing test
Audiophone	hearing aid	helps hearing, does not measure
Crescograph	growth of plants	invented by J.C. Bose
Kymograph	graphic record of muscle movement, pulse, blood pressure	physiology labs
Endoscope	views inside the body	uses optical fibres (total internal reflection)
Pulse oximeter	oxygen saturation of blood	clips on a finger
Polygraph	pulse, breathing, blood pressure together	the 'lie detector'

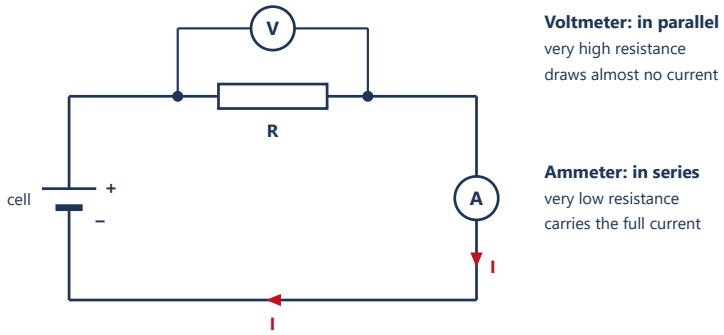
★★★ **Odometer vs speedometer**: odometer = distance covered (km); speedometer = speed right now (km/h). A **chronometer** keeps precise time; an **ammeter** measures current.

★★★ **Hygrometer vs hydrometer**: hygro = moisture in air (humidity); hydro = water, i.e. density of liquids. The **lactometer** is a hydrometer for milk.

★★ **Ammeter in series, voltmeter in parallel**: an ammeter must carry the full current, so it has very low resistance; a voltmeter must not draw current, so it has very high resistance.

★★ **Barometer vs manometer**: barometer = pressure of the atmosphere; manometer = pressure of a gas in a closed vessel or pipe.

★★ **Pyrometer vs pyrheliometer**: pyrometer = furnace temperature; pyrheliometer = sunlight intensity.



The ammeter sits in the loop itself (series), so the whole current passes through it; the voltmeter is connected across the resistor R (parallel) and draws almost no current. Current I flows out of the + terminal of the cell.

⚠ **Exam trap:** Look-alike pairs: hygrometer (humidity) / hydrometer (liquid density) / hygroscope (only shows humidity change); dynamo (makes electricity) / dynamometer (measures force or power); altimeter (height) / audiometer (hearing); odometer (distance) / speedometer (speed) / tachometer (rpm); thermostat (controls) / thermometer (measures); seismograph (instrument) / Richter scale (a scale, not an instrument).

See it around you: Your scooter's dashboard: the needle is the speedometer, the running km total is the odometer, and a bike with a 'rpm' dial has a tachometer. The milkman's lactometer floats higher in pure milk and sinks deeper when water is added.

Quick check

1. Hygrometer or hydrometer: which measures humidity?
2. Why is an ammeter joined in series and a voltmeter in parallel?
3. What does a crescograph measure, and who invented it?

Answer: 1. hygrometer (hydrometer: density of liquids) · 2. the ammeter must carry the full current (low R); the voltmeter must draw almost none (high R) · 3. plant growth; J.C. Bose

India's national standards and Indian Standard Time

CSIR-NPL

atomic clocks

UTC + 5:30

82.5° E, Mirzapur

IST Rules 2026

Every country needs one trusted keeper of its kilogram, metre and second so that a weighing scale in Patna and a meter in Chennai agree. In India that keeper is the **CSIR-National Physical Laboratory (NPL), New Delhi**, the country's **National Metrology Institute**, set up in 1947. Its standards are traceable to the BIPM, so Indian measurements are accepted worldwide.

★★★ **CSIR-NPL, New Delhi** realises and maintains India's national standards of the SI units (mass, length, time, temperature, current, light and others) and calibrates instruments against them.

★★★ **CSIR-NPL keeps Indian Standard Time (IST)** with a set of **atomic clocks (caesium standards)**, linked to world time (UTC) through the BIPM.

★★★ **IST = UTC + 5 hours 30 minutes**, based on the **82.5° E (82°30′ E) meridian**, which passes near **Mirzapur (Uttar Pradesh)**; India uses a single time zone.

★★★ The **82.5° E** meridian crosses **five states**: **Uttar Pradesh, Madhya Pradesh, Chhattisgarh, Odisha and Andhra Pradesh** (north to south). Hook: 'U-M-C-O-A'.

★★ **Legal Metrology (Indian Standard Time) Rules, 2026**: notified in **August 2026** by the Department of Consumer Affairs under the Legal Metrology Act, 2009, they make **IST the single mandatory time reference** for legal, administrative, commercial and official use (telecom, banking and payments, power grids, transport); they apply 180 days after publication in the Gazette.

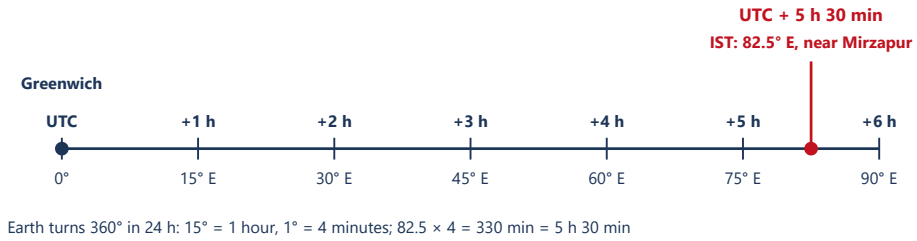
★★ **'One Nation, One Time'**: IST is sent out from CSIR-NPL through five **Regional Reference Standard Laboratories** (Ahmedabad, Bengaluru, Bhubaneswar, Faridabad, Guwahati), internet time servers and **NavIC** satellites, reducing dependence on foreign GPS time.

★ **National Prototype Kilogram No. 57** (a platinum–iridium copy) is held at CSIR-NPL; since 2019 the kilogram itself is defined through the Planck constant.

★ **Bharatiya Nirdeshak Dravya (BND)**: Indian certified reference materials issued by CSIR-NPL for testing labs (e.g. for metals, cement, pollution checks).

★ **Metric India**: India joined the Metre Convention in 1957; the Standards of Weights and Measures Act, 1956 brought metric units into use from 1958.

★ **Legal Metrology** (weights and measures used in trade, petrol pumps, shop scales) is administered by the Department of Consumer Affairs and state legal metrology departments; **BIS** sets product standards (ISI mark, hallmarking).



Earth turns 360° in 24 h: 15° = 1 hour, 1° = 4 minutes; 82.5 × 4 = 330 min = 5 h 30 min

Why IST is UTC + 5:30: the Earth turns 15° an hour, so the 82.5° E meridian near Mirzapur is 82.5 × 4 = 330 minutes, or 5 h 30 min, ahead of Greenwich. Spacing to scale.

Remember it: NPL = 'Nation's Precise Lab': it holds India's kilogram, its second and its clock. Think of IST as 'Mirzapur time' in 5½-hour lead over Greenwich.

⚠ Exam trap: IST is kept by CSIR-NPL, not by ISRO, IMD or BIS. ISRO's NavIC helps spread the time signal; IMD forecasts weather; BIS sets product standards. Also, IST is UTC + 5:30, not + 5:00.

Quick check

1. Which body keeps Indian Standard Time?
2. IST is UTC plus how much, and from which meridian?
3. Which Indian satellite system helps send IST across the country?

Answer: 1. CSIR-National Physical Laboratory, New Delhi · 2. 5 h 30 min; 82.5° E, near Mirzapur · 3. NavIC

Asked in past papers (16)

BPSC 64th Angstrom is a unit of
(a) wavelength (b) energy (c) frequency (d) velocity (e) None of the above/More than one of the above
Answer: (a) wavelength. One angstrom (Å) is 10^{-10} m, used for wavelengths and atomic sizes

BPSC 64th Frequency is measured in
(a) hertz (b) meter/second (c) radian (d) watt (e) None of the above/More than one of the above
Answer: (a) hertz. The SI unit of frequency is the hertz (one cycle per second)

BPSC 64th The unit of electric power is
(a) ampere (b) volt (c) coulomb (d) watt (e) None of the above/More than one of the above
Answer: (d) watt. The SI unit of power, electric power included, is the watt (joule per second)

BPSC 64th Which instrument is used to measure humidity?
(a) Hydrometer (b) Hygrometer (c) Pyrometer (d) Lactometer
(e) None of the above/More than one of the above
Answer: (b) Hygrometer. A hygrometer measures humidity; a hydrometer measures liquid density

BPSC 65th The unit of pressure is
(a) kg/cm^2 (b) kg/cm (c) kg/mm (d) kg/cm^3 (e) None of the above/More than one of the above
Answer: (e) None of the above/More than one of the above. Pressure is force per unit area; its SI unit is the pascal (N/m^2); kg/cm^2 is mass per area; the pressure unit is kgf/cm^2

BPSC 65th Which one of the following is a scalar quantity?
(a) Force (b) Pressure (c) Velocity (d) Acceleration (e) None of the above/More than one of the above
Answer: (b) Pressure. Pressure is a scalar; force, velocity and acceleration are vectors

BPSC 65th Which one of the following quantities does not have unit?
(a) Stress (b) Force (c) Strain (d) Pressure (e) None of the above/More than one of the above
Answer: (c) Strain. Strain is a ratio of change in size to original size, so it has no unit; Stress and pressure are both force per area, measured in pascals

BPSC 65th What is measured in hertz?
(a) Frequency (b) Energy (c) Heat (d) Quality (e) None of the above/More than one of the above
Answer: (a) Frequency. The hertz is the SI unit of frequency, one cycle per second

BPSC 66th 'Light-year' is a unit of
(a) time (b) speed (c) distance (d) intensity of light (e) None of the above/More than one of the above
Answer: (c) distance. A light-year is a unit of distance: how far light travels in one year

UPSC 2021 Which one of the following is a reason why astronomical distances are measured in light-years?
(a) Distances among stellar bodies do not change. (b) Gravity of stellar bodies does not change.
(c) Light always travels in straight line. (d) Speed of light is always same.
Answer: (d) Speed of light is always same.. A light-year is the distance light travels in vacuum in a year, about 9.46 × 10^{12} km; The speed of light in vacuum is a universal constant, about 3 × 10^8 m/s

BPSC 67th re-exam Which of the following is not a vector quantity?
(a) Displacement (b) Speed (c) Velocity (d) Torque (e) None of the above/More than one of the above
Answer: (b) Speed. Speed is a scalar; displacement, velocity and torque are vectors

BPSC 69th Current density is
(a) a scalar quantity (b) a vector quantity (c) dimensionless (d) None of the above
Answer: (b) a vector quantity. Current density is a vector, but electric current is a scalar

BPSC 70th The meter that is used to measure the distance moved by the vehicle is known as
(a) Speedometer (b) Ammeter (c) Odometer (d) Chronometer
Answer: (c) Odometer. An odometer records distance travelled; a speedometer shows instantaneous speed; A chronometer is a precise timekeeper; an ammeter measures electric current

BPSC 70th Which of the following is equivalent to tesla ?
(a) Newton per Coulomb (b) Ampere per Newton (c) Newton per ampere meter
(d) Newton per ampere-second
Answer: (c) Newton per ampere meter. From F = BIL, 1 tesla = 1 newton per ampere-metre (N A^{-1} m^{-1})

BPSC 70th re-exam What is the unit of measure of magnetic field ?
(a) Ohm (b) Tesla (c) Ampere (d) Cobalt
Answer: (b) Tesla. The SI unit of magnetic field (flux density) is the tesla; 1 T = 10^4 gauss

BPSC 71st Energy consumed in a home is 250 units then the total energy in Joule will be :
(a) 9×10^5 (b) 8×10^6 (c) 9×10^8 (d) 10^5
Answer: (c) 9×10^8. One unit of electricity is 1 kWh = 3.6 × 10^6 joules

Test yourself (13)

1. Which one of the following pairs is wrongly matched?
(a) Anemometer – wind speed (b) Hygrometer – density of liquids (c) Pyrometer – very high temperature
(d) Tachometer – rotational speed of an engine

2. Since 20 May 2019 the kilogram is defined by fixing the exact value of the
(a) Avogadro constant (b) Boltzmann constant (c) Planck constant (d) gravitational constant

3. A household meter records 50 units in a month. The energy used is about
(a) 1.8×10^8 J (b) 5×10^4 J (c) 3.6×10^6 J (d) 1.8×10^5 J

4. Which one of the following is NOT a unit of length or distance?
(a) Parsec (b) Fermi (c) Knot (d) Fathom

5. Which one of the following is a vector quantity?
(a) Electric current (b) Pressure (c) Momentum (d) Work

6. The SI prefix for 10^{-15} is
(a) atto (b) pico (c) nano (d) femto

7. Weber per square metre is the unit of
(a) magnetic flux (b) inductance (c) electric field (d) magnetic flux density

8. Jewellery hallmarked '22K' contains gold to the extent of about
(a) 75% (b) 91.6% (c) 99.9% (d) 22%

9. Which instrument is used to find the depth of the sea?
(a) Altimeter (b) Hypsometer (c) Fathometer (d) Manometer

10. Which pair of quantities have the same dimensions?
(a) Work and torque (b) Force and power (c) Momentum and energy (d) Pressure and force

11. Consider the following statements:
1. Since 20 May 2019 the kilogram is defined through the Planck constant.
2. The second is defined by the radiation of the caesium-133 atom.
3. The ampere is defined by fixing the value of the Boltzmann constant.
Which of the statements given above is/are correct?
(a) 1 only (b) 1 and 2 only (c) 2 and 3 only (d) 1, 2 and 3

12. Consider the following pairs:
Unit : Quantity
1. Tesla : magnetic flux density
2. Siemens : electrical resistance
3. Light-year : time
How many of the above pairs are correctly matched?
(a) Only one (b) Only two (c) All three (d) None

13. A jeweller sells a ring: an 18K gold band set with a 2-carat diamond. Which description of the ring is correct?
(a) The band is 18% gold; the diamond weighs 2 g (b) The band is 75% gold; the diamond weighs 2 g
(c) The band is 18% gold; the diamond weighs 0.4 g (d) The band is 75% gold; the diamond weighs 0.4 g

Answers: 1. (b) A hygrometer measures humidity; density of liquids is measured by a hydrometer. · 2. (c) The kilogram rests on h = 6.626 070 15 × 10^{-34} J s; the old metal prototype was retired. · 3. (a) 1 unit = 1 kWh = 3.6×10^6 J, so 50 units = 1.8×10^8 J. · 4. (c) A knot is a speed, one nautical mile per hour (1.852 km/h). · 5. (c) Momentum (mass × velocity) has direction; current, pressure and work are scalars. · 6. (d) Femto = 10^{-15} (fermi-sized nucleus); pico 10^{-12}, nano 10^{-9}, atto 10^{-18}. · 7. (d) 1 Wb/m² = 1 tesla, the unit of magnetic field (flux density); weber alone is flux. · 8. (b) Karat counts parts of gold in 24: 22/24 ≈ 91.6% (hence the hallmark 916). · 9. (c) A fathometer (echo sounder) times the echo of a sound pulse from the sea floor. · 10. (a) Both are [M L^2 T^{-2}]; work is a scalar in joules, torque a vector in N m. · 11. (b) h fixes the kilogram and caesium-133 the second; the ampere rests on the elementary charge e, while the Boltzmann constant fixes the kelvin. · 12. (a) Only the tesla pair is right; the siemens measures conductance (the reverse of resistance) and the light-year is a distance. · 13. (d) Karat is purity out of 24, so 18K = 18/24 = 75% gold; carat is mass, 0.2 g each, so 2 carats = 0.4 g.

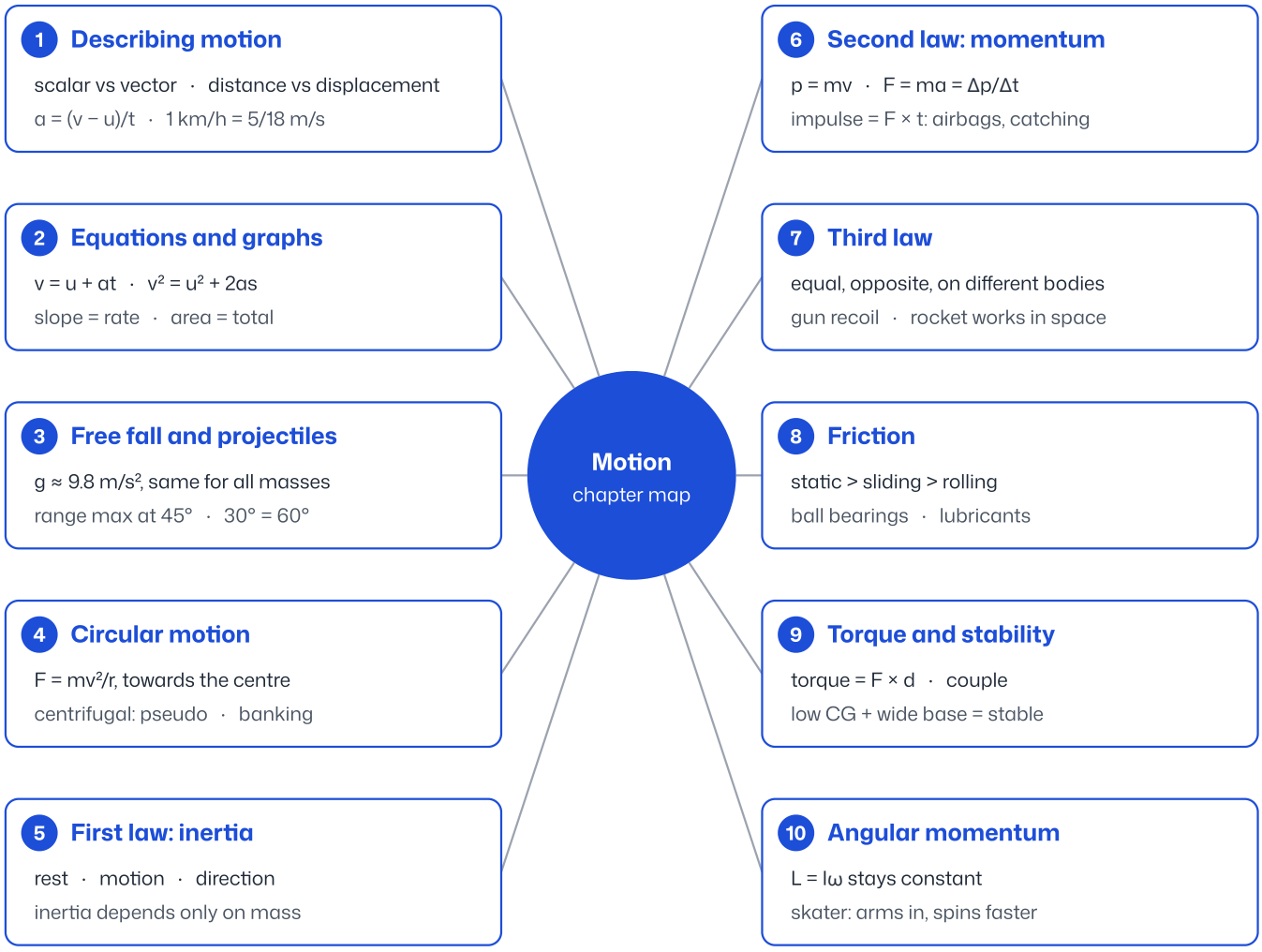
CHAPTER 2

Motion, Force and Newton's Laws

Inertia in a turning or braking bus, impulse (catching a ball), ball bearings and friction, centripetal force and one-step F = ma sums appear in almost every UPSC, BPSC and SSC paper.

Asked 10 times in past papers: UPSC 1 · BPSC 9

≈ 45 min to read ≈ 7 min to revise ★★★ Revise on: Day 1 | Day 3 | Day 7 | Day 21



Revision card

1. Distance is a scalar, displacement a vector; after one full lap of a track displacement is zero but distance is not.
2. Galileo first defined speed as distance covered per unit time.
3. Slope of distance–time graph = speed; slope of velocity–time graph = acceleration; area under velocity–time graph = displacement.
4. $v = u + at$, $s = ut + \frac{1}{2}at^2$, $v^2 = u^2 + 2as$. In vacuum every body falls with the same $g \approx 9.8\ m/s^2$, whatever its mass.
5. A projectile follows a parabola; range is maximum at 45°, and complementary angles (30° and 60°) give equal range.
6. Centripetal force points to the centre and keeps a body on a circle; centrifugal is the outward pseudo-force felt inside the rotating body (cream separator, washing-machine dryer).
7. Inertia: bus starts → you fall back (rest); bus brakes → you fall forward (motion); bus turns right → you lean left (direction).
8. $F = ma$ = rate of change of momentum; $1\ N = 1\ kg{\cdot}m/s^2 = 10^5$ dyne.
9. Impulse = $F \times t$ = change in momentum; stretching the stopping time lowers the force (goalkeeper pulls hands back, airbags, sand pits).
10. Action and reaction are equal, opposite and act on different bodies, so they never cancel.
11. Momentum is conserved without external force: gun recoil, rocket (works even in vacuum).
12. Friction order: limiting (static) > kinetic (sliding) > rolling. Ball bearings swap sliding for rolling and cut the contact area.
13. At constant velocity the net force is zero, so friction equals the applied push.
14. Low centre of gravity and wide base = stable; luggage on a bus roof makes it easier to topple. Skater pulls arms in → spins faster (angular momentum conserved).

Describing motion: scalars, vectors, speed and velocity

scalar / vector

distance vs displacement

Galileo: speed

$a = (v - u)/t$

$2v_1v_2/(v_1+v_2)$

To describe motion you need three things: how far, how fast and in which direction. Quantities that need only a size are **scalars**; those that also need a direction are **vectors**. Galileo was the first to measure motion this way, timing balls rolling down slopes.

Scalars and vectors ★★

Scalar (size only)	Vector (size + direction)
Distance	Displacement
Speed	Velocity
Mass, time, temperature	Acceleration, force, weight
Work, energy, power	Momentum, impulse, torque
Pressure, density, volume	Electric and magnetic field
Electric current (has a direction but adds like a scalar)	Angular momentum

★★★ **Galileo Galilei** first defined **speed** as the distance covered per unit time.

★★★ **Distance** = total length of the path; always positive. **Displacement** = straight-line gap from start to finish with a direction; can be positive, negative or zero.

★★ **Speed** = distance ÷ time (scalar). **Velocity** = displacement ÷ time (vector). SI unit of both: **m/s**; 1 km/h = 5/18 m/s (so 72 km/h = 20 m/s).

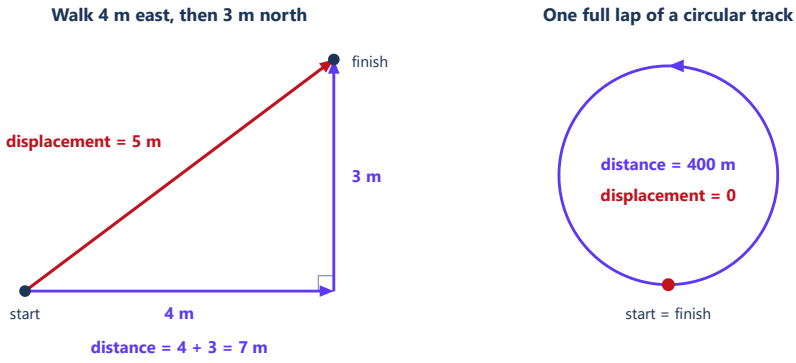
★★ **Average speed** = total distance ÷ total time. For two equal distances at speeds v_1 and v_2 it is $\mathbf{2v_1v_2/(v_1+v_2)}$, not the simple average.

★★★ **Acceleration** = rate of change of velocity, a = (v − u)/t, unit **m/s²**. Negative acceleration is called **retardation** or deceleration.

★★ **Uniform motion**: equal distances in equal times along a straight line (zero acceleration). **Non-uniform motion**: unequal distances in equal times, e.g. a falling stone, a car in traffic.

★★ A body moving in a circle at **constant speed is still accelerating**, because its direction, and so its velocity, keeps changing.

★ A **speedometer** shows instantaneous speed; an **odometer** records the total distance travelled.



Distance is the whole path; displacement is the straight gap from start to finish. Left, drawn to scale: walking 4 m + 3 m is a distance of 7 m but a displacement of only 5 m. Right: after one full lap, start and finish coincide, so the displacement is zero.

⚠ **Exam trap:** An athlete runs one full lap of a 400 m track in 50 s: distance 400 m, average speed 8 m/s, but displacement and average velocity are both **zero**. Also: a car going 40 km/h one way and 60 km/h back averages **48 km/h**, not 50.

☑ Quick check

1. One full lap of a 400 m track: distance and displacement?
2. Who first defined speed as distance covered per unit time?
3. Why is a body moving in a circle at constant speed still accelerating?

Answer: 1. 400 m; displacement zero · 2. Galileo · 3. its direction, so its velocity, keeps changing

Equations and graphs of motion

v = u + at

s = ut + ½at²

v² = u² + 2as

slope = rate

area = total

When acceleration is constant, velocity rises by the same amount every second. Three equations follow from that one idea, and a graph shows the same story at a glance: its slope and the area under it carry the answers.

★★★ **Equations of uniformly accelerated motion**: v = u + at; s = ut + ½at²; v² = u² + 2as (u = initial velocity, v = final velocity, a = acceleration, s = displacement, t = time).

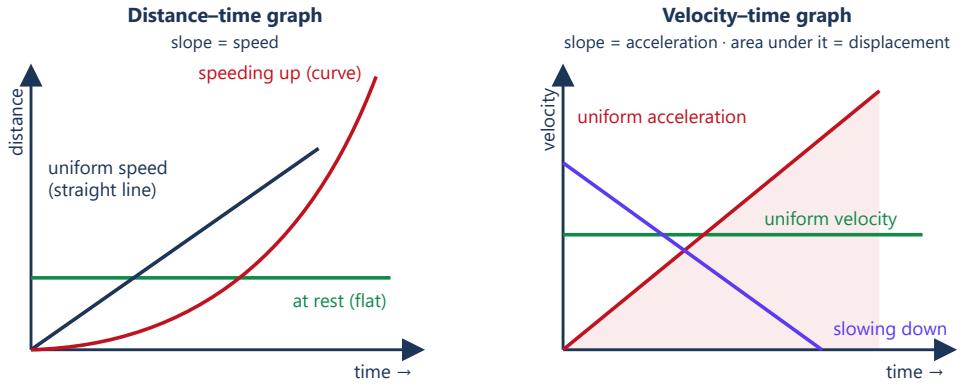
★★ A body **starting from rest** has u = 0, so s = ½at² and v = at.

★★★ **Slope of a distance–time graph = speed**; a straight sloping line means uniform speed, a flat line means the body is at rest, an upward curve means it is speeding up.

★★★ **Slope of a velocity–time graph = acceleration**; **area under it = displacement** (distance if motion is one way).

★★ A flat velocity–time line means **zero acceleration**, i.e. constant velocity; a straight line sloping down means **uniform retardation**.

★ A distance–time graph can never slope downward (distance never decreases) and no motion graph can be a vertical line (that would mean infinite speed or infinite acceleration).



A flat v–t line means zero acceleration, not zero velocity. A flat d–t line means the body is at rest.

Read the slope of a distance–time graph as speed and of a velocity–time graph as acceleration; the area under the velocity–time line is the distance covered.

See it around you: A truck starts from rest and covers 400 m in 20 s with constant acceleration; its mass is 7 tonnes. From s = ½at²: 400 = ½ × a × 20², so a = 2 m/s². Force F = ma = 7000 kg × 2 m/s² = **14,000 N**.

Remember it: Graph rule of thumb: **SLOPE tells the RATE, AREA tells the TOTAL.** Slope of distance gives speed, slope of velocity gives acceleration, area under velocity gives distance.

Quick check

1. Slope of a velocity–time graph gives _____ ; the area under it gives _____ .
2. Slope of a distance–time graph gives?
3. A body starts from rest with acceleration a. Distance covered in time t?

Answer: 1. acceleration; displacement · 2. speed · 3. s = ½at²

Free fall and projectile motion

g ≈ 9.8 m/s²

same for all masses

top: v = 0, a = g

max range at 45°

Gravity pulls every body towards Earth's centre with the same acceleration g. A heavier body feels a bigger pull, but it also has proportionally more inertia, so the two cancel. Only air resistance makes a feather lag behind a stone.

complementary angles

★★★ **Free fall**: motion under gravity alone. In **vacuum** a feather, a rubber ball and a wooden ball dropped together **land together**; acceleration g ≈ **9.8 m/s²** does not depend on mass.

★★ Two different masses falling freely have the **same velocity at every instant**, but the **force** on them (their weight) is different, proportional to mass.

★ In 1971 astronaut **David Scott** (Apollo 15) dropped a hammer and a feather on the airless Moon; they hit the ground together.

★★ For a ball thrown straight up: at the **top, velocity is zero but acceleration is still g** (downward); time going up = time coming down; it returns with the speed it was thrown.

★★ Use the equations with a = g: $v = u + gt$, $h = ut + \frac{1}{2}gt^2$, $v^2 = u^2 + 2gh$. A body dropped from rest falls about **4.9 m in the first second**.

A **projectile** is anything thrown at an angle and left to gravity: a cricket ball, a javelin, a shell, water from a hose. It moves sideways at a steady speed while gravity changes only its up-down speed, so the path bends into a **parabola**.

★★★ **Range is maximum at 45°** to the horizontal (ignoring air resistance).

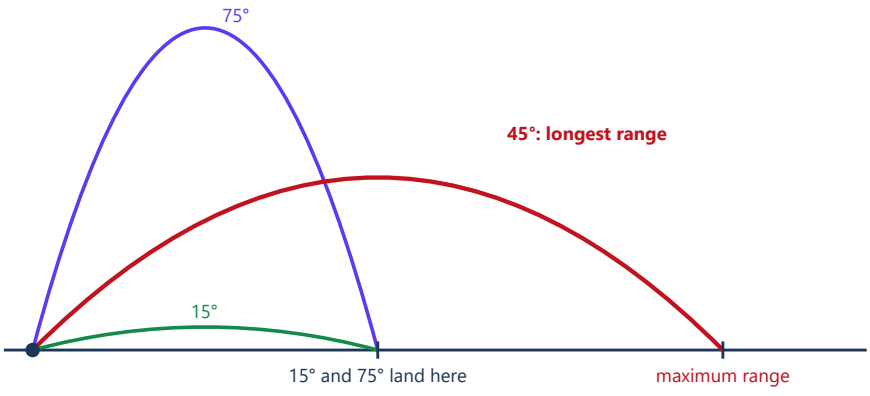
★★ **Complementary angles give equal range**: 15° and 75°, 30° and 60° land at the same spot; the steeper throw goes higher and stays longer in the air.

★★ **Horizontal velocity stays constant** (no horizontal force); the vertical velocity changes by g every second. At the highest point only the horizontal velocity remains.

★ Formulas: range $R = u^2 \sin 2\theta / g$; maximum height $H = u^2 \sin^2\theta / 2g$; time of flight $T = 2u \sin \theta / g$. At 45°, the range is 4 times the height.

★★ A bullet fired horizontally and a bullet dropped from the same height at the same moment **hit the ground together**: horizontal motion does not affect the fall.

★ A bomb released from a plane flying level keeps the plane's forward speed, so it stays directly below the plane (ignoring air) while it falls in a parabola.



Same launch speed, no air resistance. Angles that add up to 90° give equal range; the path is a parabola.

Same launch speed: 45° gives the longest range, while 15° and 75° land at the same point.

⚠ **Exam trap:** At the top of its path a ball is **not** in equilibrium and its acceleration is **not** zero; only its vertical velocity is zero. Also, mass does not change the time of fall in vacuum: the option heavier body lands first is wrong.

Quick check

1. In vacuum, a feather and a stone are dropped together. Which lands first?
2. At what angle of projection is the range maximum?
3. At the top of its flight, what is a ball's acceleration?

Answer: 1. both together (same g) · 2. 45° · 3. still g, downward (only vertical velocity is zero)

Circular motion: centripetal and centrifugal force

centripetal: inward

$F = mv^2/r$

centrifugal: pseudo

tangent

banking

centrifugation

Left alone, a moving body goes straight. To bend its path into a circle, something must keep pulling it towards the centre: that inward pull is the **centripetal force**. Sitting inside the rotating body you feel thrown outward; that felt push is the **centrifugal force**, really just your own inertia.

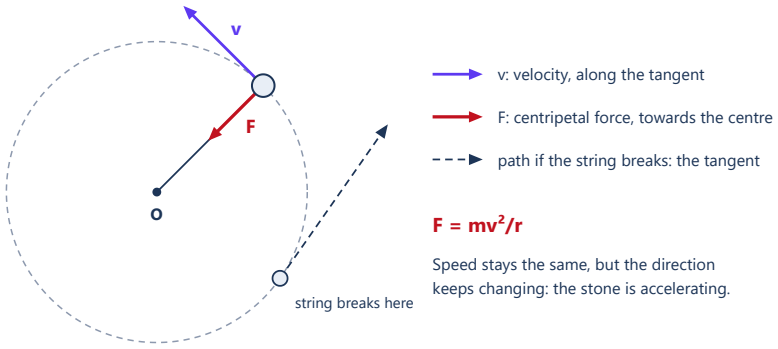
★★★ **Centripetal force** acts towards the centre and keeps a body moving on a circular path: $F = mv^2/r = m\omega^2 r$.

★★ Centripetal force is always at right angles to the motion, so it **does no work** and does not change the speed, only the direction.

★★ **Centrifugal force** is a **pseudo (apparent) force**: equal and opposite to centripetal force, felt only by an observer moving with the rotating body.

★★ If the string of a whirling stone breaks, the stone flies off along the **tangent**, not straight outward. Mud from a spinning wheel and sparks from a grinding wheel also fly off tangentially.

★ Angular velocity ω = angle turned per second (rad/s); linear speed $v = r\omega$.



A stone whirled on a string, drawn to scale. Its velocity v is along the tangent, at 90° to the string; the string's pull F points to the centre O. The speed stays the same but the direction keeps changing, so the stone is accelerating. If the string breaks, the stone flies off along the tangent, not straight outward.

What supplies the centripetal force ★★

Motion	Inward force comes from
Satellite round Earth, Moon round Earth, planet round Sun	Gravity
Electron round the nucleus (Bohr model)	Electrostatic attraction
Stone whirled on a string	Tension in the string
Car turning on a flat road	Friction between tyres and road
Car or train on a banked curve	Tilted road or raised outer rail (component of normal force)

★★★ **Centrifugation** spins a mixture fast so denser parts move outward and separate: **cream separator** (milk), **washing-machine spin dryer** (water leaves through drum holes), blood centrifuge (red cells settle at the bottom of the tube).

★ Gas **centrifuges enrich uranium** (heavier U-238 drifts outward); centrifuges also separate sugar crystals from molasses and honey from combs.

★★★ **Banking of roads**: the outer edge of a curve is raised so the tilt itself provides centripetal force, making turns safe without relying on friction. On railway curves the **outer rail is raised** (cant).

★★ A **cyclist leans inward** on a turn for the same reason; a motorcyclist in the well of death (maut ka kuan) goes round because the wall's inward push (normal force) supplies the centripetal force, while friction with the wall stops him sliding down.

Remember it: Centri-PETAL seeks the centre (Latin petere = to seek: think of a petitioner going to the court). **Centri-FUGAL** flees the centre (fugitive). Petal pulls in, fugal flies out.

⚠ **Exam trap:** A washing machine dries clothes by **centrifugation**, not diffusion or osmosis. And a satellite keeps orbiting not because gravity is absent up there but because gravity is the centripetal force bending its path.

Quick check

1. A whirling stone's string breaks. Along which line does the stone fly off?
2. Centripetal or centrifugal: which is a pseudo force?
3. A washing machine dries clothes by which process?

Answer: 1. the tangent · 2. centrifugal · 3. centrifugation

Newton's first law and inertia

law of inertia

inertia ∝ mass

inertia of rest

inertia of motion

inertia of direction

Matter is lazy: it keeps doing whatever it was doing. A body at rest stays at rest, and a moving body keeps moving in a straight line at the same speed, until a force changes that. This laziness is **inertia**, and Newton's first law (Principia, 1687) states it.

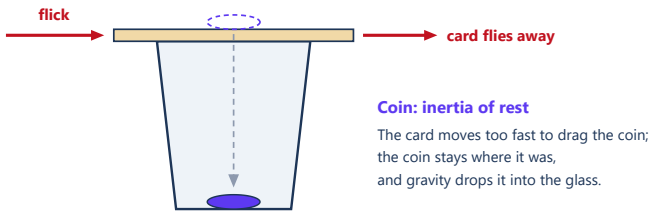
★★★ **First law (law of inertia)**: a body continues in its state of rest or of uniform motion in a straight line unless an external unbalanced force acts on it.

★★ **Inertia depends only on mass**: more mass, more inertia. It is harder to start, stop or turn a loaded truck than a bicycle.

★★ The first law gives the **definition of force**: whatever changes a body's state of rest or motion. Galileo reached the idea of inertia first with his inclined-plane experiments.

Three kinds of inertia ★★★

Inertia of	Meaning	Everyday examples
Rest	A body at rest resists being moved	Passengers fall backward when a bus starts suddenly; dust leaves a carpet when it is beaten; a coin on a card drops into the glass when the card is flicked; fruits fall when a branch is shaken
Motion	A moving body resists being stopped	Passengers fall forward when a bus brakes; a person jumping off a moving bus falls forward; an athlete runs up before a long jump; a ball keeps rolling after the push
Direction	A moving body resists a change of direction	Passengers lean left when a bus turns sharply right; mud flies off a spinning wheel along the tangent; a car skids outward on a sharp turn



Inertia of rest: flick the card away fast and the coin does not go with it; it stays where it was and drops into the glass.

Remember it: Picture a crowded DTC bus: **starts** → everyone sways back (rest); **brakes** → everyone lurches forward (motion); **swerves right** → everyone leans left (direction). The body always tries to keep its old state.

⚠ **Exam trap:** When a bus turns **right**, passengers lean **left**, not right. Their bodies keep going straight while the bus turns under them.

Quick check

1. A body's inertia depends only on its _____ .
2. A bus brakes suddenly. Which way do passengers fall, and which inertia is this?
3. A bus turns sharply right. Which way do passengers lean?

Answer: 1. mass · 2. forward: inertia of motion · 3. left (inertia of direction)

Second law, momentum and impulse

p = mv

F = Δp/Δt = ma

1 N = 10^5 dyne

Momentum is mass in motion: a slow truck and a fast bullet are both hard to stop. Force is how quickly momentum changes. So the same change of momentum can come from a big force acting briefly or a small force acting for longer, and that idea saves lives.

impulse = F × t

longer time, less force

★★★ **Momentum** p = mass × velocity, a vector; unit **kg·m/s** (= N·s).

★★★ **Second law**: force equals the **rate of change of momentum**, F = Δp/Δt = ma, and acts in the direction of the change.

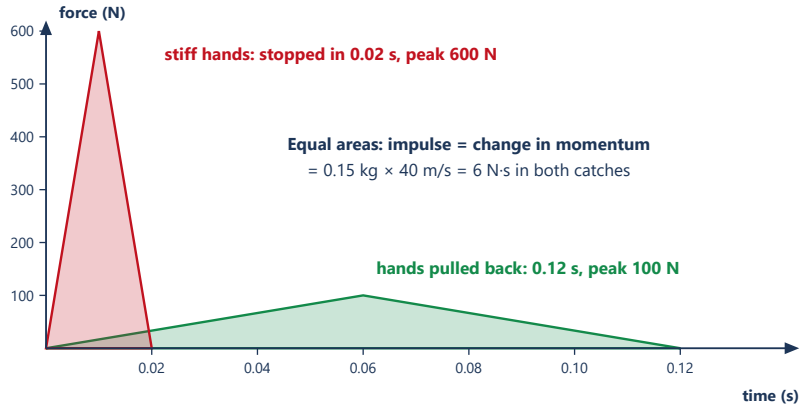
★★ **Units of force**: SI unit **newton** (1 N = 1 kg·m/s^2); CGS unit **dyne**; 1 N = **10^5 dyne**; 1 kilogram-force (kgf) = 9.8 N.

★★ The same force gives a lighter body more acceleration: an empty trolley is easier to speed up than a loaded one.

★★★ **Impulse** = force × time = change in momentum; unit N·s. For a fixed change in momentum, **a longer stopping time means a smaller force**.

Impulse in daily life ★★★

Stretch the time, cut the force	Shrink the time, raise the force
Goalkeeper or fielder pulls the hands back while catching	Karate chop breaks a brick in a split second
Airbags, seat belts and crumple zones in cars	Hammer drives a nail with a sharp blow
Sand pit or foam mats for long jump and high jump	A fall on hard concrete hurts more than on sand or mud
Bending the knees when landing from a jump	A bat hits the ball in a very short contact time
Glassware packed in straw, paper or thermocol; shock absorbers and train buffers	A boxer's sharp jab delivers a large force in a brief contact



Catching a 150 g cricket ball moving at 40 m/s, drawn to scale. Either way the change in momentum is 6 N·s, the area under each curve. Stiff hands stop it in 0.02 s with a peak force of 600 N; hands pulled back take 0.12 s and the peak falls to 100 N.

⚠ **Exam trap:** Pulling the hands back does **not** reduce the change in momentum (the ball still stops); it reduces the **rate** of change of momentum, and so the force on the hands.

Quick check

1. Newton's second law: force equals the rate of change of _____ .
2. Why does a fielder pull the hands back while catching?
3. 1 newton = how many dyne?

Answer: 1. momentum · 2. longer stopping time, so smaller force · 3. 10^5 dyne

Third law, conservation of momentum and types of force

action = reaction

different bodies

conservation of momentum

gun recoil

rocket in vacuum

contact / non-contact

Forces always come in pairs: you cannot push anything without it pushing back. Because the pair acts on two different bodies, the pushes never cancel; instead, the total momentum of the two bodies together stays the same.

★★★ **Third law**: to every action there is an **equal and opposite reaction**. The two forces act on **different bodies**, so they never cancel each other.

★★ Action and reaction are equal even when the bodies are very unequal: the apple pulls Earth up exactly as hard as Earth pulls the apple down; Earth's huge mass makes its movement negligible.

★★★ **Law of conservation of momentum**: if no external force acts, the total momentum of a system stays constant. It follows from the second and third laws.

Action and reaction around us ★★

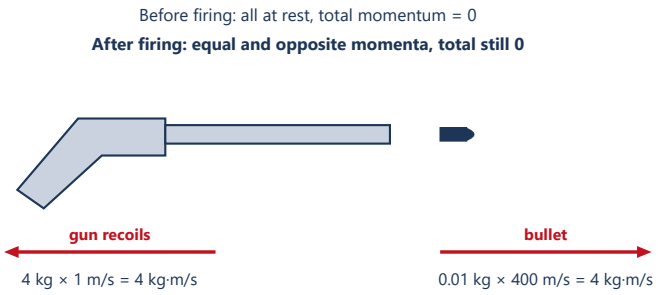
Situation	Action	Reaction
Walking	Foot pushes ground backward	Ground pushes us forward (needs friction)
Swimming, rowing a boat	Hands or oars push water back	Water pushes swimmer or boat forward
Rocket	Rocket pushes hot gas backward	Gas pushes rocket forward
Jet aircraft	Engine throws air and exhaust backward	Aircraft moves forward
Firing a gun	Gun pushes bullet forward	Bullet pushes gun back (recoil)
Jumping from a boat to the shore	Feet push boat backward	Boat pushes the jumper forward; the boat itself drifts away from the shore
Hose pipe at full flow	Water pushed forward	Pipe kicks back

★★★ **Gun recoil**: before firing total momentum is zero, so after firing m(bullet) × v(bullet) = M(gun) × V(gun). The gun is much heavier, so it recoils slowly. A 10 g bullet at 400 m/s from a 4 kg gun gives a recoil of 1 m/s.

★★★ **Rocket** works by conservation of momentum: exhaust gas thrown backward gives the rocket equal forward momentum. It carries its own oxidiser and does **not need air to push against**, so it works in space.

★★ A **jet engine** works on the same principle but breathes oxygen from the air, so it cannot work in space.

★ A bullet and its gun get equal momentum but very unequal kinetic energy: the light bullet carries almost all of it, which is why the bullet does damage and the recoil is bearable.



Gun recoil, momentum arrows drawn to scale. Before firing the total momentum is zero; after firing, a 10 g bullet at 400 m/s and a 4 kg gun at 1 m/s carry equal and opposite momenta (4 kg·m/s each), so the total is still zero.

Contact and non-contact forces ★★

Contact forces (need touching)	Non-contact forces (act across a gap)
Friction	Gravitational force
Normal reaction, tension, spring force	Magnetic force
Impact (collision) force, muscular force	Electrostatic force
Air resistance, buoyant force	Nuclear forces (inside the nucleus)

The four fundamental forces ★

Force	Relative strength	Range	Acts in
Strong nuclear	Strongest	Very short (nucleus size)	Holding protons and neutrons together
Electromagnetic	Second	Infinite	Atoms, chemistry, friction, light
Weak nuclear	Third	Very short	Beta decay, fusion in the Sun
Gravitational	Weakest	Infinite	Planets, tides, falling bodies

Remember it: Rocket rule: **a rocket does not push on the air, it pushes on its own exhaust**. Like a skater throwing a heavy bag forward and sliding backward, it needs nothing outside itself.

⚠ **Exam trap:** Magnetic, electrostatic and gravitational forces are **non-contact**; friction and impact force need contact. Also, action and reaction never cancel because they act on different bodies.

Quick check

1. Action and reaction are equal and opposite. Why do they never cancel?
2. A rocket works in space because of which law?
3. Is magnetic force a contact or a non-contact force?

Answer: 1. they act on different bodies · 2. conservation of momentum (third law) · 3. non-contact

Friction

static: self-adjusting

limiting > kinetic > rolling

coefficient μ

ball bearings

lubricants

No surface is perfectly smooth; tiny bumps lock into each other and molecules at the contact points stick together. That grip is **friction**: it opposes sliding, wastes energy as heat, and yet without it we could not walk, write or brake.

★★★ **Static friction** acts before motion starts and **adjusts itself** to match the applied force; its maximum value is **limiting friction**.

★★ **Kinetic (sliding) friction** acts on a body already sliding; it is a little **less than limiting friction**, which is why it is harder to start pushing a heavy box than to keep it moving.

★★★ **Rolling friction** is much **smaller than sliding friction**. Order: **limiting static > kinetic (sliding) > rolling**.

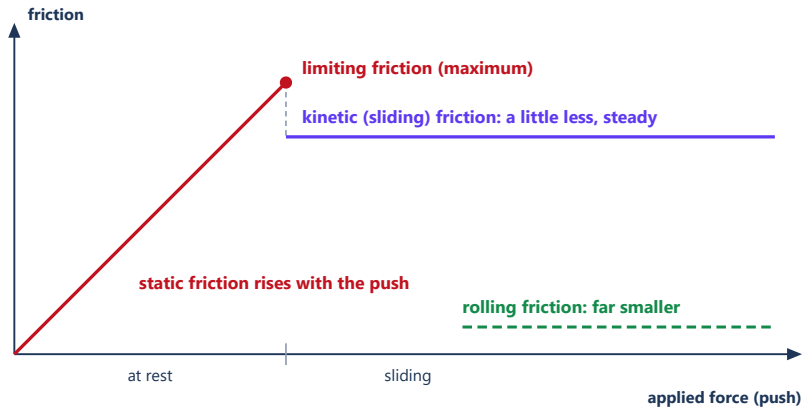
★★★ At **constant velocity** the net force is zero, so friction exactly equals the applied force: pushing a box steadily with 200 N means friction is 200 N.

★★ Friction depends on the **nature of the surfaces** and the **normal force** pressing them together, not (ideally) on the area of contact. Coefficient of friction μ = friction ÷ normal force; it has no unit.

★★ Friction turns **kinetic energy into heat**: rubbing hands warms them, brakes get hot, a matchstick lights.

★ **Pulling** a box with a rope at an angle is easier than **pushing** it down at an angle: a pull lifts slightly and reduces the normal force, a push presses it harder onto the floor.

★ The **angle of repose** is the steepest slope at which a body rests without sliding; it measures friction between the body and the slope.



Push a heavy box harder and harder. Static friction rises to match the push until it reaches its maximum, limiting friction; then the box starts sliding and friction drops a little, to kinetic friction. On wheels, rolling friction is far smaller still. Illustrative values, not to scale.

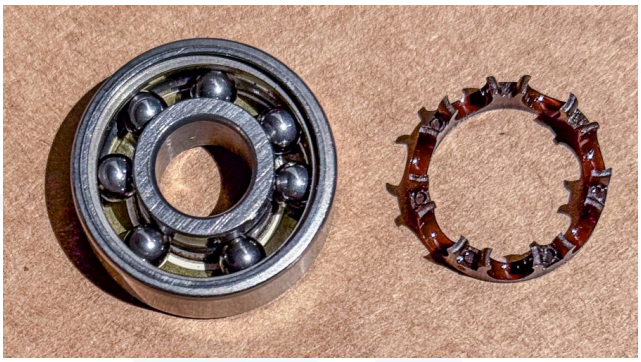
Raising and lowering friction ★★

To increase friction (need grip)	To reduce friction (need easy motion)
Treads on tyres and soles grip the road and channel water away	Lubricants: oil, grease, graphite
Sand or gravel on slippery or icy roads	Ball bearings and roller bearings
Chalk powder on a gymnast's hands	Polishing surfaces smooth
Spikes on athletes' shoes	Air cushion (hovercraft), streamlined shapes for air and water drag

★★★ **Ball bearings** convert **sliding friction into rolling friction** by **reducing the effective area of contact** between the wheel and axle; used in bicycles, cars, fans, motors.

★★ Friction is needed for **walking** (hard on ice or a soapy floor), **writing**, gripping objects, braking, and lighting a match. Wet roads cut tyre friction, so stopping distances rise after rain.

★ Fluid friction (**drag**) grows with speed; this is why aircraft, fish and birds are **streamlined**.



A ball bearing opened up, its plastic cage (right) taken out. The steel balls sit between the inner and outer rings, so when the wheel turns they roll instead of the surfaces sliding: rolling friction replaces sliding friction. Image: Fred Hsu, Wikimedia Commons, CC BY-SA 4.0

Remember it: Stuck → Sliding → Rolling: each one easier than the last. Getting a stuck almirah to budge is hardest, keeping it sliding is easier, rolling it on a trolley is easiest.

⚠ **Exam trap:** Ball bearings **reduce** the area of contact; options saying they increase the actual or effective area are wrong. And friction is not always a nuisance: walking and braking depend on it.

Quick check

1. Arrange in decreasing order: rolling, limiting and kinetic friction.
2. A box is pushed at constant velocity with 200 N. How large is the friction?
3. How do ball bearings reduce friction?

Answer: 1. limiting > kinetic > rolling · 2. 200 N (net force zero) · 3. rolling replaces sliding; less contact area

Torque, couple and centre of gravity

torque = F × d

couple

centre of gravity

low CG, wide base

stable / unstable / neutral

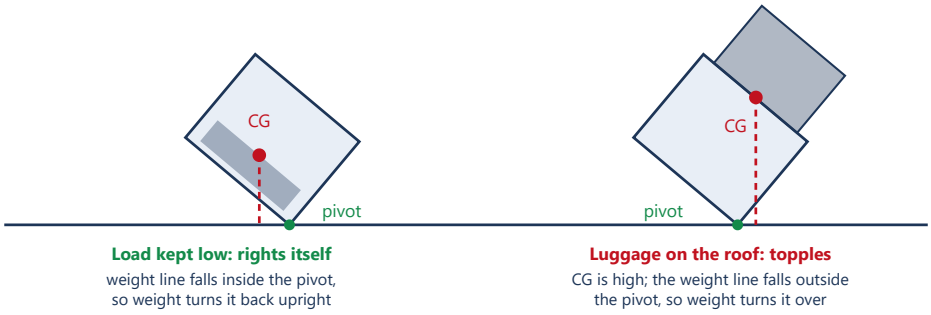
A force can turn as well as push. How much it turns depends on the force and on how far from the pivot it acts. That is why door handles sit at the far edge and a long spanner loosens a tight nut.

★★★ **Torque (moment of force)** = force × perpendicular distance from the axis; unit **N·m**; it is a vector. Pushing a door near its hinges barely moves it.

★★ A **couple** is two equal, opposite, parallel forces not in one line; it produces pure rotation without moving the body sideways: turning a steering wheel, a tap, a key, a screw-cap, winding a clock.

★★★ **Centre of gravity (CG)**: the point through which the whole weight of a body acts. It can lie outside the material, e.g. at the centre of a ring or a bangle.

★★★ **Stability** rises with a **low centre of gravity** and a **wide base**. A body topples only when the vertical line through its CG falls **outside its base**.



Same tilt, different fate: with the load low, the weight line stays inside the pivot and the vehicle rights itself; with luggage on the roof the weight line passes outside and it overturns.

Three states of equilibrium (a cone on a table) ★

State	Cone resting on	When tilted slightly
Stable	Its flat base	CG rises; it falls back to the old position
Unstable	Its tip	CG falls; it topples over
Neutral	Its curved side	CG stays at the same height; it rolls and rests anywhere

See it around you: Buses and trucks are **not loaded heavily on the roof**, and double-decker buses carry their heavy engine and chassis as low as possible, to keep the CG low. Racing cars are low and wide. The **Leaning Tower of Pisa** stands because the vertical line through its CG still falls inside its base. A man carrying a bucket in one hand leans the other way; a person climbing a hill bends forward; ships carry heavy ballast low in the hull.

Remember it: Low and wide never dies: a Sumo wrestler, a pressure cooker, a racing car. Tall and narrow with weight on top (a loaded roof carrier, a person standing in a boat) tips easily.

Quick check

1. Why is a door handle fixed far from the hinges?
2. When does a tilted body topple?
3. Turning a steering wheel with both hands applies a _____ .

Answer: 1. more distance, more torque for the same force · 2. when the vertical line through its CG falls outside its base · 3. couple

Rotation and angular momentum

moment of inertia

L = Iω conserved

skater: arms in

diver

pulsar

A spinning body has rotational inertia too, called the **moment of inertia**, which grows when mass is spread far from the axis. Spin times this inertia gives **angular momentum**, which stays fixed unless an outside torque acts. Pull the mass inward and the spin must speed up.

★★ **Moment of inertia (I)** depends on the mass and on **how far it lies from the axis of rotation**. A flywheel has a heavy rim so it resists changes in speed.

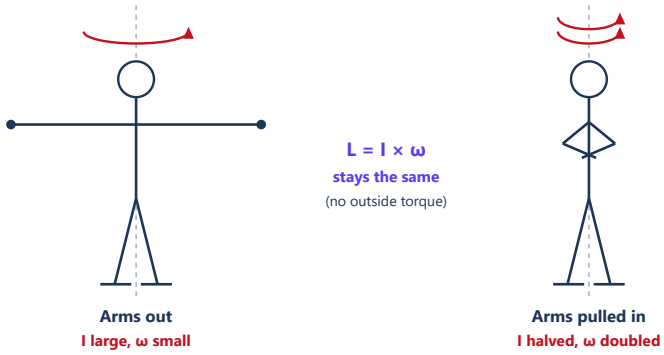
★★★ **Angular momentum** L = Iω is **conserved** when no external torque acts: if I falls, ω rises.

★★★ An **ice skater or ballet dancer** spins faster on pulling the arms in, slower on spreading them out.

★★ A **diver** curls up tightly to somersault quickly, then stretches out to slow down before entering the water.

★★ A planet moves **faster near the Sun** (Kepler's second law) for the same reason; a collapsing star spins up into a fast-spinning **pulsar**.

★ A **tightrope walker's long pole** raises the moment of inertia, slowing any tipping and giving time to correct balance.



No outside torque, so L = Iω stays the same. Pulling the arms in halves the moment of inertia here, so the spin rate doubles.

Remember it: Watch a Kathak dancer's chakkars: arms folded, the spin quickens; arms open, it slows. **Pull in to spin up.**

Quick check

1. A skater pulls her arms in. Which quantity stays constant, and what happens to her spin?
2. Moment of inertia depends on mass and on its _____ from the axis.
3. Why does a tightrope walker carry a long pole?

Answer: 1. angular momentum; she spins faster · 2. distance · 3. it raises the moment of inertia, slowing any tipping

Asked in past papers (10)

UPSC 2013 Ball bearings are used in bicycles, cars, etc., because
(a) the actual area of contact between the wheel and axle is increased
(b) the effective area of contact between the wheel and axle is increased
(c) the effective area of contact between the wheel and axle is reduced
(d) None of the above statements is correct
Answer: (c) the effective area of contact between the wheel and axle is reduced. Ball bearings replace sliding with rolling friction by cutting the area of contact

BPSC 67th re-exam The working principle of a washing machine is
(a) dialysis (b) reverse osmosis (c) diffusion (d) centrifugation
(e) None of the above/More than one of the above
Answer: (d) centrifugation. Centrifugation spins a mixture fast so its denser parts move outward and separate; A washing machine's spin drier and a cream separator work by centrifugation

BPSC 67th re-exam Who is the first person to define speed?
(a) Ptolemy (b) Galileo (c) Newton (d) Kepler (e) None of the above/More than one of the above
Answer: (b) Galileo. Galileo first defined speed as the distance covered per unit time

BPSC 68th Ball bearings are used to convert static friction into
(a) drag (b) sliding friction (c) rolling friction (d) More than one of the above (e) None of the above
Answer: (c) rolling friction. Rolling friction is much smaller than sliding friction, which ball bearings exploit

BPSC 68th A goalkeeper in a game of football pulls his hands backwards after holding the ball shot at the goal. This enables the goalkeeper to
(a) exert large force on the ball (b) increase the force exerted by the ball on hands
(c) decrease the rate of change of momentum (d) More than one of the above (e) None of the above
Answer: (c) decrease the rate of change of momentum. Force equals the rate of change of momentum (Newton's second law); Lengthening the stopping time lowers the force of impact, $F = \Delta p/\Delta t$

BPSC 68th Centripetal force is responsible to
(a) keep the body moving along the circular path (b) fly the object along a straight line
(c) independent motion of the object in space (d) More than one of the above (e) None of the above
Answer: (a) keep the body moving along the circular path. Centripetal force, directed to the centre, keeps a body moving on a circular path

BPSC 68th A bus is moving along a straight path and takes a sharp turn to the right side suddenly. The passengers sitting in the bus will
(a) fall in the forward direction (b) bent towards left side (c) bent towards right side
(d) More than one of the above (e) None of the above
Answer: (b) bent towards left side. Inertia of direction: a body keeps moving in a straight line unless a force turns it

BPSC 70th Which of the following is a non-contact force ?
(a) Magnetic force (b) Frictional force (c) Impact force (d) None of these
Answer: (a) Magnetic force. Magnetic, electrostatic and gravitational forces act without contact; Friction, normal force and impact forces need physical contact

BPSC 71st We apply a force of 200 Newtons on a wooden Box and push it on the floor at constant velocity. The marginal friction force will be :
(a) 100 Newtons (b) 200 Newtons (c) 300 Newtons (d) 400 Newtons
Answer: (b) 200 Newtons. At constant velocity the net force is zero, so friction equals the applied force

BPSC 71st A truck starts from rest down a hill with a constant acceleration. It achieves 400 meters in 20 seconds. If the weight of the truck is 7 tons then what will be the force acting on it?
(a) 11000 Newtons (b) 12000 Newtons (c) 13000 Newtons (d) 14000 Newtons
Answer: (d) 14000 Newtons. From rest with uniform acceleration, distance $s = \frac{1}{2}at^2$; Force equals mass times acceleration, $F = ma$

Test yourself (12)

1. A stone tied to a string is whirled in a horizontal circle and the string suddenly breaks. The stone will move
(a) radially outward, away from the centre of the circle (b) along the tangent to the circle at that point
(c) radially inward towards the centre (d) in a spiral path

2. Which of the following pairs gives the same horizontal range for a projectile fired with the same speed?
(a) 20° and 40° (b) 30° and 45° (c) 30° and 60° (d) 45° and 90°

3. Airbags in cars reduce injury mainly because they
(a) reduce the total change in momentum of the passenger
(b) lengthen the time taken to stop the passenger (c) increase the passenger's inertia
(d) reduce the passenger's mass

4. A rocket can accelerate in outer space because
(a) it pushes against the thin air present in space (b) gravity is absent in space
(c) exhaust gases carry momentum backward (d) space has no friction to stop it

5. Arrange in decreasing order of magnitude: rolling friction (R), kinetic friction (K), limiting friction (L)
(a) R > K > L (b) L > K > R (c) K > L > R (d) L > R > K

6. An ice skater spinning with arms outstretched pulls her arms in. Which quantity stays constant?
(a) Angular velocity (b) Moment of inertia (c) Angular momentum (d) Kinetic energy of rotation

7. Which of the following is a pseudo force?
(a) Centrifugal force (b) Centripetal force (c) Frictional force (d) Gravitational force

8. The area under a velocity–time graph gives
(a) acceleration (b) speed (c) force (d) displacement

9. Why is it unsafe to load heavy luggage on the roof of a bus?
(a) It raises the centre of gravity (b) It increases friction between the tyres and road
(c) It reduces the inertia of the bus (d) It lowers the centre of gravity of the bus

10. Consider the following statements:
1. When a bus turns sharply to the right, its passengers lean to the left.
2. Action and reaction cancel each other because they are equal and opposite.
3. The impulse on a body equals the change in its momentum.
Which of the statements given above is/are correct?
(a) 1 only (b) 2 and 3 only (c) 1 and 3 only (d) 1, 2 and 3

11. Consider the following statements:
1. A ball thrown straight up has zero acceleration at its highest point.
2. In vacuum, a feather and a stone dropped together reach the ground together.
3. Ball bearings reduce friction by replacing sliding with rolling.
How many of the above statements are correct?
(a) Only one (b) Only two (c) All three (d) None

12. A passenger in a train moving at a steady speed on a straight track tosses a coin straight up. Where does the coin land?
(a) Back in his hand (b) Behind him, towards the rear of the coach
(c) Ahead of him, towards the front of the coach (d) To one side of him

Answers: 1. (b) With no centripetal force, inertia of direction carries it straight along the tangent. · 2. (c) Complementary angles (adding up to 90°) give equal range. · 3. (b) $F = \Delta p/\Delta t$; a longer stopping time means a smaller force. · 4. (c) Rocket propulsion follows conservation of momentum and needs no outside medium. · 5. (b) Limiting static friction is greatest, then sliding, and rolling is least. · 6. (c) No external torque, so angular momentum is conserved; the spin speeds up. · 7. (a) Centrifugal force appears only in a rotating frame of reference. · 8. (d) Velocity × time = displacement; the slope gives acceleration. · 9. (a) A high CG lets the weight line fall outside the base at a smaller tilt. · 10. (c) Passengers keep going straight (inertia of direction) and impulse = $F \times t = \Delta p$; action and reaction act on different bodies, so they never cancel. · 11. (b) Statements 2 and 3 are right; at the top only the vertical velocity is zero, while the acceleration is still g downward. · 12. (a) The coin keeps the train's forward speed (inertia of motion) and moves ahead with him, as a bomb released from a level-flying plane stays below the plane.

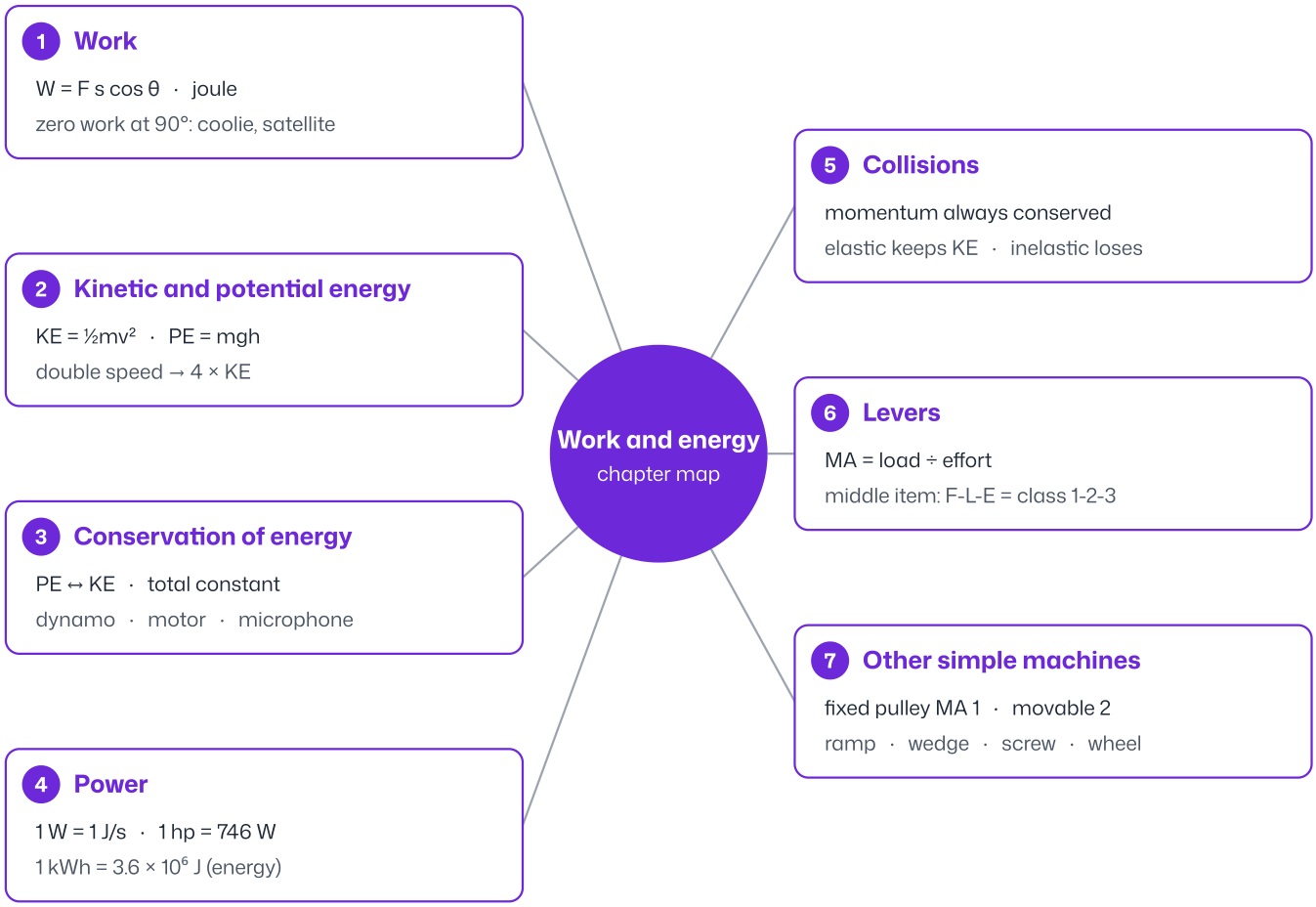
CHAPTER 3

Work, Energy, Power and Simple Machines

Exams ask simple work sums (W = F × s), zero-work cases, energy conversions in devices, conservation of energy in free fall, horsepower and kWh, and classes of lever with examples.

Asked 3 times in past papers: BPSC 3

≈ 26 min to read ≈ 4 min to revise ★★★ Revise on: Day 1 | Day 3 | Day 7 | Day 21



Revision card

1. Work W = F × s × cos θ; unit joule. Zero work when force is perpendicular to motion: coolie walking on level ground with a load, satellite in circular orbit.
2. Pushing a wall that does not move does zero work, however tiring it feels.
3. KE = ½mv² = p²/2m; doubling velocity (or momentum) makes KE four times. PE = mgh.
4. Energy is never created or destroyed; a falling body's PE turns into KE and the total stays the same.
5. Friction converts kinetic energy into heat.
6. Dynamo: mechanical → electrical; motor: electrical → mechanical; cell: chemical → electrical; microphone: sound → electrical; loudspeaker: electrical → sound.
7. Power = work ÷ time; 1 W = 1 J/s; 1 horsepower = 746 W.
8. 1 kWh (one unit of electricity) = 3.6 × 10^6 J; it is a unit of energy, not power.
9. Elastic collision conserves both momentum and KE; inelastic conserves momentum only.
10. Levers: middle item for class 1-2-3 is F-L-E (fulcrum, load, effort).
11. Class II levers always have MA > 1 (nutcracker, wheelbarrow); class III always MA < 1 (tongs, forearm).
12. A machine can multiply force or speed, never energy; efficiency is always below 100%.

Work

W = F s cos θ

joule = 10^7 erg

zero work at 90°

negative work

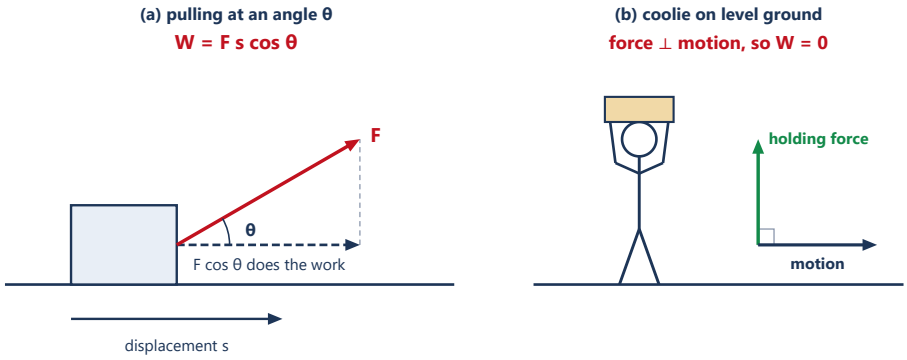
In physics, work is done only when a force **moves** something in the direction of the force. Effort alone is not work: holding a heavy bag still, or pushing a wall that does not budge, tires you but does no work on the bag or the wall.

★★★ **Work** = force × displacement in the direction of the force: **W = F s cos θ**. SI unit **joule** (1 J = 1 N × 1 m); it is a **scalar**.

★★ 1 joule = **10^7 erg** (CGS unit).

★★★ **Zero work** when force and displacement are at **90°** or when there is no displacement.

★★ **Positive work**: force along the motion (a horse pulling a cart). **Negative work**: force against the motion (friction on a sliding box, gravity on a ball thrown up, brakes on a car).



(a) Only the part of the force along the motion, F cos θ, does work (θ = 30° here, so F cos θ = 0.87 F). (b) The coolie's holding force is vertical while the load moves sideways: at 90°, cos θ = 0, so no work is done on the load.

Classic zero-work cases ★★★

Situation	Why the work is zero
Coolie carrying a load on his head and walking on level ground	He holds it up with a vertical force; it moves horizontally (90°). Work is done only when he lifts it (mgh).
Satellite in a circular orbit	Gravity points to Earth's centre, motion is along the orbit (90°), so speed stays constant
Pushing a wall or a parked truck that does not move	No displacement
Holding a suitcase still	No displacement (the muscles tire, but no work is done on the suitcase)
Tension in a pendulum string; centripetal force on a whirled stone	Force along the string is always at 90° to the motion

See it around you: A pair of oxen pulls a plough with a force of 140 N along a 15 m long field. Work = 140 N × 15 m = **2100 J**.

Exam trap: A man walking on a level road with a load on his head does **no work against gravity**, even though he is tired. Feeling tired is physiological effort, not work in physics.

Quick check

1. A coolie walks on level ground with a load on his head. Work done against gravity?
2. Work done by gravity on a satellite in a circular orbit?
3. Does friction on a sliding box do positive or negative work?

Answer: 1. zero (force ⊥ motion) · 2. zero · 3. negative

Kinetic and potential energy

$KE = \frac{1}{2}mv^2$

$KE = p^2/2m$

$2 \times v \rightarrow 4 \times KE$

$PE = mgh$

elastic PE

Energy is the capacity to do work, measured in the same unit, the joule. A moving body can do work because of its motion (**kinetic energy**); a raised or stretched body can do work because of its position or shape (**potential energy**).

★★★ **Kinetic energy** $KE = \frac{1}{2}mv^2$. Since $p = mv$, **$KE = p^2/2m$**. KE can never be negative.

★★★ **Double the velocity → KE becomes 4 times** ($KE \propto v^2$). If **momentum doubles** (same mass), KE also becomes **4 times**.

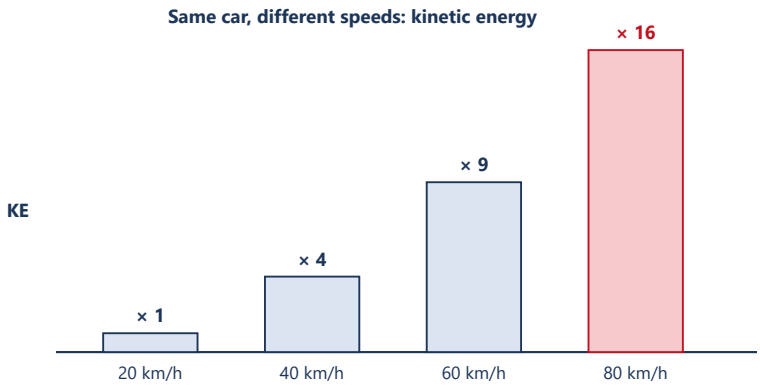
★★ If **KE doubles**, momentum becomes **√2 times**. If momentum rises by 50%, KE rises by 125% ($1.5^2 = 2.25$).

★★ Two bodies with the **same KE**: the **heavier** one has more momentum. Two bodies with the **same momentum**: the **lighter** one has more KE (bullet versus gun).

★★★ **Gravitational potential energy** PE = mgh; it is measured from a chosen reference level.

★★ **Elastic potential energy** is stored in a stretched or compressed body: a wound watch spring, a drawn bow, a catapult (gulel), a stretched rubber band.

★ Other stored forms: **chemical** energy in food, fuel and cells; **nuclear** energy in the nucleus; energy of water held behind a dam.



The same car at 20, 40, 60 and 80 km/h: kinetic energy grows as the square of the speed, 1 : 4 : 9 : 16. Bars drawn to scale.

Remember it: Speed is squared, so speed kills: a car at 80 km/h carries four times the KE of the same car at 40 km/h and needs about four times the braking distance.

⚠ **Exam trap:** Doubling the **mass** only doubles KE; doubling the **speed** makes it four times. Also, KE and momentum are not the same: momentum is a vector, KE a scalar.

Quick check

1. Velocity doubles. Kinetic energy becomes how many times?
2. Same momentum, different masses: which has more KE?
3. Energy stored in a drawn bow or a wound spring is called?

Answer: 1. 4 times · 2. the lighter one · 3. elastic potential energy

Conservation of energy and energy conversions

energy conserved

free fall: PE → KE

pendulum

friction → heat

dynamo vs motor

Energy only changes form; the total never changes. When something seems to lose energy, look for where it went: usually heat from friction, some sound, some light. Machines and power plants are just chains of conversions.

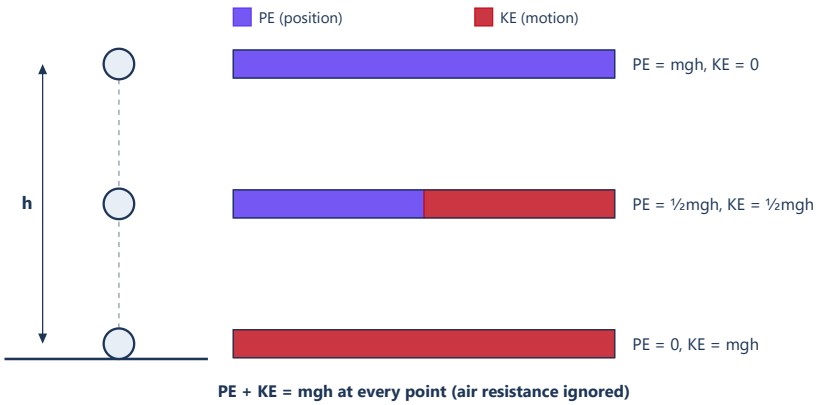
★★★ **Law of conservation of energy**: energy can neither be created nor destroyed, only changed from one form to another; the total energy of an isolated system is constant.

★★★ In **free fall** the PE keeps falling and the KE keeps rising by the same amount; total mechanical energy (KE + PE) stays the same, so the law is **not violated**.

★★ A **swinging pendulum**: maximum PE and zero KE at the extreme ends; maximum KE (highest speed) at the lowest, mean position.

★★★ **Friction converts kinetic energy into heat**; this is why mechanical energy seems to be lost and brakes, tyres and meteors heat up.

★ Einstein's **E = mc²** shows mass is also a form of energy; the Sun and nuclear reactors turn tiny amounts of mass into huge energy.



A ball dropped from height h, drawn to scale. Halfway down, half its potential energy has become kinetic energy; just before landing, all of it has. PE + KE = mgh at every point.

Energy conversions in common devices ★★★

Device / process	Converts	Into
Dynamo / electric generator	Mechanical energy	Electrical energy
Electric motor (fan, mixer, pump)	Electrical energy	Mechanical energy
Electric cell / battery (discharging)	Chemical energy	Electrical energy
Charging a battery	Electrical energy	Chemical energy
Microphone	Sound energy	Electrical energy
Loudspeaker	Electrical energy	Sound energy
Solar (photovoltaic) cell	Light energy	Electrical energy
Electric bulb, tube light, LED	Electrical energy	Light (and heat)
Electric heater, iron, geyser	Electrical energy	Heat energy
Steam engine, thermal power turbine	Heat energy	Mechanical energy
Car engine (petrol or diesel)	Chemical energy of fuel	Heat, then mechanical energy
Thermocouple	Heat energy	Electrical energy
Photosynthesis	Light energy	Chemical energy (glucose)
Burning candle	Chemical energy	Light and heat
Hydroelectric plant	Potential energy of stored water	Kinetic, then electrical energy
Nuclear reactor	Nuclear energy	Heat, then electrical energy

Bhakra Dam on the Sutlej in Himachal Pradesh. Water held high behind the dam has potential energy; it rushes down through pipes to turbines in the power house at the dam's foot (kinetic energy), and generators turn that into electrical energy, carried away by the transmission towers on the hills. Image: KawalSingh, Wikimedia Commons, public domain

Remember it: Dynamo and motor are mirror twins: **D**ynamo **D**elivers electricity from motion, **M**otor **M**oves from electricity. Mic and speaker are the same twins for sound: Mic Makes current, Speaker Speaks.

Exam trap: A **dynamo** does not make energy; it converts mechanical work into electricity. Options that swap dynamo and motor, or microphone and loudspeaker, are the usual traps.

Quick check

1. A dynamo converts _____ energy into _____ energy.
2. A ball falls freely. What happens to PE + KE?
3. Microphone or loudspeaker: which turns sound into electrical energy?

Answer: 1. mechanical → electrical · 2. it stays the same · 3. microphone

Power and efficiency

P = W/t

1 hp = 746 W

kWh = energy

3.6 × 10^6 J

efficiency < 100%

Two people can lift the same bucket up the same stairs and do the same work, but the one who does it faster is more **powerful**. Power is how fast work is done or energy is used.

★★★ **Power** P = work ÷ time = energy ÷ time; also P = force × velocity. SI unit **watt** (1 W = 1 J/s), named after James Watt.

★★★ **1 horsepower (hp) = 746 W** (≈ 0.75 kW).

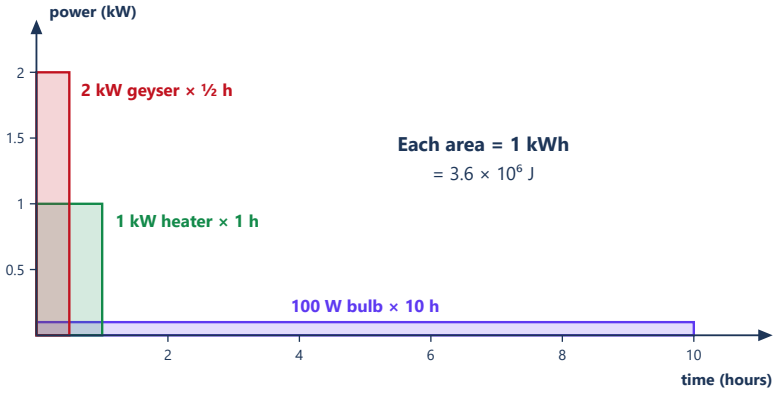
★★ 1 kilowatt (kW) = 1000 W; 1 megawatt (MW) = 10^6 W; 1 gigawatt (GW) = 10^9 W.

★★★ **Kilowatt-hour (kWh)** is the commercial **unit of energy**: 1 kWh = 1000 W × 3600 s = **3.6 × 10^6 J**. One kWh is the one unit on an electricity bill.

★★ Energy used (kWh) = power (kW) × hours: a 100 W bulb for 10 hours uses 1 kWh; a 2 kW geyser for 30 minutes uses 1 kWh.

★★★ **Efficiency** = useful output ÷ input × 100%. Always **less than 100%** in real machines, because some energy is lost as heat, sound and friction.

★ An old filament bulb turns only a small fraction (well under 10%) of its electricity into light, the rest into heat; LEDs give far more light for the same power.



Energy = power × time, the area of each rectangle, drawn to scale. A 100 W bulb for 10 hours, a 1 kW heater for 1 hour and a 2 kW geyser for half an hour each use exactly 1 kWh, one unit on the bill.

⚠ **Exam trap: kWh is energy, kW is power.** Watt is a unit of power, joule and kWh are units of energy, and horsepower is power. A question asking for the unit of electrical energy wants kWh.

☑ Quick check

1. 1 horsepower = how many watt?
2. Is kWh a unit of power or of energy? Its value in joule?
3. Why is no real machine 100% efficient?

Answer: 1. 746 W · 2. energy; 3.6×10^6 J · 3. some energy is lost as heat, sound and friction

Collisions

momentum always conserved

elastic: KE kept

inelastic: KE lost

e = 1 / 0

equal masses swap

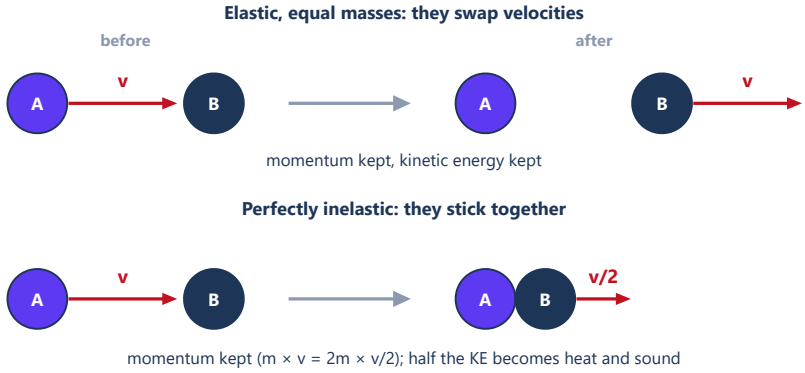
In every collision the bodies push on each other with equal and opposite forces, so **momentum is always conserved**. What may not survive is kinetic energy: some of it can turn into heat, sound or a dent.

Elastic versus inelastic collisions ★★

Feature	Elastic	Inelastic	Perfectly inelastic
Momentum	Conserved	Conserved	Conserved
Kinetic energy	Conserved	Partly lost (heat, sound, deformation)	Maximum loss
After collision	Bodies bounce apart	Bodies separate	Bodies stick together
Examples	Collisions of gas molecules and atoms; nearly so for steel or ivory balls	Most real collisions: a ball bouncing lower each time, cars in a crash	Bullet lodging in a wooden block; mud sticking to a wall
Coefficient of restitution (e)	1	Between 0 and 1	0

★★ In a head-on **elastic collision of two equal masses**, they **exchange velocities**: a moving ball stops dead and the one it hits moves off (Newton's cradle, one billiard ball striking an identical ball head-on).

★ Total energy is conserved in every collision; only the **mechanical (kinetic)** part may be lost in an inelastic one.



Two equal balls, arrow length = speed, drawn to scale. Top: in an elastic collision the moving ball stops and the other moves off with the same speed. Bottom: when they stick together they move at half the speed; momentum is unchanged, but half the kinetic energy turns into heat and sound.

Remember it: Elastic = Everything kept (momentum and KE). **Inelastic = Instead heat** (momentum kept, KE partly turned into heat and sound).

Quick check

1. Which quantity is conserved in every collision?
2. In a head-on elastic collision of two equal masses, what happens to their velocities?
3. A bullet lodges in a wooden block. What type of collision is it?

Answer: 1. momentum · 2. they exchange velocities · 3. perfectly inelastic

Simple machines and levers

MA = load ÷ effort

VR

efficiency = MA/VR

FLE: class 1-2-3

class III: MA < 1

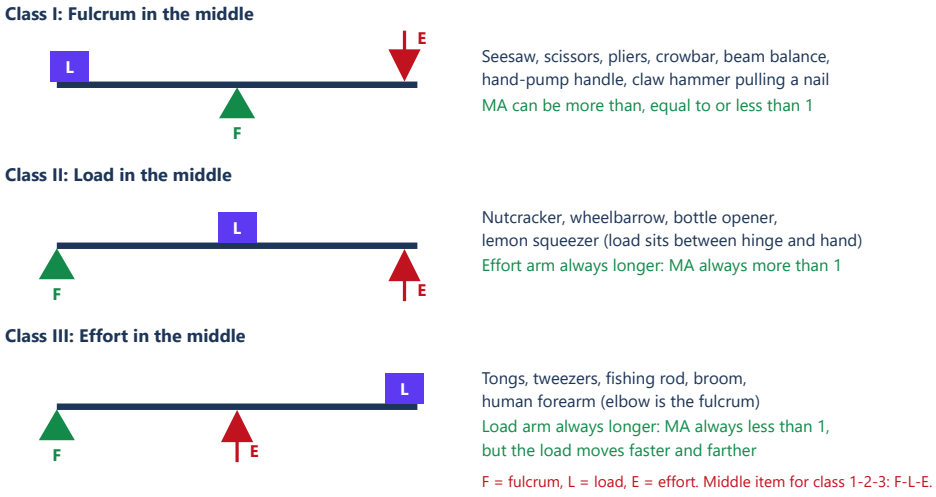
A simple machine lets a small effort move a large load, or makes a small movement of the hand turn into a large, fast movement of the load. It never gives more work than you put in: what you gain in force you pay for in distance.

★★★ **Mechanical advantage (MA)** = load ÷ effort. MA > 1 means the machine multiplies force.

★★ **Velocity ratio (VR)** = distance moved by effort ÷ distance moved by load. **Efficiency = MA ÷ VR × 100%**.

★★ The six classical simple machines: **lever, pulley, wheel and axle, inclined plane, wedge, screw**.

★★★ A **lever** is a rigid bar turning about a fixed point, the **fulcrum (F)**. Law of the lever: load × load arm = effort × effort arm. Its class depends on what lies in the middle.



The three classes of lever: what sits in the middle (fulcrum, load or effort) decides the class and the mechanical advantage.

Classes of lever ★★★

Class	In the middle	MA	Examples
I	Fulcrum	More than, equal to or less than 1	Seesaw, scissors, pliers, crowbar, beam balance, hand-pump handle, claw hammer pulling a nail
II	Load	Always more than 1	Nutcracker, wheelbarrow, bottle opener, lemon squeezer
III	Effort	Always less than 1 (gains speed and distance)	Tongs, tweezers, fishing rod, broom, human forearm (elbow = fulcrum, biceps = effort)

Remember it: FLE, 1-2-3: the thing in the middle is **F**ulcrum for class 1, **L**oad for class 2, **E**ffort for class 3. Read it as flee: F-L-E in order of class.

⚠ **Exam trap:** A **beam balance** is a class I lever with MA = 1. A **wheelbarrow** is class II (wheel is the fulcrum, load in the middle). Tongs and the forearm are class III and have MA less than 1; they trade force for speed and reach.

Quick check

1. What lies in the middle of a class II lever? Give an example.
2. Which class of lever always has MA less than 1?
3. A beam balance is which class of lever?

Answer: 1. the load: nutcracker, wheelbarrow · 2. class III (tongs, forearm) · 3. class I, MA = 1

Pulley, inclined plane, wedge, screw, wheel and axle

fixed pulley: MA 1

movable pulley: MA 2

inclined plane

wedge

screw

wheel and axle

All these machines spread the same work over a longer path. A ramp lets you push a heavy drum up gently instead of lifting it straight; a screw is just a ramp wound round a rod.

★★★ **Single fixed pulley**: MA = 1 (ideal). It gives no force advantage but **changes the direction** of effort to a convenient pull: hoisting a flag, drawing water from a well.

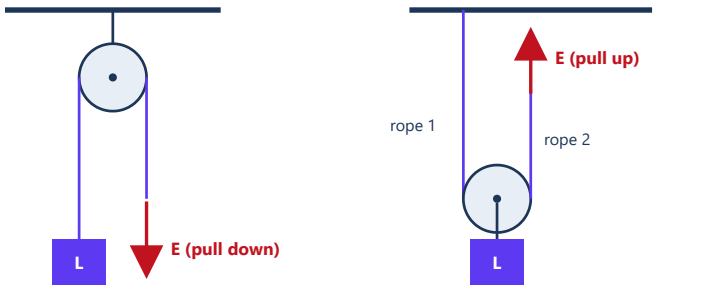
★★ **Single movable pulley**: MA = 2; the effort moves twice as far as the load. In a **block and tackle**, MA = number of rope segments supporting the load (cranes, lifts).

★★ **Inclined plane**: MA = length of slope ÷ height. Ramps for loading trucks, wheelchair ramps, and winding hill (ghat) roads are inclined planes.

★★ **Wedge**: two inclined planes back to back; it turns a push into a sideways splitting force: axe, knife, chisel, nail, plough blade.

★★ **Screw**: an inclined plane wrapped round a cylinder: screw jack (lifts a car), bolts, jar lids, spiral staircases.

★★ **Wheel and axle**: a large wheel fixed to a small axle; MA = radius of wheel ÷ radius of axle: steering wheel, screwdriver, doorknob, windlass over a well.



Single fixed pulley
MA = 1: no force gain,
only a handier direction
flag hoisting, drawing water from a well

Single movable pulley
two rope segments share the load:
MA = 2, but pull twice the length
block and tackle: MA = number of supporting ropes

A fixed pulley only changes the direction of pull; a movable pulley shares the load between two rope segments and halves the effort.

See it around you: Hill roads to Shimla or Darjeeling zig-zag instead of climbing straight up: a longer, gentler slope is an inclined plane that lets vehicles climb with less force.

Quick check

1. What does a single fixed pulley gain you?
2. Mechanical advantage of a single movable pulley?
3. A screw is an inclined plane _____ .

Answer: 1. only a handier direction (MA = 1) · 2. 2 · 3. wrapped round a cylinder

Asked in past papers (3)

BPSC 68th Which of the following energy changes involves frictional force?
(a) Potential energy to sound energy (b) Chemical energy to heat energy (c) Kinetic energy to heat energy
(d) More than one of the above (e) None of the above
Answer: (c) Kinetic energy to heat energy. Friction converts kinetic energy into heat

BPSC 71st The potential energy of a freely falling body continuously decreases.
(a) The principle of conservation of energy is violated
(b) The principle of conservation of energy is not violated (c) Gravitational force is violated
(d) Gravitational force is not violated
Answer: (b) The principle of conservation of energy is not violated. In free fall, lost potential energy becomes kinetic energy; total energy is conserved

BPSC 71st A pair of Oxen exerts a force of 140 newton while ploughing the field. The field ploughed is 15 meter long. The work done in ploughing the length of the field is :
(a) 1900 Joule (b) 2000 Joule (c) 2100 Joule (d) 2200 Joule
Answer: (c) 2100 Joule. Work done = force × displacement in the direction of the force; unit joule

Test yourself (11)

1. If the momentum of a body is doubled, its kinetic energy becomes
(a) eight times (b) four times (c) half (d) unchanged

2. In which case is the work done by the named force zero?
(a) Gravity on a ball falling freely (b) Friction on a heavy box sliding to rest on a floor
(c) Gravity on a satellite in a circular orbit (d) Engine force on an accelerating car

3. One kilowatt-hour equals
(a) 3.6×10^5 J (b) 3.6×10^6 J (c) 1000 J (d) 746 J

4. Which device converts sound energy into electrical energy?
(a) Loudspeaker (b) Microphone (c) Electric motor (d) Dynamo

5. In a nutcracker, which of the following lies between the other two?
(a) Fulcrum (b) Effort (c) Load (d) None, all three are at the same point

6. Which statement about an inelastic collision is correct?
(a) Both momentum and kinetic energy are conserved
(b) Neither momentum nor kinetic energy is conserved (c) Kinetic energy is conserved but momentum is not
(d) Momentum is conserved but kinetic energy is not

7. The human forearm lifting a weight in the palm is an example of a
(a) class I lever (b) class III lever (c) class II lever (d) wheel and axle system

8. A motor of 2 hp works for 1 hour. Roughly how much energy does it use?
(a) 1.5 kWh (b) 2 kWh (c) 0.75 kWh (d) 746 kWh

9. Consider the following statements:
1. A coolie walking on a level platform with a load on his head does no work against gravity.
2. The friction on a box sliding to rest does negative work on it.
3. The kilowatt-hour is a unit of power.
Which of the statements given above is/are correct?
(a) 1 and 2 only (b) 2 and 3 only (c) 1 and 3 only (d) 1, 2 and 3

10. Consider the following pairs:
Device or process : Energy change
1. Thermocouple : heat to electrical
2. Charging a battery : electrical to chemical
3. Photosynthesis : light to chemical
How many of the above pairs are correctly matched?
(a) Only one (b) Only two (c) All three (d) None

11. A car on an expressway speeds up from 40 km/h to 80 km/h. With the same braking force, roughly how far will it now travel before it stops, compared with before?
(a) The same distance (b) Twice as far (c) Four times as far (d) Eight times as far

Answers: 1. (b) $KE = p^2/2m$, so $KE \propto p^2$. · 2. (c) Gravity is perpendicular to the orbital motion, so $W = F\,s\cos 90° = 0$. · 3. (b) $1000\ W \times 3600\ s = 3.6 \times 10^6\ J$. · 4. (b) A microphone turns sound vibrations into electrical signals; a loudspeaker does the reverse. · 5. (c) The nut (load) sits between the hinge (fulcrum) and the hand (effort): a class II lever. · 6. (d) Momentum is always conserved; in an inelastic collision some KE turns into heat and sound. · 7. (b) The elbow is the fulcrum, the biceps effort acts in the middle, the load is in the hand. · 8. (a) $2 \times 746\ W \approx 1.49\ kW$; for 1 hour that is about 1.5 kWh. · 9. (a) The load moves at 90° to the holding force and friction acts against the motion; kWh is energy (3.6×10^6 J), the kilowatt is power. · 10. (c) All three are right; charging is the reverse of a discharging cell (chemical to electrical), and swapping the two is the usual trap. · 11. (c) Doubling the speed makes $KE = \tfrac{1}{2}mv^2$ four times, and the brakes must remove it over about four times the distance; 'twice' wrongly treats KE as proportional to v.

CHAPTER 4

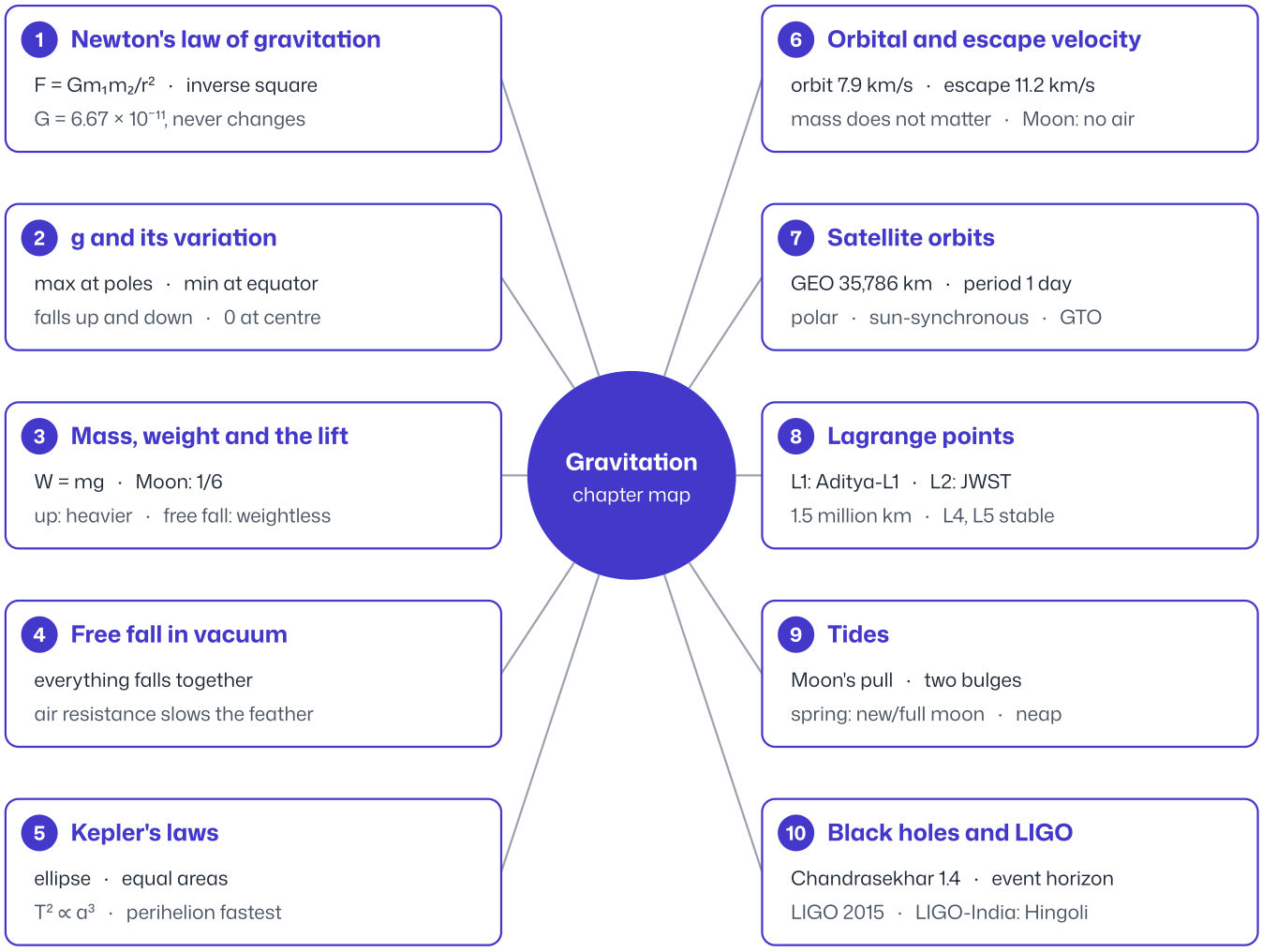
Gravitation and Satellites

Variation of g (poles, equator, depth, Earth's spin), mass vs weight, weight in a lift, free fall, escape velocity, satellite orbits and missions like Aditya-L1 and LIGO-India are asked year after year.

Asked 5 times in past papers: UPSC 1 · BPSC 4

≈ 40 min to read ≈ 7 min to revise ★★★

Revise on: Day 1 | Day 3 | Day 7 | Day 21



Revision card

1. $F = G m_1 m_2 / r^2$; $G = 6.67 \times 10^{-11}$ N·m²/kg² is the same everywhere; g ≈ 9.8 m/s² changes from place to place.
2. g is maximum at the poles, minimum at the equator; it falls with height and with depth and is zero at Earth's centre.
3. If Earth spun faster, weight at the equator would fall; at the poles it would not change.
4. Mass never changes; weight W = mg does. On the Moon weight is about 1/6 of that on Earth.
5. Lift: accelerating up → feel heavier; accelerating down → lighter; cable breaks (free fall) → weightless.
6. Astronauts in orbit are weightless because they and their craft are falling freely together, not because gravity is absent.
7. Kepler: ellipse with Sun at one focus; equal areas in equal times; $T^2 \propto a^3$.
8. Escape velocity from Earth = 11.2 km/s (Moon ≈ 2.4 km/s); it does not depend on the mass of the body.
9. The Moon has no atmosphere because its escape velocity is below the speed of gas molecules.
10. Geostationary orbit: 35,786 km above the equator, period one day, west to east. Polar/sun-synchronous orbits are low (~500–800 km) for imaging.
11. Aditya-L1 sits in a halo orbit round Sun–Earth L1, about 1.5 million km from Earth, reached on 6 January 2024.
12. Chandrasekhar limit ≈ 1.4 solar masses: above it a dead star cannot stay a white dwarf.
13. LIGO-India (Aundha, Hingoli, Maharashtra): ground broken April 2026, first observations targeted for 2030.

Newton's law of gravitation

$F = Gm_1m_2/r^2$

inverse square

$G = 6.67 \times 10^{-11}$

G vs g

Cavendish

The pull that drops an apple is the same pull that holds the Moon in orbit: Newton's great insight. Every mass attracts every other mass; the pull grows with the masses and weakens fast with distance. It is the weakest of nature's forces, but it never switches off and is always attractive.

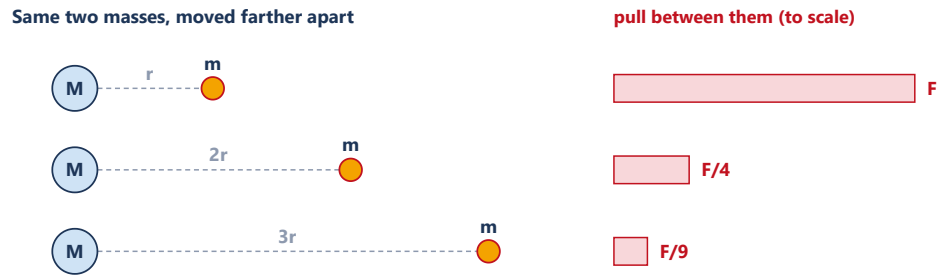
★★★ **Universal law of gravitation** (Newton, Principia, 1687): $F = G m_1 m_2 / r^2$: directly proportional to the product of the masses, inversely proportional to the **square** of the distance between their centres.

★★ Double the distance → force becomes **1/4**; double one mass → force doubles.

★★★ **G** (universal gravitational constant) = **6.67×10^{-11} N·m²/kg²**; the same everywhere in the universe and unaffected by the medium between the bodies. Henry Cavendish first measured it in 1798.

★★ Gravitational force is always **attractive**, acts along the line joining the centres, and the two bodies pull each other with **equal and opposite** forces.

★ Aryabhata (Aryabhatiya, 499 CE) stated that Earth **rotates on its axis**, explaining the daily motion of the stars.



Inverse-square law, drawn to scale: at twice the distance the pull is a quarter, at three times the distance a ninth (bar length $\propto 1/r^2$).

G versus g ★★★

	G	g
Name	Universal gravitational constant	Acceleration due to gravity
Value	6.67×10^{-11} N·m²/kg²	≈ 9.8 m/s² at Earth's surface
Changes?	Never: same everywhere	Yes: with height, depth, latitude, planet
Type	Scalar constant	Vector (points to Earth's centre)
Relation	Enters the formula $g = GM/R^2$	Set by G, Earth's mass M and radius R

⚠ **Exam trap:** G is a universal constant; g is not. A question saying G changes on the Moon is wrong; only g (1.62 m/s² there) changes.

Quick check

1. The distance between two bodies is doubled. What happens to the gravitational force?
2. Which never changes from place to place, G or g?

Answer: 1. it becomes one-fourth (F/4) · 2. G (6.67×10^{-11} N·m²/kg²); g changes

Acceleration due to gravity and its variation

g ≈ 9.8 m/s²

max at poles

falls with height

falls with depth

zero at centre

faster spin

Near Earth every freely falling body speeds up by about 9.8 m/s every second. The value depends on how far you are from Earth's centre and on Earth's spin: farther from the centre or flung outward by rotation, you feel less pull.

★★★ **g ≈ 9.8 m/s²** at the surface (about 9.78 at the equator, 9.83 at the poles). It does **not depend on the mass** of the falling body.

★★★ **Latitude**: Earth is an oblate spheroid, bulging at the equator, so the poles are closer to the centre. **g is maximum at the poles and minimum at the equator**; a body weighs most at the poles.

★★★ **Altitude**: g **decreases** as you go up ($g' \approx g(1 - 2h/R)$ for small heights). Weight is a little less on a mountain top.

★★★ **Depth**: g also **decreases** as you go down a mine ($g' = g(1 - d/R)$) and becomes **zero at Earth's centre**.

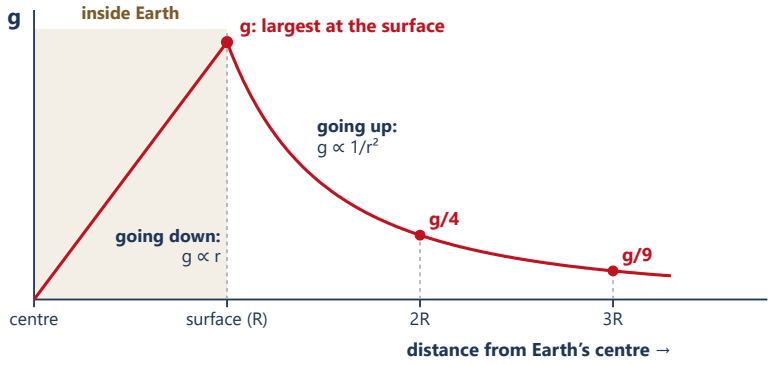
★★ For a small change of height or depth, g falls **faster going up than going down** (2h/R against d/R).

★★ **Rotation of Earth**: spin produces an outward (centrifugal) effect that reduces effective g most at the equator and not at all at the poles: $g' = g - \omega^2 R$ at the equator.

★★★ If **Earth spun faster**, weight at the equator would **decrease**; if it **stopped spinning**, weight at the equator would increase; at the poles weight would stay the same in both cases.

★ If Earth rotated about **17 times faster** (a day of about 1 h 24 min), bodies at the equator would become weightless.

★ If Earth shrank to half its radius with the same mass, g at its surface would become 4 times ($g \propto 1/R^2$).



How g changes with distance from Earth's centre (textbook model of a uniform Earth, drawn to scale): it rises in a straight line from zero at the centre to its largest value at the surface, then falls as $1/r^2$: g/4 at 2R, g/9 at 3R.

Remember it: Poles are Plump with g (max), the **Equator is Empty-ish** (min). Going up or down from the surface both lose g; the surface is the peak.

⚠ **Exam trap:** g decreases both with height **and** with depth; an option saying g increases inside a mine is wrong. At Earth's centre g is zero, but mass is unchanged.

Quick check

1. Where on Earth is g greatest, and where least?
2. What happens to g as you go down a mine, and at Earth's centre?
3. If Earth spun faster, what would happen to your weight at the equator and at the poles?

Answer: 1. greatest at the poles, least at the equator · 2. it decreases; it is zero at the centre · 3. it would fall at the equator; no change at the poles

Mass, weight and the lift

mass vs weight

W = mg

Moon: 1/6

lift: R = m(g ± a)

weightlessness

Mass is how much matter you have; weight is how hard a planet pulls on it. Carry a 60 kg person to the Moon: still 60 kg of matter, but the Moon pulls only about one-sixth as hard. A weighing machine actually reads the push of the floor on you, which is why it lies in an accelerating lift.

Mass versus weight ★★★

Mass	Weight
Quantity of matter in a body	Force of gravity on the body, W = mg
Scalar; SI unit kilogram (kg)	Vector (points down); SI unit newton (N)
Same everywhere: Earth, Moon, space	Changes with g; can be zero in free fall
Measured by a beam (common) balance	Measured by a spring balance
Measures inertia	Measures gravitational pull

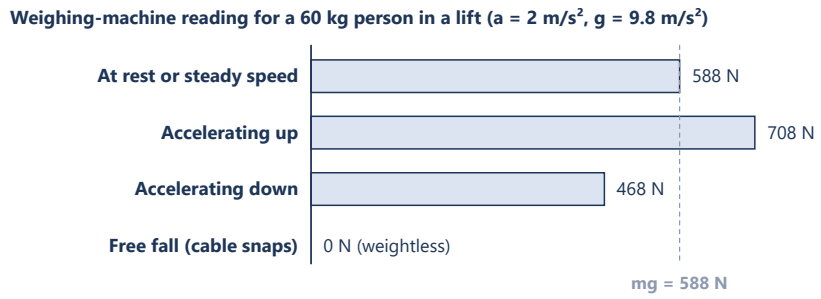
★★★ **Moon's gravity ≈ 1/6 of Earth's** (1.62 m/s²): a 60 kg person weighs about 588 N on Earth and about 98 N on the Moon; the mass stays 60 kg.

★★ On the Moon you could jump about 6 times higher; a **pendulum clock runs slower** there ($T = 2\pi\sqrt{(L/g)}$, so smaller g means a longer period).

★ Of the planets, **Jupiter** has the strongest surface gravity (about 2.5 times Earth's).

Apparent weight in a lift (reading R on a weighing machine) ★★★

Lift is	Reading	You feel
At rest or moving at constant speed (up or down)	R = mg	Normal
Accelerating upward (or slowing while going down)	R = m(g + a)	Heavier
Accelerating downward (or slowing while going up)	R = m(g − a)	Lighter
Falling freely (cable snaps, a = g)	R = 0	Weightless
Accelerating down faster than g	Negative	Pressed against the ceiling



Apparent weight in a lift, drawn to scale for a 60 kg person with a = 2 m/s²: R = m(g + a) = 708 N accelerating up, m(g − a) = 468 N accelerating down, zero in free fall. The mass (60 kg) never changes.

★★★ **Weightlessness** is the feeling of zero apparent weight in **free fall**. Astronauts in an orbiting station float because they and the station are falling round Earth together; gravity at the ISS (~400 km up) is still about **90% of surface g**.

★★ In an orbiting spacecraft a pendulum does not swing, water will not pour from a glass, a candle flame becomes round and blue, and a spring balance reads zero.

Astronauts floating inside the International Space Station (July 2011). Gravity there is still about 90% of its value at the surface; they float because they and the station are falling round Earth together. Image: NASA, Wikimedia Commons, public domain

Remember it: Accelerate up = weight up, accelerate down = weight down, cable gone = weight gone. Constant speed, up or down, changes nothing.

⚠ **Exam trap:** Two bodies of different mass falling freely on the Moon have the **same velocity at every instant** (same acceleration), but **different** forces on them, since weight is proportional to mass. Their inertia does not change during the fall.

Quick check

1. A 60 kg person goes to the Moon. What happens to the mass and to the weight?
2. A lift's cable snaps. What does the weighing machine inside read?
3. Why do astronauts float in the ISS though gravity there is about 90% of g?

Answer: 1. mass stays 60 kg; weight falls to about 1/6 · 2. zero: free fall, weightless · 3. they and the station are falling round Earth together (free fall)

Free fall in vacuum

same acceleration

feather and ball

air resistance

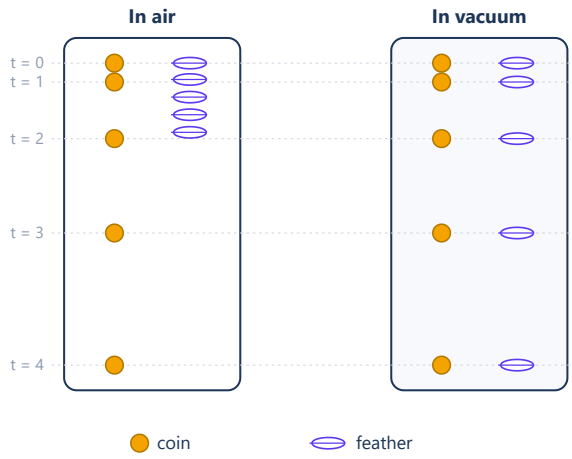
Galileo

A heavier body is pulled harder but also resists acceleration more, in exact proportion. So, with no air in the way, everything falls together. Air resistance, not gravity, makes a feather drift.

★★★ A **feather, a rubber ball and a wooden ball** dropped together in vacuum **reach the ground together**.

★★ Galileo showed that the speed of a falling body does not depend on its weight; the story of balls dropped from the Leaning Tower of Pisa illustrates this idea.

★★ In air, a crumpled paper ball falls faster than a flat sheet of the same paper: only air resistance differs.



A coin and a feather at equal time intervals. In vacuum they fall together, and the distance covered in successive intervals grows as 1 : 3 : 5 : 7 (drawn to scale). In air the feather soon drifts down at a slow, steady speed (its positions are illustrative).

Quick check

1. A feather and a ball are dropped together in vacuum. Which lands first?
2. In air, what makes a feather fall slower than a ball?

Answer: 1. neither: both land together · 2. air resistance, not gravity

Kepler's laws of planetary motion

ellipse, Sun at a focus

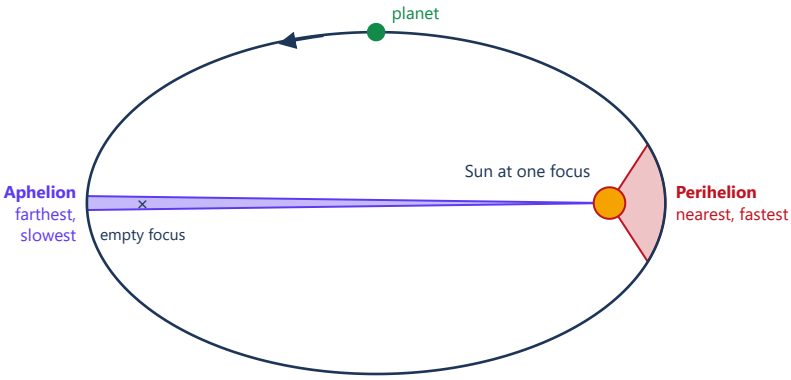
equal areas

$T^2 \propto a^3$

perihelion: fastest

January perihelion

Johannes Kepler used Tycho Brahe's careful observations to find three rules that planets obey (published 1609 and 1619). Newton later showed all three follow from his law of gravitation.



Law 1: orbit is an ellipse, Sun at one focus. Law 2: the two shaded areas are swept in equal times. Law 3: $T^2 \propto a^3$ (a = semi-major axis). Ellipse exaggerated: real planetary orbits are nearly circular.

Kepler's laws (ellipse exaggerated, not to scale): elliptical orbit with the Sun at one focus; the planet sweeps equal areas in equal times, so it moves fastest at perihelion.

Kepler's three laws ★★★

Law	Statement	What it means
1. Law of orbits	Every planet moves in an ellipse with the Sun at one focus	Distance from the Sun keeps changing: perihelion (nearest), aphelion (farthest)
2. Law of areas	The line joining planet and Sun sweeps equal areas in equal times	A planet is fastest at perihelion, slowest at aphelion (angular momentum is conserved)
3. Law of periods	Square of the orbital period ∝ cube of the semi-major axis ($T^2 \propto a^3$)	Farther planets take much longer: Mercury 88 days, Earth 1 year, Neptune about 165 years

★★ Earth reaches **perihelion in early January** and aphelion in early July, so it moves fastest round the Sun in January.

★ Seasons come from the **tilt of Earth's axis (23.5°)**, not from the change in distance: the northern winter happens when Earth is nearest the Sun.

Remember it: E-A-T: **E**llipse, equal **A**reas, **T**^{2} ∝ a^3. Kepler's laws in the order they are numbered.

Quick check

1. Kepler's first law: what is the shape of an orbit, and where is the Sun?
2. Where in its orbit does a planet move fastest?
3. Kepler's third law in symbols?

Answer: 1. an ellipse, with the Sun at one focus · 2. at perihelion, nearest the Sun · 3. $T^2 \propto a^3$

Orbital velocity, escape velocity and why satellites do not fall

continuous free fall

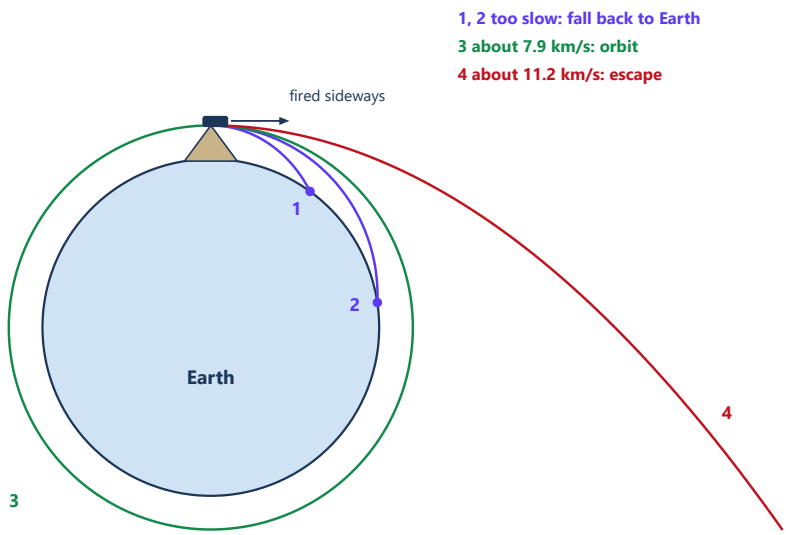
orbital: 7.9 km/s

escape: 11.2 km/s

$v_e = \sqrt{2} \times v_0$

Moon: no air

Throw a stone sideways and it curves to the ground. Throw it faster and it lands farther. Throw it at about 7.9 km/s and Earth's surface curves away as fast as the stone falls: it keeps falling but never lands. That is an orbit. Throw it at 11.2 km/s and it never comes back: that is escape.



Newton's cannon (mountain hugely exaggerated, not to scale). Fired sideways faster and faster, the ball lands farther away (1, 2), then falls round Earth for ever (3, orbit); at √2 times that speed it escapes (4). Each path is the exact orbit shape for its speed.

★★★ A satellite does not fall down because **Earth's gravity supplies exactly the centripetal acceleration** needed for its circular motion; it is in continuous free fall around Earth.

★★★ **Orbital velocity** near Earth's surface ≈ **7.9 km/s** ($v_0 = \sqrt{gR}$); it is less for higher orbits (ISS at ~400 km moves at about 7.7 km/s and circles Earth in about 92 minutes).

★★ A satellite skimming just above Earth's surface would circle it in about **84 minutes**, the shortest possible orbital period round Earth.

★★★ **Escape velocity** = minimum speed for a body to leave a planet's gravity for ever: $v_e = \sqrt{2GM/R} = \sqrt{2gR}$. For **Earth = 11.2 km/s**; for the **Moon ≈ 2.4 km/s**.

★★★ Escape velocity and orbital velocity are **independent of the mass of the body** launched (and escape velocity of the direction of launch). $\mathbf{v_e = \sqrt{2} \times v_0} \approx 1.41 \times$ orbital velocity.

★★★ The **Moon has no atmosphere**: its escape velocity (≈ 2.4 km/s) is so low that gas molecules, moving fast in its hot daytime (their rms speed), escape. Earth, with 11.2 km/s, holds on to its air.

★★ The higher the orbit, the **slower the satellite and the longer its period** ($T^2 \propto r^3$). The Moon, 3.84 lakh km away, takes about 27.3 days.

★★ If gravity suddenly vanished, a satellite would fly off along the **tangent** to its orbit.

★ Escape velocities: Mars about 5 km/s, Jupiter about 60 km/s, Sun about 618 km/s. For a black hole it exceeds the speed of light.

⚠ **Exam trap:** Satellites stay up neither because gravity is absent at that height nor because the Moon's pull cancels Earth's. Gravity is present and provides the **necessary acceleration** (centripetal). Escape velocity is the same for a pebble and a rocket.

Quick check

1. Escape velocity from Earth? Does it depend on the mass of the body?
2. Why has the Moon no atmosphere?
3. Why does a satellite not fall to Earth?

Answer: 1. 11.2 km/s; no · 2. its escape velocity (≈ 2.4 km/s) is too low to hold gas molecules · 3. gravity supplies exactly the centripetal acceleration; it keeps falling round Earth

Types of satellite orbit

GEO: 35,786 km

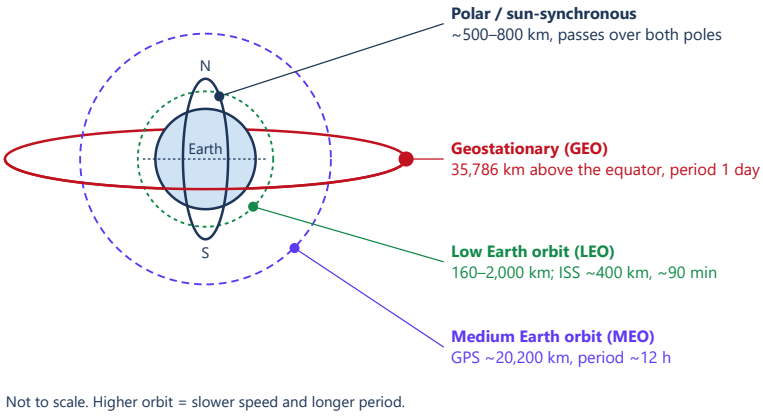
west to east

polar / sun-synchronous

GEO vs GSO

PSLV vs GSLV

Choosing an orbit is choosing a job. A satellite that must stare at one country all day sits very high over the equator; one that must photograph the whole planet in detail flies low and passes over the poles.



Main Earth orbits (not to scale): low and polar orbits for imaging, medium orbit for navigation, geostationary for communication and weather.

Orbits compared ★★★

Orbit	Height above Earth	Key feature	Uses / examples
Geostationary (GEO)	35,786 km (≈ 36,000 km), over the equator	Period = one sidereal day (23 h 56 min), moves west to east; looks fixed in the sky	Communication, DTH TV, weather: INSAT, GSAT series
Geosynchronous (GSO)	35,786 km, but orbit tilted or elliptical	Same 1-day period, but traces a figure-8 in the sky	Part of NavIC (India's navigation system) uses inclined GSO
Polar orbit	Low, typically 500–1,000 km	Passes over both poles; Earth turns beneath, so the whole globe is covered	Remote sensing, mapping, reconnaissance
Sun-synchronous (a near-polar orbit)	About 600–800 km	Crosses each place at the same local solar time, so lighting is the same every pass	Earth observation: Cartosat, Resourcesat, Oceansat; launched by PSLV
Low Earth orbit (LEO)	160–2,000 km	Fast; one orbit in ~90 minutes	ISS (~400 km), Starlink
Medium Earth orbit (MEO)	2,000–35,786 km	Period of hours	GPS (~20,200 km, 12 h), Galileo
Geosynchronous transfer orbit (GTO)	Elliptical, low perigee to ~36,000 km apogee	Transfer orbit: the satellite fires its own motor at apogee to reach GEO	Where GSLV and LVM3 drop communication satellites

★★★ **Every geostationary orbit is geosynchronous, but not every geosynchronous orbit is geostationary**: geostationary needs a circular orbit exactly above the equator.

★★ About **three geostationary satellites**, 120° apart, can cover almost the whole Earth except the polar regions. Arthur C. Clarke proposed this in 1945; the GEO belt is called the **Clarke orbit**.

★★ **PSLV** (Polar Satellite Launch Vehicle) is named after its job of placing satellites in polar and sun-synchronous orbits; **GSLV** places them in geosynchronous transfer orbit.

★ India's first satellite **Aryabhata** was launched on 19 April 1975 on a Soviet rocket; the world's first artificial satellite was **Sputnik-1** (USSR, 4 October 1957).

Remember it: GEO = Glued Even Overhead (sits still above the equator). **Polar = Photographer** (sweeps over every place). **Sun-synchronous = Same-time Shoot** (same local time, same shadows).

⚠ **Exam trap:** A geostationary satellite is at about 36,000 km, not 3,600 km or 360 km, and it orbits **west to east** with Earth, over the **equator**, not over the poles.

Quick check

1. Height and period of a geostationary orbit?
2. Every geostationary orbit is geosynchronous. Is the reverse true?
3. Which orbit suits imaging satellites like Cartosat?

Answer: 1. 35,786 km above the equator; one day · 2. no: geostationary must be circular and exactly over the equator · 3. sun-synchronous (near-polar), about 600–800 km

Lagrange points and Aditya-L1

L1 to L5

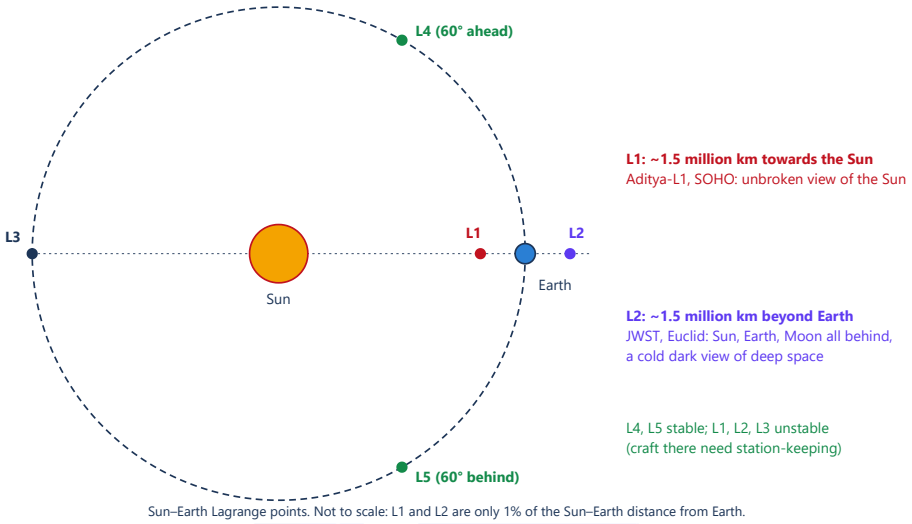
L4, L5 stable

L1: 1.5 million km

Aditya-L1

L2: JWST

Between two big bodies like the Sun and Earth there are five spots where their combined gravity provides exactly the pull a small craft needs to circle the Sun in step with Earth. A spacecraft parked there keeps the same position relative to both, saving fuel.



The five Sun–Earth Lagrange points (not to scale): L1 faces the Sun (Aditya-L1), L2 looks away into deep space (JWST).

★★ **Lagrange points** (named after Joseph-Louis Lagrange): five positions, L1 to L5, in any two-body system. **L1, L2, L3 are unstable** (a craft there must fire small thrusters now and then to stay); **L4 and L5 are stable**.

★★ **Sun–Earth L1** lies about **1.5 million km from Earth towards the Sun** (about 1% of the Sun–Earth distance). From there the Sun is never hidden by Earth or the Moon (no eclipses).

★★★ **Aditya-L1**, India's first space mission to study the Sun, was launched by **PSLV-C57 on 2 September 2023** and placed in a **halo orbit round L1 on 6 January 2024**; it carries seven instruments, including VELC to study the corona.

★★ **Sun–Earth L2**, about 1.5 million km beyond Earth (away from the Sun), hosts the **James Webb Space Telescope** (launched 25 December 2021) and **Euclid**: the Sun, Earth and Moon all lie behind them, giving a cold, dark view.

★ Jupiter's **L4 and L5** points collect thousands of asteroids called **Trojans**.

⚠ **Exam trap:** Aditya-L1 is not orbiting the Sun near its surface, and not orbiting Earth; it circles the L1 point about 1.5 million km away, between Earth and the Sun.

Quick check

1. Where is Aditya-L1 stationed?
2. When did Aditya-L1 reach its halo orbit?
3. Which Lagrange points are stable?

Answer: 1. in a halo orbit round Sun–Earth L1, about 1.5 million km from Earth · 2. 6 January 2024 (launched 2 September 2023 by PSLV-C57) · 3. L4 and L5

Tides

Moon's pull

two bulges

spring tide

neap tide

24 h 50 min

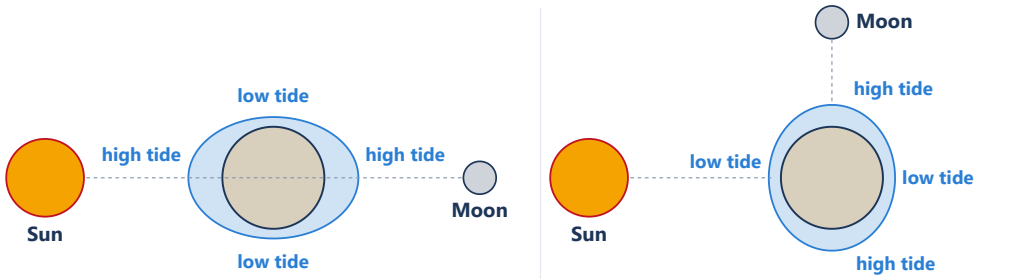
The Moon pulls the near side of Earth more strongly than the centre, and the centre more than the far side. The oceans stretch into two bulges, one facing the Moon and one opposite. As Earth turns through both bulges, most coasts get two high tides a day.

★★★ Tides are caused mainly by the **Moon's gravity**; the Sun's tide-raising effect is a little under **half** the Moon's, because tidal force depends on the **difference** in pull across Earth, which falls off with the cube of distance.

★★ Two high tides and two low tides occur roughly every **24 h 50 min** (high tides about 12 h 25 min apart), because the Moon rises about 50 minutes later each day.

★★★ **Spring tides** (highest high tides): at **new moon and full moon** (amavasya, purnima), when Sun, Earth and Moon are in a line. **Neap tides** (weakest): at the **first and last quarter**, when Sun and Moon pull at right angles.

★ Tidal friction is slowly lengthening Earth's day and has locked the Moon so that it always shows Earth the **same face**. India's best tidal-energy sites are the **Gulf of Khambhat**, the **Gulf of Kutch** and the **Sundarbans**.



(a) Spring tide
Sun, Earth, Moon in a line: new or full moon

(b) Neap tide
Sun and Moon at right angles: quarter moon

Tides, not to scale (bulges hugely exaggerated). (a) Sun and Moon pull along one line: the highest high tides and lowest low tides, spring tide. (b) They pull at right angles: the Sun's pull partly fills the Moon's low tides, giving the smallest range, neap tide.

Remember it: Spring has nothing to do with the season: think of the tide springing up when Sun and Moon pull in a line (new or full moon). Neap = Not much.

Quick check

1. Spring tides come on which days?
2. Neap tides come when the Sun and the Moon pull at what angle?
3. Which raises bigger tides, the Sun or the Moon?

Answer: 1. new moon and full moon (amavasya, purnima) · 2. at right angles (first and last quarter) · 3. the Moon; the Sun's effect is a little under half

Black holes, the Chandrasekhar limit and gravitational waves

Chandrasekhar: 1.4

white dwarf

event horizon

LIGO: 2015

LIGO-India: Hingoli

When a star runs out of fuel, gravity crushes its core. What it becomes depends on how heavy the core is: a white dwarf, a neutron star, or, if gravity wins completely, a black hole from which not even light escapes.

★★★ **Chandrasekhar limit ≈ 1.4 solar masses** (1.44): the maximum mass of a **white dwarf**. A dead core heavier than this collapses further into a **neutron star** or a **black hole**. Our Sun will end as a white dwarf.

★★★ **Subrahmanyan Chandrasekhar** worked out the limit in 1930 and shared the **1983 Nobel Prize in Physics**; NASA's **Chandra X-ray Observatory** is named after him.

★★★ **Black hole**: a region where gravity is so strong that nothing, not even light, escapes from inside its boundary, the **event horizon**; its escape velocity exceeds the speed of light. The name was popularised by John Wheeler in 1967.

★★ The **Event Horizon Telescope** released the first image of a black hole's shadow, **M87*** in galaxy M87, in April 2019, and of **Sagittarius A***, at the centre of our Milky Way, in May 2022.

★ Stephen Hawking showed (1974) that black holes should slowly give off radiation, now called **Hawking radiation**.

★★ **Gravitational waves** are ripples in space-time, travelling at the **speed of light**, produced by accelerating massive bodies such as merging black holes. **Einstein** predicted them in 1916 from his general theory of relativity.

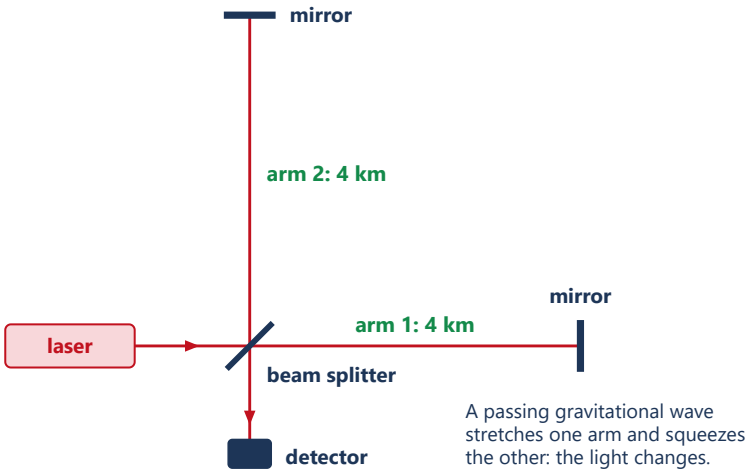
★★★ First direct detection: **14 September 2015** (GW150914) by the twin **LIGO** detectors in the USA (Hanford and Livingston), from two black holes merging about 1.3 billion light-years away. The **2017 Nobel Prize in Physics** went to Rainer Weiss, Barry Barish and Kip Thorne.

★★ **LIGO** = Laser Interferometer Gravitational-wave Observatory: two 4 km arms at right angles; laser light measures length changes far smaller than a proton. Detectors now work as a network: LIGO (USA), Virgo (Italy), KAGRA (Japan).

★★★ **LIGO-India**: a 4 km-arm detector at **Aundha in Hingoli district, Maharashtra**, built by the **Department of Atomic Energy and the Department of Science and Technology** with the US LIGO Laboratory (NSF). The Union Cabinet approved it in April 2023 at about ₹2,600 crore; **ground was broken on 23 April 2026**, and first observations are **targeted for 2030**.

★ A detector in India, far from the others, will sharply improve the ability to pinpoint where in the sky a gravitational-wave source lies.

The first image of a black hole: the dark shadow of M87* inside a ring of glowing gas, released by the Event Horizon Telescope in April 2019. Image: Event Horizon Telescope, Wikimedia Commons, CC BY 4.0



How LIGO listens for gravitational waves: a laser beam is split into two 4 km arms at right angles, sent back by mirrors and recombined at the detector. A passing wave changes the arm lengths by far less than the width of a proton, and the light at the detector changes. Not to scale.

Fate of a dying star (by mass of the leftover core) ★★

Core mass	End state	Note
Below about 1.4 solar masses (Chandrasekhar limit)	White dwarf	Held up by electron pressure; the Sun's fate
About 1.4 to roughly 2–3 solar masses	Neutron star (often a pulsar)	Teaspoon weighs billions of tonnes; spins very fast
Above roughly 2–3 solar masses	Black hole	Nothing escapes the event horizon

Remember it: Chandra's 1.4: think of a cricket score 1-for-4. Below 1.4 the star retires gently as a white dwarf; above it, it is all out: neutron star or black hole.

⚠ **Exam trap:** Gravitational waves travel at the **speed of light**, not faster, and were first detected in **2015** (announced 2016), a century after Einstein predicted them. LIGO-India is in **Maharashtra**, not Karnataka or Tamil Nadu.

Quick check

1. The Chandrasekhar limit, and what it decides?
2. When, and by what, were gravitational waves first detected?
3. Where is LIGO-India being built?

Answer: 1. ≈ 1.4 solar masses: the most a white dwarf can have · 2. 14 September 2015, by the two LIGO detectors in the USA · 3. Aundha, Hingoli district, Maharashtra

Asked in past papers (5)

UPSC 2011 An artificial satellite orbiting around the Earth does not fall down. This is so because the attraction of Earth
(a) does not exist at such distance (b) is neutralized by the attraction of the moon
(c) provides the necessary speed for its steady motion (d) provides the necessary acceleration for its motion
Answer: (d) provides the necessary acceleration for its motion. Earth's gravity supplies the centripetal acceleration that keeps a satellite in orbit

BPSC 67th If a feather, a rubber ball and a wooden ball are falling freely simultaneously from the same height in vacuum, then
(a) the feather will reach at the ground first (b) the rubber ball will reach at the ground first
(c) the wooden ball will reach at the ground first (d) all the three will reach at the ground together
(e) None of the above/More than one of the above
Answer: (d) all the three will reach at the ground together. In free fall all bodies have the same acceleration g, whatever their mass

BPSC 67th re-exam If the spinning speed of the earth increases, then the weight of the body at the equator will
(a) be doubled (b) increase (c) decrease (d) remain same
(e) None of the above/More than one of the above
Answer: (c) decrease. Effective gravity at the equator is $g - \omega^2 R$, so faster rotation lowers weight

BPSC 69th Two objects of different masses falling freely near the surface of the Moon would
(a) have different accelerations (b) undergo a change in their inertia (c) have same velocity at any instant
(d) experience forces of same magnitude
Answer: (c) have same velocity at any instant. In free fall all bodies have the same acceleration g, whatever their mass; The gravitational force on a body, its weight, is proportional to its mass

BPSC 70th re-exam There is no atmosphere on the surface of the moon because
(a) It revolves around Earth (b) It gets light from Sun
(c) Escape velocity of gas molecules is less than rms velocity (d) It is closer to Earth
Answer: (c) Escape velocity of gas molecules is less than rms velocity. No atmosphere stays where escape velocity is below gas molecules' rms speed; The Moon's escape velocity is about 2.4 km/s, against Earth's 11.2 km/s

Test yourself (12)

1. Where on Earth is the weight of a body the greatest?
(a) At the equator (b) At the poles (c) At the centre of Earth (d) At the top of Mount Everest

2. A man stands on a weighing machine in a lift. The reading will be zero when the lift
(a) moves up with constant speed (b) moves down with constant speed (c) falls freely
(d) accelerates upward

3. The escape velocity from Earth's surface for a body of mass 100 kg is 11.2 km/s. For a body of mass 400 kg it will be
(a) 44.8 km/s (b) 22.4 km/s (c) 5.6 km/s (d) 11.2 km/s

4. Which statement about a geostationary satellite is correct?
(a) It orbits over the poles (b) It moves east to west (c) Its period equals one day
(d) It orbits at about 3,600 km

5. Aditya-L1 is stationed around the Lagrange point L1, which lies
(a) on the far side of the Moon from Earth (b) between Earth and the Sun
(c) beyond Earth, away from the Sun (d) 60° ahead of Earth in its orbit

6. Spring tides occur on
(a) the first and last quarter days (b) new moon and full moon days (c) only during the spring season
(d) only at the equinoxes

7. The Chandrasekhar limit is about
(a) 1.4 times the mass of the Sun (b) 14 times the mass of the Sun (c) 1.4 times the mass of Jupiter
(d) 3 times the mass of the Sun

8. Astronauts float inside the International Space Station mainly because
(a) there is no gravity at that height (b) the Moon's pull exactly cancels Earth's pull on them
(c) they and the station are in free fall together (d) the station spins rapidly

9. The LIGO-India gravitational-wave observatory is being built in
(a) Hingoli district, Maharashtra (b) Theni district, Tamil Nadu
(c) Challakere, Chitradurga district, Karnataka (d) Hanle, Ladakh

10. Consider the following statements:
1. The acceleration due to gravity is greatest at the poles.
2. The acceleration due to gravity increases as one goes down a deep mine.
3. If Earth spun faster, a body at the equator would weigh less.
Which of the statements given above is/are correct?
(a) 1 only (b) 1 and 2 only (c) 2 and 3 only (d) 1 and 3 only

11. Consider the following statements:
1. Every geosynchronous orbit is also a geostationary orbit.
2. A geostationary satellite moves from east to west.
3. Polar remote-sensing satellites usually orbit about 36,000 km above Earth.
How many of the above statements are correct?
(a) Only one (b) Only two (c) All three (d) None

12. A pendulum clock that keeps correct time in Delhi is taken to a base on the Moon. There it will
(a) run slow, as the smaller g lengthens each swing (b) run fast, as the bob weighs less and swings freely
(c) keep correct time, as the mass of the bob is unchanged (d) stop at once, because the Moon has no air

Answers: 1. (b) g is maximum at the poles, which are nearest Earth's centre and unaffected by rotation. · 2. (c) In free fall the floor exerts no push, so apparent weight is zero. · 3. (d) Escape velocity does not depend on the mass of the body. · 4. (c) A geostationary satellite moves west to east above the equator at about 35,786 km with a one-day period. · 5. (b) Sun–Earth L1 lies on the Sun–Earth line about 1.5 million km sunward; L2 is the one beyond Earth. · 6. (b) Sun, Moon and Earth are in line at new and full moon, so their tidal pulls add up. · 7. (a) Above about 1.4 solar masses a white dwarf cannot support itself. · 8. (c) Gravity at ~400 km is about 90% of surface g; the station and crew fall round Earth together. · 9. (a) It is at Aundha in Hingoli district; Theni is the proposed INO site and Hanle hosts the Indian Astronomical Observatory. · 10. (d) g is largest at the poles and faster spin strengthens the outward effect at the equator; g falls with depth too, reaching zero at Earth's centre. · 11. (d) All three are false: only a circular orbit exactly over the equator is geostationary, it moves west to east, and polar satellites fly low, about 500 to 1,000 km up. · 12. (a) T =

$2\pi\sqrt{(L/g)}$, so the smaller g (1.62 m/s^2) gives a longer period and the clock loses time; the bob's mass does not enter the formula.

CHAPTER 5

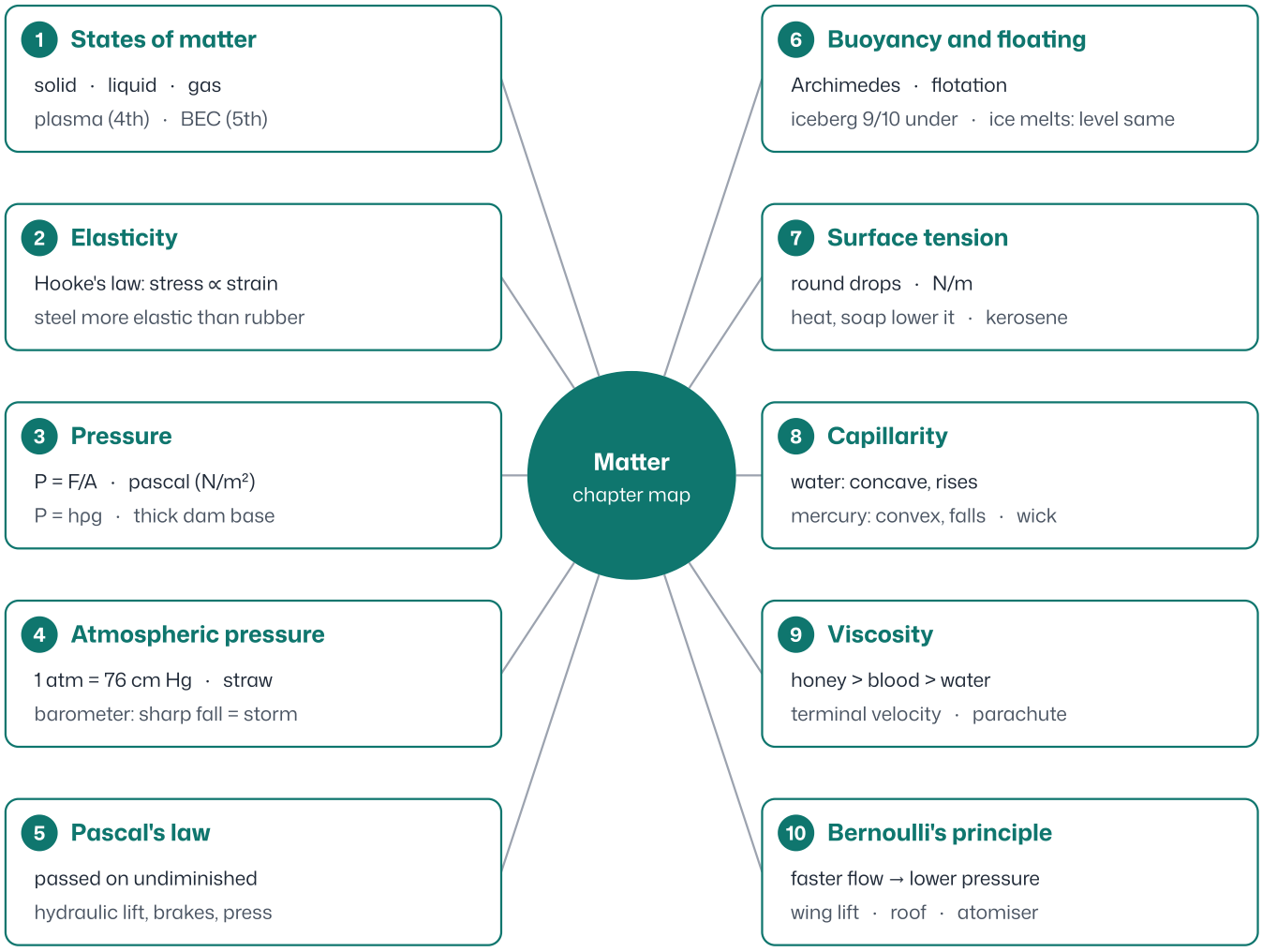
Properties of Matter: Solids and Fluids

Pressure and its unit, atmospheric pressure effects, Pascal's law, floating ice and icebergs, surface tension, capillarity (and why a straw is not capillarity), viscosity of honey versus water, and Bernoulli's principle are asked again and again.

Asked 4 times in past papers: UPSC 1 · BPSC 3

≈ 43 min to read ≈ 8 min to revise ★★★

Revise on: Day 1 | Day 3 | Day 7 | Day 21



Revision card

1. Pressure = force ÷ area; SI unit pascal (1 Pa = 1 N/m^2). 1 atm ≈ 1.013 × 10^5 Pa = 76 cm of mercury.
2. Liquid pressure rises with depth (P = hρg), so dam walls are thicker at the bottom.
3. A drinking straw, syringe and dropper work by atmospheric pressure, not capillarity.
4. Pascal's law: pressure on an enclosed liquid passes undiminished in all directions: hydraulic lift, brakes, press.
5. Archimedes: buoyant force = weight of liquid displaced. A floating body displaces its own weight of liquid.
6. Melting ice floating in water leaves the level unchanged. About 9/10 of an iceberg is under water.
7. A ship floats higher in sea water than in river water (sea water is denser); an egg floats in strong salt water.
8. Surface tension makes drops spherical; heat, soap and detergent lower it; kerosene on ponds drowns mosquito larvae.
9. Water wets glass (concave meniscus, rises in a capillary); mercury does not (convex, falls).
10. Capillarity: lamp wick, blotting paper, rise of water in plants; hoeing soil breaks capillaries and saves moisture.
11. Viscosity: honey > blood > water > air. Heating lowers a liquid's viscosity but raises a gas's.
12. Terminal velocity (Stokes' law) is why raindrops do not hurt and parachutes work.
13. Bernoulli: faster flow → lower pressure: aeroplane lift, roofs blown off in storms, atomiser, two boats drawn together.
14. Steel is more elastic than rubber (higher Young's modulus). Plasma is the 4th state, Bose–Einstein condensate the 5th.

States of matter

solid, liquid, gas

plasma: 4th state

BEC: 5th state

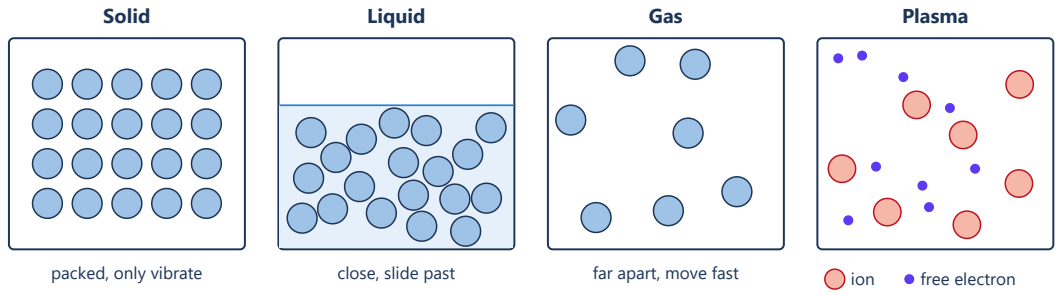
S.N. Bose

sublimation

Matter takes different states depending on how tightly its particles are held and how much energy they have. Squeeze out the energy and particles lock into a solid; add enough and they fly apart into a gas; add still more and atoms lose electrons to form plasma. Cool some atoms to almost absolute zero and they merge into one quantum blob.

Five states of matter ★★

State	Shape and volume	Particles	Examples
Solid	Fixed shape, fixed volume	Tightly packed, only vibrate	Ice, iron, wood
Liquid	Takes the container's shape, fixed volume	Close but free to slide	Water, mercury, oil
Gas	Fills the whole container	Far apart, move fast	Air, steam, LPG vapour
Plasma (4th state)	No fixed shape; conducts electricity	Ionised gas: free electrons and ions	Sun and stars, lightning, neon signs, auroras
Bose–Einstein condensate (5th state)	Atoms behave as one big quantum particle	Atoms cooled to a fraction of a degree above absolute zero	First made in 1995 from rubidium atoms



Particles in four states of matter (schematic): packed and only vibrating in a solid, close but free to slide in a liquid, far apart in a gas, and split into ions and free electrons in a plasma.

★★ **Plasma** is the **fourth state**; most of the visible matter in the universe (stars) is plasma.

★★★ **Bose–Einstein condensate (BEC)**, the **fifth state**, was predicted in 1924–25 by **Satyendra Nath Bose** and **Albert Einstein**; first created in 1995 by Eric Cornell and Carl Wieman (Nobel Prize 2001 with Wolfgang Ketterle).

★ Particles named **bosons** honour S.N. Bose; the Higgs boson is one of them.

★★ **Sublimation**: solid turns straight into gas, e.g. camphor, naphthalene balls, dry ice (solid CO_2). The reverse (gas to solid) is **deposition**.

Remember it: Heat climbs the ladder **S-L-G-P**: Solid → Liquid → Gas → Plasma. BEC sits below the bottom rung, colder than any solid.

Quick check

1. The fifth state of matter, and the Indian scientist linked to it?
2. Matter in the Sun and in lightning is in which state?
3. Camphor turning straight into vapour is called?

Answer: 1. Bose–Einstein condensate; Satyendra Nath Bose · 2. plasma, the fourth state · 3. sublimation

Elasticity: stress, strain and Young's modulus

elastic vs plastic

Hooke's law

stress ∝ strain

Young's modulus

steel > rubber

Pull a spring and it stretches; let go and it snaps back. This ability to regain shape is **elasticity**. In physics, a material is **more elastic** if it needs a **larger force** to deform it by the same amount, so steel beats rubber, even though rubber stretches more easily.

★★ **Elasticity**: the property of a body to regain its original shape and size once the deforming force is removed. **Plasticity**: it stays deformed (putty, wet clay, chewing gum).

★★ **Stress** = restoring force per unit area (unit N/m^2 = Pa). **Strain** = change in size ÷ original size (no unit).

★★★ **Hooke's law** (Robert Hooke, 17th century): within the **elastic limit**, **stress is proportional to strain**. A **spring balance** works on this law.

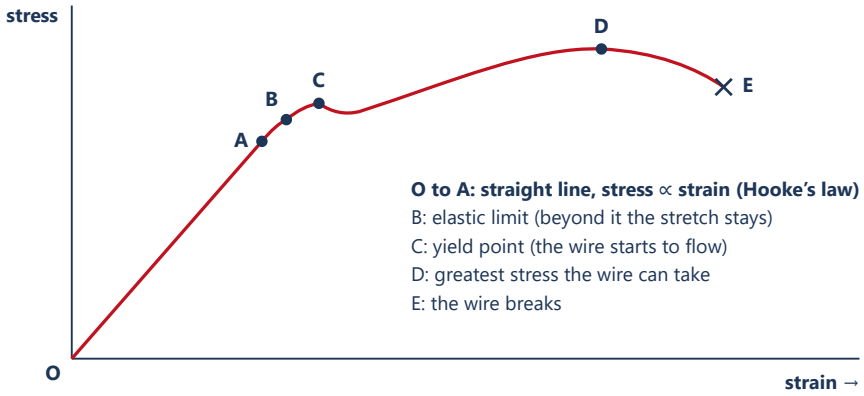
★★★ **Young's modulus** Y = longitudinal stress ÷ longitudinal strain; unit pascal. **Steel (~200 GPa) is far more elastic than rubber** (a few MPa).

★★ Other moduli: **bulk modulus** (change of volume; the only one for liquids and gases) and **shear modulus / modulus of rigidity** (change of shape; only for solids).

★ **Quartz fibre** is close to perfectly elastic; **putty** is close to perfectly plastic.

★ **Elastic fatigue**: repeated loading weakens a material over time, so old bridges are declared unsafe after years of service.

★ Beyond the elastic limit a wire stays permanently stretched; at the **breaking stress** it snaps. Steel is used in buildings and bridges because of its high Young's modulus and breaking stress.



Stress–strain graph for a metal wire (shape only, not to scale). Hooke's law holds on the straight part O to A; beyond the elastic limit B the wire stays stretched, and at E it breaks.

⚠ **Exam trap: Steel is more elastic than rubber.** Everyday language calls rubber elastic because it stretches easily, but physics measures elasticity by how strongly a body resists and recovers: steel needs much more stress for the same strain.

☑ Quick check

1. Which is more elastic, steel or rubber, and why?
2. State Hooke's law.
3. Which everyday instrument works on Hooke's law?

Answer: 1. steel: it needs far more stress for the same strain (higher Young's modulus) · 2. within the elastic limit, stress ∝ strain · 3. the spring balance

Pressure in solids and liquids

P = F/A

pascal = N/m²

wide area, low pressure

P = hρg

thick dam base

The same force can pierce or be harmless, depending on the area it is spread over. A sharp needle concentrates force on a tiny area; a wide strap spreads it out. In a liquid, pressure comes from the weight of liquid above, so it grows the deeper you go.

★★★ **Pressure** = force ÷ area (P = F/A); a scalar. SI unit **pascal (Pa) = N/m²**.

★★ Other units: **1 bar = 10^5 Pa**; **1 atmosphere ≈ 1.013 × 10^5 Pa = 760 mm (76 cm) of mercury**; 1 torr = 1 mm of mercury. Blood pressure is quoted in mm of mercury.

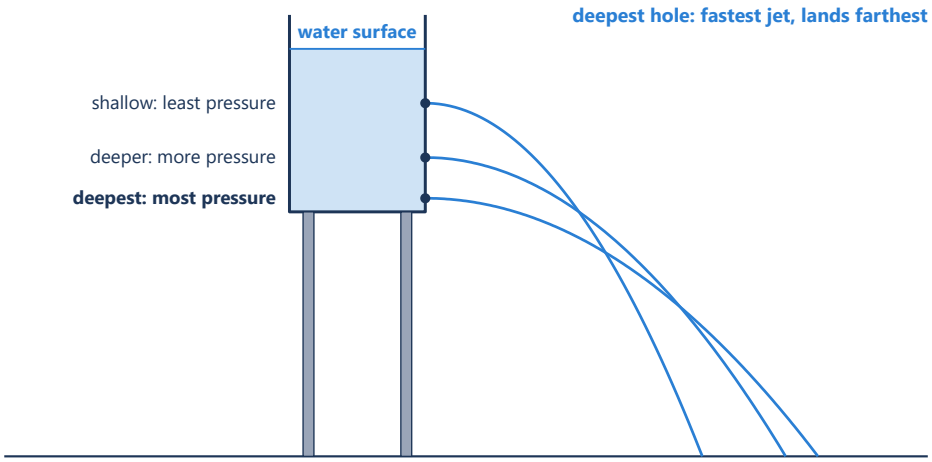
★★ **Smaller area, bigger pressure**: sharp knives and needles, pointed nails, a thin wire cutting cheese.

★★★ **Larger area, smaller pressure**: wide straps on school bags, **camel's broad feet** on sand, tractors and tanks on wide crawler tracks, wide foundations for buildings, sleepers under railway lines, snow shoes.

★★★ **Liquid pressure** P = **hρg** (depth × density × g); it increases with depth, acts **equally in all directions**, and does not depend on the shape of the vessel.

★★★ **Dam walls are made thicker at the bottom** because water pressure is greatest at the greatest depth.

★★ Deep-sea divers need pressure suits; water tanks are placed on rooftops so that height gives pressure in the taps; water spurts out fastest from the lowest hole in a can.



Liquid pressure grows with depth (P = hρg), so the deepest hole gives the fastest jet. Jets drawn with Torricelli's speed v = √(2gh); with the can raised on a stand, the deepest jet also lands farthest.

⚠ **Exam trap:** The SI unit of pressure is **N/m² (pascal)**, not N·m (that is torque or work) and not N/m (that is surface tension).

Quick check

1. SI unit of pressure?
2. Why are dam walls made thicker at the bottom?
3. Why can a camel walk easily on sand?

Answer: 1. the pascal (N/m²) · 2. liquid pressure grows with depth (P = hρg) · 3. broad feet: a larger area means a smaller pressure

Atmospheric pressure

1 atm = 76 cm of mercury

straw, syringe

pen leaks in a plane

barometer

sharp fall: storm

We live at the bottom of an ocean of air about 100 km deep. Its weight presses on every square metre with about 1 lakh newtons, but we do not notice because the fluids inside our body push back equally. When the outside push changes, as in a plane or on a mountain, we feel it.

★★★ **Normal atmospheric pressure** at sea level ≈ **1.013×10^5 Pa** = 76 cm of mercury = a water column about **10.3 m** high. It **falls with altitude**.

★★★ **Drinking straw, syringe, dropper, suction hook**: you lower the pressure inside, and the **outside air pressure pushes** the liquid in or the hook against the wall.

★★ **Nose bleeding at high altitude**: outside pressure is low while blood pressure stays the same, so tiny vessels in the nose can burst.

★★★ **Fountain pen leaks in an aeroplane**: cabin pressure is lower than the air trapped in the ink tube, so the trapped air expands and pushes ink out.

★★ Sealed chips packets **puff up** on hill roads and flights; ears pop on take-off; water boils below 100 °C in the hills, making cooking slow.

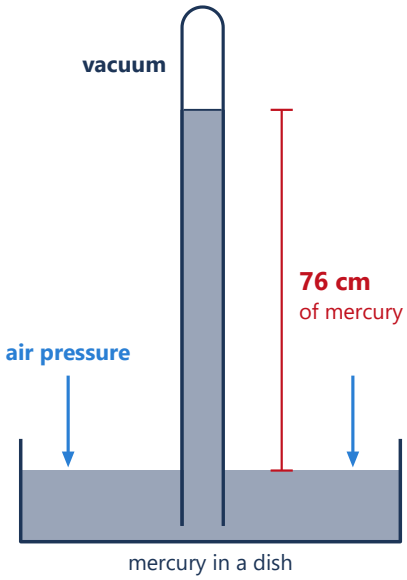
★ A suction pump cannot raise water more than about **10 m**, because atmospheric pressure can hold up only that much water.

★ **Otto von Guericke's Magdeburg hemispheres** (1654): two teams of horses could not pull apart two hemispheres from which air had been pumped out.

Otto von Guericke's Magdeburg hemispheres (1654), as engraved in his 1672 book: once the air between the two hemispheres was pumped out, teams of horses could not pull them apart. Air pressure outside held them together. Image: Gaspar Schott, Wikimedia Commons, public domain

★★ **Barometer** measures atmospheric pressure. **Evangelista Torricelli** invented the mercury barometer in 1643; mercury is used because it is very dense (a 76 cm column instead of 10.3 m of water), barely evaporates and does not wet glass.

★★ An **aneroid barometer** has no liquid; an **altimeter** in aircraft is an aneroid barometer marked in heights.



Torricelli's mercury barometer, drawn to scale: air pressing on the open dish holds up a 76 cm column of mercury, with vacuum above it. The same pressure would hold up about 10.3 m of water.

Barometer readings and the weather ★★★

Barometer reading	Likely weather
Sudden, sharp fall	Storm, cyclone or thunderstorm coming
Gradual fall	Rain likely (moist air is lighter than dry air)
Gradual rise	Fair, dry weather
Steady	No change in weather

Remember it: Barometer falls, weather falls apart: a sharp drop warns of a storm, a slow drop of rain, a rise of clear skies.

⚠ **Exam trap:** A straw works by **atmospheric pressure**, not capillarity. If there were no capillarity you could still drink through a straw, but wicks, blotting paper and the rise of sap in plants would fail.

Quick check

1. A drinking straw works because of _____ , not capillarity.
2. Why does a fountain pen leak in an aeroplane?
3. A barometer reading falls suddenly and sharply. What does it warn of?

Answer: 1. atmospheric pressure · 2. cabin pressure is lower, so air trapped in the pen expands and pushes ink out · 3. a storm

Pascal's law and hydraulic machines

Pascal's law

undiminished, all directions

Liquids hardly compress, so a push on one part of a trapped liquid is felt everywhere at once. Press a small piston and the same pressure arrives under a large piston, where it

$F_2 = F_1 \times A_2/A_1$

hydraulic brakes

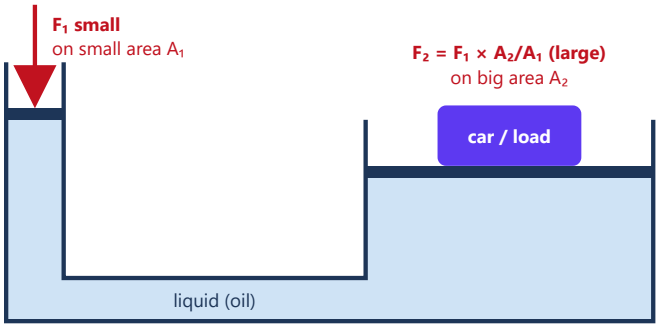
work not multiplied

acts on a bigger area and gives a bigger force. The price: the small piston must move a long way.

★★★ **Pascal's law** (Blaise Pascal): pressure applied to an **enclosed liquid** is transmitted **undiminished in all directions**.

★★★ In a hydraulic machine $F_1/A_1 = F_2/A_2$, so $\mathbf{F_2 = F_1 \times (A_2/A_1)}$: a small force on a small piston lifts a heavy load on a large piston. Force is multiplied; **work is not** (the large piston moves a shorter distance).

★★★ Applications: **hydraulic lift** (car service stations), **hydraulic brakes** (one pedal sends equal pressure to all four wheels), **hydraulic press** (Bramah press, for baling cotton and pressing metal), hydraulic jack, JCB excavator arms, dentist's and barber's chairs.



Pascal's law: the pressure F_1/A_1 reaches every part of the liquid undiminished.
Big piston gets the same pressure on a bigger area, so a bigger force; it moves a shorter distance.

Hydraulic lift: the same pressure acts on both pistons, so the big piston gets a force as many times larger as its area.

Remember it: Pascal passes pressure perfectly: the four Ps. Push a little on a little piston, lift a lot on a large one.

Quick check

1. State Pascal's law.
2. Name three machines that work on Pascal's law.
3. A hydraulic lift multiplies force. Does it multiply work?

Answer: 1. pressure on an enclosed liquid is passed on undiminished in all directions · 2. hydraulic lift, hydraulic brakes, hydraulic press · 3. no: the big piston moves a shorter distance

Buoyancy, Archimedes' principle and floating

Archimedes' principle

law of flotation

ice melts: level same

iceberg: 9/10 under

Water pushes harder on the bottom of a submerged body than on its top, because the bottom is deeper. That net upward push is the **buoyant force (upthrust)**, and Archimedes found it equals the weight of the liquid the body pushes aside. If the body is lighter than that, it floats.

★★★ **Archimedes' principle**: a body wholly or partly immersed in a fluid feels an **upward buoyant force equal to the weight of fluid it displaces**; it seems to lose that much weight.

river → sea: rises

★★★ **Law of flotation**: a body floats when its weight equals the weight of liquid it displaces. A body **less dense than the liquid floats**, a denser one sinks.

★★ The **fraction of a floating body under the liquid** = its density ÷ the liquid's density.

★★ **Density** = mass ÷ volume, SI unit **kg/m³**. **Relative density** = density of a substance ÷ density of water at 4 °C; it has **no unit**.

★★ An **iron ship floats** while an iron nail sinks: the hollow hull displaces a large volume of water, enough to equal the ship's weight.

★★ A bucket of water feels light while it is still under water in a well and heavy once it comes out.

Densities to remember (approximate, room temperature) ★★

Substance	Density (kg/m³)	Relative density
Air (sea level)	1.2	0.0012
Cork	about 240	0.24
Ice	917	0.92
Pure water (4 °C)	1000	1.00
Sea water	about 1025	1.025
Iron	about 7,870	7.9
Mercury	13,600	13.6
Gold	about 19,300	19.3
Osmium (densest element)	about 22,590	22.6

★★ **Iron floats on mercury** but sinks in water. **Lithium** (0.53 g/cm³) is the lightest metal and floats on water.

★★★ **Ice floating in a glass full to the brim**: when it melts the water **level does not change** and nothing spills, because floating ice already displaced exactly its own weight of water.

★★★ **Icebergs**: ice (917 kg/m³) in sea water (about 1025 kg/m³) floats with **about 9/10 below the surface**, hence the tip of the iceberg.

★★★ A **ship floats higher in the sea than in a river**: denser sea water needs less volume displaced. A ship sailing from a river into the sea **rises a little**. Ships carry a **load line (Plimsoll line)** showing safe loading in different waters.

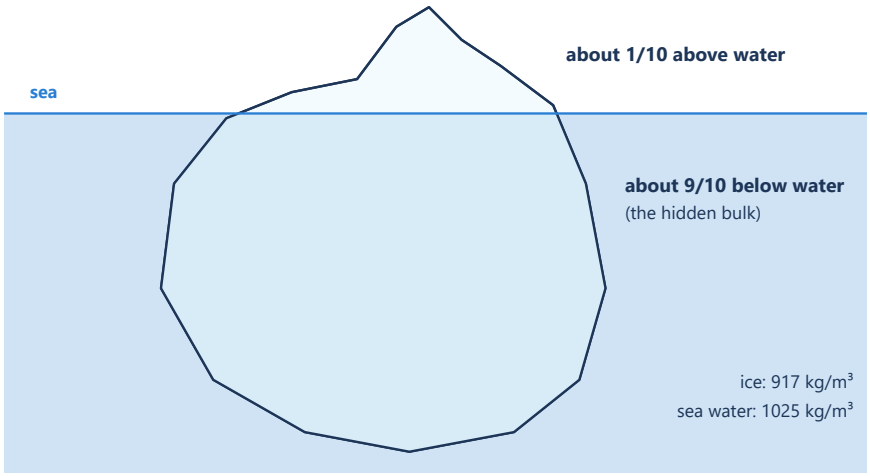
★★ An **egg sinks in fresh water but floats in strong salt water**; people float easily in the very salty **Dead Sea**.

★★ **Submarine**: fills its **ballast tanks with water** to become heavier and dive; blows the water out with **compressed air** to become lighter and rise.

★★ **Hot-air balloon**: heated air inside is less dense than the cool air outside, so the weight of cool air displaced exceeds the balloon's weight and it rises. Balloons filled with helium or hydrogen rise the same way.

★ **Lactometer** checks milk purity by its density; **hydrometer** measures the relative density of liquids (battery acid, alcohol); both float deeper in lighter liquids.

★ Fish adjust depth with an air-filled **swim bladder**; a life jacket's air raises the wearer's buoyancy.



Iceberg drawn exactly to the density ratio: ice (917 kg/m³) floating in sea water (1025 kg/m³) has 917/1025 ≈ 89.5% of its bulk below the waterline (shape drawn as a slab of uniform thickness).

Remember it: Archimedes jumped from his bath shouting **Eureka!** when the water rose: the body pushes aside its own volume, and the water pushes back up with the weight of that much water.

⚠ Exam trap: Melting ice in a full glass of water does **not** overflow and does **not** lower the level. (Ice melting in very salty water raises the level slightly, because fresh meltwater is lighter than brine.) A stone thrown out of a boat into a pond makes the pond level **fall** slightly.

Quick check

1. The buoyant force on a body equals _____ .
2. Ice floating in a glass full to the brim melts. What happens to the level?
3. A ship sails from a river into the sea. Does it rise or sink a little?

Answer: 1. the weight of fluid it displaces · 2. no change; nothing spills · 3. it rises: sea water is denser

Surface tension

stretched skin

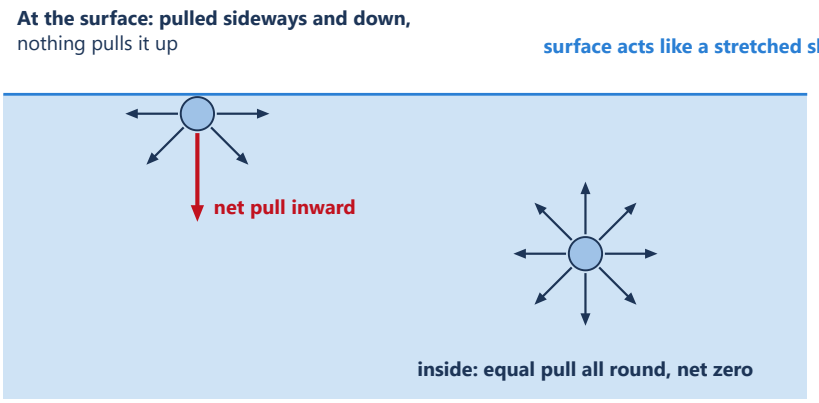
unit: N/m

spherical drops

heat, soap lower it

kerosene and larvae

A molecule inside a liquid is tugged equally from all sides, but a surface molecule is pulled only inward and sideways. So the surface behaves like a **stretched elastic skin** that tries to shrink to the smallest area. Since a sphere has the least surface for a given volume, free drops become round.



Why a liquid surface acts like a stretched skin: a molecule inside is pulled equally on all sides, but a molecule at the surface has no liquid above it, so the pulls add up to a net pull inward.

★★★ **Surface tension**: force per unit length on the liquid surface; unit **N/m** (also J/m²). Water ≈ 0.072 N/m at 25 °C; mercury is much higher (about 0.48 N/m).

★★★ **Raindrops, mercury drops and soap bubbles are spherical** because surface tension minimises area.

★★ **Rising temperature lowers surface tension**: hot water and hot soapy water clean better; hot soup spreads over the tongue and tastes better.

★★ **Soaps and detergents lower surface tension**, letting water spread into fabric fibres and lift away grease.

★★★ **Kerosene or oil on stagnant water** lowers its surface tension; **mosquito larvae**, which hang from the surface film to breathe, can no longer hold on, sink and drown.

★★ **Oil calms rough sea waves**: spread on the surface it lowers surface tension and damps the small ripples that waves build on.

★★ Insects such as **water striders walk on water**; a dry needle or razor blade laid gently floats; both rest on the surface skin.

★★ Hairs of a paintbrush spread out in water but **cling together** when lifted out; **antiseptics** like Dettol have low surface tension so they spread into cuts.

★ Dissolving **common salt slightly raises** the surface tension of water; soap, detergent and alcohol lower it.

A water strider standing on a stream. Its feet press small dimples into the surface without breaking it (the dark rings on the bed are their shadows): surface tension holds it up. Image: Tim McCormack, Wikimedia Commons, CC BY-SA 3.0

Remember it: Surface tension drops with **H-S-D: Heat, Soap, Detergent** (add oil and kerosene too). Remember the mosquito larvae: a spoon of kerosene breaks their floor.

Exam trap: Oil spreads on water because the surface tension of oil is **lower** than that of water. Kerosene kills larvae by lowering surface tension (they drown), not by poisoning the water.

Quick check

1. Why are raindrops spherical?
2. How does kerosene on a pond kill mosquito larvae?
3. SI unit of surface tension?

Answer: 1. surface tension shrinks the surface, and a sphere has the least area · 2. it lowers surface tension; the larvae cannot hang from the surface and drown · 3. N/m

Cohesion, adhesion and capillarity

cohesion vs adhesion

water: concave, rises

mercury: convex, falls

narrow tube, higher rise

hoeing saves moisture

Molecules of the same substance attract each other (**cohesion**); molecules of different substances attract too (**adhesion**). If a liquid likes the glass more than itself, it climbs the walls and creeps up a thin tube. If it likes itself more, it pulls away and sinks in the tube.

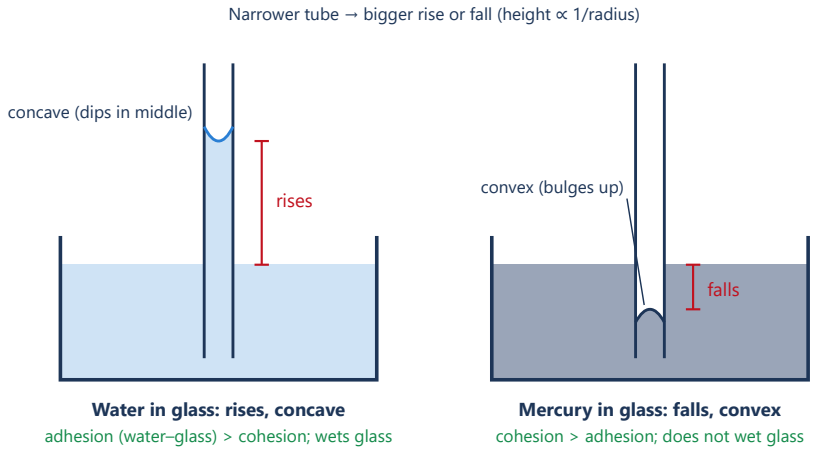
★★ **Cohesion**: attraction between like molecules (water–water). **Adhesion**: attraction between unlike molecules (water–glass).

★★★ **Water in glass**: adhesion > cohesion, so water **wets glass**, forms a **concave meniscus** (angle of contact near 0°, acute) and **rises** in a capillary tube.

★★★ **Mercury in glass**: cohesion > adhesion, so mercury **does not wet glass**, forms a **convex meniscus** (angle of contact about 140°, obtuse) and is **depressed** in a capillary.

★★ Read a water level at the **bottom** of the meniscus and a mercury level at the **top**.

★★★ **Capillarity**: rise or fall of a liquid in a narrow tube or fine pores, due to surface tension. The **narrower the tube, the higher the rise** ($h = 2T \cos\theta / r\rho g$; height $\propto$ 1/radius).



Water wets glass, curves concave and climbs the capillary; mercury does not wet glass, curves convex and is pushed down.

Capillarity at work ★★★

Example	What happens
Wick of a kerosene lamp or diya	Oil climbs the fine gaps between cotton threads to the flame
Blotting paper, towels, sponge, tissue	Ink or water is drawn into fine pores
Rise of water in plants	Water climbs fine xylem vessels (with help from transpiration pull); tall trees depend on it
Sugar cube or chalk in tea	Liquid seeps upward through pores
Damp walls	Ground water rises through brick pores; a damp-proof course blocks it
Soil moisture	Water rises to the surface through fine soil channels and evaporates

★★★ **Hoeing or ploughing** the topsoil **breaks the fine capillaries**, so ground water cannot rise to the surface and evaporate; the soil **retains moisture**. **Rolling** (pressing) the soil does the opposite and brings water up.

Remember it: Water is a hugger (loves glass, climbs up, curves like a smile from above, concave). **Mercury is a loner** (avoids glass, sinks down, bulges like a dome, convex).

⚠ **Exam trap:** Without capillarity a kerosene lamp, blotting paper and tall trees would fail, but **drinking through a straw** would still work, because it depends on atmospheric pressure.

Quick check

1. Water in a glass capillary: what is the meniscus shape, and does it rise or fall?
2. Mercury in a glass capillary: meniscus shape and level?
3. Why does hoeing the topsoil keep a field moist?

Answer: 1. concave; it rises · 2. convex; it falls · 3. it breaks the capillaries, so water cannot rise to the surface and evaporate

Viscosity, Stokes' law and terminal velocity

resistance to flow

honey > blood > water

heat: liquid ↓, gas ↑

terminal velocity

parachute

Pour honey and water side by side: honey creeps, water rushes. Each layer of a flowing fluid drags on its neighbour, like cards in a deck resisting being slid. That internal friction is **viscosity**. Heating loosens a liquid's molecules, but in a gas heating makes molecules collide more and drag harder.

★★★ **Viscosity**: a fluid's internal friction, its **resistance to flow** between layers. SI unit of the coefficient of viscosity: **pascal-second (Pa·s)**; CGS unit **poise** (1 Pa·s = 10 poise).

★★★ Order of viscosity: **honey > glycerine > blood > water > air**. Blood is about 3–4 times as viscous as water.

★★★ **Temperature**: heating **lowers the viscosity of liquids** (warm honey and engine oil flow easily) but **raises the viscosity of gases**.

★ Heavy machines use thick (high-viscosity) oils as lubricants; an ideal fluid would have zero viscosity, and liquid helium near absolute zero (a **superfluid**) actually flows with none.

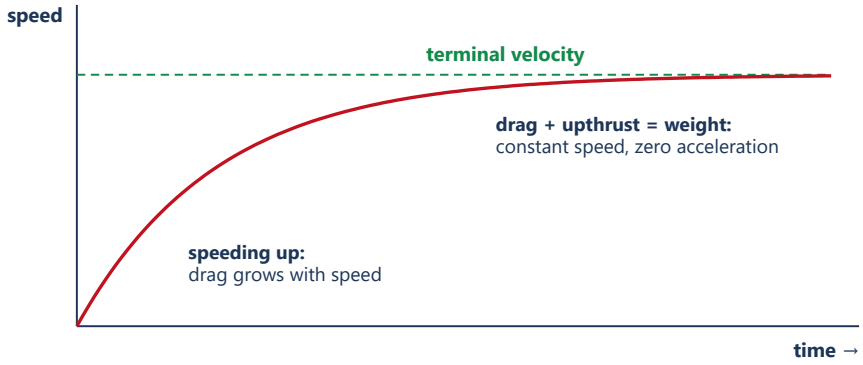
★★ **Stokes' law** (George Stokes, 1851): drag on a small sphere moving slowly through a fluid, $F = 6\pi\eta rv$, grows with viscosity η, radius r and speed v.

★★★ **Terminal velocity**: a falling body speeds up until drag plus buoyancy equals its weight; then net force is zero and it falls at a **constant speed**.

★★★ **Raindrops** reach terminal velocity of only a few metres per second, so they do not hurt; **bigger drops fall faster** (for small drops, terminal velocity $\propto r^2$). Tiny cloud droplets fall so slowly that clouds seem to float.

★★ A **parachute** has a large area that increases air drag and lowers terminal velocity to a safe landing speed of about 5 m/s, against about 55 m/s for a skydiver without one.

★ **Millikan's oil-drop experiment** used Stokes' law to measure the charge of the electron.



Speed of a falling raindrop against time: it speeds up until drag plus upthrust equals its weight, then falls at a constant terminal velocity (curve drawn for drag ∝ speed, as in Stokes' law).

★★ **Equation of continuity**: in a steady flow, area × speed stays constant, so liquid **speeds up where a pipe narrows**: pressing the mouth of a hose sends water farther; a river flows fastest where it is narrow and shallow.

★ **Streamline flow** is smooth and layered at low speed; above a critical speed it turns into chaotic **turbulent flow** (judged by the Reynolds number).

Remember it: Hot honey hurries, hot air hesitates: heat makes liquids runnier and gases stickier.

⚠ **Exam trap:** Heating lowers the viscosity of **liquids** only; for **gases** it rises. And terminal velocity means **zero acceleration**, not zero velocity.

Quick check

1. Heat a liquid and heat a gas: what happens to the viscosity of each?
2. What is terminal velocity?
3. Arrange honey, water and blood by viscosity, highest first.

Answer: 1. liquid: falls; gas: rises · 2. the constant speed reached when drag plus upthrust equals the weight: zero acceleration · 3. honey > blood > water

Bernoulli's principle

faster flow, lower pressure

aeroplane lift

roof blown off

atomiser

boats pulled together

A moving fluid has a fixed energy budget, shared between pressure and motion. Where it is forced to move faster, its pressure must drop. Daniel Bernoulli stated this in 1738, and it explains why planes fly and storms rip off roofs.

★★★ **Bernoulli's principle**: for steady flow of an ideal fluid, pressure energy + kinetic energy + potential energy per unit volume stays constant, so **where speed increases, pressure decreases**. It is conservation of energy applied to fluids.

★★★ **Aeroplane lift**: the wing (aerofoil) is shaped and tilted so that air flows **faster over the top**; pressure above falls below that underneath, pushing the wing up.

★★★ **Roofs blown off in storms**: fast wind over a roof lowers the pressure above it while still air inside pushes up; light tin roofs lift off.

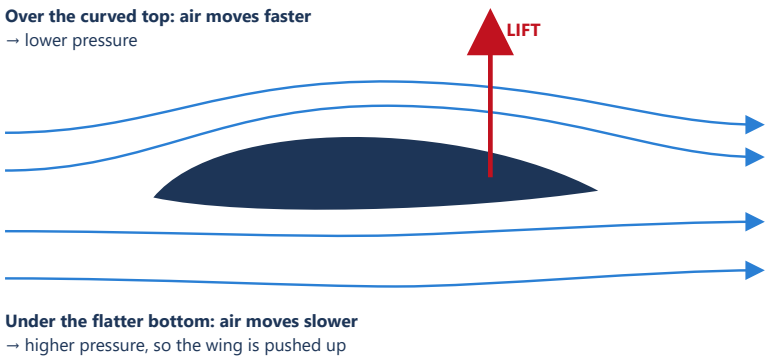
★★★ **Atomiser, perfume spray, insecticide pump (Flit gun), paint spray gun, carburettor**: a fast air jet over a tube lowers pressure there, drawing the liquid up and breaking it into a fine spray.

★★ **Two boats (or ships) moving side by side** are pulled together: water between them flows faster and its pressure drops.

★★ Standing close to a fast train is dangerous: fast-moving air between you and the train lowers the pressure, and the air behind you pushes you towards it.

★★ An umbrella turns inside out in a strong wind; dust and paper are lifted by a gust; a ping-pong ball stays balanced in a jet of air.

★ A **spinning ball curves** (a spinner's drift in cricket, a bending free kick in football) because spin makes air flow faster on one side: the **Magnus effect**. A **Venturi meter** measures flow rate from the pressure drop in a narrow throat.



Aeroplane wing: faster air above means lower pressure above, so the higher pressure below lifts the wing.

Remember it: Fast air, low pressure: think of a fast-talking salesman: lots of speed, little pressure left to argue. Speed up, pressure down.

⚠ **Exam trap:** In a storm the roof is lifted by **low pressure above**, not by high pressure from the wind pushing down. Fast flow means **lower** pressure, the opposite of what intuition suggests.

Quick check

1. Bernoulli's principle in one line?
2. Why is a roof blown off in a storm?
3. Which principle makes a perfume atomiser spray?

Answer: 1. where a fluid flows faster, its pressure is lower · 2. fast wind lowers the pressure above it; the higher pressure inside pushes it up · 3. Bernoulli's principle

Asked in past papers (4)

UPSC 2012 Consider the following statements :
If there were no phenomenon of capillarity
1. it would be difficult to use a kerosene lamp
2. one would not be able to use a straw to consume a soft drink
3. the blotting paper would fail to function
4. the big trees that we see around would not have grown on the Earth
Which of the statements given above are correct?
(a) 1, 2 and 3 only (b) 1, 3 and 4 only (c) 2 and 4 only (d) 1, 2, 3 and 4
Answer: (b) 1, 3 and 4 only. Capillarity is the rise of liquid in narrow tubes due to surface tension; Drinking through a straw works by atmospheric pressure, not capillarity

BPSC 64th What is the unit of pressure?
(a) Newton/sq. meter (b) Newton-meter (c) Newton (d) Newton/meter
(e) None of the above/More than one of the above
Answer: (a) Newton/sq. meter. Pressure is force per unit area; its SI unit is the pascal (N/m^2)

BPSC 66th The highest viscosity among the following is of
(a) water (b) air (c) blood (d) honey (e) None of the above/More than one of the above
Answer: (d) honey. Viscosity is a fluid's internal resistance to flow; Honey is far more viscous than blood, and blood more than water

BPSC 67th A piece of ice is floating in a beaker containing water up to its brim. When whole of the ice melts
(a) the water will spill on the floor (b) the level of water will come down in the beaker
(c) the level of water will first fall and then it will spill out of the beaker (d) the water level will not change
(e) None of the above/More than one of the above
Answer: (d) the water level will not change. Floating ice displaces its own weight of water, so its melting leaves the level unchanged

Test yourself (12)

1. Why does a fountain pen tend to leak when carried in an aeroplane?
(a) Ink becomes much less viscous at a great height (b) Air pressure in the cabin is lower than in the pen
(c) Gravity is weaker at height (d) Surface tension of the ink rises sharply at height

2. A ship moves from a river into the sea. It will
(a) sink a little lower (b) rise a little (c) stay at the same level (d) first rise and then sink

3. The hydraulic brakes of a car work on
(a) Archimedes' principle (b) Bernoulli's principle (c) Pascal's law (d) Hooke's law

4. Which of the following is due to atmospheric pressure and not capillarity?
(a) Oil rising in a lamp wick (b) Ink absorbed by blotting paper (c) Drawing a cold drink through a straw
(d) Water rising through the thin xylem vessels of a tree

5. When the temperature of a gas is increased, its viscosity
(a) increases (b) decreases (c) first decreases, then increases (d) does not change at all

6. Pouring kerosene on stagnant water controls mosquitoes because it
(a) poisons the water for all insects and fish (b) raises the water's temperature
(c) lowers the surface tension of water (d) raises the viscosity of water

7. Which statement about Young's modulus is correct?
(a) Rubber has a higher value than steel (b) It has no unit (c) It equals strain divided by stress
(d) Steel has a higher value than rubber

8. The roof of a house is blown off in a storm because
(a) fast wind lowers the pressure above it (b) the wind pushes the roof down very hard
(c) rain makes the roof heavy (d) air inside the house is heated

9. Mercury in a glass capillary tube shows
(a) a concave meniscus and rises (b) a convex meniscus and falls (c) a flat surface and stays level
(d) a concave meniscus and falls

10. Consider the following statements:
1. Heating lowers the viscosity of a liquid but raises that of a gas.
2. Soaps and detergents raise the surface tension of water.
3. Mercury is depressed in a glass capillary tube.
Which of the statements given above is/are correct?
(a) 1 only (b) 1 and 3 only (c) 2 and 3 only (d) 1, 2 and 3

11. Consider the following:
1. Lift on an aeroplane wing
2. A perfume atomiser drawing liquid up into a spray
3. A car's hydraulic brakes
How many of the above are explained by Bernoulli's principle?
(a) Only one (b) Only two (c) All three (d) None

12. In a kitchen experiment, an egg sinks in a glass of tap water but floats after a lot of salt is stirred in. Why?
(a) Salt raises the surface tension, and the surface film holds the egg up
(b) Salt makes the water viscous enough to stop the egg sinking
(c) Salt water is denser, so the egg displaces a greater weight of it
(d) Salt draws water out of the egg and makes it lighter

Answers: 1. (b) Trapped air in the pen expands against the lower cabin pressure and pushes ink out. · 2. (b) Sea water is denser, so less volume needs to be displaced to support the ship's weight. · 3. (c) Pedal pressure is passed undiminished through brake fluid to all wheels. · 4. (c) Sucking lowers pressure inside the straw; outside air pressure pushes the drink up. · 5. (a) Faster gas molecules transfer more momentum between layers; for liquids viscosity falls. · 6. (c) Larvae hang from the surface film; with lower surface tension they cannot stay up. · 7. (d) Steel needs far more stress for the same strain, so it is more elastic. · 8. (a) By Bernoulli's principle faster air means lower pressure; the higher pressure inside lifts the roof. · 9. (b) Cohesion exceeds adhesion, so mercury does not wet glass. · 10. (b) Statements 1 and 3 are right; soaps and detergents lower surface tension, which is how they spread into fabric and lift grease. · 11. (b) Lift and the atomiser rely on faster flow giving lower pressure; hydraulic brakes work on Pascal's law. · 12. (c) Buoyant force equals the weight of liquid displaced, so denser brine gives more upthrust on the same volume; surface tension cannot hold up a submerged egg.

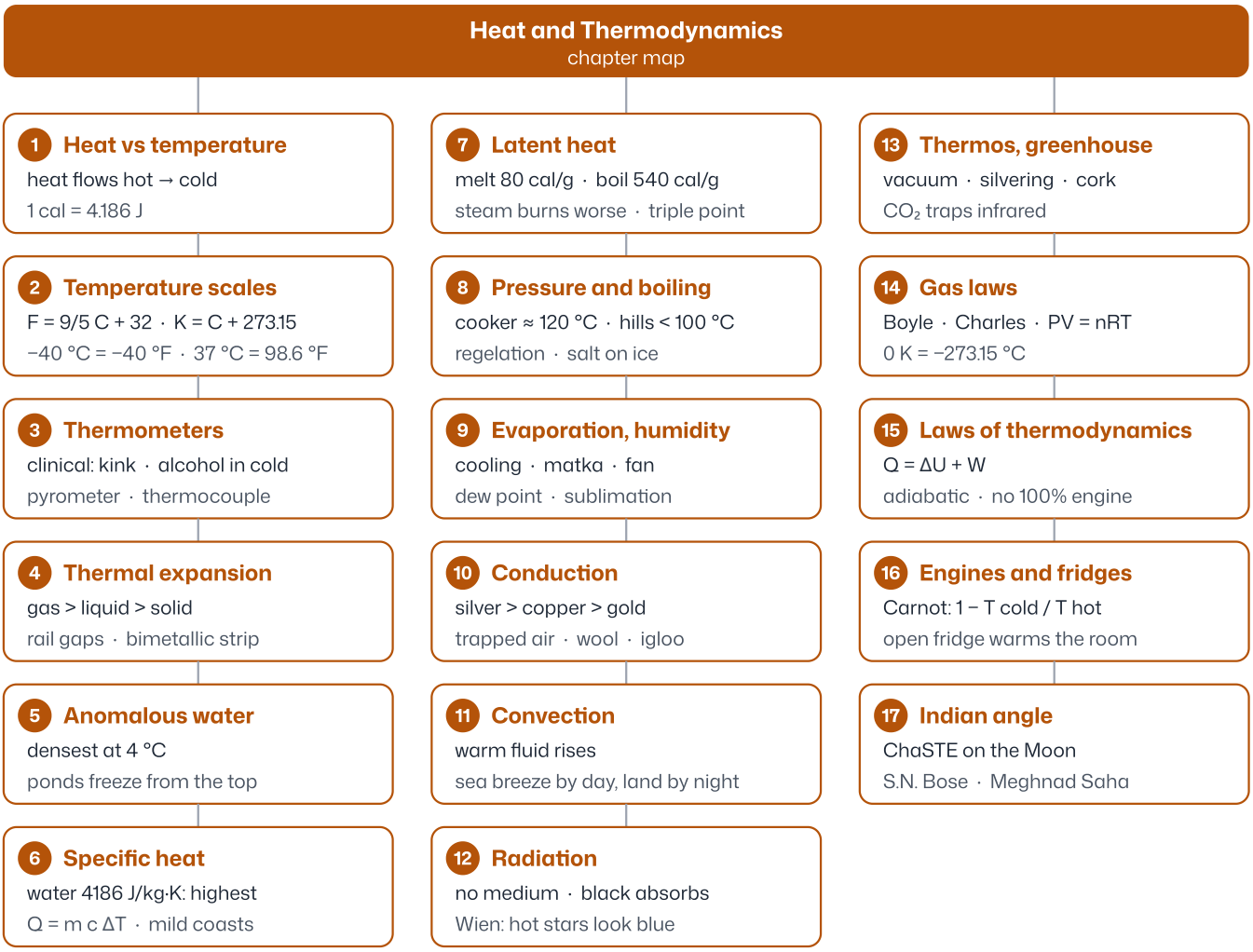
CHAPTER 6

Heat and Thermodynamics

Scale conversion, latent heat, anomalous expansion of water, boiling point and pressure, evaporative cooling and the three modes of heat transfer are asked almost every year; refrigerators and the laws of thermodynamics follow close behind.

Asked 11 times in past papers: UPSC 2 · BPSC 9

≈ 1 h 03 min to read ≈ 8 min to revise ★★★ Revise on: Day 1 | Day 3 | Day 7 | Day 21



Revision card

1. °F = 9/5 × °C + 32; K = °C + 273.15. 40 °C = 104 °F, 50 °C = 122 °F, 100 °C = 212 °F; −40 °C = −40 °F.
2. Body temperature 37 °C = 98.6 °F = 310 K. Absolute zero = 0 K = −273.15 °C.
3. Water is densest at 4 °C: ponds freeze from the top, fish survive in the 4 °C water below; pipes burst because water expands about 9% on freezing.
4. Water has the highest specific heat of common substances (4186 J/kg·K): coastal climates are mild, sea breeze by day, land breeze by night.
5. Latent heat of vaporisation of water 2260 kJ/kg (540 cal/g), of fusion of ice 334 kJ/kg (80 cal/g): steam burns worse than boiling water or air at 100 °C.
6. More pressure → higher boiling point (pressure cooker ~120 °C, set by the whistle's weight and vent area); less pressure in hills → water boils below 100 °C.
7. Pressure lowers the melting point of ice (regelation, skating); impurities lower the melting point (salt on icy roads) and raise the boiling point.
8. Evaporation causes cooling and is faster with heat, wind, large surface and dry air: matka, sweating, fan comfort, desert cooler.
9. Conduction (solids), convection (fluids), radiation (no medium, fastest). Silver and copper conduct best; mercury is a poor conductor among metals.
10. Thermos flask: vacuum stops conduction and convection, silvering stops radiation. Good absorbers are good emitters.
11. Triple point of water: 273.16 K (0.01 °C), where ice, water and vapour coexist.
12. A refrigerator with its door open warms the room: it dumps the heat it pulls out plus its motor's work. No heat engine is 100% efficient (second law).

Heat and temperature

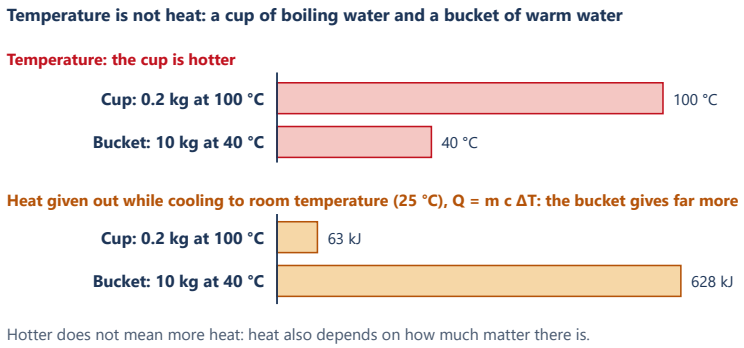
heat vs temperature

hot → cold

1 cal = 4.186 J

internal energy

Molecules are always jiggling. **Temperature** tells how fast, on average, they jiggle: it measures the **average kinetic energy** of the molecules. **Heat** is energy that flows from a hotter body to a colder one because of a temperature difference. A bucket of warm water holds more heat than a cup of boiling water, but the cup is at the higher temperature.



Temperature and heat drawn to scale. The cup is hotter (100 °C against 40 °C), but in cooling to a 25 °C room the bucket gives out ten times as much heat (628 kJ against 63 kJ), because Q = m c ΔT depends on mass too.

Heat vs temperature ★★★

	Heat	Temperature
What it is	Energy in transit due to a temperature difference	Degree of hotness; average kinetic energy of molecules
Depends on mass?	Yes (more water, more heat)	No
SI unit	joule (J)	kelvin (K), an SI base unit
Other units	calorie; 1 cal = 4.186 J; food Calorie = 1 kcal	°C, °F
Measured by	Calorimeter	Thermometer

★★★ **Direction of flow**: heat flows from **higher temperature to lower temperature**, never by itself from 'more heat' to 'less heat'. It stops when both reach the same temperature (thermal equilibrium).

★★ **Internal energy**: total kinetic and potential energy of all molecules of a body. Heating raises it.

★★ **Calorie**: heat needed to raise 1 g of water by 1 °C. **1 cal = 4.186 J** (Joule's mechanical equivalent of heat, J ≈ 4.2 J/cal).

★ **Effects of heat**: change in temperature, change of state, expansion, and changes in properties such as electrical resistance (used in resistance thermometers).

⚠ **Exam trap:** 'Heat and temperature are the same thing' is false. Two bodies at the same temperature can hold very different amounts of heat. A spark from a sparkler is at over 1000 °C but carries so little heat that it does not burn the hand.

Quick check

1. Temperature measures the _____ of the molecules.
2. Heat flows by itself from where to where?
3. 1 calorie = how many joules?

Answer: 1. average kinetic energy · 2. from higher to lower temperature · 3. 4.186 J

Temperature scales and conversion

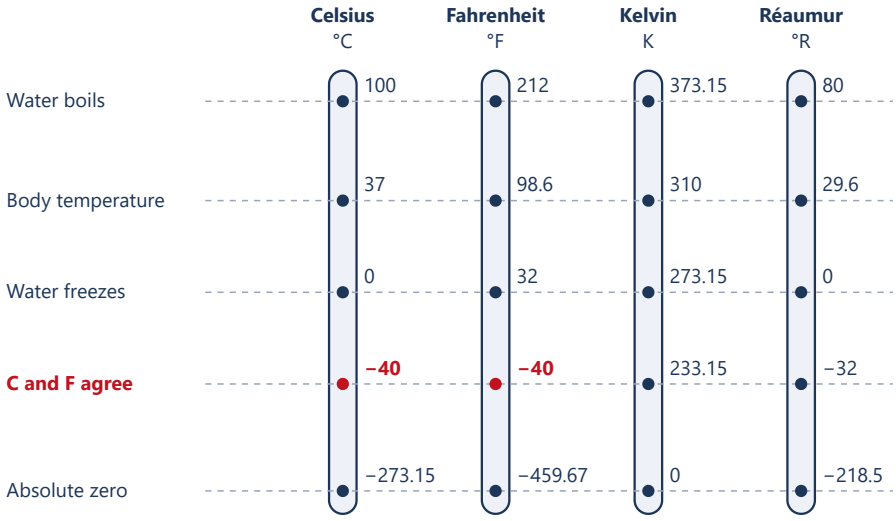
F = 9/5 C + 32

K = C + 273.15

−40 crossover

37 °C = 98.6 °F

Every scale fixes two reference points, the melting of ice and the boiling of water at normal pressure, and divides the gap into equal steps. Celsius uses 100 steps, Fahrenheit 180, Réaumur 80. So converting is just comparing the fraction of the way between ice and steam.



C/5 = (F − 32)/9 = (K − 273.15)/5 = R/4

Not to scale. Kelvin is written without the degree sign.

Same temperatures on four scales. Notice the single crossing point of Celsius and Fahrenheit at −40, and that Kelvin starts at absolute zero. Spacing not to scale.

Fixed points of the scales ★★★

Scale (inventor)	Ice point	Steam point	Steps between
Celsius °C (Anders Celsius, Sweden)	0	100	100
Fahrenheit °F (D.G. Fahrenheit, German-Dutch)	32	212	180
Kelvin K (Lord Kelvin, William Thomson)	273.15	373.15	100
Réaumur °R (R.A.F. de Réaumur, France)	0	80	80

★★★ **Master formula**: C/5 = (F − 32)/9 = (K − 273.15)/5 = R/4.

★★★ **Celsius → Fahrenheit**: F = (9/5) × C + 32. So **40 °C = 104 °F**, **50 °C = 122 °F**, 30 °C = 86 °F, 100 °C = 212 °F.

★★★ **Fahrenheit → Celsius**: C = (F − 32) × 5/9. So 212 °F = 100 °C, 68 °F = 20 °C.

★★★ **−40** is the only temperature where **Celsius and Fahrenheit read the same**.

★★★ **Normal body temperature ≈ 37 °C = 98.6 °F = 310 K**.

★★ **Kelvin = Celsius + 273.15**. A change of 1 °C equals a change of 1 K; a change of 1 °C equals 1.8 °F.

★★ **Kelvin is written without the degree sign** (300 K, not 300 °K). It is the SI unit of temperature; since 2019 it is defined by fixing the Boltzmann constant (k = 1.380649 × 10^{-23} J/K).

★ **Kelvin and Fahrenheit** read the same number at about **574.6**.

Remember it: 'Double it, take off a tenth, add 32': 40 °C → 80 → 72 → 104 °F. And remember the 'room-temperature pair': 20 °C = 68 °F, 25 °C = 77 °F.

⚠ **Exam trap:** Distractors such as 100 °F or 102 °F for 40 °C, and 75 °F for 50 °C, are close enough to tempt a guess. Work it out: multiply by 9/5 first, then add 32 (40 → 72 → 104 °F; 50 → 90 → 122 °F).

Quick check

1. 40 °C on the Fahrenheit scale?
2. At what temperature do Celsius and Fahrenheit read the same?
3. Normal body temperature in kelvin?

Answer: 1. 104 °F (40 × 9/5 + 32) · 2. −40 · 3. 310 K (37 °C)

Thermometers

clinical: kink

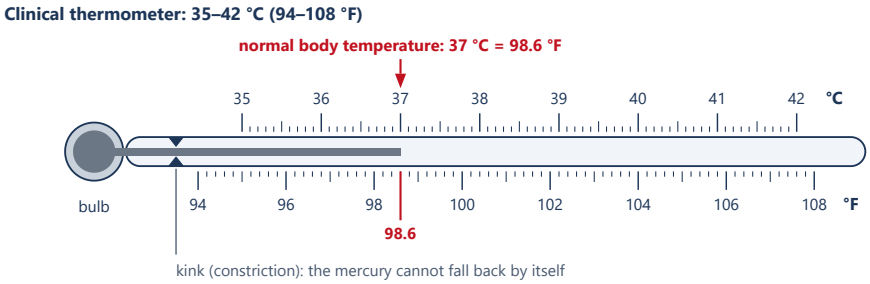
mercury freezes −39 °C

alcohol in cold

pyrometer

thermocouple

A thermometer uses some property that changes steadily with temperature: the length of a liquid column, electrical resistance, a voltage between two metals, or the colour and brightness of emitted light. The choice depends on how hot or cold the thing is.



Clinical thermometer, its two scales drawn exactly against each other: 37 °C sits at 98.6 °F. The kink near the bulb stops the mercury from falling back, so the reading stays until the thermometer is shaken down.

Which thermometer for which job ★★★

Thermometer	Works on	Range / use
Clinical	Mercury column with a kink (constriction) that stops it falling back	35–42 °C (94–108 °F); body temperature
Laboratory	Mercury column, no kink	About −10 to 110 °C
Mercury	Expansion of mercury	About −39 °C (mercury freezes) to 357 °C (it boils)
Alcohol	Expansion of coloured alcohol	Very cold places: alcohol freezes only at about −114 °C (Ladakh, Siachen, polar regions)
Six's maximum–minimum	Alcohol and mercury with index markers	Records the day's highest and lowest temperature; weather stations
Digital / infrared	Thermistor, or infrared radiation from the body	Home use; non-contact forehead guns
Platinum resistance	Resistance of platinum rises with temperature	Very precise; from about −200 °C to several hundred °C
Thermocouple	Voltage at the junction of two different metals (Seebeck effect)	Furnaces, engines; up to about 1500 °C and more
Pyrometer	Radiation emitted by the hot body; no contact	Very high temperatures: furnaces, molten metal, the Sun's surface
Constant-volume gas thermometer	Pressure of a gas at fixed volume	Standard for calibrating others

★★ **Why mercury**: it is opaque and shiny (easy to read), does not wet glass, expands uniformly, conducts heat better than other liquids (so it responds quickly) and stays liquid over a wide range.

★★ **Why alcohol in cold regions**: mercury freezes at −39 °C; alcohol stays liquid down to about −114 °C.

★★★ **Pyrometer** measures very high temperatures from a distance using the radiation a hot body gives out.

★ **Mercury thermometers** are being phased out under the **Minamata Convention on Mercury**, which India ratified in 2018; digital thermometers replace them.

★ Never wash a clinical thermometer in hot water: its range ends at about 42 °C, and the glass can crack.

Remember it: 'Pyro' means fire: pyrometer for fire-hot things. 'Clinical' means clinic: the kink keeps the reading until the doctor sees it.

Quick check

1. What stops the mercury of a clinical thermometer from falling back?
2. Why alcohol, not mercury, in Siachen?
3. Which thermometer reads a furnace's temperature from a distance?

Answer: 1. the kink (constriction) near the bulb · 2. mercury freezes at −39 °C; alcohol only at about −114 °C · 3. pyrometer (from its radiation)

Thermal expansion

gas > liquid > solid

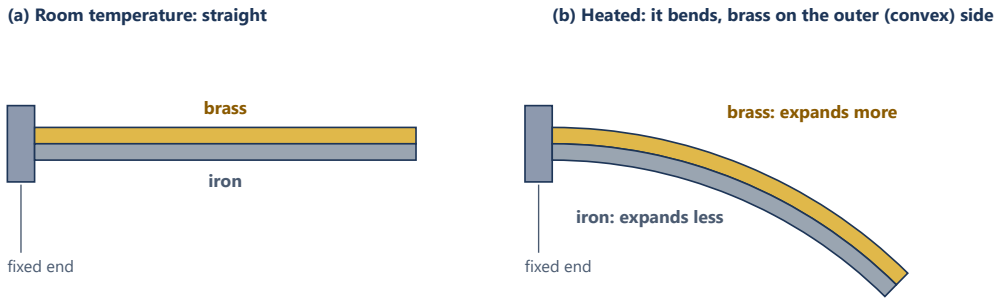
rail gaps

sagging wires

bimetallic strip

Invar

Heated molecules vibrate harder and push each other further apart, so almost everything expands on heating. Gases expand the most, liquids less, and solids the least. Engineers leave room for this; where they do not, things buckle, crack or sag.



A brass–iron bimetallic strip. Brass expands more, so on heating the strip bends with brass on the outer (convex) side; this bending opens or closes the contact of a thermostat. Bending exaggerated.

★★ **Order of expansion**: **gases > liquids > solids** for the same rise in temperature.

★ **Three coefficients** for a solid: linear (α), area (β = 2α) and volume (γ = 3α).

★★★ **Railway tracks** have small gaps (expansion joints) so that the rails can lengthen in summer without buckling.

★★ **Bridges** rest on rollers at one end, and concrete roads have gaps filled with tar, to allow expansion.

★★★ **Telephone and power wires sag in summer** (they lengthen) and become taut in winter; they are strung loose for this reason.

★★★ **Bimetallic strip**: two metals with different expansion (brass and iron) riveted together. On heating it bends, with the more-expanding brass on the outer (convex) side. It switches the **thermostat** in electric irons, geysers, refrigerators, ACs and fire alarms.

★★ **Thick glass cracks with hot water**: the inner surface expands before the outer surface heats up. Thin glass and borosilicate (Pyrex) glass, which expands very little, survive.

★★ **Tight metal lid** of a glass jar opens after dipping it in hot water: metal expands more than glass.

★★ **Iron rim of a bullock-cart wheel** is heated before fitting; on cooling it shrinks and grips tight. Hot rivets tighten the same way.

★★ **Pendulum clock loses time in summer**: the pendulum lengthens, so each swing takes longer. **Invar** (iron-nickel alloy) barely expands and is used for pendulums and measuring tapes.

★★ **Tyres burst in summer** and sealed aerosol cans explode in fire: heated gas expands and its pressure rises.

See it around you: A thermostat in an electric iron: as the plate heats up, the bimetallic strip bends away from a contact and cuts the current; as it cools, it straightens and switches the heater on again.

Quick check

1. A heated brass–iron strip bends. Which metal is on the outer (convex) side?
2. Why does a pendulum clock lose time in summer?
3. Why are small gaps left between rails?

Answer: 1. brass: it expands more · 2. the pendulum lengthens, so each swing takes longer · 3. so they can lengthen in summer without buckling

Anomalous expansion of water

densest at 4 °C

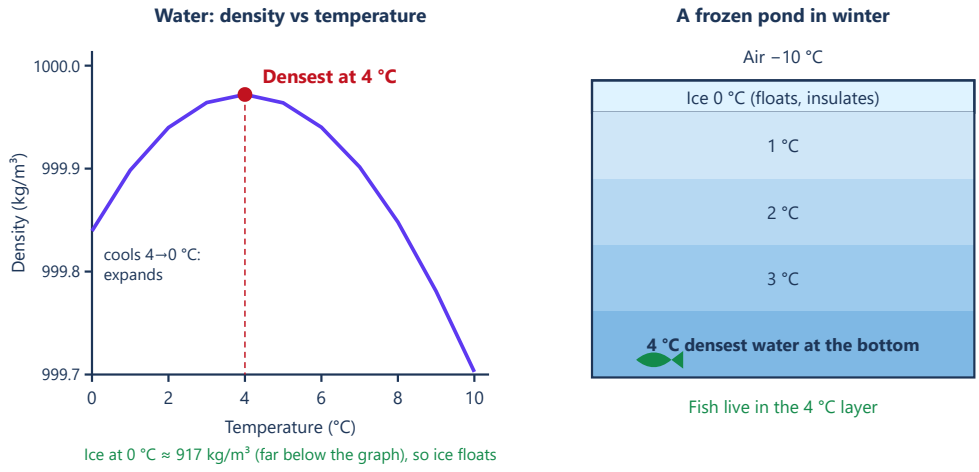
freezes from the top

ice floats

9% expansion

burst pipes

Water breaks the rule. Cooled from room temperature it contracts, but only down to **4 °C**. Below 4 °C it starts to **expand** again, and on freezing it expands by about **9%**. The reason is that water molecules begin locking into an open, hexagonal pattern held by hydrogen bonds, which takes up more room.



Water is densest at 4 °C. In a frozen pond the 4 °C water sinks and stays at the bottom, so ice forms only on top.

★★★ **Maximum density of water at 4 °C** (about 1000 kg/m³). Between 4 °C and 0 °C water expands as it cools.

★★★ **Ponds and lakes freeze from the top down**: water cooled to 4 °C is densest and sinks; colder water stays on top and freezes. Water at the bottom stays liquid at about 4 °C, so **fish and plants survive**.

★★ The **ice layer is a poor conductor**, so once formed it slows further freezing of the water below.

★★★ **Ice floats**: ice (about 917 kg/m³) is less dense than water; about nine-tenths of an iceberg is under water.

★★ **Water pipes burst** in severe winter and glass bottles crack in a freezer, because water expands on freezing.

★★ **Frost weathering**: water freezing in rock cracks widens them and breaks the rock.

⚠ **Exam trap:** Why does the bottom of a frozen lake stay liquid? The main answer is 'water is densest at 4 °C'. 'Ice is a bad conductor' is true and helps, but it is not the root reason the examiner wants.

Remember it: 'Four is the floor': the 4 °C water always settles on the lake's floor.

Quick check

1. At what temperature is water densest?
2. Why do fish survive in a frozen lake?
3. Water expands by about how much on freezing?

Answer: 1. 4 °C · 2. the densest water, at 4 °C, stays at the bottom and does not freeze · 3. about 9%

Specific heat capacity

Q = m c ΔT

water: 4186 J/kg·K

mild coasts

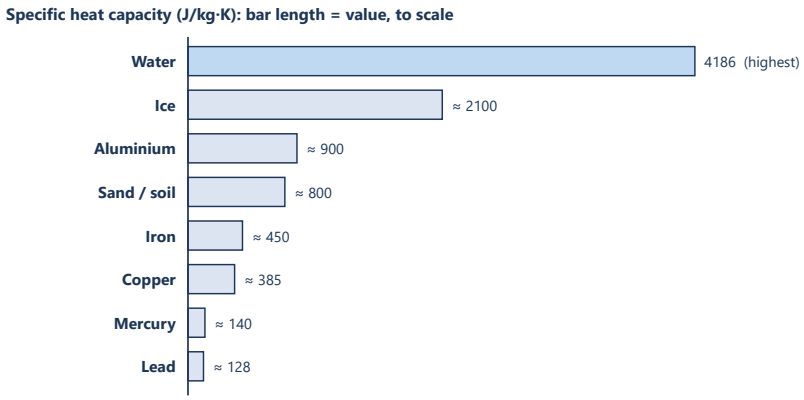
coolant

sand heats fast

Some substances need a lot of heat to warm up; others warm up at once. **Specific heat capacity** (c) is the heat needed to raise **1 kg by 1 K**. Heat taken in: **Q = m c ΔT**. Water's value is unusually large, so water warms slowly, cools slowly and stores a lot of heat.

Specific heat capacity (approx., J/kg·K) ★★

Substance	c	Note
Water	4186	Highest of common substances (1 cal/g·°C)
Ice	≈ 2100	About half of water
Aluminium	≈ 900	High for a metal
Sand / soil	≈ 800	Land heats and cools fast
Iron	≈ 450	Little energy per degree: warms quickly
Copper	≈ 385	Little energy per degree: warms quickly
Mercury	≈ 140	Low: responds quickly in a thermometer
Lead	≈ 128	Among the lowest



Specific heat capacities drawn to scale. Water needs about five times as much heat as sand to warm by the same amount, which is why the sea warms and cools so slowly.

★★★ **Water has the highest specific heat** of common substances, about **4186 J/kg·K**.

★★★ **Coastal climate is mild** (Mumbai, Chennai) while inland places (Delhi, Rajasthan) swing between extremes: the sea warms and cools slowly.

★★ **Water as coolant** in car radiators and power plants: it carries away much heat for a small rise in temperature.

★★ **Hot-water bag**: water gives out heat slowly over a long time.

★★ **Heat capacity** of a whole body = m × c (unit J/K); specific heat is per kilogram.

★ **Farmers flood fields** on frosty nights: the water releases stored heat and protects crops from frost.

See it around you: On a summer afternoon at the beach the sand burns your feet while the sea water feels cool. Both got the same sunshine; sand's low specific heat lets it heat up far more.

Quick check

1. Which common substance has the highest specific heat?
2. Why is Mumbai's climate milder than Delhi's?
3. Heat taken in by a body: Q = ?

Answer: 1. water, about 4186 J/kg·K · 2. the sea warms and cools slowly (high specific heat of water) · 3. m c ΔT

Change of state and latent heat

latent heat

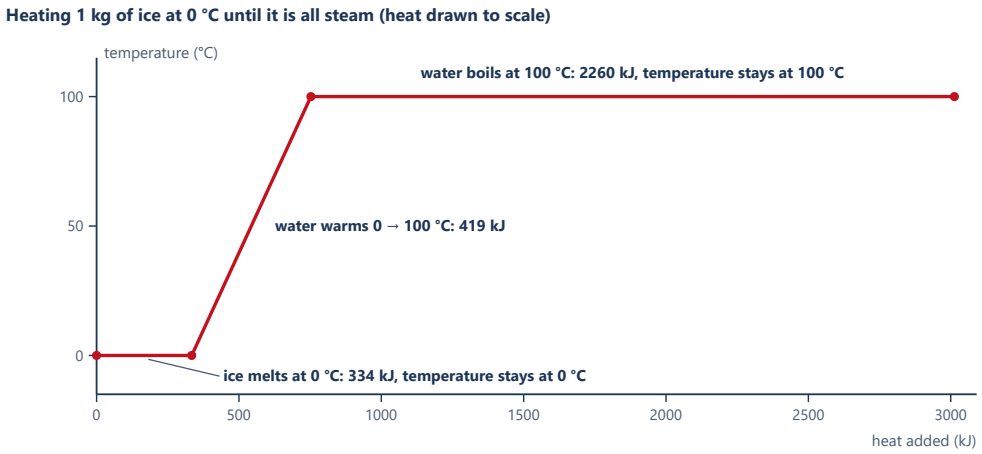
melt: 80 cal/g

boil: 540 cal/g

steam burns worse

triple point

While ice melts or water boils, the temperature stays fixed even though heat keeps going in. That 'hidden' heat breaks the bonds between molecules instead of speeding them up. It is called **latent heat**, and the same amount comes back out when the change reverses (water freezing, steam condensing).



Heating curve of 1 kg of ice, heat drawn to scale. On the two flat steps heat goes in but the temperature does not rise: 334 kJ to melt, then 2260 kJ to boil, almost seven times as much.

★★★ **Latent heat of fusion of ice** = **334 kJ/kg (80 cal/g)**: absorbed when ice at 0 °C becomes water at 0 °C.

★★★ **Latent heat of vaporisation of water** = **2260 kJ/kg (540 cal/g)**: absorbed when water at 100 °C becomes steam at 100 °C.

★★★ **Steam at 100 °C burns worse** than boiling water or hot air at 100 °C: on condensing on the skin it releases its large latent heat of vaporisation as well.

★★★ **Ice at 0 °C cools a drink better than water at 0 °C**: each kilogram of ice soaks up 334 kJ just to melt, before it even warms.

★★ **Temperature stays constant during melting and boiling**: a pot of boiling water stays at 100 °C however high the flame (at normal pressure).

★★ **Melting point** of ice = 0 °C and **boiling point** of water = 100 °C at 1 atmosphere.

★★★ **Triple point**: the one temperature and pressure where solid, liquid and gas coexist. For water: **273.16 K (0.01 °C) at about 611 Pa**.

★ **Critical temperature**: above it a gas cannot be liquefied by pressure alone.

Remember it: '80 to melt, 540 to boil': per gram of water, melting needs 80 cal and boiling needs 540 cal. Boiling is almost seven times as costly, which is why steam bites so hard.

⚠ **Exam trap:** Steam burns are worse because of its HIGH latent heat, not low. An option saying 'more dangerous due to low latent heat' mixes a right effect with a wrong reason.

Quick check

1. Latent heat of vaporisation of water in cal/g?
2. Why does steam at 100 °C burn worse than water at 100 °C?
3. Triple point of water?

Answer: 1. 540 cal/g (2260 kJ/kg) · 2. on condensing it also gives up its large latent heat · 3. 273.16 K (0.01 °C)

Boiling point, melting point and pressure

pressure ↑ → boiling point ↑

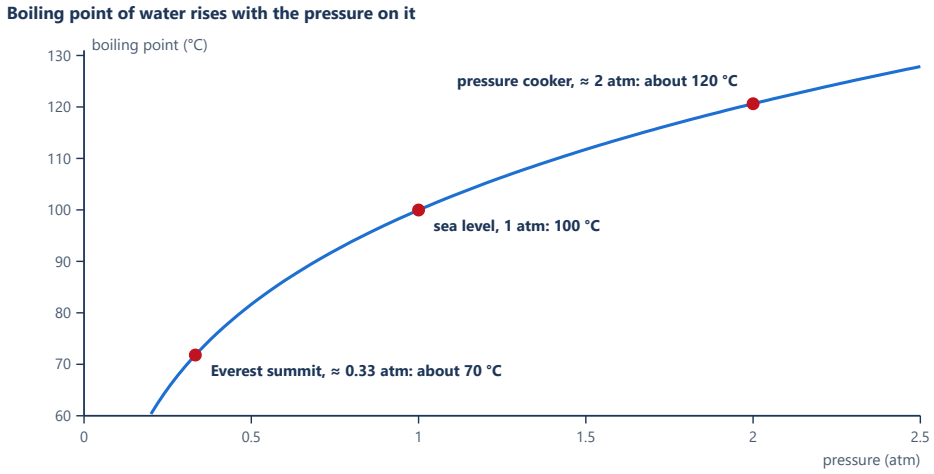
cooker ≈ 120 °C

hills: below 100 °C

regelation

salt on ice

A liquid boils when its vapour pressure equals the pressure pressing down on it. Squeeze harder (more pressure) and the liquid must get hotter before it can boil; lower the pressure and it boils sooner. Ice is special: pressure helps it melt, because water takes up less room than ice.



Boiling point of water against pressure, plotted from steam-table values. Lower the pressure and water boils well below 100 °C (hills, mountains); double it and water boils at about 120 °C (pressure cooker).

★★★ **More pressure → higher boiling point**. A **pressure cooker** raises the pressure to about 2 atmospheres, so water boils at about **120 °C** and food cooks faster.

★★★ **What sets the temperature in a cooker**: the steam pressure needed to lift the whistle, i.e. the **weight on the vent and the area of the vent hole** (pressure = weight ÷ area). A bigger flame only makes it whistle more often; it does not raise the temperature.

★★★ **Less pressure → lower boiling point**. In the hills water boils below 100 °C (about 1 °C lower for every 300 m or so; about 70 °C on top of Everest), so dal and rice cook slowly.

★★ **Pressure lowers the melting point of ice**. Under a wire or skate blade ice melts; when the pressure is removed the water refreezes. This is **regelation**.

★★ **Regelation examples**: a loaded wire passes through a block of ice and leaves it whole; snowballs stick when pressed; the thin water film under a skate blade helps it glide.

★★ **Substances that expand on melting** (wax, most solids) show the opposite: pressure raises their melting point.

★★★ **Impurities lower the melting point**: **salt is spread on icy roads** to melt snow; ice + salt forms a **freezing mixture** (down to about −20 °C) used to make kulfi and ice cream.

★★ **Impurities raise the boiling point**: salted water boils slightly above 100 °C.

★ **Antifreeze** (ethylene glycol) lowers the freezing point of radiator water in cold places.

Pressure and impurities at a glance ★★★

Change	Boiling point	Melting point of ice
Pressure increased	Rises (pressure cooker)	Falls (regelation)
Pressure decreased	Falls (hills, mountains)	Rises slightly
Impurity added (salt, sugar)	Rises	Falls (salt on roads)

⚠ **Exam trap:** 'Food cooks faster in a pressure cooker because water boils at a lower temperature' reverses the truth. Higher pressure means a HIGHER boiling point.

Quick check

1. Why does food cook faster in a pressure cooker?
2. What sets a cooker's temperature: the flame or the whistle?
3. Salt on an icy road raises or lowers the melting point?

Answer: 1. higher pressure raises the boiling point to about 120 °C · 2. the weight on the vent and the area of the vent hole · 3. lowers it

Evaporation, humidity and sublimation

evaporation cools

matka

fan and sweat

relative humidity

sublimation

In any liquid a few molecules move fast enough to escape from the surface. They carry away energy, so the molecules left behind are slower: the liquid cools. That is **evaporation**, and it happens at all temperatures, only from the surface. The heat it takes is the latent heat of vaporisation.

Evaporation vs boiling ★★

Evaporation	Boiling
At any temperature	Only at the boiling point
From the surface only	Throughout the liquid (bubbles)
Slow, silent	Fast, with bubbles
Causes cooling	Temperature stays constant while heat is supplied

★★★ **Evaporation causes cooling**: the escaping molecules take latent heat from the surface they leave.

★★★ **Evaporation is faster** with higher temperature, larger surface area, more wind and lower humidity; volatile liquids (spirit, acetone, petrol) evaporate fastest.

★★★ **A fan cools us** because moving air carries away the moist air near the skin and makes **sweat evaporate faster**. The fan does not cool the air.

★★★ **Matka (earthen pot)**: water seeps through tiny pores and evaporates from the outside, cooling the water inside. A wet cloth on a surahi works the same way.

★★ **Sweating** cools the body; **dogs pant** to evaporate water from the tongue because they have few sweat glands.

★★ **Spirit or perfume** on the palm feels cold; sprinkling water on a hot roof or courtyard cools it.

★★ **Desert cooler** cools well in dry heat but poorly in the humid monsoon, when evaporation slows. An AC also removes moisture from the air.

★★ **Relative humidity (RH)** = (water vapour actually present ÷ maximum the air can hold at that temperature) × 100. At 100% RH air is saturated and wet clothes do not dry.

★★ **Humid heat feels worse** than dry heat at the same temperature (Chennai vs Jaipur): sweat cannot evaporate.

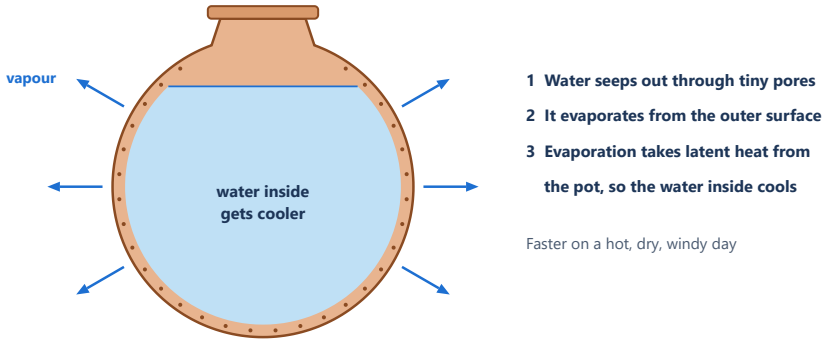
★★ **Hygrometer** measures humidity (wet-and-dry bulb hygrometer).

★★ **Dew point**: the temperature at which air becomes saturated on cooling. Below it, vapour condenses as dew, fog or mist; below 0 °C it forms frost.

★★ **Drops on a glass of iced water**: water vapour in the air cools below its dew point on the cold glass and condenses; the glass does not leak.

★★ **Sublimation**: solid turns straight into vapour without melting: **camphor, naphthalene balls, iodine, ammonium chloride, dry ice** (solid CO_2, at −78.5 °C). The reverse (vapour to solid, like frost) is **deposition**.

★ **Freeze-drying** (instant coffee) removes ice by sublimation under low pressure.



How a matka cools water. Water seeping through the pores evaporates from the outside, and the latent heat this needs is taken from the pot and the water inside. Not to scale.

See it around you: Clothes on a line dry fastest on a hot, windy, dry day in May, and slowest on a still, humid day in the monsoon.

Quick check

1. How does a fan cool us, though it does not cool the air?
2. Why does a desert cooler work poorly in the monsoon?
3. Camphor turns straight from solid into vapour. Name the process.

Answer: 1. it makes sweat evaporate faster · 2. humid air slows evaporation · 3. sublimation

Conduction

silver > copper

mercury: poorest metal

In **conduction**, heat passes from particle to particle without the material moving: a steel spoon in hot tea gets hot at the handle. Metals conduct best because their free electrons

trapped air

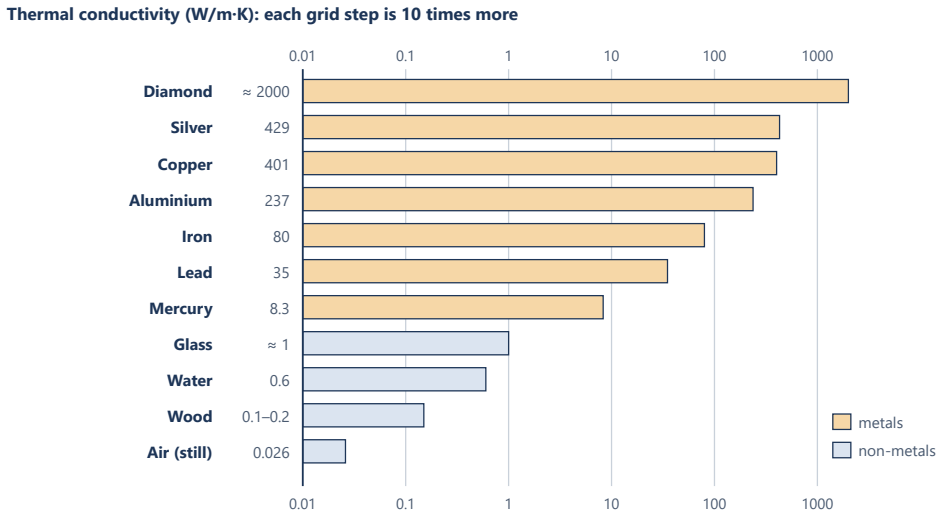
two thin blankets

metal feels colder

carry energy quickly. Trapped air is one of the poorest conductors, which is why so many insulators work by holding still air.

Thermal conductivity (approx., W/m·K, at room temperature) ★★★

Material	k	Remark
Diamond	≈ 2000	Best natural conductor of heat, though an electrical insulator
Silver	429	Best metal
Copper	401	Vessel bottoms, heat sinks
Gold	318	Third, after silver and copper
Aluminium	237	Cookware
Zinc	116	Coats iron (galvanising)
Iron	80	Tawa, kadhai
Lead	35	Poor for a metal
Mercury	8.3	Poorest conductor among common metals
Glass	≈ 1	Insulator
Water	0.6	Poor conductor
Wood	≈ 0.1–0.2	Handles
Air (still)	0.026	Excellent insulator



Thermal conductivity on a scale where each grid step is ten times the last. Metals lead by a wide margin, mercury is the poorest common metal, and still air conducts more than ten thousand times worse than copper.

★★★ **Best conductors**: **silver > copper > gold > aluminium**. **Mercury** is the poorest conductor of heat among common metals, worse than lead or zinc.

★★ **Copper-bottom vessels** spread heat fast and evenly; **handles are wood, plastic or Bakelite** (poor conductors).

★★★ **Woollen clothes keep us warm** because wool traps air, a very poor conductor; wool makes no heat of its own.

★★ **Two thin blankets are warmer than one thick blanket** of the same weight: a layer of air is trapped between them. A fluffed cotton razai warms better than a packed one.

★★ **Igloo**: packed snow holds trapped air and is a poor conductor, so body heat stays inside.

★★ **Ice wrapped in sawdust or jute** melts slowly; **double-glazed windows** with air between the panes cut heat flow; birds fluff their feathers in winter.

★★ **Metal feels colder than wood** at the same room temperature: metal conducts heat away from the hand faster.

⚠ **Exam trap:** Blankets and sweaters do not 'give heat'. They only stop the body's own heat from leaving. Similarly a metal chair is not colder than a wooden one in the same room; it only feels colder.

Quick check

1. Best metal conductor of heat?
2. Why do woollen clothes keep us warm?
3. Why does a metal chair feel colder than a wooden one in the same room?

Answer: 1. silver (then copper) · 2. wool traps air, a very poor conductor · 3. metal conducts heat away from the hand faster

Convection

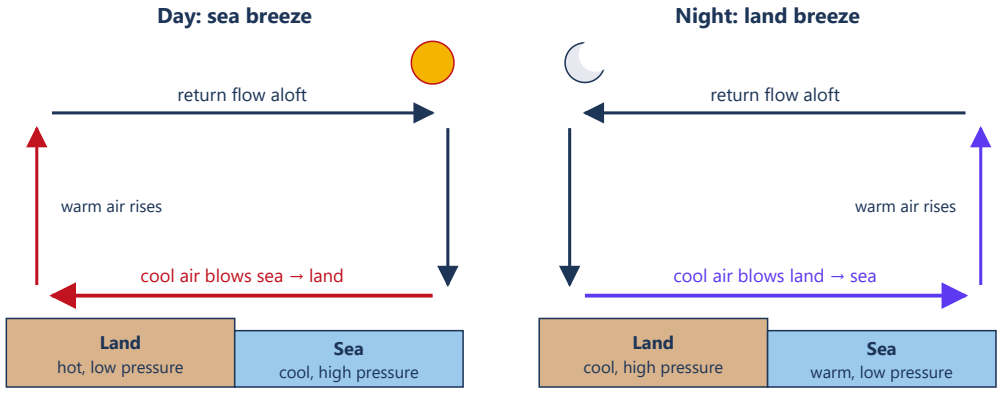
warm fluid rises

sea breeze: day

land breeze: night

ventilators high

In liquids and gases the warm part itself moves. Heated fluid expands, becomes lighter and rises; cooler, denser fluid sinks to take its place. This circulating flow is **convection**. It needs a fluid and gravity: in orbit, a candle flame is round and dim because hot gas does not rise.



Cause: land heats and cools fast (low specific heat); water changes temperature slowly

By day the land is hotter, air rises over it and sea air flows in (sea breeze). At night the pattern reverses (land breeze).

★★★ **Sea breeze (day)**: land heats faster than sea, air over land rises, cool air blows **from sea to land**.

★★★ **Land breeze (night)**: land cools faster, air over the warmer sea rises, air blows **from land to sea**.

★★ **Monsoon** is a sea breeze on the scale of a continent: summer heating of the Indian landmass draws in moist ocean air.

★★ **Ventilators sit near the ceiling** (hot stale air rises out); **AC units are fitted high** and room heaters low; the freezer is at the top of a refrigerator.

★★ **Water in a pot heats by convection currents**; chimneys draw smoke upward; ocean currents and winds carry heat round the Earth.

★ **Convection does not happen in solids** and is suppressed in weightless conditions.

Remember it: 'Sea by Sun, Land by Luna': the breeze comes from the sea in sunlight and from the land under the moon.

Quick check

1. By day, does the breeze blow from sea to land or from land to sea?
2. Why are ventilators placed near the ceiling?
3. Can convection happen in a solid?

Answer: 1. sea to land (sea breeze) · 2. hot, stale air rises and escapes · 3. no: it needs a fluid that can flow

Radiation

no medium needed

black absorbs and emits

Wien's law

Stefan: T^4

cloudy nights warmer

Every warm body gives off energy as electromagnetic waves, mostly **infrared** at everyday temperatures. This **radiation** needs no medium and travels at the speed of light, which is how the Sun's heat crosses about 15 crore km of empty space to reach Earth.

★★★ **Radiation needs no medium**; conduction and convection both need one.

★★ **Fastest mode** of heat transfer: it travels at 3×10^8 m/s.

★★★ **Good absorbers are good emitters** (Kirchhoff's law). Dull black surfaces absorb and emit best; white and shiny surfaces reflect.

★★★ **White clothes in summer** reflect sunlight; **dark clothes in winter** absorb it.

★★ **Bottoms of cooking pots are blackened** to absorb heat; a **solar cooker** is black inside with a glass lid and a mirror; 'cool roofs' are painted white.

★★ **Black body**: an ideal surface that absorbs all radiation falling on it and is also the best possible emitter. A small hole in a hollow box comes close; stars behave nearly like black bodies.

★★ **Newton's law of cooling**: rate of cooling ∝ temperature difference between the body and its surroundings (for small differences). Hot tea cools fast at first, then more slowly.

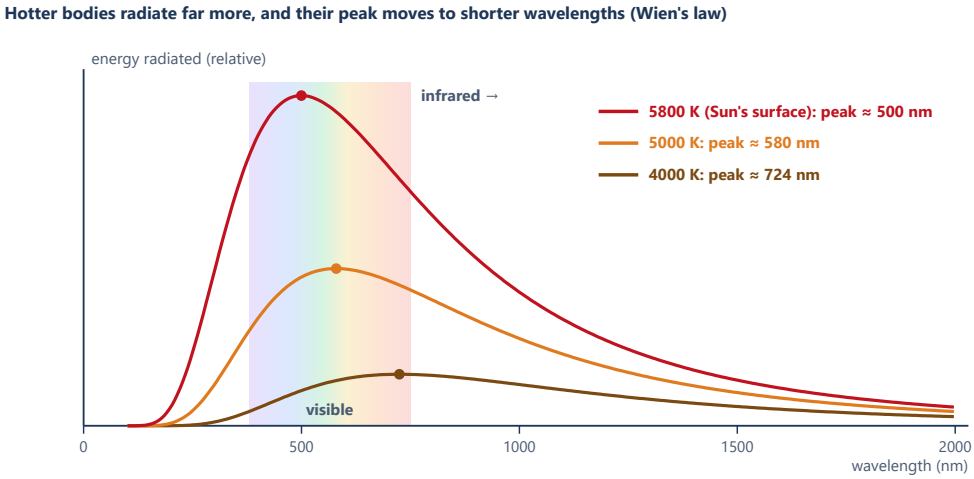
★★ **Stefan–Boltzmann law**: energy radiated per second per unit area ∝ $\mathbf{T^4}$ (absolute temperature). Double the kelvin temperature, sixteen times the radiation.

★★★ **Wien's law**: $\lambda_{max} \times T$ = constant ($\approx 2.9 \times 10^{-3}$ m·K). Hotter bodies glow at shorter wavelengths, so **hot stars look blue-white and cooler stars red**; heated iron glows red, then orange, then white.

★ **The Sun** (about 5800 K at the surface) radiates most strongly in visible light; **the Earth** (about 288 K) radiates in the infrared, around 10 μm.

★★★ **Cloudy nights are warmer than clear nights**: clouds absorb and send back the infrared the ground radiates. Dew and frost form on clear, calm nights.

★ **Meghnad Saha** (1920) linked a star's temperature to the ionisation of its gases (Saha ionisation equation), explaining why star spectra differ.



Radiation from bodies at three temperatures, computed from Planck's law. The hotter body gives out far more at every wavelength, and its peak moves to shorter wavelengths: the Sun (about 5800 K) peaks in visible light, while cooler bodies peak at longer, redder wavelengths, which is why cool stars look red.

Three modes compared ★★★

	Conduction	Convection	Radiation
Medium needed?	Yes	Yes (fluid)	No
Main in	Solids	Liquids and gases	Vacuum, any transparent medium
How	Particle to particle, no flow	Bulk movement of fluid	Electromagnetic (infrared) waves
Speed	Slow	Moderate	Fastest (speed of light)
Example	Spoon handle gets hot	Sea breeze, boiling water	Sun's heat, heat from a bonfire

Remember it: 'Conduction Touches, Convection Travels, Radiation Rays': touching particles, travelling fluid, rays across space.

Quick check

1. Which mode of heat transfer needs no medium?
2. One star looks blue-white, another red. Which is hotter?
3. Why are cloudy nights warmer than clear nights?

Answer: 1. radiation · 2. the blue-white one (Wien's law) · 3. clouds absorb the ground's infrared and send it back

Thermos flask and the greenhouse effect

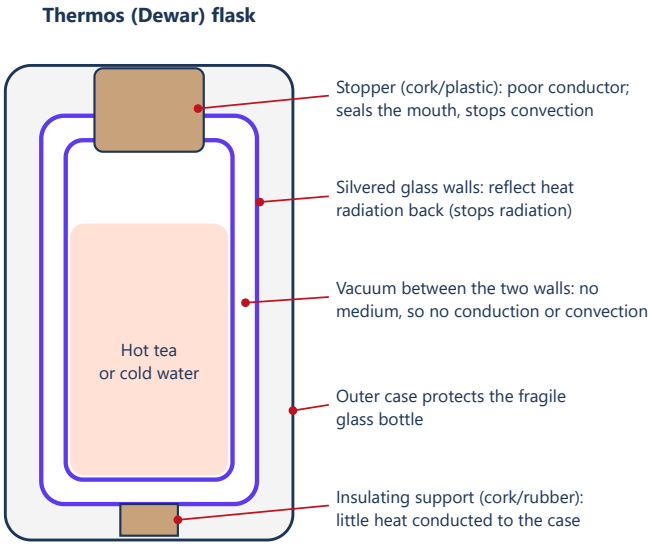
vacuum: conduction, convection

silvering: radiation

greenhouse gases

infrared trapped

A thermos flask (invented by **James Dewar**, 1892) keeps hot things hot and cold things cold by blocking all three modes at once. The greenhouse effect works the other way round: it lets sunlight in but traps the heat going out.



Each part of a thermos flask blocks one route of heat: vacuum for conduction and convection, silvering for radiation, cork for the mouth and base.

★★★ **Vacuum** between double glass walls stops **conduction and convection**.

★★★ **Silvered walls** reflect heat radiation and stop **radiation** loss or gain.

★★ **Cork or plastic stopper and supports** are poor conductors and close the remaining paths.

★★★ **Greenhouse effect**: sunlight (mostly short-wave visible light) passes through the air and warms the ground; the ground re-emits long-wave **infrared**, which **CO_2, water vapour, methane and nitrous oxide** absorb and send back down.

★★ **Without the natural greenhouse effect** Earth's average surface temperature would be about −18 °C instead of about 15 °C. Water vapour is the largest natural contributor; extra CO_2 from fuels strengthens the effect and causes global warming.

★★ **A car parked in the sun** or a glass greenhouse heats up: glass lets visible light in but blocks much of the infrared going out.

⚠ **Exam trap:** The greenhouse effect is natural and necessary; only its enhancement causes global warming. It is also different from ozone depletion, which concerns ultraviolet light.

☑ Quick check

1. In a thermos flask, what stops radiation?
2. Greenhouse gases trap which radiation going out?
3. Earth's average temperature without the natural greenhouse effect?

Answer: 1. the silvered walls · 2. infrared (long-wave) from the ground · 3. about −18 °C (instead of about 15 °C)

Gases and temperature

Boyle: $P \propto 1/V$

Charles: $V \propto T$

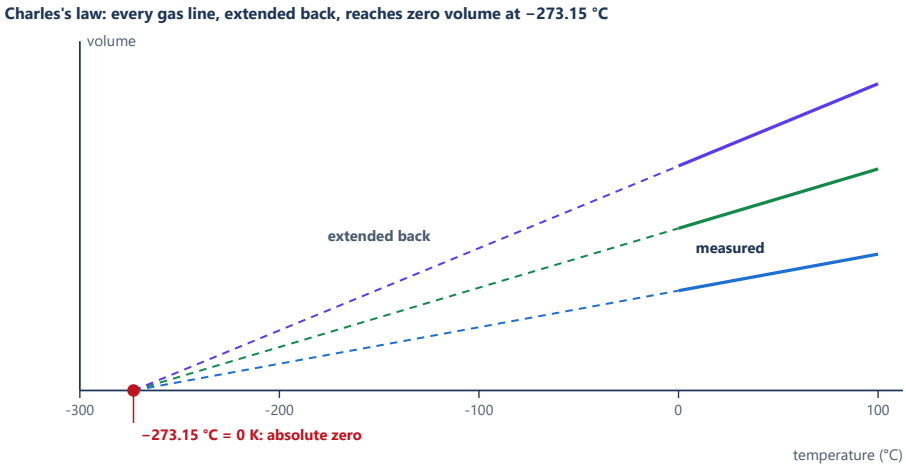
$PV = nRT$

absolute zero

Gas molecules fly about and hit the walls of their container; those hits are the pressure. Heat the gas and the molecules hit harder and more often, so either the pressure rises or the gas expands.

Gas laws ★★

Law	Kept constant	Statement	Example
Boyle's	Temperature	$P \propto 1/V$	Bubble grows as it rises in water; squeezed balloon pops
Charles's	Pressure	$V \propto T$ (kelvin)	Hot-air balloon swells and rises
Gay-Lussac's	Volume	$P \propto T$ (kelvin)	Tyres burst in summer; aerosol can explodes in fire
Avogadro's	P and T	Equal volumes of gases hold equal numbers of molecules	1 mole of gas at STP ≈ 22.4 L



Charles's law, drawn to scale. Three gas samples, each at its own fixed pressure: the volume grows in a straight line with temperature, and every line, extended back, reaches zero volume at −273.15 °C, absolute zero.

★★ **Ideal gas equation**: $PV = nRT$, with T in kelvin.

★ **Graham's law**: lighter gases diffuse faster (rate $\propto 1/\sqrt{\text{density}}$); hydrogen diffuses faster than oxygen.

★★ **Absolute zero** = **0 K = −273.15 °C = −459.67 °F**: the lowest possible temperature, where molecular motion is the least possible. It can be approached but never reached.

★ **Bose–Einstein condensate**: a state of matter formed near absolute zero, predicted by **Satyendra Nath Bose** and Einstein (1924–25) and first made in 1995.

Quick check

1. Why do tyres burst in summer?
2. Absolute zero in °C?
3. Which state of matter is named after S.N. Bose?

Answer: 1. at fixed volume, gas pressure rises with temperature (Gay-Lussac) · 2. −273.15 °C (0 K) · 3. Bose-Einstein condensate

Laws of thermodynamics

zeroth: thermometer

first: Q = ΔU + W

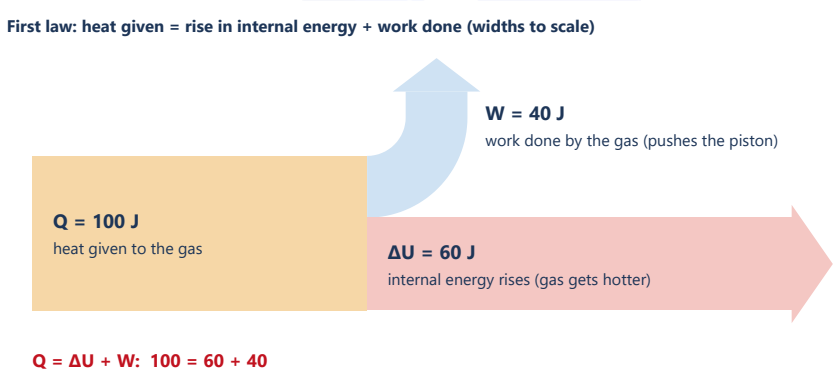
second: no 100% engine

adiabatic

Thermodynamics is the bookkeeping of heat and work. Four short laws cover it: when things share a temperature, that energy is never lost, that heat flows downhill by itself, and that absolute zero is out of reach.

The four laws in plain words ★★★

Law	Plain words	Consequence
Zeroth	If A and B are each in thermal equilibrium with C, then A and B are in equilibrium with each other	Basis of the thermometer (C is the thermometer)
First	Energy is conserved: heat given = rise in internal energy + work done (Q = ΔU + W)	No machine can give work without an energy input
Second	Heat flows by itself only from hot to cold; no engine turns all its heat into work; entropy (disorder) of the universe increases	No engine is 100% efficient; a fridge needs power
Third	Absolute zero cannot be reached in a finite number of steps; a perfect crystal at 0 K has zero entropy	0 K is a limit, not a goal



First law of thermodynamics as an energy flow, widths to scale: of 100 J of heat given to a gas, 60 J raises its internal energy and 40 J goes out as work on the piston. No energy is lost.

★★ **Isothermal process**: temperature stays constant; slow change with heat exchange through conducting walls.

★★ **Adiabatic process**: **no heat enters or leaves**; usually fast or in an insulated container. Compression heats the gas, expansion cools it.

★★ **Adiabatic examples**: a bicycle pump gets hot; air from a burst tyre feels cold; a CO_2 extinguisher frosts; rising air cools and forms clouds.

★ **Isobaric** = constant pressure (boiling in an open pot); **isochoric** = constant volume (gas heated in a sealed rigid can).

★ **Perpetual motion machine** is impossible: the first kind breaks the first law, the second kind breaks the second law.

Remember it: The laws as a card game: Zeroth, there is a game; First, you can't win (you can't get out more than you put in); Second, you can't break even (some heat is always lost); Third, you can't leave the game (0 K is never reached).

Quick check

1. Which law of thermodynamics is the basis of the thermometer?
2. Air rushing out of a burst tyre feels cold. Which process?
3. Which law rules out a 100% efficient heat engine?

Answer: 1. the zeroth law · 2. adiabatic expansion · 3. the second law

Heat engines, refrigerators, ACs and heat pumps

efficiency < 1

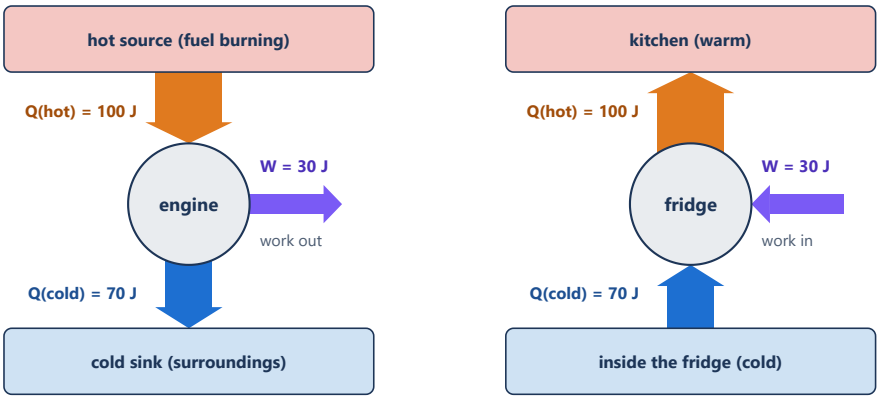
Carnot: 1 − Tc/Th

fridge moves heat

open fridge warms

Kigali Amendment

A **heat engine** takes heat from a hot source, turns part of it into work and throws the rest into a cold sink. A **refrigerator** runs the same cycle backwards: it uses work to pump heat from a cold place to a warm one, like a pump lifting water uphill.



Heat engine and refrigerator, arrow widths to scale. (a) An engine turns part of the heat into work and rejects the rest (here 30 J of 100 J, an efficiency of 30%). (b) A refrigerator uses work to pump heat out of its cold inside, so the kitchen receives that heat plus the work: 70 + 30 = 100 J.

★★ **Efficiency** of a heat engine = work done ÷ heat taken in = 1 − (heat rejected ÷ heat taken in). Always less than 1.

★★ **Carnot engine**: the ideal, most efficient engine between two temperatures; efficiency = **1 − T(cold)/T(hot)**, temperatures in kelvin.

★ **Real engines**: petrol car engines turn roughly a quarter to a third of fuel energy into work; diesel engines do better because they compress air more.

★★ **Steam engine and petrol/diesel engines** are heat engines (external and internal combustion respectively).

★★ **Refrigerator cycle**: the liquid refrigerant **evaporates** in the freezer coils and absorbs heat (latent heat); the **compressor** squeezes the vapour, heating it; the **condenser coils** at the back release that heat into the kitchen; an **expansion valve** drops the pressure and the cycle repeats.

★★★ **Fridge door left open in a closed room**: the room gets **warmer**, not cooler. The fridge only moves heat from inside to the coils outside, and adds the heat from its motor's work.

★★ **Air conditioner** is a refrigerator for a room: the indoor unit absorbs heat, the outdoor unit throws it outside along with the compressor's heat.

★★ **Heat pump**: the same machine run to pump outside heat into a house. It delivers more heat than the electricity it uses, so it beats a plain electric heater.

★★ **Refrigerants**: CFCs (Freon) damaged the ozone layer and were phased out under the Montreal Protocol; HFCs (such as R-134a) are being phased down under the **Kigali Amendment** (2016), with India's freeze due in 2028; newer units use isobutane (R-600a) or propane (R-290).

⚠ **Exam trap:** An AC or fridge does not destroy heat; it only moves it, and adds some. That is why the area around an AC's outdoor unit is hot.

See it around you: Feel the back of a running refrigerator: the grid of black coils is warm. That is the heat taken from your food, now being released into the kitchen.

Quick check

1. A fridge's door is left open in a closed room. The room gets _____ .
2. Where does the refrigerant absorb heat: in the freezer coils or the coils at the back?
3. Which amendment phases down HFC refrigerants?

Answer: 1. warmer · 2. in the freezer coils, as it evaporates · 3. the Kigali Amendment (2016)

Indian angle

ChaSTE

Chandrayaan-3

bosons

Saha: star spectra

★ **ChaSTE** (Chandra's Surface Thermophysical Experiment) on Chandrayaan-3's Vikram lander (2023) pushed a probe about 10 cm into lunar soil near the south pole. The soil temperature fell sharply within a few centimetres, showing lunar soil is a very poor conductor of heat.

★ **S.N. Bose** gave the statistics of photons and identical particles; particles that obey it are called **bosons**.

★ **Meghnad Saha** explained star spectra through temperature (thermal ionisation), the basis of classifying stars by temperature.

Satyendra Nath Bose in 1925. His statistics of photons gave bosons their name, and with Einstein he predicted the Bose–Einstein condensate. Image: Unknown author, Wikimedia Commons, public domain

Quick check

1. Which Chandrayaan-3 experiment measured the temperature of lunar soil?
2. Particles named after S.N. Bose are called _____ .

Answer: 1. ChaSTE, on the Vikram lander · 2. bosons

Asked in past papers (11)

UPSC 2011 The surface of a lake is frozen in severe winter, but the water at its bottom is still liquid. What is the reason ?
(a) Ice is a bad conductor of heat
(b) Since the surface of the lake is at the same temperature as the air, no heat is lost
(c) The density of water is maximum at 4°C (d) None of the statements (a), (b) and (c) given above is correct
Answer: (c) The density of water is maximum at 4°C. Water is densest at 4°C, so it sinks and stays liquid below ice in a frozen lake

BPSC 64th The value of 40 degrees Celsius in Fahrenheit scale is
(a) 104 °F (b) 100 °F (c) 102 °F (d) 75 °F (e) None of the above/More than one of the above
Answer: (a) 104 °F. To convert Celsius to Fahrenheit: °F = (9/5 × °C) + 32

BPSC 65th The value of 50 °C in Fahrenheit scale is
(a) 104 °F (b) 122 °F (c) 100 °F (d) 75 °F (e) None of the above/More than one of the above
Answer: (b) 122 °F. Fahrenheit = Celsius × 9/5 + 32

BPSC 66th The poorest conductor of heat among the following is
(a) copper (b) lead (c) mercury (d) zinc (e) None of the above/More than one of the above
Answer: (c) mercury. Mercury conducts heat worst among common metals; silver and copper conduct it best

UPSC 2021 In a pressure cooker, the temperature at which the food is cooked depends mainly upon which of the following?
1. Area of the hole in the lid
2. Temperature of the flame
3. Weight of the lid
Select the correct answer using the code given below.
(a) 1 and 2 only (b) 2 and 3 only (c) 1 and 3 only (d) 1, 2 and 3
Answer: (c) 1 and 3 only. Boiling point rises with pressure; a cooker's pressure is set by vent area and weight

BPSC 67th A fan produces a feeling of comfort during the hot weather because
(a) fan supplies cool air (b) our body radiates more heat in air (c) conductivity of air increases
(d) our perspiration evaporates rapidly (e) None of the above/More than one of the above
Answer: (d) our perspiration evaporates rapidly. Evaporation absorbs latent heat from the surface, so it causes cooling; Moving air speeds up evaporation by carrying away the vapour-laden air

BPSC 67th Food gets cooked faster in a pressure cooker because
(a) water starts boiling at low temperature due to high pressure
(b) water starts boiling at high temperature due to high pressure
(c) water starts boiling at low temperature due to low pressure
(d) water starts boiling at high temperature due to low pressure
(e) None of the above/More than one of the above
Answer: (b) water starts boiling at high temperature due to high pressure. The boiling point of water rises as the pressure on it increases

BPSC 67th If the doors of a refrigerator are left open for few hours, then the room temperature will
(a) decrease (b) increase (c) remain the same
(d) decrease only in the area in the vicinity of the refrigerator
(e) None of the above/More than one of the above
Answer: (b) increase. A refrigerator moves heat out and adds its motor's work, so it warms the room

BPSC 67th The temperature point at which solid, liquid and gaseous states may stay together is known as
(a) boiling point (b) melting point (c) freezing point (d) triple point
(e) None of the above/More than one of the above
Answer: (d) triple point. At the triple point, solid, liquid and gas of a substance coexist in equilibrium; Water's triple point is about 273.16 K (0.01 °C) at about 611 pascal

BPSC 70th Heat transfer that does not require a medium is called
(a) Reflection (b) Radiation (c) Convection (d) Conduction
Answer: (b) Radiation. Radiation transfers heat without a medium; conduction and convection need one

BPSC 70th re-exam Compared to a burn due to air at 100°C, the burn due to steam at 100°C is
(a) Less dangerous due to low latent heat of evaporation
(b) More dangerous due to low latent heat of evaporation
(c) More dangerous due to high latent heat of evaporation
(d) Less dangerous due to high latent heat of evaporation
Answer: (c) More dangerous due to high latent heat of evaporation. Steam at 100 °C burns worse than water or air at 100 °C due to its high latent heat

Test yourself (13)

1. A patient's temperature is 104 °F. In Celsius this is
(a) 38 °C (b) 40 °C (c) 42 °C (d) 36 °C

2. Ice at 0 °C cools a drink better than the same mass of water at 0 °C because
(a) ice is denser than water and sinks to the bottom (b) ice absorbs latent heat while melting
(c) ice has a higher specific heat than water (d) ice reflects heat away from the drink

3. Which thermometer is best suited to measure the temperature of molten iron in a furnace?
(a) Clinical thermometer (b) Alcohol thermometer (c) Pyrometer (d) Six's thermometer

4. Telephone wires sag more in summer than in winter. This is due to
(a) thermal expansion (b) radiation from the Sun (c) convection of hot air (d) regelation of the metal

5. A thick glass tumbler cracks when boiling water is poured into it, mainly because
(a) glass is a good conductor of heat (b) glass softens at 100 °C (c) its inner layer expands first
(d) steam gets trapped inside the glass

6. Consider the statements: 1. Salt sprinkled on ice lowers its melting point. 2. Increase of pressure raises the boiling point of water. 3. Water boils above 100 °C at hill stations. Which are correct?
(a) 1 and 2 only (b) 2 and 3 only (c) 1 and 3 only (d) 1, 2 and 3

7. Hot stars appear bluish-white while cooler stars appear red. This is explained by
(a) Newton's law of cooling (b) Wien's displacement law (c) Charles's law (d) Kirchhoff's law of currents

8. Clear winter nights are colder than cloudy nights because
(a) clouds themselves produce heat (b) clouds return the ground's infrared
(c) clear skies bring cold winds from the poles (d) humidity is always higher on clear nights

9. Air rushing out of a punctured tyre feels cold. The process is
(a) isothermal (b) isobaric (c) isochoric (d) adiabatic

10. Which of the following is the poorest conductor of heat?
(a) Aluminium (b) Still air (c) Glass (d) Water

11. Consider the following statements:
1. Radiation is the only one of the three modes of heat transfer that needs no medium.
2. Mercury is the best conductor of heat among common metals.
3. In a thermos flask, the vacuum stops conduction and convection, while the silvered walls stop radiation.
Which of the statements given above is/are correct?
(a) 1 only (b) 1 and 3 only (c) 2 and 3 only (d) 1, 2 and 3

12. Consider the following statements about the laws of thermodynamics:
1. The zeroth law is the basis of measuring temperature with a thermometer.
2. The first law states that no heat engine can convert all the heat it takes in into work.
3. The third law states that absolute zero can be reached in a finite number of steps.
How many of the above statements are correct?
(a) Only one (b) Only two (c) All three (d) None

13. A refrigerator is left running with its door wide open in a closed, insulated kitchen for several hours. What happens to the temperature of the kitchen?
(a) It falls, because the fridge pulls heat out of the room air
(b) It stays the same, as heat taken in equals heat given out
(c) It rises, because the motor's work also ends up as heat
(d) It falls at first, then settles below its starting value

Answers: 1. (b) C = (104 − 32) × 5/9 = 72 × 5/9 = 40 °C. · 2. (b) Each gram of ice takes 80 cal just to melt, before warming at all. · 3. (c) A pyrometer reads very high temperatures from the radiation emitted, without contact. · 4. (a) The wires lengthen when heated. · 5. (c) Glass is a poor conductor, so the uneven expansion sets up stress and cracks it. · 6. (a) In the hills pressure is lower, so water boils below 100 °C. · 7. (b) Peak wavelength × temperature is constant, so hotter bodies peak at shorter (bluer) wavelengths. · 8. (b) Without clouds, the ground's infrared radiation escapes to space. · 9. (d) Fast expansion with no time for heat exchange cools the gas. · 10. (b) Still air (about 0.026 W/m·K) conducts far less than water (0.6) or glass (about 1). · 11. (b) Mercury is the poorest conductor of heat among common metals, while silver is the best; statements 1 and 3 are correct. · 12. (a) Only statement 1 is correct: 'no engine turns all its heat into work' is the second law, and the third law says absolute zero cannot be reached in a finite number of steps. · 13. (c) A fridge only moves heat from inside to the coils at its back, and the work of its compressor adds more heat, so the closed kitchen warms up; it cannot cool the room as a whole.

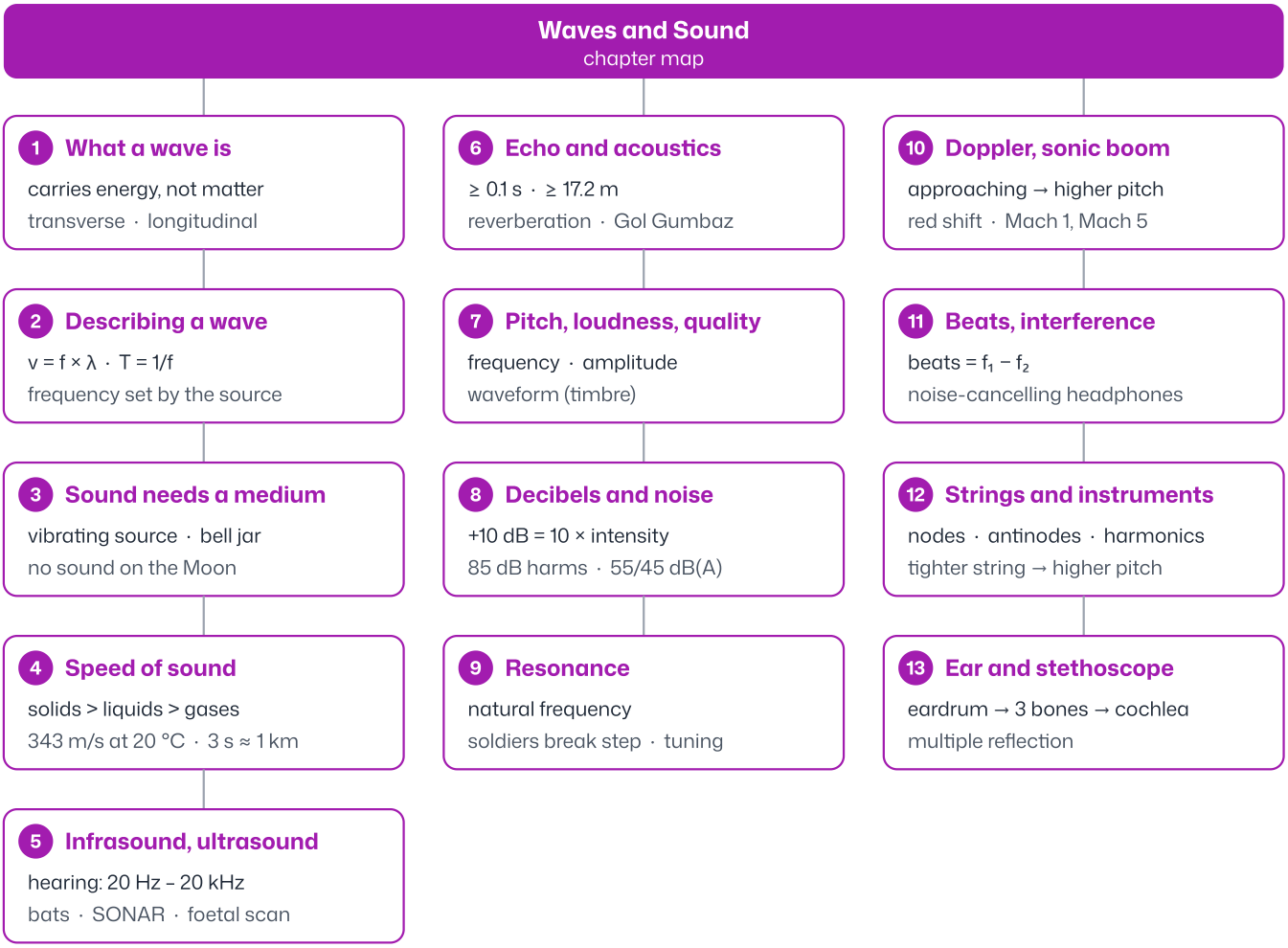
CHAPTER 7

Waves and Sound

Speed of sound in different media, longitudinal nature of sound, uses of ultrasound, pitch–loudness–quality, echo, resonance and the Doppler effect are the recurring questions.

Asked 4 times in past papers: BPSC 4

≈ 46 min to read ≈ 7 min to revise ★★★ Revise on: Day 1 | Day 3 | Day 7 | Day 21



Revision card

1. Sound is a mechanical, longitudinal wave in air (compressions and rarefactions); it needs a medium, so there is no sound on the Moon.
2. Speed of sound: solids > liquids > gases. Air ≈ 343 m/s at 20 °C (331 m/s at 0 °C), water ≈ 1500 m/s, steel ≈ 5960 m/s.
3. Speed in air rises with temperature (≈ 0.6 m/s per °C) and humidity; pressure alone has no effect.
4. $v = f \times \lambda$. Frequency in hertz. Frequency never changes when sound passes into another medium; speed and wavelength do.
5. Audible range 20 Hz–20 kHz. Below: infrasound (earthquakes, elephants, whales). Above: ultrasound (bats, dolphins, SONAR, foetal scans).
6. Pitch ↔ frequency, loudness ↔ amplitude, quality (timbre) ↔ waveform. Women's and children's voices have higher pitch.
7. Echo needs a gap of at least 0.1 s, i.e. a reflector at least about 17 m away. Reverberation = many reflections that blur together.
8. Lightning–thunder gap: every 3 seconds ≈ 1 km.
9. Resonance: driving a body at its natural frequency gives huge vibration (soldiers break step on bridges, radio tuning, sitar tuning).
10. Doppler effect: approaching source sounds higher, receding lower; red shift of galaxies shows the universe is expanding.
11. Mach number = object's speed ÷ speed of sound; above Mach 1 a sonic boom; above Mach 5 hypersonic.
12. Decibel scale is logarithmic: +10 dB = 10 × intensity. Residential limit in India: 55 dB(A) by day, 45 by night.

What a wave is

energy, not matter

transverse

longitudinal

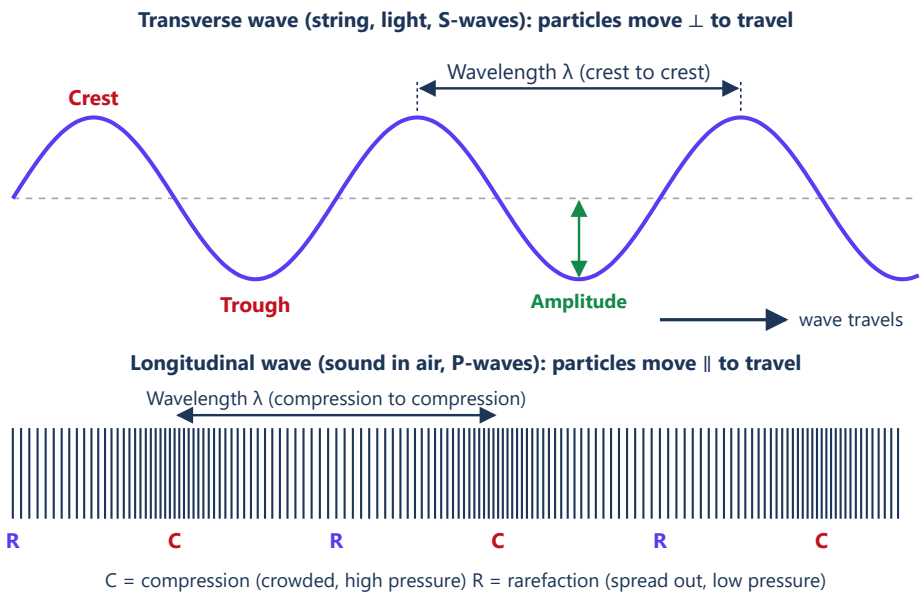
P and S waves

polarisation

Drop a stone in a pond: the ripples travel outward, but a floating leaf only bobs up and down. A **wave** carries **energy**, not matter, from one place to another. Each particle just vibrates about its own position and passes the push to its neighbour.

Mechanical vs electromagnetic waves ★★★

	Mechanical	Electromagnetic
Medium	Needed (solid, liquid or gas)	Not needed; travel through vacuum
Speed	Depends on the medium; sound in air ≈ 343 m/s	3×10^8 m/s in vacuum, same for all
Nature	Transverse or longitudinal	Always transverse
Examples	Sound, seismic waves, waves on a string, water waves	Light, radio, microwaves, X-rays, gamma rays



Top: in a transverse wave particles move up and down across the direction of travel (crests and troughs). Bottom: in a longitudinal wave they move back and forth along it (compressions and rarefactions).

Transverse vs longitudinal ★★★

	Transverse	Longitudinal
Particle motion	Perpendicular to the direction of travel	Parallel to the direction of travel
Made of	Crests and troughs	Compressions and rarefactions
Travels in	Solids, surface of liquids; EM waves in vacuum	Solids, liquids and gases
Polarisation	Possible	Not possible
Examples	Light, waves on a sitar string, seismic S-waves	Sound in air, seismic P-waves, a pushed slinky

★★★ **Sound in air (and in any liquid or gas) is longitudinal**; in solids sound can travel as both longitudinal and transverse waves.

★★ **Water surface waves** are a mix: water particles move in near-circles.

★★ **Seismic P-waves** (longitudinal) pass through solids and liquids and arrive first; **S-waves** (transverse) cannot cross liquids, which showed that Earth's outer core is liquid.

★★★ **Polarisation** happens only with transverse waves; that light can be polarised proves it is transverse. Sound cannot be polarised.

Remember it: 'Longitudinal = Lengthwise': the particles jiggle along the length of travel. 'Transverse = Traverse across': they move across it.

Quick check

1. Sound in air: a transverse or a longitudinal wave?
2. Which seismic waves cannot cross the liquid outer core?
3. Can sound be polarised?

Answer: 1. longitudinal (compressions and rarefactions) · 2. S-waves (transverse) · 3. no: only transverse waves can be

Describing a wave

$v = f \times \lambda$

$T = 1/f$

frequency never changes

energy $\propto$ amplitude^2

Five words describe any wave: how long one wave is, how many pass each second, how long one takes, how big the swing is, and how fast the wave moves. One equation links them.

Wave quantities ★★★

Quantity	Meaning	SI unit
Wavelength (λ)	Distance between two crests, or two compressions	metre (m)
Frequency (f)	Number of waves (vibrations) per second	hertz (Hz) = 1 per second
Time period (T)	Time for one full vibration; T = 1/f	second (s)
Amplitude (A)	Largest displacement from the rest position; decides energy and loudness	metre (m)
Wave speed (v)	Distance a crest or compression travels per second	m/s

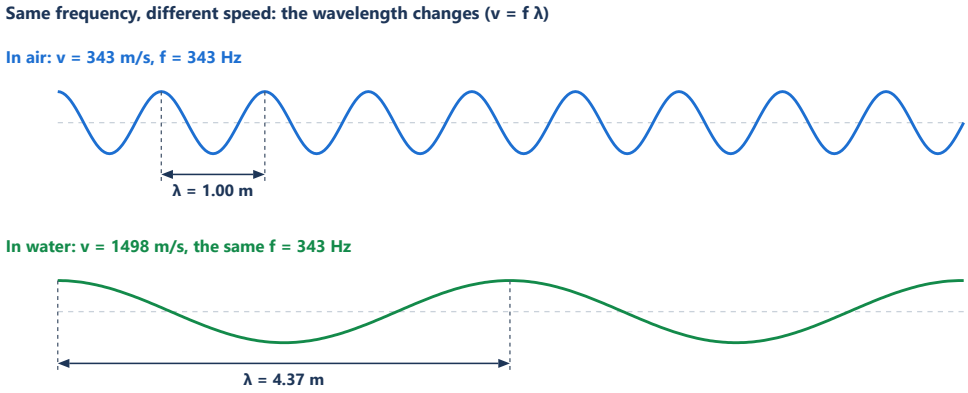
★★★ **Wave equation**: $v = f \times \lambda$. Sound at 340 m/s with frequency 340 Hz has a wavelength of 1 m.

★★★ **Frequency is set by the source** and does not change when the wave enters another medium; **speed and wavelength change**.

★★ **Hertz** is named after **Heinrich Hertz**, who first produced and detected radio waves (1887).

★ **Audible wavelengths** in air range from about 17 m (20 Hz) to about 1.7 cm (20 kHz).

★★ **Energy (intensity) of a wave** $\propto$ **amplitude^2**: double the amplitude, four times the energy.



The same 343 Hz sound in air and in water, drawn to scale as a graph of the vibration. The frequency does not change, but sound is about 4.4 times faster in water, so each wavelength is about 4.4 times longer (v = f λ).

⚠ **Exam trap:** When sound goes from air into water, its frequency (and so its pitch) stays the same; its speed and wavelength both increase about four-fold.

☑ Quick check

1. Sound of 340 Hz travels at 340 m/s. Its wavelength?
2. Sound passes from air into water. What stays the same?
3. Double the amplitude: the energy becomes how many times?

Answer: 1. 1 m (λ = v/f) · 2. frequency (and so pitch) · 3. four times

Sound and its medium

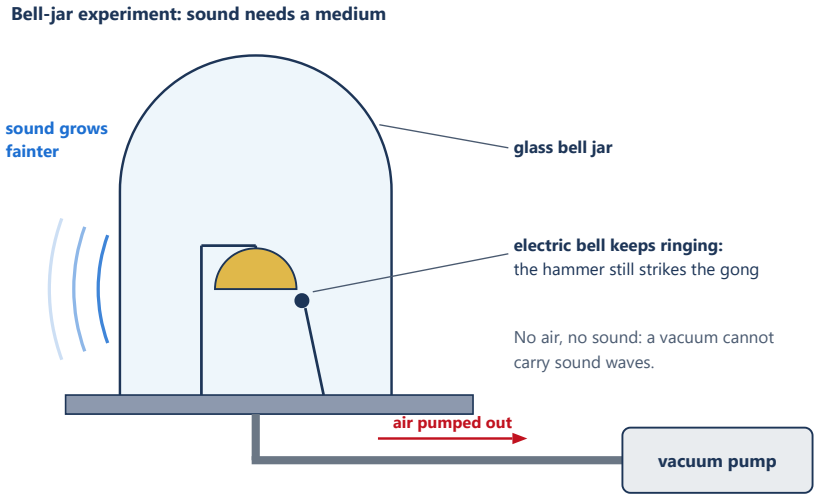
vibrating source

needs a medium

bell jar

larynx

Sound is made by **vibrating objects**: vocal cords in the larynx, a stretched tabla skin, a sitar string, the prongs of a tuning fork. The vibration squeezes and stretches the air next to it, and that pattern of compressions and rarefactions travels to the ear. With no particles to squeeze, there is no sound.



Bell-jar experiment. As the pump removes the air, the ring grows fainter though the hammer still strikes the gong: sound cannot travel through a vacuum.

★★★ **Sound needs a medium**; it cannot travel through vacuum. **On the Moon** there is no air, so astronauts talk by radio (electromagnetic waves).

★★ **Bell-jar experiment**: as air is pumped out of a jar with a ringing bell, the sound fades though the bell keeps moving.

★★ **Human voice** comes from the vocal cords in the **larynx (voice box)**. Men's cords are about 20 mm long, women's about 15 mm; shorter, thinner cords vibrate faster.

★ **Insects** make sound by beating their wings fast; a mosquito's buzz is high-pitched because its wings beat several hundred times a second.

See it around you: Put your ear to one end of a long wooden table while a friend scratches the other end gently: you hear it clearly through the wood but hardly through the air.

Quick check

1. Why do astronauts on the Moon talk by radio?
2. Air is pumped out of a jar holding a ringing bell. What happens to the sound?
3. The human voice is produced in the _____ .

Answer: 1. there is no air, and sound needs a medium · 2. it fades, though the bell keeps ringing · 3. larynx (voice box), by the vocal cords

Speed of sound

solids > liquids > gases

343 m/s at 20 °C

+0.6 m/s per °C

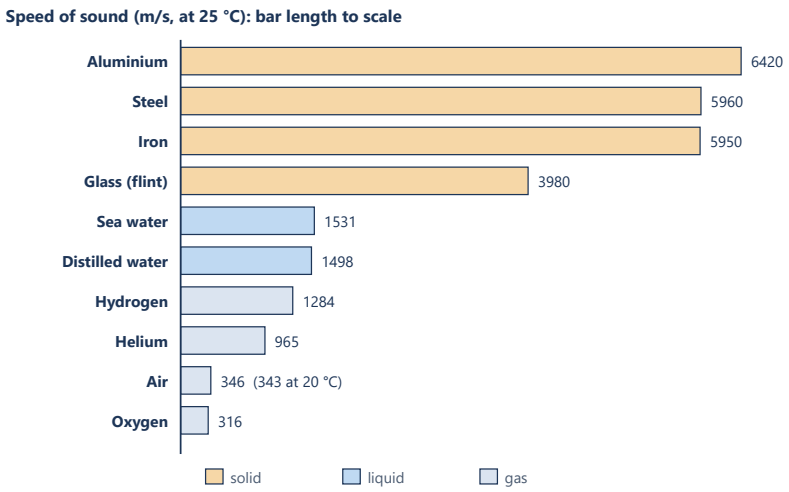
humid air: faster

3 s ≈ 1 km

Sound passes from particle to particle, so it travels fastest where particles are tightly bound and spring back quickly. Stiffness (elasticity) speeds sound up, density slows it down. Solids are so stiff that they win easily, even though they are dense.

Speed of sound (approx., at 25 °C unless stated) ★★★

Medium	Speed (m/s)	State
Aluminium	6420	Solid
Steel	5960	Solid
Iron	5950	Solid
Glass (flint)	3980	Solid
Sea water	1531	Liquid
Distilled water	1498	Liquid
Hydrogen	1284	Gas (light gas, fast)
Helium	965	Gas
Air	346 (343 at 20 °C, 331 at 0 °C)	Gas
Oxygen	316	Gas



Speed of sound at 25 °C, drawn to scale. Solids win by far; among gases the light ones (hydrogen, helium) are fastest; steel carries sound about 17 times faster than air.

★★★ **Order**: **solids > liquids > gases**. Sound is fastest in solids such as **steel**, about 17 times faster than in air.

★★★ **Temperature**: speed in air rises by about **0.6 m/s for each 1 °C** (331 m/s at 0 °C, 343 m/s at 20 °C).

★★★ **Humidity**: sound is **faster in humid air**, because moist air is lighter (less dense) than dry air at the same temperature.

★★★ **Pressure**: changing the pressure of air at constant temperature has **no effect** on the speed of sound.

★★ **Lighter gases carry sound faster**: hydrogen > helium > air > oxygen > carbon dioxide.

★★ **In a gas, $v \propto \sqrt{T}$** (T = absolute temperature in kelvin); at the same temperature, $v \propto 1/\sqrt{(\text{molar mass})}$, so sound in hydrogen is about four times faster than in oxygen.

★★ **Wind** carries sound with it: sound travels farther downwind.

★★ **All frequencies travel at the same speed** in air: the flute and the drum of an orchestra reach you together; loudness does not change speed either.

★★★ **Light (3×10^8 m/s) is about a million times faster** than sound: we see lightning before we hear thunder, see a cracker burst before hearing it, and see a distant batsman hit before hearing the bat.

★★★ **Distance of a storm**: count seconds between flash and thunder; **every 3 seconds ≈ 1 km** (sound covers about 340 m each second).

★ **At night** the air near the ground is cooler, so sound bends back down and is heard far away; by day it bends upward (refraction of sound).

★ **Sound bends round corners** (diffraction) because its wavelengths are large; we hear people round a corner but cannot see them.

Remember it: 'Steel speaks soonest': the denser-looking solid still wins, because its stiffness is enormous. And 'Three seconds, one kilometre' for every thunderstorm.

⚠ **Exam trap:** In 'fastest medium' questions hydrogen is the bait: sound is faster in hydrogen than in air, but steel (a solid) beats every gas and liquid.

Quick check

1. Steel, water, air, hydrogen: where is sound fastest?
2. Does raising the air pressure at constant temperature change the speed of sound?
3. Thunder is heard 9 s after the flash. How far away is the storm?

Answer: 1. steel · 2. no · 3. about 3 km

Audible range, infrasound and ultrasound

20 Hz – 20 kHz

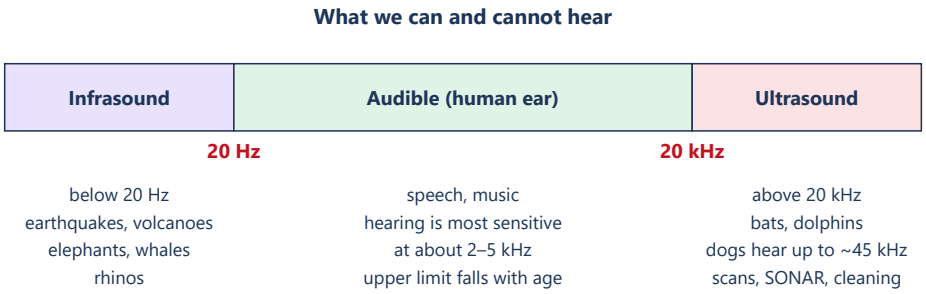
infrasound: elephants

ultrasound: bats

SONAR: d = vt/2

foetal scan

The human ear responds only to vibrations between about **20 and 20,000 per second**. Slower vibrations are **infrasound**; faster ones are **ultrasound**. Many animals hear outside our range, and ultrasound's short wavelength makes it a precise probe for seeing inside bodies and under the sea.



The human ear hears only 20 Hz to 20 kHz. Note which animals and uses sit on each side.

★★★ **Audible range** of humans: **20 Hz to 20 kHz**. The upper limit falls with age; children and young people hear the highest notes.

★★★ **Infrasound** (below 20 Hz): produced by **earthquakes** (before the main shock, which is why some animals get restless), volcanoes, a swinging pendulum; used for communication by **elephants, whales and rhinoceroses**.

★★★ **Ultrasound** (above 20 kHz): heard by **bats, dolphins, porpoises, dogs** and rats. Dogs hear up to about 45 kHz, so a 'silent' dog whistle works.

★★★ **Ultrasound scans (ultrasonography)** show the **foetus in the womb**, gall and kidney stones and tumours. Ultrasound is non-ionising, so it is safe for the foetus, unlike X-rays.

★★ **Echocardiography**: ultrasound images of the beating heart; **Doppler ultrasound** measures blood flow.

★★ **Lithotripsy**: focused high-energy sound pulses break **kidney stones** into fine grains that pass out in urine.

★★ **Ultrasonic cleaning** of jewellery, electronic parts and spiral tubes; **flaw detection** in metal blocks and welds.

★★★ **SONAR** (**SO**und **N**avigation **A**nd **R**anging) sends ultrasound into water and times the echo to find **sea depth**, submarines, shoals of fish, icebergs and shipwrecks. **Depth = speed × time ÷ 2**.

★★★ **Echolocation**: **bats** fly and hunt in the dark by emitting ultrasonic squeaks and listening for echoes; **dolphins** do the same in water.

★★ **Why ultrasound for imaging**: short wavelength gives a narrow beam and fine detail, and it travels far in water and tissue.

★★ **PCPNDT Act, 1994** (Pre-Conception and Pre-Natal Diagnostic Techniques) bans using ultrasound to determine the sex of a foetus in India.

★ **NPOL, Kochi** (a DRDO laboratory) designs the SONARs of Indian Navy ships and submarines.

See it around you: A ship's SONAR hears the echo from the seabed 2 s after sending a pulse. With sound at 1500 m/s in sea water: depth = 1500 × 2 ÷ 2 = 1500 m.

⚠ **Exam trap:** Foetal scans use ultrasound, not X-rays, microwaves or ultraviolet. And bats use ultrasound, while elephants use infrasound; examiners swap the two.

Quick check

1. Which waves are used to see a foetus in the womb?
2. Elephants and whales communicate with infrasound or ultrasound?
3. A SONAR echo returns after 2 s in sea water (1500 m/s). Depth?

Answer: 1. ultrasound · 2. infrasound (below 20 Hz) · 3. 1500 m (v × t ÷ 2)

Echo, reverberation and acoustics

0.1 s

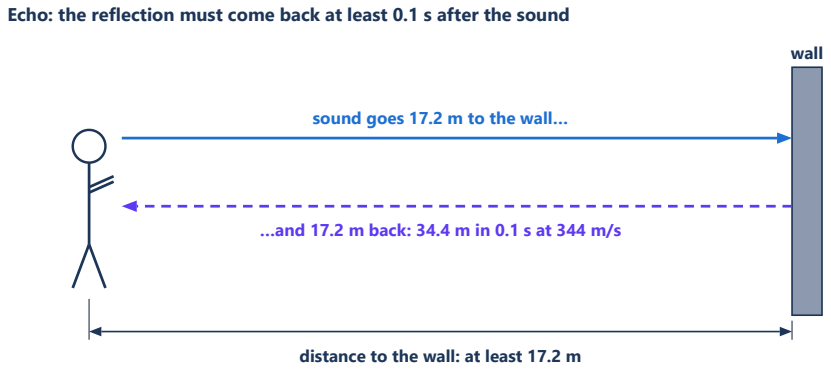
17.2 m

reverberation

sound board

Gol Gumbaz

Sound reflects like light, angle of incidence equal to angle of reflection, best from large hard surfaces. The ear keeps the sensation of a sound for about **0.1 s** (persistence of hearing). A reflection arriving later than that is heard separately as an **echo**; earlier reflections merge with the original and only prolong it.



Echo, drawn to scale (30 units per metre). The ear holds a sound for about 0.1 s, so the reflection must travel at least 34.4 m there and back at 344 m/s: the wall must be at least 17.2 m away.

★★★ **Echo** needs the reflection to arrive **at least 0.1 s** after the original sound.

★★★ **Minimum distance for an echo ≈ 17.2 m** in air (at 344 m/s, sound covers 34.4 m in 0.1 s: there and back).

★★★ **Reverberation**: persistence of sound in a hall from many reflections arriving within 0.1 s; too much of it makes speech unclear.

★★ **Reducing reverberation**: curtains, carpets, cushioned seats, fibreboard, rough plaster and other sound-absorbing materials on walls and ceiling.

★★ **Good hall acoustics**: curved ceilings and a **sound board** behind the stage reflect sound evenly to the audience.

★★ **Multiple reflection** is used in megaphones, horns, shehnai and trumpets, and the **stethoscope**.

★★ **Rolling thunder** is the sound reflected again and again from clouds and the ground.

★ **Gol Gumbaz** (Vijayapura, Karnataka) has a whispering gallery under its great dome: a whisper on one side is heard clearly on the opposite side, and a clap echoes several times.

Gol Gumbaz, Vijayapura (Karnataka). In the whispering gallery under its great dome, a whisper on one side is heard clearly on the opposite side, carried round by repeated reflection of sound from the curved wall. Image: Akshatha, Wikimedia Commons, CC BY-SA 3.0

Remember it: 'Seventeen for an echo': stand at least 17 m from a wall and clap; any closer and the echo hides inside the clap.

Quick check

1. Minimum distance from a wall to hear an echo in air?
2. Persistence of sound in a hall from many quick reflections is called _____ .
3. Which Indian monument has a famous whispering gallery?

Answer: 1. about 17.2 m · 2. reverberation · 3. Gol Gumbaz, Vijayapura

Characteristics of sound: pitch, loudness, quality

pitch ↔ frequency

loudness ↔ amplitude

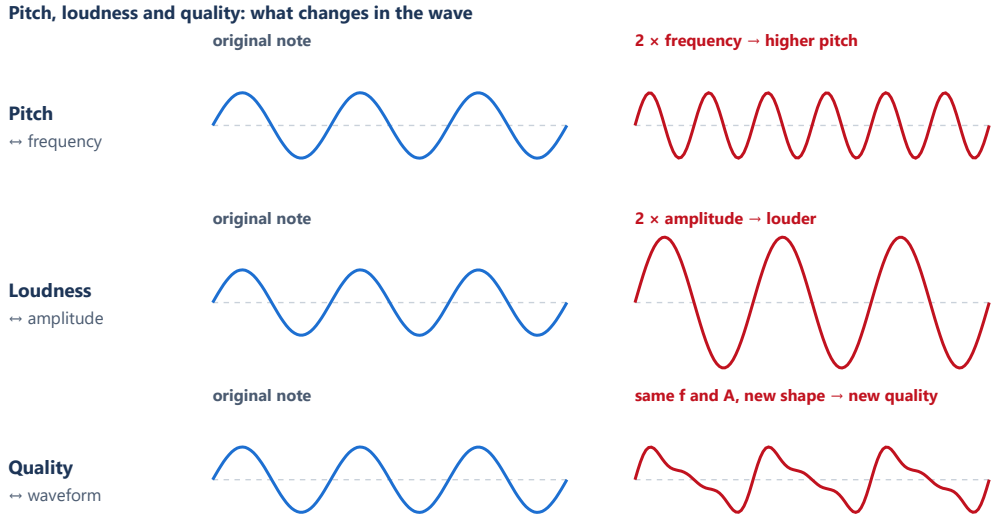
quality ↔ waveform

tone, note, noise

Two sounds can differ in three ways only. One is shriller (**pitch**), one is louder (**loudness**), or they sound different even at the same pitch and loudness, like a flute and a violin playing the same note (**quality**). Each is tied to one property of the wave.

What decides what ★★★

We hear	Depends on	Example
Pitch (shrillness)	Frequency	Women's and children's voices are shriller than men's; mosquito buzz vs lion's roar
Loudness	Amplitude (intensity ∝ amplitude²); also distance and the area vibrating	Striking a drum harder; a sitar's sound box makes it louder
Quality / timbre	Waveform (mix of overtones)	Recognising a friend's voice on the phone; flute vs violin on the same note



Each characteristic of a sound is tied to one property of its wave. Doubling the frequency raises the pitch; doubling the amplitude makes it louder; adding overtones to the same note changes its quality (timbre) but not its pitch or loudness.

★★★ **Higher frequency → higher pitch. Women's and children's voices are shriller** because their vocal cords are shorter and thinner and vibrate faster.

★★★ **Loudness depends on amplitude**, not frequency. A lion's roar is loud but low-pitched; a mosquito's buzz is faint but high-pitched.

★★ **Quality (timbre)** lets us tell instruments and voices apart: each source adds its own pattern of overtones to the main note.

★★ **Tone** = sound of a single frequency; **note** = a mix of frequencies, pleasant to hear; **noise** = irregular, unpleasant sound.

★★ **Intensity** (energy per second per unit area, W/m²) is physical; **loudness** is how the ear feels it. Intensity of a point source falls as 1/distance².

★ **Octave**: a note of double the frequency sounds like the 'same' note, higher.

Remember it: 'P-F, L-A, Q-W': Pitch–Frequency, Loudness–Amplitude, Quality–Waveform. Say it like a radio call sign.

⚠ **Exam trap:** Tuning a sitar by tightening or loosening the string changes its FREQUENCY (pitch), not its amplitude or intensity. Plucking harder changes loudness, not pitch.

Quick check

1. Pitch depends on _____ ; loudness on _____ .
2. How do you recognise a friend's voice on the phone?
3. Why are women's voices shriller?

Answer: 1. frequency; amplitude · 2. by its quality (timbre), set by the waveform · 3. shorter, thinner vocal cords vibrate faster: higher frequency

Decibels and noise pollution

+10 dB = 10 × intensity

85 dB harms

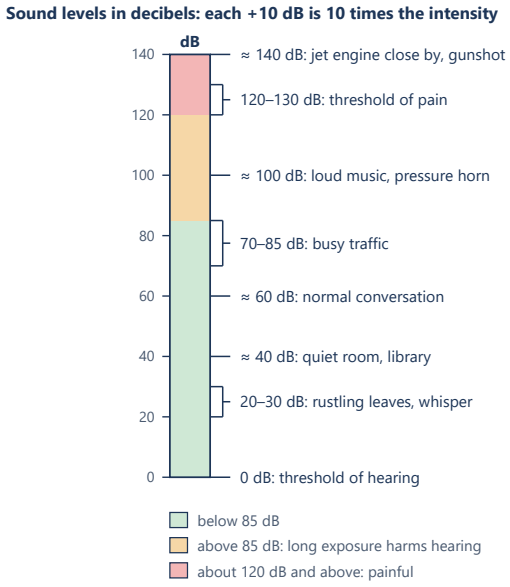
silence zone: 100 m

10 pm – 6 am

The ear handles an enormous range, from a leaf's rustle to a jet engine a trillion times more intense. So loudness is measured on a **logarithmic** scale, the **decibel (dB)**, one-tenth of a **bel** (named after Alexander Graham Bell). Each 10 dB step means ten times the intensity.

Typical sound levels ★★

Sound	Level (approx.)
Threshold of hearing	0 dB
Rustling leaves, whisper	20–30 dB
Quiet room, library	about 40 dB
Normal conversation	about 60 dB
Busy traffic	70–85 dB
Loud music, pressure horn	about 100 dB
Threshold of pain	about 120–130 dB
Jet engine close by, gunshot	about 140 dB



Sound levels on the decibel scale. Each 10 dB step is ten times the intensity, so a 100 dB horn is a million times as intense as a 40 dB library. Long exposure above about 85 dB harms hearing.

★★★ **+10 dB = 10 times the intensity**; +20 dB = 100 times; +3 dB ≈ double.

★★ **Hearing damage**: long exposure above about **85 dB** harms hearing; around 120 dB and above sound becomes painful.

★★ **Effects of noise**: hearing loss, sleeplessness, stress, high blood pressure and poor concentration.

★★ **Law in India**: the **Noise Pollution (Regulation and Control) Rules, 2000**, under the Environment (Protection) Act, 1986, set ambient limits; noise was added to the definition of air pollutant in the Air Act (amended 1987).

★★ **Silence zone**: an area of at least **100 m around hospitals, educational institutions and courts**, declared as such by the state government.

★★ **Loudspeakers** may not be used between **10 pm and 6 am** except in closed premises; a state may relax this up to midnight on a limited number of festival days a year.

Ambient noise limits in India, Leq in dB(A) (day 6 am–10 pm, night 10 pm–6 am) ★★★

Area	Day	Night
Industrial	75	70
Commercial	65	55
Residential	55	45
Silence zone	50	40

Remember it: Limits fall in steps going from factory to hospital: 75-65-55-50 by day; at night each drops by 10, except industrial, which drops only 5 (to 70).

Quick check

1. A sound rises from 60 dB to 80 dB. Its intensity becomes how many times?
2. Day and night noise limits for a residential area?
3. A silence zone covers at least how far around a hospital?

Answer: 1. 100 times · 2. 55 and 45 dB(A) · 3. 100 m

Resonance and natural frequency

natural frequency

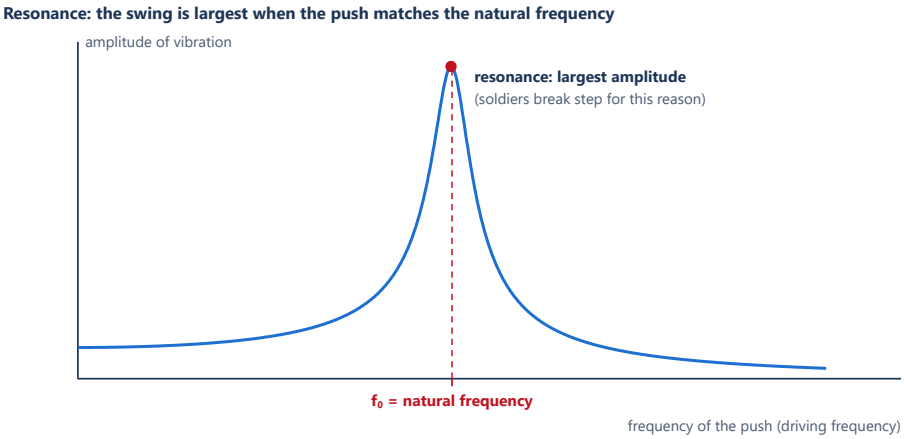
maximum amplitude

soldiers break step

radio tuning

Tacoma Narrows

Every object has a **natural frequency** at which it likes to vibrate, like a swing with its own rhythm. Push it at that same rhythm and each push adds to the last, so the swing grows huge. That is **resonance**: forced vibration at the natural frequency gives maximum amplitude.



Amplitude of a body pushed at different frequencies, computed for light damping. The swing stays small far from the natural frequency f_0 and is largest when the push matches it: that is resonance.

★★★ **Soldiers break step** while crossing a bridge: marching in step could match the bridge's natural frequency and set up dangerous resonance.

★★ **Tacoma Narrows Bridge** (USA, 1940) collapsed after wind set up growing twisting oscillations, the classic warning about resonance-like vibration in structures.

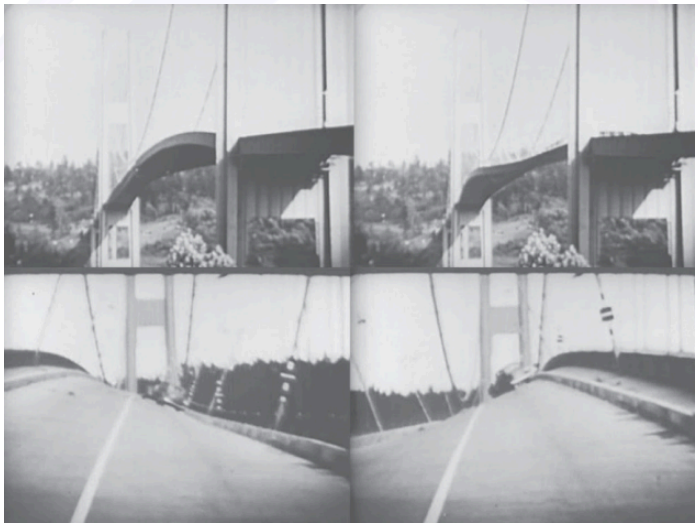
★★★ **Radio and TV tuning**: turning the knob changes the natural frequency of the receiver circuit until it matches (resonates with) one station's frequency (electrical resonance).

★★ **A singer can shatter a wine glass** by holding a loud note at the glass's natural frequency.

★★ **Sound boxes** of sitar (the gourd tumba), veena, violin and tabla resonate with the strings or skin and make the sound louder and richer.

★★ **Two tuning forks**: striking one makes an identical fork nearby start ringing on its own.

★ **Buildings and machines** are designed so that their natural frequencies stay away from those of earthquakes, wind and engines.



Tacoma Narrows Bridge, USA, 1940: film stills of the deck twisting in the wind shortly before it collapsed. Growing oscillations like these are why bridges and buildings are designed away from resonance. Image: Barney Elliot, Wikimedia Commons, CC0

See it around you: Pushing a child on a jhoola: small pushes timed with each swing build a big arc; the same pushes at random times do almost nothing.

Quick check

1. Why do soldiers break step on a bridge?
2. Tuning a radio to one station uses which effect?

Answer: 1. to avoid matching the bridge's natural frequency (resonance) · 2. electrical resonance

Doppler effect, Mach number and sonic boom

approaching: higher pitch

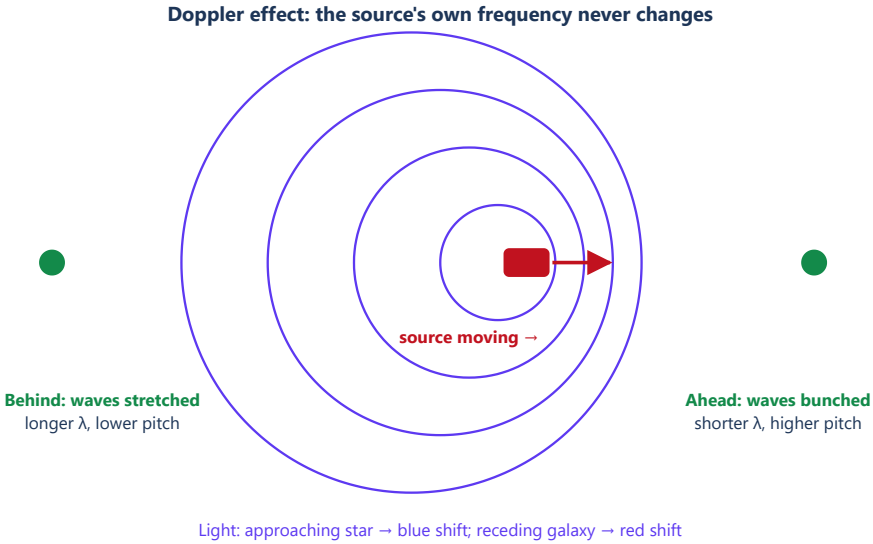
red shift

Mach number

sonic boom

supersonic vs ultrasonic

When a source moves towards you, each new wave starts a little closer, so the waves arrive bunched up: higher frequency, higher pitch. As it moves away, they arrive stretched out: lower pitch. This apparent change in frequency due to relative motion is the **Doppler effect** (Christian Doppler, 1842). It happens with light too.



Waves crowd together ahead of a moving source and spread out behind it, so the listener ahead hears a higher pitch.

★★★ **Approaching** source or listener → **higher** apparent pitch; **receding** → **lower** pitch. The source's actual frequency does not change.

★★★ **Train horn or ambulance siren** drops in pitch the moment it passes you.

★★★ **Red shift**: light from distant galaxies is shifted to longer (redder) wavelengths, so they are moving away; Edwin Hubble (1929) used this to show the **universe is expanding**.

★★ **Blue shift**: light from an approaching body shifts to shorter wavelengths; the Andromeda galaxy is blue-shifted, moving towards us.

★★ **Uses**: police **radar speed guns**, **Doppler weather radars** (track rain and cyclones), satellite tracking, Doppler ultrasound for blood flow, and bats judging the motion of insects.

★★★ **Mach number** = speed of the object ÷ speed of sound in the same medium. **Subsonic** below 1, **supersonic** above 1, **hypersonic** above 5.

★★★ **Sonic boom**: a supersonic aircraft drags a cone-shaped **shock wave** behind it; the cone sweeping over the ground is heard as a loud boom, all along the flight path, not just at the moment the plane crosses Mach 1.

★★ **Everyday shock waves**: the crack of a bullet and of a whip (its tip moves faster than sound).

★ **Indian examples**: BrahMos is a supersonic cruise missile (about Mach 2.8); DRDO's **HSTDV** demonstrated air-breathing hypersonic flight (scramjet) in 2020.

Remember it: 'Coming = Climbing, Going = Groaning': the siren climbs as it comes and groans down as it goes. For light: 'Blue Before, Red Retreating'.

⚠ **Exam trap:** The Doppler effect changes the frequency heard, not the speed of sound. And a sonic boom is not a one-time bang when the plane 'breaks the barrier'; it follows the plane as long as it flies faster than sound. Also, **supersonic** is about speed (faster than sound), **ultrasonic** is about frequency (above 20 kHz).

Quick check

1. An ambulance passes you. Does its siren's pitch go up or down?
2. What does the red shift of distant galaxies show?
3. Above which Mach number is a flight called hypersonic?

Answer: 1. down, as it moves away · 2. they are moving away: the universe is expanding · 3. Mach 5

Beats and interference

beats = $f_1 - f_2$

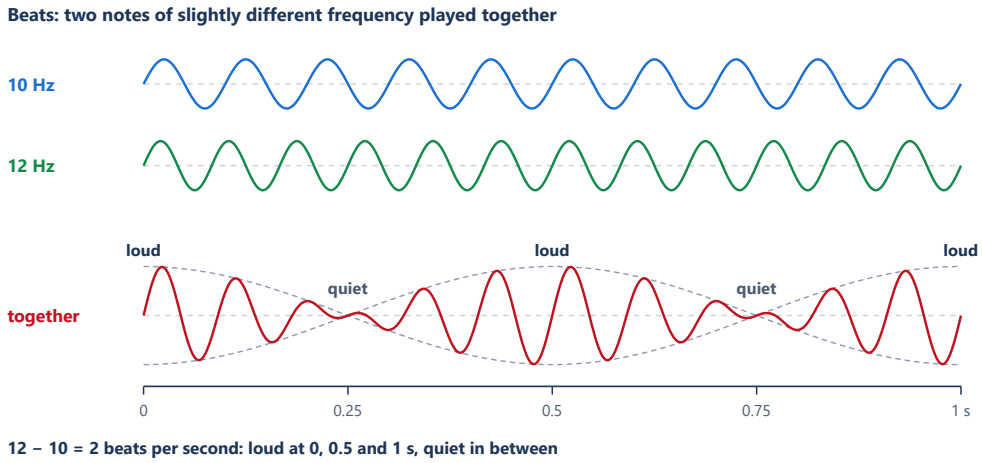
tuning by beats

constructive

destructive

noise cancelling

When two sound waves overlap they add up. Crest on crest makes it louder (constructive interference); crest on trough cancels (destructive interference). If two notes differ slightly in frequency, they drift in and out of step, so the loudness rises and falls regularly: these are **beats**.



Beats. Waves of 10 Hz and 12 Hz drift in and out of step, so the combined sound swells and fades 12 − 10 = 2 times a second. Frequencies are kept low so the waves can be seen; notes of 256 Hz and 260 Hz give 4 beats per second in the same way.

★★ **Beat frequency** = difference of the two frequencies ($f_1 - f_2$). Notes of 256 Hz and 260 Hz give 4 beats per second.

★★ **Musicians tune instruments with beats**: they adjust until the beats with a reference note (a tanpura or tuning fork) disappear.

★ **Beats are heard clearly** only when the difference is small, roughly up to 10 per second.

★★ **Noise-cancelling headphones** play a sound that is the exact opposite of outside noise, cancelling it by destructive interference.

Quick check

1. Tuning forks of 256 Hz and 260 Hz sound together. Beats per second?
2. Noise-cancelling headphones use which kind of interference?

Answer: 1. 4 · 2. destructive

Standing waves and musical instruments

nodes, antinodes

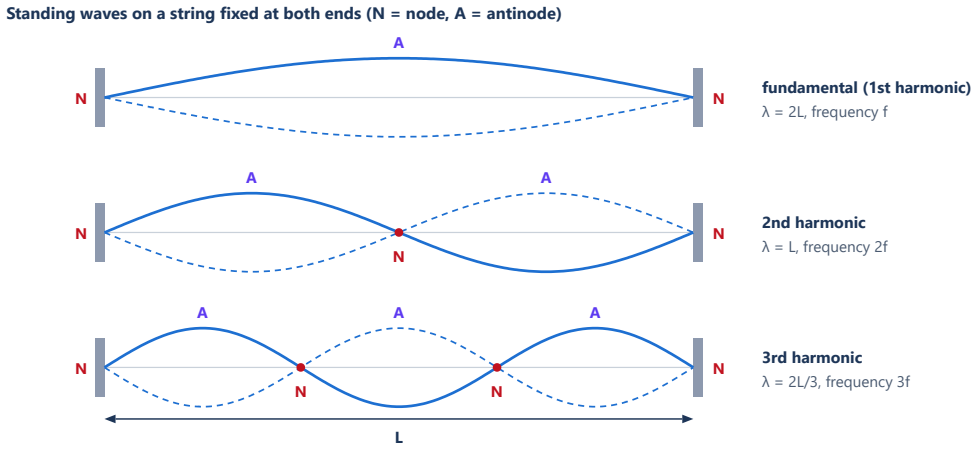
fundamental

harmonics

tension ↑ → pitch ↑

shorter air column: higher

A plucked string or a blown pipe reflects waves back and forth between its ends. Only waves that fit exactly survive, forming **standing waves** with fixed still points (**nodes**) and points of largest motion (**antinodes**). The longest fitting wave gives the **fundamental** note; shorter ones give the **overtones (harmonics)** that colour the sound.



Standing waves on a stretched string, drawn exactly. Only waves that fit between the fixed ends survive: the fundamental has λ = 2L, the next harmonics λ = L and 2L/3, giving frequencies f, 2f and 3f.

★★★ **Frequency of a stretched string** rises with **tension** and falls with **length** and **thickness (mass per unit length)**: $f \propto (1/L)\sqrt{(T/m)}$.

★★★ **Tuning a sitar or violin** by turning the pegs changes the string's **tension**, and so its **frequency**, to match the other instruments.

★★ **Pressing a string on a fret** shortens the vibrating length, giving a higher note; thicker strings give lower notes.

★★ **Wind instruments**: the vibrating air column sets the pitch; a shorter column gives a higher note (finger holes of a bansuri shorten it).

★★ **Filling a bottle with water** raises the pitch of the sound as the air column above the water shortens.

★ **A pipe closed at one end** gives only odd harmonics; a pipe open at both ends gives all harmonics, so they sound different.

★★ **Percussion**: a tighter drum skin gives a higher pitch; tabla players tap the rim straps to tune it.

★ **C.V. Raman** studied the violin and Indian drums; he showed that the black loaded centre (syahi) of the tabla and mridangam makes their overtones harmonic, giving a clear musical pitch unusual for drums.

Instruments by what vibrates ★★

Type	What vibrates	Indian examples	Others
String (chordophone)	Stretched string	Sitar, sarod, veena, santoor, ektara	Violin, guitar
Wind (aerophone)	Air column	Bansuri, shehnai, nadaswaram, harmonium (reeds)	Flute, trumpet
Membrane (membranophone)	Stretched skin	Tabla, mridangam, dholak, pakhawaj	Drum
Solid (idiophone)	The body itself	Jaltarang, ghatam, manjira, ghungroo	Cymbals, xylophone

Quick check

1. Tightening a sitar string raises or lowers its pitch?
2. As a bottle fills with water, the pitch of the sound _____ .
3. Points of a standing wave that never move are called _____ .

Answer: 1. raises it (more tension, higher frequency) · 2. rises (the air column gets shorter) · 3. nodes

The ear, stethoscope and everyday puzzles

eardrum

hammer, anvil, stirrup

cochlea

stethoscope: reflection

helium voice

★★ **How we hear**: the outer ear funnels sound to the **eardrum**, which vibrates; three tiny bones (hammer, anvil, stirrup) amplify it; the **cochlea** turns it into nerve signals for the brain.

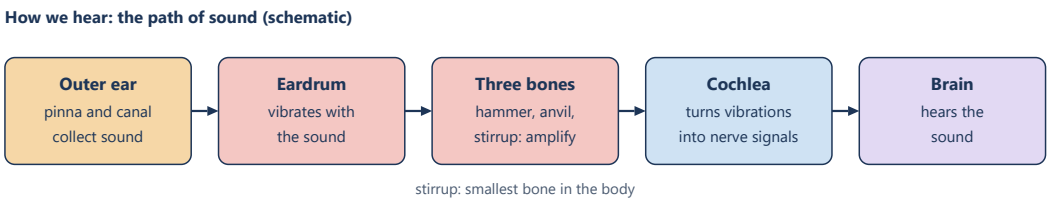
★ **Stirrup (stapes)** in the middle ear is the smallest bone in the human body.

★★★ **Stethoscope** (René Laennec, 1816): the chest-piece picks up heart and lung sounds, which reach the doctor's ears through the tubes by **multiple reflection** of sound.

★★ **Your recorded voice sounds strange** to you: normally you hear yourself partly through the bones of the skull, which adds deep tones; a recording captures only the sound through air.

★★ **Voice after inhaling helium** sounds squeaky: sound is nearly three times faster in helium, which raises the resonant frequencies of the throat and mouth and changes the voice's quality (the vocal cords' own rate barely changes).

★★ **A seashell 'sounds like the sea'**: it resonates with surrounding background noise.



The path of sound in the ear (schematic, not anatomy). The eardrum vibrates, three tiny bones amplify the vibration, and the cochlea turns it into nerve signals for the brain.

⚠ **Exam trap:** A stethoscope does not amplify sound electronically; it guides it by repeated reflection inside the tubes.

Quick check

1. Smallest bone in the human body?
2. Which part of the ear turns vibrations into nerve signals?
3. A stethoscope works on _____ of sound.

Answer: 1. the stirrup (stapes), in the middle ear · 2. the cochlea · 3. multiple reflection

Asked in past papers (4)

BPSC 65th Sound wave in air is
(a) transverse (b) longitudinal (c) electromagnetic (d) polarized
(e) None of the above/More than one of the above
Answer: (b) longitudinal. Sound in air is a longitudinal mechanical wave of compressions and rarefactions

BPSC 67th Which of the following rays/waves are used to know the growth of fetus in the womb?
(a) X-rays (b) Microwaves (c) Ultrasonic waves (d) Ultraviolet rays
(e) None of the above/More than one of the above
Answer: (c) Ultrasonic waves. Ultrasound (above 20 kHz) images the fetus because it is non-ionising

BPSC 68th Before playing the orchestra in a musical concert, a sitarist tries to adjust the tension and pluck the string suitably. By doing so, he/she is adjusting
(a) amplitude of sound (b) intensity of sound
(c) frequency of the sitar string with the frequency of other musical instruments
(d) More than one of the above (e) None of the above
Answer: (c) frequency of the sitar string with the frequency of other musical instruments. The frequency of a stretched string rises with its tension; Pitch depends on frequency; loudness depends on amplitude

BPSC 71st In which medium, the speed of sound is maximum?
(a) Steel (b) Water (c) Air (d) Hydrogen
Answer: (a) Steel. Sound is fastest in solids, slower in liquids and slowest in gases

Test yourself (13)

1. A man sees a lightning flash and hears the thunder 6 seconds later. The storm is about
(a) 1 km away (b) 2 km away (c) 6 km away (d) 500 m away

2. The speed of sound in air does NOT change with a change in
(a) temperature of the air (b) humidity of the air (c) pressure, if temperature is fixed
(d) density of the air, at fixed pressure

3. Which of the following animals communicate using infrasound?
(a) Bats (b) Dolphins (c) Elephants (d) Mosquitoes

4. The quality (timbre) of a sound depends on its
(a) amplitude (b) waveform (c) frequency (d) speed

5. When sound passes from air into water, which of these remains unchanged?
(a) Frequency (b) Wavelength (c) Speed (d) Both speed and wavelength

6. Red shift in the light of distant galaxies is evidence that
(a) they are moving towards us (b) the universe is expanding (c) they are made mostly of hydrogen gas (d) their surfaces are extremely hot

7. Soldiers are ordered to break step while crossing a suspension bridge to avoid
(a) echo (b) beats (c) Doppler effect (d) resonance

8. An increase of 20 dB in sound level means the intensity has become
(a) 2 times (b) 20 times (c) 100 times (d) 200 times

9. SONAR sends a pulse that returns from the seabed after 4 s. If sound travels at 1500 m/s in sea water, the depth is
(a) 1500 m (b) 3000 m (c) 6000 m (d) 750 m

10. The minimum distance of a reflecting wall needed to hear a distinct echo in air is about
(a) 17 m (b) 34 m (c) 10 m (d) 100 m

11. Consider the following statements:
1. The pitch of a sound depends on its frequency.
2. The loudness of a sound depends on its frequency.
3. Sound in air cannot be polarised because it is a longitudinal wave.
Which of the statements given above is/are correct?
(a) 1 and 2 only (b) 2 and 3 only (c) 1 and 3 only (d) 1, 2 and 3

12. Consider the following:
1. Bats catching insects in the dark
2. Elephants calling to one another over long distances
3. A ship's SONAR measuring the depth of the sea
In how many of the above is ultrasound used?
(a) Only one (b) Only two (c) All three (d) None

13. You stand on a railway platform while an express train passes through at a steady speed, sounding its horn all the time. What do you hear?
(a) A higher pitch as it approaches, a lower pitch once it passes
(b) A lower pitch as it approaches, a higher pitch once it passes
(c) The same pitch throughout; only the loudness changes
(d) The same pitch, but the sound reaches you faster as the train nears

Answers: 1. (b) Sound covers about 1 km in 3 s, so 6 s ≈ 2 km. · 2. (c) At constant temperature, pressure has no effect on the speed of sound in air. · 3. (c) Elephants and whales use infrasound; bats and dolphins use ultrasound. · 4. (b) Waveform (overtones) gives quality; amplitude gives loudness, frequency gives pitch. · 5. (a) Frequency is set by the source; speed and wavelength increase in water. · 6. (b) Red shift means the galaxies are moving away, as the Doppler effect for light shows. · 7. (d) Rhythmic marching could match the bridge's natural frequency. · 8. (c) Each 10 dB is a factor of 10, so 20 dB is 10 × 10. · 9. (b) Depth = 1500 × 4 ÷ 2 = 3000 m. · 10. (a) The echo must arrive 0.1 s later: 344 × 0.1 ÷ 2 ≈ 17.2 m. · 11. (c) Loudness depends on amplitude, not frequency (a lion's roar is loud but low-pitched); statements 1 and 3 are correct. · 12. (b) Bats and SONAR use ultrasound (above 20 kHz); elephants communicate with infrasound (below 20 Hz), the pair examiners usually swap. · 13. (a) Doppler effect: waves from an approaching source arrive bunched (higher frequency) and from a receding one stretched (lower); the speed of sound in air does not change.

CHAPTER 8

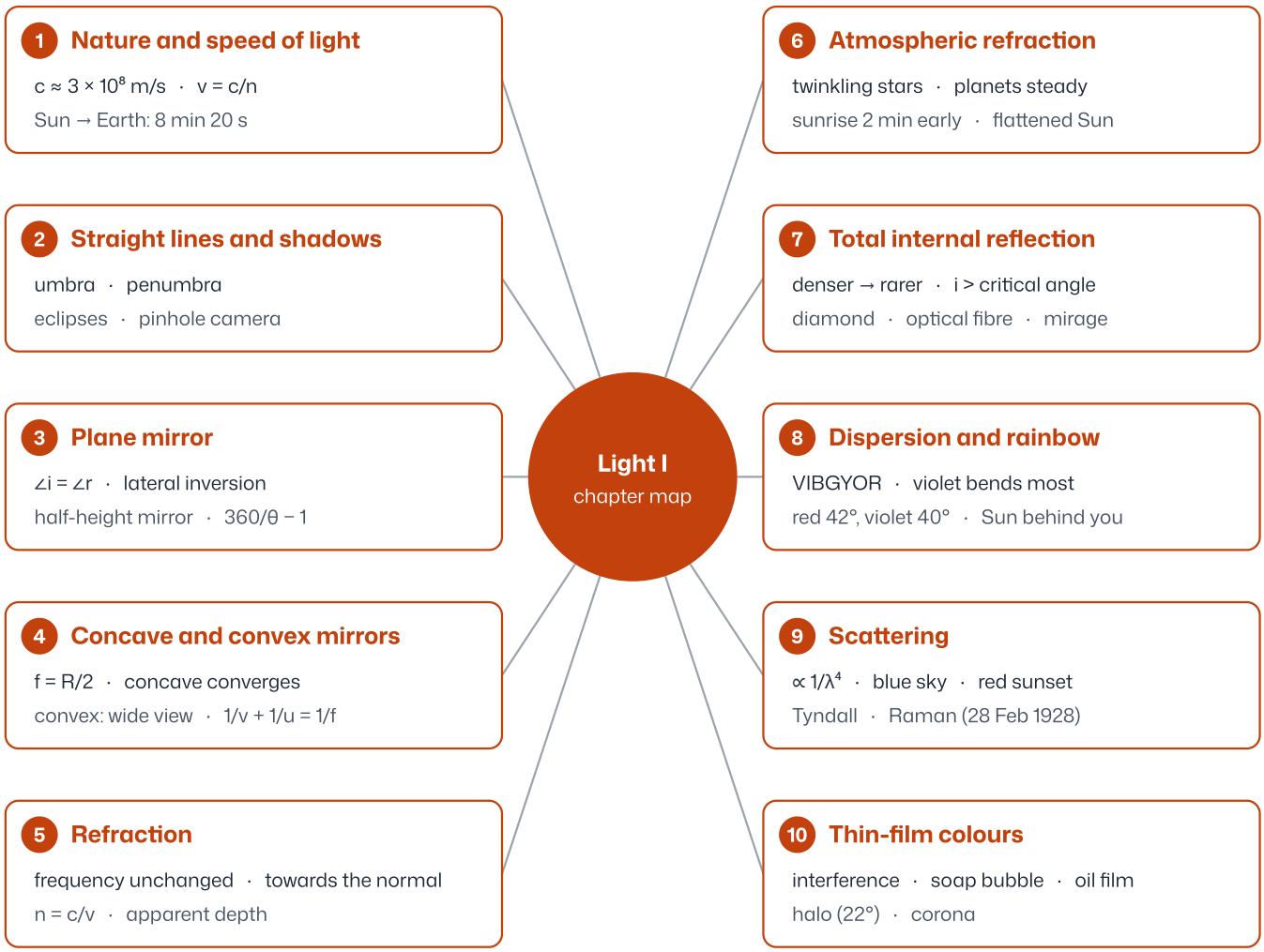
Light I: Reflection, Refraction and Optical Phenomena

Image by mirror type and object position, slowest light in the densest medium, twinkling of stars, total internal reflection, rainbow, scattering (blue sky, red sunset) and the Raman effect are asked almost every year.

Asked 10 times in past papers: UPSC 2 · BPSC 8

≈ 50 min to read ≈ 9 min to revise ★★★

Revise on: Day 1 | Day 3 | Day 7 | Day 21



Revision card

1. Light in vacuum: c ≈ 3 × 10^8 m/s; slower in water (≈ 2.25 × 10^8) and glass (≈ 2 × 10^8); slowest in diamond (n = 2.42). Sunlight reaches Earth in ≈ 8 min 20 s.
2. On refraction **frequency never changes**; speed and wavelength change. Light bends **towards the normal** entering a denser medium.
3. Shadows and the pinhole camera (real, inverted image) prove light travels in straight lines (rectilinear propagation).
4. Plane mirror: virtual, erect, same size, laterally inverted; focal length infinite; full-length mirror needs only half your height; images between two mirrors = 360/θ − 1.
5. Concave mirror: object at C → real, inverted, same-size image at C; object inside F → virtual, erect, enlarged (shaving mirror). Convex mirror: always virtual, erect, smaller, wide view (rear-view mirror).
6. Twinkling of stars, Sun seen ~2 min before sunrise and after sunset, flattened Sun at horizon, pencil bent in water, pond looking shallow: all refraction.
7. Total internal reflection needs denser → rarer and angle > critical angle (glass ≈ 42°, water ≈ 49°, diamond ≈ 24°): diamond sparkle, optical fibre, mirage, looming.
8. Prism dispersion: VIBGYOR; violet bends most, red least (Newton). Rainbow = refraction + dispersion + internal reflection; Sun behind you; red outside in the primary bow.
9. Rayleigh scattering ∝ $1/\lambda^4$: blue sky, red sunrise/sunset, red danger signals, black sky in space; white clouds scatter all colours equally.
10. Tyndall effect: beam made visible by colloidal particles (sunbeam in a dusty room, headlights in fog).
11. Raman effect: scattered light changes frequency; C.V. Raman, 28 Feb 1928; Nobel 1930; National Science Day 28 Feb.
12. Colours of soap bubbles and oil films come from interference, not dispersion.

What light is and how fast it goes

dual nature

c = 3 × 10^8 m/s

v = c/n

8 min 20 s

light year

Light is energy that travels as an **electromagnetic wave**: it needs no medium, so it crosses empty space from the Sun. Yet when it hits matter it also acts like a stream of tiny energy packets. Both pictures are true; which one shows up depends on the experiment.

★★ **Dual nature**: light behaves as a **wave** (reflection, refraction, interference, diffraction, polarisation) and as a **particle** (photoelectric effect).

★★ **Photon**: a packet (quantum) of light energy, E = hf. Einstein used light quanta in **1905** to explain the photoelectric effect (Nobel Prize **1921**).

★ **Theories in order**: Newton's corpuscles (particles) → Huygens' waves (1678) → Young's double-slit proof of waves (1801) → Maxwell: light is an electromagnetic wave (1860s) → Einstein's photons (1905).

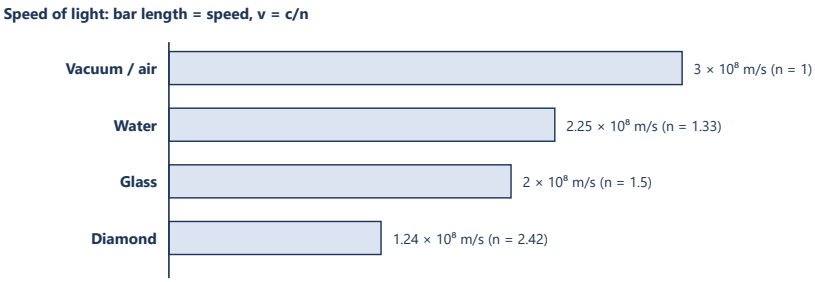
★★★ **Speed of light in vacuum** c = 299,792,458 m/s exactly (≈ **3 × 10^8 m/s**). Nothing travels faster. The metre itself is defined from this value.

★★★ **Slower in matter**: air ≈ c; water ≈ 2.25 × 10^8 m/s; glass ≈ 2 × 10^8 m/s; diamond ≈ 1.24 × 10^8 m/s. The higher the refractive index, the slower the light (v = c/n).

★★★ **Sun to Earth**: light takes ≈ **8 min 20 s** (≈ 499 s) over 1 AU (≈ 1.5 × 10^8 km). Moon to Earth ≈ **1.3 s**.

★ **First measurement** of light's speed: Ole Rømer (1676), from delays in eclipses of Jupiter's moon Io.

★★ **Light year** = distance light travels in one year ≈ 9.46×10^{15} m. It is a unit of **distance**, not time.



Speed of light drawn to scale: each bar is c/n. The higher the refractive index, the shorter the bar and the slower the light.

⚠ **Exam trap:** 'The speed of light will be minimum in: glass / water / vacuum / air' → **glass** (highest refractive index of the four). Vacuum is the fastest, not the slowest.

Remember it: Sunlight you see left the Sun **8 minutes 20 seconds ago**: think of it as 'Sun's 8:20 news'. Lightning is seen before thunder is heard because light is about a million times faster than sound.

Quick check

1. Sunlight takes about how long to reach Earth?
2. Air, water, glass, diamond: in which is light slowest, and why?
3. A light year is a unit of _____ , not of time.

Answer: 1. ≈ 8 min 20 s · 2. diamond: highest n (2.42), and v = c/n · 3. distance (≈ 9.46×10^{15} m)

Light travels in straight lines: shadows, eclipses, pinhole camera

rectilinear propagation

umbra / penumbra

solar eclipse

lunar eclipse

pinhole camera

In a uniform medium light goes in **straight lines** (rectilinear propagation). So an opaque object blocks the rays that would have passed through it, leaving a dark region behind: a **shadow**. Diffraction, interference and polarisation are wave effects and do not explain shadows.

★★★ **Shadow** forms because of **rectilinear propagation** of light: opaque objects stop light, transparent ones let it pass, translucent ones let some through.

★★ **Umbra**: the fully dark central part where no light from the source arrives. **Penumbra**: the partly lit fringe where only part of the source is hidden. A point source gives only an umbra; a big source (Sun) gives both.

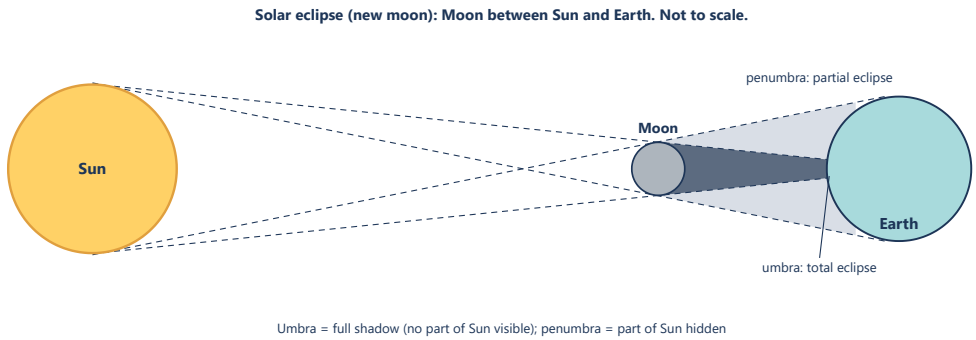
★★ **Solar eclipse**: Moon comes between Sun and Earth, only on a **new-moon day (amavasya)**. Inside the Moon's umbra: total eclipse; in the penumbra: partial eclipse. When the Moon is far (umbra does not reach Earth) the Sun's rim shows as a ring: **annular eclipse** ('ring of fire').

★★ **Lunar eclipse**: Earth comes between Sun and Moon, only on a **full-moon night (purnima)**. In a total lunar eclipse the Moon looks coppery red ('blood moon') because Earth's atmosphere bends and scatters red sunlight into the shadow.

★ **Not every month**: the Moon's orbit is tilted about 5° to Earth's orbit, so Sun, Moon and Earth line up exactly only a few times a year.

★★ **Pinhole camera**: a box with a tiny hole forms a **real, inverted** image on the opposite screen, because rays from the top of the object go straight through the hole to the bottom of the screen. A smaller hole gives a sharper but dimmer image.

★ **Never look at the Sun** during a solar eclipse without proper solar filters; a pinhole projection is the safe way.



Solar eclipse. The dark cone behind the Moon is the umbra (total eclipse where it touches Earth); the lighter region is the penumbra (partial eclipse). Not to scale.

See it around you: Under a tree on a sunny day the bright spots on the ground are **round**, whatever the shape of the gaps between leaves: each gap acts as a pinhole and makes an image of the round Sun. During a partial solar eclipse the spots turn into crescents.

Quick check

1. A shadow proves which property of light?
2. Inside the umbra or the penumbra: where is a solar eclipse total?
3. A solar eclipse can happen only on amavasya or on purnima?

Answer: 1. rectilinear propagation: it travels in straight lines · 2. umbra (penumbra gives a partial eclipse) · 3. amavasya (new moon); a lunar eclipse on purnima

Reflection and the plane mirror

laws of reflection

lateral inversion

half-height mirror

360/θ − 1

kaleidoscope

When light hits a surface and bounces back into the same medium, it is **reflected**. A smooth surface sends all parallel rays off in one direction (clear image); a rough surface scatters them in all directions. That scattered, **diffuse reflection** is how we see a page, a wall or a face.

★★★ **Laws of reflection**: (1) angle of incidence = angle of reflection, both measured from the **normal**; (2) incident ray, reflected ray and normal lie in **one plane**. They hold for plane and curved mirrors alike.

★ **Regular vs diffuse**: mirror, still water → regular (image); paper, wall, cloth → diffuse (no image, but the object becomes visible from every side).

★★★ **Plane-mirror image**: **virtual, erect, same size**, as far behind the mirror as the object is in front, and **laterally inverted** (left and right swapped).

★★★ **AMBULANCE** is painted in mirror writing on the front so that a driver ahead reads it correctly in the rear-view mirror.

★★★ **Focal length of a plane mirror = infinity** (its radius of curvature is infinite). Magnification = +1.

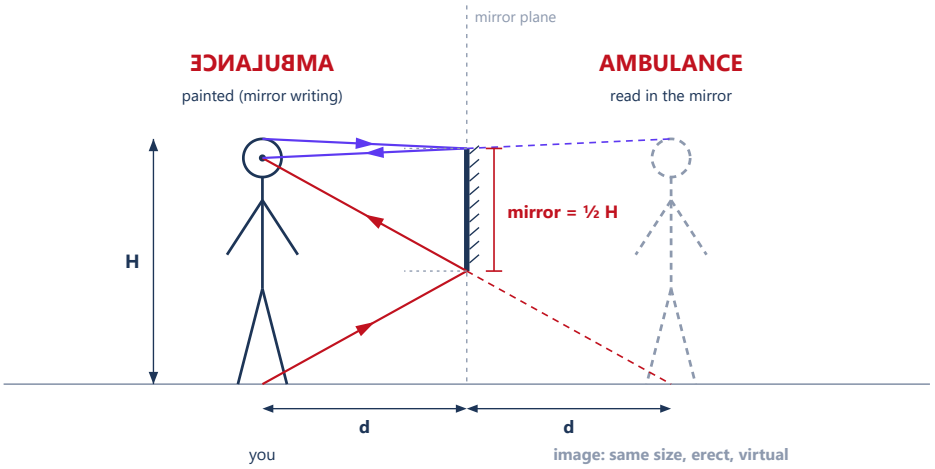
★★★ **Full-length image**: the mirror needs to be only **half your height**, whatever your distance from it (top edge level with the point midway between eyes and the top of the head).

★★ **Walking towards a mirror** at speed v, your image approaches **you** at 2v. Turning a mirror by angle θ turns the reflected ray by 2θ.

★★★ **Two mirrors at angle θ** give **360/θ − 1** images (exact when 360/θ is even): 90° → 3, 60° → 5, 45° → 7, 30° → 11. **Parallel mirrors** (θ = 0, as in a barbershop or lift) give **infinite** images.

★★ **Kaleidoscope**: three long plane mirrors at **60°** to each other form a triangular tube; repeated reflections of loose coloured bits make symmetric patterns. **Periscope**: two plane mirrors at 45°, facing each other, to see over obstacles.

Remember it: Half-height rule: light from your toes reaches your eyes after reflecting from a point **halfway down** between eyes and toes; from your hair, halfway up. So only half your height of glass is ever used.



Plane mirror, drawn to scale. Light from your toes and from the top of your head reflects at points halfway between them and your eyes, so the mirror needs only half your height (90 of 180 units here). The image is as far behind the mirror (d) as you are in front, and AMBULANCE painted in mirror writing reads correctly in the mirror.

⚠ **Exam trap:** Lateral inversion swaps **left–right**, not **up–down**. Your raised right hand appears as the image's left hand, but your head stays on top.

Quick check

1. Shortest plane mirror in which you see your full height?
2. Why is AMBULANCE painted in mirror writing?
3. How many images do two mirrors at 60° form?

Answer: 1. half your height, at any distance · 2. lateral inversion: it reads correctly in a rear-view mirror · 3. 5 (360/60 − 1)

Spherical mirrors: concave and convex

concave: converging

convex: diverging

f = R/2

object at C

rear-view mirror

A spherical mirror is a slice of a hollow shining ball. If the shining side is the **inside** (caved in), it is **concave** and pulls parallel rays together to a point: a **converging** mirror. If the shining side **bulges out**, it is **convex** and spreads rays apart: a **diverging** mirror.

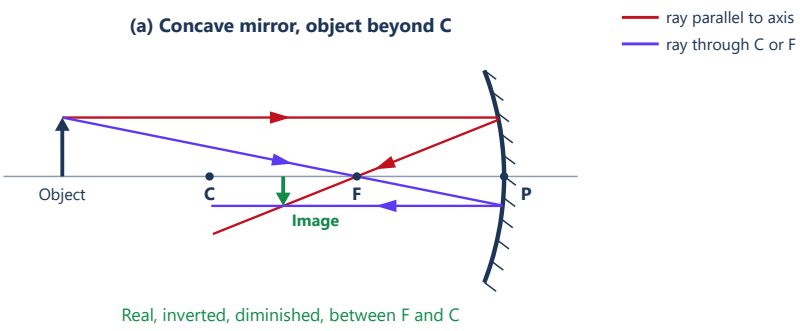
★★ **Key points**: pole P (centre of the mirror), centre of curvature C (centre of the sphere), principal focus F, radius R = PC, **focal length f = R/2**.

★★ **Concave mirror** focus is real (in front); **convex mirror** focus is virtual (behind the mirror).

★ **Three easy rays** for drawing: a ray parallel to the axis reflects through F (or appears to come from F for convex); a ray through (or towards) F reflects parallel; a ray through (or towards) C returns along itself.

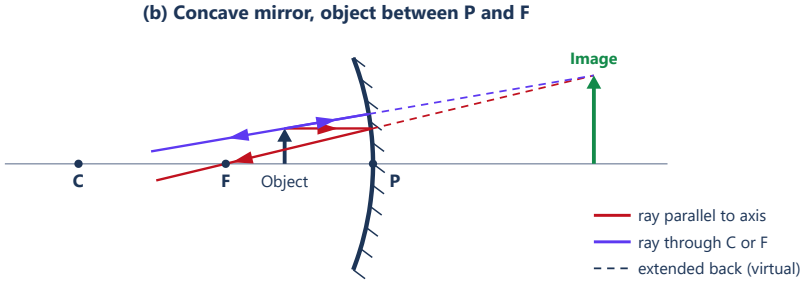
Concave mirror: where the image forms ★★★

Object at	Image at	Size	Nature	Use
Infinity	F	Point-sized	Real, inverted	Solar cooker, solar furnace
Beyond C	Between F and C	Diminished	Real, inverted	No common use
C	**C**	**Same size**	**Real, inverted**	No common use
Between C and F	Beyond C	Enlarged	Real, inverted	No common use
F	Infinity	Highly enlarged	Real, inverted	Torch, headlight (bulb at F gives a parallel beam)
Between F and P	Behind the mirror	**Enlarged**	**Virtual, erect**	Shaving / make-up mirror, dentist's mirror



Real, inverted, diminished, between F and C

(a) Concave mirror, object beyond C: real, inverted, smaller image between F and C. Drawn to scale (R = 200 units).

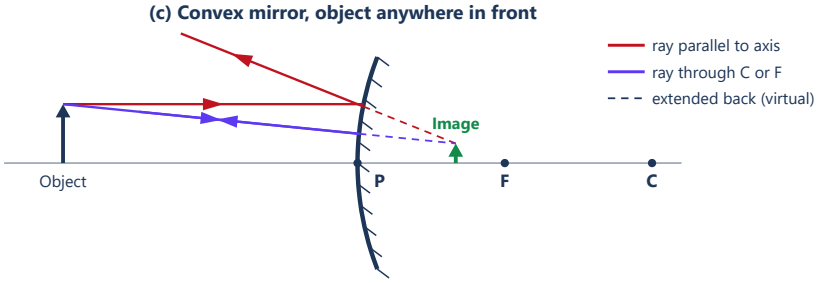


Virtual, erect, enlarged, behind the mirror

(b) Concave mirror, object between P and F: virtual, erect, enlarged image behind the mirror, as in a shaving mirror. Drawn to scale (R = 200 units).

Convex mirror ★★

Object at	Image at	Size	Nature
Infinity	F, behind the mirror	Point-sized	Virtual, erect
Anywhere in front	Between P and F, behind	Diminished	Virtual, erect



Virtual, erect, diminished, between P and F behind the mirror

(c) Convex mirror: wherever the object is, the image is virtual, erect and smaller, between P and F behind the mirror, as in a rear-view mirror. Drawn to scale (R = 200 units).

★★★ **Concave mirror uses**: shaving and make-up mirrors, dentist's and ENT doctor's mirrors (enlarged erect view), reflectors of torches, vehicle headlights and searchlights (bulb at focus), solar cookers and solar furnaces (sunlight focused to a hot spot), reflecting telescopes, dish antennas.

★★★ **Convex mirror uses**: rear-view and side mirrors of vehicles, blind-turn mirrors on hill roads, security mirrors in shops and ATMs: always an erect image and a much **wider field of view**.

★★ **Mirror formula**: 1/v + 1/u = 1/f; magnification m = h′/h = −v/u. Sign idea in one line: distances measured from the pole, positive along the incoming light and negative against it, so a concave mirror has negative f and a convex mirror positive f.

★★ **Quick identification by the image**: same-size erect → plane; larger erect → concave (object inside F); smaller erect at every distance → convex.

Remember it: Con**cave** = a **cave** you look into: it gathers light (converges). Con**vex** bulges out like a **vexed** puffed-up cheek: it spreads light and shows more of the road but smaller.

⚠ **Exam trap:** 'Objects in mirror are closer than they appear' is printed on **convex** side mirrors: the small image makes cars look farther than they are. A person who sees an **enlarged** image of himself is in front of a **concave** mirror, inside its focus.

Quick check

1. Object at C of a concave mirror: where is the image, and what is it like?
2. Which mirror is used for a vehicle's rear view, and why?
3. Focal length of a spherical mirror in terms of R?

Answer: 1. at C: real, inverted, same size · 2. convex: always erect, much wider field of view · 3. f = R/2

Refraction: why light bends

frequency unchanged

towards the normal

Snell's law

n = c/v

apparent depth

Light **changes speed** when it passes from one medium into another, and if it enters at a slant, one side of the beam slows down first, so the beam turns: this is **refraction**. Think of a car whose left wheels roll off the road into sand: those wheels slow and the car swerves. Going into a slower (optically denser) medium light bends **towards the normal**; coming out it bends **away**.

★★★ **Frequency stays the same** when light goes from one medium to another; **speed and wavelength change** (λ in medium = λ in vacuum / n). Colour depends on frequency, so a red light still looks red under water.

★★★ **Bending rule**: rarer → denser: towards the normal; denser → rarer: away from the normal. A ray along the normal (90° to the surface) goes straight without bending.

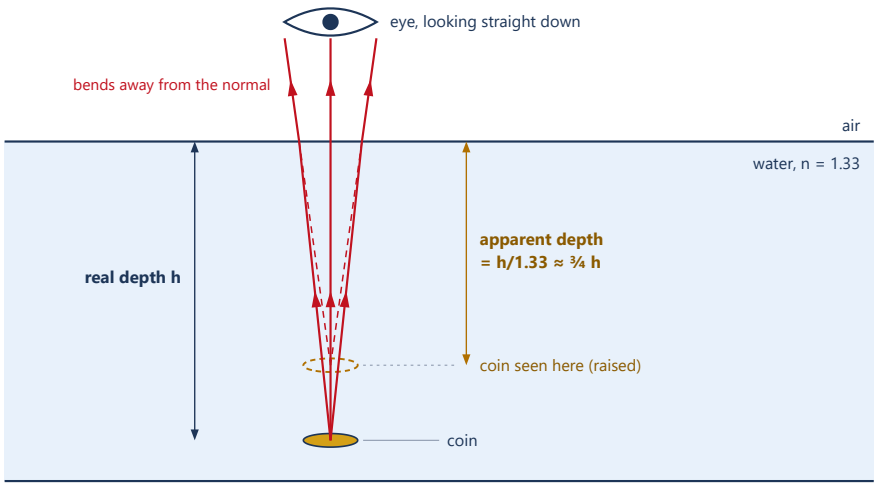
★★ **Snell's law**: sin i / sin r = constant = refractive index of the second medium relative to the first. Incident ray, refracted ray and normal lie in one plane.

★★★ **Refractive index** n = c / v (speed in vacuum ÷ speed in medium). Air 1.0003, ice 1.31, **water 1.33**, alcohol 1.36, kerosene 1.44, **glass ≈ 1.5**, rock salt 1.54, ruby 1.71, **diamond 2.42**.

★★ **n depends on colour**: in glass it is largest for violet, smallest for red; that is why a prism splits white light.

★★ **Apparent depth**: a pond, bucket or swimming pool looks **shallower** than it is (apparent depth = real depth / n ≈ ¾ of the real depth for water).

★★ **Everyday refraction**: a pencil in water looks bent at the surface; a coin at the bottom of a bowl seems raised, and comes into view when water is poured in; a fish looks higher than it really is, so a spear must be aimed below it; letters under a glass slab look raised.



Apparent depth, drawn with Snell's law for water (n = 1.33). Rays from the coin bend away from the normal as they leave the water; traced back, they meet about ¾ of the way down, so the coin looks raised. Seen from straight above, apparent depth = real depth ÷ 1.33.

⚠ **Exam trap:** Optical density is **not** mass density. Kerosene (n = 1.44) is lighter than water but optically denser; light travels slower in it than in water.

⚠ **Exam trap:** An **air bubble in water** acts as a **diverging** (concave) lens, though it is shaped like a convex lens, because the bubble is the rarer medium.

Remember it: Slow → bends towards the normal: like a student slowing down and turning to face the teacher (normal) when entering the classroom.

Quick check

1. When light enters water, which does not change: speed, wavelength or frequency?
2. Light going from air into glass bends towards or away from the normal?
3. Why does a pond look shallower than it is?

Answer: 1. frequency · 2. towards the normal (into a denser medium) · 3. refraction: apparent depth = real depth / n, about ¾ for water

Refraction by the atmosphere

twinkling

planets steady

advanced sunrise

flattened Sun

Air is not uniform: lower layers are denser than upper ones, and warm and cold pockets keep moving. So starlight and sunlight bend gradually as they come down through the atmosphere, and the bending keeps flickering.

★★★ **Twinkling of stars** is due to **atmospheric refraction**. A star is so far away that it is a **point source**; its light passes through moving air layers of changing refractive index, so its apparent position and brightness keep flickering.

★★★ **Planets do not twinkle**: they are near enough to look like small **discs**. A disc is many point sources together; their flickers average out.

★★ **No twinkling in space**: seen from the Moon or by an astronaut, stars shine steadily (no atmosphere). Stars near the horizon twinkle most (longest path through air).

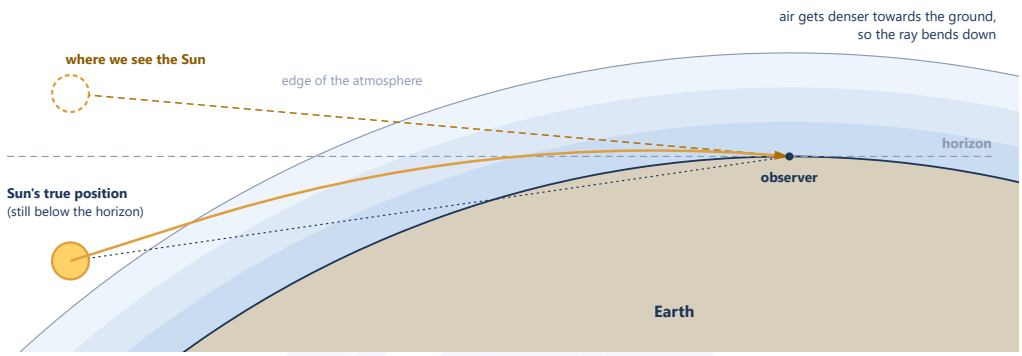
★★ **Stars appear slightly higher** than their true position, because their light bends towards the normal as it enters denser air.

★★★ **Advanced sunrise and delayed sunset**: refraction lets us see the Sun about **2 minutes before** it actually rises and **2 minutes after** it sets, lengthening the day by about 4 minutes.

★★ **Flattened (oval) Sun at the horizon**: light from the lower edge passes through denser air and is lifted more than light from the upper edge, so the disc looks squashed vertically.

★★ **Optical illusions of the sky**: twinkling of stars (refraction), the reddish Sun at dawn and dusk (scattering) and the **big-looking Sun or Moon near the horizon** (a trick of perception; refraction actually makes it slightly smaller vertically). A Moon visible at dawn or the Pole Star in the sky are real sights, not illusions.

★ **Shimmering** of objects seen through hot air above a fire, a road or a tandoor is the same effect on a small scale.



Advanced sunrise. Air gets denser towards the ground, so incoming sunlight bends down and reaches us from a little above the horizon while the Sun is still below it. Not to scale: the air layer and the bending are hugely exaggerated.

⚠ **Exam trap:** Twinkling is **refraction**, not reflection, polarisation or interference. And it is the **stars** that twinkle; planets shine steadily.

Remember it: Stars are tiny dots, planets are tiny plates: a dot flickers easily, a plate does not.

Quick check

1. Why do stars twinkle but planets do not?
2. Refraction lets us see the Sun how long before it actually rises?
3. Why does the Sun look flattened at the horizon?

Answer: 1. a star is a point source; a planet is a disc whose flickers average out · 2. about 2 minutes (the day is ≈ 4 minutes longer) · 3. its lower edge is lifted more by the denser air below

Total internal reflection

denser → rarer

critical angle

diamond sparkle

optical fibre

mirage / looming

When light goes from a denser medium into a rarer one, it bends away from the normal. Tilt the ray more and the refracted ray bends further until it skims along the surface: that angle of incidence is the **critical angle**. Tilt it any more and no light can get out at all: it is **totally reflected** back, losing almost nothing. Even the best mirror loses some light; TIR loses practically none.

★★★ **Two conditions for TIR**: light must go from **denser to rarer** medium, and the angle of incidence must be **greater than the critical angle**.

★★ **Critical angle** C: sin C = 1/n. Water ≈ **48.6°**, crown glass ≈ **42°**, diamond ≈ **24.4°** (smallest, because n is largest).

★★★ **Diamond sparkles** because its critical angle is tiny; light entering a well-cut diamond is totally reflected again and again inside before escaping through the top.

★★★ **Optical fibre**: a thin glass core of higher n inside a cladding of lower n. Light keeps hitting the boundary above the critical angle and is trapped, following the fibre even round bends. Used for internet and telephone links, endoscopy (seeing inside the body) and decorative lamps.

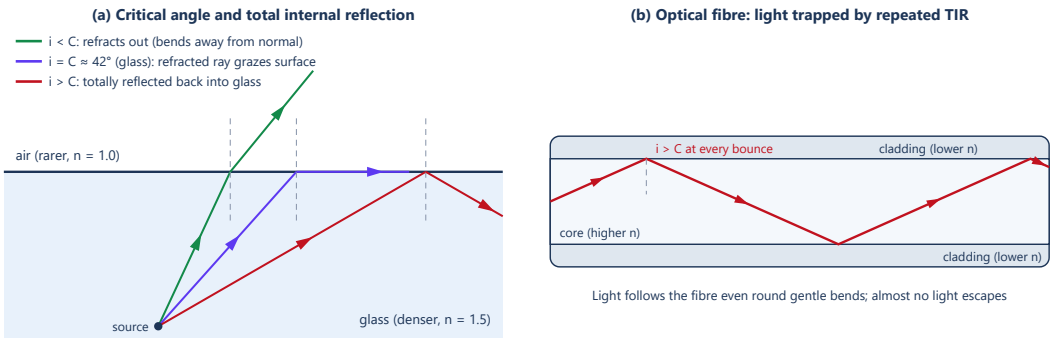
★ **Indian link**: Narinder Singh Kapany, born in Moga (Punjab), is called the father of fibre optics; Charles Kao won the 2009 Nobel Prize for showing fibres could carry signals over long distances.

★★★ **Mirage** (deserts and hot roads in summer): air near the hot ground is hotter and **rarer**. Light from the sky bends more and more upward through the layers and is finally totally reflected, so the eye sees an inverted image of the sky on the ground that looks like a pool of water.

★★ **Looming** (cold regions, polar seas): air near the cold sea is **denser** than above, so light from a distant ship bends downward and the ship appears **raised, floating in the sky**.

★★ **Silvery test tube**: an empty test tube dipped slantwise in water shines like a mirror when seen from above, because light is totally reflected at the glass–air surface inside. Pour water into the tube and the shine disappears. An **air bubble in water** shines for the same reason.

★ **Prisms in place of mirrors**: right-angled glass prisms use TIR to turn light by 90° or 180° in binoculars, periscopes and cameras; they give brighter images than silvered mirrors.



(a) Light from inside glass: below the critical angle it escapes, at the critical angle it grazes the surface, above it it is totally reflected. (b) In an optical fibre every bounce is above the critical angle, so light stays inside.

Mirage on a hot highway: the road ahead looks wet and the cars seem reflected in it. The "water" is an image of the sky, formed by refraction and total internal reflection in the hot air just above the road. Image: Michael from Calgary, AB, Canada, Wikimedia Commons, CC BY 2.0

⚠ **Exam trap:** A mirage is **not** a hallucination and not reflection from water; it is refraction through layers of hot air ending in total internal reflection, and it can be photographed.

Remember it: Mirage = hot below (desert, road), image below. Looming = cold below (sea ice), image above.

Quick check

1. The two conditions for total internal reflection?
2. Why does a diamond sparkle?
3. Mirage: is the air near the ground hotter or colder than above?

Answer: 1. denser → rarer, and angle of incidence > critical angle · 2. its critical angle is tiny (≈ 24.4°), so light is totally reflected again and again · 3. hotter and rarer (looming: colder and denser)

Dispersion and the rainbow

VIBGYOR

violet bends most

rainbow: 3 processes

red outside

Sun behind you

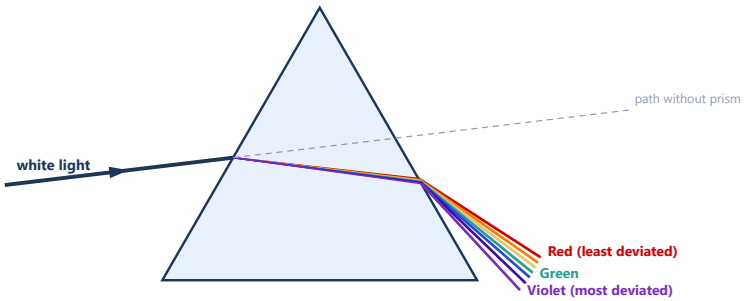
White light is a mixture of colours. Glass slows each colour by a different amount: violet most, red least. So in a prism each colour bends through a different angle and the colours fan out into a **spectrum**. This splitting is **dispersion**.

★★★ **Dispersion**: splitting of white light into seven colours, **VIBGYOR** (violet, indigo, blue, green, yellow, orange, red). **Isaac Newton** showed it with a glass prism (1666).

★★★ **Violet deviates most, red least**: glass has the highest refractive index for violet, so violet travels slowest in glass and bends most. In vacuum all colours travel at the same speed.

★★ **Recombination**: a second, inverted prism placed after the first joins the colours back into white light (Newton's proof that the colours were in sunlight, not made by the glass).

★★ **Order of wavelength**: red longest (~700 nm), violet shortest (~400 nm); frequency is the reverse.



Glass prism: each colour bends by a different amount (spread exaggerated)

Each colour leaves the prism in a different direction. All colours bend towards the base; violet bends most, red least. Spread exaggerated.

A **rainbow** is the same dispersion done by millions of raindrops. Each drop **refracts** sunlight as it enters, **reflects** it once off its back surface and **refracts** it again on the way out; both refractions spread the colours. Light comes back at about **42° for red and 40° for violet** from the line joining the Sun to your head.

★★★ **Rainbow = refraction + dispersion + internal reflection** inside water drops.

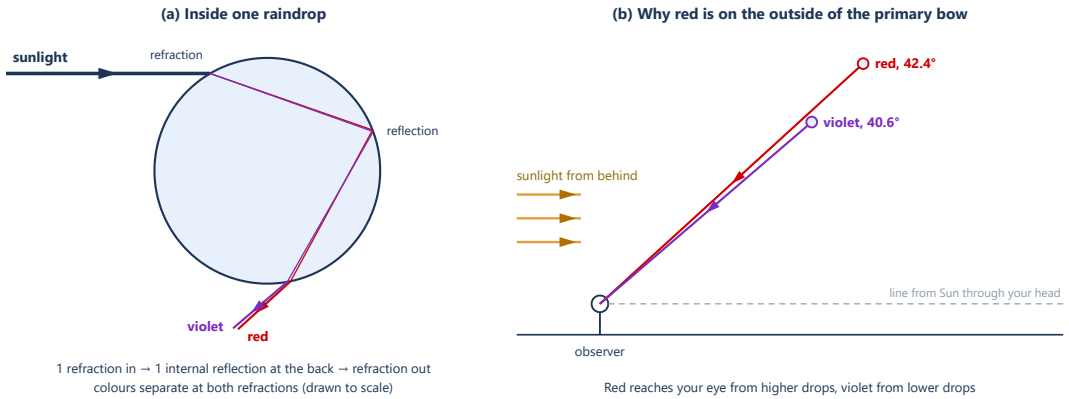
★★★ **Sun behind the observer**, rain in front: a rainbow is always seen in the part of the sky **opposite the Sun**: in the **west in the morning**, in the **east in the evening**.

★★★ **Primary rainbow**: one internal reflection, brighter, **red on the outside (top)**, violet inside.

★★ **Secondary rainbow**: two internal reflections, fainter, higher (about 51°), **colours reversed** (red inside). The darker sky between the two bows is called Alexander's band.

★ **Why rainbows are low or absent at noon**: the bow lies 42° from the point opposite the Sun; when the Sun is higher than 42° the whole bow is below the horizon. From an aircraft a rainbow can be a full circle.

★ **Each person sees a personal rainbow**, made by a different set of drops.



(a) Path inside one drop: refraction in, one reflection at the back, refraction out; colours separate at both refractions. (b) Red reaches the eye from higher drops and violet from lower ones, so red is the outer band of a primary rainbow. Both panels are drawn to scale with the minimum-deviation angles from Snell's law: red (n = 1.331) 42.4°, violet (n = 1.343) 40.6°, usually rounded to 42° and 40°.

A double rainbow. The bright primary bow has red on the outside; in the fainter secondary bow above it the colours are reversed, and the sky between the two bows is darker (Alexander's band). Image: Eric Rolph, Wikimedia Commons, CC BY-SA 2.5

⚠ **Exam trap:** The reflection inside a raindrop is called internal reflection; it is a partial reflection, because the angle at the back of the drop is less than water's critical angle. If an option lists 'dispersion, refraction and internal reflection', all three are correct.

Remember it: Morning rainbow in the West, evening rainbow in the East: keep the Sun at your back. Primary bow: **R**ed **O**utside, like the **R**oof **O**n top.

Quick check

1. In a prism, which colour deviates most, and which least?
2. Name the three processes that make a rainbow.
3. In which part of the sky do you see an evening rainbow?

Answer: 1. violet most, red least · 2. refraction, dispersion, internal reflection · 3. east, opposite the Sun

Scattering: blue sky, red sunset, Tyndall and Raman

$1/\lambda^4$

blue sky

red sunset

red signals

Tyndall effect

Raman effect

When light hits particles much smaller than its wavelength (molecules of nitrogen and oxygen), they absorb and re-send it in all directions: **scattering**. Lord Rayleigh showed that the amount scattered goes as $\mathbf{1/\lambda^4}$, so short-wavelength blue light is scattered several times more than red. Large particles (water drops, dust) scatter all colours about equally.

★★★ **Blue sky**: air molecules scatter blue far more than red; this scattered blue reaches our eyes from every direction of the sky. (Violet scatters even more, but sunlight has less violet and our eyes are less sensitive to it.)

★★★ **Red/orange Sun at sunrise and sunset**: light from the low Sun crosses a much longer path of air; most blue is scattered out on the way, leaving red and orange. At noon the path is short and the Sun looks white.

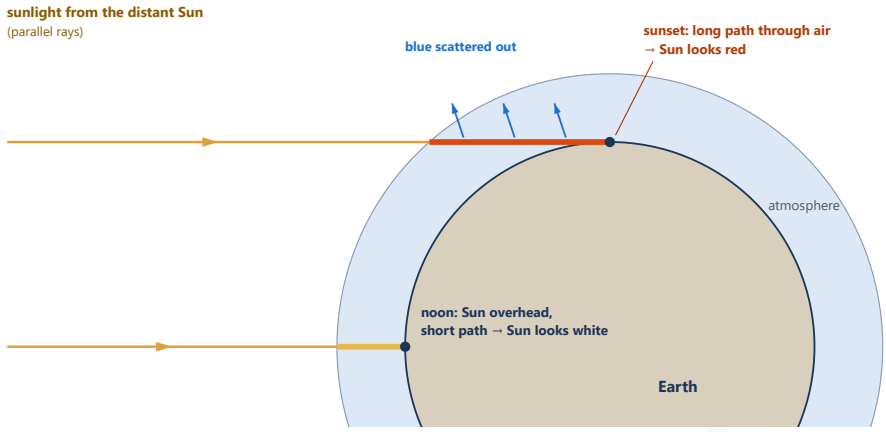
★★★ **Danger and stop signals are red**: red is scattered least, so it travels farthest through fog, smoke and dust and is seen from a distance.

★★★ **Black sky in space**: with no air to scatter sunlight, the sky looks black to astronauts and from the Moon, even in daytime.

★★ **White clouds**: cloud droplets are much larger than the wavelength of light and scatter all colours almost equally, which adds up to white. Dark rain clouds are thick enough to stop most light.

★★ **Bluish smoke** from a two-wheeler's exhaust or a cigarette: very fine particles scatter mostly blue.

★ **Blue sea**: partly reflection of the blue sky and partly because water absorbs red light and scatters blue (Raman studied this on a sea voyage in 1921).



Same sunlight, two observers. At noon the light crosses a short path of air and the Sun looks white; at sunset it skims through a much longer path, most blue is scattered out on the way, and the Sun looks red. Not to scale: the air layer is drawn far thicker than it is.

⚠ **Exam trap:** Blue sky is **scattering**, not reflection of the oceans, and not dispersion. Red danger signals are chosen because red is **least scattered**, not because it is 'most visible to the eye' (the eye is most sensitive to yellow-green).

Tyndall effect: a beam of light becomes visible from the side when it passes through a **colloid** (fine particles suspended in a medium), because the particles scatter the light. A true solution shows no such beam, so the effect separates colloids from true solutions. Named after John Tyndall.

★★ **Tyndall effect examples**: sunbeams in a dusty room or through a gap in a window, sunlight streaming through the canopy of a dense misty forest, car headlights in fog, the projector beam in a cinema hall, a torch beam through milky water.

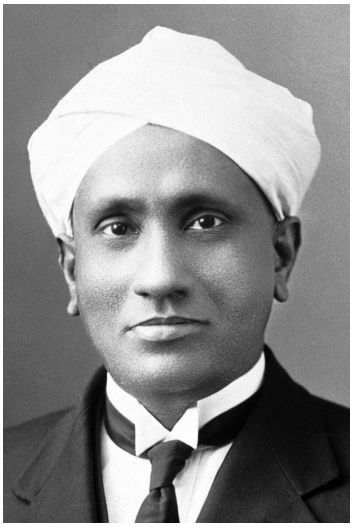
👁 **See it around you:** Switch on a torch in a dark room and nothing shows in the air; clap two dusty dusters near the beam and the path suddenly lights up. That is the Tyndall effect.

Raman effect: when light is scattered by molecules, a very small fraction of it comes out with a **slightly changed frequency (and wavelength)**, because the molecule has taken or given a little energy. The pattern of these shifts is a fingerprint of the molecule.

★★★ **C.V. Raman** discovered it with **K.S. Krishnan** in Kolkata; announced on **28 February 1928**. Raman won the **Nobel Prize in Physics, 1930**, the first Asian to win a Nobel Prize in science. He received the Bharat Ratna in 1954.

★★★ **National Science Day** is celebrated on **28 February** every year (since 1987) to mark the discovery.

★★ **Raman spectroscopy** identifies substances without destroying them: medicines, gemstones, forensic samples, art pigments; the Perseverance rover on Mars carries a Raman instrument.



C.V. Raman, who discovered the Raman effect with K.S. Krishnan (announced 28 February 1928) and won the Nobel Prize in Physics in 1930. Image: Nobel Foundation, Wikimedia Commons, public domain

Three kinds of scattering ★★★

Effect	Particles	What happens	Example
Rayleigh	Much smaller than λ (air molecules)	Short λ (blue) scattered far more ($\propto 1/\lambda^4$); frequency unchanged	Blue sky, red sunset
Tyndall	Colloidal particles (dust, smoke, fog droplets)	Path of the beam becomes visible	Sunbeam in a dusty room
Raman	Molecules	Tiny fraction of light comes out with changed frequency	Raman spectroscopy

Remember it: Raman: 28.2.28: Feb **28**, 19**28**. Science Day falls on the same date.

⚠ **Exam trap:** In Rayleigh and Tyndall scattering the colour (frequency) of scattered light is unchanged; only in the **Raman effect** does the frequency change.

Quick check

1. Rayleigh scattering is proportional to _____ .
2. Why are danger signals red?
3. Which scattering changes the frequency of light, and when was it announced?

Answer: 1. $1/\lambda^4$ (blue scattered far more than red) · 2. red is scattered least, so it is seen from farthest · 3. Raman effect, 28 February 1928

Other colour effects in daily life

interference

soap bubble, oil film

peacock feather

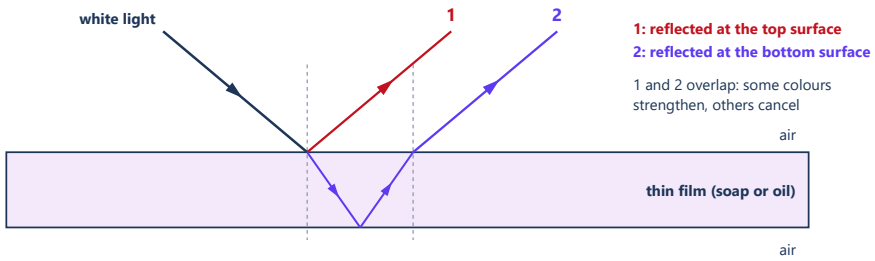
Not every display of colours is dispersion. When light reflects from the top and bottom surfaces of a very thin film, the two reflected waves overlap and reinforce some colours while cancelling others. This is **interference** (explained further in the chapter on wave optics).

halo / corona

★★★ **Soap bubbles and oil films** on a wet road show colours because of **interference** of light in thin films; the colours change as the film thickness changes.

★★ **Peacock feathers and butterfly wings** owe their shimmering colours to interference from tiny structures, not to pigment.

★ **Halo**: a ring around the Sun or Moon, made by refraction through ice crystals in high thin clouds (about 22° radius). **Corona**: small coloured rings close to the Moon, made by diffraction by water droplets.



Thin-film interference, angles from Snell's law (n = 1.33). Light reflected from the top surface (1) and from the bottom surface (2) leaves in the same direction; the two overlap, strengthening some colours and cancelling others. Film thickness hugely exaggerated.

⚠ **Exam trap:** Soap-film colours: **interference** (not diffraction, refraction or polarisation). Prism and rainbow colours: **dispersion**.

Quick check

1. The colours of a soap bubble are due to _____ .
2. Halo or corona: which is made by refraction through ice crystals?

Answer: 1. interference of light in a thin film · 2. halo (about 22°); a corona is diffraction

Asked in past papers (10)

UPSC 2013 Consider the following phenomena :
1. Size of the sun at dusk
2. Colour of the sun at dawn
3. Moon being visible at dawn
4. Twinkle of stars in the sky
5. Polestar being visible in the sky
Which of the above are optical illusions?
(a) 1, 2 and 3 (b) 3, 4 and 5 (c) 1, 2 and 4 (d) 2, 3 and 5
Answer: (c) 1, 2 and 4. Stars twinkle because their light is refracted by moving layers of air; The Sun looks larger and redder near the horizon due to the atmosphere and perception

UPSC 2013 Rainbow is produced when sunlight falls on drops of rain. Which of the following physical phenomena are responsible for this?
1. Dispersion
2. Refraction
3. Internal reflection
Select the correct answer using the codes given below.
(a) 1 and 2 only (b) 2 and 3 only (c) 1 and 3 only (d) 1, 2 and 3
Answer: (d) 1, 2 and 3. A rainbow forms by refraction, dispersion and internal reflection in raindrops

BPSC 66th Which of the following does not change when light travels from one medium to another?
(a) Velocity (b) Wavelength (c) Frequency (d) Refractive index
(e) None of the above/More than one of the above
Answer: (c) Frequency. Frequency of light stays constant on refraction; speed and wavelength change

BPSC 67th A person standing in front of a mirror finds his image larger than himself. This implies that the mirror is
(a) concave (b) plane (c) convex (d) cylindrical with bulging side outwards
(e) None of the above/More than one of the above
Answer: (a) concave. A concave mirror gives an enlarged, erect image when the object is within its focus; A plane mirror gives a same-size image and a convex mirror a smaller one

BPSC 67th Twinkling of stars in clear sky during nighttime can be explained with
(a) refraction of light (b) reflection of light (c) polarization of light (d) interference of light
(e) None of the above/More than one of the above
Answer: (a) refraction of light. Stars twinkle because of atmospheric refraction of their light

BPSC 67th When a soap film on the water is seen in the daytime, it shows beautiful colours. This phenomenon is due to
(a) diffraction of light (b) refraction of light (c) polarization of light (d) interference of light
(e) None of the above/More than one of the above
Answer: (d) interference of light. Colours of thin films such as soap bubbles and oil on water come from interference

BPSC 67th re-exam The speed of light will be minimum while passing through
(a) glass (b) water (c) vacuum (d) air (e) None of the above/More than one of the above
Answer: (a) glass. Light is slowest in the medium of highest refractive index ($v = c/n$)

BPSC 69th The image formed by concave mirror is real, inverted and of the same size as that of the object. The position of the object should be
(a) at the focus (b) at the centre of curvature (c) between the focus and centre of curvature
(d) beyond the centre of curvature
Answer: (b) at the centre of curvature. Concave mirror: an object at C gives a real, inverted, same-size image at C

BPSC 70th re-exam Which of the following is responsible for production of shadow ?
(a) Diffraction (b) Interference (c) Rectilinear propagation of light (d) Polarisation
Answer: (c) Rectilinear propagation of light. Light travels in straight lines, so an opaque object blocking it casts a shadow; Diffraction, interference and polarisation show the wave nature of light

BPSC 71st The focal distance of a plane mirror is
(a) +1 cm (b) −1 cm (c) 2 cm (d) Infinity
Answer: (d) Infinity. A plane mirror has infinite radius of curvature, so its focal length is infinite

Test yourself (12)

1. Two plane mirrors are kept at 60° to each other. How many images of an object placed between them are formed?
(a) 3 (b) 5 (c) 6 (d) Infinite

2. A ray of light passes from water into air. Which of the following is correct?
(a) It bends towards the normal and its frequency increases
(b) It bends away from the normal and its frequency is unchanged
(c) It bends away from the normal and its wavelength decreases (d) It goes straight whatever the angle

3. Which mirror is used as a rear-view mirror in vehicles, and why?
(a) Concave, because it gives an enlarged image (b) Plane, because it gives the same size image
(c) Convex, because it always gives an erect image and a wide field of view
(d) Concave, because it gives a real image

4. Consider the following: 1. Sparkling of a diamond 2. Mirage on a hot road 3. Working of an optical fibre 4. Blue colour of the sky. Which are due to total internal reflection?
(a) 1 and 2 only (b) 1, 2 and 3 only (c) 2, 3 and 4 only (d) 1, 2, 3 and 4

5. The Sun is visible a little before actual sunrise because of
(a) scattering of light (b) dispersion of light (c) atmospheric refraction (d) total internal reflection

6. In a primary rainbow, which colour is on the outer edge and where is the Sun?
(a) Violet; in front of the observer (b) Red; behind the observer (c) Red; in front of the observer
(d) Violet; behind the observer

7. Why are danger signals red?
(a) Red light is scattered the least by fog and smoke (b) Red light has the highest frequency
(c) The human eye is most sensitive to red (d) Red light travels fastest in air

8. National Science Day (28 February) commemorates the discovery of
(a) the photoelectric effect (b) Bose–Einstein statistics (c) the Raman effect (d) the Chandrasekhar limit

9. An object is placed between the focus and the pole of a concave mirror. The image is
(a) real, inverted and enlarged (b) virtual, erect and enlarged (c) virtual, erect and diminished
(d) real, inverted and same size

10. Consider the following statements:
1. Lateral inversion in a plane mirror swaps the top and bottom of the image.
2. The critical angle of diamond is smaller than that of glass.
3. Kerosene is lighter than water but optically denser than water.
Which of the statements given above is/are correct?
(a) 1 only (b) 1 and 2 only (c) 1 and 3 only (d) 2 and 3 only

11. Consider the following:
1. Twinkling of stars
2. The Sun being visible about 2 minutes before it actually rises
3. The flattened shape of the Sun near the horizon
How many of the above are caused by atmospheric refraction?
(a) Only one (b) Only two (c) All three (d) None

12. During a partial solar eclipse, the patches of sunlight on the ground under a leafy tree look like small crescents. Why?
(a) The leaves diffract sunlight into crescent shapes (b) Atmospheric refraction distorts the Sun's disc
(c) The Moon's shadow falls on the ground in patches (d) Each gap between leaves acts as a pinhole camera

Answers: 1. (b) Number of images = 360/θ − 1 = 360/60 − 1 = 5. · 2. (b) Denser to rarer: bends away from the normal; speed and wavelength increase, frequency stays the same. · 3. (c) A convex mirror forms a virtual, erect, diminished image and covers a wide area behind. · 4. (b) Blue sky is due to scattering; the other three involve total internal reflection. · 5. (c) Atmospheric refraction bends sunlight over the horizon, so the Sun is seen about 2 minutes early. · 6. (b) The primary bow has red outside and is seen opposite the Sun, which is behind the observer. · 7. (a) Red has the longest wavelength and is least scattered, so it is seen from far away. · 8. (c) C.V. Raman announced the Raman effect on 28 February 1928. · 9. (b) Inside F a concave mirror acts as a magnifier: virtual, erect, enlarged image behind the mirror. · 10.

(d) Lateral inversion swaps left and right, not top and bottom; diamond's critical angle (about 24.4°) is below glass's (about 42°), and kerosene (n = 1.44) is optically denser than water (n = 1.33). · 11. (c) All three come from light bending as it passes through layers of air of different density; the red colour of the rising Sun, by contrast, is due to scattering. · 12. (d) Each small gap works as a pinhole and forms an image of the Sun, round on a normal day and a crescent when the Moon hides part of it; this follows from light travelling in straight lines.

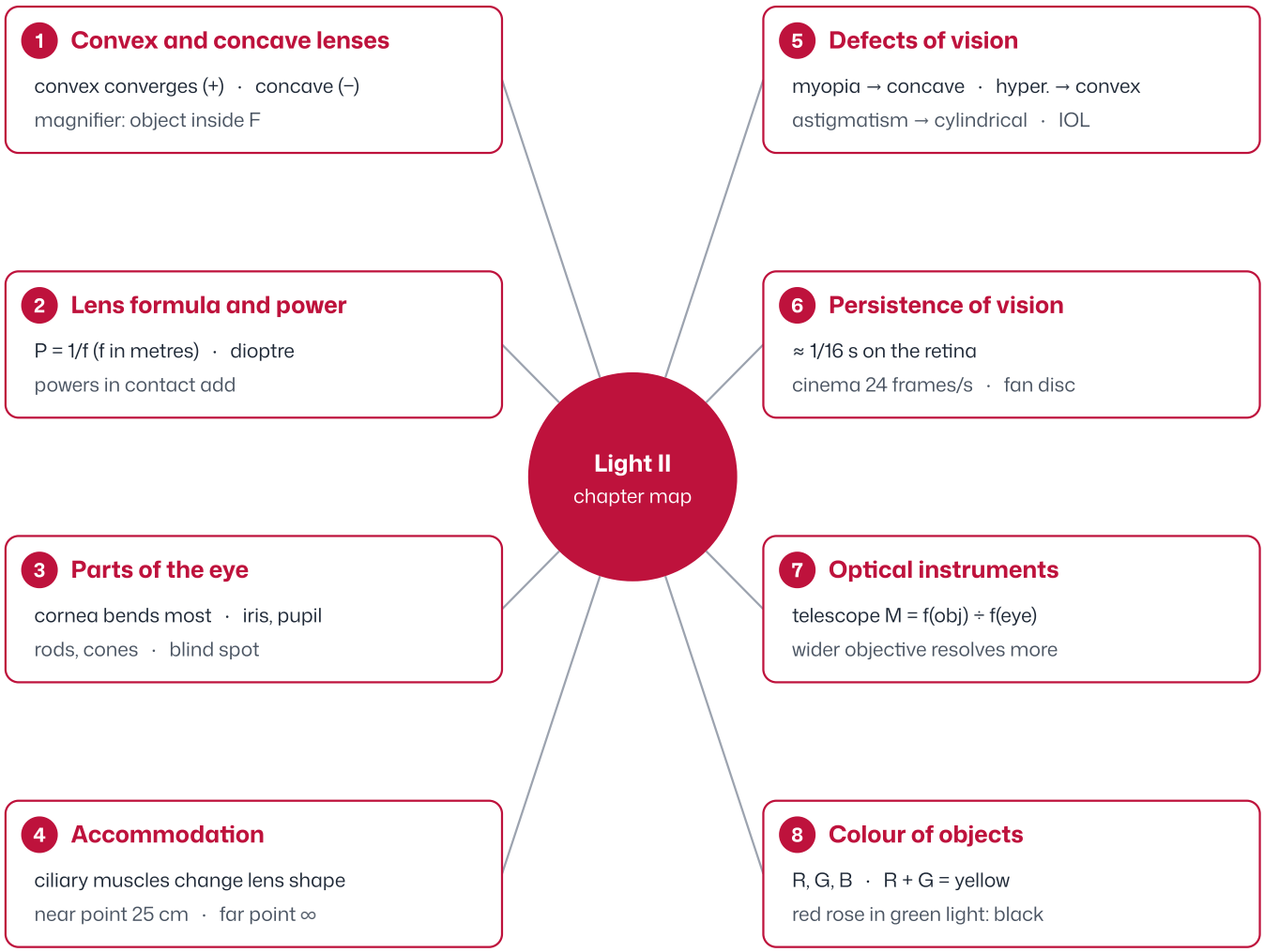
CHAPTER 9

Light II: Lenses, the Human Eye and Optical Instruments

Which lens corrects which eye defect, power in dioptres, parts of the eye, the magnifying glass, telescope resolution and the colour of objects under coloured light are the usual questions.

Asked 3 times in past papers: BPSC 3

≈ 35 min to read ≈ 5 min to revise ★★★ Revise on: Day 1 | Day 3 | Day 7 | Day 21



Revision card

1. Convex lens: thick in the middle, converging, f and power positive. Concave lens: thin in the middle, diverging, f and power negative.
2. Magnifying glass = convex lens with the object inside its focal length: virtual, erect, enlarged image.
3. Concave lens always gives a virtual, erect, diminished image.
4. Power P = 1/f (f in metres), unit dioptre (D). f = 50 cm → +2 D. Powers of lenses in contact simply add.
5. Covering part of a lens (or painting strips on it) still gives the whole image, only dimmer.
6. Eye: cornea does most of the bending; iris controls the pupil; ciliary muscles change the lens shape (accommodation); retina has rods (dim light) and cones (colour); blind spot has neither.
7. Image on the retina is real and inverted. Normal eye: near point 25 cm, far point infinity.
8. Myopia → concave lens; hypermetropia → convex lens; presbyopia → bifocal/progressive; astigmatism → cylindrical lens; cataract → surgery with an intraocular lens.
9. Night blindness: rods lack rhodopsin, made from vitamin A. Colour blindness: faulty cones, inherited, commoner in men.
10. Persistence of vision ≈ 1/16 s: cinema, a spinning fan looks like a disc.
11. Telescope resolution rises with the diameter of the objective; all big telescopes are reflecting. India's largest optical telescope: 3.6 m at Devasthal (Nainital).
12. Primary colours of light: red, green, blue; R+G = yellow, G+B = cyan, B+R = magenta, all three = white.

Convex and concave lenses

convex: converging

concave: diverging

magnifying glass

half lens covered

object at $2F_1$

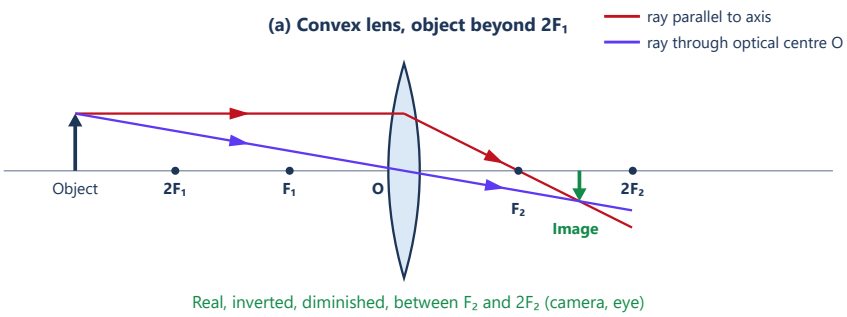
A lens is a piece of glass with curved faces. Because light bends at both faces, a lens that is **thicker in the middle** (convex) bends rays inward to meet at a point: it **converges** light. A lens **thinner in the middle** (concave) bends them outward: it **diverges** light, so the rays only seem to come from a point behind it.

Convex vs concave lens ★★★

Feature	Convex lens	Concave lens
Shape	Thicker at the centre	Thinner at the centre
Effect on parallel rays	Converges them to a real focus	Diverges them from a virtual focus
Focal length and power	Positive (+)	Negative (−)
Images	Real or virtual, depending on object position	Always virtual, erect, diminished
Uses	Magnifying glass, camera, projector, microscope, telescope, spectacles for hypermetropia	Spectacles for myopia, door peephole, Galilean telescope eyepiece

★★ **Terms**: optical centre O (rays through it go straight), principal foci F_1 and F_2 on both sides, focal length f = OF, 2F at twice the focal length.

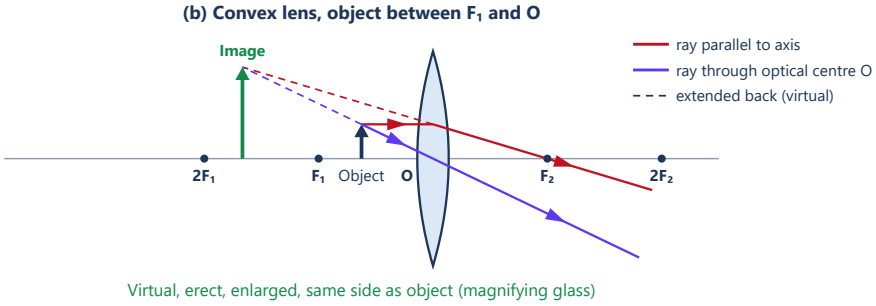
★ **Three easy rays**: a ray parallel to the axis passes through F_2 after a convex lens (or seems to come from F_1 after a concave lens); a ray through O goes straight; a ray through F_1 comes out parallel.



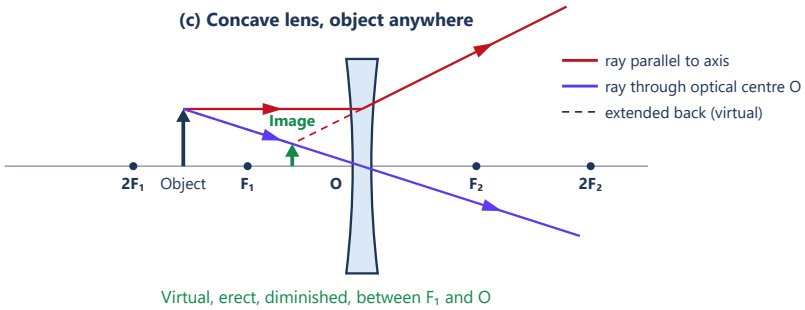
(a) Convex lens, object beyond $2F_1$: real, inverted, smaller image between F_2 and $2F_2$, as in a camera and the eye. Drawn to scale (f = 80 units).

Convex lens: where the image forms ★★★

Object at	Image at	Size	Nature	Used in
Infinity	F_2	Point-sized	Real, inverted	Burning paper with sunlight
Beyond $2F_1$	Between F_2 and $2F_2$	Diminished	Real, inverted	Camera, human eye
At $2F_1$	At $2F_2$	Same size	Real, inverted	Photocopying camera
Between F_1 and $2F_1$	Beyond $2F_2$	Enlarged	Real, inverted	Projector, objective of a microscope
At F_1	Infinity	Highly enlarged	Real, inverted	Searchlight, parallel beam
Between F_1 and O	Same side as object	Enlarged	Virtual, erect	Magnifying glass, simple microscope



(b) Convex lens, object between F_1 and O: virtual, erect, enlarged image on the same side as the object, which is how a magnifying glass works. Drawn to scale (f = 80 units).



(c) Concave lens: wherever the object is, the image is virtual, erect and smaller, between F_1 and O. Drawn to scale (f = 80 units).

★★★ **Magnifying glass (reading lens)** is a **convex lens** of short focal length, held so that the object is within its focal length.

★★ **Concave lens**: for any object position the image is virtual, erect, diminished, between F_1 and O; for an object at infinity it is a point at F_1.

★★★ **Part of the lens covered**: every part of a lens receives light from every point of the object, so covering half the lens, or painting black strips across it, still forms the **complete image**, only **less bright**.

★ **A lens in a liquid** becomes weaker, because the difference in refractive index is smaller; in a liquid of the same refractive index it stops bending light and becomes nearly invisible.

⚠ **Exam trap:** A white horse photographed through a convex lens with black stripes painted on it does **not** become a zebra. The image is a whole horse, just dimmer.

Remember it: Convex = **con-verge**, a plus (+) sign: it adds light together. Concave = **cave** that spreads light out, a minus (−) sign.

Quick check

1. A magnifying glass is a _____ lens with the object placed _____ its focal length.
2. Half of a convex lens is covered with black paper. What happens to the image?
3. What kind of image does a concave lens always form?

Answer: 1. convex; within (between F_1 and O) · 2. the whole image still forms, only dimmer · 3. virtual, erect, diminished

Lens formula and power

lens formula

P = 1/f

f in metres

dioptre

powers add

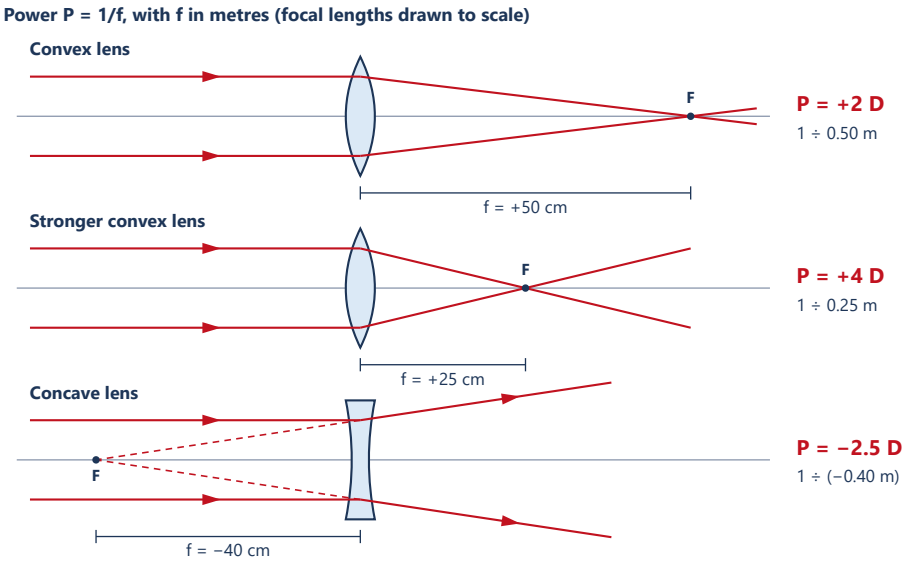
The stronger a lens bends light, the shorter its focal length. So the bending ability, called **power**, is simply the reciprocal of the focal length. Opticians write spectacle numbers in this unit.

★★ **Lens formula**: $1/v - 1/u = 1/f$; magnification $m = h'/h = v/u$. (Same sign idea as for mirrors: distances from the optical centre, positive in the direction light travels.)

★★★ **Power** P = 1/f, with f in **metres**. SI unit: **dioptre (D)** = m^{-1}. Convex lens: positive power; concave lens: negative power.

★★★ **Examples**: f = +50 cm → P = +2 D; f = +25 cm → +4 D; a lens of −2.5 D is concave with f = −40 cm.

★★ **Lenses in contact**: total power = $P_1 + P_2 + \ldots$ For example, +2.0 D and −0.5 D together act as a +1.5 D lens. Camera and microscope objectives combine lenses this way.



Power drawn to scale (1 cm = 5 units). Halving the focal length doubles the power: f = 50 cm gives +2 D, f = 25 cm gives +4 D. A concave lens of f = −40 cm spreads rays as if they came from F in front of it: P = −2.5 D.

⚠ **Exam trap:** Power uses focal length in **metres**, not centimetres. A 20 cm convex lens has power +5 D, not +0.05 D.

☑ Quick check

1. Power of a convex lens of focal length 25 cm?
2. The SI unit of the power of a lens?
3. Lenses of +2.0 D and −0.5 D are in contact. Net power?

Answer: 1. +4 D (P = 1/0.25 m) · 2. dioptre (D) = m^{-1} · 3. +1.5 D (powers add)

The human eye: parts and their jobs

cornea

iris and pupil

rods and cones

blind spot

real, inverted image

The eye is a living camera. The **cornea and lens** bend light to form a sharp image on the **retina** at the back. Light-sensitive cells in the retina turn the image into nerve signals, and the **optic nerve** carries them to the brain, which makes sense of them.

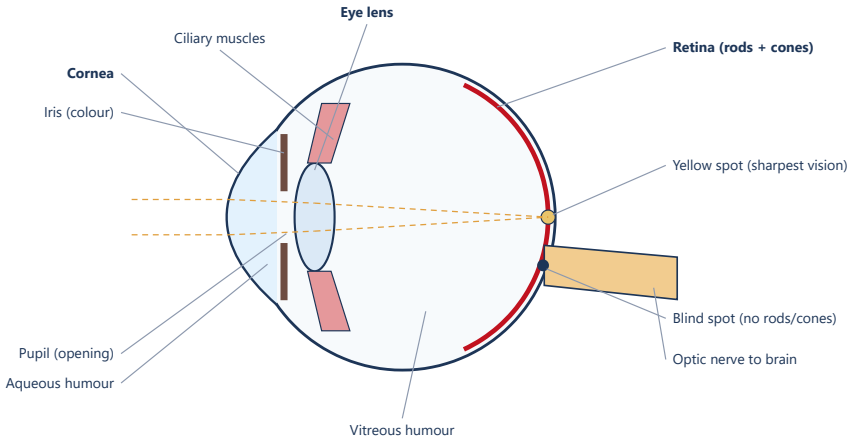


Image on the retina is real, inverted and diminished; the brain turns it upright

Section of the human eye. Light is bent mostly at the cornea, fine-focused by the lens and forms an image on the retina; the blind spot is where the optic nerve leaves.

Parts of the eye ★★★

Part	What it is	Job
Cornea	Transparent front bulge	Does **most of the bending** of light; the part transplanted after eye donation
Sclera	Tough white outer coat	Protects the eyeball
Iris	Coloured muscular ring	Controls the size of the pupil; gives the eye its colour
Pupil	Hole in the centre of the iris	Lets light in; shrinks in bright light, widens in dim light
Aqueous humour	Watery fluid behind the cornea	Keeps the shape, nourishes cornea and lens
Eye lens	Flexible, transparent, convex	Fine focusing by changing its curvature
Ciliary muscles	Ring of muscle holding the lens	Change the lens thickness (accommodation)
Vitreous humour	Clear jelly filling the eyeball	Keeps the eyeball round
Retina	Light-sensitive inner layer at the back	Screen on which the image forms
Rods	Retinal cells (about 120 million)	Dim-light and black-and-white vision; need the pigment rhodopsin
Cones	Retinal cells (about 6 million)	Bright-light and colour vision (three types: red, green, blue)
Yellow spot (macula, fovea)	Small area facing the lens	Sharpest vision; packed with cones
Blind spot	Where the optic nerve leaves the retina	No rods or cones, so no vision there
Optic nerve	Bundle of nerve fibres	Carries signals to the brain

★★★ **Image on the retina** is **real, inverted and diminished**; the brain interprets it as upright.

★★ **Cornea** contributes about two-thirds of the eye's focusing power; the lens adds the adjustable rest.

★★ **Pupil reflex**: walking from bright sunlight into a dark cinema hall you see little at first, until the pupil widens and the rods adapt.

★ **Two eyes** give a wider field of view (about 180° against about 150° for one eye) and **depth perception**, because each eye sees from a slightly different angle.

Remember it: Camera ↔ eye: **lens ↔ lens, diaphragm ↔ iris, aperture ↔ pupil, film/sensor ↔ retina, shutter ↔ eyelid**.

Quick check

1. Which part of the eye does most of the bending of light?
2. Which part controls the size of the pupil?
3. The image on the retina is real or virtual, erect or inverted?

Answer: 1. cornea (about two-thirds) · 2. iris · 3. real, inverted (and diminished)

How the eye focuses: accommodation

accommodation

ciliary muscles

near point 25 cm

far point ∞

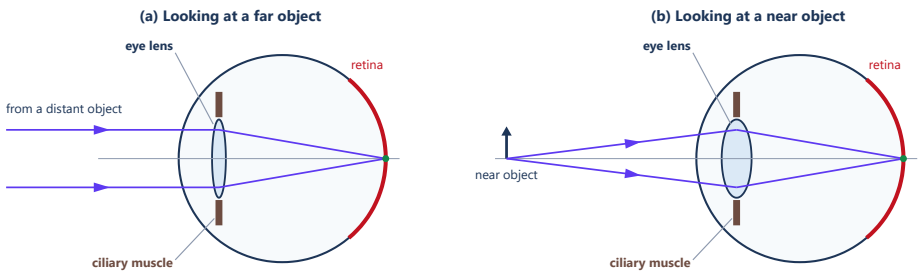
A camera focuses by moving its lens. The eye cannot move its lens, so it **changes the lens's shape** instead. Looking far, the ciliary muscles relax and the lens becomes thin (long focal length). Looking near, they contract and the lens becomes thick (short focal length). This ability is **accommodation**.

★★★ **Accommodation**: the eye's ability to change the focal length of its lens with the ciliary muscles so that both near and far objects are focused on the retina.

★★★ **Near point** of a normal adult eye = **25 cm** (least distance of distinct vision); **far point** = **infinity**. So a normal eye sees clearly from 25 cm to infinity.

★★ **Distant object**: ciliary muscles **relaxed**, lens thin, focal length maximum. **Near object**: muscles **contracted**, lens thick, focal length minimum.

★ **Near point changes with age**: a few centimetres for a small child, about 25 cm for a young adult, a metre or more in old age.



Accommodation in a model eye: cornea and lens are drawn as one thin lens, and the near object is drawn much closer than 25 cm (not to scale). (a) Far object: the ciliary muscles relax, the lens is thin and parallel rays focus on the retina. (b) Near object: the muscles contract, the lens thickens, and its shorter focal length still brings the rays to the same retina.

⚠ **Exam trap:** For far vision the ciliary muscles **relax** (they do not tighten). Reading for hours tires the eyes because the muscles stay contracted.

☑ Quick check

1. Near point and far point of a normal eye?
2. Looking at a distant object, are the ciliary muscles relaxed or contracted?
3. The eye's ability to change the focal length of its lens is called _____ .

Answer: 1. 25 cm and infinity · 2. relaxed: lens thin, focal length longest · 3. accommodation

Defects of vision and how they are fixed

myopia: concave

hypermetropia: convex

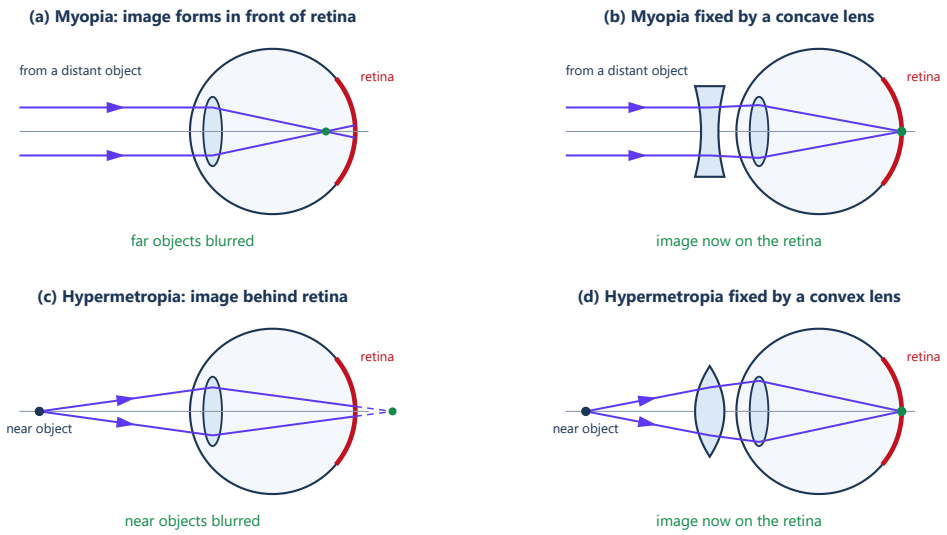
presbyopia: bifocal

astigmatism: cylindrical

cataract: IOL

night blindness: vit. A

A defective eye places the image either **in front of** the retina or **behind** it. Spectacles add a lens that undoes that error: a concave lens spreads the rays a little so they meet farther back; a convex lens converges them so they meet sooner.



Ray paths computed for a model eye. (a) Myopia: parallel rays meet before the retina. (b) A concave lens makes them meet on the retina. (c) Hypermetropia: rays from a near object would meet behind the retina. (d) A convex lens brings them onto the retina.

Defects of vision ★★★

Defect	Can see	Cannot see	Cause	Image forms	Remedy
Myopia (short-sightedness)	Near objects	Far objects	Eyeball too long, or lens too strongly curved	In front of retina	**Concave** lens (negative power)
Hypermetropia (long-sightedness)	Far objects	Near objects (near point beyond 25 cm)	Eyeball too short, or lens too weak	Behind retina	**Convex** lens (positive power)
Presbyopia (old-age sight)	Usually far	Near objects	Ciliary muscles weaken, lens stiffens with age	Behind retina for near objects	Convex reading glasses; **bifocal** (upper part concave for far, lower part convex for near) or **progressive** lenses
Astigmatism	Lines in one direction sharper than others	Everything fully sharp	Cornea curved unevenly	Not one point	**Cylindrical** lens
Cataract	Blurred, cloudy, faded view	Sharp, bright detail	Eye lens becomes cloudy (age, diabetes, UV)	Blurred: the cloudy lens scatters light	**Surgery**: cloudy lens replaced by an artificial **intraocular lens (IOL)**

★★ **LASIK** reshapes the cornea with an ultraviolet (excimer) laser to treat myopia, hypermetropia and astigmatism without spectacles.

★ **Glaucoma**: rising fluid pressure inside the eye slowly damages the optic nerve; untreated it causes permanent blindness.

★★★ **Colour blindness**: some **cones** are missing or faulty, usually red–green confusion. It is **inherited** (gene on the X chromosome), so far commoner in **men** (about 8%) than women; it has no cure and is checked with the Ishihara dot test.

★★★ **Night blindness**: the **rods** cannot work in dim light because the pigment **rhodopsin** needs **vitamin A**; vitamin A deficiency causes it (carrots, leafy greens, mango, papaya, eggs help).

★★ **Eye donation**: the **cornea** is the part transplanted; it can be taken within a few hours of death.

Remember it: Myopia → Minus lens; Hypermetropia → Higher, plus lens. Short-sighted eye is a **long** eyeball; long-sighted eye is a **short** eyeball, the opposite of the names.

⚠ Exam trap: Bifocal lenses are for presbyopia (two defects at once), not for astigmatism. Astigmatism needs a **cylindrical** lens.

Quick check

1. Which lens corrects myopia, and which hypermetropia?
2. Which lens corrects astigmatism?
3. Night blindness: which vitamin is lacking, and which cells fail?

Answer: 1. concave for myopia; convex for hypermetropia · 2. cylindrical · 3. vitamin A; the rods (rhodopsin)

Persistence of vision

1/16 s

24 frames/s

fan looks a disc

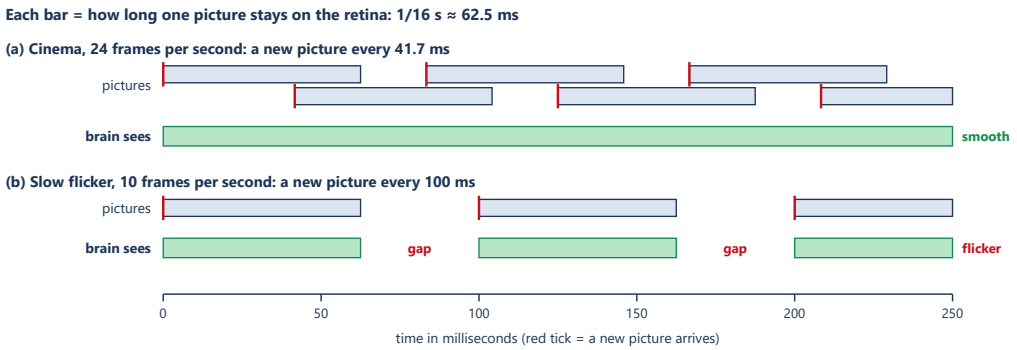
chakri ring

The retina keeps an image for a short time after the light is gone. If new images arrive faster than that, the brain blends them into smooth motion.

★★★ **Persistence of vision**: an impression stays on the retina for about **1/16 of a second**.

★★★ **Cinema** works on it: films show **24 frames per second**, faster than 16, so separate still pictures look like continuous motion.

★★ **Everyday examples**: a fast ceiling fan looks like a solid disc; a whirled sparkler or spinning firecracker (chakri) draws a ring of light; a Newton's colour disc spun fast looks nearly white; falling raindrops look like streaks.



Persistence of vision, times to scale. Each picture stays on the retina for about 1/16 s (62.5 ms). (a) At 24 frames per second a new picture arrives every 41.7 ms, before the last one fades, so the brain sees smooth motion. (b) At 10 frames per second gaps open between the pictures and the screen seems to flicker.

Remember it: Sweet sixteen: 1/16 s. Cinema plays 24 frames, safely more than 16 a second.

Quick check

1. How long does an impression stay on the retina?
2. Why does a film shown at 24 frames per second look continuous?

Answer: 1. about 1/16 s · 2. each frame arrives before the last impression fades (24 > 16 per second)

Optical instruments

microscope, telescope

M = f(obj) ÷ f(eye)

resolving power

reflecting telescopes

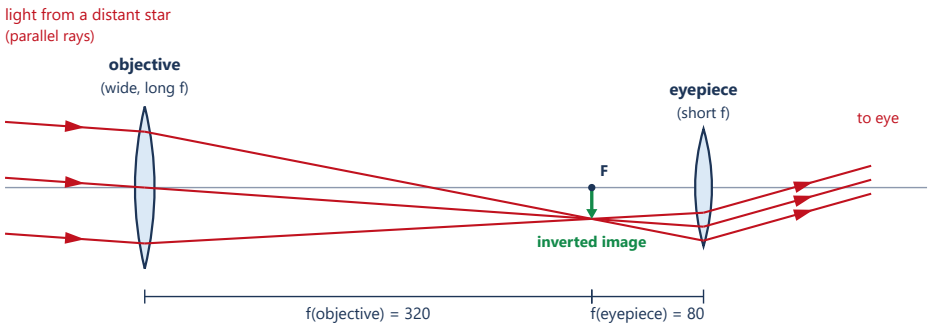
Devasthal 3.6 m

camera ↔ eye

Optical instruments either make a small near object look bigger (microscopes) or bring a distant object closer (telescopes, binoculars), or let us see round an obstacle (periscope). Most are combinations of convex lenses, concave mirrors and prisms.

Instruments at a glance ★★★

Instrument	Made of	Final image	Key fact / use
Simple microscope (magnifier)	One convex lens of short focal length	Virtual, erect, enlarged	Watchmakers, jewellers, reading fine print
Compound microscope	Two convex lenses: objective (very short f) and eyepiece	Virtual, inverted, highly enlarged	Cells, bacteria; magnification = objective × eyepiece
Astronomical (refracting) telescope	Two convex lenses: objective (long f, wide) and eyepiece (short f)	Inverted	Magnifying power = f(objective) / f(eyepiece); inverted image does not matter for stars
Terrestrial telescope	Three convex lenses (extra erecting lens)	Erect	Viewing distant objects on land; longer tube
Galilean telescope	Convex objective + concave eyepiece	Erect	Galileo, 1609; opera glasses
Reflecting telescope	Large concave mirror as objective (Newton, 1668)	Depends on design	All large research telescopes
Binoculars	Two small telescopes + right-angled prisms	Erect	Prisms use total internal reflection to turn the image upright and fold the light path
Periscope	Two plane mirrors (or prisms) at 45°	Erect, same size	Submarines, tanks, trenches
Projector	Convex lens; slide between F and 2F, placed upside down	Real, inverted, enlarged on screen	Cinema, classroom projector
Camera	Convex lens system + sensor/film	Real, inverted, diminished	Works like the eye



Magnifying power = f(objective) ÷ f(eyepiece) = 320 ÷ 80 = 4

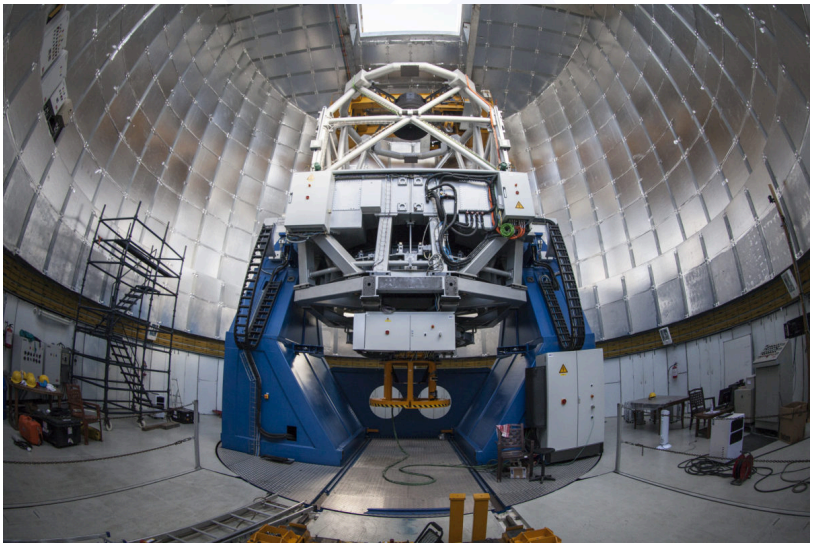
Astronomical telescope, drawn to scale: focal lengths 320 and 80 units, starlight arriving 4° off the axis. The objective forms a real, inverted image at its focus; the eyepiece, whose focus is at the same point, sends the rays out parallel again, now inclined 4 times as steeply. Magnifying power = f(objective) ÷ f(eyepiece) = 4.

★★★ **Resolving power** of a telescope (ability to show two close stars as separate) **increases with the diameter of the objective**; a wider objective also gathers more light, so fainter objects become visible.

★★★ **Why large telescopes are reflecting**: a mirror has no chromatic aberration (it reflects all colours alike), can be supported from behind, needs only one surface polished and can be made very large; big lenses sag and split colours. The largest refractor ever built for research, the Yerkes refractor (USA, 1897), has a lens only about 1 m (40 inches) wide.

★★ **Microscope resolution** improves with shorter wavelength; **electron microscopes** use electron beams with far shorter wavelength than light and see far finer detail.

★ **Binocular marking** 7 × 50 means magnification 7 and objective lenses 50 mm wide.



Inside the dome of the 3.6 m Devasthal Optical Telescope near Nainital, India's largest optical telescope (working since 2016). Like every big research telescope, it uses a mirror, not a lens, as its objective. Image: Ajay Talwar, Wikimedia Commons, CC BY 4.0

Telescopes to know (as of November 2026) ★★

Telescope	Type	Key fact
Hubble Space Telescope	Reflecting, 2.4 m mirror, in Earth orbit	NASA–ESA, launched 1990; above the atmosphere, so sharp images without twinkling
James Webb Space Telescope (JWST)	Reflecting, 6.5 m gold-coated segmented mirror, infrared	NASA–ESA–CSA, launched 25 Dec 2021; works at the Sun–Earth L2 point, about 1.5 million km from Earth
Devasthal Optical Telescope (DOT)	Reflecting, **3.6 m**	**India's largest optical telescope**; ARIES, Devasthal near Nainital, Uttarakhand; working since 2016, built with Belgium
International Liquid Mirror Telescope (ILMT)	4 m spinning mirror of liquid mercury	Devasthal; first liquid-mirror telescope in India, started observing in 2022
Giant Metrewave Radio Telescope (GMRT)	Radio: 30 dishes, each 45 m wide	Near Narayangaon, Pune; run by NCRA-TIFR; studies metre-wavelength radio waves
Himalayan Chandra Telescope	Optical, 2 m	Hanle, Ladakh (Indian Institute of Astrophysics), one of the world's highest observatories
Vainu Bappu Telescope	Reflecting, 2.3 m	Vainu Bappu Observatory, Kavalur (Tamil Nadu), run by the Indian Institute of Astrophysics; working since 1986
AstroSat	Space observatory	India's first dedicated multi-wavelength space observatory, launched by ISRO in 2015
Extremely Large Telescope (ELT)	Reflecting, 39 m	ESO, Chile; under construction, first light planned for 2029. India is a partner in the separate Thirty Meter Telescope project

Camera and eye compared ★★

Camera	Eye
Lens	Cornea + eye lens
Diaphragm	Iris
Aperture	Pupil
Film / sensor	Retina
Shutter	Eyelid
Focuses by moving the lens	Focuses by changing lens shape (accommodation)
Dark inner coating	Choroid (dark layer that stops stray light)

★★ **Spectacles**: convex lenses for hypermetropia and reading, concave for myopia, cylindrical for astigmatism; photochromic lenses darken in sunlight because ultraviolet light changes their chemistry.

⚠ **Exam trap:** A telescope's resolution depends on the **diameter** of the objective, not on its focal length or the eyepiece. A bigger eyepiece magnification only enlarges a blur.

Quick check

1. The resolving power of a telescope increases with the _____ of its objective.
2. Why are all large research telescopes reflecting?
3. India's largest optical telescope, and where is it?

Answer: 1. diameter · 2. a mirror has no chromatic aberration and can be made very large · 3. 3.6 m Devasthal Optical Telescope, near Nainital

Why we see things in colour

reflected colour

R, G, B primaries

R + G = yellow

complementary pairs

paints subtract

An object has no colour of its own in the dark. It shows the colour of the light it **reflects** (or lets through) and swallows the rest. A red rose reflects red and absorbs other colours; if no red light falls on it, it has nothing to reflect and looks black.

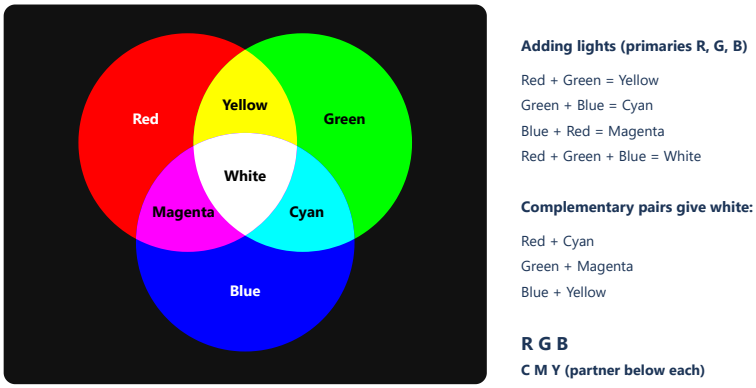
★★★ **Opaque object's colour** = colour of light it reflects. **White** reflects all colours; **black** absorbs all (so black clothes get hotter in the sun). A green leaf reflects green and absorbs red and blue for photosynthesis.

★★ **Transparent object's colour** = colour it lets through: red glass transmits only red.

★★★ **Primary colours of light**: **red, green, blue (RGB)**. Mixing light: red + green = **yellow**; green + blue = **cyan**; blue + red = **magenta**; red + green + blue = **white**. TV, mobile and LED screens make every colour from tiny RGB dots.

★★ **Complementary colours**: two colours of light that add up to white: red + cyan, green + magenta, blue + yellow.

★★ **Paints and inks mix differently** (they subtract light): printer inks use cyan, magenta, yellow and black (CMYK); blue paint + yellow paint gives green, but blue light + yellow light gives white.



Adding coloured lights on a dark screen. Where two primaries overlap you see a secondary colour; where all three overlap, white. Each secondary is the complement of the primary it lacks: Red–Cyan, Green–Magenta, Blue–Yellow.

Colour seen under coloured light ★★★

Object (in white light)	Under red light	Under green light	Under blue light
White paper	Red	Green	Blue
Red rose	Red	Black	Black
Green leaf	Black	Green	Black
Blue cloth	Black	Black	Blue
Yellow object (reflects red + green)	Red	Green	Black
Black object	Black	Black	Black

Adding coloured lights ★★

Mix	Result
Red + Green	Yellow
Green + Blue	Cyan (peacock blue)
Blue + Red	Magenta
Red + Green + Blue	White
Red + Cyan / Green + Magenta / Blue + Yellow	White (complementary pairs)

Remember it: Write **R G B** and under it **C M Y**: each letter sits under its complementary partner (Red–Cyan, Green–Magenta, Blue–Yellow). The secondary under a letter is made from the **other two** primaries.

⚠ **Exam trap:** 'Blue and yellow make green' is true only for **paints**. For **lights**, blue + yellow = white.

Quick check

1. Red light + green light gives _____ .
2. A red rose seen in pure green light looks _____ .
3. Blue + yellow light gives _____ ; blue + yellow paint gives _____ .

Answer: 1. yellow · 2. black · 3. white; green

Asked in past papers (3)

BPSC 67th re-exam What type of lens is used in magnifying glass?
(a) Convex mirror (b) Concave lens (c) Plano-concave lens (d) Convex lens
(e) None of the above/More than one of the above
Answer: (d) Convex lens. A magnifying glass is a convex lens with the object within its focal length

BPSC 68th Large number of thin strips of black paint are made on the surface of a convex lens of focal length 20 cm to catch the image of a white horse. The image will be
(a) a zebra of black stripes (b) a horse of black stripes (c) a horse of less brightness
(d) More than one of the above (e) None of the above
Answer: (c) a horse of less brightness. Covering part of a lens still forms the whole image, only less bright

BPSC 70th re-exam As the diameter of objective lens of a telescope increases, the resolution of telescope
(a) Increases (b) Decreases (c) Depends on focal length of lens (d) Remains same
Answer: (a) Increases. A telescope's resolving power rises with the diameter of its objective

Test yourself (11)

1. A person uses spectacles of power −2.0 D. The lens and the defect are
(a) convex lens of focal length 50 cm; hypermetropia (b) concave lens of focal length 50 cm; myopia
(c) concave lens of focal length 2 m; presbyopia (d) convex lens of focal length 2 m; myopia

2. The image formed on the retina of the human eye is
(a) virtual and erect (b) real and erect (c) real and inverted (d) virtual and inverted

3. Which part of the eye controls the amount of light entering it?
(a) Cornea (b) Iris (c) Ciliary muscles (d) Retina

4. The near point of a normal young adult's eye is about
(a) 2.5 cm (b) 25 cm (c) 2.5 m (d) infinity

5. Night blindness is linked to the deficiency of
(a) vitamin A (b) vitamin B12 (c) vitamin C (d) vitamin D

6. A red rose is seen under pure green light. It appears
(a) red (b) green (c) yellow (d) black

7. Which of the following is true of large astronomical telescopes?
(a) They use huge lenses because lenses have no colour defects
(b) They use concave mirrors, which show no chromatic aberration
(c) They use concave lenses as objectives (d) Their resolving power falls as the objective gets wider

8. Two thin lenses of power +3 D and −1 D are kept in contact. The combination is
(a) a concave lens of focal length 50 cm (b) a convex lens of focal length 25 cm
(c) a convex lens of focal length 50 cm (d) a convex lens of focal length 2 m

9. Consider the following statements:
1. A concave lens always forms a virtual, erect and diminished image.
2. A convex lens of focal length 20 cm has a power of +0.05 D.
3. If half of a convex lens is covered with black paper, it forms only half the image of an object.
Which of the statements given above is/are correct?
(a) 1 only (b) 2 only (c) 1 and 3 only (d) 2 and 3 only

10. Consider the following statements:
1. Myopia is corrected with a convex lens.
2. Astigmatism is corrected with a bifocal lens.
3. Night blindness is caused by faulty cones in the retina.
How many of the above statements are correct?
(a) Only one (b) Only two (c) All three (d) None

11. Seen through a magnifying glass, a pure yellow patch on a mobile phone screen turns out to be made of tiny glowing dots. Which dots are lit?
(a) Yellow dots only (b) Red and green dots (c) Blue and green dots (d) Red, green and blue dots

Answers: 1. (b) Negative power means concave; f = 1/2 m = 50 cm; concave lenses fix myopia. · 2. (c) The eye lens system forms a real, inverted, diminished image on the retina. · 3. (b) The iris changes the size of the pupil. · 4. (b) Least distance of distinct vision is 25 cm; far point is infinity. · 5. (a) Rhodopsin in the rods is made from vitamin A. · 6. (d) The rose reflects only red; with no red light falling on it, it reflects nothing. · 7. (b) Big research telescopes are reflecting; wider objectives improve resolution. · 8. (c) Total power = +2 D, so f = +0.5 m: a convex lens of 50 cm. · 9. (a) Power uses focal length in metres, so 20 cm gives +5 D; a half-covered lens still forms the whole image, only dimmer. Only statement 1 is

correct. · 10. (d) Myopia needs a concave lens and astigmatism a cylindrical lens; night blindness comes from rods lacking rhodopsin (vitamin A), while faulty cones cause colour blindness. · 11. (b) Screens build every colour from red, green and blue dots, and red + green light gives yellow; all three lit together would give white.

CHAPTER 10

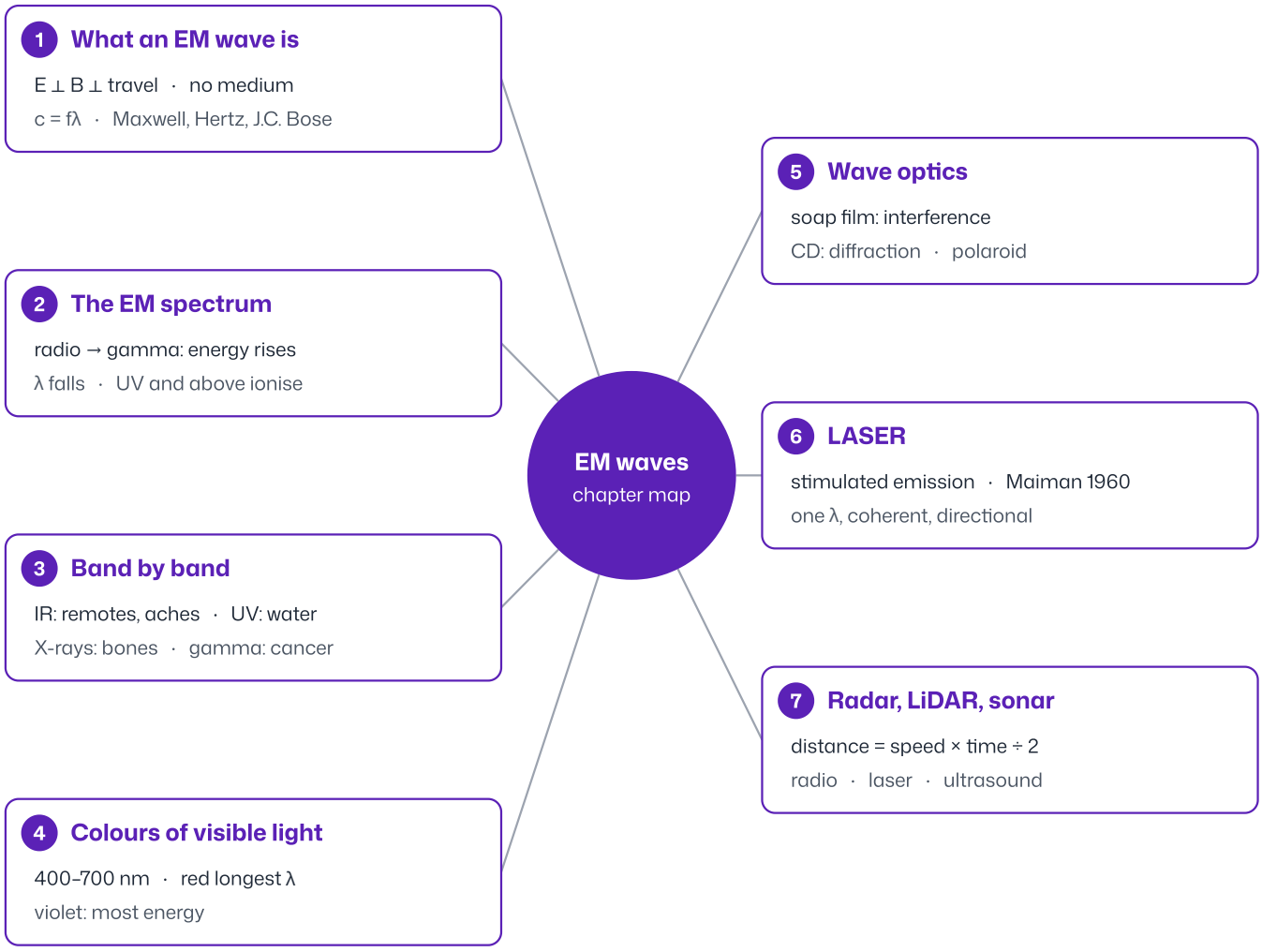
Electromagnetic Spectrum and Wave Optics

Order of the spectrum, the visible range, the use of each band (infrared for aches, UV for water purification, X-rays, gamma for cancer), the speed of EM waves, and the wave effects behind everyday colours are asked repeatedly.

Asked 7 times in past papers: UPSC 1 · BPSC 6

≈ 31 min to read ≈ 6 min to revise ★★★

Revise on: Day 1 | Day 3 | Day 7 | Day 21



Revision card

1. EM waves: oscillating electric and magnetic fields at right angles; transverse; need no medium; all travel at c ≈ 3 × 10^8 m/s in vacuum (Maxwell predicted, Hertz produced).
2. Order by rising frequency and energy: Radio → Microwave → Infrared → Visible → Ultraviolet → X-rays → Gamma. Wavelength falls in the same order.
3. Visible light ≈ 400–700 nm (wider limits about 3900–7800 Å). Red has the longest wavelength, violet the shortest.
4. Infrared = heat rays: TV remotes, night vision, physiotherapy for muscle aches, greenhouse effect.
5. UV kills microbes in water purifiers by damaging their DNA; it does not remove odour, salts or turbidity. UV-B makes vitamin D; ozone absorbs UV-C and most UV-B.
6. X-rays (Röntgen, 1895): bones, CT scans, airport scanners, crystallography; uncharged, so electric and magnetic fields do not deflect them.
7. Gamma rays: cancer radiotherapy (cobalt-60), sterilising syringes and surgical tools, food irradiation.
8. Microwaves: ovens (2.45 GHz, they set water molecules jostling), radar, satellite links, Wi-Fi.
9. Interference: soap bubbles, oil films, peacock feathers. Diffraction: bending round edges, CD colours. Polarisation: polaroid sunglasses, 3D glasses; it proves light is transverse.
10. LASER = Light Amplification by Stimulated Emission of Radiation: monochromatic, coherent, directional, intense.
11. Radar uses radio/microwaves, LiDAR uses laser light, sonar uses ultrasonic sound.

What an electromagnetic wave is

E ⊥ B ⊥ travel

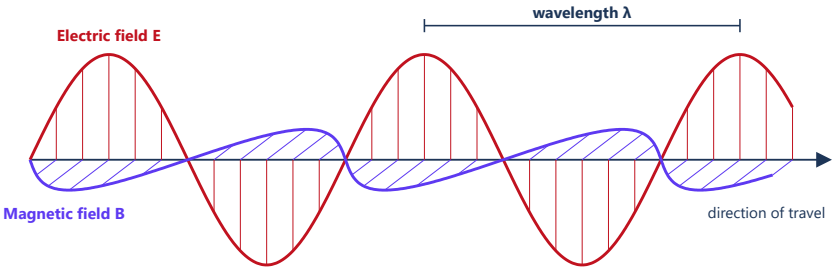
no medium needed

c = 3 × 10^8 m/s

c = fλ, E = hf

Maxwell, Hertz, Bose

A changing electric field creates a magnetic field, and a changing magnetic field creates an electric field. So once a charge oscillates, the two fields keep regenerating each other and race away as a wave, **even through empty space**. Radio, light and X-rays are all this same wave; only the wavelength differs.



E ⊥ B ⊥ direction of travel: a transverse wave that needs no medium

An electromagnetic wave: electric and magnetic fields oscillate in step, at right angles to each other and to the direction of travel.

★★★ **Speed**: every EM wave travels at **c ≈ 3 × 10^8 m/s in vacuum**, whatever its wavelength; it is slower inside matter.

★★★ **Transverse**: the electric and magnetic fields vibrate at right angles to each other and to the direction of travel. That is why light can be polarised.

★★★ **No medium needed**: EM waves cross empty space (sunlight reaches Earth); sound cannot.

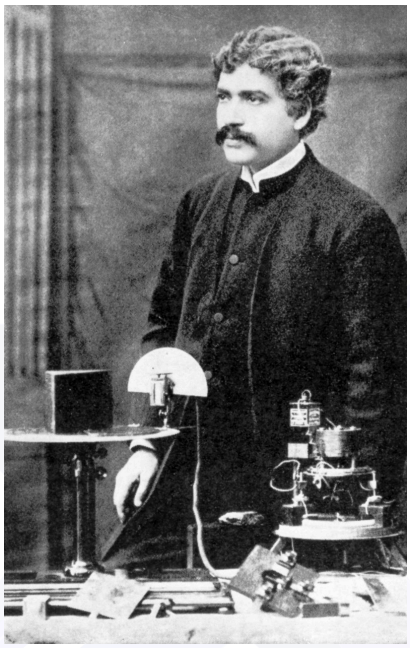
★★★ **Uncharged**: EM waves are not deflected by electric or magnetic fields. X-rays and gamma rays go straight through such fields.

★★ **Produced by accelerating (oscillating) charges**; they carry energy and momentum (light even exerts a tiny pressure, used by solar sails).

★★★ **Wave relation**: $c = f \times \lambda$. Photon energy $E = h \times f$, so higher frequency means higher energy. FM at 100 MHz has $\lambda = 3$ m; green light (~500 nm) has $f \approx 6 \times 10^{14}$ Hz.

★★ **History**: **James Clerk Maxwell** predicted EM waves and showed light is one (1860s); **Heinrich Hertz** produced and detected radio waves in the laboratory (1887–88), and the unit of frequency is named after him.

★★ **Indian pioneer**: **Jagadish Chandra Bose** generated and detected millimetre-wave (microwave) radiation in Kolkata in 1895 and invented early horn antennas and detectors. **Guglielmo Marconi** turned radio waves into long-distance wireless telegraphy (across the Atlantic, 1901).



Jagadish Chandra Bose with apparatus he built in Kolkata to generate and detect microwaves (millimetre waves) in the 1890s. Image: Birth Centenary Committee, Wikimedia Commons, public domain

EM or not? ★★★

Electromagnetic waves	NOT electromagnetic
Radio, microwave, infrared, visible light	Sound, ultrasound, infrasound (mechanical waves, need a medium)
Ultraviolet, X-rays, gamma rays	Cathode rays and beta rays (electrons), alpha rays (helium nuclei), canal rays (positive ions)
No other kind	Cosmic rays (mostly high-speed protons, despite the name)

⚠ **Exam trap:** Gamma rays are EM waves, but alpha and beta 'rays' are charged particles and **are** bent by electric and magnetic fields. Ultrasound is sound, not an EM wave.

☑ Quick check

1. Speed of every EM wave in vacuum?
2. Why do electric and magnetic fields not deflect X-rays and gamma rays?
3. Who predicted EM waves, and who first produced them in a laboratory?

Answer: 1. $c \approx 3 \times 10^8$ m/s, whatever the wavelength · 2. they are uncharged EM waves · 3. Maxwell predicted (1860s); Hertz produced (1887–88)

The electromagnetic spectrum

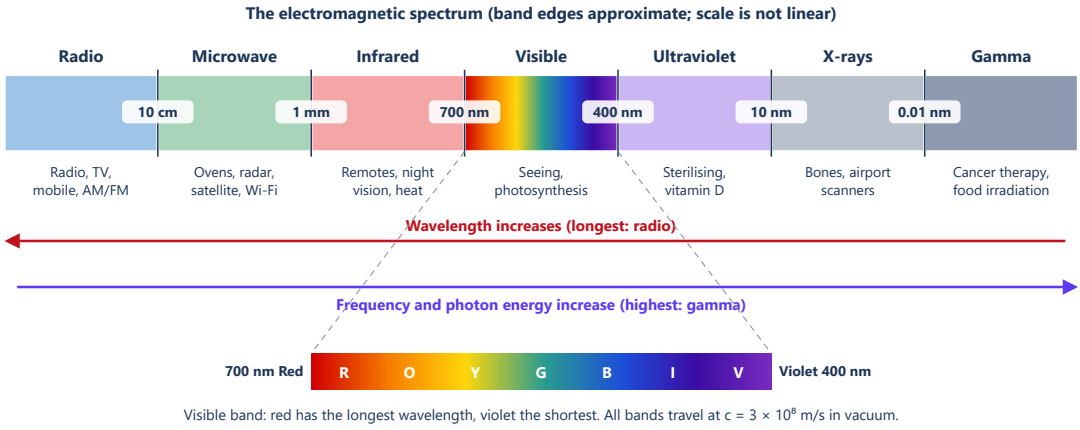
R M I V U X G

energy rises →

wavelength falls →

ionising: UV, X, γ

Arrange EM waves by wavelength and you get the **spectrum**: from radio waves as long as buildings or mountains to gamma rays smaller than an atomic nucleus. Going from radio to gamma, wavelength **falls**, frequency **rises**, and so the energy carried by each photon **rises**. Higher energy means more penetrating and, from ultraviolet onward, more harmful to living cells.



The spectrum from radio to gamma, with approximate band edges and main uses. The visible band is a tiny slice, from red (700 nm) to violet (400 nm). Not to scale.

Bands of the spectrum ★★★

Band	Wavelength (approx.)	Discovered / first produced by	Main uses
Radio	> 10 cm (up to km)	Heinrich Hertz, 1887 (predicted by Maxwell)	AM radio (~0.5–1.6 MHz), FM (88–108 MHz), TV, mobile phones, radio astronomy
Microwave	1 mm – 10 cm	J.C. Bose's millimetre-wave work, 1890s	Microwave ovens, radar, satellite and point-to-point links, Wi-Fi, GPS
Infrared (IR)	700 nm – 1 mm	William Herschel, 1800	TV/AC remotes, night vision and thermal cameras, physiotherapy heat lamps, remote sensing, optical-fibre signals
Visible	400 – 700 nm	Isaac Newton's prism spectrum, 1666	Seeing, photography, photosynthesis
Ultraviolet (UV)	10 – 400 nm	Johann Ritter, 1801	Sterilising water and tools, vitamin D, forensic and currency checks, LASIK laser
X-rays	0.01 – 10 nm	Wilhelm Röntgen, 1895	Bone images, CT scans, airport baggage scanners, crystallography
Gamma rays	< 0.01 nm	Paul Villard, 1900 (from radium)	Cancer radiotherapy, sterilising medical equipment, food irradiation

★★★ **Energy and frequency order (low → high)**: radio < microwave < infrared < visible < ultraviolet < X-rays < gamma. **Wavelength order is the reverse**: radio longest, gamma shortest.

★★ **Ionising vs non-ionising**: high-energy UV, X-rays and gamma rays can knock electrons out of atoms and damage DNA; radio, microwaves, infrared and visible light cannot. Mobile-phone signals are non-ionising.

★ **Band edges overlap**: the radio–microwave boundary is drawn anywhere from 10 cm to 1 m, so 2.45 GHz ovens and Wi-Fi ($\lambda \approx 12$ cm) count as microwaves. X-rays and gamma rays are really told apart by their source (electrons for X-rays, atomic nuclei for gamma), not by a fixed wavelength.

Remember it: Rohan's **M**ummy **I**s **V**ery **U**pset: e**X**tra **G**ames! (Radio, Microwave, Infrared, Visible, Ultraviolet, X-rays, Gamma.) Her anger, like the energy, **rises** along the sentence.

⚠ **Exam trap:** Statement-type questions often flip one link: 'wavelength of red light is less than that of violet' is **false**; red is longest. 'Gamma rays have the longest wavelength' is false; they have the shortest.

Quick check

1. Arrange by rising frequency: X-rays, radio, visible, ultraviolet.
2. Which has the longest wavelength: gamma rays, red light or radio waves?
3. Which bands are ionising?

Answer: 1. radio < visible < ultraviolet < X-rays · 2. radio waves · 3. high-energy UV, X-rays, gamma rays

Band by band: what each one does

microwave oven 2.45 GHz

IR: remotes, aches

UV-A, UV-B, UV-C

UV water purifier

X-rays: bones, CT

gamma: cancer

★★ **Radio waves**: produced by oscillating currents in antennas. Long and medium waves bend round the Earth or bounce off the **ionosphere**, so AM/short-wave radio reaches far; FM and TV need line of sight, hence tall towers.

★★ **Mobile phones and Wi-Fi** use the overlap of radio and microwaves (roughly 0.7–6 GHz; 5G also uses about 26 GHz). Rain absorbs and scatters very short waves and weakens satellite TV signals.

★★★ **Microwave oven** works at **2.45 GHz**: water (and fat, sugar) molecules are electrically lopsided, so they twist back and forth with the rapidly reversing field; this jostling heats the food. Glass, ceramic and microwave-safe plastic let microwaves through and stay cool; **metal reflects** them and can spark.

★★ **Radar** (Radio Detection And Ranging) sends microwave pulses and times the echo to find the distance and, by the Doppler shift, the speed of aircraft, ships, storms (IMD's Doppler weather radars) and speeding cars.

★★★ **Infrared = heat rays**: every warm body gives out IR. Uses: **TV and AC remotes**, **night vision and thermal cameras** (army, border security, fever screening), **heat therapy for muscle aches** by physiotherapists, drying paint, IR remote sensing of crops and forest fires.

★★ **Infrared photography** sees through haze, smoke and mist: long-wavelength infrared is scattered far less than visible light, so it is used for long-distance and satellite imaging.

★★ **Greenhouse effect**: sunlight (mainly visible) passes through glass or air; the warmed ground re-emits long-wave infrared, which glass, carbon dioxide and water vapour trap.

★★ **Optical fibres** carry mainly **near-infrared** light (about 1310 and 1550 nm), which glass absorbs least.

★★★ **Visible light**: **400–700 nm** (outer limits about 380–780 nm, i.e. about **3900–7800 Å**). The eye is most sensitive to yellow-green light (~555 nm).

★★★ **Ultraviolet**: the Sun is the main source. **UV-A** (315–400 nm) mostly reaches the ground (tanning, skin ageing); **UV-B** (280–315 nm) is mostly absorbed by ozone (sunburn, skin cancer, but also makes **vitamin D** in the skin); **UV-C** (100–280 nm) is fully absorbed by ozone and oxygen.

★★★ **UV in water purifiers** kills or inactivates bacteria and viruses by damaging their DNA. It does **not** remove odour, dissolved salts or turbidity (that needs filters or RO).

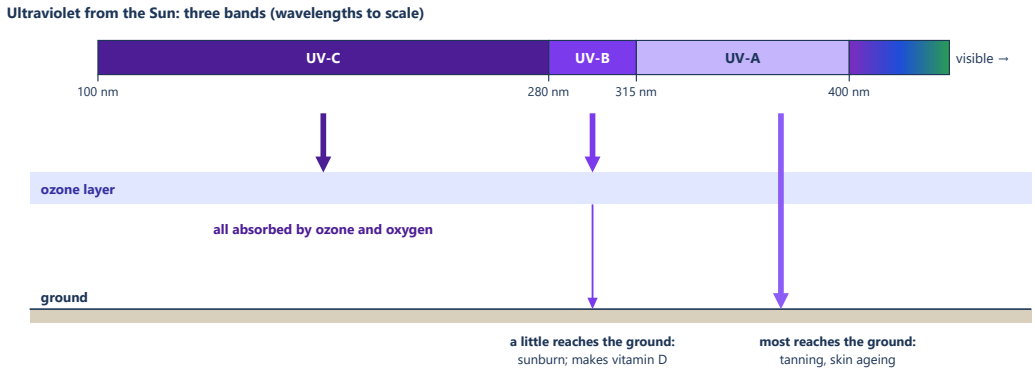
★★ **Other UV uses**: germicidal lamps in labs and hospitals, **forensic** work (body fluids and fingerprints glow), checking **currency notes** (security features glow), **sun-tan** (skin makes the pigment melanin). Welders wear dark goggles against the UV from the arc; snow reflects UV and can cause snow blindness.

★★★ **X-rays**: made when fast electrons strike a metal target (tungsten) in an X-ray tube. They pass through flesh but are absorbed by **bones** (calcium), giving shadow pictures. Uses: fractures, dental X-rays, **CT scans**, mammography, **airport and border baggage scanners**, detecting cracks in metal castings, **X-ray crystallography** (the structure of DNA was worked out from an X-ray picture).

★★ **Röntgen** received the first Nobel Prize in Physics (1901) for X-rays. Too much exposure damages cells, so radiographers stand behind lead shields.

★★★ **Gamma rays**: given out by radioactive nuclei (cobalt-60, caesium-137) and nuclear reactions. Uses: **radiotherapy** to kill cancer cells (cobalt therapy, gamma knife), **sterilising** syringes, gloves and surgical instruments, **food irradiation** to stop sprouting of onions and potatoes and kill insects in spices and mangoes.

★ **Indian food irradiation**: BARC developed the technology; the 'Krushak' plant at Lasalgaon (Nashik, Maharashtra) irradiates onions.



The Sun's ultraviolet, band edges to scale (2.2 units per nm). Ozone and oxygen absorb all UV-C and most UV-B; a little UV-B reaches the ground (sunburn, vitamin D); most UV-A gets through (tanning, skin ageing). Layer heights not to scale.

One of the first X-ray pictures, made by Wilhelm Röntgen in December 1895: his wife Anna Bertha's hand. Bones and the metal ring absorb X-rays and stand out; flesh lets most of them through. Image: Wilhelm Röntgen, Wikimedia Commons, public domain

⚠ **Exam trap: MRI** uses a strong magnet and **radio waves**, not X-rays; **ultrasound scans** use high-frequency sound. Only X-ray and CT imaging use X-rays.

⚠ **Exam trap:** Muscle-ache relief and remotes: **infrared**, not ultraviolet or microwaves. Sterilisation of water: **ultraviolet**. Sterilising packed medical equipment and cancer therapy: **gamma**.

Remember it: Hospital ladder of rays: **I**nfrared **I**roned out aches, **U**V **U**ndoes germs, **X**-ray e**X**amines bones, **G**amma **G**oes for cancer.

Quick check

1. Which radiation is used in TV remotes and to relieve muscle aches?
2. Which ultraviolet band makes vitamin D in the skin?
3. Which radiation sterilises packed syringes and treats cancer?

Answer: 1. infrared · 2. UV-B · 3. gamma rays (cobalt-60)

Colours of visible light

VIBGYOR

red: longest λ

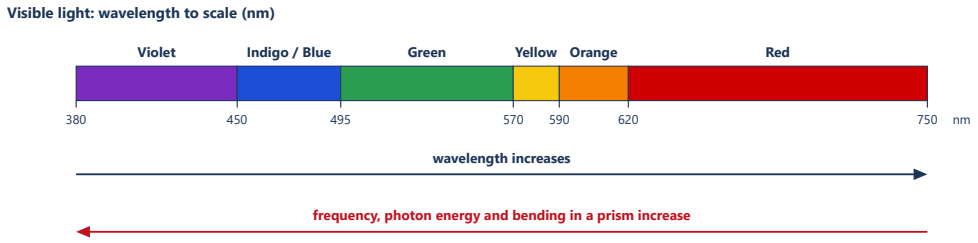
violet: most energy

1 Å = 0.1 nm

Each colour is light of a particular wavelength (strictly, frequency). Going from violet to red the wavelength increases and the frequency and photon energy decrease. In glass, violet travels slowest and bends most.

Visible colours (approximate) ★★★

Colour	Wavelength (nm)	Frequency	Bending in a prism
Violet	380–450	Highest	Most
Indigo / Blue	450–495	↓	↓
Green	495–570	↓	↓
Yellow	570–590	↓	↓
Orange	590–620	↓	↓
Red	620–750	Lowest	Least



The visible band drawn to scale (2 units per nm), with the colour boundaries from the table above. Wavelength grows from violet to red; frequency, photon energy and bending in a prism grow the other way.

★★ **Plants** absorb mainly red and blue light for photosynthesis and reflect green, which is why leaves look green.

★ **1 ångström (Å) = 10^{-10} m = 0.1 nm**, so 400 nm = 4000 Å and 700 nm = 7000 Å.

Remember it: VIBGYOR: wavelength **grows** as you read the word left to right; energy **falls**. Violet is the 'Very energetic' end.

Quick check

1. Which visible colour has the longest wavelength, and which the highest frequency?
2. 400 nm and 700 nm in ångström?

Answer: 1. red; violet · 2. 4000 Å and 7000 Å

Wave optics: interference, diffraction, polarisation

interference

Young 1801

diffraction: CD

polarisation

transverse

Three effects reveal that light is a wave. When two waves meet they add up (interference); waves spread round edges (diffraction); and a transverse wave can be filtered so it vibrates in only one plane (polarisation). Light's wavelength is tiny (about half a micrometre), so these effects show only with thin films, fine slits and special filters.

★★★ **Interference**: two light waves overlap; crest on crest gives brightness (constructive), crest on trough gives darkness (destructive). It needs **coherent** sources (same frequency, steady phase). **Thomas Young's double-slit experiment (1801)** proved light is a wave.

★★★ **Thin-film colours**: **soap bubbles**, **oil films on wet roads**, **peacock feathers** and butterfly wings shine in changing colours because light reflected from the two surfaces of a very thin layer interferes.

★ **Anti-reflection coatings** on spectacles and camera lenses use destructive interference to cut glare; noise-cancelling headphones use the same idea with sound.

★★★ **Diffraction**: bending of waves round the edges of an obstacle or through a narrow opening; strong only when the gap is comparable to the wavelength.

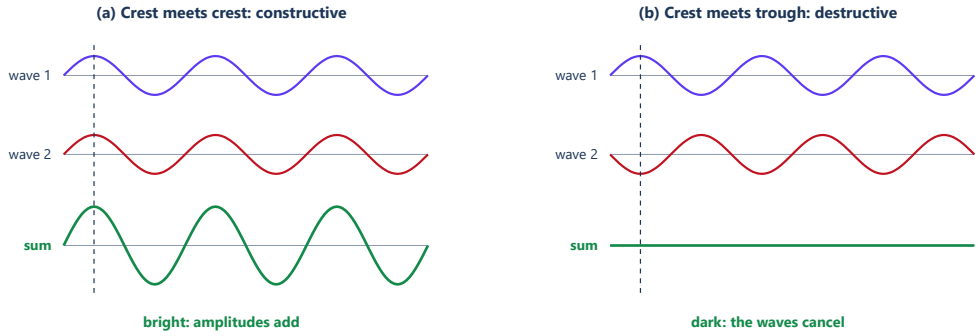
★★ **We hear round a corner but cannot see round it**: sound's wavelength (metres) is comparable to doors and walls, light's (~0.5 µm) is far smaller.

★★ **Diffraction examples**: rainbow colours on a **CD/DVD** (its closely spaced tracks act as a grating), coloured rings (corona) round the Moon through thin cloud, slightly fuzzy edges of shadows. Diffraction also limits how fine a detail a telescope or microscope can show.

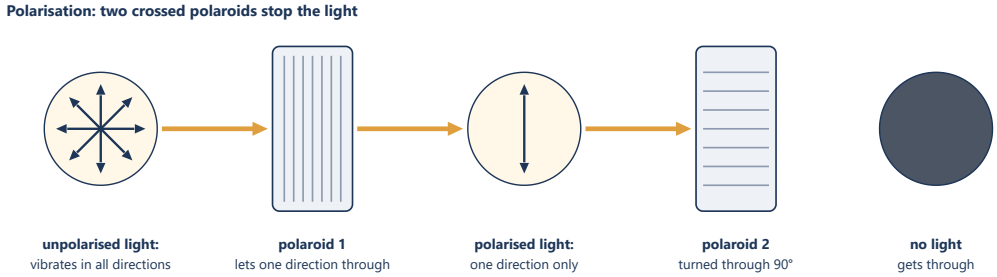
★★★ **Polarisation**: ordinary light vibrates in all directions across its path; a **polaroid** lets through only one direction. Only **transverse** waves can be polarised, so polarisation proves light is transverse. Sound in air (longitudinal) cannot be polarised.

★★ **Polarisation uses**: **polaroid sunglasses** cut glare from water, snow and roads (reflected light is partly polarised); **3D movie glasses** give each eye a differently polarised picture; **LCD screens**, camera filters, and testing stress in plastic models.

★ **Bees and some birds** navigate using the polarisation pattern of the blue sky.



Interference of two equal waves (λ = 100 units, amplitude 16). (a) In step, crest on crest: the sum has double the amplitude (32), a bright band. (b) Half a wavelength out of step, crest on trough: the sum is zero, darkness.



Seen along the beam. Ordinary light vibrates in every direction across its path; the first polaroid passes only one direction; a second polaroid turned through 90° blocks that too, so no light gets through. Only a transverse wave can be filtered like this.

Which effect proves what ★★★

Phenomenon	Explained by	Everyday example
Reflection, refraction	Both wave and particle models	Mirror, bent pencil
Interference	Wave nature	Soap bubble, oil film colours
Diffraction	Wave nature	CD colours, hearing round corners (sound)
Polarisation	Light is a **transverse** wave	Polaroid sunglasses, 3D glasses
Photoelectric effect	Particle (photon) nature	Solar cells, automatic doors

⚠ **Exam trap:** Soap-film colours are **interference**, CD colours are mainly **diffraction**, rainbow and prism colours are **dispersion**, blue sky is **scattering**. Examiners mix these four.

Remember it: **I**nterference **I**n films, **D**iffraction at **D**iscs and edges, **P**olarisation for **P**olaroids.

Quick check

1. The colours of soap bubbles and oil films are due to _____ .
2. The colours seen on a CD are mainly due to _____ .
3. Polarisation proves that light is a _____ wave.

Answer: 1. interference · 2. diffraction · 3. transverse

LASER

stimulated emission

Maiman 1960, ruby

monochromatic, coherent

LASIK

CD, DVD, Blu-ray

In a laser, atoms are pumped into an excited state; a passing photon triggers them to release identical photons in step (stimulated emission), and mirrors bounce the light back and forth to build it up. The result is light of one colour, perfectly in step and travelling in one narrow direction.

★★★ **LASER** = **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. Einstein proposed stimulated emission (1917); **Theodore Maiman** built the first laser, a **ruby laser**, in **1960**. The microwave version (maser) came first.

★★★ **Properties**: **monochromatic** (one wavelength), **coherent** (all waves in step), **highly directional** (a narrow beam that hardly spreads), and **intense**.

★★★ **Medicine**: **LASIK** eye surgery (an ultraviolet excimer laser reshapes the cornea), bloodless surgery, breaking kidney stones, removing tattoos, retina repair.

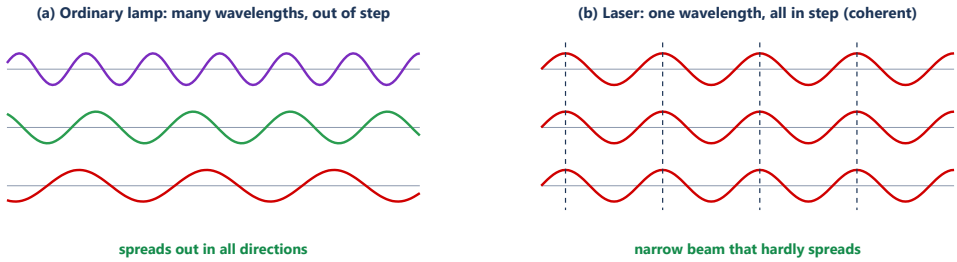
★★ **Industry and daily life**: **barcode** scanners, cutting, welding and drilling metal, laser printers, laser pointers and light shows.

★★ **Communication and sensing**: data through **optical fibres**, **LiDAR** mapping, range finders, laser-guided weapons; laser beams bounced off reflectors left on the Moon measure its distance to within centimetres.

★★ **Discs**: CD players use an infrared laser (780 nm), DVD a red laser (650 nm), **Blu-ray** a blue-violet laser (405 nm). A shorter wavelength makes a smaller spot, so more data fits on the disc.

★ **Holography** (3D pictures on credit cards and banknote strips) uses laser light; Dennis Gabor, Nobel 1971.

★ **Gravitational waves** are detected with laser interferometers (LIGO, first detection 2015). **LIGO-India** was approved in 2023 at Aundha in Hingoli district, Maharashtra.



(a) A lamp gives a mix of wavelengths with no fixed step between them. (b) A laser gives one wavelength with every wave in step (coherent): each dashed line passes through a crest of all three waves at once.

⚠ **Exam trap:** A laser's special quality is **coherence and single wavelength**, not that it travels faster than ordinary light. All light travels at c in vacuum.

Quick check

1. What does LASER stand for?
2. Four properties of laser light?
3. Who built the first laser, when, and with what?

Answer: 1. Light Amplification by Stimulated Emission of Radiation · 2. monochromatic, coherent, directional, intense · 3. Theodore Maiman, 1960, ruby

Radar, LiDAR, sonar and Li-Fi

echo: speed × time ÷ 2

radar: radio waves

LiDAR: laser

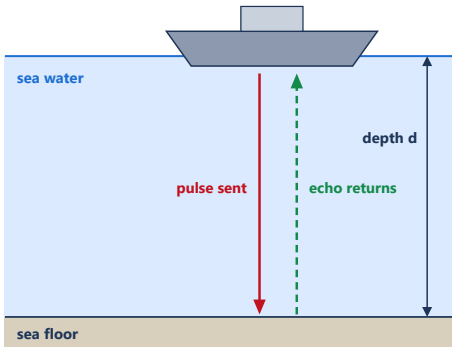
sonar: ultrasound

Li-Fi: LED light

All three ranging systems work like an echo: send out a wave, time how long its reflection takes to come back, and work out the distance (distance = speed × time ÷ 2). They differ in the kind of wave used.

Radar vs LiDAR vs sonar ★★★

	Radar	LiDAR	Sonar
Full form	Radio Detection And Ranging	Light Detection And Ranging	Sound Navigation And Ranging
Wave used	Radio waves / microwaves (EM)	Laser light, usually near-infrared (EM)	Sound, usually **ultrasonic** (mechanical)
Works best in	Air and space; sees through cloud and dark	Air; very fine detail, but blocked by fog and rain	**Water** (sound travels far in water; EM waves do not)
Uses	Air-traffic control, weather (Doppler) radar, ship navigation, speed guns	3D mapping of land and forests, self-driving cars, archaeology, flood-plain surveys	Submarine detection, mapping the sea floor, fish finding
In nature	Not used by animals	Not used by animals	Bats and dolphins use ultrasonic echoes (echolocation)



distance = speed × time ÷ 2

The wave goes down and comes back, so it covers the distance twice.

Example: echo heard after 2 s;
sound in sea water ≈ 1500 m/s
d = 1500 × 2 ÷ 2 = 1500 m

Radar and LiDAR use the same rule with $c = 3 \times 10^8$ m/s (radio waves, laser).

Echo ranging, as in a ship's sonar (ship and depth not to scale). The pulse goes down and its echo comes back, so distance = speed × time ÷ 2. Radar and LiDAR time an echo the same way, with radio waves or laser light instead of sound.

★ **Li-Fi** (Light Fidelity) sends data by flickering LED light faster than the eye can notice; it cannot pass through walls, unlike radio-based Wi-Fi.

⚠ **Exam trap:** Submarines use **sonar**, not radar, because radio waves are absorbed quickly by sea water while sound travels far.

☑ Quick check

1. Which ranging system works under water, and why?
2. Distance found from an echo = ?
3. Which uses laser light: radar, LiDAR or sonar?

Answer: 1. sonar: sound travels far in water, radio waves do not · 2. speed × time ÷ 2 · 3. LiDAR

Asked in past papers (7)

UPSC 2012 What is the role of ultraviolet (UV) radiation in the water purification systems?
1. It inactivates/kills the harmful microorganisms in water.
2. It removes all the undesirable odours from the water.
3. It quickens the sedimentation of solid particles, removes turbidity and improves the clarity of water.
Which of the statements given above is/are correct?
(a) 1 only (b) 2 and 3 only (c) 1 and 3 only (d) 1, 2 and 3
Answer: (a) 1 only. UV disinfects water by damaging microbial DNA; it does not remove odour or turbidity

BPSC 63rd The wavelength of visible spectrum is in the range
(a) 1300 Å-3900 Å (b) 3900 Å-7600 Å (c) 7800 Å-8200 Å (d) 8500 Å-9800 Å
(e) None of the above/more than one of the above
Answer: (b) 3900 Å-7600 Å. Visible light spans about 3900 to 7800 Å (390 to 780 nm)

BPSC 64th Choose the correct statement.
(a) Wavelength of red light is less than violet light. (b) Wavelength of red light is more than violet light.
(c) Wavelength of violet light is more than green light. (d) Wavelength of violet light is more than yellow light.
(e) None of the above/More than one of the above
Answer: (b) Wavelength of red light is more than violet light.. In VIBGYOR, wavelength rises from violet to red

BPSC 66th The radiations used in the treatment of muscle ache are
(a) infrared (b) microwave (c) UV (d) X-ray (e) None of the above/More than one of the above
Answer: (a) infrared. Infrared rays carry heat and are used to relieve muscle and body aches

BPSC 66th The velocity of electromagnetic waves is
(a) 3×10^{8} m s^{-1} (b) 3×10^{7} m s^{-1} (c) 3×10^{6} m s^{-1} (d) 3×10^{5} m s^{-1}
(e) None of the above/More than one of the above
Answer: (a) 3×10^{8} m s^{-1}. All electromagnetic waves travel in vacuum at about 3×10^{8} m/s

BPSC 70th Which of the following radiation is used to get relief from body aches ?
(a) Infra-red radiation (b) UV radiation (c) Visible radiation (d) None of these
Answer: (a) Infra-red radiation. Infrared rays carry heat and are used to relieve muscle and body aches

BPSC 70th re-exam One of the properties associated with X-rays is that they can be deflected by
(a) Magnetic fields only (b) Both electric and magnetic fields together (c) Electric fields only
(d) None of the above
Answer: (d) None of the above. X-rays carry no charge, so electric and magnetic fields do not deflect them

Test yourself (11)

1. Arrange in increasing order of frequency: 1. X-rays 2. Microwaves 3. Ultraviolet 4. Infrared
(a) 2, 4, 3, 1 (b) 4, 2, 3, 1 (c) 2, 3, 4, 1 (d) 1, 3, 4, 2

2. Which radiation is used to sterilise packed syringes and to treat cancer?
(a) Infrared (b) Microwaves (c) Gamma rays (d) Radio waves

3. Which of the following is NOT an electromagnetic wave?
(a) Gamma rays (b) Ultrasonic waves (c) Infrared rays (d) Microwaves

4. The colours seen on the surface of a CD are mainly due to
(a) dispersion (b) diffraction (c) polarisation (d) total internal reflection

5. Polarisation of light shows that light is
(a) a longitudinal wave (b) a transverse wave (c) a stream of charged particles (d) a mechanical wave

6. Consider these statements about lasers: 1. Laser light is monochromatic and coherent. 2. Laser light travels faster than ordinary light in vacuum. 3. LASIK surgery uses a laser to reshape the cornea. Which are correct?
(a) 1 and 2 only (b) 1 and 3 only (c) 2 and 3 only (d) 1, 2 and 3

7. Which part of sunlight is responsible for making vitamin D in the skin?
(a) Infrared (b) Visible light (c) Ultraviolet-B (d) X-rays

8. Which device uses sound waves rather than electromagnetic waves?
(a) Radar (b) LiDAR (c) Sonar (d) Li-Fi

9. Consider the following statements:
1. A UV water purifier kills microbes and also removes dissolved salts from the water.
2. X-rays are not deflected by electric or magnetic fields.
3. An MRI scan uses X-rays to form images of the body.
Which of the statements given above is/are correct?
(a) 1 only (b) 2 only (c) 3 only (d) 2 and 3 only

10. Consider the following:
1. Cathode rays
2. Cosmic rays
3. Gamma rays
How many of the above are electromagnetic waves?
(a) Only one (b) Only two (c) All three (d) None

11. Soup in a glass bowl gets hot in a microwave oven while the bowl itself stays fairly cool. Why?
(a) Glass reflects the microwaves back onto the soup
(b) Microwaves are a kind of infrared that only liquids can absorb
(c) Microwaves jostle water molecules; glass lets them through
(d) The oven gives out ultraviolet rays that pass through glass

Answers: 1. (a) Microwave < infrared < ultraviolet < X-rays. · 2. (c) High-energy gamma rays from cobalt-60 kill microbes and cancer cells. · 3. (b) Ultrasonic waves are sound waves and need a medium. · 4. (b) The closely spaced tracks act as a diffraction grating. · 5. (b) Only transverse waves can be polarised. · 6. (b) All light travels at c in vacuum; statements 1 and 3 are correct. · 7. (c) UV-B triggers vitamin D synthesis in the skin. · 8. (c) Sonar uses (mostly ultrasonic) sound; the others use radio, laser or LED light. · 9. (b) UV only kills or inactivates microbes by damaging their DNA and does not remove salts; MRI uses a strong magnet and radio waves, not X-rays. Only statement 2 is correct. · 10. (a) Only gamma rays are electromagnetic waves; cathode rays are electrons and cosmic rays are mostly high-speed protons, despite the word 'rays'. · 11. (c) At 2.45 GHz the field makes lopsided water molecules twist back and forth, heating the soup; glass and ceramic let microwaves through, while metal reflects them.

CHAPTER 11

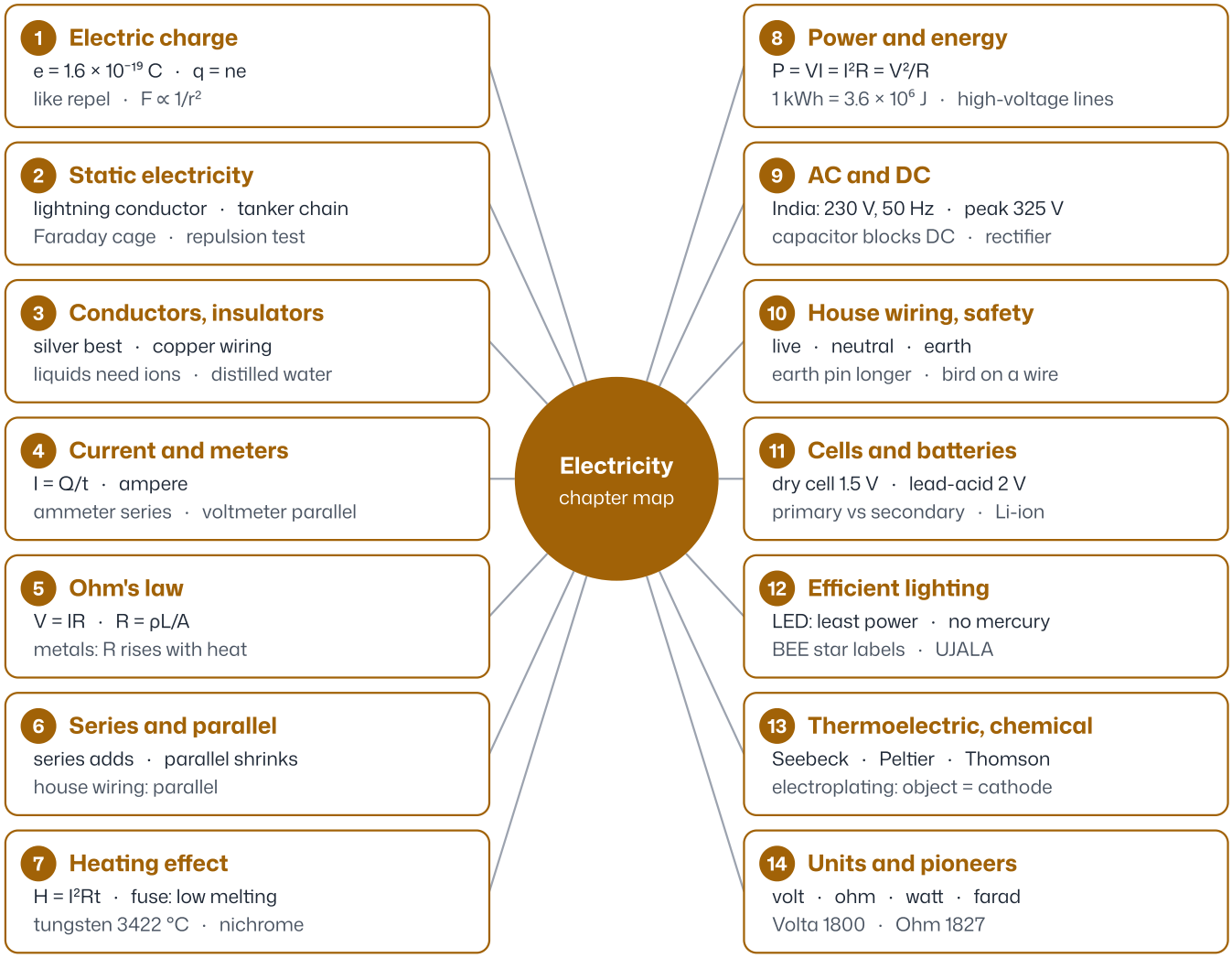
Electricity: Charge, Current and Circuits

Measuring instruments, Ohm's law, power formulas, series-parallel resistance, fuse and household safety come up almost every year, especially in BPSC.

Asked 12 times in past papers: BPSC 12

≈ 59 min to read ≈ 8 min to revise ★★★

Revise on: Day 1 | Day 3 | Day 7 | Day 21



Revision card

1. Charge is quantised (q = ne) and conserved; e = 1.6 × 10^{-19} C; 1 C ≈ 6.25 × 10^{18} electrons.
2. Ammeter measures current: in series, very low resistance. Voltmeter measures potential difference: in parallel, very high resistance.
3. Galvanometer detects small currents; potentiometer measures emf; ohmmeter measures resistance; voltameter is an electrolysis cell, not a voltmeter.
4. Ohm's law V = IR, so R = V/I; R = ρL/A. Metals' resistance rises with temperature; semiconductors' falls.
5. Series: R = R_1 + R_2 (bigger). Parallel: 1/R = 1/R_1 + 1/R_2 (smaller than the smallest). House wiring is parallel.
6. Power P = VI = I^2R = V^2/R, in watts. IR^2 is NOT a power formula.
7. 1 unit = 1 kWh = 3.6 × 10^6 J. Heat H = I^2Rt (Joule's law).
8. Fuse: tin-lead alloy, low melting point, in series on the live wire. Filament: tungsten (melts at 3422 °C), bulb filled with argon/nitrogen. Heater coil: nichrome.
9. Short circuit: resistance ≈ 0, so current becomes very large; the fuse melts or the MCB trips.
10. India: 230 V (often quoted as 220 V), 50 Hz AC (USA 120 V, 60 Hz). Current reverses 100 times a second.
11. Wire colours: live brown (old red), neutral blue (old black), earth green-and-yellow (old green). Earth pin is longest and thickest.
12. Capacitive reactance Xc = 1/(2πfC) falls with frequency; inductive reactance XL = 2πfL rises with it.
13. Thomson effect: emf along ONE conductor with a temperature gradient. Seebeck: two metals, heat → emf. Peltier: current → heating/cooling at a junction.
14. Volta made the first battery (1800). Lead-acid in cars (2 V per cell, 12 V); Li-ion in phones and EVs (Chemistry Nobel 2019).

Electric charge

like vs unlike

e = 1.6 × 10^{-19} C

q = ne

conservation

Coulomb's law

volt = J/C

Every atom holds positive protons in the nucleus and negative electrons around it. Normally they balance, so matter is neutral. Rubbing, touching or heating can move **electrons** from one body to another: the body that gains electrons turns **negative**, the one that loses them turns **positive**. Protons never move in such charging.

★★★ **Two kinds** of charge: positive and negative. **Like charges repel, unlike charges attract.**

★★★ **SI unit**: coulomb (C). Charge of one electron **e = 1.6 × 10^{-19} C** (negative); a proton carries the same amount, positive.

★★ Since the 2019 SI redefinition, e is fixed **exactly** at 1.602 176 634 × 10^{-19} C, and the ampere is defined from it.

★★★ **Quantisation**: any charge is a whole-number multiple of e (q = ne). You can never have 1.5 e on a body.

★★★ **Conservation**: charge is neither created nor destroyed; in rubbing it only moves. Glass and silk end up with equal and opposite charges.

★★ **1 coulomb** ≈ charge of **6.25 × 10^{18} electrons**.

★★ **Millikan's oil-drop experiment** (1909) measured e and showed charge comes in fixed lumps.

★ A body that becomes negative gains electrons, so its mass increases very slightly; a positive body loses a tiny mass.

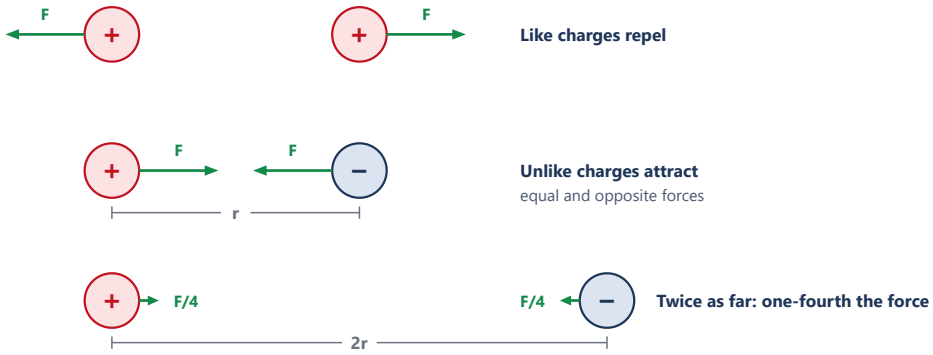
★★ **Coulomb's law** (1785): $F = k\, q_1 q_2 / r^2$, with $k \approx 9 \times 10^9$ N m^2 C^{-2}. Force doubles if one charge doubles; it falls to one-fourth if distance doubles (inverse square).

★ **In a medium** the force weakens: in water it is about 1/80 of that in air (dielectric constant of water ≈ 80). This is why water pulls salts apart so easily.

★ **Electric force vs gravity**: between two protons the electric force is about 10^{36} times the gravitational pull.

★★ **Electric field** E = force per unit charge; unit **N/C** (= V/m). Field lines start on + charges, end on − charges, and never cross.

★★ **Electric potential** = work done per unit charge to bring it from far away; unit **volt** (1 V = 1 J/C). Positive charge flows from high to low potential, like water flowing downhill.



Forces between charges, arrows to scale. Like charges repel and unlike charges attract, always with equal and opposite forces. Move the charges twice as far apart and each force falls to one-fourth ($F \propto 1/r^2$).

Remember it: GSP: Glass rubbed with Silk turns Positive. The plastic comb in dry hair, the balloon on a sweater and ebonite on wool all grab electrons and turn negative.

Quick check

1. Glass is rubbed with silk. Which way do electrons move, and what charge does the glass get?
2. Can a body carry a charge of 1.5 e? Why?
3. Double the distance between two charges: the force becomes _____ .

Answer: 1. electrons leave the glass; it turns positive · 2. no: charge is quantised, q = ne · 3. one-fourth ($F \propto 1/r^2$)

Static electricity in daily life

charging methods

repulsion test

Charge that stays put on a body is **static electricity**. It builds up when two surfaces rub, and escapes suddenly as a **spark** when it finds a path. Dry air lets it build; humid air lets it leak away slowly, which is why sparks are a winter problem, not a monsoon one.

lightning conductor

tanker chain

Faraday cage

Three ways to charge a body ★★

Method	What happens	Sign of charge gained
Friction (rubbing)	Electrons move from one surface to the other	Opposite on the two bodies
Conduction (touching)	A charged body shares its charge on contact	Same as the charging body
Induction (no contact)	A charged body nearby pushes the free electrons to one side; earthing the far side and then removing it leaves a charge	Opposite to the inducing body

★★ **Why a charged comb lifts paper bits**: it induces opposite charge on the near side of the paper, and attraction wins. Attraction alone does not prove a body is charged.

★★★ **Repulsion is the sure test** of charge: only two charged bodies can repel.

★★ **Gold-leaf electroscope** detects charge: two thin leaves receive the same charge and spread apart. The wider they open, the more charge.

★★★ **Lightning**: friction among ice and water particles separates charge inside a cumulonimbus cloud; when the field gets strong enough, air breaks down and a giant spark jumps to another cloud or to the ground. **Benjamin Franklin** showed lightning is electricity with his kite experiment (1752).

★★★ **Lightning conductor**: a pointed metal (copper) rod above the highest point of a building, joined by a thick strip to a plate buried in moist earth. Charge crowds at sharp points, so the rod leads the strike safely to the ground.

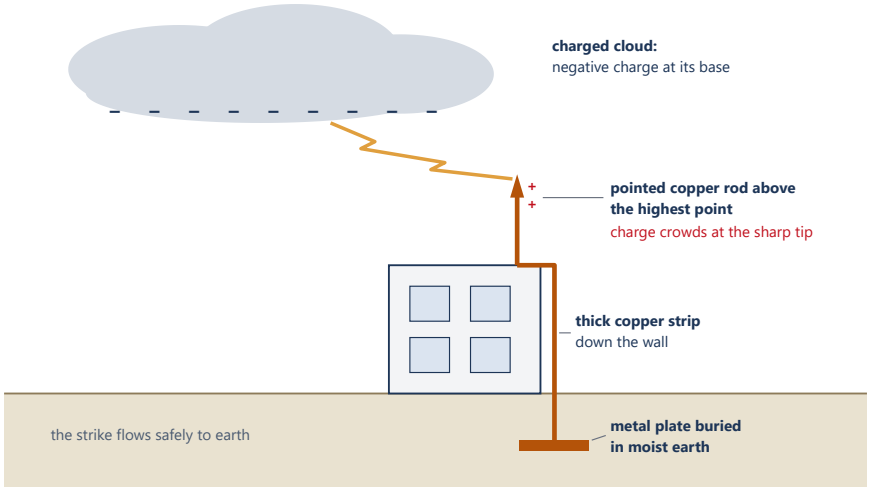
★★ **Thunder** is heard after the flash because light travels far faster than sound.

★★ **Fuel tankers** build up charge as fuel sloshes and tyres roll. A **metal chain or conducting strip** touching the road drains it to earth, so no spark ignites the fuel vapour.

★★ **Woollen and synthetic clothes** crackle and give small sparks in dry winter: rubbing charges them, and dry air cannot leak the charge away.

★★ **Charge sits on the outer surface** of a conductor and the field inside a closed metal shell is zero (**Faraday cage**). So a closed car, bus or aircraft is a safe place in a lightning storm.

★ **Uses of static**: photocopiers and laser printers (charged drum picks up toner), electrostatic precipitators that remove fly ash from thermal power plant chimneys, spray painting.



Lightning conductor. The cloud's negative base induces positive charge that crowds at the rod's sharp tip; a strike is led down the thick copper strip to the plate buried in moist earth, bypassing the building. Not to scale.

See it around you: Taking off a sweater in Delhi's December dark: you hear crackles and see tiny blue sparks. Touching a metal door handle after walking on a carpet gives a small jolt. Both are static charge escaping.

Exam trap: In a thunderstorm, standing under a lone tall tree or in an open field is dangerous; sitting inside a closed car is safe. The car protects because of its metal shell, not because of its rubber tyres.

Lightning striking the Eiffel Tower, 1902. The flash goes for the tallest metal point, and the iron structure carries the charge safely to earth: the same job a lightning conductor does for a building. Image: Gabriel Loppé, Wikimedia Commons, public domain

Quick check

1. Which is the sure test that a body is charged: attraction or repulsion?
2. Why does a fuel tanker carry a metal chain touching the road?
3. In a thunderstorm, why is a closed car safe?

Answer: 1. repulsion · 2. it drains static charge to earth, so no spark ignites the fuel vapour · 3. its metal shell (Faraday cage), not its rubber tyres

Conductors, insulators and semiconductors

free electrons

silver best

copper wiring

aluminium lines

ions in liquids

distilled water

A material conducts if it has charges free to move. Metals have a sea of free electrons. In liquids the carriers are **ions**, so a liquid conducts only if something is dissolved in it that splits into ions.

Who conducts and who does not ★★★

Type	Why	Examples
Conductor	Many free electrons; low resistance	Silver (best), copper, gold, aluminium, iron, graphite, the human body, the earth
Insulator	Almost no free charges; very high resistance	Rubber, plastic, glass, dry wood, porcelain, mica, dry air
Semiconductor	In between; conduction rises with heat or added impurities	Silicon, germanium (more in the chapter on electronics)
Conducting liquids (electrolytes)	Dissolved ions carry charge	Salt water, lemon juice, orange juice, vinegar, acids, tap water, molten salts
Poorly conducting liquids	No ions	Distilled water, kerosene, petrol, vegetable oil

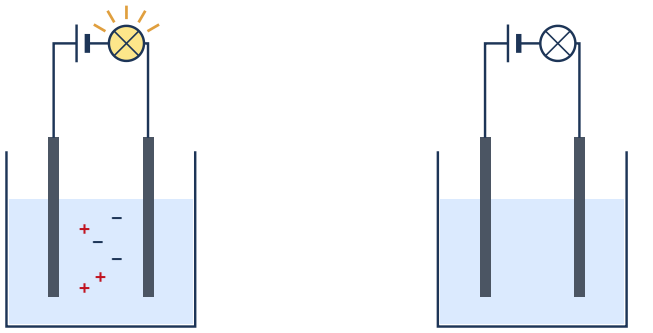
★★★ **Silver** is the best conductor; **copper** is used in household wiring (nearly as good, much cheaper); **aluminium** in overhead transmission lines (light and cheap).

★★ **Graphite** is a non-metal that conducts; it is used for electrodes and in dry-cell carbon rods.

★★ **Mercury** is a liquid metal and conducts well; it does not need ions.

★★ **Pure (distilled) water** barely conducts; the tap water that gives shocks conducts because of dissolved salts.

★ **Porcelain discs** on electric poles insulate the live wires from the pole.



The same circuit dipped in two liquids. Salt water holds ions that carry charge, so the bulb glows; distilled water has almost none, so the bulb stays dark. Lemon juice or vinegar would light the bulb too.

⚠ **Exam trap:** "Which liquid is a bad conductor: salt water, orange juice or lemon juice?" None of them. All three contain ions and conduct. Choose distilled water, oil or kerosene as the bad conductor if offered.

Quick check

1. Best conductor of electricity among metals?
2. Why is aluminium, not copper, used in overhead transmission lines?
3. Salt water, lemon juice, kerosene: which one is a poor conductor?

Answer: 1. silver · 2. it is light and cheap · 3. kerosene (no ions)

Current, potential difference and the meters that measure them

I = Q/t

electron drift

ammeter: series

voltmeter: parallel

galvanometer

voltameter ≠ voltmeter

Think of a water tank: the **height difference** (potential difference) pushes water, the **flow rate** is the current, and a **narrow pipe** is the resistance. A battery is the pump that keeps the height difference alive.

★★★ **Electric current** I = charge flowing per second, I = Q/t. Unit **ampere** (A), one of the seven SI base units; 1 A = 1 C/s.

★★★ **Conventional current** flows from + to − outside the cell; **electrons** actually drift the other way, from − to +.

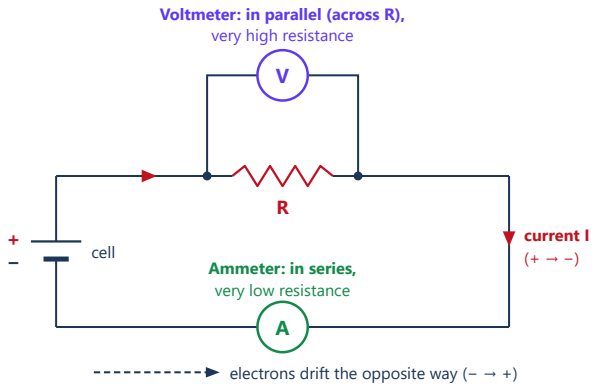
★★ **Drift speed** of electrons in a wire is tiny (well under a millimetre per second), yet a bulb lights at once because the electric field travels along the wire at nearly the speed of light.

★★★ **Potential difference** (voltage) = work done per unit charge between two points; unit **volt** (V), named after Alessandro Volta.

★★ **EMF** (electromotive force) = energy a cell gives each coulomb; measured in volts. It is not a force. Terminal voltage is a little less than emf when current flows, because the cell has internal resistance.

Instruments: what each one measures ★★★

Instrument	Measures / does	How it is connected
Ammeter	Electric current	In series; very low resistance
Voltmeter	Potential difference	In parallel; very high resistance
Galvanometer	Detects small currents and their direction	In series; becomes an ammeter with a low resistance (shunt) in parallel, a voltmeter with a high resistance in series
Potentiometer	EMF of a cell, accurately (draws no current at balance); compares emfs	Long uniform wire with a galvanometer (null method)
Ohmmeter	Resistance	Across the component, with the circuit switched off
Multimeter	Current, voltage and resistance	In series for current, in parallel for voltage
Wheatstone bridge / metre bridge	Unknown resistance	Four resistances with a galvanometer (null method)
Rheostat	Varies resistance to control current	In series
Voltameter	An electrolytic cell; shows electrolysis and measures charge passed	In series: the whole current passes through it
Energy meter	Electrical energy in kWh (units)	At the house entry
Electroscope	Detects static charge	Not in a circuit: the charged body touches its cap



Ammeter A in series, so the whole current passes through it; voltmeter V in parallel, across the resistor whose voltage it measures. Conventional current leaves the + terminal; electrons drift the other way.

Remember it: Ammeter stands in the queue (series); Voltmeter stands beside it to compare heights (parallel). An ammeter must not slow the queue, so its resistance is tiny; a voltmeter must not steal current, so its resistance is huge.

⚠ Exam trap: Voltameter ≠ voltmeter. And a galvanometer detects current; it does not measure resistance. "Galvanometer: electric resistance" is the wrongly matched pair.

Quick check

1. How is an ammeter connected, and what is its resistance?
2. Outside the cell, electrons in a wire drift from _____ to _____; conventional current flows the other way.
3. Which instrument measures the emf of a cell accurately, drawing no current at balance?

Answer: 1. in series; very low · 2. − to + · 3. potentiometer

Ohm's law and resistance

V = IR

R = ρL/A

resistivity (Ω m)

stretched wire: 4R

temperature effect

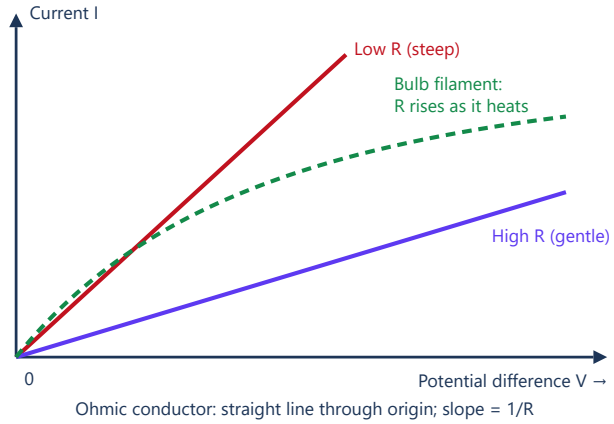
Push harder and more current flows. **Georg Simon Ohm** (1827) found that for a metal wire at steady temperature, current is exactly proportional to the voltage. The ratio V/I is fixed for that wire and is called its **resistance**.

★★★ **Ohm's law**: V = IR, so **R = V/I** and I = V/R. Holds when temperature and physical conditions stay the same.

★★★ **Unit of resistance**: ohm (Ω); 1 Ω = 1 V/A. **Conductance** G = 1/R, unit siemens (S), old name mho (℧).

★★ **V–I graph** of an ohmic conductor is a straight line through the origin. The steeper the I-vs-V line, the smaller the resistance.

★★ **Non-ohmic** devices: filament bulb (resistance rises as it heats), diode, transistor, electrolytes.



Straight line = Ohm's law obeyed. Steeper line = lower resistance. A bulb filament bends away because it gets hotter and its resistance rises.

★★★ **R = ρL/A**: resistance grows with **length** (L) and falls with **cross-sectional area** (A). ρ (rho) is the **resistivity**.

★★★ **Resistivity** depends only on the material and its temperature, not on shape or size. Unit **ohm-metre (Ω m)**.

★★ **Values at 20 °C**: silver ≈ 1.6×10^{-8} Ω m, copper ≈ 1.7×10^{-8} Ω m, nichrome ≈ 1.1×10^{-6} Ω m (about 65 times copper).

★★ **Thick wire, low resistance**: doubling the diameter makes area 4 times, so resistance falls to one-fourth.

★★ **Stretching** a wire to twice its length (volume unchanged) halves its area, so resistance becomes **4 times**.

★★★ **Temperature**: in metals resistance **rises** with heat (vibrating atoms block electrons); in **semiconductors it falls** (heat frees more charge carriers).

★ **Alloys** such as manganin and constantan barely change resistance with temperature, so standard resistors are made of them.

★★ **Superconductors** lose all resistance below a critical temperature: Heike Kamerlingh Onnes saw it in mercury at 4.2 K (1911). Used in MRI magnets and maglev trains (detail in the chapter on electronics and materials).

Remember it: VIR triangle: put V on top, I and R below. Cover what you want: V = I × R, I = V/R, R = V/I. "Very Intelligent Rahul" never forgets Ohm.

⚠ **Exam trap:** Resistance R changes with length and thickness; resistivity ρ does not. A long thin copper wire and a short thick one have different resistance but the same resistivity.

Quick check

1. A wire is stretched to twice its length. Its resistance becomes?
2. Heating raises a metal wire's resistance. What does heating do to a semiconductor's resistance?
3. Does resistivity change if you cut a wire in half?

Answer: 1. 4 times · 2. lowers it · 3. no: it depends only on the material and temperature

Series and parallel circuits

series: R adds

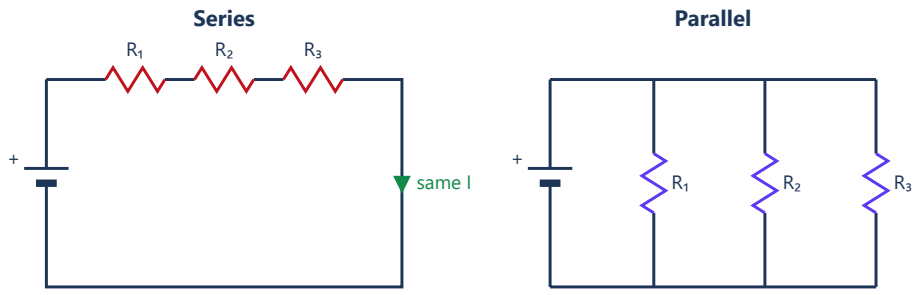
parallel: 1/R adds

house wiring parallel

60 W vs 100 W

ratio n^2

In **series** there is one path, so the same current must squeeze through every resistor one after another: resistances add. In **parallel** each resistor offers a fresh path, like opening more toll booths: the total resistance drops below even the smallest one.



$R = R_1 + R_2 + R_3$ (grows)
Same current; voltage is shared
One break: everything stops

$1/R = 1/R_1 + 1/R_2 + 1/R_3$ (shrinks)
Same voltage; current is shared
One break: the others keep working

Series: one path, same current, resistances add. Parallel: many paths, same voltage, total resistance falls.

Series vs parallel ★★★

Feature	Series	Parallel
Equivalent resistance	$R = R_1 + R_2 + R_3$ (more than the largest)	$1/R = 1/R_1 + 1/R_2 + 1/R_3$ (less than the smallest)
Current	Same through each	Divides; more through the smaller resistance
Voltage	Divides among them	Same across each
If one component fails	Whole circuit stops	Others keep working
n equal resistors R	nR	R/n
Everyday use	Fuse with the circuit; cheap decorative light strings	House wiring; car headlights

★★★ **House wiring is parallel**: every appliance gets the full 230 V, each has its own switch, one fused bulb does not black out the house, and total resistance stays low.

★★ **Two resistors in parallel**: $R = R_1R_2/(R_1 + R_2)$ ("product over sum").

★★ **Worked example**: two resistors in parallel give 1.403 kΩ; one is 2.0 kΩ. Then $1/R_2 = 1/1.403 - 1/2.0 = 0.7128 - 0.5 = 0.2128$, so $\mathbf{R_2 \approx 4.70\ k\Omega}$. Check: the total (1.403) is below both 2.0 and 4.70.

★★ **Same n resistors**: series total ÷ parallel total = $\mathbf{n^2}$. Two equal resistors: series 2R, parallel R/2, ratio 4.

★★ **Cheap decorative light strings** are often wired in series: when one bulb fails the whole string goes dark.

★ **Cells in series** add their voltages (four 1.5 V cells give 6 V); cells in parallel give the same voltage but last longer.

⚠ **Exam trap:** A 60 W and a 100 W bulb in **series**: the **60 W bulb glows brighter** (it has higher resistance, and the same current gives it more I^2R). In **parallel** (as at home) the 100 W bulb glows brighter. Examiners love to reverse this.

Quick check

1. Why is house wiring done in parallel? Give one reason.
2. A 60 W and a 100 W bulb are joined in series. Which glows brighter?
3. Two equal resistors R in parallel give?

Answer: 1. each appliance gets the full 230 V (and one failure does not stop the rest) · 2. the 60 W bulb (higher resistance) · 3. R/2

Heating effect: fuse, filament and heater

$H = I^2Rt$

nichrome element

tungsten 3422 °C

Electrons moving through a wire keep bumping into atoms and hand over energy as heat. **James Prescott Joule** measured it: the heat rises with the square of the current, so doubling the current gives four times the heat. Some devices want this heat (iron, heater), some must survive it (bulb filament), and one is designed to die from it (fuse).

fuse: tin-lead

MCB, RCCB

★★★ **Joule's law of heating**: H = I²Rt (heat in joules, current in A, resistance in Ω, time in s).

★★ **Uses of heating effect**: electric iron, room heater, geyser, toaster, kettle, hot plates, filament bulb, fuse.

★★★ **Heating element**: **nichrome** (nickel-chromium alloy): high resistivity, high melting point (about 1400 °C), does not oxidise easily when red-hot.

★★★ **Bulb filament**: **tungsten**, the metal with the highest melting point (**3422 °C**). It glows white-hot at around 2500 °C.

★★★ **Bulb gas**: filled with inert **argon and/or nitrogen** so the hot tungsten does not oxidise and evaporates more slowly. The filament is coiled to pack more length in.

★★★ **Fuse**: a short wire of **tin-lead alloy** with a **low melting point** (and higher resistivity than copper), connected **in series on the live wire**. When current exceeds its rating it melts and breaks the circuit, protecting wiring and appliances.

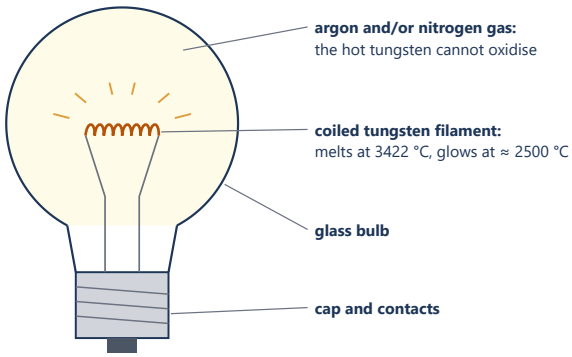
★★ **Fuse rating** is in amperes (e.g. 5 A for lights, 15 A for heavy appliances). Replacing a fuse with a thick copper wire defeats it and invites fire.

★★★ **Short circuit**: live and neutral touch directly (damaged insulation). Resistance falls to almost zero, so **current becomes very large**, wires heat up and can start a fire.

★★ **Overloading**: too many appliances on one socket draw more current than the wire is rated for.

★★★ **MCB** (miniature circuit breaker): an automatic switch that trips on overload or short circuit and can simply be switched back on; it is replacing fuses.

★★★ **ELCB / RCCB** (earth-leakage / residual-current circuit breaker): compares current in live and neutral. If some current leaks away, for example through a person to earth, it trips within a fraction of a second (typical setting 30 mA). It protects **people** from shock.



Filament bulb. The coiled tungsten filament glows white-hot at about 2500 °C without melting (melting point 3422 °C); argon and/or nitrogen inside keep it from oxidising.

Which wire for which job ★★

Device	Material	Property needed
Fuse wire	Tin-lead alloy	Low melting point
Bulb filament	Tungsten	Very high melting point
Heater, iron, toaster coil	Nichrome	High resistivity, high melting point, no oxidation
House wiring	Copper	Very low resistivity
Overhead power lines	Aluminium (often steel-reinforced)	Low resistivity, light, cheap

Remember it: Fuse is the Fragile hero: it dies so the house lives. The filament is the opposite: the toughest survivor of heat (tungsten, 3422 °C).

⚠ **Exam trap:** Fuse and MCB guard **wiring and appliances** against too much current; the ELCB/RCCB guards **people**. But if a question asks which device protects equipment from electric shock and offers only fuse, generator, motor and current controller, the answer is the **fuse**.

Quick check

1. The current through the same wire doubles for the same time. The heat produced becomes?
2. Fuse wire needs a _____ melting point; a bulb filament needs a _____ one.
3. Which device protects people from shock by tripping on leakage current?

Answer: 1. 4 times ($H = I^2Rt$) · 2. low; very high (tungsten) · 3. ELCB / RCCB

Electric power, energy and your bill

$P = VI = I^2R = V^2/R$

$1\ kWh = 3.6 \times 10^6\ J$

1 hp = 746 W

high-voltage transmission

765 kV

Power is how fast energy is used. A 1000 W iron uses energy ten times as fast as a 100 W fan. The electricity board does not bill you for power, but for **energy**: power × time.

★★★ **Electric power** $P = VI = I^2R = V^2/R$. Unit **watt** (W) = 1 J/s. 1 kW = 1000 W; 1 horsepower = 746 W.

★★★ **Energy** = power × time. Commercial unit: **kilowatt-hour (kWh) = 1 unit = 3.6×10^6 J** (1000 W × 3600 s).

★★ **Rating** "100 W, 230 V" means the bulb draws 100 W at 230 V: current = 100/230 ≈ 0.43 A, hot resistance = $V^2/P = 230^2/100 \approx 529\ \Omega$.

★★ **Same voltage, more watts = less resistance**: a 1000 W heater has far lower resistance than a 100 W bulb ($R = V^2/P$).

★★ **Sample bill**: two 60 W fans for 10 h a day = 1.2 kWh; one 1000 W geyser for 1 h = 1 kWh. Daily total 2.2 units; for 30 days 66 units; at ₹6 per unit, **₹396**.

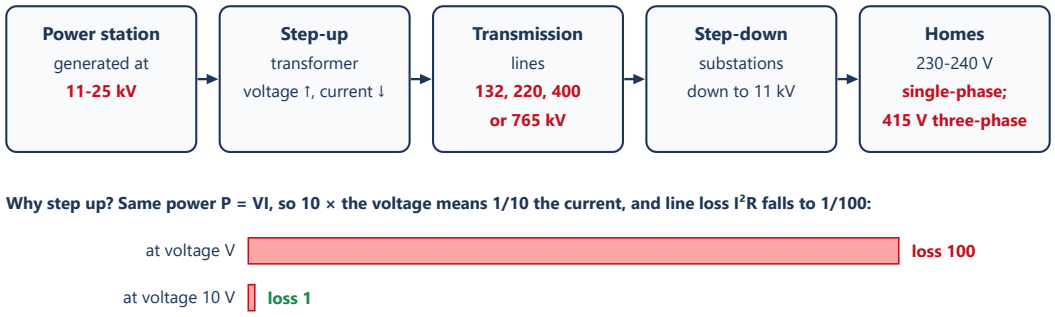
Remember it: Power is VIP: P = V·I. Then swap V = IR to get I^2R, or I = V/R to get V^2/R. Any formula with R squared (like IR^2) is a fake.

Why transmit at high voltage? For a fixed power P = VI, raising V lowers I. The heat wasted in the lines is I^2R, so it falls with the square of the current.

★★★ **Step up 10 times** in voltage → current falls to 1/10 → line loss falls to **1/100**.

★★ **In India** power is generated at roughly 11-25 kV, stepped up to 132, 220, 400 or 765 kV for transmission, then stepped down in stages to 11 kV and finally **415 V (three-phase) / 230–240 V (single-phase)** for consumers. 765 kV is the highest AC transmission voltage in commercial use in India.

★ **HVDC** lines (India runs links up to ±800 kV) carry bulk power over very long distances with lower losses.



From power station to home: voltage is stepped up for the long journey and stepped down near you. Bottom bars, drawn to scale: for the same power, 10 times the voltage cuts the line loss to 1/100.

☑ Quick check

1. 1 kilowatt-hour equals how many joules?
2. Voltage is stepped up 10 times for the same power. The line loss becomes?
3. Same 230 V supply: which has the lower resistance, a 1000 W heater or a 100 W bulb?

Answer: 1. 3.6×10^6 J · 2. 1/100 · 3. the 1000 W heater ($R = V^2/P$)

AC and DC; capacitors and inductors

230 V, 50 Hz

100 reversals a second

peak 325 V

rectifier vs inverter

Xc = 1/(2πfC)

choke coil

Direct current (DC) flows one way, as from a battery or solar cell. **Alternating current (AC)** reverses direction many times a second, as from a power-station generator. AC won the "war of currents" (Tesla and Westinghouse against Edison's DC) because transformers can step AC voltage up and down cheaply.

AC vs DC ★★★

Feature	AC	DC
Direction	Reverses periodically	One direction
Frequency	50 Hz in India; 60 Hz in USA	Zero
Source	AC generator (alternator)	Cell, battery, solar cell, DC dynamo
Voltage change	Easy, with a transformer	Needs electronic converters
Used for	Mains supply, grid, motors at home	Phones, laptops, LEDs, EV batteries, electroplating

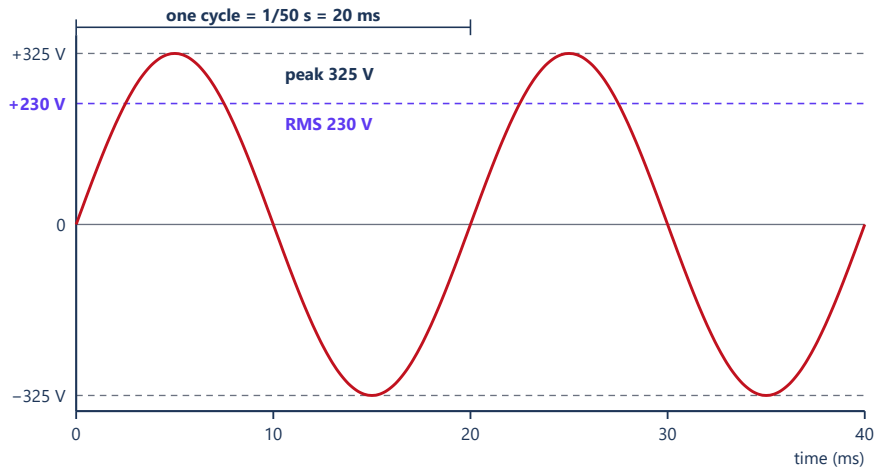
★★★ **India**: 230 V, 50 Hz single-phase supply (three-phase 415 V); the Indian Standard system voltage is 240/415 V, and **220 V** is the older figure many questions still use. **USA**: 120 V, 60 Hz. Japan uses 50 Hz in the east and 60 Hz in the west.

★★ **50 Hz** means 50 full cycles per second, so the current **reverses direction 100 times a second**.

★★ **230 V is the RMS value**; the peak voltage is √2 times it, about **325 V**.

★★ **Rectifier** (diodes) converts AC → DC (phone chargers, adapters). **Inverter** converts DC → AC (home inverter, solar systems).

★★ **AC is more dangerous** at the same voltage: its 50 Hz pulses make muscles clamp, so a victim often cannot let go.



Indian mains drawn to scale: 50 Hz, so one cycle lasts 20 ms and the current reverses 100 times a second. The voltage swings between +325 V and −325 V; 230 V is its RMS value (325 ÷ √2). DC would be a flat line.

★★ **Capacitor**: two conducting plates separated by an insulator (dielectric); it stores charge and energy in an electric field. Capacitance C = Q/V; unit **farad** (F). Practical values are in μF and pF.

★★★ **Capacitive reactance** $X_C = 1/(2\pi fC)$: **inversely proportional to frequency**. A capacitor blocks DC (f = 0) and passes high-frequency AC easily.

★★ **Inductor** (coil): opposes any change in current; unit **henry** (H). **Inductive reactance** $X_L = 2\pi fL$ rises in proportion to frequency: an inductor passes DC freely and chokes high-frequency AC.

★★ **Uses of capacitors**: starting a ceiling fan's motor, camera flash (dumps stored charge in a flash), tuning radios with an inductor, improving the power factor of motors, smoothing DC.

★ **Choke coil**: an inductor used to limit AC current (old tube lights, old fan regulators) while wasting very little power as heat, unlike a resistor.

Remember it: "Capacitor Can't stand Calm DC; inductor Loves Lazy DC." Xc falls as frequency rises; XL rises with frequency.

Quick check

1. Frequency of the mains supply in India, and in the USA?
2. How many times a second does 50 Hz AC reverse its direction?
3. Which device converts AC to DC, and which converts DC to AC?

Answer: 1. 50 Hz; 60 Hz · 2. 100 · 3. rectifier; inverter

Household wiring, earthing and electric shock

live, neutral, earth

wire colours

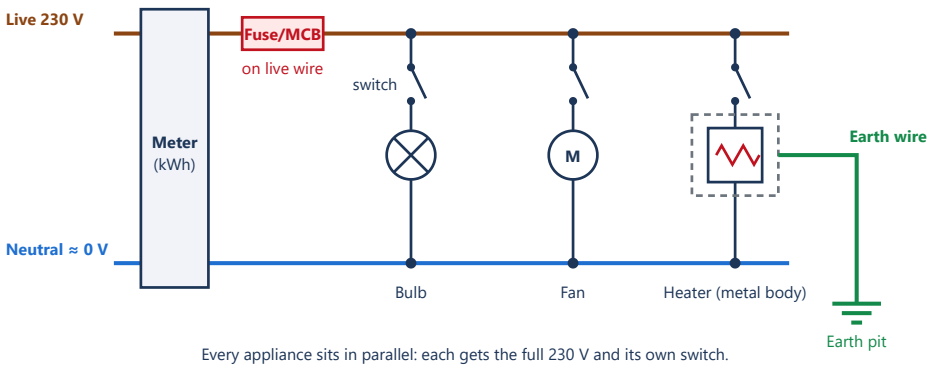
earthing

earth pin longer

bird on a wire

100 mA

Two wires come from the pole: the **live** (phase) wire at 230 V and the **neutral** wire near 0 V. A third, the **earth** wire, comes from a metal plate or pipe buried deep in moist soil next to the house. It carries no current normally; it is a safety escape route.



Every appliance sits in parallel: each gets the full 230 V and its own switch.

Fuse/MCB and every switch sit on the live wire. Appliances are in parallel. The heater's metal body is earthed, so a fault current runs to the earth pit instead of through you.

Wire colours in Indian homes ★★★

Wire	Current standard	Older installations	Potential
Live (phase)	Brown	Red	230 V
Neutral	Blue	Black	≈ 0 V
Earth	Green-and-yellow stripes	Green	0 V (ground)

Remember it: Brown = Bijli (the live one), **Blue = Back** (neutral, the return path), **Green-yellow = Ground** (like green earth).

★★★ **Earthing**: the metal body of an iron, fridge, washing machine, geyser or cooler is joined to the earth wire. If the live wire touches the body, a large current rushes to earth, the fuse blows or MCB/RCCB trips, and the body never stays at 230 V.

★★★ **Three-pin plug**: the **earth pin is longer and thicker**. Longer, so it connects first and disconnects last; thicker, so it cannot be pushed into a live or neutral hole.

★★★ **Switches and fuses go on the live wire**, so that switching off cuts the appliance away from 230 V.

★★★ **Bird on a wire is safe**: both feet touch the same wire at the same potential, so there is no potential difference across its body and no current flows. A bird or monkey that touches two wires, or a wire and the pole, is electrocuted.

★★ **Electric shock**: current through the body does the damage. About 1 mA is felt; 10-20 mA makes muscles lock; around **100 mA** across the chest can stop the heart's rhythm and kill.

★★ **Wet skin** cuts the body's resistance from roughly 100 kΩ (dry) to about 1 kΩ, so the same voltage drives a far larger current. Never touch switches with wet hands.

★★ **Rescue**: switch off the mains first, or push the person away with a dry wooden stick; never grab a person who is still in contact.

⚠ **Exam trap:** It is not the voltage alone but the **current through the body** that kills. A bird on an 11 kV line is safe; a person touching a 230 V wire while standing barefoot on wet ground is not.

Quick check

1. Live, neutral, earth: what colour is each in the current Indian standard?
2. Why is the earth pin of a three-pin plug made longer?
3. Why is a bird sitting on a single live wire safe?

Answer: 1. brown, blue, green-and-yellow · 2. so it connects first and disconnects last · 3. both feet are at the same potential, so no current flows through it

Cells and batteries

chemical → electrical

voltaic pile 1800

dry cell 1.5 V

lead-acid 2 V

primary vs secondary

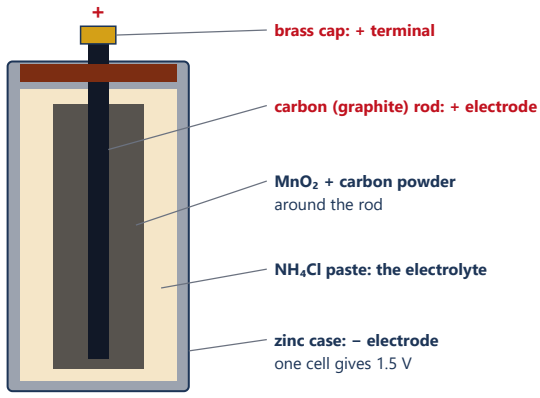
lithium-ion

A cell turns **chemical energy into electrical energy** by letting two different electrodes react through an electrolyte. **Luigi Galvani** saw frog legs twitch ("animal electricity", 1780s); **Alessandro Volta** showed the metals were the real source and built the **voltaic pile** (1800), the first battery: zinc and copper discs separated by brine-soaked cloth.

An early voltaic pile on display at the Tempio Voltiano, Volta's museum in Como, Italy: a stack of metal discs separated by brine-soaked cloth. Volta's pile (1800) was the first battery. Image: GuidoB, Wikimedia Commons, CC BY-SA 3.0

Cells you meet every day ★★★

Cell	Type	Voltage per cell	Key facts / uses
Dry cell (Leclanché type)	Primary (use and throw)	1.5 V	Zinc case (−), carbon rod (+), MnO_2 and NH_4Cl paste; torches, remotes, clocks
Alkaline cell	Primary	1.5 V	Longer life than ordinary dry cell
Button cells (silver oxide, mercury)	Primary	≈ 1.35-1.55 V	Watches, hearing aids, calculators
Lead-acid	Secondary (rechargeable)	2 V (6 cells = 12 V)	Lead and lead dioxide plates in dilute sulphuric acid; car batteries, inverters; Gaston Planté, 1859
Nickel-cadmium, nickel-metal hydride	Secondary	1.2 V	Rechargeable AA cells, cordless tools
Lithium-ion	Secondary	≈ 3.6-3.7 V	Highest energy per kg; phones, laptops, electric vehicles
Fuel cell (hydrogen-oxygen)	Runs as long as fuel is fed	≈ 0.7-1 V in use	Only by-product is water; spacecraft, fuel-cell vehicles
Solar (photovoltaic) cell	Light → electricity	≈ 0.5-0.6 V (silicon)	Gives DC; rooftop solar, satellites



Dry (Leclanché-type) cell, cut open. The zinc case is the negative electrode and the carbon rod with its brass cap the positive one; the MnO_2 mixture and the NH_4Cl paste lie between them. One cell gives 1.5 V.

★★★ **Primary cells** cannot be recharged (the reaction is one-way); **secondary cells** can be recharged by passing current backwards.

★★ **Nobel Prize in Chemistry 2019**: John Goodenough, M. Stanley Whittingham and Akira Yoshino, for developing the **lithium-ion battery**.

★ **Sodium-ion batteries** swap lithium for cheap, abundant sodium: safer and cheaper but heavier for the same energy; suited to grid storage and low-cost vehicles.

★★ **Battery capacity** is quoted in mAh or Ah (charge); energy stored = voltage × capacity, in Wh.

★ **Lead-acid** batteries are the most recycled; their sulphuric acid and lead make careless disposal toxic.

Remember it: Volta → volt; Galvani → galvanometer. The frog twitched for Galvani, but the battery belongs to Volta.

Quick check

1. Voltage of one dry cell, and of one lead-acid cell?
2. In a dry cell, which part is the negative electrode?
3. Primary or secondary: which kind of cell can be recharged?

Answer: 1. 1.5 V; 2 V · 2. the zinc case (the carbon rod is +) · 3. secondary (lead-acid, Li-ion)

Efficient lighting and star labels

lumens per watt

LED most efficient

CFL: mercury

blue LED Nobel 2014

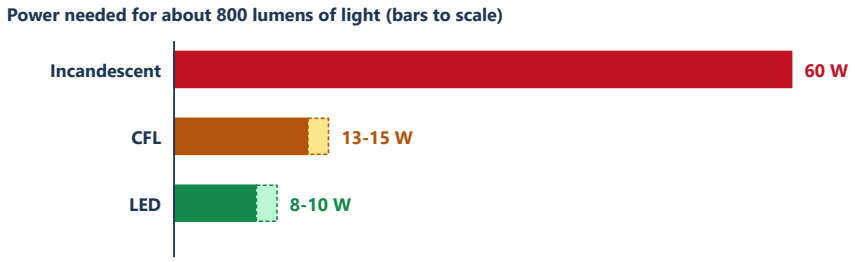
BEE stars

UJALA 2015

A filament bulb makes light by getting white-hot, so most of its energy leaves as heat. An LED makes light directly from electrons crossing a semiconductor junction, so very little is wasted. Efficiency is measured in **lumens per watt** (light out per watt in).

Bulb vs CFL vs LED (for about the same light) ★★★

Feature	Incandescent	CFL	LED
Power for ~800 lumens	60 W	13-15 W	8-10 W
Efficiency	≈ 10-17 lm/W; about 90% lost as heat	≈ 50-70 lm/W	≈ 80-150 lm/W (most efficient)
Life	≈ 1000 hours	≈ 8000-10,000 hours	15,000-50,000 hours
Hazard	Gets very hot	Contains mercury	No mercury



Power each lamp needs for about the same light (≈ 800 lumens), bars to scale. An LED does the job of a 60 W bulb with 8-10 W.

★★ **Blue LED** made white LED lighting possible: **Nobel Prize in Physics 2014** to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura.

★★ **UJALA** scheme (2015) distributed LED bulbs at low prices across India, cutting household lighting bills.

★★ **BEE star labels**: the Bureau of Energy Efficiency (set up under the Energy Conservation Act 2001, Ministry of Power) rates appliances from 1 to 5 stars; **more stars = less electricity** for the same work.

★ **Thomas Edison** made the first long-lasting practical incandescent bulb (1879).

Quick check

1. The efficiency of a lamp is measured in _____ .
2. Which lamp contains mercury: incandescent, CFL or LED?
3. More BEE stars on an appliance mean?

Answer: 1. lumens per watt · 2. CFL · 3. less electricity for the same work

Thermoelectric and chemical effects of current

Seebeck: heat → emf

Peltier: cooling

Thomson: one wire

electrolysis

object = cathode

Heat and electricity can trade places at the junction of two different metals, or along one metal that is hot at one end. These three effects carry the names of their discoverers, and examiners mix them up on purpose.

Thermoelectric effects ★★★

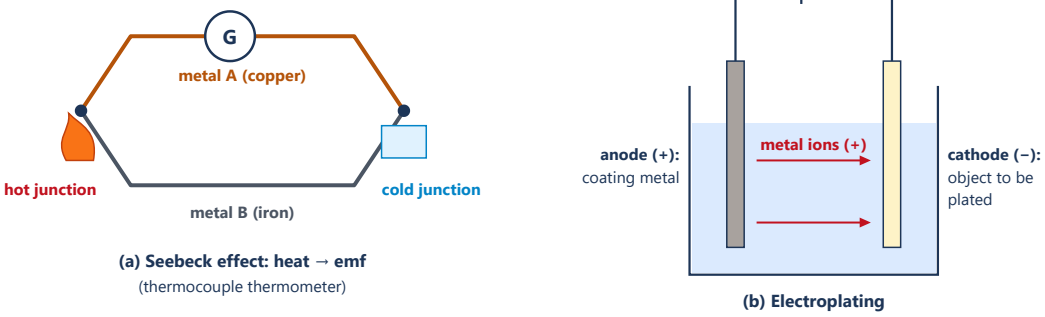
Effect	What happens	Use
Seebeck effect (1821)	Two different metals joined in a loop; junctions at different temperatures produce an emf (heat → electricity)	Thermocouple thermometers for very high temperatures; radioisotope generators on deep-space probes
Peltier effect (1834)	Current through a junction of two metals heats one junction and cools the other	Thermoelectric coolers: mini-fridges, CPU and camera-sensor cooling
Thomson effect	In a single conductor whose ends are at different temperatures, the temperature gradient sets up a potential difference; current along it absorbs or gives out heat	Theory and design of thermoelectric devices
Joule effect	Current through any resistance produces heat I^2Rt; irreversible	Heaters, irons, fuses

Remember it: Seebeck: "See" a voltage from heat (two metals). Peltier: "Pass" a current, heat moves. Thomson: one lonely wire ("Tom" is alone).

★★ **Chemical effect**: current through an electrolyte breaks it up (**electrolysis**). Faraday's laws: mass deposited ∝ charge passed.

★★ **Electroplating**: the object to be coated is the cathode (−); the coating metal is the anode. Chromium on taps and cycle parts, silver and gold on jewellery, tin on food cans.

★ **Electrolytic refining** of copper: impure copper as anode, pure copper collects on the cathode.



(a) Two different metals joined in a loop: keep one junction hot and the other cold and the galvanometer shows a current (Seebeck effect). (b) Electroplating: the coating metal is the anode (+), the object is the cathode (−), and metal ions travel through the electrolyte to coat it.

☑ Quick check

1. Thermocouple thermometers work on which effect?
2. Which effect lets a current cool one junction, as in a mini-fridge?
3. In electroplating, is the object to be coated the anode or the cathode?

Answer: 1. Seebeck effect · 2. Peltier effect · 3. cathode (−)

Units and pioneers at a glance

coulomb, ampere, volt

ohm, siemens

watt, kWh

farad, henry

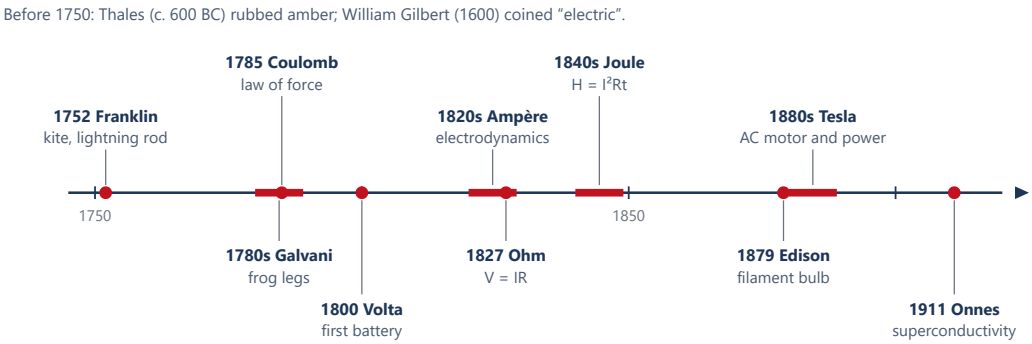
Volta, Ohm, Joule

Quantities and SI units ★★★

Quantity	Formula	SI unit
Charge	$q = ne$	coulomb (C)
Current	$I = Q/t$	ampere (A), SI base unit
Potential difference, emf	$V = W/Q$	volt (V)
Resistance	$R = V/I$	ohm (Ω)
Resistivity	$\rho = RA/L$	ohm-metre (Ω m)
Conductance	$G = 1/R$	siemens (S) or mho
Power	$P = VI = I^2R = V^2/R$	watt (W)
Energy	$E = Pt$	joule (J); commercial: kWh
Capacitance	$C = Q/V$	farad (F)
Inductance	$L = \Phi/I$	henry (H)
Electric field	$E = F/q$	N/C or V/m

Who did what ★★

Scientist	Contribution
Thales of Miletus (c. 600 BC)	Rubbed amber attracts light objects
William Gilbert (1600)	Coined "electric"; studied magnetism
Benjamin Franklin (1752)	Kite experiment; lightning conductor; named + and − charges
Charles-Augustin de Coulomb (1785)	Law of force between charges
Luigi Galvani (1780s)	Animal electricity (frog legs)
Alessandro Volta (1800)	Voltaic pile, the first battery
André-Marie Ampère (1820s)	Electrodynamics; unit of current
Georg Simon Ohm (1827)	Ohm's law
James Prescott Joule (1840s)	Heating effect $H = I^2Rt$
Thomas Edison (1879)	Practical filament bulb; DC power stations
Nikola Tesla (1880s)	AC motor and AC power system
Heike Kamerlingh Onnes (1911)	Superconductivity



Who did what, on a time line drawn to scale: dots mark single years, bars mark decades.

In India, **CSIR-National Physical Laboratory** (New Delhi) keeps the national standards of measurement, including electrical units, and the **Bureau of Indian Standards** sets the standard supply voltages and the 50 Hz frequency (IS 12360).

Quick check

1. SI unit of conductance?
2. Who built the first battery, and in which year?
3. Who discovered superconductivity (1911)?

Answer: 1. siemens (S); old name mho · 2. Alessandro Volta, 1800 · 3. Heike Kamerlingh Onnes

Asked in past papers (12)

BPSC 64th The device to measure electric current is
(a) voltmeter (b) ammeter (c) voltameter (d) potentiometer
(e) None of the above/More than one of the above
Answer: (b) ammeter. An ammeter measures electric current; a voltmeter measures potential difference

BPSC 65th The device to measure electric current is
(a) voltmeter (b) ammeter (c) voltameter (d) potentiometer
(e) None of the above/More than one of the above
Answer: (b) ammeter. An ammeter measures electric current; a voltmeter measures potential difference

BPSC 65th The unit of electric power is
(a) ampere (b) volt (c) coulomb (d) watt (e) None of the above/More than one of the above
Answer: (d) watt. Electric power is measured in watts; $P = V \times I$

BPSC 66th The total resistance of a circuit having two parallel resistors is 1.403 kilo-ohm. If one of the resistors is 2.0 kilo-ohm, then the other resistor will be
(a) 1.403 kilo-ohm (b) 2.0 kilo-ohm (c) 3.403 kilo-ohm (d) 4.70 kilo-ohm
(e) None of the above/More than one of the above
Answer: (d) 4.70 kilo-ohm. For resistors in parallel, $1/R = 1/R1 + 1/R2$; the total is below the smallest one

BPSC 67th Which of the following is not correctly matched?
(a) Voltmeter : Potential difference (b) Ammeter : Electric current (c) Potentiometer : Electromotive force
(d) Galvanometer : Electric resistance (e) None of the above/More than one of the above
Answer: (d) Galvanometer : Electric resistance. Ammeter measures current, voltmeter potential difference, potentiometer emf; A galvanometer detects small currents; an ohmmeter measures resistance

BPSC 67th re-exam Due to temperature variation along a conductor, potential variation occurs along it. This phenomenon is known as
(a) Peltier effect (b) Thomson effect (c) Joule effect (d) Seebeck effect
(e) None of the above/More than one of the above
Answer: (b) Thomson effect. Thomson effect: a temperature gradient along one conductor sets up an emf in it; Seebeck effect: junctions of two metals at different temperatures produce an emf

BPSC 69th Which of the following liquids is a bad conductor of electricity?
(a) Salted water (b) Orange juice (c) Lemon juice (d) None of the above
Answer: (d) None of the above. Liquids with dissolved ions, such as salt water and fruit juices, conduct electricity

BPSC 70th Which of the following is the resistance of the wire ?
(a) $R = I/(2V)$ (b) $R = IV$ (c) $R = I/V$ (d) $R = V/I$
Answer: (d) $R = V/I$. Ohm's law: $V = IR$, so resistance $R = V/I$

BPSC 70th re-exam Reactance of a capacitor is
(a) Inversely proportional to frequency (b) Directly proportional to frequency
(c) Inversely proportional to sq. root of frequency (d) None of the above
Answer: (a) Inversely proportional to frequency. Capacitive reactance $Xc = 1/(2\pi fC)$ falls as frequency rises; Inductive reactance $XL = 2\pi fL$ rises in proportion to frequency

BPSC 71st Which term in the following does not denote the electric power in electric circuit?
(a) I^2R (b) IR^2 (c) VI (d) V^2/R
Answer: (b) IR^2. Electric power $P = VI = I^2R = V^2/R$, using Ohm's law $V = IR$

BPSC 71st In short circuit, the value of electric current in a time circuit :
(a) Very low (b) Do not change (c) Increases very high (d) Continuously changing
Answer: (c) Increases very high. In a short circuit resistance falls to almost zero, so current becomes very large

BPSC 71st What is the device to protect equipments from the electric shock?
(a) Fuse (b) Generator (c) Motor (d) Current controller
Answer: (a) Fuse. A fuse melts and breaks the circuit when current exceeds a safe limit

Test yourself (13)

1. Three resistors of 6 Ω each are connected in parallel. The equivalent resistance is
(a) 18 Ω (b) 2 Ω (c) 3 Ω (d) 6 Ω

2. A 60 W bulb and a 100 W bulb (both rated 230 V) are joined in series to the mains. Which glows brighter?
(a) The 60 W bulb (b) The 100 W bulb (c) Both equally (d) Neither glows

3. An electric iron of 1000 W is used for 30 minutes every day for 30 days. Energy used is
(a) 30 units (b) 15 units (c) 1.5 units (d) 300 units

4. Which of these materials is used for the filament of an incandescent bulb?
(a) Nichrome (b) Tin-lead alloy (c) Tungsten (d) Copper

5. A copper wire is stretched to double its length with no change in volume. Its resistance becomes
(a) Half (b) Double (c) Unchanged (d) Four times

6. Consider the statements: 1. Resistance of a metal increases with temperature. 2. Resistance of a semiconductor increases with temperature. Which is/are correct?
(a) 1 only (b) 2 only (c) Both 1 and 2 (d) Neither 1 nor 2

7. The earth pin of a three-pin plug is made longer so that it
(a) carries the full load current of the appliance (b) connects first and disconnects last
(c) reduces the electricity bill slightly (d) acts as a fuse when the current rises

8. The device that converts AC into DC is called
(a) Rectifier (b) Inverter (c) Transformer (d) Rheostat

9. A bird sitting on a single high-voltage wire does not get a shock because
(a) its feet and claws act as good insulators of electricity (b) the current in an overhead wire is AC, not DC
(c) there is no potential difference across its body (d) the wire carries very little current

10. Which effect produces an emf when the two junctions of two different metals are kept at different temperatures?
(a) Peltier effect (b) Thomson effect (c) Joule effect (d) Seebeck effect

11. Consider the following statements:
1. An ammeter is connected in parallel with a component and has a very high resistance.
2. A voltmeter is connected in parallel with a component and has a very high resistance.
3. A potentiometer measures the emf of a cell accurately because it draws no current at balance.
Which of the statements given above is/are correct?
(a) 1 only (b) 1 and 2 only (c) 2 and 3 only (d) 1, 2 and 3

12. Consider the following statements about household electricity:
1. Fuse wire is made of a tin-lead alloy because of its low melting point.
2. The heating coil of an electric iron is made of tungsten.
3. The fuse and the switches are placed on the live wire.
How many of the above statements are correct?
(a) Only one (b) Only two (c) All three (d) None

13. A shopkeeper replaces 10 filament bulbs of 60 W with 10 LED bulbs of 9 W that give about the same light. Each bulb runs 5 hours a day. How much electricity does he save in 30 days?
(a) 2.55 units (b) 13.5 units (c) 90 units (d) 76.5 units

Answers: 1. (b) n equal resistors in parallel give R/n = 6/3 = 2 Ω. · 2. (a) The 60 W bulb has higher resistance; with the same current it gets more power (I^2R). · 3. (b) 1 kW × 0.5 h × 30 = 15 kWh = 15 units. · 4. (c) Tungsten has the highest melting point of metals (3422 °C). · 5. (d) Length doubles and area halves, so R = ρL/A becomes 2 × 2 = 4 times. · 6. (a) Metals' resistance rises with heat; semiconductors' falls because heat frees more carriers. · 7. (b) Longer pin makes the safety earth connection before live and breaks it after live. · 8. (a) A rectifier (diodes) turns AC into DC; an inverter does the reverse. · 9. (c) Both feet are at the same potential, so no current passes through the bird. · 10. (d) Seebeck effect is the principle of the thermocouple. · 11. (c) A voltmeter sits in parallel with a high resistance and a potentiometer draws no current at balance; statement 1 is wrong because an ammeter goes in series with a very low resistance. · 12. (b) Statements 1 and 3 are correct; the iron's coil is nichrome (high resistivity, no oxidation when red-hot), while tungsten is used for bulb filaments. · 13. (d) Saving = 10 × (60 − 9) W × 5 h × 30 = 76.5 kWh; 90 units is the old bulbs' whole use, 13.5 units the LEDs' use and 2.55 units only one day's saving.

CHAPTER 12

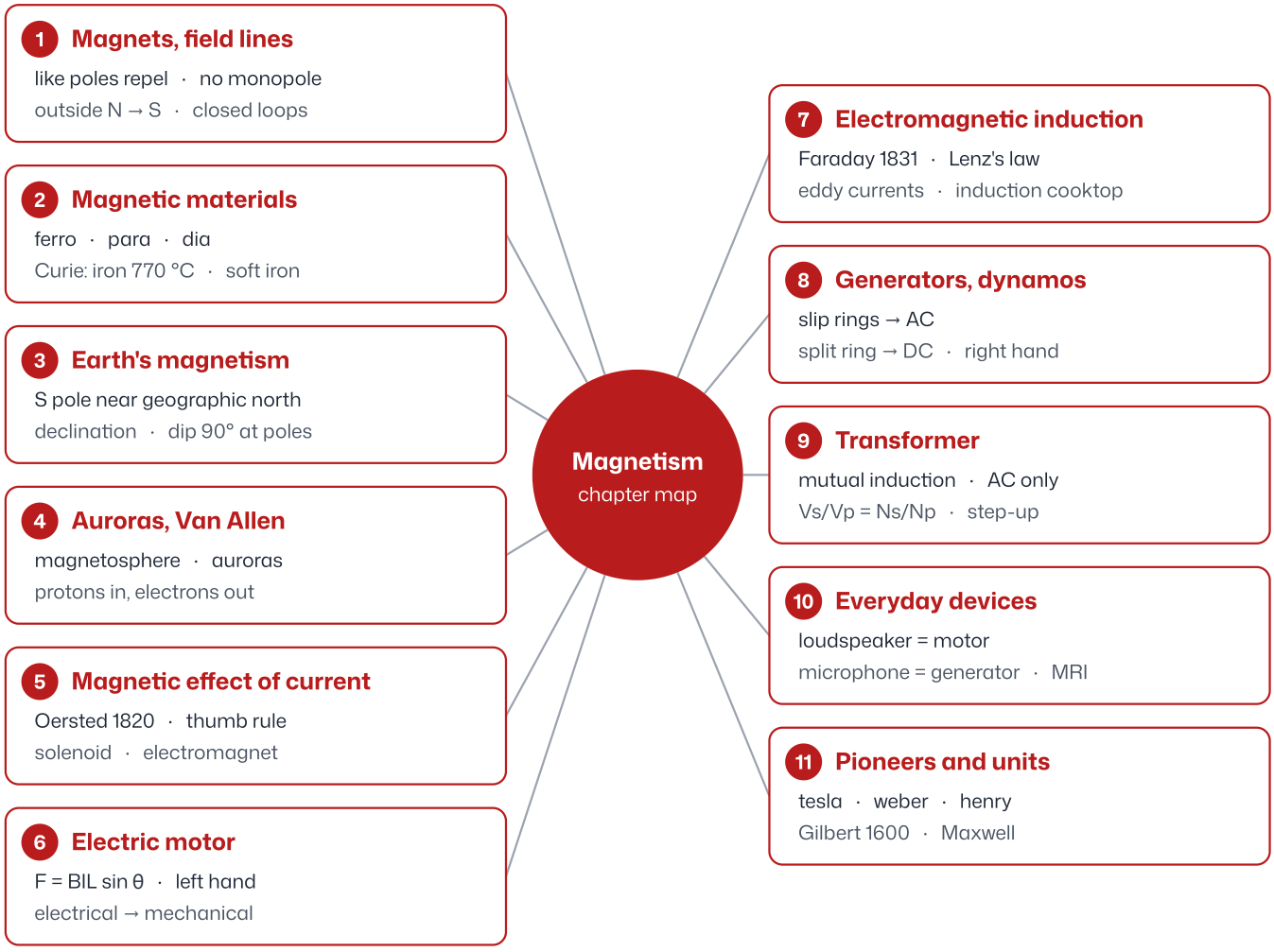
Magnetism and Electromagnetism

Motor vs generator, magnetic materials (para-, dia-, ferromagnetic), Earth's magnetism, transformers and everyday electromagnetic devices are asked most often.

Asked 3 times in past papers: BPSC 3

≈ 44 min to read ≈ 6 min to revise ★★★

Revise on: Day 1 | Day 3 | Day 7 | Day 21



Revision card

1. Like poles repel, unlike attract; repulsion is the sure test of a magnet. Break a magnet and you get two complete magnets; no single pole exists.
2. Field lines run N → S outside the magnet and S → N inside; they never cross and crowd where the field is strong.
3. Ferromagnetic: iron, cobalt, nickel, gadolinium. Paramagnetic: aluminium, platinum, oxygen. Diamagnetic: bismuth, copper, silver, gold, mercury, water.
4. Above the Curie temperature (iron 770 °C) a ferromagnet becomes paramagnetic.
5. Soft iron for electromagnets and transformer cores (magnetises and demagnetises easily); steel for permanent magnets (keeps magnetism).
6. Earth's magnetic S pole lies near geographic north. Dip is 90° at the magnetic poles and 0° at the magnetic equator.
7. Oersted (1820): a current makes a magnetic field. Faraday (1831): a changing magnetic field makes a current (electromagnetic induction).
8. Motor: electrical → mechanical, Fleming's LEFT-hand rule. Generator/dynamo: mechanical → electrical, Fleming's RIGHT-hand rule.
9. Lenz's law: the induced current opposes the change that causes it (energy conservation).
10. Dynamo/AC generator produces AC (slip rings); a DC dynamo uses a split-ring commutator. A transformer and a choke coil cannot generate current.
11. Transformer works only on AC, by mutual induction: Vs/Vp = Ns/Np. Step-up at the power station, step-down near homes.
12. Eddy currents: induction cooktops, metal detectors, eddy-current brakes; cut in transformers by laminated cores.
13. Auroras: solar-wind particles guided by Earth's field into the polar sky. Van Allen belts: trapped charged particles (discovered 1958).

Magnets and their properties

like poles repel

repulsion test

no monopole

field lines N → S

1 T = 10^4 gauss

Inside iron, the tiny magnetic effects of electrons line up in small regions called **domains**. In ordinary iron the domains point every which way and cancel. Magnetising simply turns them to face the same way; heating or hammering scrambles them again.

★★ **Natural magnet**: lodestone, a form of **magnetite (Fe_3O_4)**. Artificial magnets: bar, horseshoe, needle, ring magnets and electromagnets.

★★★ **Every magnet has two poles**, north (N) and south (S); the attraction is strongest at the poles and weakest at the middle.

★★★ **Like poles repel, unlike poles attract.**

★★★ **Repulsion is the sure test** of a magnet: a magnet attracts both a magnet's opposite pole and a plain piece of iron, but only another magnet can be repelled.

★★★ **Breaking a magnet** gives two complete smaller magnets, each with its own N and S. An isolated single pole (**monopole**) has never been found.

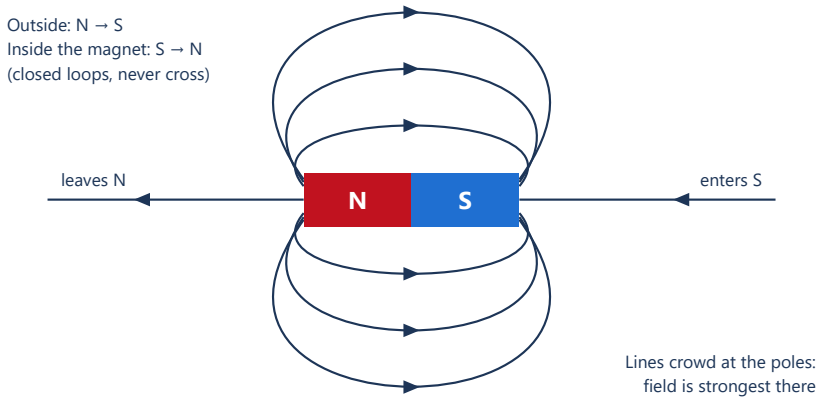
★★ **A freely suspended magnet** comes to rest in the north-south direction. This is the principle of the compass.

★★ **Induced magnetism**: an iron nail near a magnet becomes a magnet itself and can pick up another nail.

★★ **Magnetism is destroyed** by heating, hammering, dropping repeatedly, or placing the magnet inside a coil carrying AC.

★ **Storing magnets**: in pairs with opposite poles side by side, with soft-iron **keepers** across the ends, so they keep their strength.

★★ **Magnetic field** B is measured in **tesla (T)**; 1 T = 10^4 gauss. Earth's field at the surface is only about 25-65 μT (0.25-0.65 gauss).



Field lines of a bar magnet leave the N pole and enter the S pole, completing closed loops through the magnet. They never cross; where they crowd (at the poles) the field is strongest.

★★★ **Field lines** are imaginary curves that show the direction a free north pole would move. Outside the magnet they run **N → S**; inside, **S → N**. They form **closed loops**.

★★ **Two field lines never cross**: at a crossing a compass would have to point two ways at once.

★★ **Crowded lines = strong field**; evenly spaced parallel lines = uniform field (as inside a long solenoid).

★ **Neutral point**: a spot where the magnet's field exactly cancels Earth's horizontal field; a compass there points nowhere in particular.

⚠ **Exam trap:** "Attraction proves a body is a magnet": false. A plain iron bar is attracted too. Only repulsion settles it.

☑ Quick check

1. A bar magnet is broken in two. What do you get?
2. An iron bar is attracted by a magnet. Does that prove the bar is a magnet?
3. Outside a magnet, field lines run from _____ to _____ ; inside, the other way.

Answer: 1. two complete magnets, each with an N and an S pole · 2. no: only repulsion proves it · 3. N to S

Magnetic materials

ferro: Fe, Co, Ni

para: Pt, Al, O_2

dia: Bi, Cu, water

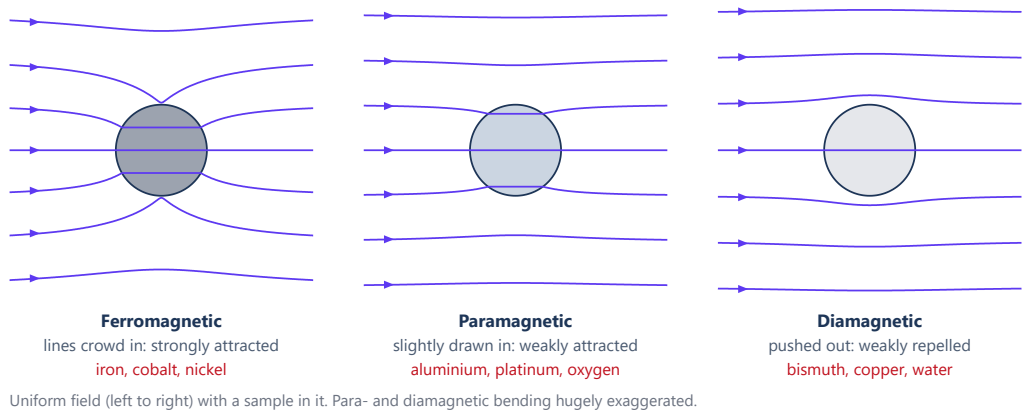
All matter responds to a magnetic field, but in three very different strengths. In **ferromagnets** domains line up strongly; in **paramagnets** single atoms line up feebly; in **diamagnets** the field induces a weak opposing effect, so they are pushed away.

Curie temperature

soft iron vs steel

Three kinds of magnetic behaviour ★★★

Type	Behaviour in a magnetic field	Examples
Ferromagnetic	Strongly attracted; can become permanent magnets; relative permeability very large	Iron, cobalt, nickel, gadolinium; alloys such as alnico, steel, neodymium (NdFeB) magnets
Paramagnetic	Weakly attracted; lose magnetism when the field is removed; relative permeability slightly above 1	Aluminium, platinum, sodium, magnesium, manganese, calcium, tungsten, oxygen (liquid oxygen clings to a magnet)
Diamagnetic	Weakly repelled; relative permeability slightly below 1	Bismuth (strongest common one), copper, silver, gold, mercury, lead, water, glass, common salt, hydrogen; superconductors (perfect diamagnets)



Uniform field (left to right) with a sample in it. Para- and diamagnetic bending hugely exaggerated.

A sample placed in a uniform magnetic field. Field lines crowd into a ferromagnetic sample, bend in slightly towards a paramagnetic one and bend away from a diamagnetic one. Lines computed for a round sample; the para- and diamagnetic bending is hugely exaggerated.

Remember it: Ferro = "Fe-Co-Ni" (the fake-coin trio a magnet grabs). **Para = "PAO"**: Platinum, Aluminium, Oxygen. **Dia = "Bi-CuAgAu + water"**: bismuth and the coinage metals copper, silver, gold push the magnet away. Careful: platinum is precious but paramagnetic.

★★★ **Curie temperature**: above it a ferromagnet loses its ferromagnetism and becomes paramagnetic. **Iron 770 °C**, nickel ≈ 358 °C, cobalt ≈ 1115 °C, gadolinium ≈ 20 °C. Named after **Pierre Curie**.

★ **Paramagnetism weakens as temperature rises** (Curie's law); diamagnetism hardly depends on temperature.

★ **Diamagnetic levitation**: a strong enough field can float water-rich objects, famously a live frog in a 16 T magnet.

★ **Ferrites** (iron-oxide ceramics) are magnetic but poor conductors, so they are used in high-frequency transformer cores and fridge-door magnets.

Soft iron vs steel ★★★

Property	Soft iron	Steel
Magnetises	Easily, strongly (high permeability)	With more effort
Keeps magnetism (retentivity)	Loses it almost at once	Keeps it
Best for	Electromagnets, transformer and motor cores, relays, magnetic shields	Permanent magnets (compass needle, loudspeaker magnet)

★★ **Magnetic shielding**: enclose an instrument in a box of soft iron (or special high-permeability alloy). Field lines prefer to travel through the box walls, so the space inside is almost field-free. Antimagnetic watches use a soft-iron inner case.

★ **Neodymium (NdFeB) magnets**, made with rare-earth elements, are the strongest permanent magnets: used in EV motors, wind turbines, earphones and hard-disk drives.

⚠ **Exam trap:** Mercury, copper, gold and silver are **diamagnetic**, not paramagnetic. Nickel is **ferromagnetic**. When asked which applies the paramagnetic theory, pick **platinum** or **aluminium**.

Quick check

1. Copper, gold, bismuth, water: what are they magnetically?
2. Above which temperature does iron stop being ferromagnetic?
3. Soft iron or steel: which is used for electromagnet cores, and which for permanent magnets?

Answer: 1. diamagnetic (weakly repelled) · 2. 770 °C (its Curie temperature) · 3. soft iron for cores; steel for permanent magnets

Earth's magnetism

geodynamo

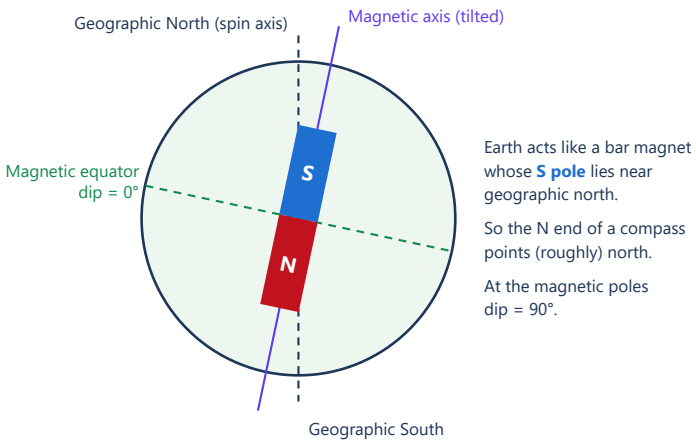
S pole in the north

declination

dip 0° to 90°

Thumba 1963

Earth behaves as if a giant bar magnet sat inside it. The field is actually produced by electric currents in the swirling molten iron of the **outer core** (the **geodynamo**). Its axis is tilted to the spin axis, so magnetic and geographic poles do not coincide, and the magnetic poles slowly wander.



Earth's imaginary bar magnet has its S pole near geographic north, which is why the N end of a compass points north. The magnetic equator (dip 0°) is at right angles to the magnetic axis.

★★★ **The magnetic pole near geographic north is magnetically a south pole**: it attracts the north-seeking end of the compass needle.

★★★ **Magnetic declination**: the angle between geographic north (true north) and magnetic north at a place, i.e. between the geographic and magnetic meridians.

★★★ **Dip (inclination)**: the angle Earth's field makes with the horizontal. **90° at the magnetic poles** (needle stands vertical), **0° at the magnetic equator** (needle lies flat). Measured with a **dip circle**.

★★ **Horizontal component** of Earth's field is largest at the magnetic equator and **zero at the magnetic poles**, so an ordinary compass is useless near the magnetic poles.

★★ **Map lines**: isogonic (equal declination), agonic (zero declination), isoclinic (equal dip), aclinic (zero dip = magnetic equator), isodynamic (equal field strength).

★★ **Compass**: a light magnetised needle pivoted to swing freely; used for navigation since ancient Chinese times. A **gyrocompass** points to true north and is unaffected by magnetism.

★★ **Thumba**, near Thiruvananthapuram, was chosen for India's first rocket launch (1963) because it lies close to the **magnetic equator**, ideal for studying the equatorial electrojet.

★ **Pole wander and reversals**: the north magnetic pole is drifting from the Canadian Arctic towards Siberia. Over geological time the field has flipped many times; the last full reversal was about 780,000 years ago. Rocks record these flips (palaeomagnetism), a key evidence for sea-floor spreading.

★ **Indian Institute of Geomagnetism** (Navi Mumbai) grew from the Colaba Observatory, Mumbai (magnetic records from 1841). Its recordings moved to **Alibag** in 1904 to escape disturbance from Bombay's electric trams.

★ **William Gilbert** (De Magnete, 1600) first argued that Earth itself is a giant magnet.

Remember it: Dip = how far the needle "dips its head": at the magnetic pole it bows fully (90°); at the magnetic equator it holds its head perfectly level (0°).

⚠ **Exam trap:** Declination and dip are different angles. Declination is in the horizontal plane (true north vs magnetic north); dip is in the vertical plane (field vs horizontal).

Quick check

1. Magnetically, the pole near geographic north is a _____ pole.
2. Angle of dip at the magnetic poles, and at the magnetic equator?
3. Why was Thumba chosen for India's first rocket launch (1963)?

Answer: 1. south · 2. 90°; 0° · 3. it lies close to the magnetic equator

Magnetosphere, auroras and Van Allen belts

solar wind

magnetosphere

borealis / australis

oxygen: green

Van Allen 1958

protons in, electrons out

The Sun constantly blows a stream of charged particles, the **solar wind**. Earth's magnetic field deflects most of it, carving out a protective bubble, the **magnetosphere**. Charged particles cannot cross field lines easily, so some get trapped and some are funnelled down near the poles.

Aurora borealis over Bear Lake, Alaska. Charged particles from the Sun, guided by Earth's field lines into the upper atmosphere near the pole, make oxygen atoms glow green. Image: Joshua Strang, US Air Force, Wikimedia Commons, public domain

★★ **Magnetosphere**: the region around Earth controlled by its magnetic field; squashed on the day side and stretched into a long tail on the night side. It shields life and satellites from much of the solar wind.

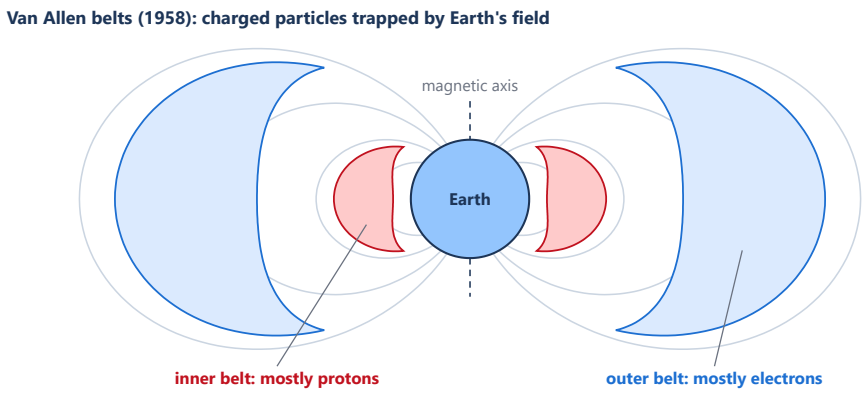
★★★ **Auroras**: charged particles guided along field lines into the upper atmosphere near the poles collide with gas atoms, which glow. **Aurora borealis** (northern lights) and **aurora australis** (southern lights).

★★ **Aurora colours**: oxygen gives the common green and the rarer red; nitrogen gives blue and purple.

★ **Strong solar storms** push auroras to lower latitudes: in May 2024 a red aurora was photographed from Hanle, Ladakh.

★★★ **Van Allen radiation belts**: two doughnut-shaped zones of charged particles trapped by Earth's field; the inner belt is rich in energetic protons, the outer belt mainly in electrons. Discovered in **1958** by **James Van Allen** from Explorer 1 data.

★ **Geomagnetic storms** can disturb GPS, radio communication and power grids, and damage satellites.



Van Allen belts in cross-section: two doughnut-shaped zones of charged particles trapped along Earth's field lines, protons mostly in the inner belt, electrons mostly in the outer. Shapes and sizes approximate.

Remember it: Van Allen: "Protons Inside, Electrons Outside" (PI-EO): protons in the inner belt, electrons in the outer.

Quick check

1. What are the northern and southern lights called?
2. Which gas gives auroras their common green colour?
3. Inner and outer Van Allen belts: which particles dominate each?

Answer: 1. aurora borealis; aurora australis · 2. oxygen · 3. inner: protons; outer: electrons

Magnetic effect of current

Oersted 1820

right-hand thumb rule

solenoid = bar magnet

anticlockwise = N

electromagnet: soft iron

In 1820 **Hans Christian Oersted** noticed a compass needle swing when current flowed in a nearby wire. That single observation joined electricity and magnetism: **moving charges make magnetic fields**. Coil the wire and the fields of all the turns add up, giving a magnet you can switch on and off.

★★★ **Oersted's experiment** (1820): a current-carrying wire deflects a compass needle; reversing the current reverses the deflection.

★★ **Field around a straight wire**: concentric circles; stronger with more current, weaker farther from the wire ($B \propto I/r$).

★★★ **Right-hand thumb rule**: grip the wire with the right hand, thumb along the current; the curled fingers show the direction of the magnetic field. (Maxwell's corkscrew rule says the same.)

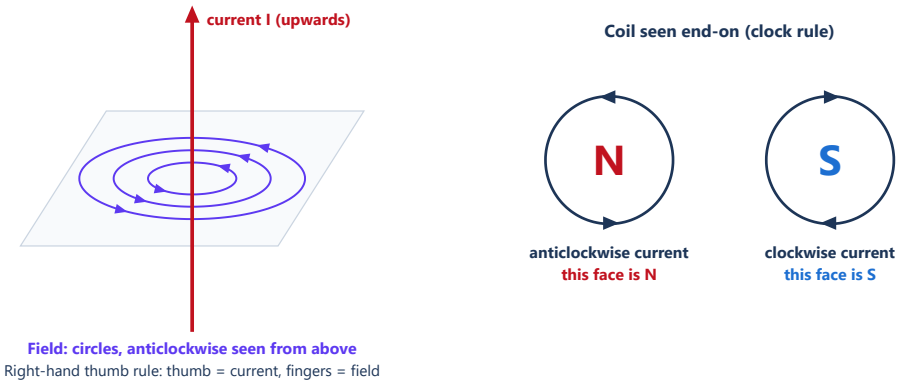
★★★ **Solenoid**: a long coil of many turns. With current it behaves like a **bar magnet**; the field inside is strong and nearly uniform.

★★ **Polarity of a coil**: looking at one end, if current flows **anticlockwise** that end is **N**; clockwise, it is **S**.

★★★ **Electromagnet**: a solenoid with a **soft-iron core**. It is a temporary magnet, strong while current flows and dead when it stops.

★★ **Stronger electromagnet**: more turns, more current, a soft-iron core.

★★ **Two parallel wires**: currents in the same direction attract; opposite directions repel.



(Left) Current flowing up a straight wire: the field is a set of circles round it, anticlockwise when seen from above. Grip the wire with your right hand, thumb along the current, and your fingers curl the same way. (Right) Clock rule for a coil: anticlockwise current makes that face N, clockwise makes it S.

Remember it: Clock rule: write N with arrows on its ends and they run anticlockwise; the S arrows run clockwise. Anticlockwise current = North face.

Where electromagnets work ★★

Device	How the electromagnet helps
Scrap-yard crane	Lifts tonnes of iron; switch off to drop it
Electric bell	Electromagnet pulls the hammer arm, which breaks the circuit, springs back and repeats (make-and-break)
Relay	A small current in the coil switches a large current circuit (cars, automation)
MRI scanner	Superconducting electromagnet makes a very strong steady field
Maglev train	Magnetic repulsion/attraction lifts the train off the track; no wheel friction
Loudspeaker, motor, generator	Coil and magnet interact to give motion or current
Particle accelerators	Powerful magnets bend and focus beams (CERN's LHC uses superconducting magnets)

★★ **Maglev speed record for a crewed train**: Japan's superconducting SCMaglev reached **603 km/h** on a test line in 2015.

Quick check

1. Who first showed that a current deflects a compass needle, and when?
2. Seen from one end of a coil, the current flows anticlockwise. Which pole is that face?
3. Two parallel wires carry currents in the same direction. Do they attract or repel?

Answer: 1. Oersted, 1820 · 2. north (N) · 3. attract

Force on a current and the electric motor

F = BIL sin θ

zero when parallel

left-hand rule

electrical → mechanical

split-ring commutator

A current-carrying wire is itself surrounded by a magnetic field. Place it between magnet poles and the two fields push on each other, so the wire is shoved sideways. Bend the wire into a loop and the two sides are pushed opposite ways: the loop turns. That is an electric motor.

★★ **Force on a conductor** F = BIL sin θ: largest when the wire is at right angles to the field, **zero when parallel**.

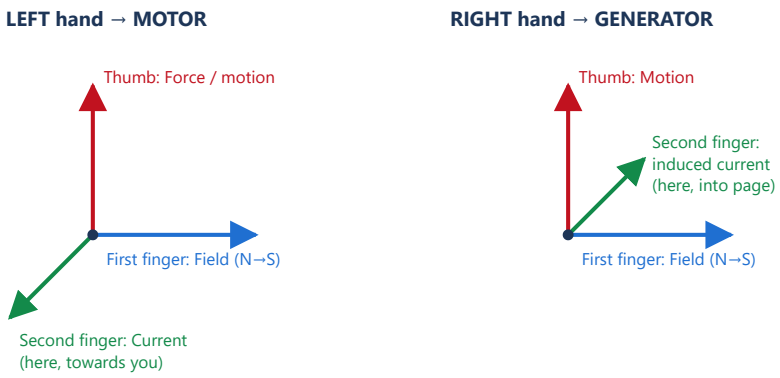
★★ **Moving charges** in a magnetic field feel a sideways (Lorentz) force, so they move in circles or spirals. This is why solar-wind particles spiral along Earth's field lines.

★★★ **Fleming's left-hand rule** (motor rule): stretch thumb, first finger and second finger of the **left** hand at right angles. **First finger = Field**, **seCond finger = Current**, **thuMb = Motion (force)**.

★★★ **Electric motor** converts **electrical energy into mechanical energy**.

★★ **DC motor parts**: armature coil, field magnet, **split-ring commutator** (reverses the current every half turn so the coil keeps spinning one way), carbon **brushes**.

★ **Uses**: fans, mixers, pumps, washing machines, electric vehicles, trains, hard-disk spindles. **Nikola Tesla** invented the AC induction motor used in most fans and pumps.



Same three fingers, different hands. Left hand gives the push on a current (motor); right hand gives the current induced by motion (generator).

Remember it: Motors drive on the LEFT, as on Indian roads → left-hand rule for motors. GeneRatoR has two Rs → Right-hand rule. And the fingers spell **F-B-I** from thumb down: thumb Force, first B (field), second I (current).

Quick check

1. Fleming's left-hand rule: what do the first finger, the second finger and the thumb show?
2. Force on a current-carrying wire lying parallel to the field?
3. Which part of a DC motor reverses the current every half turn?

Answer: 1. field, current, motion (force) · 2. zero · 3. split-ring commutator

Electromagnetic induction

changing flux

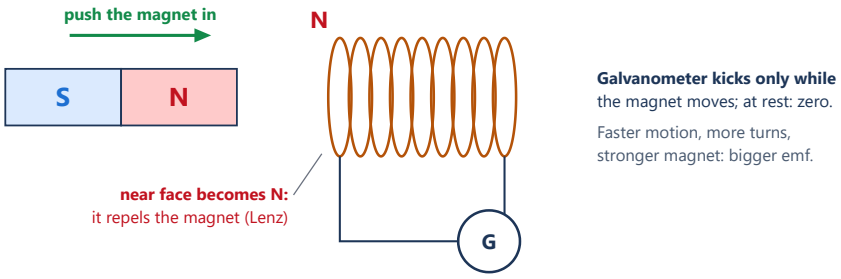
Faraday 1831

Lenz: opposes change

self / mutual induction

eddy currents

If current makes magnetism, can magnetism make current? **Michael Faraday** (1831) found yes, but only when the magnetic field through a coil is **changing**. A magnet resting inside a coil gives nothing; push it in or pull it out and the galvanometer kicks. Faster motion, bigger kick.



Push the N pole into the coil and the galvanometer kicks; hold the magnet still and the reading is zero. The near face of the coil becomes N and pushes back on the approaching magnet (Lenz's law).

★★★ **Electromagnetic induction**: a changing magnetic flux through a circuit induces an emf (and a current if the circuit is closed). Discovered by **Faraday (1831)**; Joseph Henry found it independently.

★★★ **Faraday's law**: induced emf = rate of change of magnetic flux ($\varepsilon = -N\,\Delta\Phi/\Delta t$). More turns, a stronger magnet or faster motion give a larger emf.

★★ **Ways to induce current**: move a magnet into or out of a coil, move or rotate the coil in a field, or change the current in a nearby coil.

★★★ **Lenz's law** (1834): the induced current flows in a direction that **opposes the change** that produced it. It is a consequence of the **conservation of energy**: you must do work to push the magnet in.

★★ **Fleming's right-hand rule** (generator rule): thumb = motion of the conductor, first finger = field, second finger = induced current.

★★ **Magnetic flux** $\Phi = BA\cos\theta$; unit **weber (Wb)** ($1\ \text{Wb} = 1\ \text{T m}^2$).

★★ **Self-induction**: a changing current in a coil induces an emf in the same coil that opposes the change; measured by inductance in **henry (H)**. The spark seen when switching off a fan or motor comes from this back-emf.

★★ **Mutual induction**: changing current in one coil induces emf in a nearby coil. The basis of transformers and **wireless (induction) phone chargers**.

★★ **Choke coil**: an inductor that limits AC with very little power loss; it does **not** produce current.

Remember it: Lenz says "No!": whatever you do to the flux, the induced current tries to undo it. Push a north pole in, the coil shows a north face back.

> **See it around you:** Drop a strong magnet down a copper pipe: it floats down slowly like a feather. Copper is not magnetic, but the falling magnet induces currents in the pipe that, by Lenz's law, oppose its fall.

Eddy currents are induced swirls of current inside a solid piece of metal sitting in a changing field. They heat the metal and oppose motion, which can be wasteful or useful.

Eddy currents: useful and wasteful ★★

Where	What happens
Induction cooktop	A coil carrying high-frequency AC induces eddy currents in the pan's base, which heats up; the pan must be iron or steel (magnetic base), not plain aluminium, copper or glass
Metal detector (airports, mine clearing)	Eddy currents in hidden metal disturb the detector coil's field
Eddy-current brakes	High-speed trains and roller coasters slow down smoothly without contact
Induction furnace	Melts metals by eddy-current heating
Galvanometer damping	Eddy currents stop the needle oscillating, so it settles quickly
Old electricity meter	An aluminium disc is turned by eddy currents; its spin counts the units
Transformer and motor cores (wasteful)	Eddy currents waste energy as heat; cores are made of thin insulated sheets (laminations) to cut them

Quick check

1. A magnet rests inside a coil. Is any current induced?
2. Lenz's law follows from which conservation law?
3. Why must a pan for an induction cooktop have an iron or steel base?

Answer: 1. no: only a changing flux induces an emf · 2. conservation of energy · 3. eddy currents induced in a magnetic base heat it

Generators and dynamos

mechanical → electrical

slip rings: AC

split ring: DC

bicycle dynamo: AC

3000 rpm

A generator is a motor run backwards. Spin a coil inside a magnetic field and the flux through it keeps changing, so an emf is induced. As the coil turns, each side moves first up then down through the field, so the current naturally **alternates**.

Motor vs generator ★★★

Feature	Electric motor	Generator / dynamo
Energy change	Electrical → mechanical	Mechanical → electrical
Principle	Force on a current in a magnetic field	Electromagnetic induction
Fleming's rule	Left hand	Right hand
Key part	Split-ring commutator (DC motor)	Slip rings (AC generator) or split-ring commutator (DC dynamo)
Examples	Fan, mixer, pump, EV	Power-station alternator, bicycle dynamo, wind turbine, diesel generator set

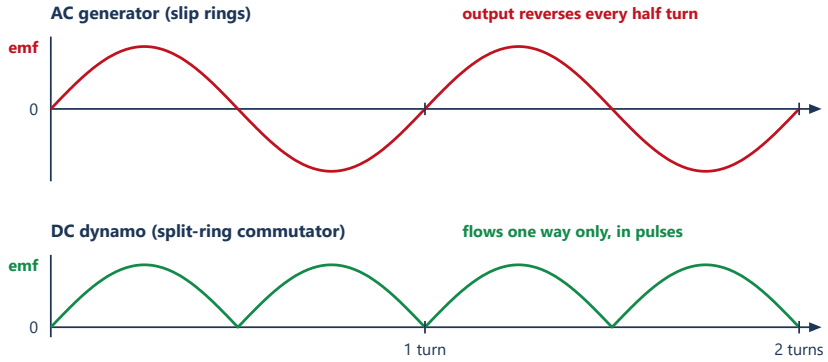
★★★ **AC generator (alternator)**: the coil's ends connect through **slip rings** to brushes, so the output follows the coil and is **AC**. All power stations (thermal, hydro, nuclear, wind) use alternators; turbines merely spin them.

★★ **DC dynamo**: a **split-ring commutator** flips the connections every half turn, so the output always flows one way (DC).

★★ **Bicycle dynamo**: a small magnet spun by the wheel inside a coil; it gives **AC**, enough to light a lamp.

★★ **In India** the grid runs at 50 Hz, so a two-pole power-station alternator spins at 3000 revolutions per minute.

★ **Faraday's disc** (1831) was the first generator: a copper disc spun between magnet poles.



Output of a coil turning steadily in a magnetic field. With slip rings the emf reverses every half turn (AC); a split-ring commutator swaps the connections every half turn, so the output flows one way only, in pulses (DC).

⚠ **Exam trap:** "An AC current can be produced by a choke coil / dynamo / transformer": only the **dynamo** generates. A transformer only changes an AC voltage it is fed; a choke only limits current.

Quick check

1. Slip rings or split ring: which gives an AC output?
2. Does a bicycle dynamo give AC or DC?
3. Choke coil, dynamo, transformer: which one generates current?

Answer: 1. slip rings · 2. AC · 3. the dynamo

Transformer and power transmission

mutual induction

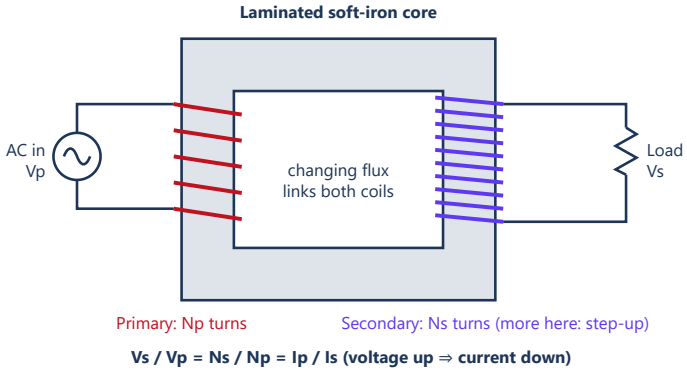
AC only

Vs/Vp = Ns/Np

step-up at the station

laminated core

A transformer has two coils wound on one soft-iron core. AC in the first (primary) coil makes a constantly changing flux in the core; that flux passes through the second (secondary) coil and induces an AC voltage there. The voltage ratio simply follows the ratio of turns.



More turns on the secondary gives a higher voltage (step-up) but a proportionally smaller current, so power stays nearly the same.

★★★ **Principle**: **mutual induction**. Works **only on AC**: steady DC gives a constant flux, so nothing is induced (and the primary may overheat).

★★★ **Turns ratio**: Vs/Vp = Ns/Np = Ip/Is. Voltage goes up exactly as much as current goes down.

★★★ **Step-up** (Ns > Np) raises voltage and lowers current: used at the **power station**. **Step-down** (Ns < Np): used at substations and the **distribution transformer near homes**, and inside chargers and adapters.

★★ **Example**: to get 12 V from 230 V, a primary of 1150 turns needs a secondary of 1150 × 12/230 = **60 turns**.

★★ **A transformer does not change frequency** and, ideally, not power: output power ≈ input power. Large transformers are about 95-99% efficient.

★★ **Losses**: copper (I^2R heating of windings), **eddy currents** (cut by a **laminated** core), hysteresis (cut by a soft-iron core), flux leakage. Transformers are cooled with oil.

★★★ **Why high-voltage transmission**: for the same power, high voltage means low current, and line loss I^2R falls with the square of the current. That is the main reason AC, which transformers can step up and down, became the standard.

★ **Transformer hum** is mainly the core vibrating at twice the supply frequency (100 Hz in India).

Remember it: Transformer = see-saw: one side (voltage) goes up, the other (current) goes down by the same factor; the turns count decides which side rises.

⚠ **Exam trap:** A step-up transformer raises **voltage**, not energy or power. It cannot give more power out than goes in, and it cannot work on a battery's DC.

Quick check

1. Why does a transformer not work on DC?
2. A primary of 1150 turns takes 230 V. How many secondary turns give 12 V?
3. Why is a transformer core laminated?

Answer: 1. steady DC gives a constant flux, so nothing is induced · 2. 60 · 3. to cut eddy-current losses

Everyday devices that use magnetism

loudspeaker: motor

microphone: generator

induction cooktop

MRI: no ionising radiation

hard disk vs SSD

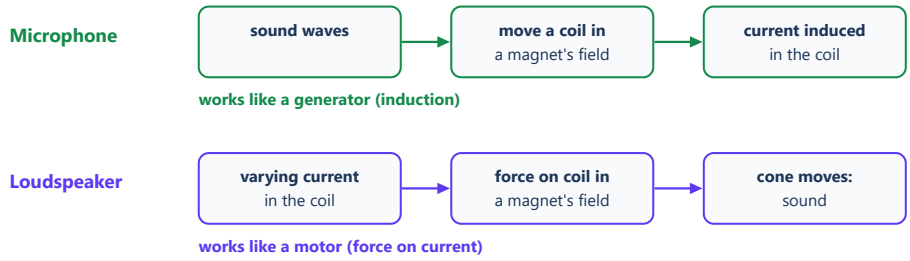
Devices and the principle behind each ★★★

Device	Principle	Key point
Electric motor	Force on current in a field	Electrical → mechanical
Generator / dynamo	Electromagnetic induction	Mechanical → electrical
Transformer	Mutual induction	Changes AC voltage; AC only
Loudspeaker	Force on current (motor effect)	Varying current in the voice coil moves the cone, making sound
Dynamic microphone	Electromagnetic induction	Sound moves a coil in a magnet's field, inducing a matching current
Electricity (energy) meter	Older: eddy currents spin an aluminium disc; now electronic and smart meters	Records kWh (units)
Induction cooktop	Eddy currents	Needs a magnetic (iron/steel) pan base
Metal detector	Eddy currents / induction	Finds hidden metal
Audio/video tape, ATM card stripe	Magnetised particles (iron oxide) store a pattern	Keep away from strong magnets
Hard disk drive	Tiny magnetised regions store bits 0 and 1; read head senses them	Pen drives and SSDs are not magnetic (flash memory)
MRI scanner	Strong magnetic field + radio waves act on hydrogen nuclei	No ionising radiation
Wireless phone charger	Mutual induction between two flat coils	Works only at very short range

★★ **MRI** (magnetic resonance imaging) uses a superconducting magnet, typically 1.5-3 T, and radio waves; it images soft tissue (brain, joints) well and, unlike X-ray or CT, uses **no ionising radiation**. Metal objects must stay out of the room.

★ **Giant magnetoresistance** read heads let hard disks store far more data: **Nobel Prize in Physics 2007** to Albert Fert and Peter Grünberg.

★ **Credit and debit cards** have moved from magnetic stripes to EMV chips and contactless (NFC) payment, which are not magnetic storage.



Mirror-image devices. In a microphone, sound moves a coil in a magnet's field and a current is induced (generator). In a loudspeaker, a varying current in the coil feels a force in the field and drives the cone (motor).

⚠ **Exam trap:** Microphone and loudspeaker are mirror images: the **microphone works like a generator** (sound → current, induction); the **loudspeaker works like a motor** (current → motion → sound).

☑ Quick check

1. A microphone works like a _____ ; a loudspeaker works like a _____ .
2. Does an MRI scan use ionising radiation?
3. Which stores data magnetically: a hard disk or a pen drive?

Answer: 1. generator; motor · 2. no: a strong magnet and radio waves · 3. the hard disk (a pen drive is flash memory)

Pioneers and units

Gilbert: De Magnete

Oersted 1820

Faraday: induction

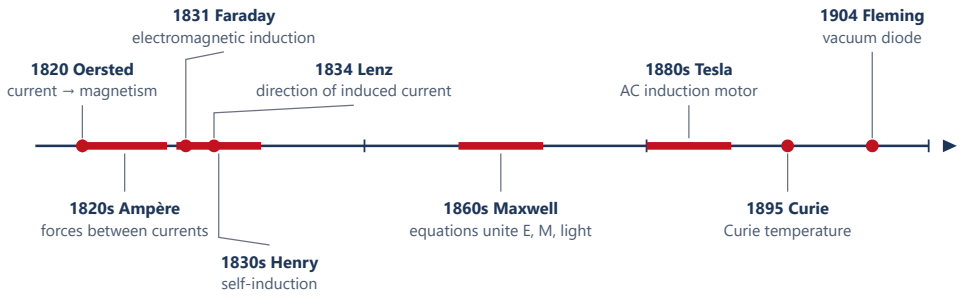
tesla, weber, henry

1 Wb = 1 T m²

Who discovered what ★★

Scientist	Contribution	Remembered in
William Gilbert (1600)	Earth is a giant magnet (De Magnete)	gilbert (old unit)
Hans Christian Oersted (1820)	Current produces a magnetic field	oersted (old unit)
André-Marie Ampère (1820s)	Forces between currents; theory of electrodynamics	ampere
Michael Faraday (1831)	First electric motor (electromagnetic rotation, 1821); electromagnetic induction; first generator (disc); laws of electrolysis	farad
Joseph Henry (1830s)	Self-induction; induction found independently	henry
Heinrich Lenz (1834)	Direction of induced current	Lenz's law
Wilhelm Weber	Magnetic measurements	weber
James Clerk Maxwell (1860s)	Equations uniting electricity, magnetism and light	maxwell (old unit)
Nikola Tesla (1880s)	AC induction motor, AC power system	tesla
John Ambrose Fleming	Left- and right-hand rules; vacuum diode (1904)	Fleming's rules
Pierre Curie (1895)	Magnetism vanishes above a critical temperature	Curie temperature

Before 1800: William Gilbert (De Magnete, 1600) showed that Earth is a giant magnet.



Who found what, on a time line drawn to scale: dots mark single years, bars mark decades.

Magnetic quantities ★★

Quantity	SI unit	Note
Magnetic field (flux density) B	tesla (T)	1 T = 10^4 gauss
Magnetic flux Φ	weber (Wb)	1 Wb = 1 T m²
Inductance	henry (H)	Self and mutual induction
Magnetic field strength H	ampere per metre (A/m)	Old unit: oersted

Quick check

1. SI unit of magnetic flux, and of magnetic field?
2. The unit of inductance is named after whom?
3. Who first argued that Earth itself is a giant magnet?

Answer: 1. weber (Wb); tesla (T) · 2. Joseph Henry (henry, H) · 3. William Gilbert (De Magnete, 1600)

Asked in past papers (3)

BPSC 64th In electrical motor
(a) heat is converted into electrical energy (b) electrical energy is converted into heat
(c) electrical energy is converted into mechanical energy
(d) mechanical energy is converted into electrical energy (e) None of the above/More than one of the above
Answer: (c) electrical energy is converted into mechanical energy. An electric motor turns electrical energy into mechanical energy; A generator turns mechanical energy into electrical energy

BPSC 67th re-exam The paramagnetic theory of magnetism applies to
(a) platinum (b) nickel (c) mercury (d) iron (e) None of the above/More than one of the above
Answer: (a) platinum. Platinum and aluminium are paramagnetic; iron, nickel and cobalt are ferromagnetic

BPSC 69th An AC current can be produced by
(a) choke coil (b) dynamo (c) transformer (d) None of the above
Answer: (b) dynamo. A dynamo (AC generator) turns mechanical energy into AC by electromagnetic induction; A transformer changes AC voltage but cannot generate current

Test yourself (12)

1. Which one of the following is diamagnetic?
(a) Aluminium (b) Nickel (c) Bismuth (d) Platinum

2. The angle of dip at the magnetic equator is
(a) 0° (b) 45° (c) 90° (d) 180°

3. Transformer cores are laminated mainly to reduce
(a) copper loss in the windings (b) eddy-current loss (c) flux linkage between coils
(d) the frequency of the supply

4. A step-up transformer has 100 turns on the primary and 2000 on the secondary. If 220 V AC is applied, the output voltage is
(a) 11 V (b) 2200 V (c) 22,000 V (d) 4400 V

5. Fleming's right-hand rule is used to find the direction of
(a) induced current in a generator (b) force on a conductor in a motor
(c) magnetic field around a straight wire (d) the charge on a capacitor

6. Which statement is NOT correct about electromagnets?
(a) They usually have a soft-iron core inside the coil (b) Their strength rises with more turns and more current
(c) They keep their magnetism after the current stops
(d) They are used in electric bells and scrap-yard cranes

7. An induction cooktop heats a steel pan mainly by
(a) infrared radiation from a hot coil (b) eddy currents induced in the pan base
(c) conduction from a red-hot plate (d) microwaves absorbed directly by the food inside

8. Auroras are seen mostly near the poles because
(a) the poles are colder, so the thin air glows more easily
(b) Earth's magnetic field guides charged solar particles there
(c) the ozone layer above the poles is much thinner than elsewhere
(d) sunlight is strongly reflected back by the polar ice sheets

9. Which device works on the principle of the motor effect (force on a current-carrying conductor)?
(a) Dynamic microphone (b) Transformer (c) Bicycle dynamo (d) Loudspeaker

10. Consider the following statements about Earth's magnetism:
1. The magnetic pole near the geographic north is magnetically a south pole.
2. The horizontal component of Earth's magnetic field is largest at the magnetic poles.
3. Magnetic declination is the angle that Earth's field makes with the horizontal.
Which of the statements given above is/are correct?
(a) 1 only (b) 1 and 2 only (c) 2 and 3 only (d) 1, 2 and 3

11. Consider the following statements:
1. Lenz's law is a consequence of the conservation of energy.
2. A transformer works on mutual induction and does not change the frequency of the supply.
3. An AC generator uses slip rings, while a DC dynamo uses a split-ring commutator.
How many of the above statements are correct?
(a) Only one (b) Only two (c) All three (d) None

12. A student connects the primary coil of a step-up transformer to a 12 V car battery, hoping to get a higher voltage for a project. Once the switch is closed and the current is steady, what does he get at the secondary coil?
(a) A steady DC voltage above 12 V, in the turns ratio
(b) No voltage, as a steady current makes an unchanging flux
(c) An AC voltage at 50 Hz, the mains frequency
(d) A higher voltage and more power than the battery supplies

Answers: 1. (c) Bismuth is weakly repelled by a magnet; aluminium and platinum are paramagnetic, nickel ferromagnetic. · 2. (a) At the magnetic equator Earth's field is horizontal, so the dip needle lies flat. · 3. (b) Thin insulated sheets break up eddy-current paths in the core. · 4. (d) $V_s = V_p \times N_s/N_p = 220 \times 20 = 4400$ V. · 5. (a) Right hand: generator (induced current). Left hand: motor (force). · 6. (c) Soft-iron electromagnets lose almost all magnetism once the current stops. · 7. (b) The coil's changing field induces eddy currents in the magnetic pan base, heating it. · 8. (b) Field lines converge at the poles, channelling solar-wind particles into the upper atmosphere. · 9. (d) A loudspeaker's coil is pushed by the magnet's field when current flows; the others use induction. · 10. (a) The pole near geographic north attracts the compass's N end, so it is a south pole; the horizontal component is zero at the magnetic poles and largest at the magnetic equator, and the angle with the horizontal is dip, not declination. · 11. (c) All three are correct: pushing a magnet against the induced current takes work, a transformer passes on the same frequency it is fed, and slip rings keep the output AC while a split ring turns it into DC. · 12. (b) A transformer needs a changing flux, so steady DC induces nothing in the secondary (and may overheat the primary); no transformer gives out more power than it takes in.

CHAPTER 13

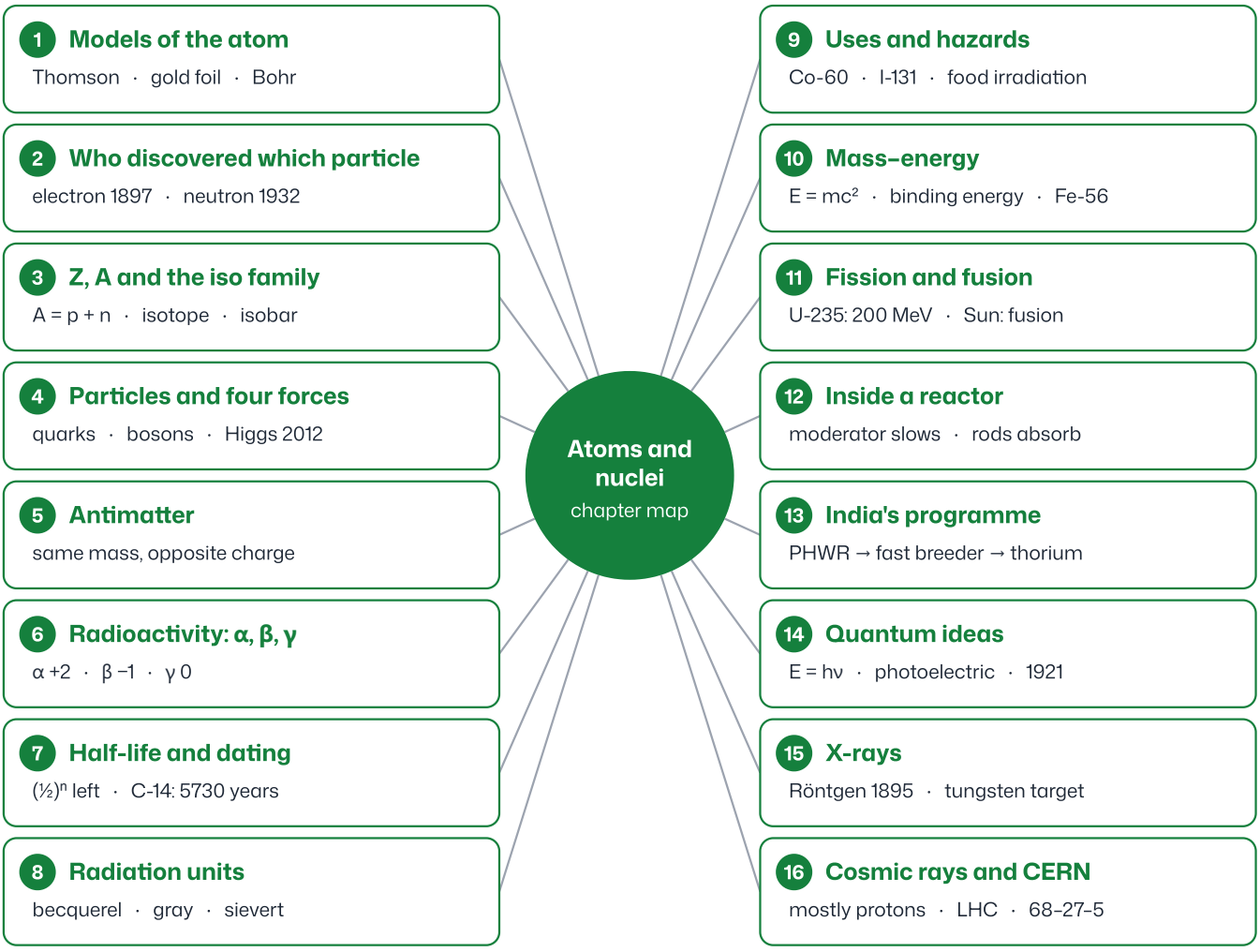
Atoms, Nuclei and Radioactivity

Discoverers of particles, α/β/γ rays, half-life and carbon dating, fission vs fusion, the Higgs boson, Einstein's photoelectric Nobel and India's nuclear programme are asked almost every year.

Asked 9 times in past papers: UPSC 3 · BPSC 6

≈ 1 h 10 min to read ≈ 8 min to revise ★★★

Revise on: Day 1 | Day 3 | Day 7 | Day 21



Revision card

1. **Electron**: J.J. Thomson (1897); **proton**: Goldstein's canal rays (1886), identified by Rutherford (1917–19); **neutron**: Chadwick (1932); **positron**: Anderson (1932); **nucleus**: Rutherford (1911).
2. **Isotopes** = same protons (Z); **isobars** = same mass number (A); **isotones** = same neutrons; **isoelectronic** = same number of electrons.
3. **α** = helium nucleus (+2), **β** = electron from the nucleus (−1), **γ** = photon (no charge). Penetration α < β < γ; ionisation α > β > γ. Stopped by paper, aluminium, lead.
4. **Half-life**: after n half-lives $(½)^n$ is left. **Carbon-14** half-life ≈ **5730 years**; dates once-living things up to ~50,000 years; rocks use **uranium–lead**.
5. **Units**: becquerel and curie (activity), gray (absorbed dose), sievert and rem (biological dose).
6. **Fission** splits heavy nuclei (U-235, Pu-239): controlled = reactor, uncontrolled = atom bomb. **Fusion** joins light nuclei: Sun and stars; **hydrogen bomb = uncontrolled fusion**.
7. **Reactor**: moderator slows neutrons (heavy water, graphite, light water); control rods absorb them (cadmium, boron, hafnium).
8. **Four forces**, strongest to weakest: strong nuclear > electromagnetic > weak > gravity. The **weak force causes beta decay**.
9. **Higgs boson** ('God particle') found at CERN's LHC in **2012**; its field explains why particles have **mass**. Bosons are named after **S.N. Bose**.
10. **Einstein's Nobel (1921)** was for the **photoelectric effect**, not relativity. **Planck** began quantum theory (1900).
11. **Cosmic rays** are charged particles, mostly **protons**. **X-rays**: Röntgen (1895), first physics Nobel (1901).
12. **India**: Bhabha's three stages PHWR → fast breeder → thorium; **Apsara** (1956) first research reactor in Asia; **Tarapur** (1969) first power plant; **PFBR** Kalpakkam first critical on **6 April 2026**.
13. India runs **24 power reactors, ≈ 8.78 GW** (2026); target **100 GW by 2047**; SHANTI Act 2025 lets private firms build nuclear plants.
14. **1 eV = 1.6 × 10^{-19} J**: a charge e accelerated through V volts gains energy **eV**.

How the picture of the atom grew

Dalton → Thomson

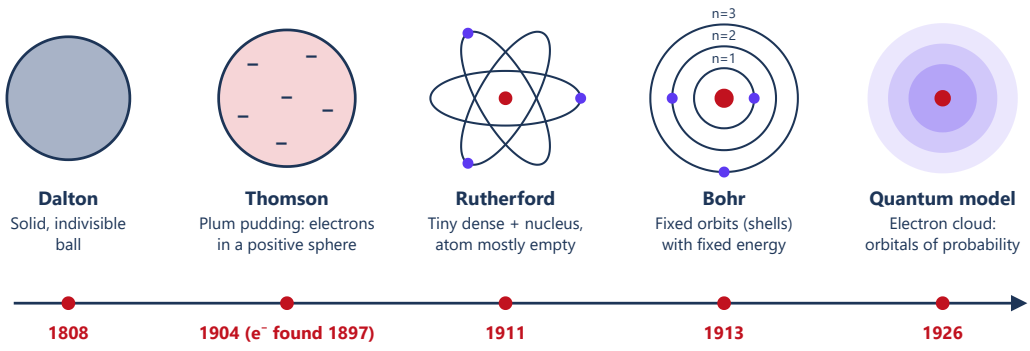
plum pudding

gold foil

Bohr orbits

electron cloud

Each atomic model was built to explain an experiment and dropped when a new experiment broke it. Read the models as a story: **solid ball → pudding → tiny nucleus → fixed shells → electron cloud**.



Five models in order. Notice how the positive charge shrinks from the whole atom (Thomson) to a tiny central nucleus (Rutherford), and how electrons go from fixed orbits (Bohr) to a cloud (quantum model).

Atomic models in order ★★★

Model (year)	Picture	Based on	What it could not explain
Dalton (1808)	Atoms are tiny, solid, indivisible balls; atoms of one element are identical	Laws of chemical combination	Electrons and the nucleus (atoms are divisible)
Thomson (1904), 'plum pudding'	Positive sphere with electrons stuck in it, like seeds in a watermelon	His discovery of the electron (1897)	Why some alpha particles bounced back from gold foil
Rutherford (1911), nuclear model	Tiny, dense, positive nucleus at the centre; electrons move around it; atom is mostly empty	Gold foil (alpha scattering) experiment of Geiger and Marsden	Why an orbiting electron does not lose energy and fall into the nucleus
Bohr (1913)	Electrons move only in fixed orbits (shells, n = 1, 2, 3...) with fixed energy; light is emitted or absorbed only when an electron jumps between shells	Line spectrum of hydrogen	Spectra of atoms with many electrons
Quantum mechanical (Schrödinger 1926; Heisenberg)	Electron is a wave; we can only give the probability of finding it (orbitals, electron cloud)	Wave nature of matter (de Broglie)	Current model

★★★ **Gold foil result**: most alpha particles went straight through (atom is mostly empty); a few were deflected; about 1 in 12,000 bounced straight back (a small, heavy, positive nucleus).

★★ **Size**: atom ≈ 10^{-10} m (1 ångström); nucleus ≈ 10^{-15} m (1 fermi). The nucleus is ~100,000 times smaller yet holds over 99.9% of the mass.

★★ **Bohr** won the Nobel Prize in Physics in **1922**; his model explains the hydrogen spectrum.

★ **Rutherford's Nobel (1908)** was in **Chemistry**, for work on radioactive substances, before his nuclear model.

Remember it: Atom models as food: Dalton's **laddoo** (solid ball) → Thomson's **watermelon** (seeds = electrons in red pulp) → Rutherford's **cricket stadium** with a **marble** at the centre → Bohr's **running track** with fixed lanes → quantum **mosquito cloud** (you know where it probably is, never exactly).

⚠ **Exam trap:** Thomson discovered the electron (1897) but did **not** discover the nucleus or the proton. The nucleus came from Rutherford's gold foil experiment. Bohr gave **fixed shells**, not the electron cloud.

Quick check

1. Which experiment showed that the atom has a tiny, dense, positive nucleus?
2. Most alpha particles went straight through the gold foil. What did that show?
3. Whose model put electrons in fixed shells, and what did it explain?

Answer: 1. Rutherford's gold foil (alpha scattering) experiment, 1911 · 2. the atom is mostly empty space · 3. Bohr (1913): the line spectrum of hydrogen

Who discovered which particle

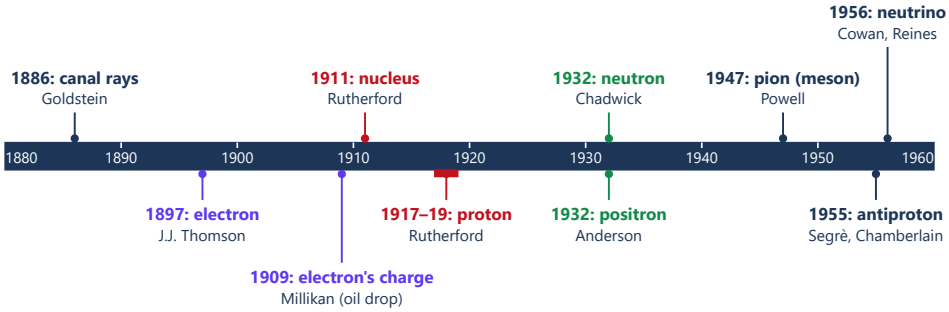
Thomson: electron

Rutherford: nucleus, proton

Chadwick: neutron

Anderson: positron

The particles inside the atom were found one by one between 1897 and 1932, mostly by firing beams through tubes and foils. Examiners love 'match the discoverer'.



The discoveries on a time line drawn to scale (one division = 10 years). The basic particles turned up between 1897 and 1932, and the neutral neutron, which leaves no track, came last.

Discoverers ★★★

Particle / idea	Discovered by	Year	How / note
Electron	J.J. Thomson	1897	Cathode rays are streams of electrons; Nobel 1906
Electron's charge	R.A. Millikan	1909	Oil-drop experiment
Proton	E. Goldstein (canal rays); E. Rutherford	1886; 1917–19	Goldstein saw positive 'canal rays'; Rutherford identified the hydrogen nucleus as the proton and named it (1920)
Nucleus	E. Rutherford	1911	Gold foil experiment
Neutron	James Chadwick	1932	Nobel 1935; made fission research possible
Positron (first antiparticle)	Carl Anderson	1932	Seen in cosmic rays; predicted by Paul Dirac (1928)
Neutrino	Predicted by Wolfgang Pauli; detected by Cowan and Reines	1930; 1956	Explains missing energy in beta decay
Meson (pion)	Predicted by Hideki Yukawa; found by Cecil Powell	1935; 1947	Carrier of the force between nucleons in Yukawa's theory
Antiproton	Segrè and Chamberlain	1955	Made in an accelerator

The three basic particles ★★

Particle	Charge	Mass	Where
Proton (p)	$+1.6 \times 10^{-19}$ C	1.6726×10^{-27} kg (≈ 1 u)	Nucleus
Neutron (n)	0	1.6749×10^{-27} kg (≈ 1 u, slightly heavier than proton)	Nucleus
Electron (e^-)	-1.6×10^{-19} C	9.11×10^{-31} kg (≈ 1/1836 of a proton)	Outside the nucleus (shells/cloud)

★★ **Cathode rays** are electrons (negative); **canal (anode) rays** are positive ions. Neither is a radioactive emission.

★★ **Neutron is the heaviest** of the three; a free neutron is unstable and decays to a proton, an electron and an antineutrino (half-life about 10 minutes).

★ **Atomic mass unit (u)** = 1/12 of the mass of a carbon-12 atom ≈ 1.66×10^{-27} kg.

Remember it: 'TE, GRP, CN': **T**homson–**E**lectron; **G**oldstein + **R**utherford–**P**roton; **C**hadwick–**N**eutron. Chadwick came last because the neutron has no charge, so it leaves no track: the shy one arrived late (1932).

⚠ **Exam trap:** Chadwick found the **neutron**, Anderson the **positron**: both in **1932**. Options often swap them, or credit Rutherford with the neutron (he only predicted it).

Quick check

1. Who discovered the neutron, and in which year?
2. The positron, the first antiparticle, was found by _____ .
3. Proton, neutron or electron: which is the heaviest?

Answer: 1. James Chadwick, 1932 · 2. Carl Anderson (1932), in cosmic rays · 3. the neutron (slightly heavier than the proton)

Atomic number, mass number and the 'iso' family

Z = protons

A = p + n

isotopes: same Z

isobars: same A

isotones: same n

The number of protons decides which element an atom is. Neutrons only add mass. So atoms can share protons, mass number or neutrons, and each kind of sharing has its own name.

★★★ **Atomic number (Z)** = number of protons (= electrons in a neutral atom). It fixes the element and its place in the periodic table.

★★★ **Mass number (A)** = protons + neutrons (together called **nucleons**). **Neutrons = A − Z**. Written as $^{12}_{6}C$: A on top, Z below.

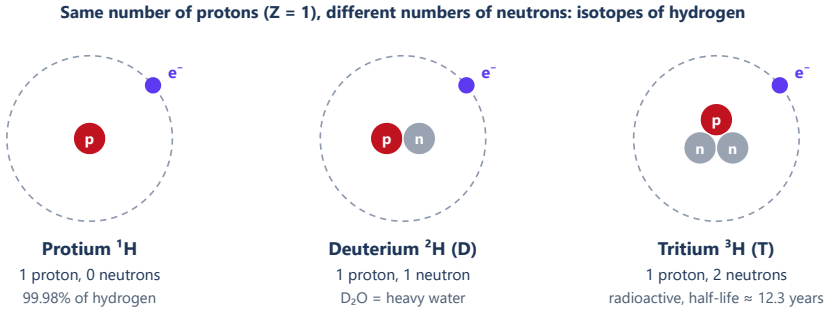
The 'iso' terms ★★★

Term	Same	Different	Example
Isotopes	Protons (Z): same element	Neutrons and mass number	^{1}H, ^{2}H, ^{3}H; C-12, C-14; U-235, U-238
Isobars	Mass number (A)	Protons (different elements)	^{40}Ar, ^{40}K, ^{40}Ca
Isotones	Neutrons	Protons and mass number	^{14}C (6p, 8n), ^{15}N (7p, 8n), ^{16}O (8p, 8n)
Isoelectronic	Number of electrons	Protons	Ne, Na^{+}, Mg^{2+}, F^{-} (all have 10 electrons)

Remember it: Look for the hidden letter: isoto**P**es = same **P**rotons; isoto**N**es = same **N**eutrons; isob**A**rs = same **A** (mass number). Isoelectronic says 'electron' in its own name.

Isotopes of hydrogen ★★

Isotope	Protons	Neutrons	Note
Protium (^{1}H)	1	0	About 99.98% of hydrogen; the only nucleus with no neutron
Deuterium (^{2}H or D)	1	1	Found by Harold Urey (1931); D_2O is **heavy water**, used as moderator
Tritium (^{3}H or T)	1	2	Radioactive (half-life ≈ 12.3 years); fuel for fusion and H-bombs



The three isotopes of hydrogen: one proton each, so one element with one chemistry; zero, one or two neutrons, so three different masses. Not to scale: a real nucleus is about 100,000 times smaller than its atom.

⚠ **Exam trap:** Isotopes have the **same chemical** properties (same electrons) but **different physical** properties (mass, density, radioactivity). Isobars are **different elements**, so their chemistry differs.

☑ Quick check

1. Mass number A = _____ ; number of neutrons = _____ .
2. Atoms with the same number of protons but different numbers of neutrons are called _____ .
3. Argon-40, potassium-40 and calcium-40 share which number, and what are they called?

Answer: 1. protons + neutrons; A − Z · 2. isotopes (same element, same chemistry) · 3. mass number 40: isobars

Fundamental particles and the four forces

quarks

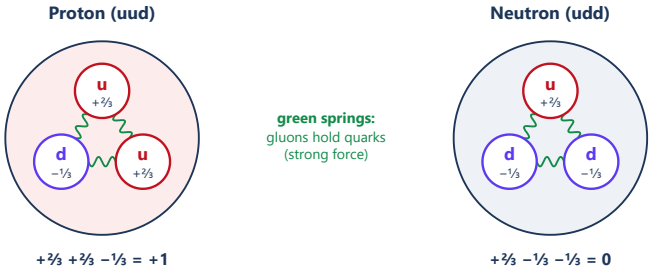
fermions vs bosons

S.N. Bose

Higgs boson 2012

strong > EM > weak > gravity

Protons and neutrons are not the smallest pieces: each is made of three **quarks**. All matter is built from quarks and leptons (such as the electron), and forces are passed between them by force-carrying particles called **bosons**.



A proton is two up quarks and one down quark (+⅔ +⅔ −⅓ = +1); a neutron is one up and two down (+⅔ −⅓ −⅓ = 0). Gluons carry the strong force that holds the quarks together.

Particle zoo at prelims depth ★★

Particle	Type	Charge	Remember
Electron	Lepton (fermion)	−1	Truly fundamental; carries electricity
Proton	Baryon: 3 quarks (up, up, down)	+1	Stable; hydrogen nucleus
Neutron	Baryon: 3 quarks (up, down, down)	0	Stable only inside nuclei
Positron	Antiparticle of electron	+1	Used in PET scans
Neutrino	Lepton	0	Almost massless; passes through Earth; 3 types
Quarks	Fundamental (fermion)	+⅔ or −⅓	6 flavours: up, down, charm, strange, top, bottom; never found alone
Mesons	Quark + antiquark	+1, 0 or −1	Short-lived (pion, kaon)
Photon	Boson	0	Carries electromagnetic force; particle of light; no rest mass
Gluon	Boson	0	Carries strong force; 'glues' quarks
W^+, W^-, Z	Bosons	±1, 0	Carry weak force; found at CERN (1983)
Higgs boson	Boson	0	'God particle'; found at CERN 2012; its field gives particles mass
Graviton	Boson (not yet found)	0	Would carry gravity

Fermions vs bosons ★★★

	Fermions	Bosons
Named after	Enrico Fermi	**Satyendra Nath Bose**
Spin	Half-integer (½, 3/2...)	Whole number (0, 1, 2...)
Pauli exclusion principle	Obey it: no two in the same state	Do not: any number can share one state
Statistics	Fermi–Dirac	**Bose–Einstein**
Examples	Electron, proton, neutron, quarks, neutrinos	Photon, gluon, W/Z, Higgs; also helium-4 atoms
Role	Make up matter	Carry forces (and give mass: Higgs)

★★★ **S.N. Bose** (Kolkata) sent his 1924 paper on counting photons to Einstein, who translated and extended it: hence **Bose–Einstein statistics**. Paul Dirac coined the word 'boson'.

★★ **Bose–Einstein condensate (BEC)**: when certain atoms are cooled to less than a millionth of a kelvin above absolute zero, they crowd into one quantum state and act as one 'super-atom', often called the **fifth state of matter**. First made in **1995** (Cornell, Wieman, Ketterle; Nobel 2001).

★★★ **Higgs boson**: predicted in **1964** (Peter Higgs and others); discovery announced on **4 July 2012** by the ATLAS and CMS experiments at CERN's **Large Hadron Collider**; Nobel 2013 to Higgs and François Englert.

★★★ **Why it matters**: the Higgs field gives elementary particles their **mass**. It has nothing to do with teleporting matter or better fission fuel.

★ **'God particle'** is a popular nickname from a 1993 book title by physicist Leon Lederman; physicists rarely use it.

The four fundamental forces ★★★

Force	Relative strength	Range	Carrier	What it does
Strong nuclear	1 (strongest)	~10^{-15} m (inside nucleus)	Gluon	Holds quarks together and binds protons and neutrons in the nucleus
Electromagnetic	~10^{-2} (≈ 1/137)	Infinite	Photon	Acts only on charged particles; holds atoms and molecules together; light, electricity, friction
Weak nuclear	~10^{-13}	~10^{-16} m	W and Z bosons	Causes **beta decay** (radioactivity); helps power the Sun
Gravity	~10^{-39} (weakest)	Infinite	Graviton (not found)	Acts on all mass; rules planets and galaxies

Remember it: 'Strong Elephants Walk Gently' = Strong > Electromagnetic > Weak > Gravity. Gravity feels strong only because Earth's mass is huge: a small magnet lifts a pin against the pull of the whole Earth.

⚠ **Exam trap: Gravity is the weakest** force, not the strongest. Gravity and electromagnetism have infinite range; the two nuclear forces act only inside the nucleus.

Quick check

1. Bosons are named after which Indian physicist?
2. What does the Higgs field give to elementary particles?
3. Put the four fundamental forces in order, strongest first.

Answer: 1. Satyendra Nath Bose · 2. their mass (Higgs boson found at CERN, 2012) · 3. strong > electromagnetic > weak > gravity

Antimatter

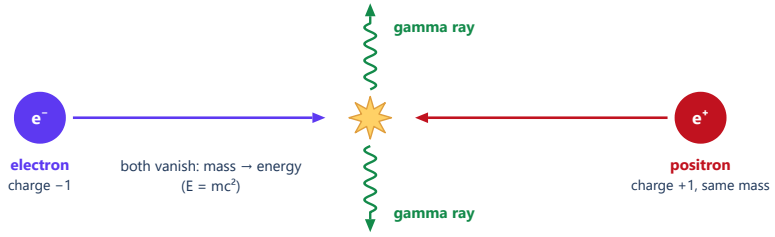
same mass, opposite charge

positron 1932

annihilation → gamma

PET scan

Every particle has an antiparticle with the **same mass but opposite charge**. When matter meets antimatter, both vanish and their whole mass turns into energy (gamma rays), exactly as $E = mc^2$ predicts.



Annihilation: an electron and a positron (same mass, opposite charge) meet and both vanish; their mass reappears as two gamma rays flying apart in opposite directions. Not to scale.

★★★ **Positron** (anti-electron) was the first antiparticle found (Anderson, 1932); the **antiproton** followed in 1955.

★★ **Anti-helium-4**, the heaviest antimatter nucleus known at the time, was created in 2011 at the Relativistic Heavy Ion Collider, **Brookhaven** (USA), by the STAR team, which included Indian scientists. In 2024 the same STAR team found a heavier, exotic one: **antihyperhydrogen-4**.

★★★ **Why make antimatter**: to probe whether stars or galaxies made of antimatter could exist and to understand why the universe ended up made almost entirely of matter (its evolution). It has no use in mineral or oil prospecting.

★★ **PET scan** (positron emission tomography): a tracer emits positrons that annihilate with electrons in the body; the gamma rays given off build the image.

★ **Antihydrogen** atoms are made and trapped at CERN to compare them with ordinary hydrogen.

⚠ **Exam trap:** Antimatter has **opposite charge, same mass** (not 'negative mass'). Antimatter is not dark matter.

Quick check

1. An antiparticle has the same _____ but the opposite _____ .
2. What happens when an electron meets a positron?
3. Which medical scan uses positrons?

Answer: 1. mass; charge · 2. both vanish; their mass turns into gamma rays ($E = mc^2$) · 3. PET (positron emission tomography)

Radioactivity and the three rays

Becquerel 1896

Curies: Po, Ra

α +2, β −1, γ 0

paper, aluminium, lead

property of the nucleus

Some nuclei have the wrong mix of protons and neutrons, or are simply too big. They become stable by throwing out particles or energy on their own: **radioactivity**. It is a property of the **nucleus**, so heat, pressure or chemical reactions cannot speed it up or slow it down.

★★★ **Henri Becquerel** discovered radioactivity in **1896** by chance: uranium salts fogged a wrapped photographic plate.

★★★ **Marie and Pierre Curie** discovered **polonium** (named after Marie's homeland, Poland) and **radium** in 1898; Marie coined the word 'radioactivity'.

★★ **Marie Curie**: first woman Nobel laureate and the only person with Nobels in two different sciences: Physics 1903 (shared with Pierre Curie and Becquerel) and Chemistry 1911.

★★ **Rutherford** named alpha and beta rays (1899); **Paul Villard** found gamma rays (1900).

★ **Artificial radioactivity**: Irène Joliot-Curie and Frédéric Joliot (1934), Chemistry Nobel 1935.

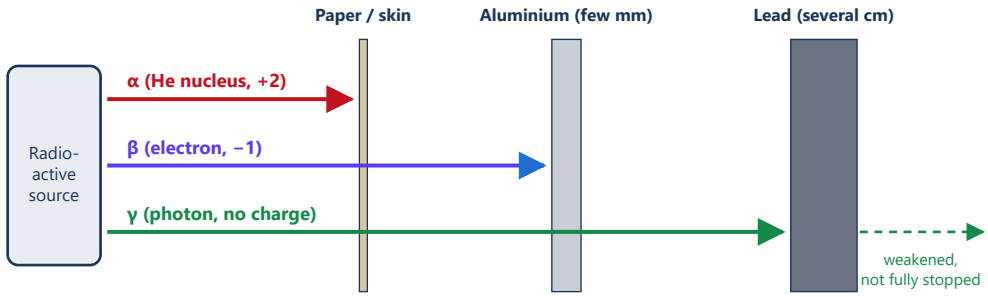
★★ **Every element heavier than lead** (Z above 82) is radioactive, e.g. uranium, thorium, radium, radon, plutonium.

★★ **Geiger–Müller counter** detects and counts radiation; a **dosimeter** or film badge records the dose a worker receives.

Marie Curie. With Pierre Curie she discovered polonium and radium (1898); she coined the word 'radioactivity' and won Nobel Prizes in Physics (1903) and Chemistry (1911). Image: Henri Manuel, Wikimedia Commons, public domain

Alpha, beta and gamma ★★★

Feature	Alpha (α)	Beta (β^-)	Gamma (γ)
Nature	Helium-4 nucleus (2 protons + 2 neutrons)	Fast electron made in the nucleus ($n \rightarrow p + e^- +$ antineutrino)	Electromagnetic wave (high-energy photon)
Charge	**+2** (positive)	−1	0
Mass	≈ 4 u (heaviest)	≈ 1/1836 u	No rest mass
Speed	~1/20 of light speed	Up to nearly light speed	Speed of light
Penetrating power	Least	Medium (~100 × α)	Most (~100 × β)
Ionising power	**Most**	Medium	Least
Stopped by	Sheet of paper, skin, few cm of air	Few mm of aluminium	Several cm of lead or thick concrete (only reduced)
In electric/magnetic field	Bends one way (slightly)	Bends the other way (strongly, being light)	Not deflected
Change in nucleus	Z − 2, A − 4	Z + 1, A unchanged	None (energy only)



Penetrating power: α < β < γ | Ionising power: α > β > γ
The heavier and more charged the particle, the faster it spends its energy ionising, so the sooner it stops.

Penetration ladder: paper stops alpha, a few millimetres of aluminium stop beta, while lead only weakens gamma.

Remember it: 'Your PAL stops ABG': **P**aper stops **A**lpha, **A**luminium stops **B**eta, **L**ead tames **G**amma. Think of a fat, slow wrestler (alpha): he collides with everything (ionises most) and so tires fastest (penetrates least).

See it around you: U-238 gives out an alpha particle and becomes thorium-234 (Z 92 → 90, A 238 → 234). Carbon-14 gives out a beta particle and becomes nitrogen-14 (Z 6 → 7, A stays 14).

Exam trap: The **positively charged** ray is **alpha**, not beta. Beta electrons come from the **nucleus** (a neutron turning into a proton), not from the electron shells. Gamma carries no charge and is not bent by fields. Cathode rays are electrons but are **not** a radioactive emission.

Quick check

1. Which of the three rays is positively charged?
2. Arrange α, β and γ by penetrating power, least first.
3. Who discovered radioactivity, and how?

Answer: 1. alpha (a helium nucleus, +2) · 2. α < β < γ (ionising power is the reverse) · 3. Henri Becquerel, 1896: uranium salts fogged a wrapped photographic plate

Half-life and radioactive dating

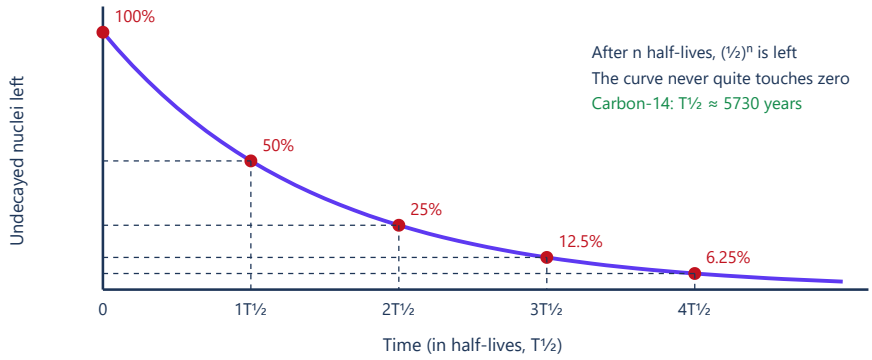
$(½)^n$ left

C-14: 5730 years

up to 50,000 years

uranium–lead for rocks

You cannot say when one nucleus will decay, but in a huge crowd a fixed fraction decays in a fixed time. The time for **half** of the nuclei to decay is the **half-life**; it is a fingerprint of each isotope.



Decay curve: every half-life cuts what is left by half (100% → 50% → 25% → 12.5%). It never quite reaches zero.

★★★ **Amount left after n half-lives** = original × (½)ⁿ. After 3 half-lives, 1/8 remains; after 10, about 1/1000.

★★ **Half-life cannot be changed** by temperature, pressure, light or chemical combination.

See it around you: Iodine-131 has a half-life of 8 days. A hospital gets 80 mg: after 8 days 40 mg, after 16 days 20 mg, after 24 days 10 mg remain.

Half-lives worth knowing ★★

Isotope	Half-life	Known for
Technetium-99m	6 hours	Most used tracer in medical imaging
Radon-222	3.8 days	Radioactive gas seeping from rocks into homes
Iodine-131	8 days	Thyroid treatment; released in reactor accidents
Cobalt-60	5.3 years	Cancer therapy, food irradiation
Tritium (H-3)	12.3 years	Fusion fuel; glow-in-the-dark signs
Strontium-90, Caesium-137	≈ 29 and 30 years	Dangerous fallout from bombs and accidents
Radium-226	1600 years	Discovered by the Curies
Carbon-14	**≈ 5730 years**	Dating once-living things
Plutonium-239	≈ 24,100 years	Bomb and breeder-reactor fuel
Uranium-235	≈ 704 million years	Reactor fuel
Uranium-238	≈ 4.5 billion years	Dating rocks; about the age of Earth

★★★ **Carbon-14 dating** (Willard Libby, 1949; Chemistry Nobel 1960): cosmic-ray neutrons turn nitrogen-14 into C-14 in the air; plants take it in as CO_2 and animals eat the plants. While alive, the C-14 : C-12 ratio stays steady; after death no new C-14 enters and it decays.

★★★ **Carbon dating works only on once-living material** (wood, bone, charcoal, cloth, paper, shells) and only up to about **50,000 years**.

★★★ **Rocks and the age of Earth** are dated by long half-life isotopes: **uranium–lead** (age of Earth ≈ 4.54 billion years), **potassium–argon** (volcanic rock), rubidium–strontium.

★ **Thermoluminescence** dates pottery and burnt bricks; **tritium** dates young groundwater.

Remember it: Carbon for Creatures, Uranium for the Unliving. C-14's half-life ≈ 5730: read it as '**5-7-3-0**: five fingers, seven days, three meals, zero excuses'.

⚠ **Exam trap:** After **two** half-lives the sample is not gone: **one quarter** remains. Carbon dating cannot date a stone tool, a dinosaur fossil 65 million years old or a meteorite.

Quick check

1. What fraction of a sample is left after 3 half-lives?
2. Half-life of carbon-14?
3. Can carbon dating give the age of a granite rock?

Answer: 1. 1/8 · 2. ≈ 5730 years · 3. no: only once-living material, up to about 50,000 years; rocks use uranium–lead

Measuring radiation: units

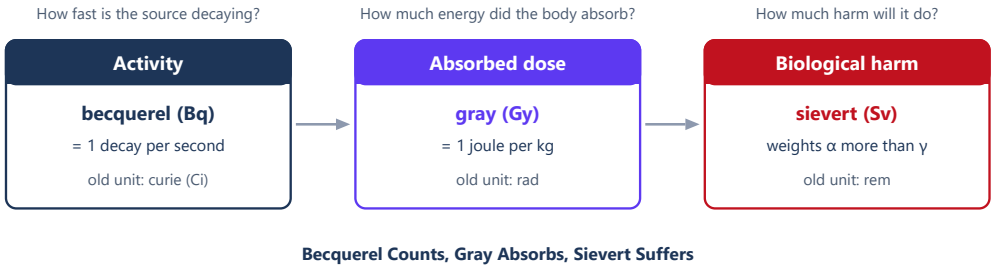
becquerel: activity

gray: absorbed dose

sievert: harm

curie, rad, rem

Three different questions need three different units: how fast is the source decaying (**activity**), how much energy did the body absorb (**absorbed dose**), and how much harm will it do (**equivalent dose**).



Three questions, three units: how fast the source decays (becquerel), how much energy the body absorbs (gray) and how much harm that does (sievert).

Radiation units ★★★

Quantity	SI unit	Older unit	Meaning
Activity	**Becquerel (Bq)** = 1 decay per second	**Curie (Ci)** = 3.7×10^{10} Bq; rutherford = 10^6 Bq	How radioactive a source is; 1 Ci ≈ activity of 1 g of radium
Absorbed dose	**Gray (Gy)** = 1 joule per kg	Rad = 0.01 Gy	Energy deposited in matter
Equivalent / effective dose	**Sievert (Sv)**	**Rem** = 0.01 Sv	Biological harm (weights alpha more than gamma)
Exposure	coulomb per kg	Roentgen (R)	Ionisation by X-rays and gamma rays in air

★★ **Natural background dose** averages about **2.4 mSv per year** worldwide; radon gas is the largest natural source.

★ **Safety rule**: less time, more distance, more shielding.

Remember it: Becquerel Counts, Gray Absorbs, Sievert Suffers. The 'old guard' partners: Curie with becquerel, rad with gray, rem with sievert.

⚠ **Exam trap:** The **becquerel** measures activity, not dose; the **sievert** (not the gray) accounts for biological damage.

Quick check

1. Which SI unit measures the biological harm of a radiation dose?
2. One becquerel equals _____ .
3. The gray measures _____ .

Answer: 1. the sievert (Sv); older unit rem · 2. one decay per second · 3. absorbed dose: 1 joule per kg

Radiation at work: uses and hazards

Co-60: cancer therapy

I-131: thyroid

tracers

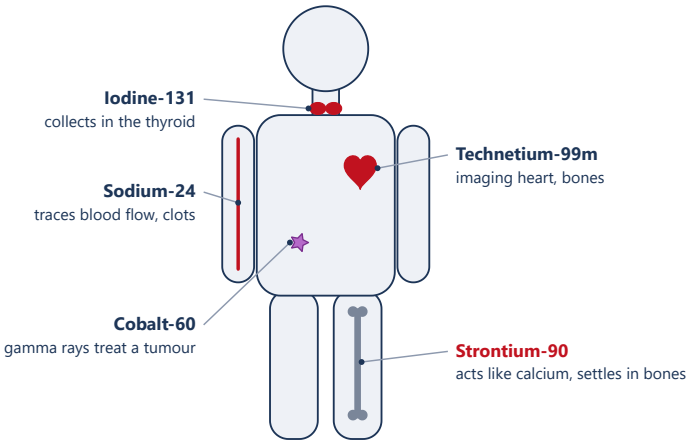
food irradiation

leukaemia

Radiation is useful for the same reason it is dangerous: it carries enough energy to knock electrons off atoms and break DNA. Aim it at a tumour or a germ and it heals; let it hit healthy cells and it harms.

Isotopes and their uses ★★★

Isotope	Use
Cobalt-60	Cancer radiotherapy ('cobalt therapy'); sterilising syringes and medical kits; food irradiation
Iodine-131	Diagnosing and treating thyroid disorders (thyroid absorbs iodine)
Technetium-99m	Imaging bones, heart and other organs (most used diagnostic tracer)
Sodium-24	Tracing blood circulation and clots; finding leaks in buried pipes
Phosphorus-32	Tracer for how plants take up fertiliser; some blood disorders
Carbon-14	Dating; tracing steps of photosynthesis
Iron-59	Studying iron absorption and anaemia
Americium-241	Household smoke detectors
Iridium-192	Industrial radiography: finding cracks in welds
Plutonium-238	Radioisotope batteries for deep-space probes (Voyager, Mars rovers)
Uranium-235, Plutonium-239	Nuclear fuel and weapons



Where some isotopes act in the body. A radioisotope behaves chemically like the normal element, so it goes where that element goes: iodine to the thyroid, strontium (like calcium) to the bones. Not to scale.

★★ **Tracers**: a tiny amount of radioisotope is added and followed with a detector, because it behaves chemically like the normal element.

★★ **Food irradiation** (gamma rays from Co-60) stops onions and potatoes sprouting, kills insects and germs and extends shelf life; the food does **not** become radioactive. BARC's KRUSHAK unit at Lasalgaon (Nashik) irradiates onions.

★ **Mutation breeding**: BARC used radiation to develop many crop varieties, such as the Trombay groundnuts.

★★★ **Hazards**: ionising radiation damages cells and DNA, causing burns, **radiation sickness**, cancers such as **leukaemia** and genetic mutations.

★★ **Bone seeker and thyroid seeker**: strontium-90 behaves like calcium and settles in bones; iodine-131 collects in the thyroid, so potassium iodide tablets are given after leaks.

★★ **Major accidents**: Three Mile Island (USA, 1979), **Chernobyl** (Ukraine, then USSR, 26 April 1986; worst ever) and **Fukushima Daiichi** (Japan, March 2011, after an earthquake and tsunami).

★ **High natural background**: monazite beach sands of Kerala (Karunagappally) give some of the highest natural radiation levels in the world.

⚠ **Exam trap:** Irradiated food is **not radioactive**, just as an X-rayed bag does not glow. Gamma rays used for sterilising leave no residue.

☑ Quick check

1. Which isotope is used for cancer radiotherapy and for sterilising syringes?
2. Why is iodine-131 dangerous after a reactor leak?
3. Does irradiated food become radioactive?

Answer: 1. cobalt-60 · 2. it collects in the thyroid (potassium iodide tablets are given) · 3. no

Mass–energy, mass defect and binding energy

$E = mc^2$

mass defect

binding energy

iron-56 peak

$1\ eV = 1.6 \times 10^{-19}\ J$

Weigh a nucleus and it is always a little **lighter** than its protons and neutrons weighed separately. The missing mass has become the energy that binds them together. Einstein's **$E = mc^2$** gives the exchange rate, and because c^2 is enormous, a tiny mass is worth a huge energy.

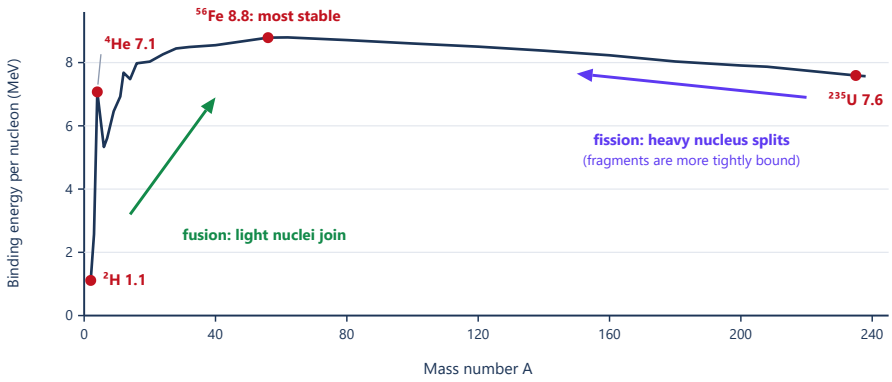
★★★ **$E = mc^2$** (Einstein, 1905, special relativity): 1 gram of mass ≡ 9×10^{13} J, roughly the energy of 20,000 tonnes of TNT.

★★★ **Mass defect** = (mass of separate nucleons) − (mass of nucleus). **Binding energy** = mass defect × c^2: the energy needed to pull the nucleus apart.

★★ **1 u of mass ≡ 931.5 MeV** of energy.

★★ **Binding energy per nucleon** peaks near **iron-56** (about 8.8 MeV). Heavy nuclei gain stability by **splitting** (fission); light nuclei by **joining** (fusion). Both release energy.

★★★ **Electron-volt (eV)**: energy gained by one electron accelerated through 1 volt = **1.6×10^{-19} J**. In general a charge q through potential difference V gains **qV**, so an electron (charge e) through V volts gains **eV** joules, whatever its mass.



Binding energy per nucleon against mass number, plotted from measured values. Iron-56 sits at the top (about 8.8 MeV), so heavy nuclei release energy by splitting (fission) and light ones by joining (fusion).

Remember it: Iron sits on the **hilltop of stability**: heavy uranium rolls down one side by breaking up, light hydrogen rolls down the other side by joining up. Either way energy is released.

⚠ **Exam trap:** In a nuclear reaction the **mass number and charge are conserved**, but **mass is not**: a little mass disappears as energy. Energy from the Sun, reactors and bombs all comes from this lost mass.

Quick check

1. Why is a nucleus lighter than its protons and neutrons weighed separately?
2. Binding energy per nucleon is highest near which nucleus?
3. Energy gained by a charge e accelerated through V volts?

Answer: 1. the missing mass (mass defect) has become binding energy, $E = mc^2$ · 2. iron-56 (about 8.8 MeV) · 3. eV joules ($1\ eV = 1.6 \times 10^{-19}$ J)

Nuclear fission and fusion

U-235 + slow neutron

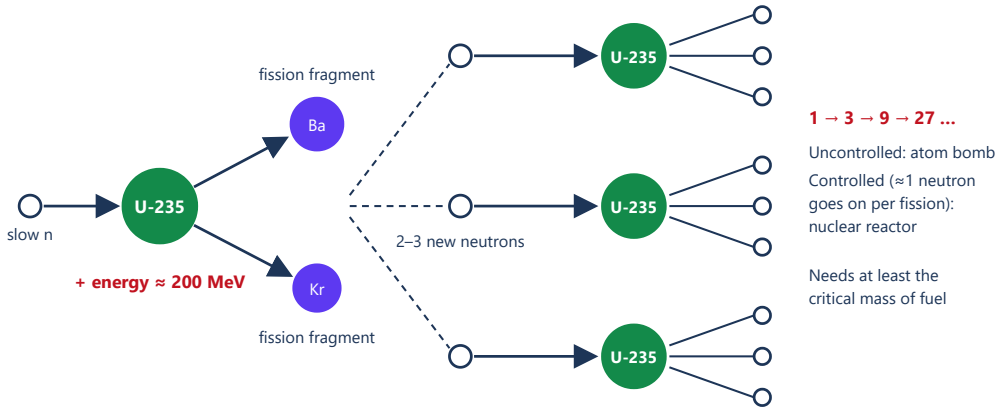
≈ 200 MeV

critical mass

Sun: fusion

H-bomb: fusion

Fission breaks a big, wobbly nucleus into two middle-sized ones; **fusion** squeezes two tiny nuclei into one. Fission needs only a slow neutron to start, so we have used it since 1942. Fusion needs temperatures of millions of degrees to beat the repulsion between positive nuclei, which is why it runs the stars but not yet our power stations.



Chain reaction: one neutron splits U-235 into two fragments plus energy and 2–3 new neutrons, each of which can split another nucleus. Uncontrolled, the numbers explode (bomb); controlled, one neutron per fission carries on (reactor).

★★★ **Discovery of fission**: Otto Hahn and Fritz Strassmann (1938); explained by Lise Meitner and Otto Frisch.

★★★ **Typical fission**: U-235 + slow neutron → barium + krypton + 2–3 neutrons + about **200 MeV**.

★★★ **Chain reaction**: neutrons from one fission cause more fissions. **Critical mass** is the least amount of fissile material that can sustain it.

★★ **Fissile** (split by slow neutrons): U-235, Pu-239, U-233. **Fertile** (turn into fissile fuel after absorbing a neutron): U-238 → Pu-239; Th-232 → U-233.

★★ **Natural uranium** is about 99.3% U-238 and only **0.7% U-235**. Power reactors using light water need it enriched to 3–5% U-235; weapons need about 90%.

★★★ **Sun and stars** shine by **fusion** of hydrogen into helium in their cores (about 15 million °C in the Sun's core); Hans Bethe explained this (Nobel 1967). The Sun turns about 4 million tonnes of mass into energy every second.

★★ **D–T fusion**: deuterium + tritium → helium-4 + neutron + 17.6 MeV. Per kilogram of fuel, fusion gives several times more energy than fission and leaves little long-lived waste.

Fission vs fusion ★★★

	Fission	Fusion
Process	Heavy nucleus splits	Light nuclei join
Fuel	U-235, Pu-239, U-233	Hydrogen isotopes (deuterium, tritium)
Needs	Slow neutron; critical mass	Extremely high temperature and pressure
Energy per kg	Very high	Higher still (several times)
Waste	Long-lived radioactive waste	Little; mainly short-lived activation
In nature	Rare (Oklo, Gabon, 2 billion years ago)	Sun and all stars
Bomb	**Atom bomb** (uncontrolled fission)	**Hydrogen / thermonuclear bomb** (uncontrolled fusion, triggered by a fission bomb)
Peaceful use today	All nuclear power plants (controlled fission)	Experimental only: ITER, tokamaks

★★ **Atom bombs used in war**: 'Little Boy' (U-235) on **Hiroshima**, 6 August 1945; 'Fat Man' (Pu-239) on **Nagasaki**, 9 August 1945. First test: Trinity, New Mexico, 16 July 1945.

★ **First hydrogen bomb**: USA, 1952; far more powerful than fission bombs.

★★ **India's tests** at Pokhran (Rajasthan): **Pokhran-I** 'Smiling Buddha', 18 May 1974; **Pokhran-II** 'Operation Shakti', 11 and 13 May 1998 (11 May is National Technology Day).

★★ **ITER** (International Thermonuclear Experimental Reactor), being built at Cadarache in southern France by seven members (EU, China, **India**, Japan, South Korea, Russia, USA). India joined in 2005 and built its giant **cryostat**, the world's largest stainless-steel vacuum chamber.

★★ **Tokamak** (a Russian acronym): a doughnut-shaped machine that holds hot plasma with strong magnetic fields. India's **Aditya** (1989) and **SST-1** (steady-state superconducting tokamak) are at the Institute for Plasma Research, Gandhinagar.

★ **Laser fusion**: the US National Ignition Facility first got more fusion energy out than laser energy in (December 2022).

Remember it: Fission = Fissure (a crack: the nucleus splits). **Fusion = Fuse** (things join, like fusing two wires). H-bomb has **H** for hydrogen: it fuses hydrogen, so it is the **fusion** bomb.

⚠ **Exam trap: Hydrogen bomb = uncontrolled fusion**; **atom bomb = uncontrolled fission**; **reactor = controlled fission**. No power plant anywhere yet runs on fusion. The Sun does not 'burn' (no chemical combustion) and does not use fission.

Quick check

1. Energy released by one U-235 fission?
2. The hydrogen bomb works by _____ ; the atom bomb by _____ .
3. What is critical mass?

Answer: 1. about 200 MeV · 2. uncontrolled fusion; uncontrolled fission · 3. the least amount of fissile material that can sustain a chain reaction

Inside a nuclear reactor

moderator slows

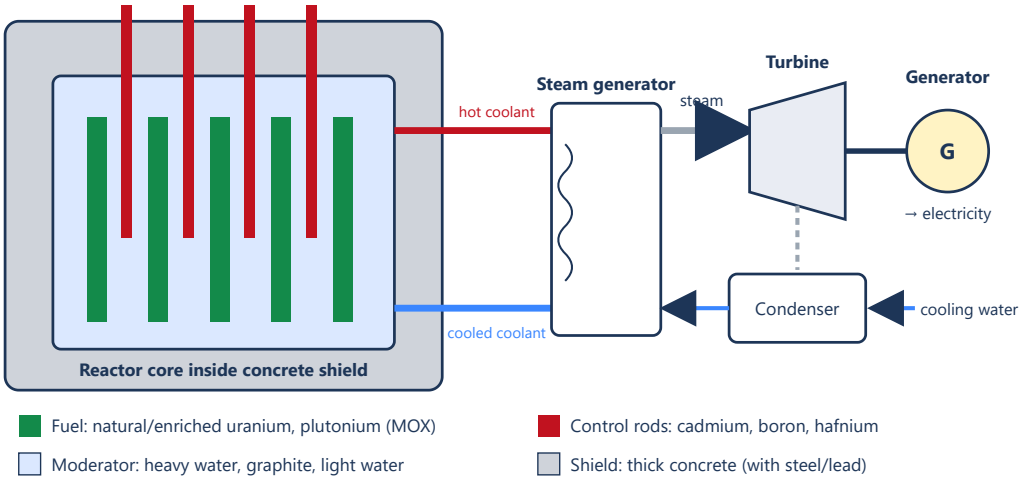
control rods absorb

heavy water D_2O

cadmium, boron, hafnium

coolant

A reactor is a fission chain reaction held exactly at the edge: on average each fission lets **one** neutron go on to cause the next. The heat boils water, the steam spins a turbine, and from there it is an ordinary power station.



A reactor plant: fuel rods heat the coolant, which makes steam in the steam generator; the steam spins the turbine and generator. Control rods slide in to slow the reaction.

Parts of a reactor ★★★

Part	Job	Materials
Fuel	Fissions to release heat	Natural uranium (India's PHWRs), enriched uranium (LWRs), plutonium/MOX (fast breeders); thorium in future
Moderator	**Slows** fast neutrons so U-235 can capture them	**Heavy water (D_2O)**, graphite, light water, beryllium
Control rods	**Absorb** extra neutrons to slow or stop the reaction	**Cadmium, boron** (boron carbide), **hafnium**
Coolant	Carries heat from core to steam generator	Heavy water, light water, liquid sodium (fast reactors), CO_2 or helium (gas-cooled)
Reflector	Bounces escaping neutrons back into the core	Graphite, beryllium, water
Shielding	Protects people from radiation	Thick concrete, steel, lead

Reactor types in India ★★

Type	Fuel	Moderator / coolant	Indian example
PHWR (pressurised heavy water)	Natural uranium	Heavy water / heavy water	Most Indian reactors: Rawatbhata (Rajasthan), Kaiga (Karnataka), Kakrapar (Gujarat), **Narora (UP)**, Kalpakkam (TN), Tarapur 3 and 4
BWR (boiling water)	Enriched uranium	Light water / light water	Tarapur 1 and 2 (Maharashtra), India's oldest
PWR / VVER (pressurised water)	Enriched uranium	Light water / light water	Kudankulam (Tamil Nadu), with Russia
Fast breeder	Plutonium–uranium (MOX or carbide)	No moderator / liquid sodium	FBTR and PFBR, Kalpakkam

★★ **First reactor**: Chicago Pile-1, 2 December 1942, built by **Enrico Fermi**'s team under a football stand.

★★ **Fast breeder reactors** use no moderator (they need fast neutrons) and produce more fissile fuel than they burn, by turning U-238 into Pu-239.

★ **Heavy Water Board** makes heavy water; India is among the world's largest producers.

Remember it: Moderator moderates (slows the speeding neutron, like a speed-breaker); **control rods Can Block Him**: **C**admium, **B**oron, **H**afnium soak up the neutron.

⚠ **Exam trap:** The **moderator slows** neutrons; it does **not absorb** them (that is the control rods' job). Heavy water is **D_2O** (deuterium oxide), not hard water.

Quick check

1. What does the moderator do? Name two moderators.
2. Which part absorbs extra neutrons, and what is it made of?
3. Which reactors use no moderator at all?

Answer: 1. slows neutrons: heavy water, graphite · 2. control rods: cadmium, boron, hafnium · 3. fast breeder reactors

India's nuclear programme

Bhabha: three stages

PHWR → FBR → thorium

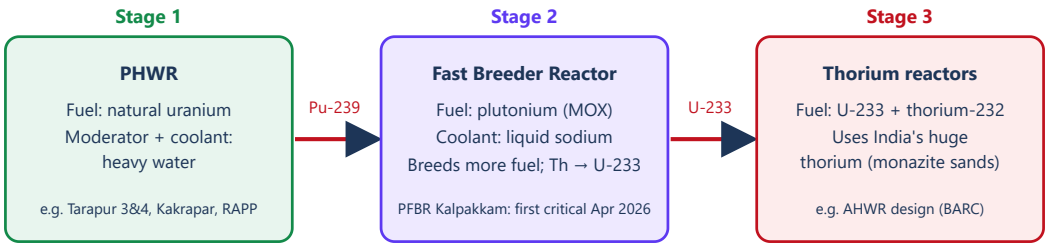
Apsara 1956

Tarapur 1969

PFBR 2026

SHANTI Act 2025

India has little uranium but some of the world's largest **thorium** reserves. Thorium cannot run a reactor by itself, so **Homi J. Bhabha** planned (1954) a three-step ladder: use uranium to make plutonium, use plutonium to turn thorium into U-233, then run reactors on thorium.



Plan by Homi J. Bhabha (1954): uranium → plutonium → thorium

Three-stage programme: each stage makes the fuel for the next. Stage 2 began with the PFBR's first criticality in April 2026.

Milestones ★★★

Year	Milestone
1945	Bhabha founds **Tata Institute of Fundamental Research** (TIFR), Mumbai
1948	**Atomic Energy Commission** set up (Bhabha chairman)
1954	**Department of Atomic Energy**; Atomic Energy Establishment, Trombay (renamed **BARC** in 1967 after Bhabha's death in 1966)
1956	**Apsara** at Trombay goes critical (4 August): India's and **Asia's first research reactor**; rebuilt as Apsara-U (2018)
1960	**CIRUS** research reactor (with Canada)
1969	**Tarapur** (Maharashtra): India's **first nuclear power station** (two BWRs, built with the USA)
1973	Rawatbhata (RAPS-1, Rajasthan): first PHWR
1974	Pokhran-I test
1985	**Dhruva** research reactor; **FBTR** (Fast Breeder Test Reactor), Kalpakkam
1996	**KAMINI**, Kalpakkam: the only reactor in the world running on **U-233** fuel
2013	**Kudankulam-1** (Tamil Nadu, 1000 MWe, Russian VVER) goes critical; India's largest units
2020	**Kakrapar-3** (Gujarat): first indigenous 700 MWe PHWR goes critical
2026	**PFBR** (500 MWe, Kalpakkam) first criticality on **6 April 2026**: stage 2 begins

★★★ **Stage 1 – PHWRs** burn **natural uranium** with heavy water; their spent fuel is reprocessed for **plutonium**.

★★★ **Stage 2 – Fast breeder reactors** burn plutonium (MOX fuel, liquid-sodium coolant) and breed more fuel; a thorium blanket turns into **U-233**. The **PFBR** was designed by **IGCAR** and built by **BHAVINI**, with about 90% Indian-made equipment.

★★★ **Stage 3 – Thorium reactors** run on U-233 and thorium-232; BARC's **Advanced Heavy Water Reactor (AHWR)** is the design.

★★ **Thorium** comes from **monazite** sands on the coasts of Kerala, Tamil Nadu, Odisha and Andhra Pradesh (also West Bengal, Jharkhand). Uranium is mined at **Jaduguda** (Jharkhand, first mine) and Tummalapalle (Andhra Pradesh).

★★★ **Fleet in 2026**: **24 power reactors** with ≈ **8.78 GW** installed capacity, run by **NPCIL**; nine more units (≈ 7.5 GW) under construction, and ten 700 MWe PHWRs approved for 'fleet mode' building.

★★ **Kudankulam** (Tirunelveli, Tamil Nadu), built with Russia: units 1 and 2 (1000 MWe each) run; units 3 to 6 are under construction, which will make it India's largest nuclear plant.

★★★ **Target**: **100 GW of nuclear power by 2047** (Viksit Bharat goal); capacity is planned to reach about 22 GW by 2031–32.

★★ **Nuclear Energy Mission** (Union Budget 2025–26): **₹20,000 crore** for indigenous **Small Modular Reactors** (SMRs, up to 300 MWe); at least **five SMRs operational by 2033**. Designs: BSMR-200 (BARC–NPCIL), SMR-55, and a high-temperature gas-cooled reactor for hydrogen.

★★ **Bharat Small Reactors (BSR)**: 220 MWe PHWRs offered to private industry for captive power (announced in Budget 2024–25).

★★★ **SHANTI Act, 2025** (Sustainable Harnessing and Advancement of Nuclear Energy for Transforming India; assent 20 December 2025): replaced the Atomic Energy Act 1962 and the Civil Liability for Nuclear Damage Act 2010 and allows **private companies** to build, own and run nuclear plants; sensitive fuel-cycle work stays with the government.

★ **Regulator**: Atomic Energy Regulatory Board (**AERB**, 1983), made a statutory body by the SHANTI Act 2025. India–US civil nuclear deal and NSG waiver: 2008.

★ **Vitrification**: India turns high-level waste into stable glass for storage and follows a **closed fuel cycle** (spent fuel is reprocessed).

Kudankulam (Tamil Nadu), built with Russia: units 1 and 2, of 1000 MWe each. The domes are the containment buildings around the reactors. Image: Reetesh Chaurasia, Wikimedia Commons, CC BY-SA 4.0

💡 **Remember it: 'U → Pu → Th'**, like climbing three floors: the ground floor (natural **U**ranium) pays for the first floor (**Pu**tonium), which builds the top floor (**Th**orium). And the reactor dates go in a neat ladder: **Apsara 1956 → Tarapur 1969 → PFBR 2026**.

⚠ **Exam trap: Apsara** was a **research** reactor (Asia's first); **Tarapur** was the first **power** plant. Tarapur 1 and 2 are **boiling water** reactors, not PHWRs. The PFBR belongs to **stage 2**, not stage 3; the thorium stage is still ahead.

Quick check

1. Name India's three nuclear power stages in order.
2. Asia's first research reactor, and India's first nuclear power station?
3. Which 2025 law lets private companies build and run nuclear plants?

Answer: 1. PHWRs (natural uranium) → fast breeders (plutonium) → thorium reactors · 2. Apsara (1956); Tarapur (1969) · 3. the SHANTI Act, 2025

Quantum ideas: Planck, Einstein, de Broglie

E = hν

photoelectric effect

threshold frequency

Einstein Nobel 1921

λ = h/mv

Around 1900 physicists found that light and energy come in **packets** (quanta), not as a smooth flow. This one idea explains why light can knock electrons out of metal, why atoms give sharp spectral lines and why electrons behave like waves.

★★★ **Max Planck** (1900): energy is emitted in packets, **E = hν** (h = Planck's constant ≈ 6.63×10^{-34} J s, ν = frequency). Father of quantum theory; Nobel 1918.

★★★ **Photoelectric effect**: light of high enough frequency falling on a metal knocks out electrons. Seen by Hertz (1887); explained by **Einstein (1905)** using light particles (photons).

★★★ **Einstein's Nobel Prize in Physics (1921)** was for the **photoelectric effect**, not for relativity or $E = mc^2$.

★★★ **Threshold frequency**: below it, no electron comes out however bright the light. Above it, emission is instant.

★★★ **Frequency decides energy, intensity decides number**: the energy of each ejected electron rises with frequency; brighter light only ejects **more** electrons.

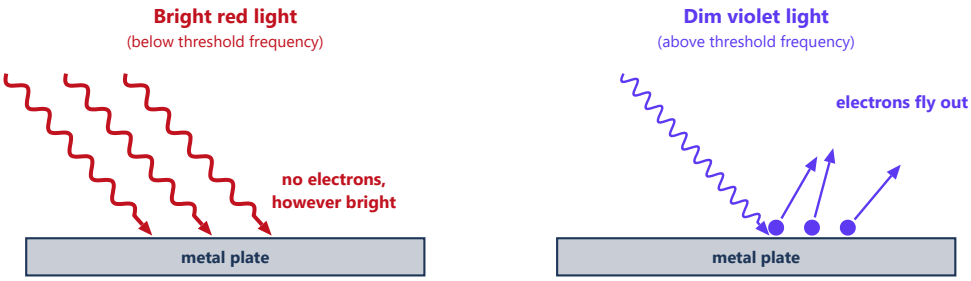
★★ **Uses**: photocells in automatic doors, burglar alarms, light meters and old film sound-tracks; it underlies image sensors. Solar cells use the related **photovoltaic** effect.

★★ **de Broglie** (1924): every moving particle is also a wave, **λ = h / (mv)** (Nobel 1929). This wave nature of electrons is used in the **electron microscope**.

★★ **Heisenberg's uncertainty principle** (1927): the position and momentum of a particle cannot both be known exactly at the same time (Nobel 1932).

★ **Compton effect** (1923): X-rays bounce off electrons like billiard balls, more proof that light acts as particles.

★★ **Raman effect** (C.V. Raman, 28 February 1928): light scattered by molecules changes colour slightly; Nobel 1930, first Asian Nobel in science. **National Science Day** is 28 February.



Frequency decides the energy of each electron; brightness decides only how many come out.

Photoelectric effect. Red light of any brightness ejects no electrons from this metal because its frequency is below the threshold; even dim violet light ejects them. The red wave is drawn with 1.75 times the violet wavelength (about 700 nm against 400 nm).

Light: wave or particle? ★★

Shows wave nature	Shows particle nature
Interference, diffraction, polarisation	Photoelectric effect, Compton effect
Young's double slit	Black-body radiation (Planck)

Remember it: Father and son settled it: **J.J. Thomson** got a Nobel (1906) for showing the electron is a **particle**; his son **G.P. Thomson** got one (1937) for showing it is a **wave**. Both were right: that is wave–particle duality.

⚠ **Exam trap:** Brighter light does **not** give faster electrons; it gives more of them. A dim violet light can eject electrons that a blinding red light cannot.

Quick check

1. Einstein's 1921 Nobel Prize was for _____ .
2. Brighter light on a metal gives more electrons or faster electrons?
3. Light below the threshold frequency ejects how many electrons?

Answer: 1. the photoelectric effect (not relativity) · 2. more electrons; their energy depends on the frequency · 3. none, however bright it is

X-rays

Röntgen 1895

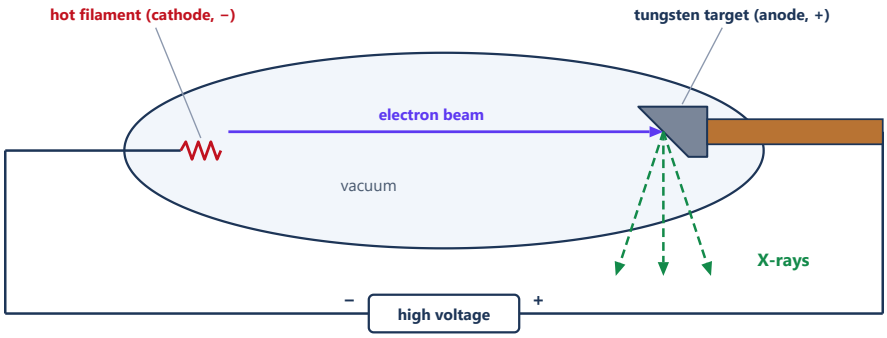
first physics Nobel 1901

tungsten target

from electrons, not nucleus

MRI: no X-rays

Fire fast electrons at a heavy metal and they stop suddenly; the lost energy comes out as very short-wavelength light that passes through flesh but not bone. That is an X-ray.



X-ray tube (Coolidge tube): electrons from the hot filament are pulled across the vacuum by a high voltage and stopped by the tungsten target; the energy they lose comes out as X-rays. Not to scale.

★★★ **Wilhelm Röntgen** discovered X-rays on **8 November 1895** (Germany); he received the **first Nobel Prize in Physics (1901)**. Element 111, roentgenium, is named after him.

★★★ **Production**: electrons from a hot filament are accelerated by high voltage onto a **tungsten** target (high atomic number and very high melting point) in a vacuum tube (Coolidge tube).

★★ **Nature**: electromagnetic waves, wavelength ≈ **0.01–10 nm** (between ultraviolet and gamma), travel at light speed, carry no charge and are not bent by electric or magnetic fields.

★★ **Hard X-rays** (higher energy) penetrate more and are used for imaging; **soft X-rays** are absorbed more easily.

★★ **X-ray crystallography** (the Braggs, Nobel 1915) reveals atomic arrangements; Rosalind Franklin's X-ray photos helped show DNA's double helix.

★ **X-ray astronomy**: India's **AstroSat** (2015) and **XPoSat** (launched 1 January 2024, India's first X-ray polarimetry satellite).

Uses of X-rays ★★

Field	Use
Medicine	Fractures, dental checks, chest (TB) X-ray, **CT scan** (rotating X-ray beam), mammography
Treatment	Radiotherapy to destroy cancer cells
Security	Airport baggage scanners
Industry	Finding cracks and flaws in welds and castings
Science and art	Crystal structures; hidden layers under paintings

⚠ **Exam trap: X-rays come from electrons** slowing down outside the nucleus; **gamma rays come from the nucleus**. Lead aprons protect because lead (dense, high atomic number) absorbs them. MRI uses magnets and radio waves, **not** X-rays.

Quick check

1. Who discovered X-rays, and which prize followed?
2. Why is the target in an X-ray tube made of tungsten?
3. X-rays or gamma rays: which come from the nucleus?

Answer: 1. Wilhelm Röntgen (1895); the first Nobel Prize in Physics (1901) · 2. high atomic number and very high melting point · 3. gamma rays; X-rays come from electrons slowing down

Cosmic rays, CERN and the universe

cosmic rays: protons

LHC: 27 km, Geneva

India: associate 2017

dark energy 68%

Big Bang 13.8 billion years

Earth is constantly hit by fast particles from space, and big machines like CERN's collider recreate such collisions on purpose. Both help answer what the universe is made of, where surprisingly most of it turns out to be dark.

★★★ **Cosmic rays** are **high-energy charged particles** from space: about 90% **protons**, about 9% alpha particles (helium nuclei), the rest heavier nuclei and electrons.

★★ **Victor Hess** discovered them in 1912 on balloon flights (Nobel 1936). Hitting the air, they make showers of secondary particles such as **muons**, and they create carbon-14.

★★ **Homi Bhabha** worked out the theory of cosmic-ray cascade showers (Bhabha–Heitler, 1937). The **GRAPES-3** experiment at Ooty (TIFR) studies cosmic rays today.

★ **Neutrinos**: atmospheric neutrinos were among the first detected deep in the **Kolar Gold Fields** mines (1965); the India-based Neutrino Observatory (INO) is planned at Bodi West Hills, Theni (Tamil Nadu).

★★★ **CERN** (European Organization for Nuclear Research, 1954) near **Geneva** on the France–Switzerland border runs the **Large Hadron Collider (LHC)**: a **27 km** ring about 100 m underground where protons collide at nearly light speed; its superconducting magnets are cooled to 1.9 K.

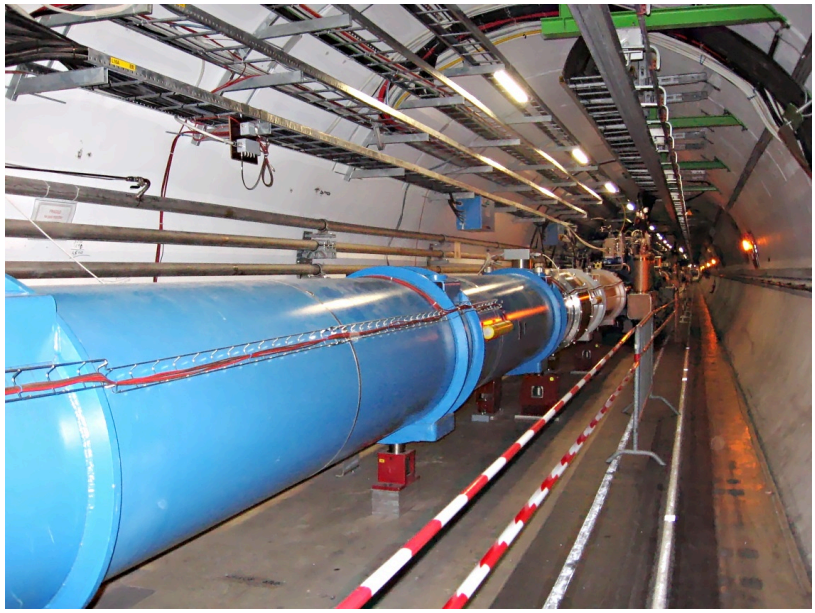
★★ **India** has been an **associate member of CERN since 2017**; Indian scientists work on the CMS and ALICE experiments.

★ **World Wide Web** was invented at CERN by Tim Berners-Lee (1989).

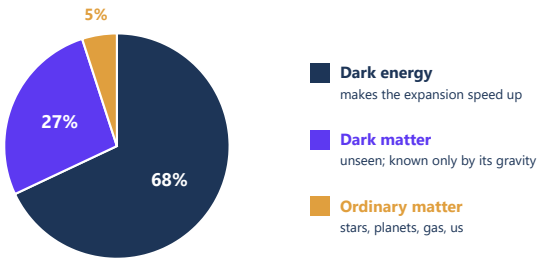
★★ **Dark matter** (~27% of the universe): unseen matter detected only by its gravity, e.g. stars at a galaxy's edge orbit too fast for the visible mass.

★★ **Dark energy** (~68%): unknown energy making the universe's expansion **speed up** (found 1998; Nobel 2011). Ordinary matter is only about **5%**.

★★ **Big Bang**: the universe began about **13.8 billion years** ago from an extremely hot, dense state; its leftover glow is the **cosmic microwave background** (≈ 2.7 K), found by Penzias and Wilson in 1964 (Nobel 1978).



Inside the LHC tunnel at CERN: the blue tube holds the superconducting magnets, cooled to 1.9 K, that steer protons round the 27 km ring. Image: Julian Herzog, Wikimedia Commons, CC BY-SA 3.0



What the universe is made of: dark energy about 68%, dark matter about 27%, and everything we can see only about 5%. Each slice is drawn to its share.

Remember it: 68–27–5: the universe is a thali where dark energy is the rice (68), dark matter the dal (27) and everything we can see, stars, planets and us, is just the pickle (5).

⚠ Exam trap: Cosmic rays are **particles, not electromagnetic rays**, and they are **charged** (mostly protons), despite the name 'rays'. The LHC smashes **protons** (and lead ions), not electrons.

Quick check

1. Cosmic rays are mostly _____ .
2. Where is CERN's Large Hadron Collider, and how long is its ring?
3. Shares of dark energy, dark matter and ordinary matter in the universe?

Answer: 1. protons (charged particles, not electromagnetic rays) · 2. near Geneva, on the France–Switzerland border; 27 km · 3. about 68%, 27% and 5%

Asked in past papers (9)

UPSC 2012 A team of scientists at Brookhaven National Laboratory including those from India created the heaviest anti-matter (anti-helium nucleus). What is/are the implication/implications of the creation of anti-matter?
1. It will make mineral prospecting and oil exploration easier and cheaper.
2. It will help probe the possibility of the existence of stars and galaxies made of anti-matter.
3. It will help understand the evolution of the universe.
Select the correct answer using the codes given below :
(a) 1 only (b) 2 and 3 only (c) 3 only (d) 1, 2 and 3
Answer: (b) 2 and 3 only. Antimatter particles have the same mass but opposite charge to their matter partners; Creating antimatter helps probe why the universe is made mostly of matter

UPSC 2013 The known forces of nature can be divided into four classes, viz., gravity, electromagnetism, weak nuclear force and strong nuclear force. With reference to them, which one of the following statements is not correct?
(a) Gravity is the strongest of the four (b) Electromagnetism acts only on particles with an electric charge
(c) Weak nuclear force causes radioactivity
(d) Strong nuclear force holds protons and neutrons inside the nucleus of an atom
Answer: (a) Gravity is the strongest of the four. Of the four fundamental forces, the strong nuclear force is strongest and gravity weakest; The weak nuclear force causes beta decay; the strong force binds the nucleus

UPSC 2013 The efforts to detect the existence of Higgs boson particle have become frequent news in the recent past. What is/are the importance/importances of discovering this particle?
1. It will enable us to understand as to why elementary particles have mass.
2. It will enable us in the near future to develop the technology of transferring matter from one point to another without traversing the physical space between them.
3. It will enable us to create better fuels for nuclear fission.
Select the correct answer using the codes given below.
(a) 1 only (b) 2 and 3 only (c) 1 and 3 only (d) 1, 2 and 3
Answer: (a) 1 only. The Higgs field gives elementary particles their mass; its boson was found in 2012

BPSC 56th-59th Cosmic rays
(a) are charged particles (b) are uncharged particles (c) can be charged as well as uncharged
(d) None of the above
Answer: (a) are charged particles. Primary cosmic rays are high-energy charged particles, mostly protons

BPSC 60th-62nd 'God particle' is
(a) Neutrino (b) Higgs Boson (c) Meson (d) Positron (e) None of the above/More than one of the above
Answer: (b) Higgs Boson. The Higgs boson is popularly called the 'God particle'; The Higgs field gives elementary particles their mass; its boson was found in 2012

BPSC 64th Einstein got the Nobel Prize for
(a) relativity (b) Bose-Einstein condensation (c) mass-energy equivalence (d) photoelectric effect
(e) None of the above/More than one of the above
Answer: (d) photoelectric effect. Einstein won the 1921 Physics Nobel for explaining the photoelectric effect

BPSC 67th Hydrogen bomb is based on the principle of
(a) controlled fusion reaction (b) uncontrolled fusion reaction (c) controlled fission reaction
(d) uncontrolled fission reaction (e) None of the above/More than one of the above
Answer: (b) uncontrolled fusion reaction. A hydrogen bomb releases energy by uncontrolled fusion of light nuclei; Controlled fission runs nuclear reactors; uncontrolled fission is the atom bomb

BPSC 68th Which among the following is a positively charged particle emitted by a radioactive element?
(a) Beta ray (b) Alpha ray (c) Cathode ray (d) More than one of the above (e) None of the above
Answer: (b) Alpha ray. Alpha particles are helium nuclei with +2 charge; beta particles are electrons

BPSC 70th re-exam An electron of mass M kg and charge e coulomb travels from rest through a potential difference of V volts. The final energy in joules would be
(a) e/V (b) MeV (c) eV/M (d) eV
Answer: (d) eV. A charge q accelerated through potential difference V gains kinetic energy qV; One electron-volt (eV) is the energy an electron gains across 1 volt: 1.6×10^{-19} J

Test yourself (13)

1. Which pair of particle and discoverer is correctly matched?
(a) Neutron – J.J. Thomson (b) Positron – Carl Anderson (c) Proton – James Chadwick
(d) Electron – Ernest Rutherford

2. Iodine-131 has a half-life of 8 days. What fraction of a sample remains after 24 days?
(a) 1/3 (b) 1/6 (c) 1/8 (d) 1/4

3. Carbon-14 (6 protons) and nitrogen-15 (7 protons) are
(a) isotones (b) isobars (c) isotopes (d) isoelectronic

4. In a nuclear reactor, the moderator
(a) absorbs extra neutrons to stop the reaction (b) slows down fast neutrons
(c) carries heat to the steam generator (d) shields workers from radiation

5. Which statement about the photoelectric effect is correct?
(a) Brighter light gives each ejected electron more kinetic energy
(b) Below the threshold frequency, no electrons are emitted
(c) Any colour of light ejects electrons from any metal if it is bright enough
(d) It is evidence for the wave nature of light

6. Radiocarbon dating cannot be used to find the age of
(a) a wooden boat (b) an animal bone (c) a granite rock (d) charcoal from an old hearth

7. The second stage of India's three-stage nuclear programme is based on
(a) PHWRs fuelled by natural uranium (b) thorium-fuelled advanced heavy water reactors
(c) fusion tokamaks (d) fast breeder reactors fuelled by plutonium

8. Consider: 1. Gamma rays are deflected by a magnetic field. 2. Alpha particles have the highest ionising power.
3. Beta particles originate in the nucleus. Which are correct?
(a) 1 and 2 only (b) 2 and 3 only (c) 1 and 3 only (d) 1, 2 and 3

9. Which unit measures the biological harm caused by a dose of radiation?
(a) Becquerel (b) Gray (c) Curie (d) Sievert

10. The hydrogen bomb releases energy mainly through
(a) uncontrolled fusion of light nuclei (b) controlled fusion of light nuclei (c) uncontrolled fission of uranium
(d) chemical combustion of hydrogen

11. Consider the following statements:
1. Isotopes of an element have the same chemical properties but different physical properties.
2. Isobars have the same number of protons but different mass numbers.
3. Ne and Na^+ are isoelectronic.
Which of the statements given above is/are correct?
(a) 1 only (b) 2 and 3 only (c) 1, 2 and 3 (d) 1 and 3 only

12. Consider the following statements:
1. Onions irradiated with gamma rays from cobalt-60 become radioactive.
2. The becquerel is the unit that measures the biological harm caused by radiation.
3. Heating a radioactive sample does not change its half-life.
How many of the above statements are correct?
(a) Only one (b) Only two (c) All three (d) None

13. At an excavation, archaeologists find a charcoal hearth, a stone hand-axe and a pottery shard lying together. Which of these can be dated directly by carbon-14 dating?
(a) The stone hand-axe only (b) The pottery shard only (c) The charcoal only (d) All three of them

Answers: 1. (b) Anderson found the positron in cosmic rays in 1932; Chadwick found the neutron and Thomson the electron. · 2. (c) 24 days = 3 half-lives, so $(½)^3 = 1/8$ remains. · 3. (a) Both have 8 neutrons (14 − 6 = 15 − 7 = 8): same neutrons = isotones. · 4. (b) Moderators such as heavy water or graphite slow neutrons; control rods absorb them; the coolant carries heat. · 5. (b) Emission needs frequency above the threshold; intensity only changes how many electrons come out; the effect shows light's particle nature. · 6. (c) Carbon-14 dating needs once-living material; rocks are dated with uranium–lead or potassium–argon. · 7. (d) Stage 1 PHWR (natural U) → stage 2 fast breeders (Pu; PFBR critical April 2026) → stage 3 thorium. · 8. (b) Gamma rays carry no charge and are not deflected; alpha ionises most; beta electrons come from neutrons decaying in the nucleus. · 9. (d) Sievert (and the older rem) weights dose by biological effect; becquerel and curie measure activity, gray measures absorbed energy. · 10. (a) A thermonuclear (hydrogen) bomb uses uncontrolled fusion, set off by a fission trigger. · 11. (d) Isotopes share electrons, so their chemistry matches while their mass differs, and Ne and Na^+ both have 10 electrons; statement 2 describes isotopes, since isobars share the mass number and differ in protons. · 12. (a) Only statement 3 is correct; irradiated food does not become radioactive, and the becquerel measures activity (decays per second), while the sievert measures biological harm. · 13. (c) Carbon-14 dating works only on once-living material such as charcoal (up to about 50,000 years); pottery is dated by thermoluminescence, and stone never took in carbon from the air.

CHAPTER 14

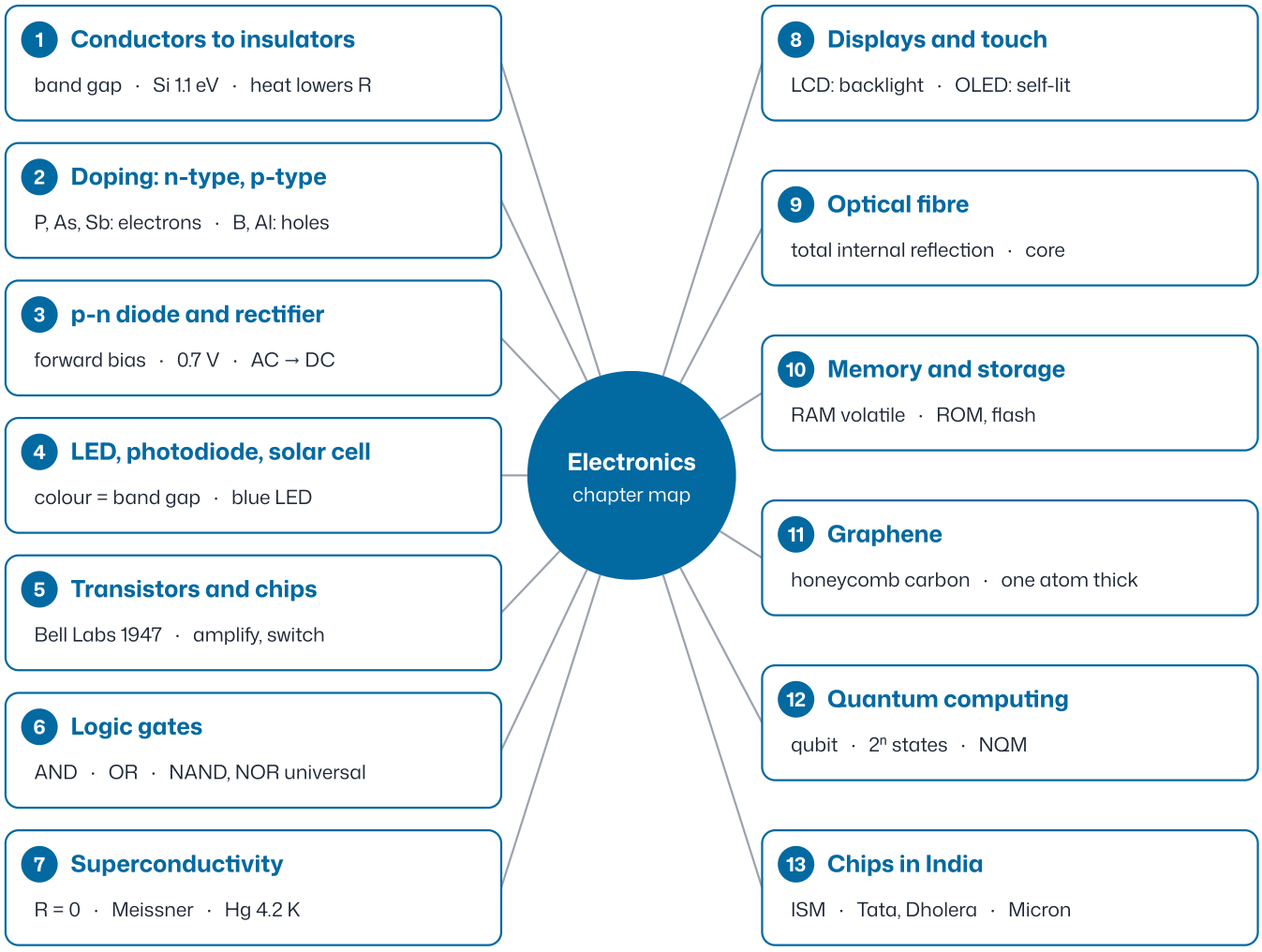
Semiconductors, Electronics and Modern Devices

How a semiconductor's resistance changes with heat, n-type vs p-type doping, what diodes, LEDs, photodiodes and solar cells do, and LED vs CFL, sodium lamp or OLED vs LCD comparisons are the regular questions.

Asked 6 times in past papers: UPSC 3 · BPSC 3

≈ 48 min to read ≈ 6 min to revise ★★★

Revise on: Day 1 | Day 3 | Day 7 | Day 21



Revision card

1. **Heating a semiconductor lowers its resistance** (more free electrons); heating a metal raises it.
2. **Band gap**: conductors none (bands overlap); silicon ≈ 1.1 eV, germanium ≈ 0.7 eV; insulators above 3 eV (diamond ≈ 5.5 eV).
3. **n-type**: pentavalent dopant (P, As, Sb) → electrons are majority. **p-type**: trivalent dopant (B, Al, Ga, In) → holes are majority. Both stay electrically neutral.
4. **p-n diode** conducts only in **forward bias** (p to +). A **rectifier** turns AC into DC; an **inverter** turns DC into AC.
5. **LED**: forward-biased junction gives light; colour set by band gap. **Blue LED** (Nobel 2014) made white LED lamps possible.
6. **CFL** = mercury vapour + phosphor; **LED** = semiconductor; LED lasts longer and uses less power.
7. **Sodium street lamp**: almost single-colour yellow light spread in all directions (360°); LED street light is directional, longer-lived and shows true colours.
8. **Photodiode** (reverse biased, fast) suits digital and optical-fibre signals; **photoelectric / solar (photovoltaic) cell** turns light energy into electrical energy.
9. **Transistor** (Bardeen, Brattain, Shockley, 1947) amplifies and switches; **integrated circuit**: Jack Kilby (1958) and Robert Noyce.
10. **NAND and NOR** are the universal gates.
11. **Superconductor**: zero resistance below a critical temperature plus **Meissner effect** (expels magnetic field) → MRI, maglev, LHC magnets.
12. **OLED** pixels make their own light (no backlight): flexible, rollable and transparent screens; **LCD** needs a backlight.
13. **Optical fibre** guides light by **total internal reflection**; huge bandwidth, no electrical interference.
14. **India Semiconductor Mission**: Micron's Sanand (Gujarat) chip packaging plant began production in Feb 2026; India's first commercial fab (Tata, Dholera) is being built.

Conductors, insulators and semiconductors

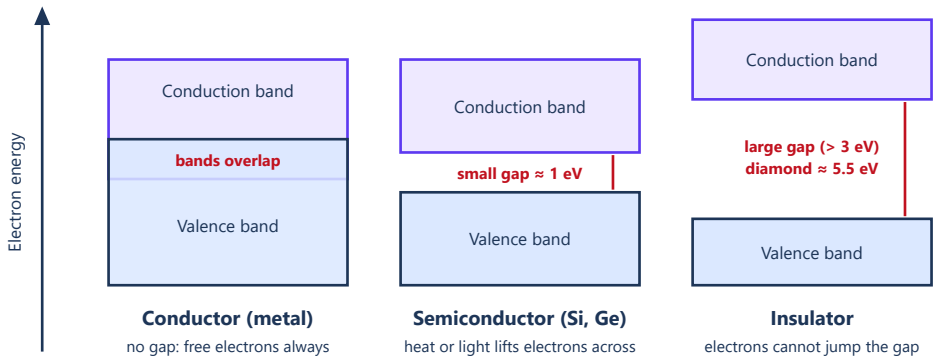
band gap

Si 1.1 eV, Ge 0.7 eV

heat lowers resistance

thermistor

Electrons in a solid can only have energies inside certain **bands**. Electrons in the lower **valence band** are tied to atoms; only those lifted to the upper **conduction band** can carry current. The width of the empty **band gap** between them decides whether a material conducts.



Si gap ≈ 1.1 eV, Ge ≈ 0.7 eV. Bigger gap → fewer free electrons → poorer conductor.

Band picture (not to scale): in a metal the bands overlap; in a semiconductor the gap is small enough for heat or light to lift electrons across; in an insulator it is too wide.

Three kinds of solids ★★★

Property	Conductor	Semiconductor	Insulator
Band gap	None (bands overlap)	Small (≈ 1 eV)	Large (above 3 eV)
Free electrons at room temperature	Very many	A few	Almost none
Examples	Silver, copper, aluminium, graphite	Silicon, germanium, gallium arsenide	Glass, rubber, wood, diamond, mica
When heated	**Resistance rises**	**Resistance falls**	Stays very high
At absolute zero (0 K)	Still conducts	Behaves as a perfect insulator	Insulator

★★★ **Semiconductor + heat**: extra heat frees more electrons from bonds, so its **resistance decreases** (negative temperature coefficient). In metals, heat makes atoms vibrate more and block electrons, so resistance **increases**.

★★ **Thermistor**: a semiconductor whose resistance falls sharply with temperature; used in digital thermometers and fire alarms.

★★★ **Silicon (Si)** and **germanium (Ge)** are group-14 elements with **4 valence electrons**. Band gap: Si ≈ **1.1 eV**, Ge ≈ **0.7 eV**.

★★ **Why silicon rules**: it is the second most abundant element in Earth's crust (sand is SiO_2), works at higher temperatures than germanium (wider gap) and grows a protective oxide layer that is ideal for chips.

★ **Compound semiconductors**: gallium arsenide (LEDs, space solar cells), gallium nitride (blue LEDs, fast phone chargers), silicon carbide (electric-vehicle power electronics), cadmium telluride (thin-film solar).

Remember it: Heat makes a **metal lazy** (crowded, jostling atoms → more resistance) but wakes a **semiconductor up** (freed electrons → less resistance). Think: a hot day jams the metro (metal), but in a village (semiconductor) it brings more people out onto the road.

⚠ **Exam trap:** On heating, a semiconductor's resistance **decreases**, not increases. Its conductivity lies between metals and insulators, but its behaviour with temperature is the **opposite** of a metal's.

Quick check

1. Heat a semiconductor: does its resistance rise or fall?
2. Band gap of silicon and of germanium?
3. How many valence electrons do silicon and germanium have?

Answer: 1. falls (more free electrons); a metal's rises · 2. Si ≈ 1.1 eV; Ge ≈ 0.7 eV · 3. 4 (group 14)

Intrinsic and extrinsic semiconductors: doping

doping

hole

n-type: P, As, Sb

p-type: B, Al, Ga, In

crystal stays neutral

Pure silicon conducts poorly. Replace about one atom in a million with an atom that has **one electron more or one less**, and conductivity jumps a thousandfold or more. This deliberate impurity is **doping**.

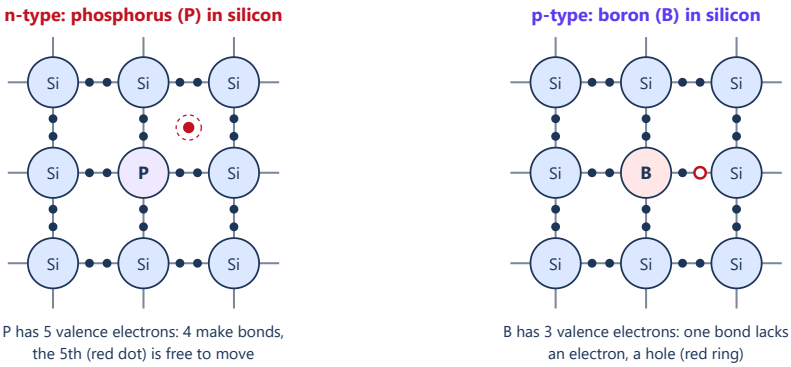
★★ **Intrinsic** semiconductor = pure Si or Ge. Heat breaks some bonds, making **free electrons and holes in equal numbers**.

★★★ **Hole**: the empty place left when an electron leaves a bond. Neighbouring electrons jump into it, so the hole moves like a **positive charge**.

★★ **Extrinsic** semiconductor = doped semiconductor; doping makes one kind of carrier outnumber the other (majority vs minority carriers).

n-type vs p-type ★★★

	n-type	p-type
Dopant	**Pentavalent** (5 valence electrons): phosphorus, arsenic, antimony	**Trivalent** (3 valence electrons): boron, aluminium, gallium, indium
Dopant called	Donor (gives an electron)	Acceptor (accepts an electron, leaves a hole)
Majority carriers	**Electrons**	**Holes**
Minority carriers	Holes	Electrons
Overall charge	Neutral	Neutral



Doping silicon, as a flat picture of a 3D crystal. Each line is a bond holding two shared electrons (dots). Phosphorus brings a fifth electron with no bond to join, so it is free to carry current (n-type); boron brings only three, leaving one bond short of an electron, a hole (p-type).

💡 **Remember it: 'PAS' passes an electron**: **P**, **A**s, **S**b (5 valence) give a spare electron → **n**-type (**n**egative carriers). **'BAGI' baggy pants have holes**: **B**, **A**l, **G**a, **I**n (3 valence) leave holes → **p**-type (**p**ositive holes).

⚠ **Exam trap:** An n-type crystal is **not negatively charged** and a p-type crystal is **not positively charged**: each dopant atom brings equal protons and electrons. 'n' and 'p' only name the majority carrier.

Quick check

1. Silicon doped with a pentavalent element: which type, and which majority carrier?
2. Name a trivalent dopant and the type it makes.
3. Is an n-type crystal negatively charged?

Answer: 1. n-type; electrons · 2. boron (or aluminium, gallium, indium): p-type · 3. no: it stays electrically neutral

The p-n junction diode and rectifiers

depletion layer

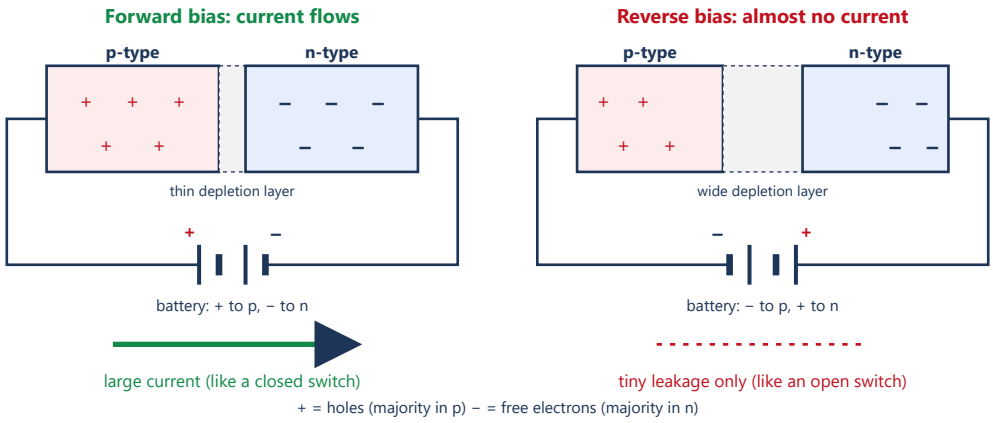
forward bias: p to +

0.7 V for silicon

rectifier: AC → DC

Zener: regulator

Join p-type and n-type silicon and electrons and holes near the boundary cancel each other, leaving a thin **depletion layer** with a small voltage barrier. Push the right way and the barrier shrinks so current flows; push the wrong way and it widens so current stops. A diode is a **one-way valve** for current.



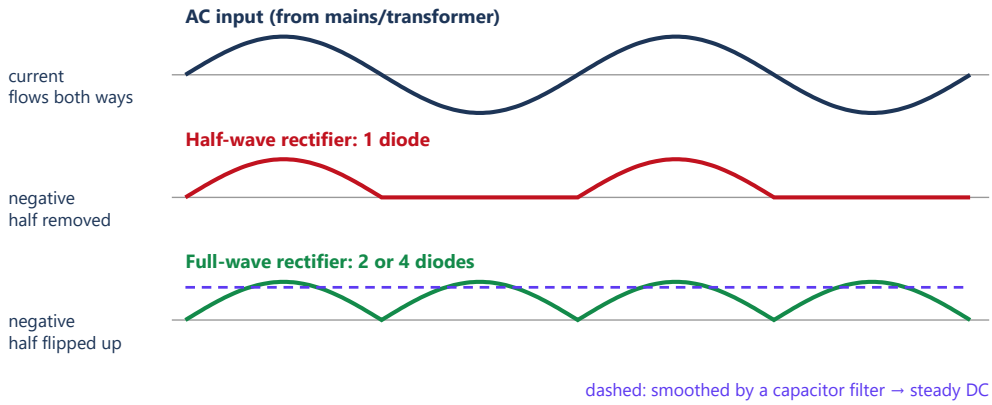
Forward bias (p to +) thins the depletion layer and current flows; reverse bias (p to −) widens it and only a tiny leakage current flows.

★★★ **Forward bias**: p-side to **+**, n-side to **−**: barrier lowered, **large current** (acts like a closed switch). Silicon needs about **0.7 V** to start conducting (germanium about 0.3 V).

★★★ **Reverse bias**: p-side to −, n-side to +: depletion layer widens, **almost no current**. At a large enough reverse voltage it **breaks down**.

★★ **Zener diode**: heavily doped diode built to work in reverse breakdown; it holds a steady voltage, so it is used as a **voltage regulator**.

See it around you: A diode works like the non-return valve in a water-tank pipe, or the one-way turnstile at a metro exit: easy one way, blocked the other.



Rectification: a half-wave rectifier throws away the negative half; a full-wave rectifier flips it up. A capacitor then smooths the bumps into steady DC.

★★★ **Rectifier** converts **AC into DC** using diodes. **Half-wave**: one diode, uses only half of each cycle. **Full-wave**: two diodes with a centre-tapped transformer, or **four diodes in a bridge**; uses both halves.

★★ **Filter**: a capacitor after the rectifier smooths the pulsing output into nearly steady DC. A phone charger is a transformer (or switching circuit) + rectifier + filter + regulator.

Which device does what ★★

Device	Job
Rectifier	AC → DC
Inverter	DC → AC (home inverter runs fans from a battery)
Transformer	Raises or lowers **AC** voltage; does not work on steady DC
Zener / regulator	Keeps output voltage steady
Capacitor filter	Smooths ripples

⚠ **Exam trap: Rectifier = AC to DC; inverter = DC to AC.** Options often swap them. A diode conducts in **forward** bias, not reverse.

☑ Quick check

1. In forward bias, the p-side is joined to which terminal?
2. Rectifier or inverter: which turns AC into DC?
3. Which diode is used as a voltage regulator?

Answer: 1. the positive (+) terminal · 2. the rectifier (an inverter turns DC into AC) · 3. the Zener diode

Semiconductors and light: LEDs, photodiodes and solar cells

LED: forward biased

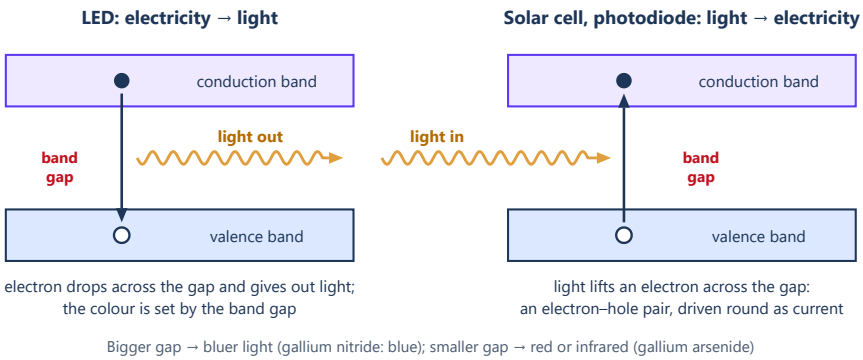
photodiode: reverse biased

solar cell: light → power

In a semiconductor, light and electricity can be traded. Push current through a junction and electrons falling across the band gap **give out light** (LED). Shine light on a junction and the photons **create electron–hole pairs**, giving a current (photodiode, solar cell).

colour = band gap

blue LED, Nobel 2014



Light and the band gap. In an LED an electron drops from the conduction band into a hole and gives out light; in a solar cell or photodiode, light lifts an electron across the gap, making an electron–hole pair that flows as current.

Light-related semiconductor devices ★★★

Device	How it is used	Energy change	Best for
LED	Forward biased	Electrical → light	Lamps, displays, indicators, TV remotes (infrared LED)
Photodiode	**Reverse biased**	Light → electrical **signal**; very fast and proportional to light	**Digital/optical signals**: optical-fibre receivers, remote-control receivers, barcode readers, light meters
Solar (photovoltaic) cell	No external battery; large-area junction	**Light → electrical power**	Solar panels, calculators, satellites
LDR (light-dependent resistor, photoconductive)	Resistance falls in light	Light controls current	Automatic street lights, camera exposure
Photoemissive cell (photoemitter)	Vacuum tube; light knocks electrons from a metal (photoelectric effect)	Light → current	Older automatic doors, burglar alarms, film sound-tracks

★★★ **Photoelectric cell** (any of these light-sensing cells) **converts light energy into electrical energy**.

★★★ **LED colour depends on the band gap** of its material: gallium arsenide → infrared (TV remote), gallium arsenide phosphide → red, orange, yellow; gallium nitride / indium gallium nitride → **blue** and green.

★★★ **Blue LED**: Isamu Akasaki, Hiroshi Amano and Shuji Nakamura, **Physics Nobel 2014**. A blue LED coated with a yellow phosphor gives **white light**, so it made LED bulbs possible.

★ **First visible (red) LED**: Nick Holonyak, 1962.

★★ **Solar cell** is usually **silicon**; sunlight frees electrons that the junction's built-in field pushes round the circuit (photovoltaic effect). Common panels convert about **20%** of sunlight; a single silicon junction cannot exceed about one third (≈ 33%).

★ **CCD and CMOS image sensors** in cameras are arrays of tiny light-sensing elements; the CCD won the 2009 Physics Nobel (Boyle and Smith).

Lamps compared ★★★

Lamp	How light is made	Light per watt	Life (approx.)	Notes
Incandescent bulb	Tungsten filament glows white-hot	≈ 10–15 lm/W	≈ 1,000 h	About 90% of power wasted as heat
CFL	**Mercury vapour** gives UV; **phosphor** coating turns it into visible light	≈ 50–70 lm/W	≈ 8,000–10,000 h	Contains mercury: hazardous waste
LED	**Semiconductor** junction	≈ 80–150 lm/W	≈ 25,000–50,000 h	**Most efficient**, no mercury, **directional** light, good colour
Sodium vapour (street)	Electric discharge in sodium vapour	High	Shorter than LED	Almost **monochromatic yellow** (≈ 589 nm), poor colour rendering; shines in **all directions (360°)**

★★ **UJALA** (2015) spread cheap LED bulbs to households and the **Street Lighting National Programme** replaced street lamps with LEDs; both are run by EESL.

Remember it: LED = 'Light Emitted when Driven forward'; photodiode = 'Photo-Detector' that likes standing **backwards** (reverse bias) to catch light fast. Solar cell is the **farmer**: it harvests power, not signals.

⚠ **Exam trap:** A **CFL does not outlive an LED**; the LED lasts several times longer and uses less power. **Sodium lamps** spread light all round and look yellow; LED street lights point light downward and show colours truly. For **digital** applications the photodiode, not the photovoltaic cell, is the right choice.

Quick check

1. What decides the colour of an LED's light?
2. For a fast digital or optical-fibre signal: photodiode or solar cell?
3. Why did the blue LED win the 2014 Physics Nobel?

Answer: 1. the band gap of its semiconductor · 2. photodiode (reverse biased, fast) · 3. with a yellow phosphor it gives white light, which made LED lamps possible

Transistors, chips and Moore's law

Bell Labs 1947

Bardeen, Brattain, Shockley

emitter, base, collector

Before 1947, radios and computers used hot, bulky **vacuum tubes**. The transistor did the same job (amplify and switch) in a tiny piece of solid material, and putting millions of them on one chip created modern electronics.

★ **Vacuum tubes**: John Fleming's diode valve (1904) and Lee de Forest's triode (1906). ENIAC (1945–46), an early computer, used about 18,000 tubes.

amplifier and switch

IC: Kilby, Noyce

★★★ **Transistor**: invented in **1947** at **Bell Labs** (USA) by **John Bardeen, Walter Brattain and William Shockley**; Physics Nobel **1956**. The first one was made of germanium.

★★ **Bardeen** is the only person with two Physics Nobels (1956 transistor; 1972 theory of superconductivity).

★★★ **Structure**: three layers, **npn** or **pnp**, with three terminals: **emitter, base, collector**. A small base current controls a large collector current.

★★★ **Two jobs**: **amplifier** (makes weak signals strong: radios, microphones, hearing aids) and **switch** (on/off = 1/0 in digital circuits).

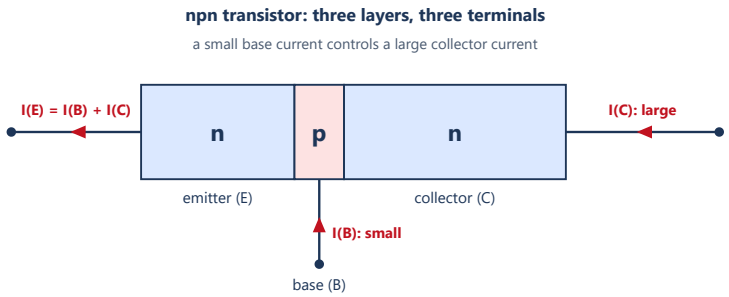
★ **MOSFET** (field-effect transistor) is the type used in almost all chips; it is the most manufactured device in history.

★★★ **Integrated circuit (IC/chip)**: many transistors, resistors and capacitors on one small piece of silicon. **Jack Kilby** (Texas Instruments, 1958; Nobel 2000) and **Robert Noyce** (Fairchild, 1959, silicon IC; later co-founded Intel) invented it independently.

★★ **Moore's law** (Gordon Moore, 1965): the number of transistors on a chip **doubles about every two years**.

★★ **Chip making**: patterns are printed on thin silicon **wafers** by **photolithography** (light through a mask); 'nm node' sizes describe how small the features are.

★ **First microprocessor**: Intel 4004 (1971). India's own processor designs include **SHAKTI** (IIT Madras, RISC-V based) and **VEGA** (C-DAC).



An npn transistor: a thin p-type base between two n-type layers. A small current into the base lets a large current flow from collector to emitter, which is why the transistor can amplify and switch. Arrows show conventional current.

Remember it: Transistor = TRANSfer + resISTOR: it transfers a weak signal into a strong one. Inventors' initials **B-B-S** (Bardeen, Brattain, Shockley) at **B**ell labs: three B's and an S in **1947**.

⚠ **Exam trap:** The transistor (1947) is not the integrated circuit (1958). Shockley co-invented the transistor, not the IC; Kilby and Noyce made the IC.

Quick check

1. Who invented the transistor, where and when?
2. The two jobs of a transistor?
3. Who invented the integrated circuit?

Answer: 1. Bardeen, Brattain and Shockley, at Bell Labs, 1947 · 2. amplifier and switch · 3. Jack Kilby (1958) and Robert Noyce, independently

Logic gates

AND: all inputs 1

OR: any input 1

NAND, NOR: universal

XOR: inputs differ

Digital circuits work with only two values, **1 (on/high)** and **0 (off/low)**, following George Boole's algebra. A logic gate is a small transistor circuit that gives an output according to a fixed rule.

Truth table (inputs A and B) ★★★

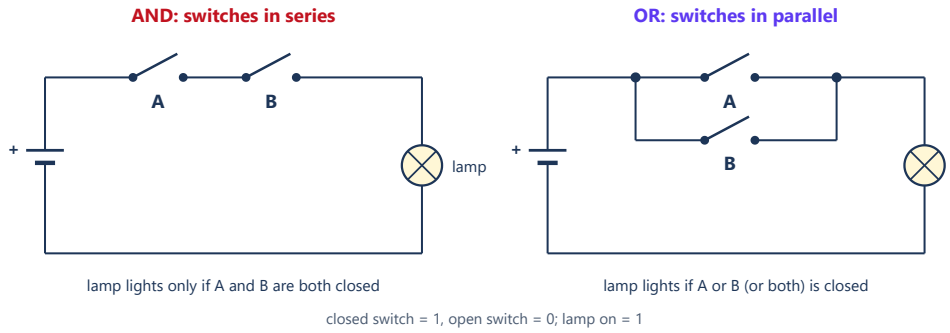
A	B	AND	OR	NAND	NOR	XOR	NOT A
0	0	0	0	1	1	0	1
0	1	0	1	1	0	1	1
1	0	0	1	1	0	1	0
1	1	1	1	0	0	0	0

★★ **AND**: output 1 only if **all** inputs are 1 (two switches in series). **OR**: output 1 if **any** input is 1 (switches in parallel). **NOT**: one input, flips it.

★★ **NAND = NOT + AND**, **NOR = NOT + OR**: they give the opposite of AND and OR.

★★★ **Universal gates**: **NAND** and **NOR**. Any other gate, and so any digital circuit, can be built from NAND gates alone or NOR gates alone.

★ **XOR** (exclusive OR): 1 when the inputs **differ**; used in adding binary numbers.



Gates as switches. AND is two switches in series: the lamp lights only if both are closed. OR is two switches in parallel: either one is enough. Closed = 1, open = 0.

Remember it: AND is a strict parent: both 'yes' needed. **OR is a lenient parent**: any one 'yes' will do. Put an **N** in front and the child rebels: every answer flips.

See it around you: A lift door closes only if the door sensor AND the overload sensor are both clear (AND). A car's interior light comes on if ANY door is open (OR).

Quick check

1. Which two gates are universal?
2. Output of an AND gate for inputs 1 and 0?
3. Output of an OR gate for inputs 1 and 0?

Answer: 1. NAND and NOR · 2. 0 · 3. 1

Superconductivity

zero resistance

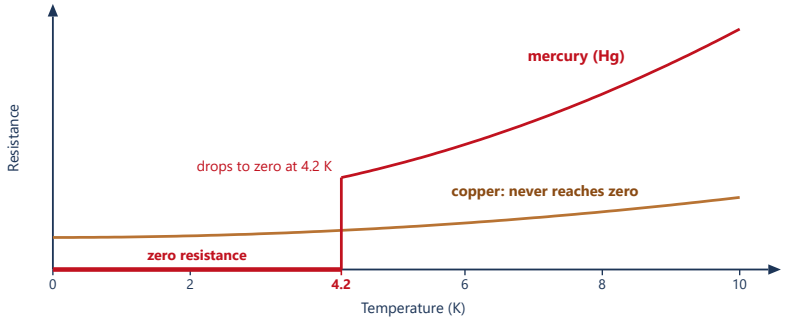
Meissner effect

mercury 4.2 K

YBCO 92 K

MRI, maglev, LHC

Cool some materials below a certain **critical temperature** and their electrical resistance vanishes completely; a current set flowing in a superconducting ring keeps going for years. They also push magnetic fields out, so a magnet can float above them.



Resistance against temperature (shape only, resistance not to scale). Mercury's resistance falls as it cools, then drops suddenly to exactly zero at 4.2 K; copper's never reaches zero, however cold it gets.

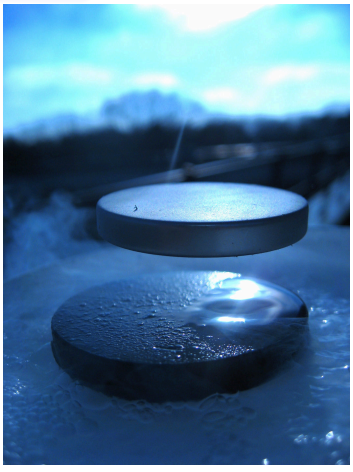
★★★ **Discovery**: Heike Kamerlingh Onnes, **1911**: mercury lost all resistance at **4.2 K** (−269 °C), cooled by liquid helium (Nobel 1913).

★★★ **Two signatures**: (1) **zero electrical resistance** below the critical temperature; (2) **Meissner effect** (1933): the material **expels magnetic field** lines (perfect diamagnetism), which makes **magnetic levitation** possible.

★★ **BCS theory** (Bardeen, Cooper, Schrieffer, 1957; Nobel 1972): electrons pair up (Cooper pairs) and flow without scattering.

★★ **High-temperature superconductors**: copper-oxide ceramics (Bednorz and Müller, 1986; Nobel 1987). **YBCO** works at about **92 K**, above the boiling point of cheap **liquid nitrogen (77 K)**.

★ **No material superconducts at room temperature and normal pressure** yet. Good ordinary conductors such as copper, silver and gold do not become superconductors even near absolute zero.



The Meissner effect: a magnet floats above a YBCO superconductor cooled by liquid nitrogen (77 K), because the superconductor pushes the magnetic field out. Image: Julien Bobroff and Frédéric Bouquet (LPS, Orsay), Wikimedia Commons, CC BY-SA 3.0

Uses of superconductors ★★

Use	Why superconductor
MRI scanners	Very strong, steady magnetic fields from niobium–titanium coils with no power loss
Maglev trains	Strong magnets lift and push the train with no wheel friction (e.g. Japan's SCMaglev)
Particle accelerators and fusion	**LHC** at CERN and **ITER** tokamak magnets
SQUIDs	Detect extremely weak magnetic fields (e.g. from the brain)
Power cables, fault-current limiters	Carry current with almost no loss
Quantum computers	Superconducting circuits make qubits

⚠ **Exam trap:** A superconductor is not just a 'very good conductor': it has **exactly zero** resistance **and** expels magnetic fields. It works only **below** its critical temperature, which for all known materials is far below room temperature at normal pressure.

☑ Quick check

1. Who discovered superconductivity, in which metal, and at what temperature?
2. The two signatures of a superconductor?
3. Why is YBCO easier to use than mercury?

Answer: 1. Kamerlingh Onnes, 1911: mercury at 4.2 K · 2. zero resistance, and the Meissner effect (magnetic field pushed out) · 3. it superconducts at about 92 K, above the 77 K of cheap liquid nitrogen

Displays and touchscreens

LCD needs a backlight

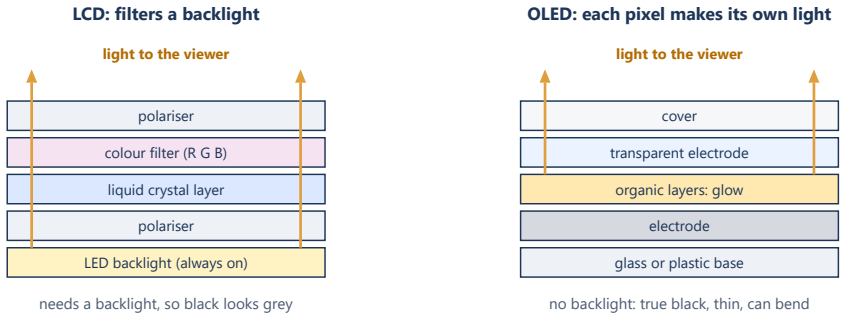
'LED TV' = LCD

OLED: self-lit pixels

flexible, rollable

capacitive: finger charge

A screen either **makes its own light** at each pixel (OLED, plasma, old CRT) or **filters a backlight** (LCD). Self-lit pixels can switch off fully, which gives true black and allows thin, bendable screens.



LCD and OLED in cross-section (layer thicknesses not to scale). An LCD's backlight is always on and the liquid crystal only blocks or passes its light; an OLED's organic layers glow by themselves, so it needs no backlight.

Display technologies ★★★

Type	How it works	Backlight?	Plus points	Minus points
CRT (old TV)	Electron beam hits phosphor dots	No	Good colours	Bulky, heavy
LCD	**Liquid crystals** twist polarised light to block or pass a backlight	**Yes**	Cheap, long-lived	Greys instead of true black; rigid; narrower viewing angle
'LED TV'	An **LCD lit by an LED backlight**	Yes (LEDs)	Thinner, brighter, efficient	Still an LCD
QLED	LCD with a **quantum-dot** layer for purer colours	Yes	Bright, vivid	Still needs backlight
OLED	**Organic** compounds glow at each pixel when current flows	**No** (self-emissive)	True black, very thin, wide angle, **flexible, rollable, transparent** screens	Costlier; risk of burn-in

★★★ **OLED advantages over LCD**: can be made on **flexible plastic**, so **roll-up displays** (even in clothing) and **transparent displays** are possible; used in phones (AMOLED), smartwatches and foldables.

★ **Quantum dots** (tiny semiconductor crystals whose colour depends on size) won the 2023 Chemistry Nobel.

★ **E-ink** (e-readers) reflects room light like paper and uses power only when the page changes.

Touchscreens ★★

	Resistive	Capacitive
Senses	**Pressure**: two flexible conducting layers touch	**Electric charge** of the finger changes the field of a transparent conductive coating (indium tin oxide)
Works with	Finger, stylus, gloved hand, fingernail	Bare finger or special stylus; not ordinary gloves
Multi-touch	Usually no	Yes (pinch-zoom)
Seen in	Older ATMs, POS machines, factory panels	Smartphones, tablets

⚠ **Exam trap:** Most 'LED TVs' are **LCDs** with LED backlights; only **OLED** (and micro-LED) pixels give their own light. A capacitive phone screen ignores a gloved finger because cloth does not conduct.

Quick check

1. Which needs a backlight: LCD or OLED?
2. Why can OLED screens be rolled up or made transparent?
3. Why does a capacitive screen ignore a gloved finger?

Answer: 1. LCD · 2. each pixel makes its own light, and it can be built on flexible plastic · 3. it senses the finger's electric charge, and cloth does not conduct

Optical fibre communication

total internal reflection

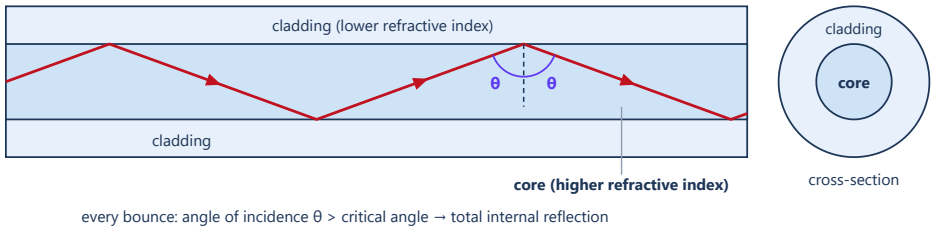
core n > cladding n

infrared light

N.S. Kapany

Charles Kao

An optical fibre is a hair-thin strand of very pure glass. Light entering it keeps hitting the wall at a large angle and is **totally internally reflected** again and again, so it travels kilometres with little loss, even round bends.



Light in an optical fibre meets the core–cladding boundary at more than the critical angle every time, so it is totally reflected again and again. Not to scale: the core is drawn far wider and the bounces far steeper than in a real fibre.

★★★ **Principle**: **total internal reflection**. The inner **core** has a **higher refractive index** than the surrounding **cladding**; light striking the boundary above the critical angle is fully reflected.

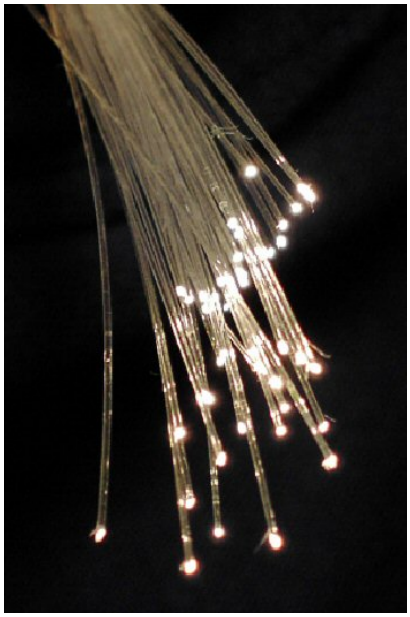
★★ **Material and light**: silica glass (or plastic for short links); long-distance links use **infrared** light (around 1310 and 1550 nm) from lasers or LEDs.

★★★ **Advantages**: enormous **bandwidth**, very low loss over long distances, **immune to electromagnetic interference** and lightning, hard to tap (secure), thin and light, no cross-talk, no spark risk.

★★ **Uses**: internet backbone and **undersea cables**, 4G/5G towers, **BharatNet** (broadband to gram panchayats), medical **endoscopes**, decorative lamps.

★★ **Narinder Singh Kapany** (born in Moga, Punjab) coined the term 'fibre optics' (1960) and is called the father of fibre optics; **Charles Kao** showed low-loss glass fibres could carry signals (Nobel 2009).

See it around you: Shine a torch into a stream of water pouring from a bottle: the light follows the curved stream. That is total internal reflection, the same trick as in a fibre.



A bundle of glass fibres lit from the far end: light comes out only at the cut tips, because total internal reflection keeps it inside each strand. Image: BigRiz, Wikimedia Commons, CC BY-SA 3.0

⚠ **Exam trap:** The signal in a fibre is **light**, not electric current, and the principle is **total internal reflection**, not plain refraction or diffraction.

☑ Quick check

1. Optical fibres work on which principle?
2. Which has the higher refractive index: the core or the cladding?
3. Who is called the father of fibre optics?

Answer: 1. total internal reflection · 2. the core · 3. Narinder Singh Kapany

Memory and storage

volatile: RAM

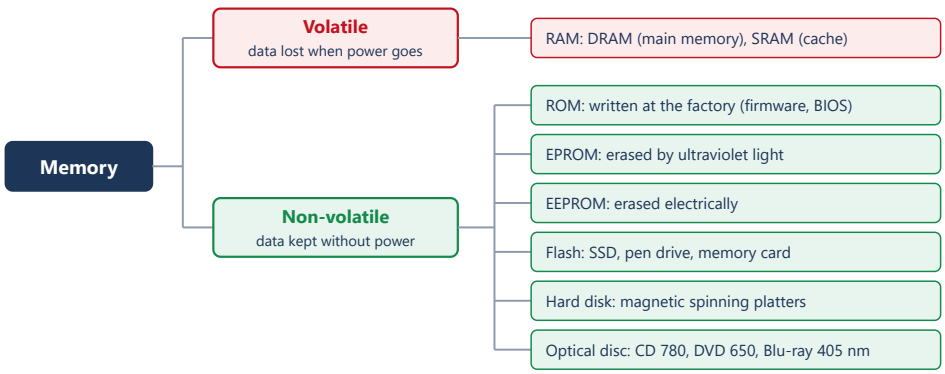
non-volatile: ROM, flash

EPROM: UV erase

SSD = flash

Blu-ray 405 nm

Computers need fast scratch space that can be wiped (**RAM**) and permanent storage that survives power cuts (**ROM**, flash, disks). The key word is **volatile**: data lost when power goes.



Memory sorted by the one question examiners ask: is the data lost when the power goes (volatile) or kept (non-volatile)?

Memory types ★★

Type	Volatile?	Notes	Example use
RAM (random access memory)	**Yes**	Fast working memory; DRAM (cheap, main memory) and SRAM (faster, cache)	Programs currently open
ROM (read-only memory)	No	Written at the factory	Firmware, BIOS
EPROM	No	Erased by **ultraviolet** light and rewritten	Older firmware chips
EEPROM	No	Erased **electrically**	Settings in devices
Flash memory	No	A fast EEPROM; no moving parts	**SSD**, pen drive, memory card, phone storage
Hard disk (HDD)	No	Magnetic spinning platters; cheaper per GB, slower	Bulk storage
Optical disc	No	Laser reads pits: CD 780 nm (infrared), DVD 650 nm (red), **Blu-ray 405 nm (blue-violet)**	Movies, archives

★ **1 byte = 8 bits**; in computer memory 1 KB = 1024 bytes, then MB, GB, TB.

★ **SSD vs HDD**: SSD (flash) is faster, silent and shock-proof because nothing moves.

Remember it: RAM = 'Remembers As long as Mains is on'. Blu-ray stores more because **blue** light has a **shorter wavelength**, so it can read smaller pits.

⚠ **Exam trap:** RAM is **volatile**, ROM and flash are not. An SSD is flash memory, not a faster hard disk.

Quick check

1. Which memory loses its data when the power goes off?
2. How is an EPROM erased?
3. Why does a Blu-ray disc hold more than a DVD?

Answer: 1. RAM (volatile) · 2. by ultraviolet light · 3. its blue-violet laser (405 nm) has a shorter wavelength, so it reads smaller pits

Graphene and 2D materials

one atom thick

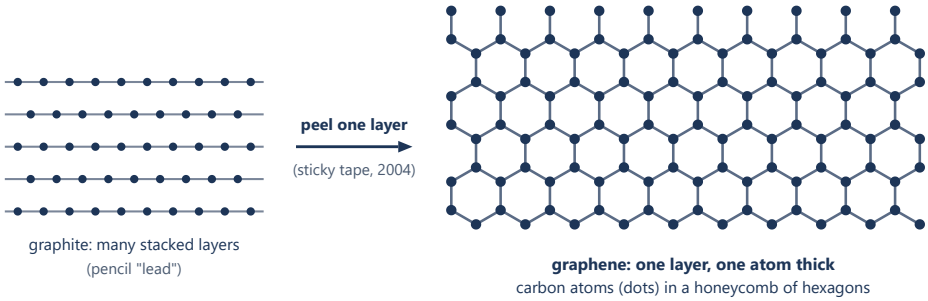
honeycomb of carbon

Geim, Novoselov 2010

200 × steel

no band gap

Peel graphite (pencil 'lead') down to a single sheet of carbon atoms and you get **graphene**, the first truly two-dimensional material. Being one atom thick gives it strange, record-breaking properties.



Graphite is many stacked sheets of carbon; peel off one sheet and you have graphene, one atom thick. Every bond in the sheet has the same length, so the hexagons are regular.

★★★ **Graphene** = a single layer of **carbon atoms in a hexagonal (honeycomb) lattice**; an allotrope of carbon like diamond, graphite, fullerene and carbon nanotubes.

★★ **Discovery**: Andre Geim and Konstantin Novoselov (University of Manchester) peeled it off graphite with **sticky tape** in 2004; Physics Nobel **2010**.

★★★ **Properties**: thinnest material known, about **200 times stronger than steel** of the same thickness, excellent conductor of **heat and electricity**, nearly **transparent** (absorbs about 2.3% of light), flexible and impermeable to gases.

★★ **Uses being developed**: flexible electronics and touchscreens, faster batteries and supercapacitors, sensors, water purification membranes, strong light composites.

★ **Other 2D materials**: hexagonal boron nitride ('white graphene', an insulator), **molybdenum disulphide** (MoS_2, a semiconductor with a band gap), phosphorene.

⚠ **Exam trap:** Graphene has **no band gap**, so on its own it cannot switch off like silicon; that is why MoS_2 and other 2D semiconductors are studied for transistors. Graphene is carbon, not silicon.

Quick check

1. Graphene is a single layer of which atoms, in what pattern?
2. How was graphene first isolated, and by whom?
3. Why can graphene alone not replace silicon in transistors?

Answer: 1. carbon atoms, in a hexagonal (honeycomb) lattice · 2. peeled from graphite with sticky tape by Geim and Novoselov (2004; Nobel 2010) · 3. it has no band gap, so it cannot switch off

Quantum computing and qubits

superposition

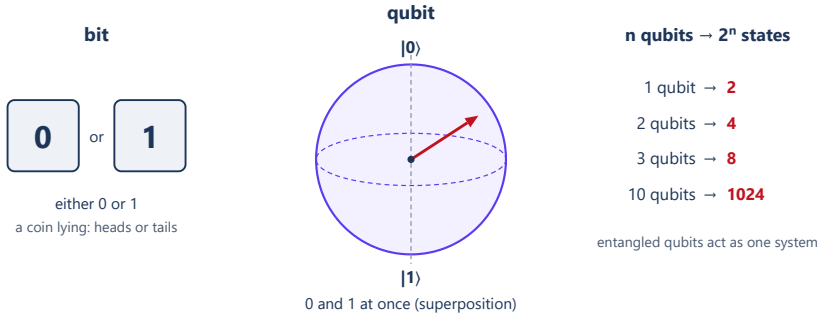
entanglement

n qubits → 2^n states

decoherence

NQM: DST

A normal bit is either 0 or 1. A **qubit** can be in a **superposition** of 0 and 1 at once, and qubits can be **entangled** so that they act as one system. This lets some problems be solved far faster than any normal computer could manage.



A bit is either 0 or 1. A qubit can be a blend of both at once, pictured as an arrow that may point anywhere on a sphere between |0⟩ and |1⟩. Each extra qubit doubles the number of states held together.

★★★ **Qubit**: superposition + entanglement. **n qubits** can represent **2^n** states together (10 qubits → 1024).

★★ **Problem: decoherence**: heat, vibration or stray fields destroy the fragile quantum state, so most qubits are kept near **absolute zero** (thousandths of a kelvin) and shielded.

★★ **Qubit types**: superconducting circuits, trapped ions, photons, neutral atoms.

★★ **Uses**: drug and material design, optimisation, weather and climate models. A large quantum computer could break today's public-key encryption, hence **post-quantum cryptography** and **quantum key distribution (QKD)** for secure links.

★ **Nobels**: 2022 (Aspect, Clauser, Zeilinger) for experiments with entangled photons; 2025 (Clarke, Devoret, Martinis) for quantum tunnelling in electric circuits, the basis of superconducting qubits.

★★★ **National Quantum Mission (NQM)**: approved April 2023, **₹6,003.65 crore** for 2023–24 to 2030–31, run by the **Department of Science and Technology**. Goals: quantum computers with **50–1000 physical qubits in 8 years**, satellite-based secure quantum communication over **2000 km**, quantum sensors and atomic clocks, quantum materials.

★★ **Four thematic hubs (T-Hubs)**: **IISc Bengaluru** (quantum computing), **IIT Madras** with C-DOT (communication), **IIT Bombay** (sensing and metrology), **IIT Delhi** (materials and devices). In 2026 the government reported more than half of the mission's targets met within three years, including more than 1,000 km of quantum-secure communication links.

Remember it: A bit is a **coin lying on the table** (heads or tails); a qubit is a **spinning coin** (both until you look). Entangled qubits are **twin coins**: stop one and you instantly know the other.

⚠ **Exam trap:** Quantum computers will not replace laptops for everyday work; they speed up only certain problems. India's NQM is under **DST**, not ISRO or MeitY.

Quick check

1. How many states can 10 qubits represent together?
2. Which department runs India's National Quantum Mission?
3. Why are most qubits kept near absolute zero?

Answer: 1. 1024 (2 multiplied by itself 10 times) · 2. the Department of Science and Technology (DST) · 3. heat and stray fields destroy the fragile quantum state (decoherence)

Making chips in India

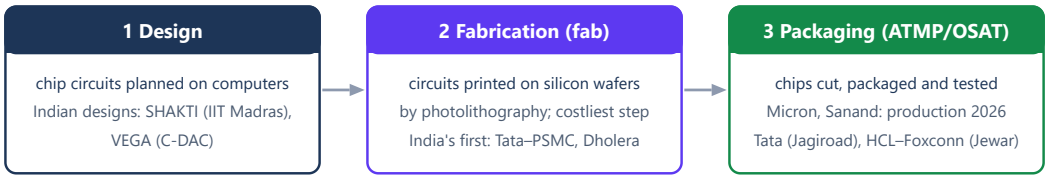
fab vs ATMP/OSAT

ISM: 2021, MeitY

Tata–PSMC, Dholera

Micron, Sanand

A chip passes through two big stages: **fabrication** (a 'fab' prints circuits on silicon wafers, the costliest step) and **assembly, testing and packaging** (ATMP/OSAT units cut, package and test the chips). India began with packaging units and its first commercial fab.



India Semiconductor Mission (December 2021, MeitY): 12 projects approved by mid-2026
1 silicon fab, 2 compound-semiconductor fabs, 9 packaging (ATMP/OSAT) units

A chip's journey: design, then fabrication on silicon wafers (the costliest step), then assembly, testing and packaging. India has started with packaging plants and is building its first commercial fab.

★★ **India Semiconductor Mission (ISM)**: launched December 2021 under the ₹76,000 crore Semicon India Programme, within the Ministry of Electronics and IT (MeitY).

★★ **Approved by mid-2026**: **12 projects** in six states worth about **₹1.64 lakh crore**: one silicon fab, two compound-semiconductor fabs and nine packaging (ATMP/OSAT) units.

★★★ **First commercial fab**: **Tata Electronics** with Taiwan's PSMC at **Dholera, Gujarat** (under construction). Packaging units include Tata (Jagiroad, Assam), CG Power–Renesas and Kaynes (Sanand, Gujarat) and an HCL–Foxconn unit near **Jewar (Uttar Pradesh)**.

★★★ **Micron's ATMP plant at Sanand (Gujarat)**, the first project approved under ISM, was inaugurated on **28 February 2026** and began commercial production of memory modules; other Sanand packaging units followed during 2026.

★ **ISM 2.0**, announced in the Union Budget 2026–27 and approved in 2026 with an outlay of **₹1,27,500 crore**, focuses on chip-making equipment, materials, Indian chip designs and supply chains.

⚠ **Exam trap: OSAT/ATMP is not a fab**: packaging plants do not make the silicon wafers themselves. India's first commercial silicon fab is the Tata–PSMC plant at **Dholera**, not Micron's Sanand plant.

Quick check

1. Which is India's first commercial silicon fab, and where?
2. Is Micron's Sanand plant a fab?
3. Under which ministry is the India Semiconductor Mission?

Answer: 1. Tata Electronics with PSMC, at Dholera (Gujarat) · 2. no: an assembly, testing and packaging (ATMP) plant · 3. the Ministry of Electronics and IT (MeitY)

Asked in past papers (6)

UPSC 2011 What is the difference between a CFL and an LED lamp ?
1. To produce light, a CFL uses mercury vapour and phosphor while an LED lamp uses semi-conductor material.
2. The average life span of a CFL is much longer than that of an LED lamp.
3. A CFL is less energy-efficient as compared to an LED lamp.
Which of the statements given above is/are correct ?
(a) 1 only (b) 2 and 3 only (c) 1 and 3 only (d) 1, 2 and 3
Answer: (c) 1 and 3 only. A CFL uses mercury vapour and phosphor; an LED uses a semiconductor junction; LED lamps last longer and are more energy-efficient than CFLs

UPSC 2017 Organic Light Emitting Diodes (OLEDs) are used to create digital display in many devices. What are the advantages of OLED displays over Liquid Crystal displays ?
1. OLED displays can be fabricated on flexible plastic substrates.
2. Roll-up displays embedded in clothing can be made using OLEDs.
3. Transparent displays are possible using OLEDs.
Select the correct answer using the code given below :
(a) 1 and 3 only (b) 2 only (c) 1, 2 and 3 (d) None of the above statements is correct
Answer: (c) 1, 2 and 3. OLED pixels emit their own light, so they need no backlight; OLEDs allow flexible, rollable and transparent displays, unlike backlit LCDs

BPSC 66th On heating, the resistance of a semiconductor
(a) increases (b) decreases (c) remains same (d) first increases and then decreases
(e) None of the above/More than one of the above
Answer: (b) decreases. A semiconductor's resistance decreases as its temperature rises

UPSC 2021 With reference to street-lighting, how do sodium lamps differ from LED lamps?
1. Sodium lamps produce light in 360 degrees but it is not so in the case of LED lamps.
2. As street-lights, sodium lamps have longer life span than LED lamps.
3. The spectrum of visible light from sodium lamps is almost monochromatic while LED lamps offer significant colour advantages in street-lighting.
Select the correct answer using the code given below.
(a) 3 only (b) 2 only (c) 1 and 3 only (d) 1, 2 and 3
Answer: (c) 1 and 3 only. Sodium vapour lamps give near-monochromatic yellow light in all directions; LED street lights are directional, longer-lived and render colours better

BPSC 68th Which of the following photoelectric devices is most suitable for digital applications?
(a) Photovoltaic cell (b) Photoemitter (c) Photodiode (d) More than one of the above
(e) None of the above
Answer: (c) Photodiode. A reverse-biased photodiode gives a fast on-off current response to light; A photovoltaic (solar) cell is built to convert light into electric power

BPSC 69th A photoelectric cell is a device which
(a) converts light energy into electric energy (b) converts electric energy into light energy
(c) stores light energy (d) None of the above
Answer: (a) converts light energy into electric energy. A photoelectric cell converts light energy into electrical energy

Test yourself (12)

1. Doping pure silicon with a small amount of arsenic produces
(a) a p-type semiconductor with holes as majority carriers
(b) an n-type semiconductor with electrons as majority carriers (c) an intrinsic semiconductor
(d) an insulator

2. A device that converts alternating current into direct current is a
(a) inverter (b) transformer (c) rectifier (d) oscillator

3. Which pair consists of universal logic gates?
(a) NAND and NOR (b) AND and OR (c) NOT and XOR (d) OR and NOT

4. The Meissner effect refers to
(a) the fall in a semiconductor's resistance on heating
(b) the expulsion of magnetic field from a superconductor (c) light emission from a forward-biased junction
(d) ejection of electrons from a metal by light

5. The colour of light given out by an LED mainly depends on
(a) the supply voltage (b) the size of the LED chip (c) the band gap of the semiconductor
(d) the length of its leads

6. Consider: 1. An OLED screen needs a backlight. 2. A common 'LED TV' is an LCD lit by LEDs. 3. A capacitive touchscreen senses the electric charge of the finger. Which are correct?
(a) 1 only (b) 1 and 3 only (c) 2 only (d) 2 and 3 only

7. Optical fibres carry signals using the principle of
(a) total internal reflection (b) diffraction (c) dispersion (d) polarisation

8. Which memory loses its data when the power is switched off?
(a) ROM (b) Flash memory in an SSD (c) RAM (d) EPROM

9. Graphene is
(a) an allotrope of silicon used in chips (b) a single layer of carbon atoms arranged in a honeycomb lattice
(c) a superconductor at room temperature (d) an organic dye used in OLED screens

10. Consider the following statements:
1. On heating, the resistance of a semiconductor decreases.
2. In a p-type semiconductor, holes are the majority carriers, so the crystal carries a net positive charge.
3. A Zener diode is used as a voltage regulator by working it in reverse breakdown.
Which of the statements given above is/are correct?
(a) 1 only (b) 1 and 3 only (c) 2 and 3 only (d) 1, 2 and 3

11. Consider the following statements:
1. A photodiode is normally operated in forward bias.
2. A CFL lasts longer than an LED lamp that gives the same light.
3. Copper becomes a superconductor when cooled close to absolute zero.
How many of the above statements are correct?
(a) Only one (b) Only two (c) All three (d) None

12. A bank locker opens only when the manager's key and the customer's key are both turned. Taking a turned key as 1 and an unturned key as 0, the lock follows which logic gate?
(a) AND (b) OR (c) NOR (d) XOR

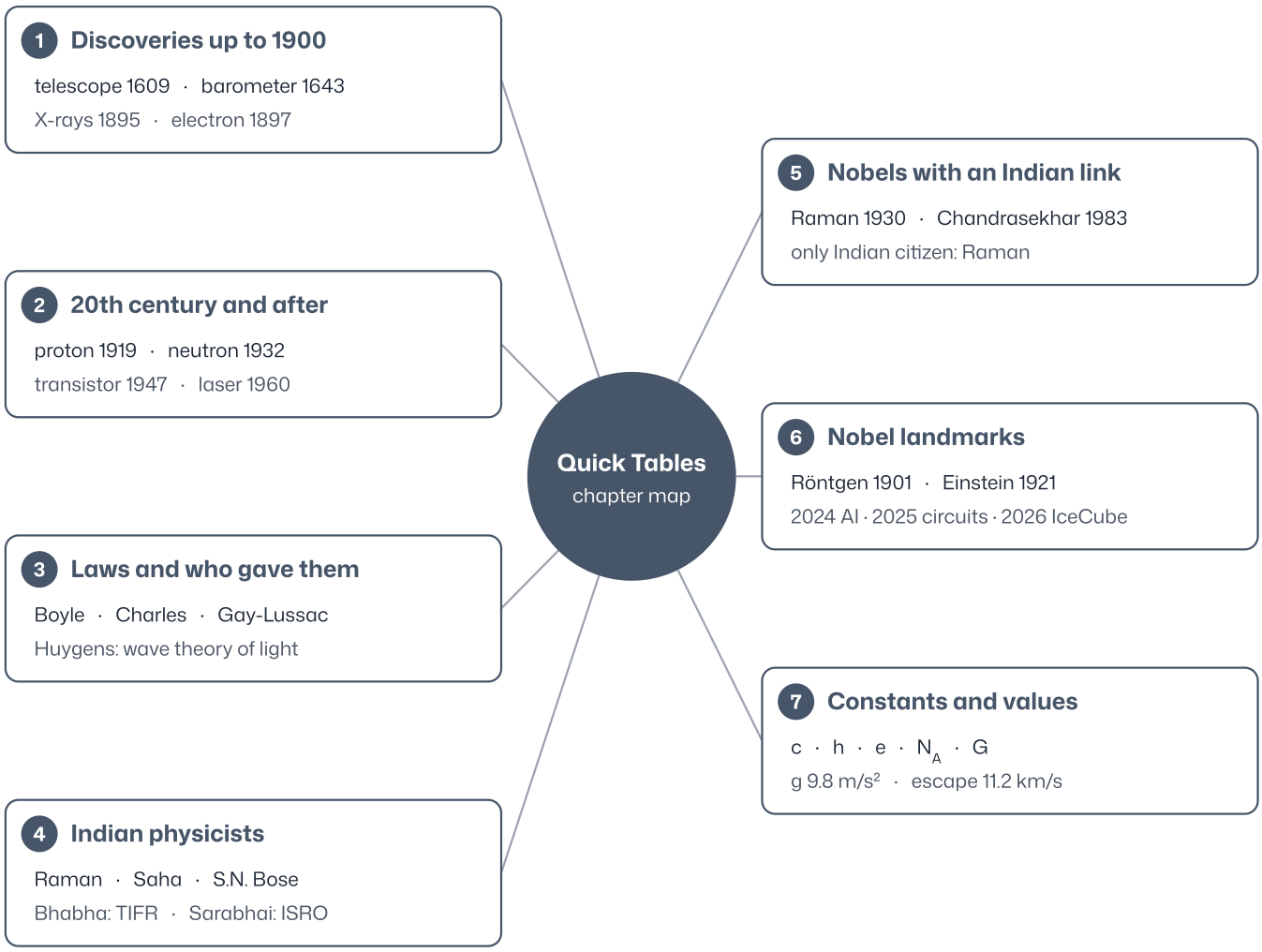
Answers: 1. (b) Arsenic is pentavalent and donates an extra electron, giving n-type silicon. · 2. (c) Diode rectifiers convert AC to DC; inverters do the reverse; transformers only change AC voltage. · 3. (a) Any digital circuit can be built from NAND gates alone or NOR gates alone. · 4. (b) Below its critical temperature a superconductor pushes out magnetic field lines, enabling levitation. · 5. (c) Photon energy equals roughly the band gap: GaN gives blue, GaAsP red, GaAs infrared. · 6. (d) OLED pixels emit their own light; most 'LED TVs' are LED-backlit LCDs; capacitive screens respond to the finger's charge. · 7. (a) Light hits the core–cladding boundary beyond the critical angle and is fully reflected along the fibre. · 8. (c) RAM is volatile; ROM, EPROM and flash keep data without power. · 9. (b) Graphene is one-atom-thick carbon, isolated in 2004 by Geim and Novoselov (Nobel 2010). · 10. (b) Heat frees more carriers, so a semiconductor's resistance falls, and a Zener diode holds a steady voltage in reverse breakdown; a p-type crystal stays neutral, since 'p' only names the majority carrier. · 11. (d) None is correct: a photodiode works in reverse bias, an LED lasts several times longer than a CFL, and good ordinary conductors such as copper never superconduct, however cold they get. · 12. (a) AND gives 1 only when all inputs are 1; OR would open the locker with either key alone, and XOR would keep it shut when both keys are turned.

CHAPTER 15

Scientists, Discoveries, Laws and Constants: Quick Tables

State papers and SSC ask 'who invented / discovered / gave which law' and 'which Indian scientist is linked to what'; UPSC uses the same names inside statement questions. This chapter puts them in one place for revision.

≈ 34 min to read ≈ 2 min to revise ★★★ Revise on: Day 1 | Day 3 | Day 7 | Day 21



Revision card

1. 1895-96-97: X-rays (Röntgen), radioactivity (Becquerel), electron (J.J. Thomson). Proton: Rutherford (1919). Neutron: Chadwick (1932).
2. Telescope used for astronomy: Galileo (1609); barometer: Torricelli (1643); pendulum clock: Huygens (1656); electric cell: Volta (1800).
3. Induction and dynamo: Faraday (1831); telephone: Bell (1876); radio: Marconi (1895); transistor: Bardeen, Brattain, Shockley (1947); laser: Maiman (1960).
4. Raman effect announced 28 February 1928 (National Science Day); Nobel 1930, first Asian science Nobel.
5. S. Chandrasekhar: Nobel 1983; Chandrasekhar limit ≈ 1.4 solar masses for a white dwarf.
6. S.N. Bose: Bose–Einstein statistics (1924); 'bosons' are named after him; he did not receive a Nobel.
7. Homi Bhabha: TIFR (1945), Atomic Energy Commission (1948), three-stage nuclear plan. Vikram Sarabhai: PRL (1947), ISRO (1969).
8. Meghnad Saha: thermal ionisation equation (stars). J.C. Bose: crescograph and early microwave radio (1895).
9. Physics Nobels 2024: Hopfield and Hinton (machine learning); 2025: Clarke, Devoret, Martinis (quantum tunnelling in circuits); 2026: Francis Halzen (IceCube neutrinos).
10. Einstein's 1921 Nobel was for the photoelectric effect, not relativity. Bardeen is the only person with two physics Nobels.
11. $c \approx 3 \times 10^{8}$ m/s; $h = 6.626 \times 10^{-34}$ J s; $e = 1.6 \times 10^{-19}$ C; $N_A = 6.022 \times 10^{23}$ mol^{-1}; $G = 6.674 \times 10^{-11}$ N m^2 kg^{-2}.
12. Absolute zero = 0 K = −273.15 °C; sound in air ≈ 343 m/s at 20 °C; escape velocity from Earth = 11.2 km/s.

Discoveries and inventions up to 1900

telescope: Galileo 1609

barometer: Torricelli

dynamo: Faraday 1831

telephone: Bell 1876

X-rays 1895

Early physics grew from instruments: once people could see farther (telescope), measure air pressure (barometer) and keep exact time (pendulum clock), laws followed. The 1800s then turned electricity from a curiosity into cells, motors, generators and the telephone.

Instruments and machines ★★★

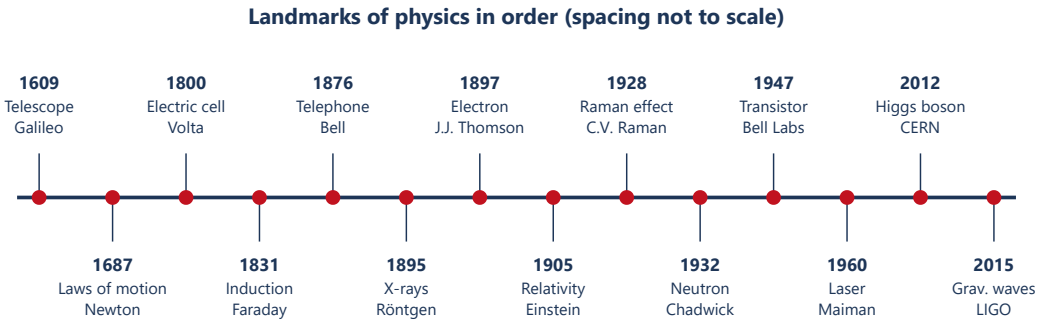
Invention / discovery	Who	Year
Compound microscope	Zacharias Janssen (credited)	c. 1590
Thermoscope (first thermometer)	Galileo Galilei	c. 1593
Telescope	Hans Lippershey (first patent claim); Galileo first turned it to the sky	1608; 1609
Barometer	Evangelista Torricelli	1643
Air (vacuum) pump	Otto von Guericke	1650
Pendulum clock	Christiaan Huygens	1656
Steam engine	Thomas Newcomen (first working engine); James Watt (separate condenser, the efficient engine)	1712; 1769
Mercury thermometer, Fahrenheit scale	Daniel Gabriel Fahrenheit	1714; 1724
Celsius (centigrade) scale	Anders Celsius	1742
Lightning conductor	Benjamin Franklin	1752
Electric cell (voltaic pile)	Alessandro Volta	1800
Miners' safety lamp	Humphry Davy	1815
Electric motor (principle)	Michael Faraday	1821
Electromagnetic induction, dynamo (generator)	Michael Faraday	1831
Electric telegraph, Morse code	Samuel Morse	1837
Lead-acid (rechargeable) battery	Gaston Planté	1859
Telephone	Alexander Graham Bell	1876
Phonograph	Thomas Alva Edison	1877
Practical incandescent bulb	Thomas Edison (also Joseph Swan)	1879
Radio waves produced and detected	Heinrich Hertz	1887
Wireless signalling with microwaves	J.C. Bose (Kolkata)	1895
Radio (wireless telegraphy)	Guglielmo Marconi	1895
Diesel engine	Rudolf Diesel	1890s

Discoveries at the end of the 19th century ★★★

Discovery	Who	Year
X-rays	Wilhelm Conrad Röntgen (Germany)	1895
Radioactivity (in uranium salts)	Henri Becquerel (France)	1896
Electron (cathode rays are particles)	J.J. Thomson (UK)	1897
Polonium and radium	Marie and Pierre Curie	1898

Remember it: X-R-E in 95-96-97: X-rays, Radioactivity, Electron came in three straight years, like counting 5-6-7. Communication chain: 'Morning Bell Makes Breakfast': Morse telegraph (1837) → Bell telephone (1876) → Marconi radio (1895) → Baird television (1926).

⚠ Exam trap: Galileo did not invent the telescope; he improved it and was first to use it for astronomy. James Watt did not build the first steam engine; Newcomen did, Watt made it efficient. Faraday's dynamo makes electricity; Volta's cell stores chemical energy.



1895-96-97: X-rays, radioactivity, electron came in three straight years

Fourteen landmarks in order. Use it to answer 'arrange chronologically' questions.

Quick check

1. Did Galileo invent the telescope?
2. X-rays, radioactivity, electron: who found each, and when?
3. Who built the first working steam engine, and what did Watt add?

Answer: 1. no: he improved it and first turned it to the sky (1609) · 2. Röntgen 1895, Becquerel 1896, J.J. Thomson 1897 · 3. Newcomen (1712); Watt added the separate condenser (1769)

Discoveries and inventions of the 20th century and after

electron → proton → neutron

neutron: Chadwick 1932

transistor 1947

laser: Maiman 1960

fission: Hahn

Modern physics and electronics ★★★

Invention / discovery	Who	Year
Quantum theory (energy in packets)	Max Planck	1900
Aeroplane (powered flight)	Wright brothers	1903
Special relativity, $E = mc^2$, photoelectric effect explained	Albert Einstein	1905
Superconductivity	Heike Kamerlingh Onnes	1911
Atomic nucleus (gold-foil experiment)	Ernest Rutherford	1911
Cosmic rays	Victor Hess	1912
Atomic model with fixed orbits	Niels Bohr	1913
General relativity	Albert Einstein	1915
Proton	Ernest Rutherford	1919
Wave nature of matter	Louis de Broglie	1924
Television (first public demonstration)	John Logie Baird	1926
Uncertainty principle	Werner Heisenberg	1927
Raman effect	C.V. Raman (with K.S. Krishnan)	1928
Expanding universe (Hubble's law)	Edwin Hubble	1929
Neutron	James Chadwick	1932
Positron (first antiparticle)	Carl D. Anderson	1932
Cyclotron (particle accelerator)	Ernest O. Lawrence	1931
Radar	Robert Watson-Watt	1935
Nuclear fission	Otto Hahn and Fritz Strassmann (explained by Lise Meitner and Otto Frisch)	1938
First nuclear reactor (Chicago Pile-1)	Enrico Fermi	1942
Transistor	John Bardeen, Walter Brattain, William Shockley (Bell Labs)	1947
Maser	Charles Townes	1954
Integrated circuit (IC)	Jack Kilby (1958); Robert Noyce (1959)	1958–59
Laser (ruby)	Theodore Maiman	1960
Visible-light LED	Nick Holonyak	1962
Pulsar	Jocelyn Bell Burnell	1967
World Wide Web (at CERN)	Tim Berners-Lee	1989
Higgs boson found (LHC, CERN)	ATLAS and CMS teams	2012
Gravitational waves detected	LIGO (USA)	2015

★★★ **Order of the atom's particles**: electron (Thomson, 1897) → proton (Rutherford, 1919) → neutron (Chadwick, 1932).

★★ **Canal rays** (positive rays) were found by **Eugen Goldstein** (1886); they led towards the proton.

★★ **Gamma rays** were identified by **Paul Villard** (1900); **alpha and beta rays** were named by **Rutherford**.

★★ **Optical fibre**: **Narinder Singh Kapany** (Indian-born) pioneered light transmission through glass fibres in the 1950s; **Charles Kao** showed low-loss fibres could carry signals (Nobel 2009).

★ **Blue LED** (which made white LED lamps possible): Akasaki, Amano and Nakamura, Nobel 2014.

★ **Hydrogen bomb**: Edward Teller (with Stanislaw Ulam), tested 1952. **Atom bomb**: Manhattan Project led scientifically by J. Robert Oppenheimer, 1945.

Remember it: Breakfast order for the atom: Tea → Rusk → Chai = Thomson (electron) → Rutherford (proton) → Chadwick (neutron). 1932 was the 'year of new particles': neutron and positron together.

⚠ **Exam trap:** Rutherford found the nucleus (1911) and the proton (1919), not the neutron. Hahn and Strassmann found fission, Fermi built the first reactor. The transistor came from Bell Labs, not from Edison.

Quick check

1. Who discovered the proton, and who the neutron?
2. The transistor (1947) came from which laboratory?
3. Who discovered nuclear fission, and who built the first reactor?

Answer: 1. Rutherford (1919); Chadwick (1932) · 2. Bell Labs (Bardeen, Brattain, Shockley) · 3. Hahn and Strassmann (1938); Fermi (1942)

Famous laws and who gave them

Archimedes: buoyancy

gas laws: what is fixed

Huygens: waves

Lenz: direction

Fleming: LM-RG

A law is a short statement of how nature always behaves. Exams ask the match 'law – scientist – what it says', so learn each in one line with its everyday use.

Laws and principles ★★★

Law / principle	Given by	In one line
Principle of buoyancy (flotation)	Archimedes	upthrust = weight of fluid displaced; ships float, hydrometers work
Law of the lever	Archimedes	effort × effort arm = load × load arm
Laws of planetary motion	Johannes Kepler	elliptical orbits; equal areas in equal times; $T^2 \propto r^3$
Law of falling bodies	Galileo Galilei	without air, all bodies fall with the same acceleration
Law of refraction	Willebrord Snell	sin i ÷ sin r = constant (refractive index)
Pascal's law	Blaise Pascal	pressure on a confined fluid spreads equally; hydraulic lift, brakes
Boyle's law	Robert Boyle	PV = constant at fixed temperature
Hooke's law	Robert Hooke	stress ∝ strain within the elastic limit; spring balance
Wave theory of light	Christiaan Huygens	light travels as waves
Laws of motion; universal gravitation	Isaac Newton (1687)	inertia, F = ma, action–reaction; $F = Gm_1m_2/r^2$
Law of cooling	Isaac Newton	rate of cooling ∝ temperature difference with surroundings
Bernoulli's principle	Daniel Bernoulli	faster flow, lower pressure; aeroplane lift, atomiser
Charles's law	Jacques Charles	V ∝ T at fixed pressure
Gay-Lussac's (pressure) law	Joseph Gay-Lussac	P ∝ T at fixed volume
Coulomb's law	Charles-Augustin de Coulomb	force between charges $\propto q_1q_2/r^2$
Avogadro's law	Amedeo Avogadro	equal volumes of gases at same T, P hold equal numbers of molecules
Dalton's law of partial pressures	John Dalton	total pressure = sum of partial pressures
Ohm's law	Georg Simon Ohm	V = IR at constant temperature
Laws of electromagnetic induction; laws of electrolysis	Michael Faraday	changing magnetic flux induces emf
Lenz's law	Heinrich Lenz	induced current opposes the change that causes it
Graham's law of diffusion	Thomas Graham	rate of diffusion $\propto 1/\sqrt{\text{density}}$
Doppler effect	Christian Doppler	pitch rises as a source approaches, falls as it recedes
Joule's law of heating	James Prescott Joule	heat = I^2Rt
Kirchhoff's laws	Gustav Kirchhoff	current law at junctions, voltage law around loops

Stokes' law	George Gabriel Stokes	viscous drag on a falling sphere ∝ radius × speed
Electromagnetic theory (Maxwell's equations)	James Clerk Maxwell	light is an electromagnetic wave
Stefan–Boltzmann law	Josef Stefan, Ludwig Boltzmann	power radiated ∝ T^4
Wien's displacement law	Wilhelm Wien	hotter body glows at shorter wavelength (red → white → blue)
Left-hand (motor) and right-hand (generator) rules	John Ambrose Fleming	direction of force / induced current
Mass–energy equivalence	Albert Einstein	$E = mc^2$
Exclusion principle	Wolfgang Pauli	no two electrons share all four quantum numbers
Uncertainty principle	Werner Heisenberg	position and momentum cannot both be exactly known
Hubble's law	Edwin Hubble	galaxies recede at speed ∝ their distance

Remember it: Gas laws by what is kept fixed: 'Boys Take, Children Play, Girls Vote' → Boyle keeps T fixed, Charles keeps P fixed, Gay-Lussac keeps V fixed. Fleming: Left = Motor, Right = Generator ('LM-RG', like a left-hand motorist and right-hand generator).

⚠ **Exam trap:** Newton gave the corpuscular (particle) theory of light; Huygens gave the wave theory. Kepler described planetary orbits; Newton explained them with gravitation. Lenz's law gives direction, Faraday's law gives size of induced emf.

Quick check

1. What does Boyle's law keep fixed?
2. Wave theory of light: Newton or Huygens?
3. Lenz's law or Faraday's law: which gives the direction of the induced current?

Answer: 1. temperature (PV = constant) · 2. Huygens (Newton gave the corpuscle theory) · 3. Lenz's law

Indian physicists and their work

Raman effect 1928

S.N. Bose: bosons

J.C. Bose: crescograph

Saha: hot stars

Bhabha: TIFR, BARC

Sarabhai: ISRO

Modern Indian physics began in Kolkata labs around 1900 and grew into institutions that still run India's nuclear and space programmes. Link each name to one idea and one institution.

Who did what ★★★

Scientist	Known for	Institution / honour
C.V. Raman	Raman effect: scattered light changes wavelength (1928); also acoustics of tabla and mridangam, why the sea is blue	IACS Kolkata; Nobel 1930; Bharat Ratna 1954; founded Raman Research Institute, Bengaluru (1948)
J.C. Bose	Wireless microwave signalling (1895), crystal detector; showed plants respond to stimuli; invented the crescograph	Founded Bose Institute, Kolkata (1917)
S.N. Bose	Bose–Einstein statistics (1924); particles obeying it are 'bosons'	Dhaka University; Padma Vibhushan 1954; National Professor
Meghnad Saha	Saha ionisation equation (1920): explains spectra and temperature of stars	Founded Saha Institute of Nuclear Physics, Kolkata; chaired Calendar Reform Committee (1952)
Homi J. Bhabha	Cosmic-ray showers, Bhabha scattering; father of India's nuclear programme; three-stage plan	Founded TIFR (1945); first chairman, Atomic Energy Commission (1948); BARC named after him
Vikram Sarabhai	Cosmic rays; father of India's space programme	Founded PRL Ahmedabad (1947); INCOSPAR (1962); ISRO (1969); Thumba launch station
S. Chandrasekhar	Chandrasekhar limit: a white dwarf heavier than ≈ 1.4 solar masses must collapse	University of Chicago; Nobel 1983; NASA's Chandra X-ray Observatory named after him
G.N. Ramachandran	Biophysics: Ramachandran plot of protein shapes; triple helix of collagen	University of Madras
E.C.G. Sudarshan	Quantum optics (Sudarshan–Glauber representation); V–A theory of weak force; idea of tachyons	-
Satish Dhawan	Fluid dynamics; led ISRO 1972–84	Satish Dhawan Space Centre, Sriharikota
Raja Ramanna	Led India's first nuclear test, Pokhran (1974)	BARC
A.P.J. Abdul Kalam	Project director of SLV-3 (1980); guided-missile programme	'Missile Man'; Bharat Ratna 1997; President 2002–07
Jayant Narlikar	Hoyle–Narlikar theory of gravity (cosmology)	Founder director, IUCAA Pune
Anna Mani	Meteorological instruments: solar radiation, ozone, wind	India Meteorological Department
Narinder Singh Kapany	Pioneer of fibre optics	-

Kolkata scientists before 1937. Seated, left to right: Meghnad Saha, J.C. Bose, J.C. Ghosh. Standing, second from left: S.N. Bose. The two Boses are different people: J.C. Bose made the crescograph; bosons are named after S.N. Bose. Image: Unknown photographer (S.N. Bose National Centre archive), Wikimedia Commons, public domain

★★★ **National Science Day, 28 February**, marks the announcement of the Raman effect in 1928 (celebrated since 1987).

★★★ **Raman's Nobel (1930)** was the first Nobel in any science to an Asian; the first Asian Nobel of any kind was Rabindranath Tagore (Literature, 1913).

★★ **Raman effect uses**: Raman spectroscopy identifies molecules by the tiny colour shift of scattered light (drug testing, gem testing, planetary rovers).

★★ **'Boson'** was coined by Paul Dirac in honour of S.N. Bose; the Higgs boson ('God particle') carries his name.

★★ **Chandrasekhar** was born in Lahore (1910), was C.V. Raman's nephew, and became a US citizen; his Nobel (shared with William Fowler) was for the structure and evolution of stars.

★★ **Bhabha's three-stage plan**: natural uranium reactors → fast breeder reactors (plutonium) → thorium-based reactors, to use India's large thorium reserves.

★★ **Apsara (1956)**, India's first research reactor and the first in Asia, was built under Bhabha at Trombay; the Trombay establishment was renamed BARC in 1967.

★★ **Sarabhai and Thumba**: India's first rocket (a Nike-Apache) rose from Thumba, Kerala on 21 November 1963; the Chandrayaan landers are named Vikram after him.

★ **Ancient roots**: Kanada (Vaisheshika school) proposed indivisible particles (paramanu); Aryabhata held that the Earth spins on its axis.

The builders: Homi J. Bhabha (left, 1955), who founded TIFR and led India's atomic energy programme, and Vikram Sarabhai (right, 1969), founder of ISRO. Image: Bhabha: IAEA Imagebank, CC BY-SA 2.0; Sarabhai: NASA, public domain; both Wikimedia Commons, cropped

Remember it: Kolkata trio: Raman scattered light, Saha heated stars, S.N. Bose counted particles. Builders duo: Bhabha built the atom programme (TIFR, BARC), Sarabhai built the space programme (PRL, ISRO). 'Bhabha = Bomb-free power; Sarabhai = Satellites'.

⚠ **Exam trap:** The crescograph is J.C. Bose's, not S.N. Bose's; bosons are S.N. Bose's, not J.C. Bose's. ISRO's founder is Sarabhai, not Bhabha; TIFR's founder is Bhabha, not Sarabhai.

Quick check

1. National Science Day, 28 February, marks what?
2. Crescograph or bosons: which belongs to J.C. Bose?
3. Who founded TIFR, and who founded ISRO?

Answer: 1. the announcement of the Raman effect (1928) · 2. crescograph (bosons honour S.N. Bose) · 3. Homi Bhabha (1945); Vikram Sarabhai (1969)

Nobel Prizes in Physics with an Indian connection

Raman 1930

Salam 1979

Chandrasekhar 1983

LIGO-India: Hingoli

Indian links to the physics Nobel ★★★

Year	Laureate	For	Indian link
1930	C.V. Raman	scattering of light; the Raman effect	Indian citizen; work done in Kolkata
1979	Abdus Salam (with Glashow, Weinberg)	electroweak unification	born in undivided Punjab, British India
1983	S. Chandrasekhar (with William Fowler)	physics of the structure and evolution of stars	born in Lahore, British India; US citizen
2001	Cornell, Ketterle, Wieman	making a Bose–Einstein condensate	state predicted from S.N. Bose's statistics
2013	Englert, Higgs	theory of the Higgs boson	'boson' honours S.N. Bose
2017	Weiss, Barish, Thorne	detection of gravitational waves (LIGO)	Indian scientists were part of the LIGO collaboration; LIGO-India is being built

★★★ **Only one Indian citizen** has won the physics Nobel: **C.V. Raman (1930)**.

★★ **LIGO-India**: a gravitational-wave detector approved by the Union Cabinet in 2023, being built at **Aundha, Hingoli district, Maharashtra**, with DAE and DST.

★ **India and CERN**: India became an Associate Member State of CERN in 2017; Indian physicists worked on the CMS and ALICE experiments at the LHC.

⚠ **Exam trap:** Other Indian-linked science Nobels are not in physics: Ronald Ross (Medicine 1902, born in Almora), Har Gobind Khorana (Medicine 1968), Venkatraman Ramakrishnan (Chemistry 2009). S.N. Bose and J.C. Bose never won a Nobel.

☑ **Quick check**

1. How many Indian citizens have won the physics Nobel?
2. What was S. Chandrasekhar's 1983 Nobel for?
3. Where is LIGO-India being built?

Answer: 1. one: C.V. Raman (1930) · 2. the structure and evolution of stars · 3. Aundha, Hingoli district, Maharashtra

Nobel physics: landmark facts and recent winners

Röntgen 1901

Einstein: photoelectric

Bardeen: two physics Nobels

Marie Curie

2024: neural networks

The Nobel Prizes come from Alfred Nobel's will; the physics prize is chosen by the Royal Swedish Academy of Sciences and handed over on 10 December, the date of Nobel's death. The first physics prize was given in 1901.

★★★ **First physics Nobel (1901)**: Wilhelm Röntgen, for X-rays.

★★★ **Einstein (1921)**: for services to theoretical physics and **the law of the photoelectric effect**, not for relativity.

★★ **Marie Curie**: first woman Nobel laureate (Physics 1903, with Pierre Curie and Becquerel) and the only person to win in two different sciences (Chemistry 1911).

★★ **John Bardeen**: only person with two physics Nobels (1956 transistor; 1972 theory of superconductivity).

★ **Youngest physics laureate**: Lawrence Bragg, 25, shared 1915 with his father William Henry Bragg (X-ray crystal analysis).

★ **Father and son winners**: J.J. Thomson (1906, electron as particle) and G.P. Thomson (1937, electron as wave); Niels Bohr (1922) and Aage Bohr (1975).

★ **Women physics laureates (5)**: Marie Curie 1903, Maria Goeppert Mayer 1963, Donna Strickland 2018, Andrea Ghez 2020, Anne L'Huillier 2023.

Classic physics Nobels ★★

Year	Laureate(s)	For
1903	Becquerel; Pierre and Marie Curie	radioactivity
1909	Marconi, Braun	wireless telegraphy
1918	Max Planck	energy quanta
1922	Niels Bohr	structure of atoms
1935	James Chadwick	neutron
1956	Shockley, Bardeen, Brattain	transistor
1964	Townes, Basov, Prokhorov	maser–laser principle
1971	Dennis Gabor	holography
2000	Jack Kilby (with Alferov, Kroemer)	integrated circuit
2009	Charles Kao; Boyle and Smith	optical fibres; CCD image sensor
2014	Akasaki, Amano, Nakamura	blue LED
2015	Kajita, McDonald	neutrino oscillations (neutrinos have mass)
2019	Peebles; Mayor and Queloz	cosmology; first exoplanet around a Sun-like star

Physics Nobels 2020–2026 ★★★

Year	Laureate(s)	For
2020	Roger Penrose; Reinhard Genzel, Andrea Ghez	black holes form in general relativity; supermassive compact object at the Milky Way's centre
2021	Syukuro Manabe, Klaus Hasselmann; Giorgio Parisi	physical modelling of Earth's climate and global warming; disorder and fluctuations in complex systems
2022	Alain Aspect, John Clauser, Anton Zeilinger	experiments with entangled photons; pioneering quantum information science
2023	Pierre Agostini, Ferenc Krausz, Anne L'Huillier	attosecond pulses of light to study electron motion
2024	John Hopfield, Geoffrey Hinton	foundational work enabling machine learning with artificial neural networks
2025	John Clarke, Michel Devoret, John Martinis	macroscopic quantum tunnelling and energy quantisation in an electric circuit (basis of superconducting qubits)
2026	Francis Halzen (sole laureate)	decisive contributions to the IceCube Neutrino Observatory and the discovery of high-energy neutrinos from space

Remember it: Recent run as a story: Climate (2021) → Quantum links (2022) → Flash of light in attoseconds (2023) → AI brains (2024) → Quantum circuits (2025) → Ice catching ghosts (2026). 'C-Q-F-A-Q-I'. IceCube sits in a cubic kilometre of Antarctic ice at the South Pole.

Exam trap: The 2024 physics prize (Hopfield, Hinton) was for neural networks; the 2024 chemistry prize was for protein structure (AlphaFold). Attosecond = 10^{-18} s, not 10^{-15} s (that is a femtosecond).

Quick check

1. Einstein's 1921 Nobel: for relativity or for the photoelectric effect?
2. Who won the first physics Nobel (1901), and for what?
3. What was the 2024 physics Nobel (Hopfield, Hinton) for?

Answer: 1. the photoelectric effect · 2. Röntgen, for X-rays · 3. machine learning with artificial neural networks

Important physical constants and values

$c \approx 3 \times 10^8$ m/s

$h = 6.626 \times 10^{-34}$ J s

G vs g

escape 11.2 km/s

sound 343 m/s

Since 2019 seven constants have exact, fixed values (they define the SI units); others such as G are measured. Learn the rounded value with its unit and the condition it holds in.

Universal constants ★★★

Constant	Symbol	Value	Note
Speed of light in vacuum	c	299 792 458 m/s ≈ 3×10^{8} m/s	exact; the top speed in nature
Planck constant	h	6.626×10^{-34} J s	exact; defines the kilogram
Elementary charge	e	1.602×10^{-19} C	exact; charge of a proton (electron −e)
Avogadro constant	N_A	6.022×10^{23} mol^{-1}	exact; particles in one mole
Boltzmann constant	k	1.381×10^{-23} J/K	exact
Universal gas constant	R	8.314 J mol^{-1} K^{-1}	$R = N_A \times k$
Universal gravitational constant	G	6.674×10^{-11} N m^2 kg^{-2}	measured (first by Henry Cavendish, 1798); same everywhere in the universe
Stefan–Boltzmann constant	σ	5.67×10^{-8} W m^{-2} K^{-4}	radiation ∝ T^4
Permittivity of free space	ε_0	8.854×10^{-12} F/m	-
Electron mass	m_e	9.11×10^{-31} kg	-
Proton mass	m_p	1.673×10^{-27} kg	≈ 1836 electron masses
Neutron mass	m_n	1.675×10^{-27} kg	slightly heavier than a proton
Atomic mass unit	u	1.66×10^{-27} kg	1/12 of a carbon-12 atom

Everyday physical values ★★★

Quantity	Value	Condition / note
Acceleration due to gravity g	9.8 m/s² (standard 9.806 65)	at sea level; greatest at poles, least at equator, zero at Earth's centre
g on the Moon	≈ 1.6 m/s² (about 1/6 of Earth's)	-
Absolute zero	0 K = −273.15 °C = −459.67 °F	lowest possible temperature
Speed of sound in air	≈ 331 m/s at 0 °C; ≈ 343 m/s at 20 °C	rises about 0.6 m/s per °C
Speed of sound in water	≈ 1480 m/s	about 4 times air
Speed of sound in steel	≈ 5000–6000 m/s	fastest in solids
Standard atmospheric pressure	101 325 Pa = 760 mm Hg	at sea level
Mechanical equivalent of heat J	4.186 J per calorie	Joule's experiment
Density of water	1000 kg/m³	maximum at 4 °C
Refractive index	water 1.33; glass ≈ 1.5; diamond 2.42	for yellow light
Solar constant	≈ 1361 W/m² (≈ 1.36 kW/m²)	sunlight at top of the atmosphere
Time for sunlight to reach Earth	≈ 8 minutes 20 seconds	1 AU ÷ c
Escape velocity from Earth	11.2 km/s	independent of the mass of the object
Orbital velocity near Earth's surface	≈ 7.9 km/s	for a satellite skimming the surface
Earth's mean radius	≈ 6371 km	-

Remember it: Four '6's to keep apart: $h = 6.6 \times 10^{-34}$ (tiny, quantum), $N_A = 6.0 \times 10^{23}$ (huge, counting), $G = 6.67 \times 10^{-11}$ (gravity, weak), $e = 1.6 \times 10^{-19}$ (charge). Exponents grow 'smaller as things get stranger': gravity −11, charge −19, Boltzmann −23, Planck −34.

⚠ Exam trap: g (9.8 m/s²) changes from place to place; G (6.674×10^{-11}) is the same everywhere. Escape velocity 11.2 km/s is not the speed of a satellite in orbit (≈ 7.9 km/s near the surface). Light in water or glass is slower than c.

Quick check

1. G or g: which is the same everywhere?
2. Escape velocity from Earth, and orbital velocity near its surface?
3. Absolute zero in degrees Celsius?

Answer: 1. G = 6.674×10^{-11} N m² kg^{-2} · 2. 11.2 km/s; ≈ 7.9 km/s · 3. −273.15 °C

Test yourself (13)

1. Who discovered the neutron?
(a) Ernest Rutherford (b) James Chadwick (c) J.J. Thomson (d) Niels Bohr

2. The Raman effect deals with
(a) scattering of light (b) photoelectric emission (c) radioactive decay (d) superconductivity

3. The Chandrasekhar limit, the maximum mass of a stable white dwarf, is about
(a) 1.4 solar masses (b) 3.2 solar masses (c) 0.5 solar mass (d) 10 solar masses

4. The 2024 Nobel Prize in Physics was awarded for
(a) attosecond pulses of light (b) quantum tunnelling in electric circuits
(c) experiments with entangled photons (d) machine learning with artificial neural networks

5. Who invented the mercury barometer?
(a) Galileo Galilei (b) Blaise Pascal (c) Evangelista Torricelli (d) Robert Boyle

6. The Tata Institute of Fundamental Research (TIFR) was founded by
(a) Homi J. Bhabha (b) Vikram Sarabhai (c) Meghnad Saha (d) C.V. Raman

7. Which pair is wrongly matched?
(a) Telephone – Alexander Graham Bell (b) Electric cell – Alessandro Volta (c) X-rays – Wilhelm Röntgen
(d) Transistor – Thomas Edison

8. The value of the Avogadro constant is about
(a) 6.626×10^{-34} mol^{-1} (b) 1.602×10^{-19} mol^{-1} (c) 6.022×10^{23} mol^{-1} (d) 6.674×10^{-11} mol^{-1}

9. The 2026 Nobel Prize in Physics went to Francis Halzen for work on
(a) the Higgs boson (b) gravitational waves (c) high-energy neutrinos detected by IceCube
(d) exoplanets around Sun-like stars

10. Who gave the laws of planetary motion?
(a) Nicolaus Copernicus (b) Johannes Kepler (c) Galileo Galilei (d) Isaac Newton

11. Consider the following statements:
1. James Watt built the first working steam engine.
2. Galileo did not invent the telescope; he improved it and used it to study the sky.
3. C.V. Raman is the only Indian citizen to have won the Nobel Prize in Physics.
Which of the statements given above is/are correct?
(a) 1 only (b) 1 and 2 only (c) 2 and 3 only (d) 1, 2 and 3

12. Consider the following pairs:
Gas law : Quantity kept fixed
1. Boyle's law : Temperature
2. Charles's law : Volume
3. Gay-Lussac's law : Volume
How many of the pairs given above are correctly matched?
(a) Only one (b) Only two (c) All three (d) None

13. During a cricket match on a stormy evening (air at about 20 °C), a spectator sees a lightning flash and hears its thunder 3 seconds later. Roughly how far away was the strike?
(a) About 1 km (b) About 3 km (c) About 100 m (d) About 4.4 km

Answers: 1. (b) Chadwick found the neutron in 1932 and won the 1935 Nobel; Rutherford found the nucleus and proton. · 2. (a) Light scattered by molecules shifts slightly in wavelength; announced 28 February 1928. · 3. (a) Above about 1.4 solar masses a white dwarf collapses further into a neutron star or black hole. · 4. (d) Hopfield and Hinton won in 2024; attosecond pulses were 2023, entangled photons 2022, circuits 2025. · 5. (c) Torricelli made the first mercury barometer in 1643. · 6. (a) Bhabha founded TIFR in 1945; Sarabhai founded PRL, Saha the Saha Institute, Raman the Raman

Research Institute. · 7. (d) The transistor was made at Bell Labs in 1947 by Bardeen, Brattain and Shockley. · 8. (c) N_A = 6.022×10^{23} per mole; the other numbers belong to h, e and G. · 9. (c) Halzen led the IceCube Neutrino Observatory at the South Pole, which found high-energy neutrinos from space. · 10. (b) Kepler's three laws (1609, 1619) describe orbits; Newton later explained them by gravitation. · 11. (c) Galileo improved the telescope (1609) and turned it on the sky, and Raman (1930) is the only Indian citizen with the physics Nobel; Thomas Newcomen built the first working steam engine (1712), and Watt made it efficient. · 12. (b) Boyle keeps temperature fixed and Gay-Lussac keeps volume fixed; Charles's law keeps pressure fixed, which is why $V \propto T$. · 13. (a) Light arrives almost at once, so distance ≈ 343 m/s × 3 s ≈ 1 km; 4.4 km wrongly uses the speed of sound in water (≈ 1480 m/s).

NIGHT-BEFORE REVISION

Every ★★★ fact in one place

The facts examiners return to again and again, chapter by chapter. Read these the night before the exam, and on the morning of it.

1. Units, Measurement and Measuring Instruments

★ **Base quantities (7)**: length, mass, time, electric current, temperature, amount of substance, luminous intensity. Force, velocity, work and pressure are derived.

★ **Scalar**: has only size (magnitude). Mass, length, time, speed, distance, temperature, work, energy, power, pressure, density, volume, charge, potential, frequency.

★ **Vector**: has size and direction and adds by the triangle (parallelogram) rule. Displacement, velocity, acceleration, force, weight, momentum, impulse, torque, angular momentum, electric field, magnetic field.

★ **Electric current is a scalar** even though it 'flows' in a direction: two currents meeting at a junction simply add, they do not follow vector addition.

★ **Current density** (current per unit area) **is a vector**; it points along the flow at each point.

★ **Pressure is a scalar**: at a point in a fluid it acts equally in all directions. The force it produces on a surface is a vector.

★ **2019 redefinition**: agreed by the 26th CGPM in November 2018, in force from **20 May 2019** (World Metrology Day). The values of h, e, k and N_A were fixed exactly.

★ **Kilogram** is now defined by the **Planck constant h = 6.626 070 15 × 10^{-34} J s**. The old platinum–iridium cylinder (International Prototype Kilogram, 1889) kept at Sèvres near Paris was retired.

★ **Second** = time of **9 192 631 770** oscillations of the radiation from the **caesium-133** atom (atomic clock definition since 1967).

★ **Tesla from F = BIL**: force on a wire = field × current × length, so B = F/(IL) and **1 T = 1 N A^{-1} m^{-1}** (newton per ampere-metre). Also 1 T = 1 Wb/m^2 = **10^4 gauss**.

★ **Watt** is the unit of all power, electric power included: P = VI, so 1 W = 1 V × 1 A.

★ **Hertz** = one cycle per second; it measures frequency of any wave or vibration (sound, AC mains at 50 Hz in India, radio).

★ **Quantities with no unit (dimensionless)**: **strain** (change in length ÷ original length), refractive index, relative density (specific gravity), coefficient of friction, Poisson's ratio, relative permittivity (dielectric constant), Mach number, efficiency.

★ **Stress and pressure** are both force per area, so both are measured in **pascal**. Strain has no unit because it is a ratio of two lengths.

★ **Everyday prefixes**: kilo 10^3, mega 10^6, giga 10^9, tera 10^{12}; milli 10^{-3}, micro 10^{-6}, nano 10^{-9}, pico 10^{-12}.

★ **Light-year measures distance, not time.** Light covers about 3 × 10^5 km every second; in a year that adds up to about 9.46 × 10^{12} km.

★ **Why astronomers use light-years**: the **speed of light in vacuum is the same everywhere and always**, so it makes a perfect, unchanging yardstick for huge distances.

★ **Order of size**: AU < light-year < parsec. 1 ly ≈ 63 000 AU; 1 pc ≈ 3.26 ly.

★ **kWh to joule**: 1 kWh = 1000 W × 3600 s = **3.6 × 10^6 J**. Example: 250 units = 250 × 3.6 × 10^6 = **9 × 10^8 J**.

★ **kWh is energy, kW is power.** The meter counts energy used; the rating on a heater (2 kW) is its power.

★ **Pressure** = force ÷ area; SI unit **pascal (N/m^2)**. 'kg/cm^2' is strictly mass per area; the pressure unit is **kgf/cm^2** (kilogram-force per square centimetre). So if the options are only kg/cm^2, kg/cm, kg/mm and kg/cm^3, the answer is **none of these**: each is a mass unit over a length, area or volume.

★ **Decibel** (one-tenth of a **bel**, after Alexander Graham Bell): 0 dB = faintest audible sound; whisper ≈ 30 dB; talk ≈ 60 dB; long exposure above ≈ 85 dB damages hearing; pain around 120–130 dB.

★ **Odometer vs speedometer**: odometer = distance covered (km); speedometer = speed right now (km/h). A **chronometer** keeps precise time; an **ammeter** measures current.

★ **Hygrometer vs hydrometer**: hygro = moisture in air (humidity); hydro = water, i.e. density of liquids. The **lactometer** is a hydrometer for milk.

★ **CSIR-NPL, New Delhi** realises and maintains India's national standards of the SI units (mass, length, time, temperature, current, light and others) and calibrates instruments against them.

★ **CSIR-NPL keeps Indian Standard Time (IST)** with a set of **atomic clocks (caesium standards)**, linked to world time (UTC) through the BIPM.

★ **IST = UTC + 5 hours 30 minutes**, based on the **82.5° E (82°30′ E) meridian**, which passes near **Mirzapur (Uttar Pradesh)**; India uses a single time zone.

★ The **82.5° E** meridian crosses **five states**: **Uttar Pradesh, Madhya Pradesh, Chhattisgarh, Odisha and Andhra Pradesh** (north to south). Hook: 'U-M-C-O-A'.

2. Motion, Force and Newton's Laws

★ **Galileo Galilei** first defined **speed** as the distance covered per unit time.

★ **Distance** = total length of the path; always positive. **Displacement** = straight-line gap from start to finish with a direction; can be positive, negative or zero.

★ **Acceleration** = rate of change of velocity, a = (v − u)/t, unit **m/s^2**. Negative acceleration is called **retardation** or deceleration.

- **Equations of uniformly accelerated motion**: $v = u + at$; $s = ut + \frac{1}{2}at^2$; $v^2 = u^2 + 2as$ (u = initial velocity, v = final velocity, a = acceleration, s = displacement, t = time).
- **Slope of a distance–time graph = speed**; a straight sloping line means uniform speed, a flat line means the body is at rest, an upward curve means it is speeding up.
- **Slope of a velocity–time graph = acceleration**; **area under it = displacement** (distance if motion is one way).
- **Free fall**: motion under gravity alone. In **vacuum** a feather, a rubber ball and a wooden ball dropped together **land together**; acceleration $g \approx$ **9.8 m/s²** does not depend on mass.
- **Range is maximum at 45°** to the horizontal (ignoring air resistance).
- **Centripetal force** acts towards the centre and keeps a body moving on a circular path: $F = mv^2/r = m\omega^2 r$.
- **Centrifugation** spins a mixture fast so denser parts move outward and separate: **cream separator** (milk), **washing-machine spin dryer** (water leaves through drum holes), blood centrifuge (red cells settle at the bottom of the tube).
- **Banking of roads**: the outer edge of a curve is raised so the tilt itself provides centripetal force, making turns safe without relying on friction. On railway curves the **outer rail is raised** (cant).
- **First law (law of inertia)**: a body continues in its state of rest or of uniform motion in a straight line unless an external unbalanced force acts on it.
- **Momentum** p = mass × velocity, a vector; unit **kg·m/s** (= N·s).
- **Second law**: force equals the **rate of change of momentum**, $F = \Delta p/\Delta t = ma$, and acts in the direction of the change.
- **Impulse** = force × time = change in momentum; unit N·s. For a fixed change in momentum, **a longer stopping time means a smaller force**.
- **Third law**: to every action there is an **equal and opposite reaction**. The two forces act on **different bodies**, so they never cancel each other.
- **Law of conservation of momentum**: if no external force acts, the total momentum of a system stays constant. It follows from the second and third laws.
- **Gun recoil**: before firing total momentum is zero, so after firing m(bullet) × v(bullet) = M(gun) × V(gun). The gun is much heavier, so it recoils slowly. A 10 g bullet at 400 m/s from a 4 kg gun gives a recoil of 1 m/s.
- **Rocket** works by conservation of momentum: exhaust gas thrown backward gives the rocket equal forward momentum. It carries its own oxidiser and does **not need air to push against**, so it works in space.
- **Static friction** acts before motion starts and **adjusts itself** to match the applied force; its maximum value is **limiting friction**.
- **Rolling friction** is much **smaller than sliding friction**. Order: **limiting static > kinetic (sliding) > rolling**.
- At **constant velocity** the net force is zero, so friction exactly equals the applied force: pushing a box steadily with 200 N means friction is 200 N.
- **Ball bearings** convert **sliding friction into rolling friction** by **reducing the effective area of contact** between the wheel and axle; used in bicycles, cars, fans, motors.
- **Torque (moment of force)** = force × perpendicular distance from the axis; unit **N·m**; it is a vector. Pushing a door near its hinges barely moves it.
- **Centre of gravity (CG)**: the point through which the whole weight of a body acts. It can lie outside the material, e.g. at the centre of a ring or a bangle.
- **Stability** rises with a **low centre of gravity** and a **wide base**. A body topples only when the vertical line through its CG falls **outside its base**.
- **Angular momentum** $L = I\omega$ is **conserved** when no external torque acts: if I falls, ω rises.
- An **ice skater or ballet dancer** spins faster on pulling the arms in, slower on spreading them out.

3. Work, Energy, Power and Simple Machines

- **Work** = force × displacement in the direction of the force: **$W = F s \cos\theta$**. SI unit **joule** (1 J = 1 N × 1 m); it is a **scalar**.
- **Zero work** when force and displacement are at **90°** or when there is no displacement.
- **Kinetic energy** $KE = \frac{1}{2}mv^2$. Since $p = mv$, **$KE = p^2/2m$**. KE can never be negative.
- **Double the velocity → KE becomes 4 times** ($KE \propto v^2$). If **momentum doubles** (same mass), KE also becomes **4 times**.
- **Gravitational potential energy** $PE = mgh$; it is measured from a chosen reference level.
- **Law of conservation of energy**: energy can neither be created nor destroyed, only changed from one form to another; the total energy of an isolated system is constant.
- In **free fall** the PE keeps falling and the KE keeps rising by the same amount; total mechanical energy (KE + PE) stays the same, so the law is **not violated**.
- **Friction converts kinetic energy into heat**; this is why mechanical energy seems to be lost and brakes, tyres and meteors heat up.
- **Power** P = work ÷ time = energy ÷ time; also P = force × velocity. SI unit **watt** (1 W = 1 J/s), named after James Watt.
- **1 horsepower (hp) = 746 W** (≈ 0.75 kW).
- **Kilowatt-hour (kWh)** is the commercial **unit of energy**: 1 kWh = 1000 W × 3600 s = **3.6×10^6 J**. One kWh is the one unit on an electricity bill.
- **Efficiency** = useful output ÷ input × 100%. Always **less than 100%** in real machines, because some energy is lost as heat, sound and friction.
- **Mechanical advantage (MA)** = load ÷ effort. MA > 1 means the machine multiplies force.
- A **lever** is a rigid bar turning about a fixed point, the **fulcrum (F)**. Law of the lever: load × load arm = effort × effort arm. Its class depends on what lies in the middle.
- **Single fixed pulley**: MA = 1 (ideal). It gives no force advantage but **changes the direction** of effort to a convenient pull: hoisting a flag, drawing water from a well.

4. Gravitation and Satellites

- **Universal law of gravitation** (Newton, Principia, 1687): $F = G\,m_1m_2 / r^2$: directly proportional to the product of the masses, inversely proportional to the **square** of the distance between their centres.
- **G** (universal gravitational constant) = $\mathbf{6.67 \times 10^{-11}\ N{\cdot}m^2/kg^2}$; the same everywhere in the universe and unaffected by the medium between the bodies. Henry Cavendish first measured it in 1798.
- **$g \approx 9.8\ m/s^2$** at the surface (about 9.78 at the equator, 9.83 at the poles). It does **not depend on the mass** of the falling body.
- **Latitude**: Earth is an oblate spheroid, bulging at the equator, so the poles are closer to the centre. **g is maximum at the poles and minimum at the equator**; a body weighs most at the poles.
- **Altitude**: g **decreases** as you go up ($g' \approx g(1 - 2h/R)$ for small heights). Weight is a little less on a mountain top.
- **Depth**: g also **decreases** as you go down a mine ($g' = g(1 - d/R)$) and becomes **zero at Earth's centre**.
- If **Earth spun faster**, weight at the equator would **decrease**; if it **stopped spinning**, weight at the equator would increase; at the poles weight would stay the same in both cases.
- **Moon's gravity ≈ 1/6 of Earth's** (1.62 m/s^2): a 60 kg person weighs about 588 N on Earth and about 98 N on the Moon; the mass stays 60 kg.
- **Weightlessness** is the feeling of zero apparent weight in **free fall**. Astronauts in an orbiting station float because they and the station are falling round Earth together; gravity at the ISS (~400 km up) is still about **90% of surface g**.
- A **feather, a rubber ball and a wooden ball** dropped together in vacuum **reach the ground together**.
- A satellite does not fall down because **Earth's gravity supplies exactly the centripetal acceleration** needed for its circular motion; it is in continuous free fall around Earth.
- **Orbital velocity** near Earth's surface ≈ **7.9 km/s** ($v_0 = \sqrt{(gR)}$); it is less for higher orbits (ISS at ~400 km moves at about 7.7 km/s and circles Earth in about 92 minutes).
- **Escape velocity** = minimum speed for a body to leave a planet's gravity for ever: $v_e = \sqrt{(2GM/R)} = \sqrt{(2gR)}$. For **Earth = 11.2 km/s**; for the **Moon ≈ 2.4 km/s**.
- Escape velocity and orbital velocity are **independent of the mass of the body** launched (and escape velocity of the direction of launch). **$v_e = \sqrt{2} \times v_0 \approx 1.41 \times$ orbital velocity.**
- The **Moon has no atmosphere**: its escape velocity (≈ 2.4 km/s) is so low that gas molecules, moving fast in its hot daytime (their rms speed), escape. Earth, with 11.2 km/s, holds on to its air.
- **Every geostationary orbit is geosynchronous, but not every geosynchronous orbit is geostationary**: geostationary needs a circular orbit exactly above the equator.
- **Aditya-L1**, India's first space mission to study the Sun, was launched by **PSLV-C57 on 2 September 2023** and placed in a **halo orbit round L1 on 6 January 2024**; it carries seven instruments, including VELC to study the corona.
- Tides are caused mainly by the **Moon's gravity**; the Sun's tide-raising effect is a little under **half** the Moon's, because tidal force depends on the **difference** in pull across Earth, which falls off with the cube of distance.
- **Spring tides** (highest high tides): at **new moon and full moon** (amavasya, purnima), when Sun, Earth and Moon are in a line. **Neap tides** (weakest): at the **first and last quarter**, when Sun and Moon pull at right angles.
- **Chandrasekhar limit ≈ 1.4 solar masses** (1.44): the maximum mass of a **white dwarf**. A dead core heavier than this collapses further into a **neutron star** or a **black hole**. Our Sun will end as a white dwarf.
- **Subrahmanyan Chandrasekhar** worked out the limit in 1930 and shared the **1983 Nobel Prize in Physics**; NASA's **Chandra X-ray Observatory** is named after him.
- **Black hole**: a region where gravity is so strong that nothing, not even light, escapes from inside its boundary, the **event horizon**; its escape velocity exceeds the speed of light. The name was popularised by John Wheeler in 1967.
- First direct detection: **14 September 2015** (GW150914) by the twin **LIGO** detectors in the USA (Hanford and Livingston), from two black holes merging about 1.3 billion light-years away. The **2017 Nobel Prize in Physics** went to Rainer Weiss, Barry Barish and Kip Thorne.
- **LIGO-India**: a 4 km-arm detector at **Aundha in Hingoli district, Maharashtra**, built by the **Department of Atomic Energy and the Department of Science and Technology** with the US LIGO Laboratory (NSF). The Union Cabinet approved it in April 2023 at about ₹2,600 crore; **ground was broken on 23 April 2026**, and first observations are **targeted for 2030**.

5. Properties of Matter: Solids and Fluids

- **Bose–Einstein condensate (BEC)**, the **fifth state**, was predicted in 1924–25 by **Satyendra Nath Bose** and **Albert Einstein**; first created in 1995 by Eric Cornell and Carl Wieman (Nobel Prize 2001 with Wolfgang Ketterle).
- **Hooke's law** (Robert Hooke, 17th century): within the **elastic limit**, **stress is proportional to strain**. A **spring balance** works on this law.
- **Young's modulus** Y = longitudinal stress ÷ longitudinal strain; unit pascal. **Steel (~200 GPa) is far more elastic than rubber** (a few MPa).
- **Pressure** = force ÷ area (P = F/A); a scalar. SI unit **pascal (Pa) = N/m^2**.
- **Larger area, smaller pressure**: wide straps on school bags, **camel's broad feet** on sand, tractors and tanks on wide crawler tracks, wide foundations for buildings, sleepers under railway lines, snow shoes.
- **Liquid pressure** P = **hρg** (depth × density × g); it increases with depth, acts **equally in all directions**, and does not depend on the shape of the vessel.
- **Dam walls are made thicker at the bottom** because water pressure is greatest at the greatest depth.

- **Normal atmospheric pressure** at sea level ≈ **1.013×10^5 Pa** = 76 cm of mercury = a water column about **10.3 m** high. It **falls with altitude**.
- **Drinking straw, syringe, dropper, suction hook**: you lower the pressure inside, and the **outside air pressure pushes** the liquid in or the hook against the wall.
- **Fountain pen leaks in an aeroplane**: cabin pressure is lower than the air trapped in the ink tube, so the trapped air expands and pushes ink out.
- **Pascal's law** (Blaise Pascal): pressure applied to an **enclosed liquid** is transmitted **undiminished in all directions**.
- In a hydraulic machine $F_1/A_1 = F_2/A_2$, so $\mathbf{F_2 = F_1 \times (A_2/A_1)}$: a small force on a small piston lifts a heavy load on a large piston. Force is multiplied; **work is not** (the large piston moves a shorter distance).
- Applications: **hydraulic lift** (car service stations), **hydraulic brakes** (one pedal sends equal pressure to all four wheels), **hydraulic press** (Bramah press, for baling cotton and pressing metal), hydraulic jack, JCB excavator arms, dentist's and barber's chairs.
- **Archimedes' principle**: a body wholly or partly immersed in a fluid feels an **upward buoyant force equal to the weight of fluid it displaces**; it seems to lose that much weight.
- **Law of flotation**: a body floats when its weight equals the weight of liquid it displaces. A body **less dense than the liquid floats**, a denser one sinks.
- **Ice floating in a glass full to the brim**: when it melts the water **level does not change** and nothing spills, because floating ice already displaced exactly its own weight of water.
- **Icebergs**: ice (917 kg/m³) in sea water (about 1025 kg/m³) floats with **about 9/10 below the surface**, hence the tip of the iceberg.
- A **ship floats higher in the sea than in a river**: denser sea water needs less volume displaced. A ship sailing from a river into the sea **rises a little**. Ships carry a **load line (Plimsoll line)** showing safe loading in different waters.
- **Surface tension**: force per unit length on the liquid surface; unit **N/m** (also J/m²). Water ≈ 0.072 N/m at 25 °C; mercury is much higher (about 0.48 N/m).
- **Raindrops, mercury drops and soap bubbles are spherical** because surface tension minimises area.
- **Kerosene or oil on stagnant water** lowers its surface tension; **mosquito larvae**, which hang from the surface film to breathe, can no longer hold on, sink and drown.
- **Water in glass**: adhesion > cohesion, so water **wets glass**, forms a **concave meniscus** (angle of contact near 0°, acute) and **rises** in a capillary tube.
- **Mercury in glass**: cohesion > adhesion, so mercury **does not wet glass**, forms a **convex meniscus** (angle of contact about 140°, obtuse) and is **depressed** in a capillary.
- **Capillarity**: rise or fall of a liquid in a narrow tube or fine pores, due to surface tension. The **narrower the tube, the higher the rise** ($h = 2T\cos\theta / r\rho g$; height ∝ 1/radius).
- **Hoeing or ploughing** the topsoil **breaks the fine capillaries**, so ground water cannot rise to the surface and evaporate; the soil **retains moisture**. **Rolling** (pressing) the soil does the opposite and brings water up.
- **Viscosity**: a fluid's internal friction, its **resistance to flow** between layers. SI unit of the coefficient of viscosity: **pascal-second (Pa·s)**; CGS unit **poise** (1 Pa·s = 10 poise).
- Order of viscosity: **honey > glycerine > blood > water > air**. Blood is about 3–4 times as viscous as water.
- **Temperature**: heating **lowers the viscosity of liquids** (warm honey and engine oil flow easily) but **raises the viscosity of gases**.
- **Terminal velocity**: a falling body speeds up until drag plus buoyancy equals its weight; then net force is zero and it falls at a **constant speed**.
- **Raindrops** reach terminal velocity of only a few metres per second, so they do not hurt; **bigger drops fall faster** (for small drops, terminal velocity ∝ r^2). Tiny cloud droplets fall so slowly that clouds seem to float.
- **Bernoulli's principle**: for steady flow of an ideal fluid, pressure energy + kinetic energy + potential energy per unit volume stays constant, so **where speed increases, pressure decreases**. It is conservation of energy applied to fluids.
- **Aeroplane lift**: the wing (aerofoil) is shaped and tilted so that air flows **faster over the top**; pressure above falls below that underneath, pushing the wing up.
- **Roofs blown off in storms**: fast wind over a roof lowers the pressure above it while still air inside pushes up; light tin roofs lift off.
- **Atomiser, perfume spray, insecticide pump (Flit gun), paint spray gun, carburettor**: a fast air jet over a tube lowers pressure there, drawing the liquid up and breaking it into a fine spray.

6. Heat and Thermodynamics

- **Direction of flow**: heat flows from **higher temperature to lower temperature**, never by itself from 'more heat' to 'less heat'. It stops when both reach the same temperature (thermal equilibrium).
- **Master formula**: C/5 = (F − 32)/9 = (K − 273.15)/5 = R/4.
- **Celsius → Fahrenheit**: F = (9/5) × C + 32. So **40 °C = 104 °F**, **50 °C = 122 °F**, 30 °C = 86 °F, 100 °C = 212 °F.
- **Fahrenheit → Celsius**: C = (F − 32) × 5/9. So 212 °F = 100 °C, 68 °F = 20 °C.
- **−40** is the only temperature where **Celsius and Fahrenheit read the same**.
- **Normal body temperature ≈ 37 °C = 98.6 °F = 310 K**.
- **Pyrometer** measures very high temperatures from a distance using the radiation a hot body gives out.
- **Railway tracks** have small gaps (expansion joints) so that the rails can lengthen in summer without buckling.
- **Telephone and power wires sag in summer** (they lengthen) and become taut in winter; they are strung loose for this reason.

- **Bimetallic strip**: two metals with different expansion (brass and iron) riveted together. On heating it bends, with the more-expanding brass on the outer (convex) side. It switches the **thermostat** in electric irons, geysers, refrigerators, ACs and fire alarms.
- **Maximum density of water at 4 °C** (about 1000 kg/m^3). Between 4 °C and 0 °C water expands as it cools.
- **Ponds and lakes freeze from the top down**: water cooled to 4 °C is densest and sinks; colder water stays on top and freezes. Water at the bottom stays liquid at about 4 °C, so **fish and plants survive**.
- **Ice floats**: ice (about 917 kg/m^3) is less dense than water; about nine-tenths of an iceberg is under water.
- **Water has the highest specific heat** of common substances, about **4186 J/kg·K**.
- **Coastal climate is mild** (Mumbai, Chennai) while inland places (Delhi, Rajasthan) swing between extremes: the sea warms and cools slowly.
- **Latent heat of fusion of ice** = **334 kJ/kg (80 cal/g)**: absorbed when ice at 0 °C becomes water at 0 °C.
- **Latent heat of vaporisation of water** = **2260 kJ/kg (540 cal/g)**: absorbed when water at 100 °C becomes steam at 100 °C.
- **Steam at 100 °C burns worse** than boiling water or hot air at 100 °C: on condensing on the skin it releases its large latent heat of vaporisation as well.
- **Ice at 0 °C cools a drink better than water at 0 °C**: each kilogram of ice soaks up 334 kJ just to melt, before it even warms.
- **Triple point**: the one temperature and pressure where solid, liquid and gas coexist. For water: **273.16 K (0.01 °C) at about 611 Pa**.
- **More pressure → higher boiling point**. A **pressure cooker** raises the pressure to about 2 atmospheres, so water boils at about **120 °C** and food cooks faster.
- **What sets the temperature in a cooker**: the steam pressure needed to lift the whistle, i.e. the **weight on the vent and the area of the vent hole** (pressure = weight ÷ area). A bigger flame only makes it whistle more often; it does not raise the temperature.
- **Less pressure → lower boiling point**. In the hills water boils below 100 °C (about 1 °C lower for every 300 m or so; about 70 °C on top of Everest), so dal and rice cook slowly.
- **Impurities lower the melting point**: **salt is spread on icy roads** to melt snow; ice + salt forms a **freezing mixture** (down to about −20 °C) used to make kulfi and ice cream.
- **Evaporation causes cooling**: the escaping molecules take latent heat from the surface they leave.
- **Evaporation is faster** with higher temperature, larger surface area, more wind and lower humidity; volatile liquids (spirit, acetone, petrol) evaporate fastest.
- **A fan cools us** because moving air carries away the moist air near the skin and makes **sweat evaporate faster**. The fan does not cool the air.
- **Matka (earthen pot)**: water seeps through tiny pores and evaporates from the outside, cooling the water inside. A wet cloth on a surahi works the same way.
- **Best conductors**: **silver > copper > gold > aluminium**. **Mercury** is the poorest conductor of heat among common metals, worse than lead or zinc.
- **Woollen clothes keep us warm** because wool traps air, a very poor conductor; wool makes no heat of its own.
- **Sea breeze (day)**: land heats faster than sea, air over land rises, cool air blows **from sea to land**.
- **Land breeze (night)**: land cools faster, air over the warmer sea rises, air blows **from land to sea**.
- **Radiation needs no medium**; conduction and convection both need one.
- **Good absorbers are good emitters** (Kirchhoff's law). Dull black surfaces absorb and emit best; white and shiny surfaces reflect.
- **White clothes in summer** reflect sunlight; **dark clothes in winter** absorb it.
- **Wien's law**: $\lambda_{max} \times T$ = constant ($\approx 2.9 \times 10^{-3}$ m·K). Hotter bodies glow at shorter wavelengths, so **hot stars look blue-white and cooler stars red**; heated iron glows red, then orange, then white.
- **Cloudy nights are warmer than clear nights**: clouds absorb and send back the infrared the ground radiates. Dew and frost form on clear, calm nights.
- **Vacuum** between double glass walls stops **conduction and convection**.
- **Silvered walls** reflect heat radiation and stop **radiation** loss or gain.
- **Greenhouse effect**: sunlight (mostly short-wave visible light) passes through the air and warms the ground; the ground re-emits long-wave **infrared**, which **CO_2, water vapour, methane and nitrous oxide** absorb and send back down.
- **Fridge door left open in a closed room**: the room gets **warmer**, not cooler. The fridge only moves heat from inside to the coils outside, and adds the heat from its motor's work.

7. Waves and Sound

- **Sound in air (and in any liquid or gas) is longitudinal**; in solids sound can travel as both longitudinal and transverse waves.
- **Polarisation** happens only with transverse waves; that light can be polarised proves it is transverse. Sound cannot be polarised.
- **Wave equation**: **$v = f \times \lambda$**. Sound at 340 m/s with frequency 340 Hz has a wavelength of 1 m.
- **Frequency is set by the source** and does not change when the wave enters another medium; **speed and wavelength change**.
- **Sound needs a medium**; it cannot travel through vacuum. **On the Moon** there is no air, so astronauts talk by radio (electromagnetic waves).
- **Order**: **solids > liquids > gases**. Sound is fastest in solids such as **steel**, about 17 times faster than in air.
- **Temperature**: speed in air rises by about **0.6 m/s for each 1 °C** (331 m/s at 0 °C, 343 m/s at 20 °C).

- **Humidity**: sound is **faster in humid air**, because moist air is lighter (less dense) than dry air at the same temperature.
- **Pressure**: changing the pressure of air at constant temperature has **no effect** on the speed of sound.
- **Light (3×10^8 m/s) is about a million times faster** than sound: we see lightning before we hear thunder, see a cracker burst before hearing it, and see a distant batsman hit before hearing the bat.
- **Distance of a storm**: count seconds between flash and thunder; **every 3 seconds ≈ 1 km** (sound covers about 340 m each second).
- **Audible range** of humans: **20 Hz to 20 kHz**. The upper limit falls with age; children and young people hear the highest notes.
- **Infrasound** (below 20 Hz): produced by **earthquakes** (before the main shock, which is why some animals get restless), volcanoes, a swinging pendulum; used for communication by **elephants, whales and rhinoceroses**.
- **Ultrasound** (above 20 kHz): heard by **bats, dolphins, porpoises, dogs** and rats. Dogs hear up to about 45 kHz, so a 'silent' dog whistle works.
- **Ultrasound scans (ultrasonography)** show the **foetus in the womb**, gall and kidney stones and tumours. Ultrasound is non-ionising, so it is safe for the foetus, unlike X-rays.
- **SONAR** (**SO**und **N**avigation **A**nd **R**anging) sends ultrasound into water and times the echo to find **sea depth**, submarines, shoals of fish, icebergs and shipwrecks. **Depth = speed × time ÷ 2**.
- **Echolocation**: **bats** fly and hunt in the dark by emitting ultrasonic squeaks and listening for echoes; **dolphins** do the same in water.
- **Echo** needs the reflection to arrive **at least 0.1 s** after the original sound.
- **Minimum distance for an echo ≈ 17.2 m** in air (at 344 m/s, sound covers 34.4 m in 0.1 s: there and back).
- **Reverberation**: persistence of sound in a hall from many reflections arriving within 0.1 s; too much of it makes speech unclear.
- **Higher frequency → higher pitch**. **Women's and children's voices are shriller** because their vocal cords are shorter and thinner and vibrate faster.
- **Loudness depends on amplitude**, not frequency. A lion's roar is loud but low-pitched; a mosquito's buzz is faint but high-pitched.
- **+10 dB = 10 times the intensity**; +20 dB = 100 times; +3 dB ≈ double.
- **Soldiers break step** while crossing a bridge: marching in step could match the bridge's natural frequency and set up dangerous resonance.
- **Radio and TV tuning**: turning the knob changes the natural frequency of the receiver circuit until it matches (resonates with) one station's frequency (electrical resonance).
- **Approaching** source or listener → **higher** apparent pitch; **receding** → **lower** pitch. The source's actual frequency does not change.
- **Train horn or ambulance siren** drops in pitch the moment it passes you.
- **Red shift**: light from distant galaxies is shifted to longer (redder) wavelengths, so they are moving away; Edwin Hubble (1929) used this to show the **universe is expanding**.
- **Mach number** = speed of the object ÷ speed of sound in the same medium. **Subsonic** below 1, **supersonic** above 1, **hypersonic** above 5.
- **Sonic boom**: a supersonic aircraft drags a cone-shaped **shock wave** behind it; the cone sweeping over the ground is heard as a loud boom, all along the flight path, not just at the moment the plane crosses Mach 1.
- **Frequency of a stretched string** rises with **tension** and falls with **length** and **thickness (mass per unit length)**: $f \propto (1/L)\sqrt{(T/m)}$.
- **Tuning a sitar or violin** by turning the pegs changes the string's **tension**, and so its **frequency**, to match the other instruments.
- **Stethoscope** (René Laennec, 1816): the chest-piece picks up heart and lung sounds, which reach the doctor's ears through the tubes by **multiple reflection** of sound.

8. Light I: Reflection, Refraction and Optical Phenomena

- **Speed of light in vacuum** c = 299,792,458 m/s exactly (≈ **3×10^8 m/s**). Nothing travels faster. The metre itself is defined from this value.
- **Slower in matter**: air ≈ c; water ≈ 2.25×10^8 m/s; glass ≈ 2×10^8 m/s; diamond ≈ 1.24×10^8 m/s. The higher the refractive index, the slower the light ($v = c/n$).
- **Sun to Earth**: light takes ≈ **8 min 20 s** (≈ 499 s) over 1 AU (≈ 1.5×10^8 km). Moon to Earth ≈ **1.3 s**.
- **Shadow** forms because of **rectilinear propagation** of light: opaque objects stop light, transparent ones let it pass, translucent ones let some through.
- **Laws of reflection**: (1) angle of incidence = angle of reflection, both measured from the **normal**; (2) incident ray, reflected ray and normal lie in **one plane**. They hold for plane and curved mirrors alike.
- **Plane-mirror image**: **virtual, erect, same size**, as far behind the mirror as the object is in front, and **laterally inverted** (left and right swapped).
- **AMBULANCE** is painted in mirror writing on the front so that a driver ahead reads it correctly in the rear-view mirror.
- **Focal length of a plane mirror = infinity** (its radius of curvature is infinite). Magnification = +1.
- **Full-length image**: the mirror needs to be only **half your height**, whatever your distance from it (top edge level with the point midway between eyes and the top of the head).
- **Two mirrors at angle θ** give **360/θ − 1** images (exact when 360/θ is even): 90° → 3, 60° → 5, 45° → 7, 30° → 11. **Parallel mirrors** (θ = 0, as in a barbershop or lift) give **infinite** images.

- **Concave mirror uses**: shaving and make-up mirrors, dentist's and ENT doctor's mirrors (enlarged erect view), reflectors of torches, vehicle headlights and searchlights (bulb at focus), solar cookers and solar furnaces (sunlight focused to a hot spot), reflecting telescopes, dish antennas.
- **Convex mirror uses**: rear-view and side mirrors of vehicles, blind-turn mirrors on hill roads, security mirrors in shops and ATMs: always an erect image and a much **wider field of view**.
- **Frequency stays the same** when light goes from one medium to another; **speed and wavelength change** (λ in medium = λ in vacuum / n). Colour depends on frequency, so a red light still looks red under water.
- **Bending rule**: rarer → denser: towards the normal; denser → rarer: away from the normal. A ray along the normal (90° to the surface) goes straight without bending.
- **Refractive index** n = c / v (speed in vacuum ÷ speed in medium). Air 1.0003, ice 1.31, **water 1.33**, alcohol 1.36, kerosene 1.44, **glass ≈ 1.5**, rock salt 1.54, ruby 1.71, **diamond 2.42**.
- **Twinkling of stars** is due to **atmospheric refraction**. A star is so far away that it is a **point source**; its light passes through moving air layers of changing refractive index, so its apparent position and brightness keep flickering.
- **Planets do not twinkle**: they are near enough to look like small **discs**. A disc is many point sources together; their flickers average out.
- **Advanced sunrise and delayed sunset**: refraction lets us see the Sun about **2 minutes before** it actually rises and **2 minutes after** it sets, lengthening the day by about 4 minutes.
- **Two conditions for TIR**: light must go from **denser to rarer** medium, and the angle of incidence must be **greater than the critical angle**.
- **Diamond sparkles** because its critical angle is tiny; light entering a well-cut diamond is totally reflected again and again inside before escaping through the top.
- **Optical fibre**: a thin glass core of higher n inside a cladding of lower n. Light keeps hitting the boundary above the critical angle and is trapped, following the fibre even round bends. Used for internet and telephone links, endoscopy (seeing inside the body) and decorative lamps.
- **Mirage** (deserts and hot roads in summer): air near the hot ground is hotter and **rarer**. Light from the sky bends more and more upward through the layers and is finally totally reflected, so the eye sees an inverted image of the sky on the ground that looks like a pool of water.
- **Dispersion**: splitting of white light into seven colours, **VIBGYOR** (violet, indigo, blue, green, yellow, orange, red). **Isaac Newton** showed it with a glass prism (1666).
- **Violet deviates most, red least**: glass has the highest refractive index for violet, so violet travels slowest in glass and bends most. In vacuum all colours travel at the same speed.
- **Rainbow = refraction + dispersion + internal reflection** inside water drops.
- **Sun behind the observer**, rain in front: a rainbow is always seen in the part of the sky **opposite the Sun**: in the **west in the morning**, in the **east in the evening**.
- **Primary rainbow**: one internal reflection, brighter, **red on the outside (top)**, violet inside.
- **Blue sky**: air molecules scatter blue far more than red; this scattered blue reaches our eyes from every direction of the sky. (Violet scatters even more, but sunlight has less violet and our eyes are less sensitive to it.)
- **Red/orange Sun at sunrise and sunset**: light from the low Sun crosses a much longer path of air; most blue is scattered out on the way, leaving red and orange. At noon the path is short and the Sun looks white.
- **Danger and stop signals are red**: red is scattered least, so it travels farthest through fog, smoke and dust and is seen from a distance.
- **Black sky in space**: with no air to scatter sunlight, the sky looks black to astronauts and from the Moon, even in daytime.
- **C.V. Raman** discovered it with **K.S. Krishnan** in Kolkata; announced on **28 February 1928**. Raman won the **Nobel Prize in Physics, 1930**, the first Asian to win a Nobel Prize in science. He received the Bharat Ratna in 1954.
- **National Science Day** is celebrated on **28 February** every year (since 1987) to mark the discovery.
- **Soap bubbles and oil films** on a wet road show colours because of **interference** of light in thin films; the colours change as the film thickness changes.

9. Light II: Lenses, the Human Eye and Optical Instruments

- **Magnifying glass (reading lens)** is a **convex lens** of short focal length, held so that the object is within its focal length.
- **Part of the lens covered**: every part of a lens receives light from every point of the object, so covering half the lens, or painting black strips across it, still forms the **complete image**, only **less bright**.
- **Power** P = 1/f, with f in **metres**. SI unit: **dioptre (D)** = m^{-1}. Convex lens: positive power; concave lens: negative power.
- **Examples**: f = +50 cm → P = +2 D; f = +25 cm → +4 D; a lens of −2.5 D is concave with f = −40 cm.
- **Image on the retina** is **real, inverted and diminished**; the brain interprets it as upright.
- **Accommodation**: the eye's ability to change the focal length of its lens with the ciliary muscles so that both near and far objects are focused on the retina.
- **Near point** of a normal adult eye = **25 cm** (least distance of distinct vision); **far point** = **infinity**. So a normal eye sees clearly from 25 cm to infinity.
- **Colour blindness**: some **cones** are missing or faulty, usually red–green confusion. It is **inherited** (gene on the X chromosome), so far commoner in **men** (about 8%) than women; it has no cure and is checked with the Ishihara dot test.

- **Night blindness**: the **rods** cannot work in dim light because the pigment **rhodopsin** needs **vitamin A**; vitamin A deficiency causes it (carrots, leafy greens, mango, papaya, eggs help).
- **Persistence of vision**: an impression stays on the retina for about **1/16 of a second**.
- **Cinema** works on it: films show **24 frames per second**, faster than 16, so separate still pictures look like continuous motion.
- **Resolving power** of a telescope (ability to show two close stars as separate) **increases with the diameter of the objective**; a wider objective also gathers more light, so fainter objects become visible.
- **Why large telescopes are reflecting**: a mirror has no chromatic aberration (it reflects all colours alike), can be supported from behind, needs only one surface polished and can be made very large; big lenses sag and split colours. The largest refractor ever built for research, the Yerkes refractor (USA, 1897), has a lens only about 1 m (40 inches) wide.
- **Opaque object's colour** = colour of light it reflects. **White** reflects all colours; **black** absorbs all (so black clothes get hotter in the sun). A green leaf reflects green and absorbs red and blue for photosynthesis.
- **Primary colours of light**: **red, green, blue (RGB)**. Mixing light: red + green = **yellow**; green + blue = **cyan**; blue + red = **magenta**; red + green + blue = **white**. TV, mobile and LED screens make every colour from tiny RGB dots.

10. Electromagnetic Spectrum and Wave Optics

- **Speed**: every EM wave travels at **$c \approx 3 \times 10^8$ m/s in vacuum**, whatever its wavelength; it is slower inside matter.
- **Transverse**: the electric and magnetic fields vibrate at right angles to each other and to the direction of travel. That is why light can be polarised.
- **No medium needed**: EM waves cross empty space (sunlight reaches Earth); sound cannot.
- **Uncharged**: EM waves are not deflected by electric or magnetic fields. X-rays and gamma rays go straight through such fields.
- **Wave relation**: $c = f \times \lambda$. Photon energy $E = h \times f$, so higher frequency means higher energy. FM at 100 MHz has $\lambda = 3$ m; green light (~500 nm) has $f \approx 6 \times 10^{14}$ Hz.
- **Energy and frequency order (low → high)**: radio < microwave < infrared < visible < ultraviolet < X-rays < gamma. **Wavelength order is the reverse**: radio longest, gamma shortest.
- **Microwave oven** works at **2.45 GHz**: water (and fat, sugar) molecules are electrically lopsided, so they twist back and forth with the rapidly reversing field; this jostling heats the food. Glass, ceramic and microwave-safe plastic let microwaves through and stay cool; **metal reflects** them and can spark.
- **Infrared = heat rays**: every warm body gives out IR. Uses: **TV and AC remotes**, **night vision and thermal cameras** (army, border security, fever screening), **heat therapy for muscle aches** by physiotherapists, drying paint, IR remote sensing of crops and forest fires.
- **Visible light**: **400–700 nm** (outer limits about 380–780 nm, i.e. about **3900–7800 Å**). The eye is most sensitive to yellow-green light (~555 nm).
- **Ultraviolet**: the Sun is the main source. **UV-A** (315–400 nm) mostly reaches the ground (tanning, skin ageing); **UV-B** (280–315 nm) is mostly absorbed by ozone (sunburn, skin cancer, but also makes **vitamin D** in the skin); **UV-C** (100–280 nm) is fully absorbed by ozone and oxygen.
- **UV in water purifiers** kills or inactivates bacteria and viruses by damaging their DNA. It does **not** remove odour, dissolved salts or turbidity (that needs filters or RO).
- **X-rays**: made when fast electrons strike a metal target (tungsten) in an X-ray tube. They pass through flesh but are absorbed by **bones** (calcium), giving shadow pictures. Uses: fractures, dental X-rays, **CT scans**, mammography, **airport and border baggage scanners**, detecting cracks in metal castings, **X-ray crystallography** (the structure of DNA was worked out from an X-ray picture).
- **Gamma rays**: given out by radioactive nuclei (cobalt-60, caesium-137) and nuclear reactions. Uses: **radiotherapy** to kill cancer cells (cobalt therapy, gamma knife), **sterilising** syringes, gloves and surgical instruments, **food irradiation** to stop sprouting of onions and potatoes and kill insects in spices and mangoes.
- **Interference**: two light waves overlap; crest on crest gives brightness (constructive), crest on trough gives darkness (destructive). It needs **coherent** sources (same frequency, steady phase). **Thomas Young's double-slit experiment (1801)** proved light is a wave.
- **Thin-film colours**: **soap bubbles**, **oil films on wet roads**, **peacock feathers** and butterfly wings shine in changing colours because light reflected from the two surfaces of a very thin layer interferes.
- **Diffraction**: bending of waves round the edges of an obstacle or through a narrow opening; strong only when the gap is comparable to the wavelength.
- **Polarisation**: ordinary light vibrates in all directions across its path; a **polaroid** lets through only one direction. Only **transverse** waves can be polarised, so polarisation proves light is transverse. Sound in air (longitudinal) cannot be polarised.
- **LASER** = **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. Einstein proposed stimulated emission (1917); **Theodore Maiman** built the first laser, a **ruby laser**, in **1960**. The microwave version (maser) came first.
- **Properties**: **monochromatic** (one wavelength), **coherent** (all waves in step), **highly directional** (a narrow beam that hardly spreads), and **intense**.
- **Medicine**: **LASIK** eye surgery (an ultraviolet excimer laser reshapes the cornea), bloodless surgery, breaking kidney stones, removing tattoos, retina repair.

11. Electricity: Charge, Current and Circuits

- **Two kinds** of charge: positive and negative. **Like charges repel, unlike charges attract.**
- **SI unit**: coulomb (C). Charge of one electron **$e = 1.6 \times 10^{-19}$ C** (negative); a proton carries the same amount, positive.
- **Quantisation**: any charge is a whole-number multiple of e ($q = ne$). You can never have 1.5 e on a body.

- **Conservation**: charge is neither created nor destroyed; in rubbing it only moves. Glass and silk end up with equal and opposite charges.
- **Repulsion is the sure test** of charge: only two charged bodies can repel.
- **Lightning**: friction among ice and water particles separates charge inside a cumulonimbus cloud; when the field gets strong enough, air breaks down and a giant spark jumps to another cloud or to the ground. **Benjamin Franklin** showed lightning is electricity with his kite experiment (1752).
- **Lightning conductor**: a pointed metal (copper) rod above the highest point of a building, joined by a thick strip to a plate buried in moist earth. Charge crowds at sharp points, so the rod leads the strike safely to the ground.
- **Silver** is the best conductor; **copper** is used in household wiring (nearly as good, much cheaper); **aluminium** in overhead transmission lines (light and cheap).
- **Electric current** I = charge flowing per second, I = Q/t. Unit **ampere** (A), one of the seven SI base units; 1 A = 1 C/s.
- **Conventional current** flows from + to − outside the cell; **electrons** actually drift the other way, from − to +.
- **Potential difference** (voltage) = work done per unit charge between two points; unit **volt** (V), named after Alessandro Volta.
- **Ohm's law**: V = IR, so **R = V/I** and I = V/R. Holds when temperature and physical conditions stay the same.
- **Unit of resistance**: ohm (Ω); 1 Ω = 1 V/A. **Conductance** G = 1/R, unit siemens (S), old name mho (℧).
- **R = ρL/A**: resistance grows with **length** (L) and falls with **cross-sectional area** (A). ρ (rho) is the **resistivity**.
- **Resistivity** depends only on the material and its temperature, not on shape or size. Unit **ohm-metre (Ω m)**.
- **Temperature**: in metals resistance **rises** with heat (vibrating atoms block electrons); in **semiconductors it falls** (heat frees more charge carriers).
- **House wiring is parallel**: every appliance gets the full 230 V, each has its own switch, one fused bulb does not black out the house, and total resistance stays low.
- **Joule's law of heating**: $H = I^2Rt$ (heat in joules, current in A, resistance in Ω, time in s).
- **Heating element**: **nichrome** (nickel-chromium alloy): high resistivity, high melting point (about 1400 °C), does not oxidise easily when red-hot.
- **Bulb filament**: **tungsten**, the metal with the highest melting point (**3422 °C**). It glows white-hot at around 2500 °C.
- **Bulb gas**: filled with inert **argon and/or nitrogen** so the hot tungsten does not oxidise and evaporates more slowly. The filament is coiled to pack more length in.
- **Fuse**: a short wire of **tin-lead alloy** with a **low melting point** (and higher resistivity than copper), connected **in series on the live wire**. When current exceeds its rating it melts and breaks the circuit, protecting wiring and appliances.
- **Short circuit**: live and neutral touch directly (damaged insulation). Resistance falls to almost zero, so **current becomes very large**, wires heat up and can start a fire.
- **MCB** (miniature circuit breaker): an automatic switch that trips on overload or short circuit and can simply be switched back on; it is replacing fuses.
- **ELCB / RCCB** (earth-leakage / residual-current circuit breaker): compares current in live and neutral. If some current leaks away, for example through a person to earth, it trips within a fraction of a second (typical setting 30 mA). It protects **people** from shock.
- **Electric power** $P = VI = I^2R = V^2/R$. Unit **watt** (W) = 1 J/s. 1 kW = 1000 W; 1 horsepower = 746 W.
- **Energy** = power × time. Commercial unit: **kilowatt-hour (kWh) = 1 unit = 3.6 × 10^6 J** (1000 W × 3600 s).
- **Step up 10 times** in voltage → current falls to 1/10 → line loss falls to **1/100**.
- **India**: 230 V, 50 Hz single-phase supply (three-phase 415 V); the Indian Standard system voltage is 240/415 V, and **220 V** is the older figure many questions still use. **USA**: 120 V, 60 Hz. Japan uses 50 Hz in the east and 60 Hz in the west.
- **Capacitive reactance** $X_C = 1/(2\pi fC)$: **inversely proportional to frequency**. A capacitor blocks DC (f = 0) and passes high-frequency AC easily.
- **Earthing**: the metal body of an iron, fridge, washing machine, geyser or cooler is joined to the earth wire. If the live wire touches the body, a large current rushes to earth, the fuse blows or MCB/RCCB trips, and the body never stays at 230 V.
- **Three-pin plug**: the **earth pin is longer and thicker**. Longer, so it connects first and disconnects last; thicker, so it cannot be pushed into a live or neutral hole.
- **Switches and fuses go on the live wire**, so that switching off cuts the appliance away from 230 V.
- **Bird on a wire is safe**: both feet touch the same wire at the same potential, so there is no potential difference across its body and no current flows. A bird or monkey that touches two wires, or a wire and the pole, is electrocuted.
- **Primary cells** cannot be recharged (the reaction is one-way); **secondary cells** can be recharged by passing current backwards.

12. Magnetism and Electromagnetism

- **Every magnet has two poles**, north (N) and south (S); the attraction is strongest at the poles and weakest at the middle.
- **Like poles repel, unlike poles attract.**
- **Repulsion is the sure test** of a magnet: a magnet attracts both a magnet's opposite pole and a plain piece of iron, but only another magnet can be repelled.
- **Breaking a magnet** gives two complete smaller magnets, each with its own N and S. An isolated single pole (**monopole**) has never been found.
- **Field lines** are imaginary curves that show the direction a free north pole would move. Outside the magnet they run **N → S**; inside, **S → N**. They form **closed loops**.

- **Curie temperature**: above it a ferromagnet loses its ferromagnetism and becomes paramagnetic. **Iron 770 °C**, nickel ≈ 358 °C, cobalt ≈ 1115 °C, gadolinium ≈ 20 °C. Named after **Pierre Curie**.
- **The magnetic pole near geographic north is magnetically a south pole**: it attracts the north-seeking end of the compass needle.
- **Magnetic declination**: the angle between geographic north (true north) and magnetic north at a place, i.e. between the geographic and magnetic meridians.
- **Dip (inclination)**: the angle Earth's field makes with the horizontal. **90° at the magnetic poles** (needle stands vertical), **0° at the magnetic equator** (needle lies flat). Measured with a **dip circle**.
- **Auroras**: charged particles guided along field lines into the upper atmosphere near the poles collide with gas atoms, which glow. **Aurora borealis** (northern lights) and **aurora australis** (southern lights).
- **Van Allen radiation belts**: two doughnut-shaped zones of charged particles trapped by Earth's field; the inner belt is rich in energetic protons, the outer belt mainly in electrons. Discovered in **1958** by **James Van Allen** from Explorer 1 data.
- **Oersted's experiment** (1820): a current-carrying wire deflects a compass needle; reversing the current reverses the deflection.
- **Right-hand thumb rule**: grip the wire with the right hand, thumb along the current; the curled fingers show the direction of the magnetic field. (Maxwell's corkscrew rule says the same.)
- **Solenoid**: a long coil of many turns. With current it behaves like a **bar magnet**; the field inside is strong and nearly uniform.
- **Electromagnet**: a solenoid with a **soft-iron core**. It is a temporary magnet, strong while current flows and dead when it stops.
- **Fleming's left-hand rule** (motor rule): stretch thumb, first finger and second finger of the **left** hand at right angles. **First finger = Field**, **seCond finger = Current**, **thuMb = Motion (force)**.
- **Electric motor** converts **electrical energy into mechanical energy**.
- **Electromagnetic induction**: a changing magnetic flux through a circuit induces an emf (and a current if the circuit is closed). Discovered by **Faraday (1831)**; Joseph Henry found it independently.
- **Faraday's law**: induced emf = rate of change of magnetic flux ($\varepsilon = -N\,\Delta\Phi/\Delta t$). More turns, a stronger magnet or faster motion give a larger emf.
- **Lenz's law** (1834): the induced current flows in a direction that **opposes the change** that produced it. It is a consequence of the **conservation of energy**: you must do work to push the magnet in.
- **AC generator (alternator)**: the coil's ends connect through **slip rings** to brushes, so the output follows the coil and is **AC**. All power stations (thermal, hydro, nuclear, wind) use alternators; turbines merely spin them.
- **Principle**: **mutual induction**. Works **only on AC**: steady DC gives a constant flux, so nothing is induced (and the primary may overheat).
- **Turns ratio**: $V_s/V_p = N_s/N_p = I_p/I_s$. Voltage goes up exactly as much as current goes down.
- **Step-up** ($N_s > N_p$) raises voltage and lowers current: used at the **power station**. **Step-down** ($N_s < N_p$): used at substations and the **distribution transformer near homes**, and inside chargers and adapters.
- **Why high-voltage transmission**: for the same power, high voltage means low current, and line loss I^2R falls with the square of the current. That is the main reason AC, which transformers can step up and down, became the standard.

13. Atoms, Nuclei and Radioactivity

- **Gold foil result**: most alpha particles went straight through (atom is mostly empty); a few were deflected; about 1 in 12,000 bounced straight back (a small, heavy, positive nucleus).
- **Atomic number (Z)** = number of protons (= electrons in a neutral atom). It fixes the element and its place in the periodic table.
- **Mass number (A)** = protons + neutrons (together called **nucleons**). **Neutrons = A − Z**. Written as $^{12}_{6}C$: A on top, Z below.
- **S.N. Bose** (Kolkata) sent his 1924 paper on counting photons to Einstein, who translated and extended it: hence **Bose–Einstein statistics**. Paul Dirac coined the word 'boson'.
- **Higgs boson**: predicted in **1964** (Peter Higgs and others); discovery announced on **4 July 2012** by the ATLAS and CMS experiments at CERN's **Large Hadron Collider**; Nobel 2013 to Higgs and François Englert.
- **Why it matters**: the Higgs field gives elementary particles their **mass**. It has nothing to do with teleporting matter or better fission fuel.
- **Positron** (anti-electron) was the first antiparticle found (Anderson, 1932); the **antiproton** followed in 1955.
- **Why make antimatter**: to probe whether stars or galaxies made of antimatter could exist and to understand why the universe ended up made almost entirely of matter (its evolution). It has no use in mineral or oil prospecting.
- **Henri Becquerel** discovered radioactivity in **1896** by chance: uranium salts fogged a wrapped photographic plate.
- **Marie and Pierre Curie** discovered **polonium** (named after Marie's homeland, Poland) and **radium** in 1898; Marie coined the word 'radioactivity'.
- **Amount left after n half-lives** = original × $(½)^n$. After 3 half-lives, 1/8 remains; after 10, about 1/1000.
- **Carbon-14 dating** (Willard Libby, 1949; Chemistry Nobel 1960): cosmic-ray neutrons turn nitrogen-14 into C-14 in the air; plants take it in as CO_2 and animals eat the plants. While alive, the C-14 : C-12 ratio stays steady; after death no new C-14 enters and it decays.

- **Carbon dating works only on once-living material** (wood, bone, charcoal, cloth, paper, shells) and only up to about **50,000 years**.
- **Rocks and the age of Earth** are dated by long half-life isotopes: **uranium–lead** (age of Earth ≈ 4.54 billion years), **potassium–argon** (volcanic rock), rubidium–strontium.
- **Hazards**: ionising radiation damages cells and DNA, causing burns, **radiation sickness**, cancers such as **leukaemia** and genetic mutations.
- **$E = mc^2$** (Einstein, 1905, special relativity): 1 gram of mass ≡ 9×10^{13} J, roughly the energy of 20,000 tonnes of TNT.
- **Mass defect** = (mass of separate nucleons) − (mass of nucleus). **Binding energy** = mass defect × c^2: the energy needed to pull the nucleus apart.
- **Electron-volt (eV)**: energy gained by one electron accelerated through 1 volt = **1.6×10^{-19} J**. In general a charge q through potential difference V gains **qV**, so an electron (charge e) through V volts gains **eV** joules, whatever its mass.
- **Discovery of fission**: Otto Hahn and Fritz Strassmann (1938); explained by Lise Meitner and Otto Frisch.
- **Typical fission**: U-235 + slow neutron → barium + krypton + 2–3 neutrons + about **200 MeV**.
- **Chain reaction**: neutrons from one fission cause more fissions. **Critical mass** is the least amount of fissile material that can sustain it.
- **Sun and stars** shine by **fusion** of hydrogen into helium in their cores (about 15 million °C in the Sun's core); Hans Bethe explained this (Nobel 1967). The Sun turns about 4 million tonnes of mass into energy every second.
- **Stage 1 – PHWRs** burn **natural uranium** with heavy water; their spent fuel is reprocessed for **plutonium**.
- **Stage 2 – Fast breeder reactors** burn plutonium (MOX fuel, liquid-sodium coolant) and breed more fuel; a thorium blanket turns into **U-233**. The **PFBR** was designed by **IGCAR** and built by **BHAVINI**, with about 90% Indian-made equipment.
- **Stage 3 – Thorium reactors** run on U-233 and thorium-232; BARC's **Advanced Heavy Water Reactor (AHWR)** is the design.
- **Fleet in 2026**: **24 power reactors** with **≈ 8.78 GW** installed capacity, run by **NPCIL**; nine more units (≈ 7.5 GW) under construction, and ten 700 MWe PHWRs approved for 'fleet mode' building.
- **Target**: **100 GW of nuclear power by 2047** (Viksit Bharat goal); capacity is planned to reach about 22 GW by 2031–32.
- **SHANTI Act, 2025** (Sustainable Harnessing and Advancement of Nuclear Energy for Transforming India; assent 20 December 2025): replaced the Atomic Energy Act 1962 and the Civil Liability for Nuclear Damage Act 2010 and allows **private companies** to build, own and run nuclear plants; sensitive fuel-cycle work stays with the government.
- **Max Planck** (1900): energy is emitted in packets, **$E = h\nu$** (h = Planck's constant ≈ 6.63×10^{-34} J s, ν = frequency). Father of quantum theory; Nobel 1918.
- **Photoelectric effect**: light of high enough frequency falling on a metal knocks out electrons. Seen by Hertz (1887); explained by **Einstein (1905)** using light particles (photons).
- **Einstein's Nobel Prize in Physics (1921)** was for the **photoelectric effect**, not for relativity or $E = mc^2$.
- **Threshold frequency**: below it, no electron comes out however bright the light. Above it, emission is instant.
- **Frequency decides energy, intensity decides number**: the energy of each ejected electron rises with frequency; brighter light only ejects **more** electrons.
- **Wilhelm Röntgen** discovered X-rays on **8 November 1895** (Germany); he received the **first Nobel Prize in Physics (1901)**. Element 111, roentgenium, is named after him.
- **Production**: electrons from a hot filament are accelerated by high voltage onto a **tungsten** target (high atomic number and very high melting point) in a vacuum tube (Coolidge tube).
- **Cosmic rays** are **high-energy charged particles** from space: about 90% **protons**, about 9% alpha particles (helium nuclei), the rest heavier nuclei and electrons.
- **CERN** (European Organization for Nuclear Research, 1954) near **Geneva** on the France–Switzerland border runs the **Large Hadron Collider (LHC)**: a **27 km** ring about 100 m underground where protons collide at nearly light speed; its superconducting magnets are cooled to 1.9 K.

14. Semiconductors, Electronics and Modern Devices

- **Semiconductor + heat**: extra heat frees more electrons from bonds, so its **resistance decreases** (negative temperature coefficient). In metals, heat makes atoms vibrate more and block electrons, so resistance **increases**.
- **Silicon (Si)** and **germanium (Ge)** are group-14 elements with **4 valence electrons**. Band gap: Si ≈ **1.1 eV**, Ge ≈ **0.7 eV**.
- **Hole**: the empty place left when an electron leaves a bond. Neighbouring electrons jump into it, so the hole moves like a **positive charge**.
- **Forward bias**: p-side to **+**, n-side to **−**: barrier lowered, **large current** (acts like a closed switch). Silicon needs about **0.7 V** to start conducting (germanium about 0.3 V).
- **Reverse bias**: p-side to −, n-side to +: depletion layer widens, **almost no current**. At a large enough reverse voltage it **breaks down**.
- **Rectifier** converts **AC into DC** using diodes. **Half-wave**: one diode, uses only half of each cycle. **Full-wave**: two diodes with a centre-tapped transformer, or **four diodes in a bridge**; uses both halves.
- **Photoelectric cell** (any of these light-sensing cells) **converts light energy into electrical energy**.
- **LED colour depends on the band gap** of its material: gallium arsenide → infrared (TV remote), gallium arsenide phosphide → red, orange, yellow; gallium nitride / indium gallium nitride → **blue** and green.

- **Blue LED**: Isamu Akasaki, Hiroshi Amano and Shuji Nakamura, **Physics Nobel 2014**. A blue LED coated with a yellow phosphor gives **white light**, so it made LED bulbs possible.
- **Transistor**: invented in **1947** at **Bell Labs** (USA) by **John Bardeen, Walter Brattain and William Shockley**; Physics Nobel **1956**. The first one was made of germanium.
- **Structure**: three layers, **npn** or **pnp**, with three terminals: **emitter, base, collector**. A small base current controls a large collector current.
- **Two jobs**: **amplifier** (makes weak signals strong: radios, microphones, hearing aids) and **switch** (on/off = 1/0 in digital circuits).
- **Integrated circuit (IC/chip)**: many transistors, resistors and capacitors on one small piece of silicon. **Jack Kilby** (Texas Instruments, 1958; Nobel 2000) and **Robert Noyce** (Fairchild, 1959, silicon IC; later co-founded Intel) invented it independently.
- **Universal gates**: **NAND** and **NOR**. Any other gate, and so any digital circuit, can be built from NAND gates alone or NOR gates alone.
- **Discovery**: Heike Kamerlingh Onnes, **1911**: mercury lost all resistance at **4.2 K** (−269 °C), cooled by liquid helium (Nobel 1913).
- **Two signatures**: (1) **zero electrical resistance** below the critical temperature; (2) **Meissner effect** (1933): the material **expels magnetic field** lines (perfect diamagnetism), which makes **magnetic levitation** possible.
- **OLED advantages over LCD**: can be made on **flexible plastic**, so **roll-up displays** (even in clothing) and **transparent displays** are possible; used in phones (AMOLED), smartwatches and foldables.
- **Principle**: **total internal reflection**. The inner **core** has a **higher refractive index** than the surrounding **cladding**; light striking the boundary above the critical angle is fully reflected.
- **Advantages**: enormous **bandwidth**, very low loss over long distances, **immune to electromagnetic interference** and lightning, hard to tap (secure), thin and light, no cross-talk, no spark risk.
- **Graphene** = a single layer of **carbon atoms in a hexagonal (honeycomb) lattice**; an allotrope of carbon like diamond, graphite, fullerene and carbon nanotubes.
- **Properties**: thinnest material known, about **200 times stronger than steel** of the same thickness, excellent conductor of **heat and electricity**, nearly **transparent** (absorbs about 2.3% of light), flexible and impermeable to gases.
- **Qubit**: superposition + entanglement. **n qubits** can represent $\mathbf{2^n}$ states together (10 qubits → 1024).
- **National Quantum Mission (NQM)**: approved April 2023, **₹6,003.65 crore** for 2023–24 to 2030–31, run by the **Department of Science and Technology**. Goals: quantum computers with **50–1000 physical qubits in 8 years**, satellite-based secure quantum communication over **2000 km**, quantum sensors and atomic clocks, quantum materials.
- **First commercial fab**: **Tata Electronics** with Taiwan's PSMC at **Dholera, Gujarat** (under construction). Packaging units include Tata (Jagiroad, Assam), CG Power–Renesas and Kaynes (Sanand, Gujarat) and an HCL–Foxconn unit near **Jewar (Uttar Pradesh)**.
- **Micron's ATMP plant at Sanand (Gujarat)**, the first project approved under ISM, was inaugurated on **28 February 2026** and began commercial production of memory modules; other Sanand packaging units followed during 2026.

15. Scientists, Discoveries, Laws and Constants: Quick Tables

- **Order of the atom's particles**: electron (Thomson, 1897) → proton (Rutherford, 1919) → neutron (Chadwick, 1932).
- **National Science Day, 28 February**, marks the announcement of the Raman effect in 1928 (celebrated since 1987).
- **Raman's Nobel (1930)** was the first Nobel in any science to an Asian; the first Asian Nobel of any kind was Rabindranath Tagore (Literature, 1913).
- **Only one Indian citizen** has won the physics Nobel: **C.V. Raman (1930)**.
- **First physics Nobel (1901)**: Wilhelm Röntgen, for X-rays.
- **Einstein (1921)**: for services to theoretical physics and **the law of the photoelectric effect**, not for relativity.

FACTS THAT CHANGE

Where to check them

Records, missions, laws, office-holders and prizes can change after this book is printed. They are stated here as of November 2026. Each is published by the official body named below: check its website for the latest position.

Chapter	Fact	Published by	Website
1	SI units and their definitions; decisions of the 28th CGPM (October 2026)	International Bureau of Weights and Measures (BIPM)	bipm.org
1	Indian Standard Time and India's national measurement standards	CSIR-National Physical Laboratory	nplindia.in
1	Legal Metrology (Indian Standard Time) Rules, 2026	Department of Consumer Affairs	consumeraffairs.nic.in
4	Aditya-L1 and other Indian space missions	Indian Space Research Organisation (ISRO)	isro.gov.in
4	LIGO-India: construction and observing dates	Department of Atomic Energy; LIGO Laboratory	dae.gov.in · ligo.caltech.edu
7	Noise limits and silence zones (Noise Pollution Rules, 2000)	Central Pollution Control Board	cpcb.nic.in
9	Indian telescopes: Devasthal, Vainu Bappu, GMRT	ARIES; Indian Institute of Astrophysics; NCRA-TIFR	aries.res.in · iiap.res.in · ncra.tifr.res.in
9	Extremely Large Telescope: first-light date	European Southern Observatory (ESO)	eso.org
11	Supply voltage and electrical standards	Bureau of Indian Standards	bis.gov.in
13	Reactors in operation, PFBR and the three-stage programme	Department of Atomic Energy	dae.gov.in
13	SHANTI Act, 2025 and other Acts of Parliament	India Code (Legislative Department)	indiacode.nic.in
13	Radiation safety regulation	Atomic Energy Regulatory Board	aerb.gov.in
14	India Semiconductor Mission: approved projects and outlay	India Semiconductor Mission (MeitY)	ism.gov.in
14	National Quantum Mission	Department of Science and Technology	dst.gov.in
14, 15	Nobel Prizes in Physics	The Nobel Prize	nobelprize.org
All	Government decisions, approvals and Budget announcements	Press Information Bureau	pib.gov.in

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Read once. Remember on exam day.

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16
years of UPSC & BPSC papers, every question covered

400
must-know ★★★ facts

189
diagrams drawn for this book

105
memory tricks

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practice MCQs

Two speeds: read it once in about 12 hours; revise the revision cards and every ★★★ fact in about 2 hours the night before.

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