Chapter 1: Physical Quantities and Measurements

Physics is built on physical quantities that can be measured directly or indirectly using instruments. This chapter introduces the difference between physical and non-physical quantities, base and derived quantities, the International System of Units (SI), scientific notation, and prefixes used with SI units.

It also covers the common laboratory instruments used to measure length, mass, time and volume, along with the concepts of errors, uncertainty, significant figures, precision, accuracy, and rounding off measured values.

Learning Objectives

- Differentiate between physical and non-physical quantities
- Differentiate between base and derived physical quantities and units
- Use the seven SI base units along with their symbols
- Express numerical data using scientific notation and SI prefixes
- Use common lab instruments (metre rule, Vernier Callipers, micrometer screw gauge, measuring cylinder, stopwatch) with correct least count
- Identify human, systematic and random errors and understand uncertainty in measurement
- Differentiate between precision and accuracy, and round off measured values correctly

Key Concepts

1.1 Physical and Non-Physical Quantities

Physical quantities are features that can be measured directly or indirectly using tools and instruments, such as length, volume, density, time and temperature — each consisting of a magnitude (number) and a unit. Non-physical quantities such as love, affection, fear, wisdom and beauty cannot be measured with instruments; they depend on the perception of the observer and can only be described qualitatively or compared using pre-determined criteria, indices, or survey techniques.

1.2 Base and Derived Physical Quantities

Base quantities are a small set of physical quantities arbitrarily selected by scientists to play a key role — length, mass, time, temperature, electric current, intensity of light, and amount of substance. Derived physical quantities are all quantities described in terms of one or more base quantities; for example, speed (distance/time) and density (mass/volume) are derived quantities. A measurement is a process of comparing an unknown quantity with a widely accepted standard quantity, called a unit. A measurement without a unit is meaningless.

1.3 International System of Units (SI)

In 1961, the International Committee on Weights and Measures recommended a system of seven base units, called SI (Système International), now used worldwide: length (metre, m), mass (kilogram, kg), time (second, s), temperature (kelvin, K), electric current (ampere, A), intensity of light (candela, cd), and amount of substance (mole, mol). Derived units are expressed in terms of base units, e.g. area = length × breadth = m^2, speed = distance/time = $m\ s^{-1}$; other named derived units include newton (force), pascal (pressure), coulomb (electric charge) and radian (plane angle). SI prefixes (from atto 10^{-18} to exa 10^{18} — including milli 10^{-3}, centi 10^{-2}, kilo 10^{3}, mega 10^{6}) are added before SI units to conveniently express very large or very small quantities; the kilogram is the only base unit that already has a prefix built in.

Rules for writing SI units correctly: each unit is represented by a symbol, not an abbreviation (s not sec, A not amp); symbols do not take a plural form (5 kg, not 5 kgs); unit names do not begin with a capital letter except when named after a scientist's symbol (N for newton, K for kelvin, Pa for pascal); a prefix is written close to the unit with no space (mm, not m m); units multiplied together are written one space apart (N m); and compound prefixes are not allowed (7 µs, not 7 mms).

1.4 Scientific Notation

Scientific notation is a short way of representing very large or very small numbers as a number from 1 to 9 multiplied by a whole-number power of 10. To convert, the decimal point is moved until only one non-zero digit remains on the left; the number of places moved becomes the exponent — positive if moved left, negative if moved right. For example, the average Sun–Earth distance 138,000,000 km is written 1.38×10^8 km, while the diameter of a hydrogen atom, 0.000,000,000,052 m, is written 5.2×10^{-11} m. Addition and subtraction require equal exponents (adjust the decimal point first); multiplication and division of powers of 10 follow the usual exponent rules (add exponents when multiplying, subtract when dividing).

1.5 Length Measuring Instruments

Metre Rule: used for general laboratory length measurement; smallest division (least count) is 1 mm. Reading must be taken with the eye directly above the scale to avoid parallax error (an error caused by viewing the scale from an angle).

Vernier Callipers: measures small lengths to 1/10th of a millimetre using a main scale (1 mm divisions) and a sliding Vernier scale (9 mm divided into 10 equal parts). Least count = 1 main-scale division − 1 Vernier-scale division = 1 mm − 0.9 mm = 0.1 mm. Jaws A and B measure external dimensions, jaws C and D measure internal dimensions, and the tail (depth gauge) measures the depth of hollow objects. Reading = main scale reading + (least count × Vernier scale division that coincides). Zero error occurs if the zeros of the two scales do not coincide when the jaws are closed: positive zero error (Vernier zero to the right of main scale zero) is subtracted from the observed reading; negative zero error (Vernier zero to the left) is added to the observed reading.

Micrometer Screw Gauge: measures very small lengths such as wire diameter or sheet thickness, using a main scale on the sleeve (0.5 mm divisions) and a circular scale on the thimble (50 divisions). Least count = pitch of screw ÷ number of divisions on circular scale = 0.5 mm ÷ 50 = 0.01 mm. The ratchet prevents over-tightening. Zero error rules mirror the Vernier Callipers: if the circular scale zero is below the horizontal reference line, the error is subtracted; if above, it is added.

Measuring Tape: measures from 1 mm to several metres with a least count of 1 mm, used for longer distances. Range/least-count summary: Measuring Tape (1 cm–several m, 1 mm), Metre Rule (1 mm–1 m, 1 mm), Vernier Callipers (0.1 mm–15 cm, 0.1 mm), Micrometer Screw Gauge (0.01 mm–2.5 cm, 0.01 mm).

1.6 Mass, Time and Volume Measuring Instruments

Mass: In physics, mass (quantity of matter) and weight (force of gravity on a body) are distinct. Mass is found by weighing on a physical balance based on the principle of levers — the base is levelled, the object is placed on the left pan, and standard weights are added to the right pan until the pointer balances at zero.

Time: A stopwatch measures event duration, with an analogue least count of 0.1 s (electronic/digital stopwatches can measure to 0.01 s or finer). Other timing devices: atomic clock (~10^{-10} s), ticker-tape timer (0.02 s), pendulum/wall clock (hours, minutes, seconds), and radioactive decay clock (used to date remains over thousands of years).

Volume: A measuring cylinder (marked in cm^3 or mL) measures the volume of liquids and non-dissolvable solids by reading the liquid level at the meniscus — the bottom edge for a concave (water) surface, the top edge for a convex (mercury) surface, with the eye kept level with the meniscus to avoid parallax error. For solids too large for a measuring cylinder, a displacement can (overflow can) is used: water displaced by the submerged solid is collected and its volume measured, which equals the volume of the solid.

1.7 Errors in Measurement

No measurement is perfect; three main types of error affect measured values. Human (personal) errors arise from limitations of human perception, such as misreading a scale or reaction-time delay in timing — reduced by proper training and by using automated/digital instruments. Systematic errors affect all readings equally in a consistent way, often due to zero error, poor calibration, or incorrect marking of an instrument — reduced by comparing against a more accurate instrument and applying a correction factor. Random errors occur when repeated measurements under the same conditions give different values, due to unpredictable fluctuations (e.g. temperature, pressure, voltage) — reduced by taking multiple readings and averaging, such as timing 30 oscillations of a pendulum and dividing by 30 to find the period of one oscillation.

1.8 Uncertainty and Significant Figures

Every measurement (except a count) carries some uncertainty, set largely by the smallest division (least count) of the instrument used. For a metre rule marked in millimetres, the maximum uncertainty is about ±0.05 cm — half the least count on either side of the recorded reading. Uncertainty in small lengths or short time intervals can be reduced by taking multiple readings and averaging.

Significant figures are the digits of a measurement that are reliably known, plus one final estimated (doubtful) digit. Rules for zeros: a zero between two digits is significant (5.06 m has 3 significant figures); zeros to the left of the first non-zero digit are not significant (0.0034 m has 2 significant figures); zeros to the right of a decimal point are significant (2.40 mm has 3 significant figures); and in scientific notation, all digits before the exponent are significant (3.50×10^4 m has 3 significant figures).

1.9 Precision, Accuracy and Rounding Off

Precision refers to how close together a group of repeated measurements are to each other, and is determined mainly by the least count of the instrument used — a smaller least count gives higher precision. Accuracy refers to how close a measured value is to the true or accepted value, and is reflected by the number of significant figures recorded — more significant figures generally indicate higher accuracy. Using the classic bullseye example: arrows clustered together but off-centre are precise but not accurate; arrows scattered around the centre are accurate but not precise; arrows clustered near the centre are both precise and accurate.

When rounding a number to a given number of significant figures: if the digit after the last retained digit is more than 5, round up; if less than 5, keep it unchanged. For the special case where the digit is exactly 5: if the digit before the 5 is odd, round up; if it is even, leave it unchanged (e.g. 4.45×10^2 m rounds to 4.4×10^2 m, while 4.55×10^2 m rounds to 4.6×10^2 m).

Important Definitions

What is a physical quantity?

A quantity that can be measured directly or indirectly using instruments, and consists of a magnitude (number) and a unit.

What is a base quantity?

One of a small set of physical quantities arbitrarily chosen by scientists as fundamental — length, mass, time, temperature, electric current, intensity of light, and amount of substance.

What is a derived quantity?

A physical quantity described in terms of one or more base quantities, such as speed, area, volume or density.

What is the least count of an instrument?

The smallest measurement that can be taken accurately with that instrument.

What is zero error?

An error in an instrument where the zeros of its two scales do not exactly coincide when its jaws or measuring faces are closed, causing every reading to be consistently too high or too low.

What are significant figures?

The digits of a measurement that are reliably known, plus the first doubtful (estimated) digit.

Define precision.

How close together a group of repeated measurements are to each other, determined mainly by the least count of the instrument.

Define accuracy.

How close a measured value is to the true or accepted value, reflected by the number of significant figures recorded.

Key Formulas

Topic	Formula
Area	Area = length × breadth (unit: m^2)

Speed	Speed = Distance ÷ Time (unit: m s^{-1})
Least count of Vernier Callipers	L.C. = 1 Main Scale division − 1 Vernier Scale division = 1 mm − 0.9 mm = 0.1 mm
Vernier Callipers reading	Length = Main scale reading + (Least count × Vernier scale division)
Least count of Screw Gauge	L.C. = Pitch of screw ÷ No. of divisions on circular scale = 0.5 mm ÷ 50 = 0.01 mm
Screw Gauge reading	Thickness = Main scale reading + (Circular scale reading × Least count)
Maximum uncertainty (metre rule)	Uncertainty ≈ ± half of the least count of the instrument

Diagrams

SI Base Units: The seven base quantities of the International System of Units with their standard units and symbols

Vernier Callipers Reading: Main scale and Vernier scale positions used to calculate a length reading with least count 0.1 mm

Precision vs Accuracy: Bullseye comparison of precise-not-accurate, accurate-not-precise, and both precise-and-accurate measurement sets

Short Questions & Answers

Can a non-physical quantity be measured directly with an instrument?

No. A non-physical quantity such as love or beauty cannot be measured using tools and instruments; it can only be described qualitatively or compared using pre-determined criteria or survey techniques.

What is measurement, and what are its two parts?

Measurement is the process of comparing an unknown quantity with a standard quantity. It has two parts: a number and a unit.

Why do we need a standard unit?

Without a standard unit, measurements taken by different people (e.g. using hand spans or steps) would differ and cause confusion; a standard unit ensures the same measurement result regardless of who measures.

Name three base quantities and three derived quantities.
Base quantities: length, mass, time. Derived quantities: speed, area, density.

What is parallax error and how is it avoided?
Parallax error occurs when a scale is read from an angle instead of directly in front of the eye; it is avoided by keeping the eye perpendicular to (directly above) the scale.

Why is the kilogram unusual among SI base units?
It is the only SI base unit whose name already includes a prefix (kilo).

How is the least count of a Vernier Callipers found?
By subtracting one Vernier scale division from one main scale division (1 mm − 0.9 mm = 0.1 mm), or equivalently, dividing the smallest main-scale division by the total number of Vernier divisions.

What is a doubtful digit in a measurement?
The last digit of a recorded measurement, which is estimated rather than exactly known, and carries the possibility of error.

Long Questions & Answers

Explain the difference between base and derived physical quantities, giving SI base units with symbols.

Base quantities are the small set of physical quantities scientists have arbitrarily chosen as fundamental: length (metre, m), mass (kilogram, kg), time (second, s), temperature (kelvin, K), electric current (ampere, A), intensity of light (candela, cd), and amount of substance (mole, mol). Derived quantities are described in terms of one or more base quantities — for example, speed depends on distance and time (both base quantities), while density depends on mass and volume. Derived units such as the newton, pascal and coulomb are expressed as combinations of the seven SI base units.

Describe how a length is measured and a zero error corrected using a Vernier Callipers.

An object is placed between jaws A and B. The main scale reading just before the zero of the Vernier scale is noted, then the Vernier division that lines up exactly with a main scale division is found. The length equals the main scale reading plus (least count × Vernier division number). To check zero error, the jaws are closed: if the zeros of the two scales coincide exactly, there is no zero error. If the Vernier zero lies to the right of the main scale zero (positive zero error), the instrument reads too high and the zero error is subtracted from every observed reading. If the Vernier zero lies to the left (negative zero error), the instrument reads too low and the zero error is added to every observed reading.

Identify and explain the three types of errors that occur in measurements.

Human (personal) errors arise from limitations of human perception, such as misjudging a pointer's position on a scale or delayed reaction time when starting/stopping a clock; they are reduced through proper training and by using automated or digital instruments. Systematic errors affect every reading in the same consistent way, usually due to zero error, poor calibration, or incorrect marking of an instrument; they are reduced by comparison with a more accurate instrument and applying a correction factor. Random errors occur when repeated measurements under identical conditions give different values, due to unpredictable environmental fluctuations such as temperature or voltage changes; their effect is reduced by taking several readings and calculating the average.

Differentiate between precision and accuracy of a measurement with examples.

Precision refers to how close a group of repeated measurements are to one another, and depends mainly on the least count of the instrument used — a smaller least count (e.g. a screw gauge's 0.01 mm versus a metre rule's 1 mm) gives higher precision. Accuracy refers to how close a measured value is to the true or accepted value, and is reflected in the number of significant figures recorded. Using a bullseye analogy: arrows landing close together but away from the centre are precise but not accurate; arrows scattered around the centre are accurate but not precise; arrows landing close together near the centre are both precise and accurate.

Multiple Choice Questions (MCQs)

The instrument most suitable for measuring the thickness of a few sheets of cardboard is a: (A) metre rule (B) measuring tape (C) Vernier Callipers (D) micrometer screw gauge

Correct answer: (C) Vernier Callipers. A Vernier Callipers (least count 0.1 mm) is well suited to measuring the thickness of a few sheets of cardboard.

One femtometre is equal to: (A) 10^{-9} m (B) 10^{-15} m (C) 10^{9} m (D) 10^{15} m

Correct answer: (B) 10^{-15} m. The prefix femto (f) represents 10^{-15}.

A light year is a unit of: (A) light (B) time (C) distance (D) speed

Correct answer: (C) distance. A light year measures distance — the distance light travels in one year.

Which one is a non-physical quantity? (A) distance (B) density (C) colour (D) temperature

Correct answer: (C) colour. Colour, as commonly perceived, is a non-physical quantity that cannot be measured directly with a standard instrument in the same sense as distance, density, or temperature.

Least count of a Vernier Callipers whose main scale division is 0.5 mm and 10 Vernier divisions equal 9 main scale divisions is: (A) 0.5 mm (B) 0.1 mm (C) 0.05 mm (D) 0.001 mm

Correct answer: (C) 0.05 mm. L.C. = smallest main scale division ÷ total Vernier divisions = 0.5 mm ÷ 10 = 0.05 mm.

A displacement can is used to measure: (A) mass of a liquid (B) mass of a solid (C) volume of a liquid (D) volume of a solid

Correct answer: (D) volume of a solid. A displacement can measures the volume of an irregular solid by the volume of liquid it displaces.

Zeros on the left side of the first non-zero digit in a measured value are: (A) always significant (B) never significant (C) significant only in scientific notation (D) significant only if followed by a decimal

Correct answer: (B) never significant. Leading zeros (before the first non-zero digit) are never counted as significant figures.

Precision of a measurement is determined mainly by: (A) the observer's experience (B) the least count of the instrument (C) the number of significant figures reported (D) the size of the object measured

Correct answer: (B) the least count of the instrument. Precision depends on the least count of the instrument being used — a smaller least count gives more precise readings.

The pitch of a screw gauge with main scale division 0.5 mm and 50 circular divisions gives a least count of: (A) 0.5 mm (B) 0.05 mm (C) 0.01 mm (D) 0.001 mm

Correct answer: (C) 0.01 mm. L.C. = pitch ÷ number of circular divisions = 0.5 mm ÷ 50 = 0.01 mm.

A systematic error in an instrument is best reduced by: (A) taking a single very careful reading (B) comparing with a more accurate instrument and applying a correction (C) averaging many repeated readings (D) increasing the observer's reaction speed

Correct answer: (B) comparing with a more accurate instrument and applying a correction. Systematic errors are consistent and are corrected by comparison with a known accurate instrument, applying a correction factor.

Quick Revision Summary

- Physical quantities are measurable (magnitude + unit); non-physical quantities are not (love, beauty, fear)
- 7 SI base units: metre, kilogram, second, kelvin, ampere, candela, mole
- Scientific notation: one non-zero digit before decimal × power of 10
- Least counts: metre rule 1 mm; Vernier Callipers 0.1 mm; screw gauge 0.01 mm; measuring tape 1 mm
- Zero error: positive → subtract from reading; negative → add to reading
- 3 types of error: human, systematic, random — random errors reduced by averaging repeated readings
- Significant figures: leading zeros not significant; zeros between/after decimal digits are significant

- Precision ← least count of instrument; Accuracy ← closeness to true value / significant figures

Exam Tips

- Memorise all 7 SI base units with their symbols exactly (case matters: kg not Kg, s not S)
- Practice least count and reading calculations for Vernier Callipers and screw gauge — these are common numerical questions
- Learn the zero error correction rules (positive → subtract, negative → add) with a worked example
- Be ready to classify a described error as human, systematic, or random in short-answer questions
- Practice converting numbers into and out of scientific notation, and applying SI prefixes correctly
- Remember the rounding-off rule for the special case of a trailing digit exactly equal to 5 (round to even/odd)

Chapter 2: Kinematics

Mechanics is the branch of physics dealing with motion and the forces that cause it. It is divided into kinematics, the study of motion without considering the forces that cause it, and dynamics, which deals with forces and their effect on motion.

This chapter covers scalar and vector quantities, vector addition using the head-to-tail rule, types of motion, distance versus displacement, speed versus velocity, acceleration, distance-time and speed-time graphs and their gradients, the equations of motion, and free fall acceleration under gravity.

Learning Objectives

- Differentiate between scalar and vector quantities and represent vectors graphically
- Determine the resultant of two or more vectors graphically using the head-to-tail rule
- Differentiate between translatory, rotatory and vibratory motion
- Differentiate between distance and displacement, and between speed and velocity
- Define and calculate average speed, average velocity and acceleration
- Sketch, plot and interpret distance-time and speed-time graphs, and calculate gradients
- Determine distance travelled from the area under a speed-time graph
- Apply the three equations of motion, including motion under gravity using $g \approx 10\ \text{m s}^{-2}$

Key Concepts

2.1 Scalars and Vectors

A scalar is a physical quantity completely described by its magnitude only — examples include distance, length, time, speed, energy and temperature; scalars are added like ordinary numbers (5 m + 3 m = 8 m). A vector is a physical quantity that needs both magnitude and direction to describe it completely — examples include displacement, velocity, acceleration, weight and force. A vector is written as a bold letter or a letter with an arrow ($\vec{v}$), and is represented graphically as a straight line with an arrowhead, whose length (to scale) shows magnitude and whose direction shows the vector's direction, measured as an angle θ from the x-axis (anticlockwise from the positive x-axis).

Two or more vectors can be combined into a single resultant vector using the head-to-tail rule: representative lines of the vectors are redrawn so the head of one coincides with the tail of the next; the resultant is the single vector drawn from the tail of the first vector to the head of the last vector. This graphical method gives both the magnitude and direction of the resultant, unlike simple scalar addition.

2.2 Rest and Motion

A body is at rest if it does not change its position with respect to its surroundings, and in motion if it continuously changes its position with respect to its surroundings. Rest and motion are always relative — a passenger seated in a moving train is at rest relative to other passengers but in motion relative to an observer standing on the platform.

2.3 Types of Motion

There are three general types of motion. Translatory motion occurs when every particle of a body moves uniformly in the same direction (e.g. a moving car or train); it has three sub-types — linear motion (along a straight line, e.g. a freely falling body), random motion (along an irregular path, e.g. the flight of a bee), and circular motion (along a circle, e.g. a Ferris wheel). Rotatory motion occurs when every point of a body moves around a fixed axis (e.g. an electric fan or a spinning top). Vibratory motion occurs when a body repeats a to-and-fro motion about a fixed mean position (e.g. a swing).

2.4 Distance and Displacement

Distance is the length of the actual path travelled during motion; it is a scalar quantity. Displacement is a vector quantity whose magnitude is the shortest distance between the initial and final positions, directed from the initial to the final position. For motion along a curved path from A to B, the distance equals the length of the curved path, while the displacement is the straight line from A to B. The SI unit of both is the metre.

2.5 Speed and Velocity

Speed is the distance covered in unit time: $v = S/t$ (a scalar quantity, SI unit $m\ s^{-1}$). The instantaneous speed is the speed shown by a speedometer at a given instant, while average speed = total distance covered ÷ total time taken. Velocity is the net displacement of a body in unit time: $v_{av} = d/t$ (a vector quantity, direction same as displacement); it distinguishes direction of motion, unlike speed. Velocity is uniform if both the speed and direction of a moving body remain unchanged; if either changes, the velocity is non-uniform (variable).

2.6 Acceleration

Acceleration is the time rate of change of velocity: $a_{av} = (v_f - v_i)/t = \Delta v/t$ (a vector quantity, SI unit $m\ s^{-2}$). Acceleration is positive when velocity increases and negative when velocity decreases; negative acceleration is also called deceleration or retardation. If the rate of change of velocity is constant, the acceleration is uniform; otherwise it is non-uniform (this chapter deals only with uniform acceleration).

2.7 Graphs of Motion

A distance-time graph plots distance S (y-axis, dependent variable) against time t (x-axis, independent variable). A straight line indicates motion with uniform speed; a line curving upward indicates increasing speed (acceleration); a line curving downward indicates decreasing speed (deceleration); and a horizontal line indicates the body is at rest. The gradient (slope) of a distance-time graph equals the average speed of the body: slope = $(S_2 - S_1)/(t_2 - t_1) = S/t = v_{av}$.

A speed-time graph plots speed v against time t. A straight line rising uniformly indicates motion with uniform acceleration; a horizontal line indicates constant speed (zero acceleration). The gradient of a speed-time graph equals the average acceleration of the body: slope = $(v_2 - v_1)/(t_2 - t_1) = \Delta v/t = a_{av}$.

2.8 Area Under a Speed-Time Graph

The distance moved by an object equals the area under its speed-time graph, measured up to the time axis. For constant speed v over time t, the area is a rectangle = v × t, matching S = vt. For speed increasing uniformly from 0 to v over time t (uniform acceleration from rest), the area is a right triangle = ½ × base × perpendicular = ½ v t, matching the average speed (0+v)/2 multiplied by time.

2.9 Equations of Motion and Free Fall

For a body with initial velocity v_i, final velocity v_f, time t, distance S, and uniform acceleration a, the three equations of motion are: $v_f = v_i + at$; $S = v_i t + \frac{1}{2}at^2$; and $2aS = v_f^2 - v_i^2$. These assume motion along a straight line, use only magnitudes of vectors (with sign convention for direction), and assume uniform acceleration; the direction of initial velocity is taken as positive.

A freely falling body under Earth's gravity experiences gravitational acceleration g, directed downward, with a value of 9.8 $m\ s^{-2}$ (approximated as 10 $m\ s^{-2}$ for calculations). Since free fall is straight-line motion with uniform acceleration, the equations of motion apply with a replaced by g: $v_f = v_i + gt$; $S = v_i t + \frac{1}{2}gt^2$; and $2gS = v_f^2 - v_i^2$. If a body is released from rest, $v_i = 0$; g is taken as positive in the downward direction; if a body is thrown vertically upward, g is taken as negative and the final velocity is zero at the highest point.

Important Definitions

What is a scalar quantity?

A physical quantity that can be described completely by its magnitude only, such as distance, time, speed or temperature.

What is a vector quantity?

A physical quantity that needs both magnitude and direction to describe it completely, such as displacement, velocity, acceleration or force.

What is displacement?

A vector quantity whose magnitude is the shortest distance between the initial and final positions of a motion, directed from the initial to the final position.

What is average speed?

The total distance covered divided by the total time taken: $v_{av} = S/t$.

What is velocity?

The net displacement of a body in unit time; a vector quantity with the same direction as the displacement.

What is acceleration?

The time rate of change of velocity of a body: $a = \Delta v/t$.

What does the gradient of a distance-time graph represent?

The average speed of the body.

What does the gradient of a speed-time graph represent?

The average acceleration of the body.

Key Formulas

Topic	Formula
Average speed	v_{av} = Total distance covered ÷ Total time taken = S/t
Average velocity	v_{av} = Displacement ÷ Time = d/t
Average acceleration	$a_{av} = (v_f - v_i) \div t = \Delta v/t$
1st equation of motion	$v_f = v_i + at$
2nd equation of motion	$S = v_i t + \frac{1}{2} a t^2$
3rd equation of motion	$2aS = v_f^2 - v_i^2$
Free fall equations	Same as above with a replaced by $g \approx 10\ m\ s^{-2}$ (downward positive)
Distance from speed-time graph	Distance = Area under the speed-time graph

Diagrams

Types of Motion: Translatory (linear, random, circular), rotatory and vibratory motion with examples

Distance-Time Graph Shapes: How the shape of a distance-time graph shows rest, uniform speed, acceleration and deceleration

Area Under Speed-Time Graph: Distance covered equals the shaded area under a speed-time graph for uniformly accelerated motion from rest

Short Questions & Answers

Define scalar and vector quantities with one example each.

A scalar has magnitude only, e.g. speed. A vector has both magnitude and direction, e.g. velocity.

State the head-to-tail rule for vector addition.

Representative lines of the vectors are redrawn so the head of one coincides with the tail of the next; the resultant is drawn from the tail of the first vector to the head of the last vector.

What is the difference between distance and displacement?

Distance is the total length of the actual path travelled (a scalar); displacement is the shortest straight-line distance between initial and final positions, with direction (a vector).

What are distance-time and speed-time graphs?

A distance-time graph shows how the distance covered by a body varies with time; a speed-time graph shows how its speed varies with time.

Will a body moving with uniform speed always have uniform velocity? Give a reason.

Not necessarily — if the direction of motion keeps changing (e.g. circular motion at constant speed), the velocity is non-uniform even though the speed is constant, because velocity also depends on direction.

Can a body have acceleration while moving with constant speed?

Yes, if its direction is continuously changing (e.g. circular motion), since acceleration depends on the change in velocity, which is a vector.

What is the value of g used for calculations in this chapter, and in which direction does it act?

$g \approx 10\ \text{m s}^{-2}$, and it always acts vertically downward, toward the centre of the Earth.

What quantity does the area under a speed-time graph represent?
The distance covered by the object during that time interval.

Long Questions & Answers

Explain the three types of motion with examples.

Translatory motion occurs when every particle of a body moves uniformly in the same direction, such as a moving train or car; it includes linear motion (straight-line, e.g. a falling body), random motion (irregular path, e.g. a bee in flight), and circular motion (along a circle, e.g. a Ferris wheel). Rotatory motion occurs when every point of a body moves around a fixed axis, such as an electric fan or a spinning top. Vibratory motion occurs when a body repeats a to-and-fro motion about a fixed mean position, such as a swing.

Differentiate between speed and velocity, and between uniform and non-uniform velocity.

Speed is a scalar quantity equal to distance covered per unit time ($v = S/t$) and gives no information about direction. Velocity is a vector quantity equal to displacement per unit time ($v = d/t$) and has the same direction as the displacement. Velocity is uniform if both the speed and direction of motion remain unchanged; if either the speed or the direction (or both) changes, the velocity is non-uniform.

Explain what the gradients of a distance-time graph and a speed-time graph represent, using diagrams to support your answer.

The gradient (slope) of a distance-time graph, calculated as $(S_2 - S_1)/(t_2 - t_1)$, equals the average speed of the body over that interval — a straight line gives uniform speed, an upward curve gives acceleration, a downward curve gives deceleration, and a horizontal line means the body is at rest. The gradient of a speed-time graph, calculated as $(v_2 - v_1)/(t_2 - t_1)$, equals the average acceleration of the body — a straight rising line indicates uniform acceleration, while a horizontal line indicates zero acceleration (constant speed).

Prove that the area under a speed-time graph is equal to the distance covered by an object.

For an object moving with constant speed v over time t, the speed-time graph is a horizontal line, and the area under it up to the time axis is a rectangle of sides t and v, giving area = v × t, which matches the distance formula S = vt. For an object accelerating uniformly from rest to speed v over time t, the speed-time graph is a straight rising line from the origin, and the area under it is a right-angled triangle with base t and height v, giving area = ½ × v × t. This matches the distance found using average speed: distance = average speed × time = (0+v)/2 × t = ½vt. In both cases, the area under the speed-time graph numerically equals the distance covered.

Multiple Choice Questions (MCQs)

The numerical ratio of displacement to distance is: (A) always less than one (B) always equal to one (C) always greater than one (D) equal to or less than one

Correct answer: (D) equal to or less than one. Displacement (the shortest path) can equal distance (a straight path) or be less than it (a curved/indirect path), so the ratio is equal to or less than one.

If a body does not change its position with respect to a fixed point, it is in a state of: (A) rest (B) motion (C) uniform motion (D) variable motion

Correct answer: (A) rest. Not changing position relative to a fixed point/surroundings defines a state of rest.

A ball is dropped from a tower; the distance covered in the first second is: (A) 5 m (B) 10 m (C) 50 m (D) 100 m

Correct answer: (A) 5 m. Using $S = v_i t + \frac{1}{2}gt^2$ with $v_i=0$, $g=10\ m\ s^{-2}$, $t=1$ s: $S = \frac{1}{2} \times 10 \times 1^2 = 5$ m.

The area under the speed-time graph is numerically equal to: (A) velocity (B) uniform velocity (C) acceleration (D) distance covered

Correct answer: (D) distance covered. The area under a speed-time graph, up to the time axis, gives the distance covered.

Gradient of the speed-time graph is equal to: (A) speed (B) velocity (C) acceleration (D) distance covered

Correct answer: (C) acceleration. The slope of a speed-time graph gives the average acceleration.

Gradient of the distance-time graph is equal to the: (A) speed (B) velocity (C) distance covered (D) acceleration

Correct answer: (A) speed. The slope of a distance-time graph gives the average speed.

A body accelerates uniformly from rest to 144 km h^{-1} in 20 s. The distance it covers is: (A) 100 m (B) 400 m (C) 1400 m (D) 1440 m

Correct answer: (B) 400 m. $v_f = 144$ km $h^{-1} = 40$ m s^{-1}. Using $S = v_i t + \frac{1}{2}at^2$ with $a = v_f/t = 2$ m s^{-2}: $S = \frac{1}{2} \times 2 \times 20^2 = 400$ m.

Which physical quantity is measured by the gradient of a distance-time graph at rest (horizontal line)? (A) Non-zero constant speed (B) Zero speed (C) Constant acceleration (D) Increasing speed

Correct answer: (B) Zero speed. A horizontal distance-time graph line means distance is not changing, so speed = 0 (the body is at rest).

Which of the following is a vector quantity? (A) distance (B) speed (C) displacement (D) time

Correct answer: (C) displacement. Displacement has both magnitude and direction, making it a vector; the others are scalars.

An object falls freely from rest. Using $g = 10$ m s^{-2}, its velocity after 4 s is: (A) 10 m s^{-1} (B) 20 m s^{-1} (C) 40 m s^{-1} (D) 80 m s^{-1}

Correct answer: (C) 40 m s^{-1}. $v_f = v_i + gt = 0 + 10 \times 4 = 40$ m s^{-1}.

Quick Revision Summary

- Scalar = magnitude only; Vector = magnitude + direction
- Vector addition: head-to-tail rule gives the resultant vector
- 3 types of motion: translatory (linear/random/circular), rotatory, vibratory
- Distance = path length (scalar); Displacement = shortest path with direction (vector)
- Speed = S/t (scalar); Velocity = d/t (vector)
- Acceleration = $\Delta v/t$; positive = speeding up, negative = deceleration

- Gradient of distance-time graph = average speed; gradient of speed-time graph = average acceleration
- Area under speed-time graph = distance covered
- 3 equations of motion: $v_f = v_i + at$; $S = v_i t + \frac{1}{2}at^2$; $2aS = v_f^2 - v_i^2$
- Free fall: $g \approx 10\ m\ s^{-2}$ downward; negative if body thrown upward

Exam Tips

- Always identify given values (v_i, v_f, a or g, t, S) first, then choose the matching equation of motion
- Remember the sign convention: direction of initial velocity is positive; opposite direction is negative
- For free fall problems, check whether the body starts from rest ($v_i = 0$) or is thrown upward (g is negative, $v_f = 0$ at the highest point)
- Practice reading distance-time and speed-time graph shapes — rest, uniform motion, acceleration, and deceleration each has a distinct shape
- Memorise that area under a speed-time graph = distance, and be ready to calculate it for rectangles and triangles
- Draw a clear vector diagram with a scale and angle when solving vector representation questions

Chapter 3: Dynamics

Kinematics describes motion without considering its cause. Dynamics is concerned with the forces that produce and change the motion of bodies — whenever there is acceleration, a force is present to cause it.

This chapter covers the concept and types of force (contact and non-contact), the four fundamental forces of nature, free-body diagrams, Newton's three laws of motion, mass and weight, instruments used to measure mass and force, friction and terminal velocity, and momentum, impulse, and the principle of conservation of momentum.

Learning Objectives

- Differentiate between contact and non-contact forces, and identify different types of forces
- State the four fundamental forces of nature and compare their relative strengths
- Represent forces acting on a body using free-body diagrams
- State and apply Newton's first, second and third laws of motion
- Differentiate between mass and weight, and calculate weight using $w = mg$
- Justify the use of mechanical/electronic balances and a force meter to measure mass and weight
- Analyse the dissipative effect of friction and the concept of terminal velocity
- Define and calculate momentum and impulse, and apply the principle of conservation of momentum

Key Concepts

3.1 Concept and Types of Force

A force is a push or pull that starts, stops, or changes the magnitude or direction of the velocity of a body. Forces are of two major types. Contact forces act at the point of contact between two objects — examples include friction (resists relative motion between surfaces), drag (resistance from a fluid), thrust (upward force from a liquid on an immersed object), normal force (reaction from a surface, perpendicular to it), air resistance, tension force, and elastic force (restores deformed materials to their original shape). Non-contact (field) forces act between objects that are not touching, also called action-at-a-distance forces — examples include gravitational force, electrostatic force, and magnetic force.

3.2 The Four Fundamental Forces

All forces in nature fall under four fundamental forces. Gravitational force is the weakest of the four, but is long-range, extending to infinite distance while weakening with distance; it is described by Newton's law of gravitation, $F = Gm_1m_2/r^2$, where $G = 6.67 \times 10^{-11}$ N m² kg⁻². Electromagnetic force, which includes electrostatic and magnetic forces, is stronger than gravity, is also long-range, and is responsible for chemical reactions and (at the macroscopic level) friction. Strong nuclear force binds protons and neutrons together in the nucleus, overcoming electromagnetic repulsion between protons; it is short-range, acting only over about 10^{-14} m. Weak nuclear force is responsible for radioactive decay (such as beta decay), is stronger than gravity but weaker than electromagnetic force, and is short-range, acting over about 10^{-17} m. Pakistani scientist Dr. Abdus Salam, along with Sheldon Glashow and Steven Weinberg, won the 1979 Nobel Prize in Physics for showing that the weak nuclear force and electromagnetic force are two aspects of a single unified electroweak force.

3.3 Free-Body Diagrams

A free-body diagram shows the relative magnitudes and directions of all forces acting on an object in a given situation. The object is represented as a box, and force arrows are drawn outward from its centre in the direction of each force, with arrow length representing magnitude and each force labelled by type (e.g. weight, friction, normal force).

3.4 Newton's Laws of Motion

Newton's First Law: a body continues its state of rest or of uniform motion in a straight line unless acted upon by some external force. This is also called the law of inertia — inertia is the property of a body to resist a change in its state of rest or motion, and mass is a measure of an object's inertia (greater mass means greater inertia).

Newton's Second Law: if a net external force acts on a body, it produces acceleration in the direction of the force; the acceleration is directly proportional to the force and inversely proportional to the mass, giving $F = ma$. One newton is defined as the force that produces an acceleration of 1 m s^{-2} in a body of mass 1 kg (1 N = 1 kg m s^{-2}). Since velocity is a vector, a force can change a body's speed, direction, or both.

Newton's Third Law: for every action, there is an equal and opposite reaction — if one body exerts a force on a second body, the second body exerts an equal and opposite force on the first. Action and reaction act on two different bodies, so they never cancel each other. Examples: a block resting on a table exerts its weight downward on the table, and the table exerts an equal normal reaction force upward on the block; when a bullet is fired, it moves forward with force F (action) while the gun recoils backward with reaction force R.

Newton's laws apply with very high accuracy to everyday motion but are not exact for particles moving at speeds close to the speed of light, where Einstein's relativistic mechanics is needed instead.

3.5 Mass and Weight

Mass is the quantity of matter in a body and is a measure of the body's inertia — it is a scalar quantity, remains constant everywhere, has SI unit kilogram (kg), and is measured with an ordinary balance. Weight is the gravitational force with which the Earth (or another planet) attracts a body toward its centre — it is a vector quantity directed downward, with SI unit newton (N), and is measured using a spring balance (force meter), not an ordinary balance.

A gravitational field is the region around a mass in which another mass experiences a gravitational force. Gravitational field strength g is the gravitational force per unit mass: $g = w/m$, so weight is given by $w = mg$ (equivalent to the acceleration of free fall). Since g varies with location and altitude, an object's weight varies from place to place even though its mass stays the same; at any given location, weight remains proportional to mass, so masses can be compared by comparing weights there.

3.6 Measuring Mass and Weight

A mechanical balance uses a rigid beam pivoting on a central knife-edge, with pans on each end; the object is balanced against standard weights. A mechanical platform balance (for heavy items like flour or cement bags) places the fulcrum near one end so small calibrated weights at the other end balance a much heavier load. An electronic balance requires no standard weights, is more precise, and displays mass directly (some models also compute price from a per-kg rate). A force meter (spring balance or newton meter) measures force/weight directly in newtons using the compression or stretching of an internal spring against a calibrated scale; digital force meters are also available.

3.7 Friction and Terminal Velocity

Friction is a dissipative force — energy used to overcome it is converted to heat (e.g. warming of rubbed hands, hot machine parts, worn tyres, and burning meteors from air friction). Sliding friction between two solid surfaces has two forms: static friction (opposes the start of motion, up to a maximum called limiting friction) and kinetic friction (acts once the object is sliding). Rolling friction occurs when an object rolls over a surface (e.g. wheels, ball bearings) and is roughly one hundred times smaller than sliding friction, because the rolling surface touches only at a point with no relative sliding motion.

Terminal velocity is the constant velocity reached by a falling object when the upward force of air resistance exactly balances the downward force of gravity, so the object stops accelerating (e.g. a parachutist descending safely). Methods used to reduce friction include polishing sliding surfaces, applying oil or grease (liquid friction is less than solid friction), converting sliding friction to rolling friction using ball bearings, and streamlining vehicles/vessels to allow smooth (streamline) airflow or water flow around them.

3.8 Momentum, Impulse and Conservation of Momentum

Momentum is the quantity of motion of a moving body, defined as the product of its mass and velocity: $p = mv$. It is a vector quantity with SI unit kg m s^{-1} (equivalent to N s). Impulse is the product of a large force acting for a short time interval and equals the total change in momentum it produces: Impulse = $F \times \Delta t$

$= m \times \Delta v = m(v_f - v_i)$. Rearranged, this gives Newton's second law in terms of momentum: $F = \Delta p/\Delta t$ — the rate of change of momentum of a body equals the net force acting on it.

The principle of conservation of momentum states that if no external force acts on an isolated system, the total momentum of the system after an interaction (such as a collision) equals its total momentum before the interaction: $m_1v_1 + m_2v_2$ (before) $= m_1v_1' + m_2v_2'$ (after). This principle applies to both macroscopic objects (e.g. colliding balls, a recoiling gun) and microscopic particles such as atoms and molecules. Everyday applications of impulse and momentum concepts include drawing hands back while catching a fast ball (increasing contact time to reduce force), soft packing materials for fragile goods, seatbelts, airbags, and vehicle crumple zones — all reduce the force of impact by increasing the time over which momentum changes.

Important Definitions

What is a force?

A push or pull that starts, stops, or changes the magnitude or direction of velocity of a body.

What is inertia?

The property of a body to maintain its state of rest or of uniform motion in a straight line; mass is a measure of inertia.

State Newton's first law of motion.

A body continues its state of rest or of uniform motion in a straight line unless acted upon by some external force.

State Newton's second law of motion.

If a net external force acts on a body, it produces acceleration in the direction of the force; acceleration is directly proportional to the force and inversely proportional to the mass ($F = ma$).

State Newton's third law of motion.

For every action, there is always an equal and opposite reaction, acting on two different bodies.

What is weight?

The gravitational force with which the Earth attracts a body toward its centre; weight = mass × gravitational field strength ($w = mg$).

What is terminal velocity?

The constant velocity reached by a falling object when the upward air resistance balances the downward force of gravity, so the object no longer accelerates.

What is momentum?

The product of a moving body's mass and velocity ($p = mv$); a vector quantity.

Key Formulas

Topic	Formula
Newton's law of gravitation	$F = G m_1 m_2 / r^2$ ($G = 6.67 \times 10^{-11}$ N m² kg⁻²)
Weight	$w = mg$ ($g \approx 10$ N kg^{-1} or 10 m s^{-2})
Gravitational field strength	$g = w/m$
Newton's second law	$F = ma$ (1 N = 1 kg m s^{-2})
Momentum	$p = mv$
Impulse	Impulse = $F \times \Delta t = m \times \Delta v = m(v_f - v_i)$
Force as rate of change of momentum	$F = \Delta p/\Delta t$
Conservation of momentum	$m_1v_1 + m_2v_2$ (before) $= m_1v_1' + m_2v_2'$ (after)

Diagrams

Types of Forces: Classification of contact and non-contact forces with examples of each

Newton's Three Laws of Motion: Summary of the first, second and third laws with their key statements

Terminal Velocity: Velocity-time graph showing a falling object's speed levelling off at terminal velocity

Short Questions & Answers

What kinds of changes in motion can a force produce?

A force can start motion, stop motion, or change the speed or direction (or both) of a moving body.

Give five examples of contact forces.

Friction, drag, thrust, normal force, and tension force (air resistance and elastic force are also acceptable).

Define impulse of a force.

Impulse is the product of a large force and the short time interval for which it acts, equal to the total change in momentum it produces: Impulse = $F\Delta t = m\Delta v$.

Why has Newton's first law never been directly observed on Earth?

Because friction and air resistance act on all moving bodies on Earth, so a body never truly moves with zero net external force acting on it.

Define terminal velocity.

The constant velocity attained by a freely falling object when the upward force of air resistance equals the downward force of gravity.

How can you show that rolling friction is less than sliding friction?

A wheeled object requires much less force to keep moving at constant speed than an identical object without wheels sliding over the same surface, showing rolling friction is significantly smaller.

Why is the force in Newton's second law called the net force?

Because several forces may act on a body simultaneously; it is their vector sum (net/resultant force) that determines the resulting acceleration.

In what direction should an astronaut fire a hand rocket to return to the spaceship?

Away from the spaceship — by Newton's third law, firing the rocket away from the spaceship produces a reaction force that pushes the astronaut toward the spaceship.

Long Questions & Answers

State and explain Newton's three laws of motion with examples.

Newton's first law states that a body continues its state of rest or uniform motion unless acted on by an external force — e.g. passengers lurch forward when a bus stops suddenly because their bodies tend to continue moving. Newton's second law states that a net force produces acceleration in its own direction, proportional to the force and inversely proportional to mass, giving $F = ma$ — e.g. a truck accelerates less than a bicycle under the same applied force because of its greater mass. Newton's third law states that for every action there is an equal and opposite reaction acting on a different body — e.g. a bullet fired forward from a gun (action) causes the gun to recoil backward (reaction).

Differentiate between mass and weight.

Mass is the quantity of matter in a body, a scalar quantity measured in kilograms, that stays constant everywhere and is measured with an ordinary balance. Weight is the gravitational force pulling a body toward the centre of a planet, a vector quantity measured in newtons ($w = mg$), that varies with location because gravitational field strength g varies with location and altitude, and is measured with a spring balance (force meter) rather than an ordinary balance.

Describe static and kinetic friction using the example of a block on a table, and explain terminal velocity.

When a horizontal pulling force is gradually applied to a block resting on a table (e.g. via weights added to a pan connected by a string), an opposing force called static friction initially prevents the block from moving; this increases up to a maximum called limiting friction. Once the applied force exceeds limiting friction, the block begins to slide, and the opposing friction during sliding is called kinetic friction. Terminal velocity occurs when a body falling through air (or another fluid) accelerates until the upward air resistance force grows large enough to balance the downward weight; beyond this point, the net force is zero, so the body falls at a constant (terminal) velocity — as seen in a parachutist's steady descent.

State the principle of conservation of momentum and explain it using a collision example.

The principle states that if no external force acts on an isolated system, the total momentum of the system after an interaction equals its total momentum before the interaction. For two balls of masses m_1 and m_2 moving with velocities v_1 and v_2 that collide and move off with velocities v_1' and v_2', $m_1v_1 + m_2v_2 = m_1v_1' + m_2v_2'$. For example, when a moving ball strikes an identical stationary ball, momentum transfers from the first ball to the second: the striking ball can come to rest while the second ball moves off with the same momentum the first ball had before the collision, showing total momentum is conserved.

Multiple Choice Questions (MCQs)

When we kick a stone, we get hurt. This is due to: (A) inertia (B) velocity (C) momentum (D) reaction

Correct answer: (D) reaction. By Newton's third law, the stone exerts an equal and opposite reaction force back on the foot, causing pain.

Which of the following is a non-contact force? (A) Friction (B) Air resistance (C) Electrostatic force (D) Tension in a string

Correct answer: (C) Electrostatic force. Electrostatic force acts between charged objects without physical contact; the others require contact.

A ball with momentum p hits a solid wall and bounces back with the same speed. Its momentum p' after collision is: (A) $p' = p$ (B) $p' = -p$ (C) $p' = 2p$ (D) $p' = -2p$

Correct answer: (B) $p' = -p$. The ball reverses direction with the same magnitude of velocity, so its momentum reverses sign: $p' = -p$.

Conservation of linear momentum is a direct consequence of: (A) Newton's first law of motion (B) Newton's second law of motion (C) Newton's third law of motion (D) None of these

Correct answer: (C) Newton's third law of motion. Conservation of momentum follows from Newton's third law — the equal and opposite forces during interaction cause equal and opposite changes in momentum.

Newton's law of gravitation states force is: (A) directly proportional to r^2 (B) inversely proportional to r^2 (C) directly proportional to (m_1+m_2) (D) independent of mass

Correct answer: (B) inversely proportional to r^2. $F = Gm_1m_2/r^2$ — gravitational force is inversely proportional to the square of the distance between the masses.

The SI unit of momentum is: (A) N (B) kg m s^{-1} (C) kg m s^{-2} (D) J

Correct answer: (B) kg m s^{-1}. Momentum $p = mv$ has units of kg × m s^{-1} = kg m s^{-1} (equivalent to N s).

One newton is the force that produces an acceleration of 1 m s^{-2} in a mass of: (A) 1 g (B) 1 kg (C) 10 kg (D) 100 kg

Correct answer: (B) 1 kg. By definition, 1 N = 1 kg × 1 m s^{-2}, i.e. the force needed to accelerate a 1 kg mass at 1 m s^{-2}.

A lubricant reduces friction between two surfaces mainly by: (A) decreasing temperature (B) acting as ball bearings (C) preventing direct contact of the surfaces (D) providing rolling friction

Correct answer: (C) preventing direct contact of the surfaces. A lubricant forms a thin liquid layer that keeps the two solid surfaces from direct contact, reducing friction.

Rolling friction compared to sliding friction is approximately: (A) 100 times greater (B) 100 times smaller (C) equal (D) 10 times greater

Correct answer: (B) 100 times smaller. Rolling friction is about one hundred times smaller than sliding friction because there is no relative sliding at the contact point.

A large force acting on an object for a very short time makes it easiest to determine the: (A) magnitude of the force alone (B) time interval alone (C) product of force and time (impulse) (D) none of these

Correct answer: (C) product of force and time (impulse). Since the exact force and exact contact time are both hard to measure individually, their product — the impulse (equal to the change in momentum) — is what can be determined.

Quick Revision Summary

- Force = push/pull that changes speed, direction, or state of motion
- Contact forces: friction, drag, thrust, normal, tension, elastic, air resistance

- Non-contact forces: gravitational, electrostatic, magnetic (also strong/weak nuclear)
- 4 fundamental forces (weakest to strongest): gravitational, weak nuclear, electromagnetic, strong nuclear
- Newton's 1st law: inertia; 2nd law: F=ma; 3rd law: action-reaction pairs on different bodies
- Mass = quantity of matter (scalar, kg, constant); Weight = mg (vector, N, varies with location)
- Static friction ≤ limiting friction; kinetic friction acts during sliding; rolling friction ≪ sliding friction
- Terminal velocity: air resistance balances weight, so acceleration becomes zero
- Momentum p = mv; Impulse = $F\Delta t = \Delta p$
- Conservation of momentum: total momentum before collision = total momentum after (isolated system)

Exam Tips

- Memorise the three statements of Newton's laws precisely — exam questions often ask to 'state' them exactly
- Practice distinguishing contact vs non-contact forces and classifying examples correctly
- Be clear on the mass vs weight distinction: mass is constant and scalar; weight = mg, is a vector, and varies with location
- Work through F=ma, p=mv, and impulse numericals step by step, listing given values before selecting the formula
- Remember real-life applications of momentum conservation and impulse (airbags, seatbelts, crumple zones, catching a ball) — these are common short-answer topics
- Know the order-of-magnitude ranges for strong (10^{-14} m) and weak (10^{-17} m) nuclear forces, and that Dr. Abdus Salam shared the 1979 Nobel Prize for the electroweak unification

Chapter 4: Turning Effects of Force

A force does not only produce straight-line acceleration; it can also turn a rigid body about a point, as when opening a door or a tap. This chapter studies the turning (rotational) effect of a force, called torque, along with related concepts of moment arm, couple, and resolution of forces into rectangular components.

It then covers the principle of moments, centre of gravity and centre of mass, equilibrium and its two conditions, the three states of equilibrium (stable, unstable, neutral) and how to improve stability, and finally circular motion and centripetal force.

Learning Objectives

- Differentiate between like and unlike parallel forces
- Calculate the moment (torque) of a force as force × perpendicular distance from the pivot
- Resolve a force into its rectangular (perpendicular) components and recombine them
- Apply the principle of moments to balanced systems
- Define centre of mass and centre of gravity, and locate the centre of gravity of a lamina
- State and apply the two conditions of equilibrium
- Identify stable, unstable and neutral equilibrium, and propose ways to improve stability
- Describe circular motion qualitatively and calculate centripetal force using $F_c = mv^2/r$

Key Concepts

4.1 Parallel Forces and Their Addition

Forces acting parallel to one another are called parallel forces. If they act in the same direction, they are like parallel forces; if in opposite directions, they are unlike parallel forces. Since force is a vector, two or more forces acting in a plane can be added using the head-to-tail rule (as with any vectors) to find their resultant force, both in magnitude and direction.

4.2 Turning Effect of a Force (Torque)

A rigid body is one in which the distance between any two of its points stays constant under an applied force. During rotation, all particles of a rigid body move along fixed circles centred on a common straight line called the axis of rotation. The line along which a force acts is its line of action; the perpendicular distance from the axis of rotation to this line of action is called the moment arm (or lever arm) of the force. The turning effect of a force depends both on its magnitude and on the length of its moment arm — a larger force or a larger moment arm produces a greater turning effect (this is why door handles are placed far from the hinge, and spanners are held at their far end).

Moment of force, or torque (τ), is defined as the product of the force and its moment arm: $\tau = F \times \ell$. Its SI unit is newton metre (N m). Torque is taken as positive if it tends to produce anticlockwise rotation, and negative if it tends to produce clockwise rotation; torque is zero when the line of action of the force passes through the axis of rotation (moment arm = 0). A couple is formed when two equal and opposite parallel forces act at two different points of the same body (e.g. turning a steering wheel, key, or tap); a couple produces a net torque even though the net force is zero.

4.3 Resolution of Vectors

Just as vectors can be combined into a resultant, a single vector can be resolved (broken down) into two or more components whose combined effect equals the original vector. A force is usually resolved into two perpendicular (rectangular) components. For a force F acting at angle θ with the x-axis, the x-component is $F_x = F \cos \theta$ and the y-component is $F_y = F \sin \theta$. Conversely, given the components, the magnitude of the original force can be found using the Pythagorean theorem, $F = \sqrt{(F_x^2 + F_y^2)}$, and its direction from $\tan \theta = F_y/F_x$.

4.4 Principle of Moments

The principle of moments states that when a body is in a balanced position, the sum of clockwise moments about any point equals the sum of anticlockwise moments about that same point. For weights w_1 and w_2 at distances ℓ_1 and ℓ_2 on one side of a pivot, balanced by weight w_3 at distance ℓ_3 on the other side: $w_1\ell_1 + w_2\ell_2 = w_3\ell_3$. This principle is applied in balances, see-saws, and tools like crowbars and spanners.

4.5 Centre of Gravity and Centre of Mass

The centre of gravity of a body is the point where its total weight appears to act; a body supported exactly at its centre of gravity remains balanced without rotating. For regular shapes, the centre of gravity lies at the geometric centre (e.g. the intersection of the diagonals of a rectangle, or the intersection of the medians of a triangle). For an irregular plane lamina, the centre of gravity is found experimentally by suspending it freely from different points and using a plumb line; the point where the plumb lines from different suspension points intersect is the centre of gravity.

The centre of mass is the point where the entire mass of a body or system is assumed to be concentrated, and where Newton's second law can be applied to describe the overall motion of the system even if its parts move differently. On the surface of the Earth, where gravitational field strength g is essentially uniform over an object's size, the centre of mass coincides with the centre of gravity.

4.6 Equilibrium and Its Conditions

A body is in equilibrium if it has no acceleration. Static equilibrium describes a body at rest (e.g. a book on a table); dynamic equilibrium describes a body moving with uniform velocity (e.g. a parachutist descending at constant speed). The first condition of equilibrium (translational equilibrium) requires the vector sum of all external forces on the body to be zero: $\Sigma F_x = 0$ and $\Sigma F_y = 0$. The second condition of equilibrium (rotational equilibrium) requires the vector sum of all torques about any point to be zero: $\Sigma\tau = 0$. A body is in complete equilibrium only when both conditions are satisfied simultaneously — satisfying the first condition alone still allows an unbalanced couple to rotate the body.

4.7 States of Equilibrium and Stability

There are three states of equilibrium for a balanced body. In stable equilibrium, a body returns to its original position after a slight tilt, because the resulting torque pushes it back (e.g. a cone resting on its base) — this occurs as long as the centre of mass stays above the base. In unstable equilibrium, a body moves further away from its original position after a slight tilt and does not return (e.g. a cone balanced on its tip), because the centre of mass falls outside the base once tilted. In neutral equilibrium, a body settles into a new position after being disturbed, with no change in the height of its centre of mass, and neither returns nor moves further away (e.g. a cylinder or ball resting on a flat surface).

Stability of an object can be improved by lowering its centre of gravity and/or widening its base of support — for example, loading heavy cargo low in a bus or ship, or designing racing cars with a low centre of mass and wheels set outside the main body. Balancing toys stay stable because their centre of gravity remains below the pivot point at all times, so any disturbance is automatically corrected as the centre of gravity is pulled back down.

4.8 Circular Motion and Centripetal Force

An object moving in a circle at uniform speed continuously changes direction, so its velocity (a vector) is always changing even though its speed is constant; this requires a constant force directed toward the centre of the circle, perpendicular to the velocity at every instant. This force is called centripetal force, and its magnitude is given by $F_c = mv^2/r$, where m is the mass, v is the speed, and r is the radius of the circular path. Real-life sources of centripetal force include: tension in a string for a whirled stone, gravity for the Moon orbiting Earth or a satellite orbiting Earth, and friction between wet clothes and the drum in a washing machine spin cycle (allowing water, which lacks sufficient centripetal force, to escape through the holes).

Important Definitions

What are like and unlike parallel forces?

Parallel forces acting in the same direction are like parallel forces; those acting in opposite directions are unlike parallel forces.

What is the moment arm of a force?

The perpendicular distance from the axis of rotation to the line of action of the force.

Define torque (moment of force).

The product of a force and its moment arm: $\tau = F \times \ell$, measured in newton metres (N m).

What is a couple?

Two equal and opposite parallel forces acting at two different points of the same body, producing a net torque with zero net force.

Define centre of gravity.

The point of a body where its total weight is considered to act.

Define centre of mass.

The point of a body or system where the whole mass is assumed to be concentrated for analysing overall motion.

State the first condition of equilibrium.

The vector sum of all external forces acting on a body must be zero ($\Sigma F_x = 0$ and $\Sigma F_y = 0$).

What is centripetal force?

The force directed toward the centre of a circular path that keeps an object moving in that circle at constant speed, given by $F_c = mv^2/r$.

Key Formulas

Topic	Formula
Torque (moment of force)	$\tau = F \times \ell$ (ℓ = moment arm, unit: N m)
x-component of a force	$F_x = F \cos \theta$
y-component of a force	$F_y = F \sin \theta$
Magnitude from components	$F = \sqrt{F_x^2 + F_y^2}$
Direction from components	$\theta = \tan^{-1}(F_y / F_x)$

Principle of moments	Sum of clockwise moments = Sum of anticlockwise moments
1st condition of equilibrium	$\Sigma F_x = 0$ and $\Sigma F_y = 0$
2nd condition of equilibrium	$\Sigma\tau = 0$
Centripetal force	$F_c = mv^2 / r$

Diagrams

Torque and Moment Arm: The relationship between force, moment arm and torque about a pivot

Three States of Equilibrium: Stable, unstable and neutral equilibrium compared using a cone on its base, tip, and side

Centripetal Force in Circular Motion: Velocity tangent to the circle and centripetal force directed toward the centre

Short Questions & Answers

Define like and unlike parallel forces.

Like parallel forces act in the same direction; unlike parallel forces act in opposite directions, while remaining parallel to each other.

What are rectangular components of a vector?

The two mutually perpendicular components (usually along the x and y axes) into which a vector can be resolved, given by $F_x = F \cos \theta$ and $F_y = F \sin \theta$.

What is the line of action of a force?

The straight line along which a force acts.

Give an example of a body which is moving yet in equilibrium.

A parachutist descending at constant (terminal) velocity is in dynamic equilibrium, since the net force on them is zero even though they are moving.

Define centre of mass and centre of gravity of a body.

Centre of mass is the point where the whole mass of a body is assumed concentrated; centre of gravity is the point where the whole weight of a body is considered to act. On Earth's surface, where g is uniform, the two coincide.

What are the two basic principles used to improve stability?

Lowering the centre of gravity and increasing (widening) the base area of support.

Why is a cylinder resting on its curved surface in neutral equilibrium?

Because when it is rolled slightly, its centre of mass stays at the same height and there is no torque pulling it back or pushing it further, so it simply settles in its new position.

How can you prove that centripetal force always acts perpendicular to velocity?

If the force had a component along the direction of velocity, it would change the object's speed; since the object moves at constant speed in a circle, the force must have zero component along v, meaning it acts exactly perpendicular to v, i.e. $F \cos 90° = 0$.

Long Questions & Answers

Explain the principle of moments with an example, and state the conditions of equilibrium.

The principle of moments states that when a body is balanced, the sum of clockwise moments about any point equals the sum of anticlockwise moments about that point. For example, when two weights w_1 and w_2 at distances ℓ_1 and ℓ_2 on one side of a pivoted metre rule balance a third weight w_3 at distance ℓ_3 on the other side, $w_1\ell_1 + w_2\ell_2 = w_3\ell_3$. A body is in complete equilibrium only when both conditions of equilibrium hold: the first condition requires the vector sum of all external forces to be zero ($\Sigma Fx = 0$, $\Sigma Fy = 0$), ensuring no linear acceleration; the second condition requires the vector sum of all torques about any point to be zero ($\Sigma\tau = 0$), ensuring no rotational acceleration.

Describe how the centre of gravity of an irregular-shaped lamina can be determined experimentally.

The lamina is suspended freely from a point near its edge, allowing it to hang and settle; a plumb line is hung from the same suspension point, and a straight line is marked on the lamina along the plumb line's path — the centre of gravity must lie somewhere on this line. The lamina is then suspended from a different point, and the process is repeated to mark a second line. The point where the two marked lines intersect is the centre of gravity of the lamina.

Differentiate between stable, unstable and neutral equilibrium with examples.

In stable equilibrium, a body returns to its original position after a small tilt because the resulting torque restores it, as long as its centre of mass stays above its base — e.g. a cone resting on its flat base. In unstable equilibrium, a body moves further away from its original position after a small tilt because its centre of mass falls outside the base, and the torque continues to move it away — e.g. a cone balanced precariously on its tip. In neutral equilibrium, a body settles into its new position after being disturbed, with no change in the height of its centre of mass and no torque pulling it back or pushing it further — e.g. a ball or cylinder resting on a flat, level surface.

Explain centripetal force and describe two real-life sources of it.

An object moving in a circle at constant speed continuously changes direction, so a resultant force perpendicular to its velocity must act on it at all times, directed toward the centre of the circle; this is called centripetal force, given by $F_c = mv^2/r$. One real-life source is the tension in a string when a stone is whirled in a horizontal circle — the string pulls the stone toward the centre, and if released, the stone flies off along a straight tangent line since the centripetal force disappears. Another source is Earth's gravity acting on the Moon or an orbiting satellite — the gravitational pull continuously curves their motion toward Earth's centre, keeping them in a roughly circular orbit instead of moving off in a straight line.

Multiple Choice Questions (MCQs)

A particle is acted upon simultaneously by two forces of 4 N and 3 N. The net force on the particle is: (A) 1 N (B) between 1 N and 7 N (C) 5 N (D) 7 N

Correct answer: (B) between 1 N and 7 N. Depending on the angle between the two forces, the resultant can range from $|4-3|=1$ N (opposite directions) to $4+3=7$ N (same direction), so it lies between 1 N and 7 N.

A force F makes an angle of 60° with the x-axis. Its y-component equals: (A) F (B) F sin60° (C) F cos60° (D) F tan60°

Correct answer: (B) F sin60°. The y-component of a force is $F_y = F \sin \theta$, so here it equals F sin60°.

Moment of a force is also called: (A) moment arm (B) couple (C) couple arm (D) torque

Correct answer: (D) torque. The moment of a force is also known as torque.

A body is completely in equilibrium when: (A) $\Sigma F = 0$ and $\Sigma \tau = 0$ (B) $\Sigma F = 0$ and $\Sigma \tau \neq 0$ (C) $\Sigma F \neq 0$ and $\Sigma \tau = 0$ (D) $\Sigma F \neq 0$ and $\Sigma \tau \neq 0$

Correct answer: (A) $\Sigma F = 0$ and $\Sigma \tau = 0$. Complete equilibrium requires both the first condition ($\Sigma F = 0$) and the second condition ($\Sigma \tau = 0$) to hold simultaneously.

A tightrope walker balances using a long bamboo stick. This applies the: (A) law of conservation of momentum (B) Newton's second law of motion (C) principle of moments (D) Newton's third law of motion

Correct answer: (C) principle of moments. Adjusting the stick shifts the combined centre of gravity and balances torques, applying the principle of moments.

In stable equilibrium, the centre of gravity of a body lies: (A) at the highest position (B) at the lowest position (C) at any position (D) outside the body

Correct answer: (B) at the lowest position. A body in stable equilibrium typically has its centre of gravity as low as possible, increasing resistance to toppling.

The centre of mass of a body: (A) lies always inside the body (B) lies always outside the body (C) lies always on the surface of the body (D) may lie within, outside, or on the surface

Correct answer: (D) may lie within, outside, or on the surface. Depending on the shape of the body (e.g. a ring or a cup), the centre of mass can be inside, outside, or on the surface of the body.

A cylinder resting on its circular (curved) base is in: (A) stable equilibrium (B) unstable equilibrium (C) neutral equilibrium (D) none of these

Correct answer: (C) neutral equilibrium. As a cylinder rolls slightly, its centre of mass height does not change, so it is in neutral equilibrium.

Centripetal force is given by: (A) rF (B) rF cosθ (C) mv^2/r (D) mv/r^2

Correct answer: (C) mv^2/r. The formula for centripetal force is $F_c = mv^2/r$.

Torque is zero when the line of action of a force: (A) is perpendicular to the moment arm (B) passes through the axis of rotation (C) is parallel to the axis of rotation (D) is at 45° to the axis of rotation

Correct answer: (B) passes through the axis of rotation. If the line of action passes through the axis of rotation, the moment arm is zero, making the torque zero.

Quick Revision Summary

- Like parallel forces: same direction; Unlike parallel forces: opposite direction
- Torque $\tau = F \times$ moment arm; anticlockwise = positive, clockwise = negative
- Couple = two equal, opposite, parallel forces at different points → produces torque, zero net force
- $F_x = F\cos\theta$, $F_y = F\sin\theta$; $F = \sqrt{F_x^2+F_y^2}$, $\theta = \tan^{-1}(F_y/F_x)$
- Principle of moments: sum of clockwise moments = sum of anticlockwise moments
- Centre of gravity = point where weight acts; Centre of mass = point where mass is concentrated
- 1st condition of equilibrium: $\Sigma F = 0$; 2nd condition: $\Sigma\tau = 0$
- Stable: returns after tilt; Unstable: moves away after tilt; Neutral: stays in new position, no height change
- Improve stability: lower centre of gravity + widen base
- Centripetal force $F_c = mv^2/r$, always directed toward the centre, perpendicular to velocity

Exam Tips

- Practice resolving forces into F_x and F_y components — this skill underlies torque, equilibrium, and inclined-force numericals
- Memorise both conditions of equilibrium precisely and know when each alone is insufficient
- Use the cone examples (on base, on tip, on side) to remember stable/unstable/neutral equilibrium quickly
- Practice principle-of-moments numericals (see-saws, metre rules, crowbars) — identify clockwise vs anticlockwise moments carefully
- Remember $F_c = mv^2/r$ and identify the real-world source of centripetal force (tension, gravity, friction, normal force) in each scenario
- Draw clear diagrams labelling force, moment arm, and pivot point for torque questions — partial credit is often given for correct diagrams

Chapter 5: Work, Energy and Power

Work is done when a force acting on an object moves it through some distance. Energy is the ability to do work, and is transferred between systems whenever work is done. This chapter defines work, kinetic and potential energy, and the principle of conservation of energy.

It then surveys renewable and non-renewable sources of energy used for electricity generation, and defines power and efficiency, explaining why no real machine can reach 100% efficiency.

Learning Objectives

- Define work done and use $W = F \times d$ (and $W = FS \cos \theta$) to solve problems
- Define energy, and describe how energy can be stored in different forms
- Derive and apply Kinetic Energy = $\frac{1}{2}mv^2$ and Gravitational Potential Energy = mgh
- State and apply the principle of conservation of energy
- Differentiate between and list renewable and non-renewable energy sources
- Describe how useful energy is obtained from various natural resources, with their advantages and disadvantages
- Define and calculate power ($P = W/t$) and efficiency (% efficiency = useful output/total input × 100)
- Explain why a system cannot have 100% efficiency and why perpetual energy machines are impossible

Key Concepts

5.1 Work

Work is defined as the product of the magnitude of a force and the distance covered in the direction of the force: $W = F \times S$. If a force acts but produces no displacement (e.g. pushing against a fixed wall), or if the displacement occurs with zero applied force, the work done is zero. When a force F acts at angle θ to the direction of motion, only its component along the motion, $F \cos \theta$, does work:

$W = FS \cos\theta$. If $\theta = 0°$, $W = FS$ (maximum); if $\theta = 90°$, $W = 0$ (e.g. carrying a bag horizontally does zero work against gravity, since the upward supporting force is perpendicular to the horizontal displacement). Work is a scalar quantity, since it carries no directional information. Graphically, the area under a force-distance graph represents the work done. The SI unit of work is the joule (J): one joule is the work done when a force of one newton moves a body through one metre in the direction of the force (1 J = 1 N m).

5.2 Energy: Kinetic and Potential

Energy is the ability of a body to do work; like work, it is a scalar quantity with SI unit joule (J). There are two basic forms of mechanical energy: kinetic energy and potential energy. Kinetic energy is the energy a body possesses due to its motion. It can be derived by finding the work needed to bring a moving body to rest: for a body of mass m moving with velocity v, $E_k = \frac{1}{2}mv^2$. Doubling the speed of a body quadruples its kinetic energy, since E_k depends on v^2.

Potential energy is the energy a body possesses due to its position or state of deformation. Gravitational potential energy is the energy a body has due to its height above a reference level: raising a body of mass m through height h requires work equal to its weight times height, so $E_p = mgh$. Other forms of stored (potential) energy include elastic (strain) potential energy in a compressed or stretched spring, chemical potential energy stored in a battery or fuel, nuclear energy hidden in atomic nuclei (released during nuclear fission), electrostatic energy, and thermal (internal) energy released by burning fossil fuels.

5.3 Conservation of Energy

The principle of conservation of energy states that energy cannot be created or destroyed; it may be transformed from one form to another, but the total amount of energy in an isolated system remains constant. For a body of mass m falling freely from height h (with negligible air resistance), the sum of potential and kinetic energy stays equal to mgh at every point of the fall: at the top, $E_p = mgh$ and $E_k = 0$; partway down at height x remaining, $E_p = mgx$ and $E_k = mg(h - x)$; and just before hitting the ground, $E_p = 0$ and $E_k = mgh$. On impact, this kinetic energy is dissipated as heat and sound into the surroundings. Energy that is 'lost' during real processes (such as friction) is not actually destroyed — it is converted to heat that dissipates into the environment and becomes unavailable for useful work (waste energy).

5.4 Sources of Energy

Fossil fuel energy comes from burning coal, oil, and natural gas; the heat produced generates steam that drives turbines connected to electric generators. Hydroelectric generation converts the gravitational potential energy of water stored behind a dam into kinetic energy as it falls, which spins a turbine to generate electricity. Solar energy from the Sun can be used directly for heating (via solar panels with blackened metal plates) or converted to electricity using photovoltaic (solar) cells connected in series to form panels, or by concentrating sunlight to boil water for steam turbines.

Nuclear energy is released as heat when the nucleus of a heavy atom (e.g. uranium, plutonium) splits apart in nuclear fission inside a reactor; the heat produces steam that drives turbine generators (Pakistan operates nuclear power stations at Karachi and Chashma). Geothermal energy uses heat from hot rocks deep underground (heated by radioactive decay) to convert pumped-down water into steam that drives generators; where such water reaches the surface naturally, it appears as hot springs or geysers. Wind energy uses windmills/wind turbines to convert the kinetic energy of moving air into electricity, typically using wind farms of many turbines. Tidal energy captures the rise and fall of sea levels (caused by the Moon's gravity) by trapping water behind a dam and releasing it through turbines. Wave energy uses floating devices (such as Salter's duck) that move with sea waves to drive generators. Biofuel energy is obtained from biomass (plants, food waste, animal dung, sewage) either by direct combustion to produce steam, or by anaerobic digestion in a sealed digester to produce methane-rich biogas, or by fermentation to produce ethanol as a petrol substitute.

5.5 Renewable vs Non-Renewable Sources

Renewable energy sources are naturally replenished after use and will not run out — these include hydroelectric, solar, wind, tidal, wave, and geothermal energy. Non-renewable energy sources are depleted with continued use and cannot be quickly replaced once exhausted — these include fossil fuels (which took millions of years to form from buried organic remains) and nuclear fuel (limited in quantity).

Fossil fuels are a widely used but expensive energy source that also cause air pollution harmful to human health. Hydroelectric energy is the cheapest and pollution-free, though it can cause waterlogging of nearby land by raising the water table. Solar, wind, tidal, and wave energy are pollution-free but have high initial setup costs. Nuclear energy is relatively cheap and can meet large energy demands, but carries the risk of radioactive leakage and the challenge of safely disposing of nuclear waste; wind turbines can be noisy and are sometimes considered visually intrusive. All wasted energy from any energy conversion process ultimately becomes thermal pollution, contributing to global warming.

5.6 Power

Power is the time rate of doing work (or equivalently, the rate of energy transfer): $P = W/t$. It is a scalar quantity. The SI unit of power is the watt (W): one watt equals one joule of work done per second ($1\ W = 1\ J\ s^{-1}$). Larger units include the kilowatt ($1\ kW = 10^3\ W$) and megawatt ($1\ MW = 10^6\ W$); the horsepower (British engineering unit) equals 746 W.

5.7 Efficiency and Perpetual Machines

Efficiency measures what fraction of the input energy supplied to a system is converted into useful output energy, with the rest wasted (usually as heat). Percentage efficiency = (Useful output energy ÷ Total input energy) × 100, which can equivalently be expressed using power: % Efficiency = (Useful power output ÷ Total power input) × 100. Since some energy is always lost to friction, air resistance, and heat in any real machine, no system can achieve 100% efficiency; a hypothetical machine with output equal to input (100% efficiency) is called an ideal machine, which does not exist in practice.

A perpetual energy machine is a hypothetical device that could run forever and do work indefinitely without any external energy source — this is impossible because it would require generating more energy than it consumes, violating the principle of conservation of energy; real mechanical systems always lose some energy as heat due to friction and air resistance.

Important Definitions

Define work.

The product of the magnitude of a force and the distance covered in the direction of the force: $W = F \times S$.

Define energy.

The ability of a body to do work; measured in joules, the same unit as work.

Define kinetic energy.

The energy a body possesses due to its motion: $E_k = \frac{1}{2}mv^2$.

Define gravitational potential energy.

The energy a body possesses due to its position/height above a reference level: $E_p = mgh$.

State the principle of conservation of energy.

Energy cannot be created or destroyed; it can only be transformed from one form to another, and the total amount of energy remains constant.

Define power.

The time rate of doing work: $P = W/t$, measured in watts.

Define efficiency of a working system.

The ratio of useful output energy to total input energy, usually expressed as a percentage.

Why can't any real machine reach 100% efficiency?

Because some input energy is always lost as heat due to friction, air resistance, and other unavoidable dissipative effects during operation.

Key Formulas

Topic	Formula
Work (force along motion)	$W = F \times S$
Work (force at angle θ)	$W = F S \cos\theta$
Kinetic energy	$E_k = \frac{1}{2} m v^2$
Gravitational potential energy	$E_p = m g h$

Conservation of mechanical energy	Ep + Ek = constant (mgh, in free fall)
Power	P = W/t = Energy transferred / time
Horsepower	1 hp = 746 W
Percentage efficiency	% Efficiency = (Useful output energy / Total input energy) × 100

Diagrams

Renewable and Non-Renewable Energy Sources: Classification of common energy sources into renewable and non-renewable categories

Conservation of Energy in Free Fall: Potential and kinetic energy at three points of a fall, showing their sum stays constant

Efficiency of Common Systems: Typical percentage efficiency of a diesel engine, petrol engine, electric motor, and bicycle

Short Questions & Answers

What is the work done on an object that remains at rest when a force is applied on it?

Zero — since work requires displacement in the direction of the force, and the object does not move, no work is done.

How can a slow-moving car have more kinetic energy than a fast-moving motorcycle?

Because kinetic energy depends on both mass and the square of velocity ($E_k = \frac{1}{2}mv^2$); if the car's mass is large enough, it can have greater kinetic energy than a lighter, faster motorcycle.

Define work and state its SI unit.

Work is the product of force and the distance moved in the direction of the force; its SI unit is the joule (J).

What is the potential energy of a body of mass m raised through height h?

Ep = mgh.

Define efficiency of a working system. Why can't a system have 100% efficiency?

Efficiency is the ratio of useful output energy to total input energy; a system can't reach 100% because some energy is always lost as heat due to friction and other unavoidable effects.

What is power? Name its SI unit.

Power is the time rate of doing work; its SI unit is the watt (W), equal to one joule per second.

Differentiate between renewable and non-renewable energy sources.

Renewable sources (e.g. solar, wind, hydro) are naturally replenished and won't run out; non-renewable sources (e.g. fossil fuels, nuclear fuel) are depleted with use and take an extremely long time (or cannot) be replaced.

Can the kinetic energy of a body ever be negative?

No — since $E_k = \frac{1}{2}mv^2$ depends on v^2 (always positive or zero) and mass is always positive, kinetic energy can never be negative.

Long Questions & Answers

Derive the expression for kinetic energy of a moving body, and explain how doubling velocity affects it.

The kinetic energy of a body equals the work done by an opposing force F to bring it to rest over distance S: Ek = F × S. Using F = ma and, from a velocity-time graph, $S = (v+0)/2 \times t = vt/2$ with $a = v/t$, substitution gives $E_k = ma \times (vt/2) = \frac{1}{2}m(v/t)(vt) = \frac{1}{2}mv^2$. Since kinetic energy depends on the square of velocity, doubling the velocity of a body increases its kinetic energy by a factor of four ($2^2 = 4$), not just double.

State the law of conservation of energy and explain it using the example of a freely falling body.

The law states that energy cannot be created or destroyed, only transformed from one form to another, with the total amount remaining constant. For a body of mass m dropped from height h with negligible air resistance: at the top, all its energy is potential ($E_p = mgh$, $E_k = 0$); partway down, at a distance x below the start, it has lost potential energy mgx which has become kinetic energy ($E_p = mg(h-x)$, $E_k = mgx$), and the total Ep + Ek still equals mgh; just before hitting the ground, all the energy has become kinetic ($E_p = 0$, $E_k = mgh$). At every stage, the total mechanical energy remains mgh, confirming the conservation of energy — upon impact, this energy converts to heat and sound dissipated into the environment.

Differentiate between renewable and non-renewable sources of energy, giving three examples of each.

Renewable energy sources are naturally replenished after use and effectively never run out — examples include hydroelectric energy (from falling water), solar energy (from sunlight), and wind energy (from moving air); tidal and wave energy are further examples. Non-renewable energy sources are used up faster than they can be replaced and exist in limited quantities — examples include fossil fuels like coal, oil, and natural gas (which took millions of years to form), and nuclear fuel such as uranium (limited in supply). Renewable sources are generally pollution-free but have higher initial setup costs, while non-renewable sources like fossil fuels are cheaper to access initially but cause significant air pollution and environmental harm.

Explain what is meant by the efficiency of a machine, how it is calculated, and why there is a limit to it.

Efficiency measures how much of the energy put into a machine (input energy) is converted into useful output energy, expressed as a percentage: % Efficiency = (Useful output energy ÷ Total input energy) × 100. It can also be calculated using power instead of energy when the process rate matters. There is always a limit to efficiency because some input energy is inevitably lost as heat due to friction between moving parts, air resistance, and other dissipative effects; this lost energy is not available to do useful work. Since no machine can eliminate all such losses, no real machine can achieve 100% efficiency, and a perpetual motion machine (one that keeps working forever without an external energy source) is impossible, as it would violate the principle of conservation of energy.

Multiple Choice Questions (MCQs)

Work done is maximum when the angle between force F and displacement d is: (A) 0° (B) 30° (C) 60° (D) 90°

Correct answer: (A) 0°. $W = FS\cos\theta$ is maximum when $\cos\theta = 1$, i.e. when $\theta = 0°$ (force and displacement in the same direction).

A joule can also be written as: (A) kg m s^{-2} (B) kg m s^{-1} (C) kg m^2 s^{-3} (D) kg m^2 s^{-2}

Correct answer: (D) kg m^2 s^{-2}. 1 J = 1 N·m = 1 kg m s^{-2} × m = 1 kg m^2 s^{-2}.

The SI unit of power is: (A) joule (B) newton (C) watt (D) second

Correct answer: (C) watt. Power is measured in watts (W), equal to one joule per second.

A bullet of mass 0.05 kg has a speed of 300 m s^{-1}. Its kinetic energy is: (A) 2250 J (B) 4500 J (C) 1500 J (D) 1125 J

Correct answer: (A) 2250 J. $E_k = \frac{1}{2}mv^2 = \frac{1}{2} \times 0.05\ \text{kg} \times (300)^2 = \frac{1}{2} \times 0.05 \times 90000 = 2250$ J.

If a car doubles its speed, its kinetic energy will be: (A) the same (B) doubled (C) increased to three times (D) increased to four times

Correct answer: (D) increased to four times. Since $E_k \propto v^2$, doubling speed quadruples (increases four times) the kinetic energy.

The energy possessed by a body due to its position is: (A) kinetic energy (B) potential energy (C) chemical energy (D) solar energy

Correct answer: (B) potential energy. Energy due to position (e.g. height) is potential energy.

If the momentum of an object is doubled while its mass stays the same, its kinetic energy will: (A) double (B) increase to four times (C) reduce to one-half (D) remain the same

Correct answer: (B) increase to four times. Since $p=mv$ and $E_k=p^2/2m$, doubling p (at constant m) quadruples E_k.

Which of the following is NOT a renewable energy source? (A) Hydroelectric energy (B) Fossil fuels (C) Wind energy (D) Solar energy

Correct answer: (B) Fossil fuels. Fossil fuels are non-renewable, as they take millions of years to form and are used up much faster than they are replaced.

A machine with output energy equal to input energy would have efficiency of: (A) 50% (B) 75% (C) 90% (D) 100%

Correct answer: (D) 100%. A hypothetical 'ideal machine' with no energy losses would have 100% efficiency, though this is not achievable in practice.

The power of a 2 kW water pump raising water to a height of 5 m in one minute is used to lift approximately: (A) 1000 litres (B) 1200 litres (C) 2000 litres (D) 2400 litres

Correct answer: (D) 2400 litres. Energy in 1 min = 2000 W × 60 s = 120000 J = mgh = m × 10 × 5, so m = 2400 kg ≈ 2400 litres of water.

Quick Revision Summary

- Work W = F×S (same direction) or W = FScosθ (at angle θ); SI unit: joule (N·m)
- Kinetic energy Ek = ½mv²; doubling v quadruples Ek
- Gravitational potential energy Ep = mgh
- Conservation of energy: total energy constant, only transforms between forms
- Renewable: hydro, solar, wind, tidal, wave, geothermal, biofuel
- Non-renewable: fossil fuels (coal, oil, gas), nuclear fuel
- Power P = W/t; SI unit: watt (1 W = 1 J/s); 1 hp = 746 W
- % Efficiency = useful output energy ÷ total input energy × 100
- No machine reaches 100% efficiency; perpetual motion machines are impossible

Exam Tips

- Always check the angle between force and displacement before applying W=FScosθ — a common exam trap is assuming W=FS even when θ≠0
- Remember Ek depends on v² — practice 'what happens if speed doubles/triples' style questions
- Practice energy conservation numericals for falling bodies: identify Ep and Ek at each labelled point and confirm their sum is constant
- Memorise which energy sources are renewable vs non-renewable, and be ready to justify why (regeneration time)
- Be comfortable converting between W, kW, MW, and hp in power problems

- For efficiency questions, clearly identify 'useful output energy' vs 'total input energy' before applying the formula

Chapter 6: Mechanical Properties of Matter

This chapter studies how materials respond to applied forces: how solids deform elastically according to Hooke's law, how density describes how tightly matter is packed, and how pressure is transmitted through solids, liquids, and gases.

It covers pressure in liquids and the atmosphere, instruments for measuring pressure (barometer, manometer), and Pascal's law, which explains how hydraulic systems like car lifts and vehicle brakes multiply force.

Learning Objectives

- Explain that forces can change the size and shape of an object, and distinguish elastic from inelastic materials
- State Hooke's law and use $k = F/x$ to solve problems involving springs, identifying the limit of proportionality on a load-extension graph
- Describe real-world applications of Hooke's law such as spring scales, galvanometers, and clock balance wheels
- Define density, use Density = Mass/Volume, and describe how density is measured for regular and irregular solids
- Define pressure, use $P = F/A$, and explain how pressure depends on both force and contact area in everyday situations
- Derive and apply $P = \rho gh$ for pressure in a liquid at a given depth
- Describe atmospheric pressure, how it varies with height, how it is measured using a barometer and manometer, and how it relates to weather
- State Pascal's law and explain how it is applied in hydraulic presses and hydraulic brakes

Key Concepts

6.1 Deformation of Solids

A force applied to an object that changes its size or shape is called a deforming force — for example, a spring stretches (extension) or compresses under an applied force, and a tennis ball flattens briefly when struck by a racket. A material is said to be elastic if it regains its original size and shape once the deforming force is removed; this property is called elasticity. Most materials are elastic only up to a certain point called the elastic limit — beyond this limit, the deformation becomes permanent and the material does not return to its original shape even after the force is removed. Materials such as clay dough or plasticine that do not spring back at all are called inelastic materials.

6.2 Hooke's Law

Hooke's law states that within the elastic limit, the extension or compression x of a spring is directly proportional to the applied force F: $F \propto x$, or $F = kx$, where k is the spring constant (a measure of the spring's stiffness), given by $k = F/x$ with SI unit $N\ m^{-1}$. A graph of force against extension is a straight line through the origin as long as the elastic limit is not exceeded — the point at which the graph stops being a straight line is called the limit of proportionality. Beyond this point the spring is permanently deformed and the graph is no longer linear. The slope (gradient) of the linear part of a force-extension graph equals the spring constant.

Hooke's law underlies many everyday devices: spring scales use the extension (or compression) of a spring to measure weight; the balance wheel of a mechanical clock uses a spring to regulate the back-and-forth motion that keeps time; and a galvanometer (a current-detecting instrument) uses a tiny 'hair spring' to return its pointer to zero and to provide electrical connections to its coil, with the pointer's deflection proportional to the current flowing through it.

6.3 Density

Different substances of equal volume generally have different masses, because their molecules differ in size, mass, and how closely they are packed. Density is defined as mass per unit volume: Density = Mass/Volume, with SI unit $kg\ m^{-3}$ (also commonly expressed in $g\ cm^{-3}$). Denser substances (like iron or steel) pack more, heavier molecules into the same volume than less dense substances (like wood or packing foam). Engineers and architects account for the density of building materials when designing roads, bridges, and buildings, since it affects the strength needed in foundations and supporting pillars.

The density of a regularly shaped solid is found by measuring its mass (with a balance) and calculating its volume from its dimensions. For an irregularly shaped solid, the volume is found by submerging it in a liquid (in which it does not dissolve) inside a measuring cylinder and noting the rise in liquid level, which equals the object's volume.

6.4 Pressure

Pressure is defined as the force acting normally (at right angles) on unit area of a surface: $P = F/A$, where F is the force and A is the contact area. Its SI unit is the pascal (Pa), equal to one newton per square metre ($N\ m^{-2}$). For a given force, pressure increases as the contact area decreases — this is why a sharp knife edge, a pointed pin, or football studs concentrate force onto a small area to cut, pierce, or grip more effectively, while wide, flat surfaces (like an elephant's large feet or snowshoes) spread force over a larger area to reduce pressure.

6.5 Pressure in Liquids

The pressure at depth h in a liquid of density ρ can be derived by considering a horizontal area A at that depth: the liquid column above it has volume $V = Ah$, mass $m = \rho Ah$, and weight $F = mg = \rho Ahg$. Since pressure is force per unit area, $P = F/A = \rho Ahg/A$, giving $P = \rho gh$. This shows that liquid pressure increases with both depth and density, and does not depend on the shape or area of the container. Pressure in a liquid acts at right angles (normal) to any surface it touches — if a hole is made in a container, the liquid spurts out perpendicular to the surface before curving downward under gravity, and a lower hole produces a stream that travels farther, showing that pressure increases with depth.

6.6 Atmospheric Pressure

The atmosphere is the layer of air surrounding the Earth; its constantly moving molecules collide with surfaces and exert a force per unit area called atmospheric pressure, which acts equally in all directions because air molecules move randomly. At sea level, standard atmospheric pressure is about 1.013×10^5 Pa — an enormous pressure that goes unnoticed because it is balanced by air pressure inside our bodies. The atmosphere extends to roughly 100 km, and its density (and hence pressure) decreases continuously with altitude: pressure falls to about 55 kPa at 5 km altitude and about 1 kPa at 30 km, so measuring atmospheric pressure at a point can reveal its altitude — the lower the pressure, the greater the altitude. Because atmospheric pressure also falls when air becomes less dense due to increased water vapour, a drop in atmospheric pressure often signals approaching rain clouds, which is why meteorologists use pressure changes to forecast weather.

6.7 Measurement of Atmospheric Pressure: The Barometer

A barometer is an instrument that measures atmospheric pressure using the height of a supported mercury column. A simple mercury barometer is made from a glass tube about one metre long, closed at one end, completely filled with mercury, and inverted into a dish of mercury; the nearly empty (vacuum) space above the mercury in the tube has almost zero pressure. The pressure at the base of the mercury column inside the tube equals the atmospheric pressure pushing down on the mercury surface in the open dish, since both points are at the same level: $P = \rho g h$. At standard atmospheric pressure (1.013×10^5 Pa) with mercury density 13.6×10^3 kg m^{-3}, this height works out to 760 mm — the traditional 'mm of mercury' reference for atmospheric pressure.

6.8 Measurement of Pressure by Manometer

A manometer is a simple U-shaped glass tube containing mercury, used to measure the pressure of an enclosed gas. When both ends of the tube are open to the atmosphere, the mercury levels in the two arms are equal. When one arm is connected to a gas supply (with the other arm left open), if the mercury level in the connected (short) arm is lower than in the open (long) arm, the gas pressure is greater than atmospheric pressure; if the mercury level in the connected arm is higher, the gas pressure is less than atmospheric pressure.

6.9 Pascal's Law

When a balloon or a tyre is inflated, pressure applied at one point is felt uniformly throughout the object — this demonstrates that a fluid transmits applied pressure equally in all directions. Pascal's law states that when pressure is applied at one point in an enclosed fluid, it is transmitted equally to all parts of the fluid without loss. This principle underlies hydraulic systems, which can move heavy loads and generate large forces because liquids are incompressible and do not absorb the energy applied to them.

In a hydraulic press, a small piston of area A_1 and a large piston of area A_2 are connected by a liquid-filled pipe. A force F_1 applied to the small piston creates pressure $P = F_1/A_1$, which is transmitted equally to the large piston, producing a much larger force $F_2 = P \times A_2 = (F_1/A_1) \times A_2$. Since $A_2 > A_1$, it follows that $F_2 > F_1$ — a small force on the small piston produces a much larger force on the large piston, making the system a force multiplier. This principle is used in hydraulic presses (for compressing cotton bales), car lifts at service stations, and hydraulic brakes, where pressing the brake pedal transmits liquid pressure from a small master cylinder to larger cylinders at each wheel, pushing brake pads against discs or drums to slow the vehicle.

Important Definitions

What is a deforming force, and what is elasticity?

A deforming force is a force that changes the size or shape of an object; elasticity is the property by which a material returns to its original size and shape once the deforming force is removed.

State Hooke's law.

Within the elastic limit, the extension or compression of a spring is directly proportional to the applied force: $F = kx$, where k is the spring constant.

Define spring constant and give its unit.

The spring constant k is the force needed to produce unit extension in a spring ($k = F/x$); its SI unit is newton per metre ($N\ m^{-1}$).

Define density.

Density is the mass of a substance per unit volume: Density = Mass/Volume, measured in $kg\ m^{-3}$.

Define pressure and state its SI unit.

Pressure is the force acting normally on unit area of a surface: $P = F/A$; its SI unit is the pascal (Pa), equal to $1\ N\ m^{-2}$.

What is atmospheric pressure?

The force per unit area exerted by the weight and molecular collisions of the atmosphere on the Earth's surface and on all objects within it; standard value at sea level is 1.013×10^5 Pa.

State Pascal's law.

When pressure is applied at one point in an enclosed fluid, it is transmitted equally to all parts of the fluid without loss.

Why is a hydraulic press called a force multiplier?

Because a small force applied on its smaller piston produces, via a larger piston area, a much greater output force, following $F_2 = (F_1/A_1) \times A_2$.

Key Formulas

Topic	Formula
Hooke's law / spring constant	$F = kx$, $k = F/x$
Density	Density = Mass / Volume
Pressure	$P = F/A$
Pressure in a liquid at depth h	$P = \rho g h$
Hydraulic press force multiplication	$F_2 = (F_1/A_1) \times A_2$
Standard atmospheric pressure	$P_0 \approx 1.013 \times 10^5$ Pa ($\approx$ 760 mm of mercury)

Diagrams

Force-Extension Graph (Hooke's Law): A load-extension graph showing the linear region where Hooke's law holds, and the limit of proportionality beyond which the spring is permanently deformed

Pressure Increases with Depth in a Liquid: Water streams from three holes at different heights in a container, showing that pressure (and jet distance) increases with depth

Hydraulic Press: Force Multiplication: A small force F1 on a small piston (area A1) produces a much larger force F2 on a large piston (area A2), following Pascal's law

Short Questions & Answers

Why do heavy animals like elephants have large, flat feet?

A large contact area spreads their weight over a bigger surface, reducing the pressure exerted on the ground so their legs and the ground can bear it comfortably.

Why is it painful to walk barefoot on pebbles but not on flat ground?

Pebbles reduce the contact area between the foot and the ground, so the same reaction force produces much higher pressure, which is felt as pain.

Distinguish between force and pressure.

Force is a push or pull measured in newtons, while pressure is the force acting normally per unit area ($P=F/A$), measured in pascals — the same force can produce very different pressures depending on the contact area.

What is the relationship between liquid pressure and depth?

Liquid pressure increases directly with depth, following $P = \rho g h$ — the deeper a point is below the surface, the greater the pressure at that point.

Does an object remain elastic beyond its elastic limit? Explain.

No — beyond the elastic limit, the deformation becomes permanent and the object no longer returns to its original size and shape even when the deforming force is removed.

What is the basic principle used in a hydraulic brake system?

Pascal's law: pressure applied at the brake pedal's master cylinder is transmitted equally through the brake fluid to the larger pistons at each wheel, producing a much larger braking force.

Give one application of Pascal's law from daily life.

Hydraulic car lifts at service stations use a small applied force on a narrow piston to lift the much greater weight of a car, because pressure is transmitted equally throughout the enclosed hydraulic fluid.

Why does atmospheric pressure decrease with altitude?

At higher altitudes the air is less dense (fewer air molecules above a given point), so there is a smaller weight of air pressing down, resulting in lower atmospheric pressure.

Long Questions & Answers

State Hooke's law and describe, with reference to a load-extension graph, how the spring constant is found and what happens beyond the elastic limit.

Hooke's law states that within the elastic limit, the extension x produced in a spring is directly proportional to the applied force F, i.e. $F = kx$, where k is the spring constant (a measure of the spring's stiffness) given by $k = F/x$ with unit N m^{-1}. If force is plotted against extension, this relationship appears as a straight line passing through the origin, and the gradient (slope) of this line equals the spring constant. This straight-line behaviour continues only up to the limit of proportionality; beyond this point on the graph, equal increases in force no longer produce equal increases in extension, the spring is permanently deformed, and the graph curves and no longer follows Hooke's law.

Derive the expression for the pressure at depth h in a liquid, and explain why pressure increases with depth.

Consider a horizontal area A at depth h within a liquid of density ρ. The volume of liquid directly above this area is $V = Ah$, so its mass is $m = \rho V = \rho Ah$, and its weight (the force pressing down on area A) is $F = mg = \rho Ahg$. Since pressure is force per unit area, $P = F/A = (\rho Ahg)/A = \rho gh$. This shows that pressure increases with depth h because a deeper point has a taller, heavier column of liquid above it exerting greater downward force on the same area; pressure also increases with the liquid's density ρ, since denser liquid weighs more for the same volume.

Describe the construction and working of a simple mercury barometer, and explain how it measures atmospheric pressure.

A simple mercury barometer consists of a glass tube about one metre long, closed at one end, completely filled with mercury, and then inverted vertically into an open dish of mercury, with a metre scale placed alongside to measure the height of the mercury column. The space above the mercury inside the closed end of the tube is nearly a vacuum, with pressure close to zero. The pressure at a point inside the tube at the level of the mercury surface in the open dish equals the pressure at the corresponding point in the dish (since both are at the same level in a connected liquid), and this equals the atmospheric pressure pushing down on the open mercury surface, given by $P = \rho g h$. At standard atmospheric pressure, this supports a mercury column of height 760 mm, so the height of the mercury column directly indicates the atmospheric pressure — a taller column means higher atmospheric pressure, and a shorter column means lower atmospheric pressure (e.g. at higher altitude).

Explain Pascal's law and describe how it is applied in a hydraulic press to multiply force.

Pascal's law states that when pressure is applied at any point in an enclosed fluid, it is transmitted equally, without loss, to every part of the fluid and to the walls of its container. A hydraulic press applies this principle using two connected cylinders of different cross-sectional areas, A_1 (small) and A_2 (large), filled with an incompressible liquid. When a force F_1 is applied to the small piston, it creates pressure $P = F_1/A_1$ in the liquid; by Pascal's law, this same pressure acts on the large piston, producing an output force $F_2 = P \times A_2 = (F_1/A_1) \times A_2$. Since A_2 is much greater than A_1, F_2 is much greater than F_1 — a modest input force on the small piston is converted into a much larger output force on the large piston, making the system a force multiplier used in hydraulic presses, car lifts, and hydraulic brakes.

Multiple Choice Questions (MCQs)

The SI unit of spring constant is: (A) N m (B) N m^{-1} (C) N m^{-2} (D) N s^{-1}
Correct answer: (B) N m^{-1}. Spring constant $k = F/x$, so its unit is newton per metre, N m^{-1}.

A material that returns to its original shape after a deforming force is removed is called: (A) Plastic (B) Elastic (C) Rigid (D) Malleable
Correct answer: (B) Elastic. This property of returning to original shape and size is called elasticity, and such a material is elastic.

Pressure is defined as: (A) Force × Area (B) Force / Area (C) Mass / Volume (D) Force × Volume
Correct answer: (B) Force / Area. Pressure $P = F/A$, force acting normally per unit area.

The SI unit of pressure, the pascal, is equivalent to: (A) 1 N m (B) 1 N m^{-1} (C) 1 N m^{-2} (D) 1 kg m^{-3}

Correct answer: (C) 1 N m^{-2}. 1 pascal (Pa) = 1 N m^{-2}, one newton of force per square metre of area.

Pressure at a depth h in a liquid of density ρ is given by: (A) $P = \rho/gh$ (B) $P = \rho gh$ (C) $P = gh/\rho$ (D) $P = \rho g/h$

Correct answer: (B) $P = \rho gh$. The standard relation for liquid pressure at depth is $P = \rho gh$.

Standard atmospheric pressure at sea level is approximately: (A) 1.013×10^3 Pa (B) 1.013×10^4 Pa (C) 1.013×10^5 Pa (D) 1.013×10^6 Pa

Correct answer: (C) 1.013×10^5 Pa. Standard atmospheric pressure at sea level is about 1.013×10^5 Pa, equivalent to 760 mm of mercury.

A barometer measures: (A) Density of liquids (B) Spring constant (C) Atmospheric pressure (D) Force on a piston

Correct answer: (C) Atmospheric pressure. A barometer is an instrument used specifically to measure atmospheric pressure via a supported mercury column.

In a hydraulic press, if A_2 is much greater than A_1, then compared to F_1, the output force F_2 is: (A) Much smaller (B) Equal (C) Much greater (D) Zero

Correct answer: (C) Much greater. Since $F_2 = (F_1/A_1) \times A_2$ and $A_2 > A_1$, the output force F_2 is much greater than the input force F_1 — the system multiplies force.

A block of density 8000 kg m^{-3} and volume 60 cm^3 (= 60×10^{-6} m^3) has a mass of: (A) 0.048 kg (B) 0.48 kg (C) 4.8 kg (D) 48 kg

Correct answer: (B) 0.48 kg. Mass = Density × Volume = 8000 kg m^{-3} × 60×10^{-6} m^3 = 0.48 kg.

Which principle explains why hydraulic car brakes apply equal pressure to all wheel cylinders? (A) Hooke's law (B) Archimedes' principle (C) Pascal's law (D) Law of conservation of momentum

Correct answer: (C) Pascal's law. Pascal's law states pressure applied to an enclosed fluid is transmitted equally to every part of the fluid, which is exactly how hydraulic brake systems work.

Quick Revision Summary

- Deforming force changes size/shape; elastic materials regain shape, inelastic ones do not
- Hooke's law: $F = kx$ (within elastic limit); k = spring constant = slope of force-extension graph
- Density = Mass/Volume; SI unit kg m^{-3}
- Pressure $P = F/A$; SI unit pascal (Pa) = N m^{-2}; smaller area → larger pressure for same force
- Pressure in a liquid: $P = \rho gh$ — increases with depth and density
- Standard atmospheric pressure ≈ 1.013×10^5 Pa ≈ 760 mm of mercury; decreases with altitude
- Barometer measures atmospheric pressure; manometer measures gas pressure relative to atmosphere
- Pascal's law: pressure in an enclosed fluid is transmitted equally in all directions
- Hydraulic press: $F_2 = (F_1/A_1) \times A_2$ — small input force produces large output force (force multiplier)

Exam Tips

- Always convert cm and mm to metres before substituting into $P = \rho gh$ or $P = F/A$ formulas
- Remember diameter vs radius when calculating piston areas in hydraulic press problems ($A = \pi r^2$)
- In load-extension graph questions, identify the straight-line (Hooke's law) region before reading off the spring constant as the slope
- For pressure problems on irregular objects, remember volume can be found by water displacement
- Practice distinguishing 'force' from 'pressure' explicitly in short-answer responses — a common source of lost marks
- Memorise the standard values: atmospheric pressure ≈ 1.013×10^5 Pa, mercury density = 13.6×10^3 kg m^{-3}, water density = 1000 kg m^{-3}

Chapter 7: Thermal Properties of Matter

This chapter explains matter's behaviour using the kinetic molecular theory: how the arrangement and motion of particles differ in solids, liquids, gases, and plasma (the fourth state of matter). It then defines temperature and heat, and explains how temperature relates to the internal (kinetic + potential) energy of a substance's molecules.

The chapter also covers how thermometers work, the three common temperature scales (Celsius, Fahrenheit, Kelvin) and how to convert between them, and the key properties — sensitivity, range, and linearity — that determine how well a thermometer performs.

Learning Objectives

- Describe qualitatively the particle structure of solids, liquids, and gases, relating properties to intermolecular forces, spacing, and particle motion
- Describe plasma as the fourth state of matter and give examples of where it occurs
- Relate particle motion to temperature, including the concept of absolute zero (~ -273°C)
- State that increasing an object's temperature increases its internal energy
- Explain how a temperature-dependent physical property can be used to measure temperature
- Explain the need for fixed points (ice point, steam point) in calibrating thermometers
- Describe sensitivity, range, and linearity as properties of a thermometer
- Differentiate the structure and function of liquid-in-glass and thermocouple thermometers, and convert temperatures between Celsius, Fahrenheit, and Kelvin scales

Key Concepts

7.1 Kinetic Molecular Theory of Matter

According to kinetic molecular theory, matter is made of tiny particles called molecules that are always in motion (vibrational, rotational, or linear), with a mutual force of attraction (intermolecular force) between them that weakens as the distance between molecules increases. Molecules possess kinetic energy due to their motion and potential energy due to this force of attraction; when a substance is heated, its molecules move more vigorously, increasing their kinetic energy — so the temperature of a substance depends on the average kinetic energy of its molecules.

In solids, strong intermolecular forces hold molecules at fixed positions, though they still vibrate about these points — giving solids a definite shape and definite volume. In liquids, the intermolecular force is too weak to fix molecules in place, so they slide over each other in random directions — liquids have a definite volume but take the shape of their container. In gases, molecules are far apart with very weak intermolecular forces, so gases have neither a definite shape nor a definite volume.

Plasma is a gas in which most atoms are ionized into positive ions and free electrons that move freely through the gas; because of these charged particles, plasma conducts electric current and behaves very differently from an ordinary gas, which is why it is called the fourth state of matter. The Sun and most stars exist in the plasma state, and plasma also occurs in neon/plasma lights, gas discharge tubes, and lightning streamers (the ionized conducting paths formed during early lightning formation).

7.2 Temperature and Heat

Temperature is defined as the degree of hotness or coldness of a body. More precisely, temperature is the physical quantity that determines the direction of flow of thermal energy — heat always flows from a body at higher temperature to one at lower temperature when they are in contact, as demonstrated by a metal spoon placed in hot water becoming warm at its other end. Heat is therefore defined as the energy transferred from one object to another due to a difference in temperature between them.

The sum of the kinetic and potential energies of all the molecules of an object is called its internal energy. Heating a substance makes its molecular motion more vigorous, increasing its internal energy and raising its temperature. It is incorrect to say a substance 'contains heat' — a substance contains internal energy, while the word heat refers only to energy that is actually in transit from a hotter body to a colder one.

7.3 Thermometers and Thermometric Properties

A thermometer is a device used for the exact measurement of temperature, since touch alone cannot give a precise value. Thermometers work by using a physical property of a substance that changes measurably and predictably with temperature — this is called a thermometric property. Good thermometric substances should be good conductors of heat, respond quickly to temperature changes, expand uniformly, have a high boiling point and low freezing point (for a wide range), have large expansivity, not wet glass, not vaporize easily, and be visible.

A liquid-in-glass thermometer uses the thermal expansion of a liquid (commonly mercury or coloured alcohol) inside a glass bulb connected to a narrow capillary tube; as temperature rises, the liquid expands and moves up the tube, and the position of the liquid thread indicates the temperature on a marked scale. Mercury is silvery and easily visible, is a good conductor so it responds quickly, and has a wide usable range (freezes at -39°C, boils at 357°C). Alcohol has six times the expansivity of mercury (giving finer precision) but has a much lower boiling point (78°C), limiting it to lower-temperature measurements, though its very low freezing point (-112°C) suits it to extremely cold conditions.

A thermocouple thermometer consists of two wires of different materials (e.g. copper and iron) joined at two junctions; when the junctions are at different temperatures, a small current flows due to a potential difference (voltage) that increases with the temperature difference between the junctions. With one junction held at a fixed reference temperature (e.g. an ice bath at 0°C), the other junction's temperature can be read from a calibrated millivolt meter. Because only a small mass of metal needs to heat up, thermocouples respond quickly and are well suited to measuring very high or rapidly changing temperatures.

7.4 Temperature Scales and Fixed Points

To construct a temperature scale, two reference temperatures called fixed points are needed: the steam point (the temperature of steam above boiling water at standard atmospheric pressure, the upper fixed point) and the ice point (the melting point of pure ice, the lower fixed point). Three common scales assign different numbers to these points: on the Celsius (centigrade) scale, the ice point is 0°C and the steam point is 100°C, giving 100 equal divisions of 1°C each; on the Fahrenheit scale, the ice point is 32°F and the steam point is 212°F, giving 180 divisions of 1°F each; on the Kelvin (absolute) scale, used in scientific work, the ice point is 273 K and the steam point is 373 K, so 1 K equals 1°C in size.

The zero of the Kelvin scale, called absolute zero, is the temperature (about -273.15°C, taken as -273°C for calculations) at which molecules would have essentially zero average kinetic energy — it is the lowest possible temperature in the universe, and matter cannot exist below it.

7.5 Converting Between Temperature Scales

The three scales are related by simple formulas. To convert Celsius to Fahrenheit: $TF = (9/5) \times TC + 32$. To convert Fahrenheit to Celsius: $TC = (5/9) \times (TF - 32)$. To convert between Celsius and Kelvin: $TK = TC + 273$. These conversions allow a temperature measured on one scale to be expressed on any of the others.

7.6 Sensitivity, Range, and Linearity of Thermometers

Sensitivity refers to a thermometer's ability to detect small temperature changes — a thermometer with scale markings every 0.1°C is more sensitive (gives more precise readings) than one marked only every 1°C. Range refers to the span of temperatures a thermometer can accurately measure — a clinical thermometer has a narrow range (e.g. 35°C to 45°C) suited to body temperature, while a laboratory thermometer has a wider range (e.g. -10°C to 110°C); the thermometric liquid used sets natural limits on range, since mercury freezes at -39°C and boils at 357°C, while alcohol (freezing at -112°C, boiling at 78°C) extends the lower limit but restricts the upper limit.

Linearity refers to how directly proportional the scale reading is to the actual temperature across the whole range — a good thermometer produces evenly spaced scale markings for equal temperature increments throughout its range, ensuring consistent accuracy from one end of the scale to the other.

7.7 Structure of a Liquid-in-Glass Thermometer

A liquid-in-glass thermometer has a narrow, uniform capillary tube connected to a small bulb filled with mercury or alcohol. The bulb's thin glass walls allow heat to conduct quickly from the object being measured into the liquid, and the small volume of liquid responds rapidly to temperature changes, making the thermometer sensitive. The narrowness and uniformity of the capillary bore ensures that the liquid expands evenly along its length, which is essential for producing a linear (evenly spaced) measuring scale. Mercury's combination of low freezing point and high boiling point gives it a long usable temperature range, which is why it remains a common choice despite alcohol's greater sensitivity (expansivity).

Important Definitions

Define temperature.
The degree of hotness or coldness of a body; more precisely, the physical quantity that determines the direction of flow of thermal energy between two bodies in contact.

Define heat.
The energy that is transferred from one object to another due to a difference in temperature between them.

Define internal energy.
The sum of the kinetic and potential energies of all the molecules that make up an object.

What is absolute zero?
The lowest possible temperature, about -273°C (0 K), at which the molecules of a substance have essentially zero average kinetic energy.

What is a thermometric property?

A physical property of a substance that changes measurably and predictably with temperature, allowing it to be used to construct a thermometer (e.g. liquid expansion, electrical resistance, thermo-electric voltage).

Define sensitivity of a thermometer.
The ability of a thermometer to detect and register small changes in temperature; finer scale markings mean greater sensitivity.

Define the range of a thermometer.
The span of temperatures, from lowest to highest, over which a thermometer can measure accurately.

Define linearity of a thermometer.
The property by which equal changes in temperature produce equal, evenly spaced changes on the thermometer's scale throughout its entire range.

Key Formulas

Topic	Formula
Celsius to Fahrenheit	$T_F = (9/5) \times T_C + 32$
Fahrenheit to Celsius	$T_C = (5/9) \times (T_F - 32)$
Celsius to Kelvin	$T_K = T_C + 273$
Absolute zero	≈ -273°C = 0 K
Ice point (Celsius / Fahrenheit / Kelvin)	0°C = 32°F = 273 K
Steam point (Celsius / Fahrenheit / Kelvin)	100°C = 212°F = 373 K

Diagrams

States of Matter: Particle Arrangement: Particle spacing and motion in solids, liquids, gases, and plasma, based on kinetic molecular theory

Comparing Temperature Scales: Ice point and steam point shown side by side on the Celsius, Fahrenheit, and Kelvin scales

Structure of a Liquid-in-Glass Thermometer: Labelled diagram showing the bulb, capillary tube, thermometric liquid, and scale

Short Questions & Answers

Why do solids have a fixed shape and fixed volume?

Because the strong intermolecular forces in a solid hold its molecules at fixed positions (though they still vibrate about these points), giving the solid a definite shape and volume.

Why do gases have neither a fixed shape nor a fixed volume?

Because gas molecules are far apart with very weak intermolecular forces, allowing them to move freely and spread to fill whatever container they are in, with no fixed arrangement.

What is the effect of raising the temperature of a substance on its molecules?

Raising the temperature makes the molecules move more vigorously, increasing their average kinetic energy and hence the substance's internal energy.

Distinguish between heat and internal energy.

Internal energy is the total kinetic and potential energy possessed by all the molecules of a substance at any time; heat is the energy specifically in transit from a hotter body to a colder one due to their temperature difference — a body possesses internal energy but does not 'contain' heat.

What determines the direction of heat flow between two bodies?

Temperature difference — heat always flows from the body at higher temperature to the body at lower temperature when they are in contact.

Why is mercury commonly preferred over alcohol as a thermometric liquid?

Mercury has a much wider usable temperature range (freezing at -39°C and boiling at 357°C, compared to alcohol's boiling point of only 78°C), is a good heat conductor for fast response, and is easily visible due to its silvery colour.

What is meant by the linearity of a thermometer?

Linearity means that equal changes in temperature produce equal, evenly spaced changes on the thermometer's scale across its full range, ensuring consistent accuracy.

Why are the walls of a thermometer's bulb made thin?
Thin bulb walls allow heat to conduct quickly from the object being measured into the thermometric liquid, making the thermometer respond faster and more sensitively to temperature changes.

Long Questions & Answers

Describe, using kinetic molecular theory, how the particle arrangement and motion differ in solids, liquids, and gases, and explain plasma as a fourth state of matter.

According to kinetic molecular theory, all matter consists of molecules in constant motion, held together to varying degrees by intermolecular forces of attraction. In solids, these forces are strong enough to hold molecules at fixed positions, though the molecules still vibrate about these points; this gives solids a definite shape and definite volume. In liquids, intermolecular forces are weaker, allowing molecules to slide over one another in random directions — liquids therefore have a definite volume but take the shape of their container. In gases, molecules are far apart and intermolecular forces are very weak, so gas molecules move freely and independently, meaning gases have neither a definite shape nor a definite volume. Plasma, sometimes called the fourth state of matter, is a gas in which most atoms have been ionized into positive ions and free electrons; because these charged particles move freely and conduct electric current, plasma behaves very differently from an ordinary gas. Plasma occurs in the Sun and other stars, in neon and plasma lights, in gas discharge tubes, and in the ionized conducting paths (lightning streamers) formed during lightning.

Define temperature and heat, and explain their relationship to internal energy.

Temperature is the degree of hotness or coldness of a body, and more precisely is the physical quantity that determines the direction in which thermal energy flows between two bodies in contact — heat always flows from the hotter (higher temperature) body to the colder (lower temperature) one. Heat is defined as the energy transferred from one object to another as a result of a temperature difference between them. All matter is made of molecules possessing kinetic energy (due to motion) and potential energy (due to intermolecular attractive forces); the sum of these energies for all the molecules in an object is its internal energy. When a substance is heated, its molecules move more vigorously, increasing its internal energy, which is observed as a rise in temperature. It is important to note that a substance does not 'contain' heat — it contains internal energy, and the term 'heat' refers only to energy that is actively being transferred between bodies due to a temperature difference.

Compare the Celsius, Fahrenheit, and Kelvin temperature scales, including their fixed points and how to convert between them.

All three scales are built using two fixed reference points: the ice point (melting point of pure ice) and the steam point (boiling point of water at standard atmospheric pressure). On the Celsius scale, these points are assigned values of 0°C and 100°C, with the interval divided into 100 equal parts of 1°C each. On the Fahrenheit scale, the ice point is 32°F and the steam point is 212°F, with the interval divided into 180 parts of 1°F each — meaning a Fahrenheit degree is a smaller unit than a Celsius degree. On the Kelvin (absolute) scale, used for scientific work, the ice point is 273 K and the steam point is 373 K, so the size of 1 K equals the size of 1°C, and its zero (absolute zero, about -273°C) is the theoretical point of minimum molecular kinetic energy. Conversions between the scales use $TF = (9/5)TC + 32$ (Celsius to Fahrenheit), $TC = (5/9)(TF - 32)$ (Fahrenheit to Celsius), and $TK = TC + 273$ (Celsius to Kelvin).

Explain what is meant by the sensitivity, range, and linearity of a thermometer, and describe how the structure of a liquid-in-glass thermometer is designed to optimise these properties.

Sensitivity is a thermometer's ability to detect small temperature changes — finer scale spacing means greater sensitivity and more precise readings. Range is the span of temperatures over which the thermometer can measure accurately, which is limited by the freezing and boiling points of the thermometric liquid used. Linearity is the extent to which equal temperature changes produce equal, evenly spaced changes on the scale throughout the whole range, ensuring consistent accuracy. In a liquid-in-glass thermometer, sensitivity is improved by using a thin-walled bulb (for fast heat conduction) containing a small volume of liquid (which heats up and expands quickly) together with a narrow capillary tube (so a small volume change produces a large, easily readable movement of the liquid thread). Range depends on the properties of the chosen liquid: mercury offers a wide range (-39°C to 357°C) suitable for most everyday and laboratory uses, while alcohol, though more sensitive due to greater expansivity, has a much lower boiling point (78°C) that restricts its upper range, though its very low freezing point (-112°C) suits it for extremely cold conditions. Linearity is achieved by using a uniform (evenly-bored) capillary tube, which ensures the liquid expands by an equal amount along its length for each equal rise in temperature, producing evenly spaced scale markings.

Multiple Choice Questions (MCQs)

According to kinetic molecular theory, molecules in a solid mainly: (A) Move randomly (B) Vibrate about fixed positions (C) Slide over each other (D) Move in straight lines only

Correct answer: (B) Vibrate about fixed positions. In a solid, strong intermolecular forces hold molecules at fixed positions, but the molecules still vibrate about these points.

The gas in which atoms are ionized into positive ions and electrons is called: (A) Vapour (B) Aerosol (C) Plasma (D) Colloid

Correct answer: (C) Plasma. This ionized, conducting state of matter is called plasma, often referred to as the fourth state of matter.

Temperature determines the direction of flow of: (A) Mass (B) Thermal energy (C) Electric charge (D) Momentum

Correct answer: (B) Thermal energy. Temperature is the physical quantity that determines the direction in which thermal energy (heat) flows between two bodies.

The internal energy of an object is the sum of the: (A) Mass and volume of its molecules (B) Kinetic and potential energies of its molecules (C) Heat and work done on it (D) Pressure and temperature of its molecules

Correct answer: (B) Kinetic and potential energies of its molecules. Internal energy is defined as the sum of the kinetic energy (due to motion) and potential energy (due to intermolecular forces) of all the molecules in an object.

On the Kelvin scale, the ice point (melting point of ice) corresponds to: (A) 0 K (B) 100 K (C) 273 K (D) 373 K

Correct answer: (C) 273 K. The ice point is 273 K on the Kelvin scale (equivalent to 0°C).

30°C is equivalent to how many degrees Fahrenheit? (A) 54°F (B) 86°F (C) 62°F (D) 30°F

Correct answer: (B) 86°F. TF = (9/5)×30 + 32 = 54 + 32 = 86°F.

Absolute zero is approximately: (A) 0°C (B) -100°C (C) -173°C (D) -273°C

Correct answer: (D) -273°C. Absolute zero, the lowest possible temperature, is approximately -273°C (0 K).

A thermocouple thermometer generates a reading based on: (A) Liquid expansion (B) Gas pressure change (C) Voltage from two junctions at different temperatures (D) Change in colour

Correct answer: (C) Voltage from two junctions at different temperatures. A thermocouple uses two wires of different materials joined at two junctions; a temperature difference between the junctions produces a measurable voltage.

A thermometer with scale markings every 0.1°C compared to one with markings every 1°C is: (A) Less sensitive (B) More sensitive (C) Equally sensitive (D) Has a wider range

Correct answer: (B) More sensitive. Finer scale divisions mean the thermometer can detect smaller temperature changes, making it more sensitive.

Mercury is preferred over alcohol in many thermometers mainly because: (A) It has a lower freezing point than alcohol (B) It has a much wider temperature range and is a good conductor (C) It has greater expansivity than alcohol (D) It is cheaper to produce

Correct answer: (B) It has a much wider temperature range and is a good conductor. Mercury's wide range (-39°C to 357°C), good thermal conductivity, and clear visibility make it a preferred thermometric liquid despite alcohol having greater expansivity.

Quick Revision Summary

- Kinetic molecular theory: matter = moving molecules + intermolecular attractive forces
- Solids: fixed shape & volume (molecules vibrate in place); Liquids: fixed volume, no fixed shape; Gases: neither fixed
- Plasma = ionized gas (positive ions + electrons), the fourth state of matter; conducts electricity
- Temperature = degree of hotness/coldness; determines direction of heat flow
- Heat = energy in transit due to temperature difference; internal energy = KE + PE of molecules
- Fixed points: ice point (melting ice) and steam point (boiling water at standard pressure)
- Celsius: 0–100°C; Fahrenheit: 32–212°F; Kelvin: 273–373 K; absolute zero ≈ -273°C
- $T_F = (9/5)T_C + 32$; $T_C = (5/9)(T_F - 32)$; $T_K = T_C + 273$
- Thermometer qualities: sensitivity (small changes detected), range (span measurable), linearity (even scale spacing)
- Liquid-in-glass thermometer: thin bulb + narrow uniform capillary for sensitivity & linearity; thermocouple: fast response via junction voltage

Exam Tips

- Memorise all three conversion formulas (C↔F, C↔K) and practice both directions
- Remember: a Fahrenheit degree is smaller than a Celsius degree (180 divisions vs 100 over the same temperature span)
- For 'why' questions on thermometer design, connect the feature directly to sensitivity, range, or linearity — examiners look for the correct term
- Distinguish clearly between heat (energy in transit) and internal energy (energy possessed) in written answers — a very common exam trap
- For plasma questions, remember the key distinguishing feature: it conducts electricity due to free ions and electrons
- Practice fixed-point/scale-conversion numericals (e.g. mercury thread position problems) — these appear frequently in exams

Chapter 8: Magnetism

This chapter studies magnets and magnetism: the properties of magnetic poles, the concept of a magnetic field and its field lines, and the difference between temporary and permanent magnets, including electromagnets and their many practical uses.

It also explains magnetism at the atomic level through the domain theory of magnetism (paramagnetic, diamagnetic, and ferromagnetic materials), how magnets are made and demagnetised, and applications of magnetism in recording technology and magnetic shielding.

Learning Objectives

- Describe the forces between magnetic poles and between magnets and magnetic materials, using the terms north pole, south pole, attraction, and repulsion
- Describe induced magnetism and differentiate between temporary and permanent magnets
- Describe a magnetic field as a region in which a magnetic pole experiences a force, and state how field direction and field strength are represented
- Describe uses of permanent magnets and electromagnets
- Explain qualitatively, using domain theory, how materials can be magnetised and demagnetised
- Differentiate between ferromagnetic, paramagnetic, and diamagnetic materials with reference to domain theory
- Analyse applications of magnets in recording technology and describe how electronic devices are protected from strong magnetic fields
- State that soft magnetic materials such as soft iron can be used to provide magnetic shielding

Key Concepts

8.1 Magnetic Materials and Properties of Magnets

Materials that are attracted to magnets are called magnetic materials — iron, nickel, and cobalt are magnetic, while materials such as brass, copper, wood, glass, and plastic are non-magnetic and unaffected by a magnet. A magnet can attract magnetic materials even without direct contact, acting at a distance through its magnetic field.

A freely suspended bar magnet always comes to rest pointing in a north-south direction; the end pointing north is called the north pole (N) and the end pointing south is the south pole (S). When two magnets are brought close together, like poles (N-N or S-S) repel each other, while unlike poles (N-S) attract — like poles repel and unlike poles attract. This repulsion between like poles is the definitive test for identifying whether an object is a true magnet (since a magnetic material, unlike a magnet, is always attracted to either pole and never repelled). It is not possible to isolate a single magnetic pole: breaking a bar magnet into pieces, however many, always produces smaller complete magnets each with their own N-pole and S-pole.

8.2 Induced Magnetism, Temporary and Permanent Magnets

Magnetization (or induced magnetism) is the process by which a magnetic material such as iron or steel becomes a magnet — for example, when the S-pole of a true magnet is brought near a piece of iron, it induces an N-pole in the near end of the iron and an S-pole in the far end. This induced magnetism disappears once the true magnet is removed, at least for materials like soft iron.

Temporary magnets (commonly made of soft iron, such as paper clips, iron nails, and electromagnets) only display magnetism while in the presence of an external magnetic field, and lose it once that field is removed. Permanent magnets (made of materials such as steel, cobalt, alnico, and ferrite) retain their magnetic properties indefinitely, either occurring naturally or being manufactured by placing suitable materials in a strong magnetic field for a sufficient time.

8.3 Magnetic Fields and Lines of Force

A magnetic field is the region around a magnet in which another magnetic object experiences a force. The pattern of a magnetic field can be visualised using iron filings sprinkled around a magnet, or traced using a small compass, whose needle aligns along the magnetic lines of force at each point. The direction of the magnetic field at any point is defined as the direction in which the N-pole of a compass needle points when placed at that point; field lines appear to originate from the north pole and end at the south pole.

The magnetic field has both magnitude and direction at every point. Its strength is proportional to the number of field lines passing through a unit area perpendicular to them — so the field is stronger where lines are closely spaced (near the poles) and weaker where lines are spread further apart. When two magnets are placed near each other, their combined field can produce a neutral point, where the fields due to each magnet cancel exactly.

8.4 Uses of Permanent Magnets

Permanent magnets are essential components of DC motors and AC/DC electric generators, moving-coil loudspeakers, door catchers and refrigerator door seals, magnetic separators (used in flour mills to remove iron fragments from grain), medical instruments for removing iron splinters from the eye, and resetting mechanisms in maximum-minimum thermometers.

In an AC generator, rotating a coil between the poles of a permanent magnet changes the magnetic field through the coil, inducing an EMF that drives an alternating current in an external circuit; an electric motor works by the reverse process. In a moving-coil loudspeaker, a varying electric current (representing a sound signal) flows through a voice coil placed in the field of a permanent magnet; the resulting varying force makes the coil and its attached cone vibrate, producing sound.

8.5 Electromagnets and Their Uses

An electromagnet is formed when an iron core (such as a nail) is wound with a coil of wire and an electric current is passed through the coil; the current produces a magnetic field that magnetises the iron core, but this magnetism is temporary and disappears once the current stops. Increasing the number of battery cells (current) or the number of coil turns increases the strength of the electromagnet's magnetic field.

Electromagnets are used in electric bells, magnetic relays (a low-current input circuit that uses an electromagnet to switch on a separate high-current circuit), circuit breakers (which detach an armature from a copper strip to break the circuit when current becomes excessive, protecting appliances), telephone receivers (where a varying current changes the electromagnet's pull on an iron diaphragm to reproduce sound), maglev trains (which use induced magnetism to levitate above the guideway, eliminating wheel friction and enabling speeds up to 400 km/h), and electromagnetic cranes (used in scrapyards and steel works, capable of lifting heavy iron and steel objects and releasing them simply by switching off the current).

8.6 Domain Theory of Magnetism

The magnetic field of a bar magnet resembles that of a current-carrying solenoid, suggesting that magnetism arises from moving electric charges. Within atoms, electrons both orbit the nucleus and spin on their own axis, and both motions produce a magnetic field; depending on how these fields combine, an atom may or may not have a net magnetic field. In paramagnetic materials (such as aluminium and lithium), the orbital and spin magnetic fields of electrons partly support one another, so the atom behaves as a weak magnet. In diamagnetic materials (such as copper, bismuth, and water), these fields cancel out entirely, leaving the atom with no net magnetic field.

In ferromagnetic materials (such as iron, steel, nickel, and cobalt), large groups of about 10^{16} neighbouring atoms have their electron spins naturally aligned parallel to each other, forming a highly magnetized region about 0.1 mm in size called a magnetic domain, each behaving like a tiny magnet with its own N and S poles. In an unmagnetized piece of ferromagnetic material, these domains are randomly oriented and their fields cancel out overall. Applying an external magnetic field causes favourably-oriented domains to grow at the expense of others, and rotates the alignment of remaining domains toward the field direction — magnetizing the material. In soft iron, domains realign easily but return to random orientation once the external field is removed (ideal for electromagnets and transformer cores); in steel, domains are harder to realign but retain their alignment once magnetized, which is why steel is used for permanent magnets. Non-ferromagnetic materials like aluminium and copper do not form domains, so magnetism cannot be induced in them this way.

8.7 Magnetisation and Demagnetisation

A steel bar can be magnetised by stroking: in the single-touch method, one pole of a permanent magnet is stroked repeatedly across the bar in the same direction (lifting the magnet clear before each return stroke); in the double-touch method (more efficient), stroking begins from the centre of the bar outward using unlike poles of two magnets simultaneously. In both methods, the pole produced at the end of the bar is opposite to the stroking pole. Alternatively, a steel bar can be magnetised by placing it inside a solenoid (a long coil of several hundred turns of insulated wire) and passing a strong direct current through it; the polarity produced is found using the right-hand grip rule — gripping the solenoid so the curled fingers point in the direction of conventional current flow, the thumb points toward the N-pole.

Magnets can be demagnetised in three ways: heating strongly (thermal vibrations disturb the alignment of magnetic domains), hammering (mechanical shock disturbs domain alignment), or by slowly withdrawing the magnet from inside a solenoid carrying alternating current (the constantly reversing field scrambles the domain alignment).

8.8 Applications in Recording Technology and Magnetic Shielding

Electromagnets are widely used in recording technology to store audio, video, and computer data through induced magnetism in magnetic tapes and hard disks (both coated with a ferromagnetic material such as iron oxide). In magnetic tape recording, a recording head (an electromagnet with a horse-shoe-shaped iron core) produces a fringe field at a narrow gap; as the coated tape moves past this gap, the fringe field induces and permanently retains a pattern of magnetism in the tape's coating, corresponding to the original sound or picture signal. In hard disk recording, a small electromagnetic head writes binary digits by magnetising tiny spots on a spinning disk in different directions and reads them back by detecting each spot's magnetisation direction; disks offer near-instant access compared to the slower sequential access of tape.

Soft iron has high magnetic permeability, meaning it readily allows magnetic field lines (flux) to pass through it. Enclosing a sensitive electronic device in a soft iron casing shields it from external magnetic fields, since the magnetic flux preferentially passes through the high-permeability iron shell rather than through the device inside — protecting devices such as compasses, speakers, and other magnetically sensitive electronics. Soft iron's high permeability is also why it is used for the cores of transformers and electromagnets, since it magnetises easily when current flows and demagnetises quickly when current stops.

Important Definitions

What is a magnetic material?

A material that is attracted to a magnet, such as iron, nickel, or cobalt; non-magnetic materials like wood, glass, and plastic are not attracted.

State the law of magnetic poles.

Like poles repel each other, and unlike poles attract each other.

Define a magnetic field.

The region around a magnet in which another magnetic object experiences a force.

What is the direction of a magnetic field at a point?

The direction in which the N-pole of a compass needle points when placed at that point.

Differentiate between temporary and permanent magnets.

Temporary magnets (e.g. soft iron, electromagnets) display magnetism only while an external magnetic field is present and lose it when the field is removed; permanent magnets (e.g. steel, alnico) retain their magnetism indefinitely.

What is a magnetic domain?

A region of about 0.1 mm in a ferromagnetic material where roughly 10^{16} neighbouring atoms have their electron spins aligned parallel, making the region behave like a tiny magnet.

Define an electromagnet.

A temporary magnet formed when an electric current flows through a coil of wire wound around an iron core, magnetising the core only while the current flows.

What is magnetic shielding, and which material is commonly used for it?

Enclosing a sensitive device in a casing that redirects external magnetic flux away from it; soft iron, due to its high magnetic permeability, is commonly used for this purpose.

Key Formulas & Rules

Topic	Rule / Relation
Law of poles	Like poles repel; unlike poles attract
Field strength	∝ number of field lines per unit area (perpendicular to lines)
Right-hand grip rule (solenoid)	Curl fingers in current direction → thumb points to N-pole
Domain size (ferromagnetic)	≈ 0.1 mm, containing ≈ 10^{16} aligned atoms

Diagrams

Attraction and Repulsion of Magnetic Poles: Like poles (N-N or S-S) repel; unlike poles (N-S) attract

Magnetic Field Lines Around a Bar Magnet: Field lines running from the N-pole to the S-pole, closely spaced (stronger field) near the poles

Domain Theory: Unmagnetized vs Magnetized Iron: Randomly oriented magnetic domains in unmagnetized iron versus aligned domains after magnetisation

Short Questions & Answers

What are temporary and permanent magnets?

Temporary magnets show magnetism only in the presence of an external magnetic field and lose it once that field is removed (e.g. soft iron, electromagnets); permanent magnets retain their magnetism indefinitely (e.g. steel, alnico).

Define the magnetic field of a magnet.

The region around a magnet in which another magnetic object or pole experiences a force.

What are magnetic lines of force?

Imaginary lines representing the direction and pattern of a magnetic field, drawn so that the field's direction at any point is tangent to the line and the density of lines indicates field strength.

Name some uses of permanent magnets and electromagnets.

Permanent magnets: electric motors, loudspeakers, door catchers, magnetic separators. Electromagnets: electric bells, magnetic relays, circuit breakers, telephone receivers, cranes.

What are magnetic domains?

Small regions (about 0.1 mm) within a ferromagnetic material where large groups of atoms have their electron spins aligned parallel, so the region behaves as a tiny magnet.

Which type of magnetic field is formed by a current-carrying long coil (solenoid)?

A field pattern very similar to that of a bar magnet, with distinct N and S poles at its two ends.

Differentiate between paramagnetic and diamagnetic materials.

In paramagnetic materials, the orbital and spin magnetic fields of electrons in an atom partly support one another, giving a net weak magnetic field; in diamagnetic materials, these fields cancel out completely, giving no net magnetic field.

Why is it not possible to isolate a single magnetic pole?

Because breaking a magnet into any number of pieces always produces smaller complete magnets, each with its own N-pole and S-pole — a single isolated pole cannot be obtained.

Long Questions & Answers

Describe how you would identify whether an unknown object is a magnet or simply a magnetic material.

Bring one end of the unknown object close to one pole (say the N-pole) of a freely suspended bar magnet. If the object is attracted, it could either be a magnet with its opposite (S) pole facing the suspended magnet, or it could simply be an unmagnetised magnetic material — attraction alone does not distinguish between the two. To confirm, bring the same end of the object close to the other pole (S-pole) of the suspended magnet: if the object is again attracted, it is not a magnet but merely a magnetic material (since a magnetic material is always attracted to any pole); however, if the object is repelled by this second pole, then the object must itself be a magnet, since only two like poles can repel each other. Repulsion between like poles is therefore the definitive test for identifying a true magnet.

Explain the domain theory of magnetism and use it to differentiate between paramagnetic, diamagnetic, and ferromagnetic materials.

According to domain theory, magnetism at the atomic level arises from the motion of electrons — both their orbit around the nucleus and their spin on their own axis generate small magnetic fields. In paramagnetic materials (e.g. aluminium, lithium), the orbital and spin fields of electrons in an atom partially reinforce one another, so each atom behaves as a weak magnetic dipole, though the material as a whole shows only weak magnetism. In diamagnetic materials (e.g. copper, bismuth, water), these electron fields cancel out completely, leaving atoms with no net magnetic field. In ferromagnetic materials (e.g. iron, steel, nickel, cobalt), large groups of about 10^{16} neighbouring atoms have their electron spins naturally aligned parallel to one another, forming highly magnetized regions called magnetic domains, each about 0.1 mm in size and behaving like a tiny magnet. In an unmagnetized ferromagnetic material, these domains point in random directions and their fields cancel overall; applying an external magnetic field causes favourably aligned domains to grow and other domains to rotate into alignment, magnetizing the material as a whole.

Describe, with the help of a diagram, how the strength of a magnetic field is represented and interpreted using magnetic lines of force.

The strength of a magnetic field at any point is represented by the closeness (density) of the magnetic field lines there: field lines drawn closer together indicate a stronger field, while lines spread further apart indicate a weaker field. Near the poles of a bar magnet, the field lines converge closely together, showing that the field is strongest in these regions; moving away from the poles, the lines spread out, showing the field becomes progressively weaker. The direction of the field at any point is given by the direction a compass needle's N-pole would point if placed there, and field lines are conventionally drawn running from the N-pole, around the magnet, to the S-pole. When two magnets are placed near one another, their combined field pattern can produce a neutral point, where the fields due to the two magnets exactly cancel and the net field is zero — at this point, a compass needle would show no preferred direction due to the magnets.

Describe two methods of magnetising a steel bar and two methods of demagnetising a magnet.

Steel bars can be magnetised by stroking: in the single-touch method, one pole of a permanent magnet is drawn repeatedly across the bar in the same direction, being lifted clear before each return pass, while in the more efficient double-touch method, two magnets with unlike poles are stroked simultaneously outward from the centre of the bar. In both methods, the polarity produced at the stroked end is opposite to the stroking pole used. Alternatively, a steel bar can be magnetised by placing it inside a solenoid with several hundred turns of wire and passing a strong direct current through it; the resulting polarity is found using the right-hand grip rule. Demagnetisation can be achieved by heating the magnet strongly, since thermal vibrations disrupt the alignment of magnetic domains; by hammering or striking the magnet, which mechanically disturbs domain alignment; or by slowly withdrawing the magnet from inside a solenoid carrying alternating current, whose constantly reversing field scrambles the domain orientations.

Multiple Choice Questions (MCQs)

Which of the following is NOT a magnetic material? (A) Cobalt (B) Iron (C) Aluminium (D) Nickel

Correct answer: (C) Aluminium. Aluminium is not attracted to ordinary magnets and is classified as a (weakly) paramagnetic, not ferromagnetic, material; cobalt, iron, and nickel are all strongly magnetic materials.

Like magnetic poles placed near each other will: (A) Attract (B) Repel (C) Have no effect on each other (D) Cancel out completely

Correct answer: (B) Repel. Like poles (N-N or S-S) always repel each other; only unlike poles attract.

Breaking a bar magnet into several pieces produces: (A) Isolated N-poles only (B) Isolated S-poles only (C) Each piece with its own N and S pole (D) Pieces with no magnetism at all

Correct answer: (C) Each piece with its own N and S pole. It is impossible to isolate a single magnetic pole — every piece of a broken magnet becomes a complete magnet with its own N-pole and S-pole.

A material that retains its magnetism only while an external magnetic field is present is called a: (A) Permanent magnet (B) Temporary magnet (C) Diamagnetic material (D) Non-magnetic material

Correct answer: (B) Temporary magnet. A temporary magnet (e.g. soft iron or an electromagnet) is magnetic only in the presence of an external field, losing its magnetism once that field is removed.

The direction of a magnetic field at a point is defined by: (A) The S-pole of a compass needle placed there (B) The N-pole of a compass needle placed there (C) The direction of gravity at that point (D) The nearest magnetic pole

Correct answer: (B) The N-pole of a compass needle placed there. By convention, the magnetic field direction at a point is the direction the N-pole of a compass needle points when placed at that point.

The strength of a magnetic field is indicated by: (A) The colour of the field lines (B) How closely spaced the field lines are (C) The total number of poles present (D) The temperature of the magnet

Correct answer: (B) How closely spaced the field lines are. Field strength is proportional to the density (closeness) of magnetic field lines per unit area — closely spaced lines mean a stronger field.

In ferromagnetic materials, a magnetic domain is best described as: (A) A single isolated atom (B) A region where electron spins of many atoms are aligned parallel (C) The N-pole of the material only (D) A region with no magnetic properties

Correct answer: (B) A region where electron spins of many atoms are aligned parallel. A magnetic domain is a region (about 0.1 mm) where a large group of atoms ($\sim 10^{16}$) have their electron spins naturally aligned parallel, so the region behaves like a tiny magnet.

Which material is most suitable for making a permanent magnet? (A) Soft iron (B) Steel (C) Aluminium (D) Copper

Correct answer: (B) Steel. Steel's domains are difficult to realign but retain their alignment once magnetised, making it well suited for permanent magnets (unlike soft iron, which easily loses its magnetism).

A magnet can be demagnetised by: (A) Cooling it to a very low temperature (B) Heating it strongly, hammering it, or using an A.C. solenoid (C) Wrapping it in plastic (D) Placing it near a compass

Correct answer: (B) Heating it strongly, hammering it, or using an A.C. solenoid. Demagnetisation methods include heating strongly (disrupting domain alignment via thermal vibration), hammering (mechanical disruption), and slowly withdrawing the magnet from a solenoid carrying alternating current.

Soft iron is used for magnetic shielding mainly because it has: (A) Low density (B) High magnetic permeability (C) High electrical resistance (D) Low melting point

Correct answer: (B) High magnetic permeability. Soft iron's high magnetic permeability allows magnetic flux to pass preferentially through it rather than through a shielded device, protecting the device from external magnetic fields.

Quick Revision Summary

- Magnetic materials: iron, nickel, cobalt; attracted to magnets even without contact

- Like poles repel, unlike poles attract; isolated single poles are impossible
- Induced magnetism: a magnetic material becomes magnetised near a true magnet, may be temporary or permanent
- Temporary magnets (soft iron, electromagnets) lose magnetism when field removed; permanent magnets (steel, alnico) retain it
- Magnetic field = region where a magnetic object feels a force; direction = N-pole of compass; strength ∝ field line density
- Permanent magnet uses: motors, generators, loudspeakers, door catchers, separators
- Electromagnet uses: bells, relays, circuit breakers, telephone receivers, maglev trains, cranes
- Domain theory: paramagnetic (weak net field), diamagnetic (no net field), ferromagnetic (aligned domains, ~10^{16} atoms, ~0.1mm)
- Magnetise by: stroking (single/double touch) or solenoid + DC current (right-hand grip rule for polarity)
- Demagnetise by: heating, hammering, or A.C. solenoid withdrawal
- Recording tech uses induced magnetism (tapes, hard disks); soft iron shields devices via high permeability

Exam Tips

- Remember the repulsion test is the only reliable way to confirm an object is a true magnet, not just a magnetic material
- Practice applying the right-hand grip rule for solenoid polarity — a frequent diagram-based exam question
- Keep the three domain-theory categories (paramagnetic, diamagnetic, ferromagnetic) and their example materials clearly separated in your answers
- Link each use of permanent magnets and electromagnets to the specific device by name — exam questions often ask 'name a device that uses...'
- For magnetic field diagrams, always show field lines running from N to S and getting denser near the poles
- Remember: soft iron = easy to magnetise/demagnetise (electromagnets, shielding); steel = hard to magnetise but retains it (permanent magnets)

Chapter 9: Nature of Science

This final chapter steps back from specific physics topics to examine the nature of physics itself: its scope as the fundamental science of matter, energy, space, and time, and its many branches and interdisciplinary connections with fields ranging from biology to computer science.

It also explains the scientific method — the systematic process of observation, hypothesis, experiment, theory, and law by which scientific knowledge is built and tested — and clarifies how science, technology, and engineering relate to and depend upon one another.

Learning Objectives

- Describe physics as the study of matter, energy, space, time, and their mutual connections and interactions
- Explain, with examples, the many sub-fields and interdisciplinary fields of physics
- Explain how physics is a subset of the physical sciences and of the natural sciences
- Explain that science is a collaborative field requiring interdisciplinary researchers to share knowledge and critique ideas
- Understand the terms hypothesis, theory, and law in the context of physics research
- Explain falsifiability as the idea that a theory is scientific only if it makes assertions that can be disproven
- Differentiate between the terms science, technology, and engineering, with suitable examples

Key Concepts

9.1 Scope of Physics

Science is the collective, organized knowledge about natural phenomena, built by asking how and why things behave as they do and searching for order and regularity in apparently diverse phenomena. As scientific knowledge grew rapidly in the nineteenth century, the study of nature was classified into biological sciences (the study of living things) and physical sciences (the study of non-living things), with physics forming a fundamental part of the physical sciences alongside chemistry and geology.

Physics is the fundamental science dealing with the constituents of the universe — matter, energy, space, and time — and their mutual relationships and interactions, seeking to understand everything from subatomic particles to galaxies. Space is the three-dimensional extent in which objects and events occur, providing a framework for describing position and motion; time measures the sequence and duration of events and is often considered a fourth dimension (for example, the special theory of relativity describes time dilation, where time passes more slowly for an observer moving at very high speed relative to one at rest). Physics explores how these concepts connect — general relativity describes how space and time are influenced by gravity and speed (such as light bending around massive stars), while quantum mechanics explains the behaviour of particles at the atomic and subatomic scale.

9.2 Branches of Physics

As physics research has expanded, it has grown into several major branches. Mechanics studies motion and its causes, based on Newton's laws (classical mechanics). Heat and thermodynamics deals with thermal energy and its flow between bodies. Acoustics studies the physical nature of audible sound. Optics studies the physical behaviour of visible light. Electromagnetism studies electromagnetic phenomena and the relationship between electric current and magnetic fields.

Quantum mechanics explains the behaviour of particles at atomic and subatomic scales. Relativistic mechanics explains how space and time are not absolute but relative to the observer, and how they are influenced by gravity and speed. Nuclear physics studies the properties of atomic nuclei, while particle physics studies subatomic and elementary particles — the fundamental building blocks of matter. Astronomy studies the distribution of celestial bodies such as planets, stars, and galaxies, cosmology explores the large-scale structure and evolution of the universe, and solid state physics studies the specific properties of matter in solid form.

9.3 Interdisciplinary Nature of Physics

The interdisciplinary nature of physics refers to its integration with other fields of study, since physics provides fundamental principles, techniques, and methods that are useful across many disciplines. Biophysics applies physics principles and techniques to biological systems, such as the mechanics of biological structures and the physical properties of cells and tissues. Medical physics applies physical principles to health diagnosis and treatment, including imaging techniques (X-rays, ultrasound, MRI, CT scans) and radiation therapy for cancer.

Astrophysics studies the physical properties and processes of celestial bodies and phenomena, such as how matter and energy interact in space. Geophysics applies physical principles to study the Earth's internal structure, magnetic and gravitational fields, and phenomena such as earthquakes and volcanoes. Climate physics studies physical processes in the environment, including atmospheric dynamics, climate change, and weather. Computational physics uses computational techniques and methods to solve complex physical problems that are otherwise difficult to analyse directly.

9.4 Why Interdisciplinary Collaboration Matters

Modern science depends on collaboration because complex issues require expertise from multiple fields at once — for example, understanding and mitigating climate change requires knowledge from meteorology, oceanography, physics, chemistry, and environmental science together, while combating health crises such as recent epidemics required combined expertise from biology, chemistry, physics, medical technology, and data science.

Interdisciplinary approaches also foster innovation, since combining different perspectives and methods often produces novel breakthroughs that would not emerge from any single field working alone — nanotechnology, for instance, blends physics, chemistry, materials science, and engineering to create materials and devices at the nanoscale, while artificial intelligence draws on computer science, mathematical logic, and neuroscience together. Rapid global sharing of knowledge — through the internet, conferences, workshops, collaborative research projects, and journals — further accelerates scientific progress by allowing researchers from different fields to exchange fresh findings and ideas quickly.

9.5 The Scientific Method: Observation, Hypothesis, and Experiment

The scientific method is a systematic approach for investigating natural and physical phenomena and solving problems about them. It generally proceeds through the following steps: identifying an issue or problem, gathering information through observation, proposing a hypothesis (a possible explanation), testing the hypothesis through experiment or evidence, analysing the resulting data to reach a conclusion (a theory), and — after extensive repeated testing across a wide range of related situations — formulating a law.

Observation is the first step: collecting data about a natural process through ordinary observation or experimentation — for example, observing that an opaque object placed in a light path produces a shadow. A hypothesis is then proposed as a testable explanation based on the observed data — for example, hypothesising that shadows form because light travels in a straight line. An experiment is an organized, repeatable procedure designed to test the truth of a hypothesis — for example, aligning several cards each with a small hole so that light from a torch is visible only when all the holes line up in a straight line, confirming that light travels in straight lines.

9.6 Theory, Falsifiability, and Law

Once a hypothesis has been successfully and repeatedly verified through careful experimentation, it becomes a theory — a logical explanation of the causes and effects of a natural event or issue, applicable to similar phenomena. A theory allows scientists to make predictions about previously unknown aspects of nature, which are then tested through further experiments; if test results disagree with the prediction, the hypothesis is revised or rejected.

Falsifiability is the principle that a theory can only be considered scientific if it makes assertions that could, in principle, be tested and shown to be false. This requirement ensures scientific theories are built on specific, testable claims rather than vague or untestable beliefs, distinguishing genuine science from pseudo-science. When a theory has been tested extensively across many situations and is generally accepted as true, it becomes a law — a statement about the behaviour of nature that both explains past observations and predicts future ones (for example, the law that light travels in a straight line, from which the shape of shadows can be predicted). It is important to remember that scientific theories and laws are human ideas about how nature works, and remain open to being revised or disproven as new evidence and insights emerge.

9.7 Science, Technology, and Engineering

Physics is often the scientific core underlying inventions and technologies. Technology refers to the methods and techniques (whether machines or software) developed using scientific knowledge — for example, automobile technology is based on the principles of thermodynamics, radar technology is based on the detection and reflection of electromagnetic waves, and laser technology is based on the principles of atomic physics, with applications in medicine, industry, telecommunication, and space exploration.

Engineering is the process of applying scientific principles and technologies to design instruments, tools, and structures that meet specific real-world needs, while balancing factors such as cost and safety — for example, a civil engineer designs bridges that withstand wind, earthquakes, and heavy traffic; a software engineer designs user-friendly smartphone applications; and an aviation engineer selects lightweight materials that can withstand the stresses of flight. Although science, technology, and engineering are distinct fields, they work closely together: scientific discoveries lead to new technologies, and engineers rely on scientific knowledge to design solutions that shape and improve everyday life.

Important Definitions

What is science?

The collective, organized knowledge about natural phenomena, processes, and events, built through observation, questioning, and systematic study.

Define physics.

The fundamental science that studies matter, energy, space, time, and their mutual relationships and interactions.

What is a hypothesis?

A proposed, testable explanation of an observed phenomenon, put forward to be tested through experiment or evidence.

What is a theory in science?

A logical explanation of the causes and effects of a natural event, developed after a hypothesis has been successfully and repeatedly verified through experimentation.

What is a scientific law?

A statement about the behaviour of nature that has been extensively tested and generally accepted as true, capable of explaining past observations and predicting future ones.

Define falsifiability.

The principle that a theory is scientific only if it makes assertions that can, in principle, be tested and potentially shown to be false.

Differentiate between technology and engineering.

Technology refers to the methods and techniques developed using scientific knowledge (e.g. laser technology); engineering is the process of applying scientific principles and technologies to design and build things that meet specific practical needs.

What is interdisciplinary research?

Research that combines expertise, methods, and perspectives from multiple academic fields to address complex problems that no single discipline could adequately solve alone.

Key Ideas & Relationships

Topic	Summary
Scientific method sequence	Observation → Hypothesis → Experiment → Theory → Prediction → Law
Falsifiability requirement	A scientific theory must make testable predictions that could be proven false

Two main branches of science	Biological sciences (living things) and Physical sciences (non-living things)
Science–Technology–Engineering relationship	Science (discovery) → Technology (methods/tools) → Engineering (applied design & building)

Diagrams

The Scientific Method: The sequence of steps from observation through hypothesis, experiment, and theory, to an established law

Branches and Interdisciplinary Fields of Physics: Major branches of physics and its interdisciplinary connections with fields such as biophysics, medical physics, and geophysics

Science, Technology, and Engineering: How scientific discovery leads to technology, which engineering applies to design real-world solutions

Short Questions & Answers

What is science? Name its two main groups.

Science is the collective, organized knowledge about natural phenomena; its two main groups are the biological sciences (study of living things) and the physical sciences (study of non-living things).

What is physics all about? Name some of its branches.

Physics is the fundamental science of matter, energy, space, and time and their interactions; its branches include mechanics, heat and thermodynamics, optics, electromagnetism, quantum mechanics, and nuclear physics.

What is meant by interdisciplinary fields? Give a few examples.

Interdisciplinary fields combine physics with other disciplines to study specific problems, such as biophysics (physics applied to biology), medical physics (physics applied to diagnosis and treatment), and geophysics (physics applied to Earth's structure).

List the main steps of the scientific method.

Identifying a problem, gathering information through observation, proposing a hypothesis, testing it through experiment, analysing data to form a theory, and repeated testing to establish a law.

What is a hypothesis? Give an example.
A hypothesis is a testable proposed explanation for an observation; for example, hypothesising that shadows form because light travels in a straight line.

Distinguish between a theory and a law of physics.
A theory is a logical explanation of a phenomenon that has been verified through experimentation; a law is a statement that has been tested extensively across many situations and is generally accepted as always true, both explaining past observations and predicting future ones.

What is the basis of laser technology?
Laser technology is based on the principles of atomic physics.

What is the falsifiability concept? How is it important?
Falsifiability is the requirement that a scientific theory must make assertions that could potentially be proven false through testing; it is important because it distinguishes genuine, testable scientific theories from vague or untestable claims.

Long Questions & Answers

Describe the main steps of the scientific method, using the example of demonstrating that light travels in a straight line.

The scientific method begins with observation: noting, for example, that an opaque object placed in a beam of light produces a shadow. From this observation, a hypothesis is proposed — that shadows form because light travels in a straight line. This hypothesis is then tested through an experiment: aligning several cards, each with a small hole, in a straight line in front of a torch; light is visible through the holes only when all the cards are properly aligned, and moving any card out of line blocks the light. After the hypothesis is confirmed through careful, repeatable experimentation, it becomes a theory — a logical explanation applicable to similar phenomena. From this theory, predictions can be made and tested further, such as predicting that the shadow of a round object will be round and that of a rectangular object will be rectangular. Once the theory has been tested extensively across many different situations and consistently holds true, it becomes an accepted law of science: light travels in a straight line.

Explain what is meant by falsifiability, and why it is an essential requirement for a scientific theory.

Falsifiability is the principle that a theory can only be considered scientific if it makes specific assertions or predictions that could, in principle, be tested and shown to be false. This requirement is essential because it forces scientific theories to be precise and testable rather than vague or unfalsifiable — a claim that can never be disproven under any circumstances cannot be meaningfully tested, and therefore cannot be considered scientific, no matter how appealing it may seem. Falsifiability is what distinguishes genuine scientific theories, which are open to being challenged and potentially overturned by new evidence, from pseudo-scientific or unfounded beliefs that are structured to avoid ever being disproven. It also underlies the provisional nature of scientific knowledge: theories and laws are the best current explanations supported by available evidence, but remain open to revision or replacement if future experiments reveal results that contradict them.

Explain the interdisciplinary nature of physics and why collaboration across scientific disciplines is important, with examples.

Physics, as a fundamental science, provides principles, methods, and techniques that are applied across many other fields of study, giving rise to interdisciplinary branches such as biophysics (applying physics to biological systems), medical physics (applying physics to diagnosis and treatment, such as MRI and radiation therapy), astrophysics (studying the physical processes of celestial bodies), geophysics (studying the Earth's internal structure and processes), and computational physics (using computational methods to solve complex physical problems). Collaboration across these and other disciplines is essential because many of today's most pressing challenges are too complex for any single field to address alone — for instance, addressing climate change requires combined expertise from meteorology, oceanography, physics, chemistry, and environmental science, while responding to health crises requires combined efforts from biology, chemistry, physics, medical technology, and data science.

Interdisciplinary collaboration also drives innovation, since combining different perspectives and methods can produce breakthroughs that would not emerge from any single field working in isolation — as seen in nanotechnology (blending physics, chemistry, and materials science) and artificial intelligence (blending computer science, mathematics, and neuroscience). Rapid global sharing of research through the internet, conferences, and journals further accelerates the pace of scientific progress made possible by such collaboration.

Differentiate between science, technology, and engineering, explaining how they relate to and depend on one another, with examples.

Science, and physics in particular, is the systematic pursuit of knowledge about how the natural world works, developing theories and laws that explain and predict natural phenomena. Technology refers to the methods, techniques, machines, or software developed by applying scientific knowledge to practical ends — for example, automobile technology applies the principles of thermodynamics, radar technology applies the principles of electromagnetic wave detection and reflection, and laser technology applies the principles of atomic physics. Engineering is the process of applying scientific principles and existing technologies to design and build specific instruments, structures, or systems that meet real-world needs, while carefully balancing factors such as cost, safety, and practicality — for example, a civil engineer designs bridges able to withstand wind, earthquakes, and traffic loads, a software engineer designs user-friendly smartphone applications, and an aviation engineer selects lightweight materials able to withstand the stresses of flight. Although these three fields are distinct in focus, they are deeply interconnected: scientific discoveries make new technologies possible, and engineers depend on both scientific principles and existing technologies to design solutions that improve everyday life.

Multiple Choice Questions (MCQs)

Physics is a branch of: (A) social science (B) life science (C) physical science (D) biological science

Correct answer: (C) physical science. Physics belongs to the physical sciences, which study non-living things, alongside chemistry and geology.

Which branch of science plays a vital role in technology and engineering? (A) Biology (B) Chemistry (C) Geology (D) Physics

Correct answer: (D) Physics. Physics provides the fundamental principles that underlie most technological and engineering advances.

Automobile technology is primarily based on the principles of: (A) acoustics (B) electromagnetism (C) optics (D) thermodynamics

Correct answer: (D) thermodynamics. Automobile engines and related technology are based on the principles of thermodynamics, dealing with heat and its conversion to work.

A user-friendly smartphone software application is an example of: (A) laser technology (B) information technology (C) medical technology (D) electronic technology

Correct answer: (B) information technology. Software applications fall under information technology, which develops methods and tools for processing and managing information.

The working of refrigeration and air conditioning primarily involves: (A) electromagnetism (B) mechanics (C) climate science (D) thermodynamics

Correct answer: (D) thermodynamics. Refrigeration and air conditioning rely on thermodynamic principles governing the transfer and flow of heat energy.

According to the scientific method, the final, most rigorously tested outcome is a: (A) Hypothesis (B) Experimentation (C) Theory (D) Law

Correct answer: (D) Law. A law represents the most extensively tested and generally accepted outcome of the scientific method, built up from repeated confirmation of a theory.

The statement 'If I do not study for this test, then I will not get a good grade' is an example of a: (A) theory (B) observation (C) prediction (D) law

Correct answer: (C) prediction. This statement forecasts a specific outcome based on a condition, making it a prediction rather than an established theory or law.

Which of the following are recognized methods of scientific investigation? (A) Observation (B) Experimentation (C) Research (D) All of these

Correct answer: (D) All of these. Observation, experimentation, and research are all valid and commonly used methods of scientific investigation.

A hypothesis is best described as: (A) An assertion that may or may not be testable (B) A possible, testable answer to a question, supported by initial evidence (C) A universally accepted fact (D) The final stage of the scientific method

Correct answer: (B) A possible, testable answer to a question, supported by initial evidence. A hypothesis is a proposed, testable explanation put forward based on available evidence, meant to be tested through further experimentation.

Noting that 'the colour of a door is brown' is an example of: (A) observation (B) hypothesis (C) prediction (D) law

Correct answer: (A) observation. Simply noting a directly observable fact, without proposing an explanation or making a forecast, is an observation.

Quick Revision Summary

- Science = organized knowledge of nature; two branches: biological sciences (living) and physical sciences (non-living)
- Physics = study of matter, energy, space, time, and their interactions
- Major branches: mechanics, thermodynamics, acoustics, optics, electromagnetism, quantum mechanics, relativistic mechanics, nuclear/particle physics, astronomy, cosmology, solid state physics
- Interdisciplinary fields: biophysics, medical physics, astrophysics, geophysics, climate physics, computational physics
- Interdisciplinary collaboration is essential for complex problems (climate change, health crises) and drives innovation (nanotechnology, AI)
- Scientific method: observation → hypothesis → experiment → theory → prediction → law
- Falsifiability: a scientific theory must make testable, potentially disprovable predictions
- Science = knowledge; Technology = methods/tools from science; Engineering = applying science & technology to build solutions

- Theories and laws are human explanations, always open to revision with new evidence

Exam Tips

- Keep the sequence of the scientific method (observation → hypothesis → experiment → theory → law) firmly memorised — exam questions often test correct ordering
- Practice classifying example statements as observation, hypothesis, prediction, or law — this is a very common MCQ style in this chapter
- Learn at least 2-3 named branches of physics and 2-3 interdisciplinary fields with one real-world example each
- When explaining falsifiability, always mention that a theory must be capable of being proven wrong to count as scientific
- For science vs technology vs engineering questions, use the chain: science discovers → technology enables → engineering builds/applies
- Use the concrete 'light travels in a straight line' example as a model answer for scientific-method questions