بِسۡمِ اللّٰہِ الرَّحۡمٰنِ الرَّحِیۡمِ

IN THE NAME OF ALLAH, THE ALL-MERCIFUL, THE ALL-COMPASSIONATE

PHYSICS (TECH)

9

PUNJAB CURRICULUM AND TEXTBOOK BOARD, LAHORE

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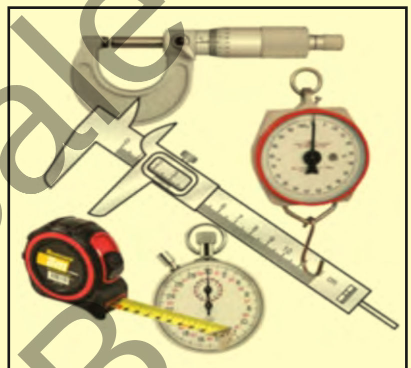
CONTENTS

Chapter 1

Physical Quantities and Measurements

Student Learning Outcomes

After completing this chapter, students will be able to:



- Describe physics as the study of matter, energy, space, time and their mutual connections and interactions
- Differentiate between physical and non-physical quantities
- Explain with examples that physics is based on physical quantities [Including that these consist of a magnitude and a unit]
- Differentiate between base and derived physical quantities and units.
- Use the seven units of System International (SI) along with their symbols and physical quantities (standard definitions of SI units are not required)
- Analyse and express numerical data using scientific notation [in measurements and calculations.]
- Analyse and express numerical data using prefixes [interconverting the prefixes and their symbols to indicate multiple and submultiple for both base and derived units.]
- Identify and explain the reason for common sources of human and systematic errors in experiments.
- Determine an average value for an empirical reading [Including small distance and for a short interval of time by measuring multiples (including the period of oscillation of a pendulum)] The uncertainty in measurements and describe the need using significant figures for recording and stating results of various measurements.
- Differentiate between precision and accuracy.
- Round off and justify measured estimates to make them reasonable. [Based on empirical data to an appropriate number of significant figures]
- Determine the least count of a data collection instrument (analogue) from its scale.

We are living in a physical world where we observe many natural phenomena and objects around us such as Sun, stars, moon, oceans, plants, winds, rains, etc. People have always been curious to know the reality of such happenings. This has led certain people to investigate the facts and laws working in this world. This field of observation and experimentation to understand about the world around us is known as science. Everything in our lives is closely linked to science and the discoveries made by the scientists. In order to obtain reliable results from experiments, the primary thing is to make accurate measurements.

Physical quantities and their measurements have always been the matter of interest for the scientists. They have been investigating to improve the methods and instruments for accurate measurements of the physical quantities. In this chapter, we will discuss physical quantities, their measurements and related contents.

1.1 Scope of Physics

Physics is the fundamental science that deals with the constituents of the universe, that is, matter, energy, space, time and their mutual relationships and interactions. It strives to understand how the universe works, from the smallest subatomic particles to the largest star and galaxies. We have studied some of the basic properties of matter, energy and their mutual inter-relationship in the earlier chapters of this book. We will discuss in detail the concept of space and time in the higher classes. Briefly, the space is the three-dimensional extent in which all objects and events occur. It provides framework to define positions and motions of various objects under some force.

The time measures the sequence and durations of events. It is considered fourth dimension. For example, oscillating motion such as that of a swinging pendulum relies on the time interval that determines frequency of oscillations. Another example is the time dilation which is a phenomenon discussed by special theory of relativity where time passes slowly for an observer moving at ultra-high speed compared to one relatively at rest. Physics explores how these fundamental concepts are inter-connected. For example, the theory of relativity explains how space and time are not absolute quantities but are related to each other. It describes the relationship between space and time and how they are influenced by gravity and speed, for example, the bending of light around massive objects like stars. Another branch of physics, the quantum mechanic, explains the behaviour of particles at the atomic and subatomic levels. It is how the physics has applied its principles to wide variety of phenomena, from everyday occurrences such as related to motion and heat to the extreme conditions found in the universe.

1.2 Physical and Non-Physical Quantities

We describe various natural phenomenon, events and human behaviour using some of their features and terms such as love, affection, fear, wisdom, beauty, length, volume, density, time, temperature, etc. Some of these can be

We describe various natural phenomenon, events and human behaviour using some of their features and terms such as love, affection, fear, wisdom,

beauty, length, volume, density, time, temperature, etc. Some of these can be measured directly and indirectly using some tools and instruments such as length of an object using a ruler, time duration of an event using a clock, the temperature (the degree of hotness) of somebody using a thermometer. They are called physical quantities. The foundation of physics rests upon physical quantities through which the laws and principles of physics are expressed.

Other quantities quoted above such as love, affection, fear, wisdom, and beauty cannot be measured using tools and instruments. They often pertain to the perception or interpretation of the observer. They can be described or estimated qualitatively or compared using some pre-determined criteria, indices or through survey techniques. Non-physical quantities mostly help to understand and to analyse human behaviour, emotions and social interactions.

Quick Quiz

Does a non-physical quantity have dimensions?

1.3 Base and Derived Physical Quantities

Physics is a science of physical world where we interact with many different types of material objects. These objects are exposed in terms of their measurable features known as physical quantities such as length, breadth, thickness, mass, volume, density, time, temperature, etc. Out of these, the scientists have selected arbitrarily some quantities to play a key role. They are called base quantities. All the quantities which can be described in terms of one or more base quantities are called derived physical quantities. For example, speed is a derived quantity which depends on distance and time which are base quantities whereas density of a material is described in terms of mass and volume.

Measurement of a Physical Quantity

A measurement is a process of comparison of an unknown quantity with a widely accepted standard quantity.

Activity 1.1

The teacher should facilitate this activity and initiate discussion as per direction.
One student should measure the length of a writing board with his hand. The same should be repeated by four or five students. Are all the measurements same? If they differ, then why? What is the solution to avoid confusion?

In the early days people used to measure length using hand or arm, foot or steps. This measurement may result in confusion as the measurement of different people may differ from each other because of different sizes of their hands, arms or steps. To avoid such confusion, there is a need of a standard so that measurement by any person may result the same. **This standard of**

measurement is known as a unit.

A measurement consists of two parts, a number and a unit. A measurement without unit is meaningless.

Not very far in the past, every country in the world had its own units of measurements. However, problems were faced when people of different countries exchanged scientific information or traded with other countries using different units. Eventually, people got the idea of standardizing the units of measurements which could be used by all countries for efficient working and growth of mutual trade, business and share scientific information.

1.4 International System of Units

The international committee on weights and measures in 1961 recommended the use of a system consisted of seven base units known as international system of units, abbreviated as SI. This system is in use all over the world.

Use of SI measurements helps all scientists to share and compare their observations and results easily. The seven base units are given in Table 1.1. Their values are fixed with reference to international standards.

Table 1.1

Sr. No.	Physical quantity	Unit	Symbol
1.	Length	metre	m
2.	Mass	kilogram	kg
3.	Time	second	s
4.	Temperature	kelvin	K
5.	Electric current	ampere	A
6.	Intensity of light	candela	cd
7.	Amount of substance	mole	mol

Derived Units

Base units cannot be derived from one another and neither can they be resolved into anything more basic. While the units of derived quantities such as speed, area, volume, force, pressure and electric charge can be derived using the base units. These units are called derived units.

The units which can be expressed in terms of base units are called derived units.

For example, Area = length × breadth

= metre × metre

= square metre

= metre^2 or m^2

Table 1.2

Sr. No.	Physical quantity	Unit	Symbol
1.	Area	square metre	m^2
2.	Volume	cubic metre	m^3
3.	Speed	metre per second	ms^{-1}
4.	Force	newton	N
5.	Pressure	pascal	Pa
6.	Electric charge	coulomb	C
7.	Plane angle	radian	rad

Speed = Distance/Time = metre/second = m s^{-1}
A few derived units with specific names and symbols are given in Table 1.2.

Quick Quiz

(a) Write the unit of charge in terms of base unit ampere and second.
(b) Express the unit of pressure "pascal" in some other units.

SI Prefixes

The SI is a decimal system. Prefixes are used to write units by powers of 10. The big quantities like 50000000 m and small quantities like 0.00004 m are not convenient to write down. The use of prefixes makes them simple. The quantity 50000000 m can be written as 5×10^7 m. Similarly, the quantity 0.00004 m can be written as 4×10^{-5} m.

Prefixes are the words or symbols added before SI unit such as milli, centi, kilo, mega, giga (Table1.3). The prefixes given in Table 1.4 should be known for use of SI units effectively. For example, one thousandth (1/1000) of a metre is millimetre. The thickness of a thin wire can be expressed conveniently in millimetres whereas a long distance is expressed in kilometres which is 1000 metres.

Multiples and sub-multiples of mass measurement are given in Table 1.4 whereas multiples and sub-multiples of length are given in Table 1.5. The following examples will explain the meaning of prefixes.

(i) $5000 \text{ mm} = \frac{5000}{1000} \text{ m} = 5 \text{ m}$

(ii) $50000 \text{ cm} = \frac{50000}{100} \text{ m} = 500 \text{ m}$

(iii) $3000\text{g} = \frac{3000}{1000} \text{ kg} = 3 \text{ kg}$

(iv) $2000\ \mu\text{s} = 2000 \times 10^{-6} \text{ s} = 2 \times 10^{-3} \text{ s} = 2 \text{ ms}$

Table 1.3: Prefixes used with SI units

Prefix	Symbol	Powers of Ten
atto	a	10^{-18}
femto	f	10^{-15}
pico	p	10^{-12}
nano	n	10^{-9}
micro	µ	10^{-6}
milli	m	10^{-3}
centi	c	10^{-2}
deci	d	10^{-1}
kilo	k	10^{3}
mega	M	10^{6}
giga	G	10^{9}
tera	T	10^{12}
peta	P	10^{15}
exa	E	10^{18}

Table 1.4

100 kg	1 quintal
10 quintal or 1000 kg	1 tonne

Table 1.5

1 m	100 cm
1 cm	10 mm
1 km	1000 m
1 mm	10^{-3} m
1 cm	10^{-2} m
1 km	10^{3} m

Do You Know?

The kilogram is the only base unit that has a prefix.

Quick Quiz

100 m is equal to:
(a) 1000 µm (b) 1000 cm
(c) 100,000 mm (d) 1 km

1.5 Scientific Notation

It is short way of representing very large or very small numbers. Writing otherwise, the values of these quantities, take up much space. They are difficult to read, their relative sizes are difficult to visualize and they are awkward to use in calculations. Their decimal places are more conveniently expressed as powers of 10. The numerical part of the quantity is written as a number from 1 to 9 multiplied by whole number powers of 10. To write numbers using scientific notation, move the decimal point until only one non-zero digit remains on the left. Then count the number of places through which the decimal point is moved and use this number as the power or exponents of 10. The average distance from the Sun to the Earth is 138,000,000 km. In scientific notation, this distance would be written as 1.38×10^8 km. The number of places, decimal moved to the left is expressed as a positive exponent of 10.

Diameter of hydrogen atom is about 0.000,000,000,052 m. To write this number in scientific notation, the decimal point is moved 11 places to the right. As a result, the diameter is written as 5.2×10^{-11} m. The number of places moved by the decimal to the right is expressed as a negative exponent of 10.

Example 1.1

Solve the following:

(a) $5.123 \times 10^4 \text{ m} + 3.28 \times 10^5 \text{ m}$

(b) $2.57 \times 10^{-2} \text{ mm} - 3.43 \times 10^{-3} \text{ mm}$

For Your Information!

The negative exponents have values less than one. For example, $1 \times 10^{-2} = 0.01$

Solution

(a) $5.123 \times 10^4 \text{ m} + 3.28 \times 10^5 \text{ m}$

$= 5.123 \times 10^4 \text{ m} + 32.8 \times 10^4 \text{ m}$

$= (5.123 + 32.8)\, 10^4 \text{ m}$

$= 37.923 \times 10^4 \text{ m}$

$= 3.7923 \times 10^5 \text{ m}$

Quick Quiz

Express the following into scientific notation:

(a) 0.00534 m (b) 2574.32 kg

(c) 0.45 m (d) 0.004 kg

(e) 186000 s

(b) $2.57 \times 10^{-2} \text{ mm} - 3.43 \times 10^{-3} \text{ mm}$

$= 2.57 \times 10^{-2} \text{ mm} - 0.343 \times 10^{-2} \text{ mm}$

$= (2.57 - 0.343)\, 10^{-2} \text{ mm}$

$= 2.227 \times 10^{-2} \text{ mm}$

$= 2.227 \times 10^{-2} \times 10^{-3} \text{ m}$

$= 2.227 \times 10^{-5} \text{ m}$

For Your Information!

Addition and subtraction of numbers is only possible if they have the same exponents. If they do not have the same exponents, make them equal by the displacement of the position of the decimal point.

For Your Information!

Use of SI units require special care, particularly in writing prefixes.

- Each unit is represented by a symbol not by an abbreviation. For example, for SI not S.I., for second s not sec, for ampere A not amp, for gram g not gm.
- Symbols do not take plural form. For example, 10 mN, 100 N, 5 kg, 60 s.
- Full name of unit does not begin with capital letter. For example, metre, second, newton except Celsius.
- Symbols appear in lower case, m for metre, s for second, exception is only L for litre.
- Symbols named after scientist's name have initial letters capital. For example, N for newton, K for kelvin and Pa for pascal.
- Prefix is written before and close to SI unit. Examples: ms, mm, mN, not m s, m m, m N.
- Units are written one space apart. For example, N m, N s.
- Compound prefixes are not allowed. For example,

(i) 7 μμs should be written as 7 ps.

(ii) 5×10^4 cm should be written as 5×10^2 m.

Example 1.2

Find the value of each of the following quantities:

(a) $(4 \times 10^3 \text{ kg})(6 \times 10^6 \text{ m})$

(b) $\dfrac{6 \times 10^6 \text{ m}^3}{2 \times 10^{-2} \text{ m}^2}$

Solution

(a) $(4\times10^3 \text{ kg})(6\times10^6 \text{ m}) = (4\times6)\times10^{3+6} \text{ kg m}$

$= 24 \times 10^9 \text{ kg m}$

$= 2.4 \times 10^{10} \text{ kg m}$

(b) $\dfrac{6 \times 10^6 \text{ m}^3}{2 \times 10^{-2} \text{ m}^2} = \dfrac{6}{2} \times 10^{6-(-2)} \text{ m}^{3-2}$

$= 3 \times 10^8 \text{ m}$

Branches of Physics

1. Mechanics
2. Heat and Thermodynamics
3. Acoustics
4. Optics
5. Electromagnetism
6. Quantum Mechanics
7. Relativistic Mechanics
8. Nuclear Physics
9. Particle Physics
10. Astronomy
11. Solid State Physics

For Your Information!

The symbol of the base units are universal independent of the language used in the written text.

1.6 Errors in Measurements

Measurements using tools and instruments are never perfect. They inherit some errors and differ from their true values. The best we shall do is to ensure that the errors are as small as reasonably possible. A scientific measurement should indicate the estimated error in the measured values. Usually, there are three types of experimental errors affecting the measurements.

(i) Human Errors **(ii) Systematic Errors** **(iii) Random Errors**

(i) Human Errors

They occur due to personal performance. The limitation of the human perception such as the inability to perfectly estimate the position of the pointer on a scale. Personal errors can also arise due to faulty procedure to read the scale. The correct measurement needs to line up your eye right in front of the level. In timing experiments, the reaction time of an individual to start or stop clock also affects the measured value. Human error can be reduced by ensuring proper training, techniques and procedure to handle the instruments and avoiding environmental distraction or disturbance for proper focusing. The best way is to use automated or digital instruments to reduce the impact of human errors.

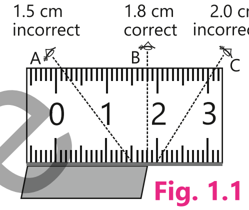


Fig. 1.1

(ii) Systematic Errors

They refer to an effect that influences all measurements of particular measurements equally. It produces a consistence difference in reading. It occurs due to some definite rule. It may occur due to zero error of instrument, poor calibration of instrument or incorrect marking. The effect of this kind of error can be reduced by comparing the instrument with another which is known to be more accurate. Thus, a correction factor can be applied.

(iii) Random Errors

It is said to occur when repeated measurements of a quantity give different values under the same conditions. It is due to some unknown causes which are unpredictable.

The experimenter have a little or no control over it. Random error arise due to sudden fluctuation or variation in the environmental conditions. For example, changes in temperature, pressure, humidity, voltage, etc. The effect of random errors can be reduced using several or multiple readings and then taking their average or mean value. Similarly, for the measuring time period of oscillating pendulum, the time of several oscillations, say 30 oscillations is noted and then mean or average value of one oscillation is determined.

Quick Quiz

Identify Personal, Systematic and Random errors:

1. Your eye level may move a bit while reading the meniscus.
2. Air current may cause the balance to fluctuate.
3. The balance may not be properly calibrated.
4. Some of the liquid may have evaporated while it is being measured.

1.7 Uncertainty in a Measurement

There is no such thing as a perfect measurement. Whenever a physical quantity is measured except counting, there is inevitably some uncertainty about its determined value due to some instrument. This uncertainty may be due to use of a number of reasons. One reason is the type of instrument being used. We know that every measuring instrument is calibrated to a certain smallest division and this fact puts a limit to the degree of accuracy which can be achieved while measuring with it. Suppose that we want to measure the length of a straight line with the help of a metre rule calibrated in millimetres. Let the end point of the line lies between 10.3 cm and 10.4 cm marks. By convention, if the end of the line does not touch or cross the midpoint of the smallest division, the reading is confined to the previous division. In case the end of the line seems to be touching or have crossed the midpoint, the reading is extended to the next division. Thus, in this example, the maximum uncertainty is ± 0.05 cm. It is, infact, equivalent to an uncertainty of 0.1 cm equal to the least count of the instrument divided into two parts, half above and half below the recorded reading.

Uncertainty in Digital Instruments

Some modern measuring instruments have a digital scale. We usually estimate one digit beyond what is certain. With digital scale, this is reflected in fluctuation of the last digit.

The uncertainty in small length such as diameter of a wire and short interval of time can be reduced further by taking multiple readings and then finding average value. For example, the average time of one oscillation of a simple pendulum is usually found by measuring the time for thirty oscillations.

The uncertainty or accuracy in the value of a measured quantity can be indted conveniently by using significant figures.

1.8 Significant Figures

We can count the number of candies in a jar and know it exactly by counting but we cannot measure the height of the jar exactly. All measurements include uncertainties depending upon the refinement of the instrument which is used for measurement.

It is important to reflect the degree of uncertainty in a measurement by recording the observation in significant figures.

The significant figures or digits are the digits of a measurement which are reliably known.

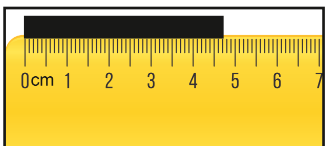


Fig. 1.2

Figure 1.2 shows a rod whose length is measured with a ruler. The measurement shows the length in between 4.6 cm and 4.7 cm. Since the length of the rod is slightly more than 4.6 cm but less than 4.7 cm, so the first student estimates it to be 4.6 cm whereas the second student takes it as 4.7 cm. The first student thinks that the edge is nearer to 6 mm mark whereas the second student considers the edge of the rod nearer to 7 mm mark. It is difficult to decide what is the true length.

Both students agree on digit 4 but the next digit is doubtful which has been determined by estimation only and has a probability of error. Therefore, it is known as a doubtful digit. In any measurement, the accurately known digits and the first doubtful digit are known-as significant figures.

Quick Quiz

Name some repetitive processes occuring in nature which could serve as reasonable time standard.

The following points are to be kept in mind while determining the number of significant figures in any data. All digits from 1 to 9 are significant. However, zeros may or may not be significant. In case of zeros, the following rules apply:

(a) A zero between two digits is considered significant. For example in 5.06m, the number of significant figures is 3.

(b) Zeros on the left side of the measured value are not significant. For example, in 0.0034 m, the number of significant figures is 2.

(c) Zeros on the right side of a decimal are considered significant. For example, in 2.40 mm the significant digits are 3.

(d) If numbers are recorded in scientific notation, then all the digits before the exponent are significant. For example, in 3.50×10^4 m, the significant figures are 3.

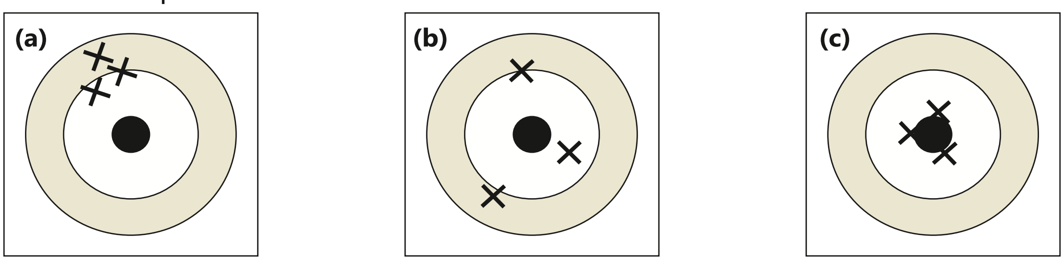
Quick Quiz

How many significant figures are there in each of the following?

(a) 1.25×10^2 m (b) 12.5 cm (c) 0.125 m (d) 0.000125 km

1.9 Precision and Accuracy

A physical measurements should be precise as well as accurate. These are two separate concepts and need clear distinction. Generally, precision of a measurement refers to how close together a group of measurements actually are to each other. Accuracy of a measurement refers how close the measured value is to some accepted or true value.



Precise not accurate — Accurate not precise — Accurate and precise

Fig. 1.3

A classic illustration is helpful to distinguish the two concepts. Consider a target or bullseye hit by arrows in Fig. 1.3. To be precise, arrows must hit near each other (Fig.1.3-a) and to be accurate, arrows must hit near the bullseye

(Fig. 1.3-b). Consistently hitting near the centre of bullseye indicates both precision and accuracy (Fig. 1.3-c). When these concepts are applied to measurements, the precision is determined by the instrument being used for measurement. The smaller the least count, the more precise is the measurement. A measurement is accurate if it correctly reflects the size of the object being measured. Accuracy depends on fractional uncertainty in the measurement. Infact, it is relative measurement which is important. The smaller the size of physical quantity, the more precise instrument is needed to be used. The accuracy of measurement is reflected by the number of significant figures, the larger is the number of significant figures, the higher is the accuracy.

1.10 Rounding off the Digits

When rounding off numbers to a certain number of significant figures, do so to the nearest value. If the last digit is more than 5, the retained digit is increased by one and if it is less than 5, it is retained as such.

For example:

(i) Round off to 2 significant figures: 2.512×10^3 m. **Ans.** 2.5×10^3 m

(ii) Round off to 3 significant figures: 3.4567×10^4 kg. **Ans.** 3.46×10^4 kg

For the integer 5, there is an arbitrary rule:
If the number before the 5 is odd, one is added to the last digit retained.
If the number before the 5 is even, it remains the same:

For example:

(i) Round off to 2 significant figures: 4.45×10^2 m.

(ii) Round off to 2 significant figures: 4.55×10^2 m.

Answer: 4.4×10^2 m

Answer: 4.6×10^2 m

Sometimes, logic is applied to decide the fate of a digit. If we round off to 2 significant figures 4.452×10^2 m, the answer should be 4.5×10^2 m since 4.452×10^2 m is more closer to 4.5×10^2 m than 4.4×10^2 m.

Do You Know?

An Electronic timer can measure time intervals as short as one-ten thousands (1/10,000) of a second.

EXERCISE

A Multiple Choice Questions

Tick (✓) the correct answer.

1.1 One femtometre is equal to:
(a) 10^{-9} m (b) 10^{-15} m (c) 10^{9} m (d) 10^{15} m

1.2 A light year is a unit of:
(a) light (b) time (c) distance (d) speed

1.3 Which one is a non-physical quantity?
(a) distance (b) density (c) colour (d) temperature

1.4 Two rods with lengths 12.321 cm and 10.3 cm are placed side by side, the difference in their lengths is:
(a) 2.02 cm (b) 2.0 cm (c) 2 cm (d) 2.021 cm

1.5 Which of the following measures are likely to represent the thickness of a sheet of this book?
(a) 6×10^{-25} m (b) 1×10^{-4} m (c) 1.2×10^{-15} m (d) 4×10^{-2} m

B Short Answer Questions

1.1 Can a non-physical quantity be measured? If yes, then how?

1.2 What is measurement? Name its two parts.

1.3 Why do we need a standard unit for measurements?

1.4 Write the name of 3 base quantities and 3 derived quantities.

1.5 Which SI unit will you use to express the height of your desk?

1.6 Write the name and symbols of all SI base units.

1.7 Why prefix is used? Name three sub-multiple and three multiple prefixes with their symbols.

1.8 What is meant by:
(a) 5 pm (b) 15 ns (c) 6 μm (d) 5 fs

C Constructed Response Questions

1.1 In what unit will you express each of the following?
(a) Thickness of a five-rupee coin: ________
(b) Length of a book: ________
(c) Length of football field: ________
(d) The distance between two cities: ________
(e) Mass of five-rupee coin: ________
(f) Mass of your school bag: ________
(g) Duration of your class period: ________
(h) Volume of petrol filled in the tank of a car: ________

1.2 Why might a standard system of measurement be helpful to a tailor?

1.3 The end of a metre scale is worn out. Where will you place a pencil to find the length?

1.4 Why is it better to place the object close to the metre scale?

1.5 Why a standard unit is needed to measure a quantity correctly?

1.6 Suggest some natural phenomena that could serve as a reasonably accurate time standard.

D Comprehensive Questions

1.1 What is meant by base and derived quantities? Give the names and symbols of SI base units.

1.2 Give three examples of derived unit in SI. How are they derived from base units? Describe briefly.

1.3 Identity and explain the reasons for human errors, random errors and systematic errors in experiments.

1.4 Differentiate between precision and accuracy of a measurement with examples.

E Numerical Problems

1.1 Calculate the number of seconds in a (a) day (b) week (c) month and state your answers using SI prefixes. (86.4 ks, 604.8 ks, 2.592 Ms)

1.2 State the answers of problem 1.1 in scientific notation.

[8.64×10^4 s, 6.048×10^5 s, 2.592×10^6 s]

1.3 Solve the following addition or subtraction. State your answers in scientific notation.

(a) 4×10^{-4} kg + 3×10^{-5} kg (b) 5.4×10^{-6} m − 3.2×10^{-5} m

[(a) 4.3×10^{-4} kg (b) -2.66×10^{-5} m]

1.4 Solve the following multiplication or division. State your answers in scientific notation.

(a) $(5 \times 10^4\ \text{m}) \times (3 \times 10^{-2}\ \text{m})$ (b) $\dfrac{6 \times 10^8\ \text{kg}}{3 \times 10^4\ \text{m}^3}$

(a) 1.5×10^3 m^2 (b) 2.0×10^4 kg m^{-3}

1.5 Calculate the following and state your answer in scientific notation.

$$\frac{(3 \times 10^2\ \text{kg}) \times (4.0\ \text{km})}{5 \times 10^2\ \text{s}^2}$$

(2.4×10^3 kg m s^{-2})

1.6 State the number of significant digits in each measurement.

(a) 0.0045 m (b) 2.047 m (c) 3.40 m (d) 3.420×10^4 m

[(a) 2 (b) 4 (c) 3 (d) 4]

1.7 Write in scientific notation:

(a) 0.0035 m (b) 206.4×10^2 m [(a) 3.5×10^{-3} m, (b) 2.064×10^4 m)]

1.8 Write using correct prefixes:

(a) 5.0×10^4 cm (b) 580×10^2 g (c) 45×10^{-4} s [(0.5 km, 58 kg, 4.5 ms)]

Chapter 2

Kinematics

Student Learning Outcomes

After completing this chapter, students will be able to:

- Differentiate between scalar and vector quantities:
  [A scalar has magnitude (size) only and that a vector quantity has magnitude and direction. Students should be able to represent vectors graphically]
- Justify that distance, speed, time, mass, energy, and temperature are scalar quantities.
- Justify that displacement, force, weight, velocity, acceleration are vector quantities.
- Determine graphically, the resultant of two or more vectors.
- Differentiate between distance and displacement, speed and velocity.
- Define and calculate average speed [average speed = (total distance travelled)/ (total time taken)]
- Differentiate between average and instantaneous speed (speed shown by speedometer of a vehicle is the speed at any instant.)
- Differentiate between uniform velocity and non -uniform velocity
- Define and calculate acceleration [Includes deriving the units of acceleration as ms^{-2} from the formula $a = \Delta v / \Delta t$ and using the formula to solve problems. This also includes knowing that that deceleration is negative acceleration and using fact in calculations.]
- Differentiate between uniform acceleration and non -uniform acceleration
- Sketch, plot and interpret distance, time and speed-time graphs
  [This includes determining from the shape of a distance -time graph when an object is:
  [(a) at rest, (b) moving with constant speed, (c) accelerating, (d) decelerating. Students are also required to know how to calculate speed from the gradient of a distance - time graph. It also includes determining from the shape of a speed -time graph when an object is:
  (a) at rest, (b) moving with constant speed, (c) moving with constant acceleration.]
- Use the approximate value of g as 10 m s^{-2} for free fall acceleration near Earth to solve problems
- Analyse the distance travelled in speed vs time graphs [By determining the area under the graph for cases of motion with constant speed or constant acceleration]
- Calculate acceleration from the gradient of a speed-time graph

Mechanics is the branch of physics that deals with the motion of objects and the forces that change it.

Generally, mechanics is divided into two branches:

1. Kinematics **2. Dynamics**

Kinematics is the study of motion of objects without referring to forces. On the other hand, dynamics deals with forces and their effect on the motion of objects.

In our everyday life, we observe many objects in motion. For example, cars, buses, bicycles, motorcycles moving on the roads, aeroplanes flying through air, water flowing in canals or some object falling from the table to the ground.

The motion of these objects can be studied with or without considering the force which causes motion in them or changes it.

2.1 Scalars and Vectors

Before we study kinematics in detail, we should know about the nature of various physical quantities. Some quantities are called scalars and the others vectors.

A scalar is that physical quantity which can be described completely by its magnitude only.

Magnitude includes a number and an appropriate unit. When we ask a shopkeeper to give us 5 kilograms of sugar, he can fully understand how much quantity we want. It is the magnitude of mass of sugar. Mass is a scalar quantity. Some other examples of scalar quantities are distance, length, time, speed, energy and temperature. Scalar quantities can be added up like numbers.

For example, 5 metres + 3 metres = 8 metres.

On the other hand,

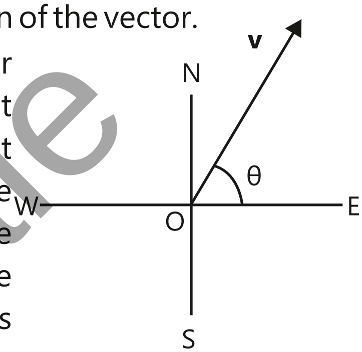
A vector is that physical quantity which needs magnitude as well as direction to describe it completely.

The examples of vector quantities are displacement, velocity, acceleration, weight, force, etc. The velocity of a car moving at 90 kilometre per hour (25 m s^{-1}) towards north can be represented by a vector. Velocity is a vector quantity because it has magnitude 25 m s^{-1} and direction (towards north). Vectors cannot be added like scalars. There are specific methods to add up vectors. These methods take their directions also into consideration.

Representation of vectors

In the textbooks, symbol used for a vector is a bold face letter such as **A, v, F** and **d** etc. Since we cannot write in bold face script on paper, so a vector is written as the letter with a small arrow over it, i.e. $\vec{A}$, $\vec{v}$, $\vec{F}$, $\vec{d}$. The magnitude of a vector is given by italic letter without arrow head. A vector can be represented graphically by drawing a straight line with an arrow head at one end. The length of line represents the magnitude of the vector quantity according to a suitable scale while the direction of arrow indicates the direction of the vector.

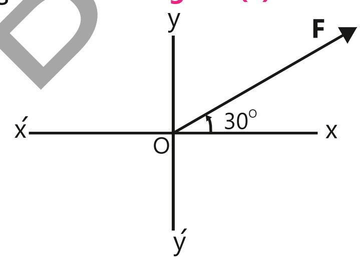
To represent the direction, two mutually perpendicular lines are required. We can draw one line to represent east-west direction and the other line to represent north-south direction as shown in Fig.2.1(a). The direction of a vector can be given with respect to these lines. Mostly, we use any two lines which are perpendicular to each other. Horizontal line ($x\acute{x}$) is called x-axis and vertical line ($y\acute{y}$) is called y-axis (Fig. 2.1-b). The point where these axes meet is known as origin. The origin is usually denoted by O. These axes are also called reference axes.



A vector **v** making an angle θ towards north from east

Fig 2.1 (a)

A vector is drawn starting from the origin of the reference axes towards the given direction. The direction is usually given by an angle θ (theta) with x-axis. The angle with x-axis is always measured from the right side of x-axis in the anti-clockwise direction.



A vector **F** making angle 30° with x-axis

Fig. 2.1 (b)

Example 2.1

Draw the velocity vector **v**; a velocity of 300 m s^{-1} at an angle of 60° to the east of north.

Solution

(i) Draw two mutually perpendicular lines indicating N, S, E & W.

(ii) Select a suitable scale. If 100 m s^{-1} = 1 cm, then 300 m s^{-1} are represented by 3 cm line.

(iii) Draw 3 cm line OP at an Angle of 60° starting from N towards E.

(iv) Make an arrow head at the end of line OP. The OP is the vector **v**.

For Your Information!

For geographical direction, the reference line is north – south whereas for Cartesian coordinate system +ve *x*-axis is the reference.

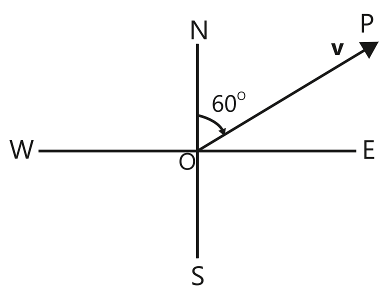


Fig. 2.2

Example 2.2

Draw a force vector **F** having magnitude of 350 N and acting at an angle of 60° with x-axis.

Solution

(i) Draw horizontal and vertical lines to represent x-axis and y-axis as shown in Fig. 2.3.

(ii) Scale: If 100 N = 1 cm, then

350 N = 3.5 cm

(iii) Draw 3.5 cm line OQ at an angle of 60° with x-axis.

(iv) Make an arrow head at the end of the line OQ. The OQ is the vector **F**.

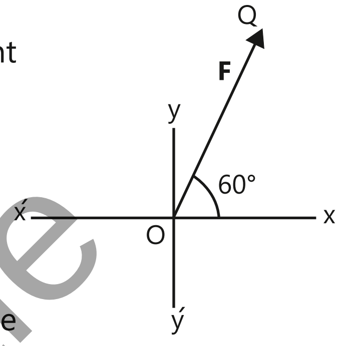


Fig. 2.3

Resultant Vector

We can add two or more vectors to get a single vector. This is called as resultant vector. It has the same effect as the combined effect of all the vectors to be added. We have to determine both magnitude and direction of the resultant vector, therefore, it is quite different from that of scalar addition. One method of addition of vectors is the graphical method.

Addition of Vectors by Graphical Method

Let us add two vectors $\mathbf{v}_1$ and $\mathbf{v}_2$ having magnitudes of 300 N and 400 N acting at angles of 30° and 60° with x-axis. By selecting a suitable scale 100 N = 1cm, we can draw the vectors as shown in Fig. 2.4 (a).

To add these vectors, we apply a rule called **head-to-tail rule**, which states that:

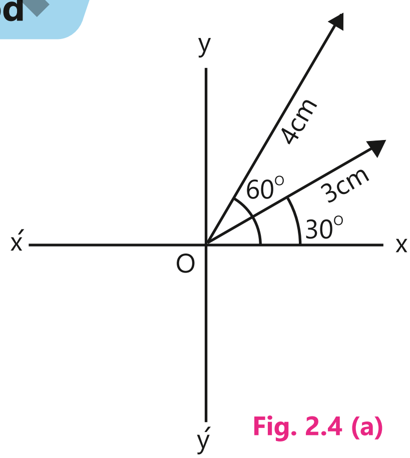


Fig. 2.4 (a)

To add a number of vectors, redraw their representative lines such that the head of one line coincides with the tail of the other. The resultant vector is given by a single vector which is directed from the tail of the first vector to the head of the last vector.

Measured length of resultant vector is 6.8 cm (Fig.2.4-b). According to selected scale, magnitude of the resultant vector **v** is 680 N and direction is angle 49° with x-axis.

We can find the resultant vector of more than two vectors by adding them with the same way applying head-to-tail rule.

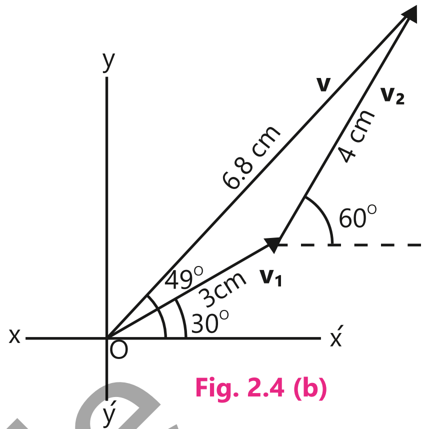


Fig. 2.4 (b)

2.2 Rest and Motion

When we look around us, we see many things like buildings, trees, electric poles, etc. which do not change their positions. We say that they are in a state of rest.

Fig. 2.5 (a)

If a body does not change its position with respect to its surroundings, it is said to be at rest.

Suppose a motorcyclist is standing on the road (Fig. 2.5-a). An observer sees that he is not changing his position with respect to his surroundings i.e., a nearby building, tree or a pole. He will say that the motorcyclist is at rest.

Now let us see what does motion mean? When the motorcyclist is driving (Fig. 2.5-b), the observer will notice that he is continuously changing his position with respect to the surroundings. Then the observer will say that the motorcyclist is in motion.

If a body continuously changes its position with respect to its surroundings, it is said to be in motion.

Fig. 2.5 (b)

The state of rest or motion of a body is always relative. For example, a person standing in the compartment of a moving train is at rest with respect to the other passengers in the compartment but he is in motion with respect to an observer standing on the platform of a railway station.

2.3 Distance and Displacement

We know that motion is the action of an object going from one place to another or change of position. The length between the original and final positions may be measured in two ways as either distance or displacement.

The distance is the length of actual path of the motion.

Let a person be travelling from Lahore to Multan in a car. On reaching Multan, he reads the speedometer and notices that he has travelled a distance of 320 km. It is the distance travelled by that person. Obviously, it is not the shortest distance from Lahore to Multan, as the car took many turns in the way. He did not travel along a straight line.

The displacement of an object is a vector quantity whose magnitude is the shortest distance between the initial and final positions of the motion and its direction is from the initial position to the final position.

We can also call this as the change in position. Note that displacement is a vector quantity whereas distance is a scalar quantity. Following example will explain the difference between distance and displacement.

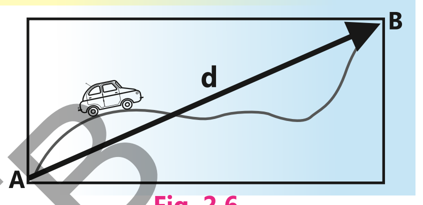


Fig. 2.6

Suppose a car travels from a position A to B. The curved line is the actual path followed by the car (Fig. 2.6). The total distance covered by the car will be equal to the length of the curved line AB. The displacement **d** is the straight line AB directed from A to B as indicated by the arrow head. The SI unit for the displacement is the same as that of distance.

2.4 Speed and Velocity

Brain Teaser!

The car while moving on a circular road may have constant speed, but its velocity is changing at every instant. Why?

We are often interested to know how fast a body is moving. For this purpose, we have to find the distance covered in unit time which is known as speed. If a body covers a distance S in time t, its speed v will be written as:

$$\text{Speed} = \frac{\text{Distance}}{\text{Time}} \qquad v = \frac{S}{t}$$

$$\text{or} \quad S = vt \quad \text{.............................(2.1)}$$

Do You Know?

The fastest land mammal (cheetah) and the fastest fish (sailfish) have the same highest recorded speed of 110 km h^{-1}.

The speed is a scalar quantity. The SI unit of speed is $m\,s^{-1}$ or $km\,h^{-1}$.
It is obvious that speed of a vehicle does not remain constant throughout the journey. If the reading of the speedometer of the vehicle is observed, it is always changing. The speed of a vehicle that is shown by its speedometer at any instant is called **instantaneous speed**. Practically we make use of the **average speed**. It is defined as:

$$\text{Average speed} = \frac{\text{Total distance covered}}{\text{Total time taken}} \quad \text{or} \quad v_{av} = \frac{S}{t}$$

Example 2.3

An eagle dives to the ground along a 300 m path with an average speed of 60 m s^{-1}. How long does it take to cover this distance?

Solution

Total distance covered = S = 300 m
Average speed = v_{av} = 60 m s^{-1}
Total time taken = t = ?
Using the equation $v_{av} = \frac{S}{t}$
or $t = \frac{S}{v_{av}}$

putting the values t = 300 m / 60 m s^{-1} = 5 s

For Your Information!

Mount st. Helens erupted in 1980, causing rocks to travel at velocities up to 400 km h^{-1}

Velocity

The speed of an object does not tell anything about the direction of motion. To take into account the direction, the vector concept is needed. For this, we have to find the displacement **d** between the initial and final positions.

The net displacement of a body in unit time is called velocity.

If a body moves from point A to B along a curved path as shown in Fig.2.11, the displacement **d** is the straight line AB, then

$$\text{Average velocity} = \frac{\text{Displacement}}{\text{Time}} \quad \text{or} \quad \mathbf{v}_{av} = \frac{\mathbf{d}}{t} \quad \text{.............(2.2)}$$

Velocity is a vector quantity. The Equation (2.2) shows that the direction of velocity **v** is the same as that of displacement **d**. The SI unit of velocity is also m s^{-1} or km h^{-1}. Consider the example of a car moving towards north at the rate of 70 km h^{-1}.To differentiate between speed and velocity, we shall say that the speed of car is 70 km h^{-1} which is a scalar quantity. The velocity of the car is a vector quantity whose magnitude is 70 km h^{-1} and is directed towards north.

Uniform and Non-uniform Velocity

The velocity is said to be uniform if the speed and direction of a moving body does not change. If the speed or direction or both of them change, it is known as variable velocity or non-uniform velocity.

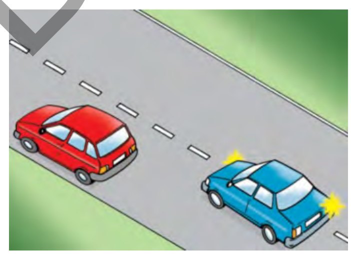
Practically, a vehicle does not move in a straight line throughout its journey. It changes its speed or its direction frequently. The example of a body moving with uniform velocity is the downward motion of a paratrooper. When a paratrooper jumps from an aeroplane, he falls freely for a few moments. Then the parachute opens. At this stage the force of gravity acting downwards on the paratrooper is balanced by the resistance of air on the parachute that acts upward. Consequently, the paratrooper moves down with uniform velocity.

For Your Interest!

Time-lapse photo of motorway traffic, the velocity of cars showing straight lines. White lines are the headlights and the red lines are taillights of vehicles moving in opposite directions.

2.5 Acceleration

Whenever the velocity of an object is increasing, we say that the object is accelerating. For example, when a car overtakes another one, it accelerates to a greater velocity (Fig.2.7). In contrary to that the velocity decreases when brakes are applied to slow down a bicycle or a car. In both the cases, a change in velocity occurs.



While overtaking, a car accelerates to a greater velocity.

Fig. 2.7

Acceleration is defined as the time rate of change of velocity.

The change in velocity can occur in magnitude or direction or both of them. The acceleration is positive if the velocity is increasing and it is negative if the velocity is decreasing. Negative acceleration is also called deceleration or retardation.

Acceleration is a vector quantity like velocity, but the direction of acceleration is that of change of velocity. If a body is moving with an initial velocity $\mathbf{v}_i$ and after some time t its velocity changes to $\mathbf{v}_f$, the change in velocity is $\Delta\mathbf{v} = \mathbf{v}_f - \mathbf{v}_i$ that occurs in time t. In this case, rate of change of velocity i.e., acceleration will be average acceleration.

$$\text{Average acceleration} = \frac{\text{Change in velocity}}{\text{Time taken}}$$

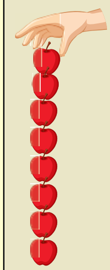
$$\mathbf{a}_{av} = \frac{\mathbf{v}_f - \mathbf{v}_i}{t} \quad \text{............} \quad (2.3)$$

Equation (2.3) can be written as $\mathbf{a}_{av} \quad \frac{\Delta \mathbf{v}}{t}$

The SI unit of acceleration is m s^{-2}.

If acceleration a is constant, then Eq 2.3 can be written as: $v_f = v_i + at$

Fascinating Snap:
This is a photograph of a falling apple dropped from som height. The images of apple are captured by the camera at 60 flashes per second. The widening spaces between the images indicate the acceleration of the apple.



Uniform and Non-uniform Acceleration

If time rate of change of velocity is constant, the acceleration is said to be uniform.

If anyone of the magnitude or direction or both of them changes it is called variable or non-uniform acceleration. In this class, we will solve problems only for the motion of the bodies having uniform acceleration and not the variable acceleration.

Example 2.4

A plane starts running from rest on a run-way as shown in the figure below. It accelerates down the run-way and after 20 seconds attains a velocity of 252 km h^{-1}. Determine the average acceleration of the plane.

Solution:

Initial velocity = $v_i = 0$

Final velocity = v_f = 252 km h^{-1}

$$= \frac{252 \times 10^3 \text{ m}}{60 \times 60 \text{ s}} = 70 \text{ m s}^{-1}$$

Time taken = t = 20 s

Average acceleration = a_{av} = ?

Using $a_{av} = \frac{v_f - v_i}{t}$

Putting the values

$$a_{av} = \frac{70 \text{ m s}^{-1} - 0}{20 \text{ s}}$$

$$a_{av} = 3.5 \text{ m s}^{-2}$$

2.6 Graphical Analysis of Motion

A graph is a pictorial diagram in the form of a straight line or a curve which shows the relationship between two physical quantities. Usually, we draw a graph on a paper on which equally spaced horizontal and vertical lines are drawn. Generally, every 10th line is a thick line on the graph paper. In order to draw a graph, two mutually perpendicular thick lines xox́ and yoý are selected as x and y axes as shown in Fig 2.8. The point where the two axes intersect each other is known as origin O. Positive values along x-axis are taken to the right side of the origin and negative values are taken to the left side. Similarly, positive values along y-axis are taken above the origin whereas negative values are taken below the origin. Normally, the independent quantity is taken along x-axis and dependent variable quantity along y-axis. For example, in distance-time graph, *t* is independent and *S* is dependent variable. Therefore, *t* should be along x-axis and *S* along y-axis.

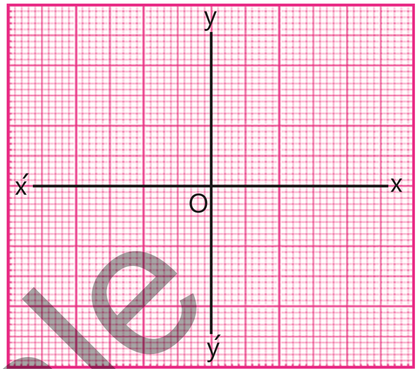


Fig. 2.8

To represent a physical quantity along any axis, a suitable scale is chosen by considering the minimum and maximum values of the quantity.

Distance-Time Graph

Distance-time graph shows the relation between distance *S* and time *t* taken by a moving body.

Let a car be moving in a straight line on a motorway. Suppose that we measure its distance from starting point after every one minute, and record it in the table given below:

Time *t* (min)	0	1	2	3	4	5
Distance *S* (km)	0	1.2	2.4	3.6	4.8	6.0

Follow the steps given below to draw a graph on a centimetre graph paper:

(i) Take time *t* along x-axis and distance *S* along y-axis.

(ii) Select suitable scales (1 minute = 1 cm) along x-axis and (1.2 km =1 cm) along y-axis. The graph paper shown here is not to the scale.

(iii) Mark the values of each big division along x and y axes according to the scale.

(iv) Plot all pairs of values of time and distance by marking points on the graph paper.

(v) Join all the plotted points to obtain a best straight line as shown in Fig. 2.9. From the table, we can observe that car has covered equal distance in equal intervals of time. This shows that the car moves with uniform speed. Therefore, a straight line graph between time and distance represents motion with uniform speed.

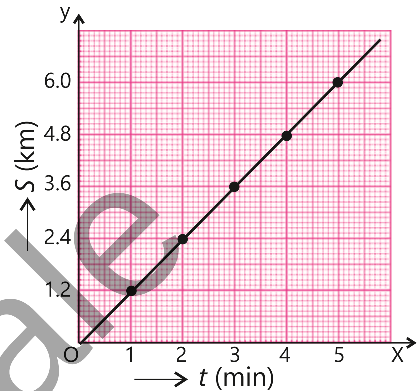


Fig. 2.9

Now consider another journey of the car as recorded in the table given below:

Time *t* (min)	0	1	2	3	4	5
Distance *S* (km)	0	0.240	0.960	2.160	3.840	6.000

Table shows that speed goes on increasing in equal intervals of time. This is very obvious from the graph as shown in Fig. 2.10. The graph line is curved upward. This is the case when the body (car) is moving with certain acceleration.

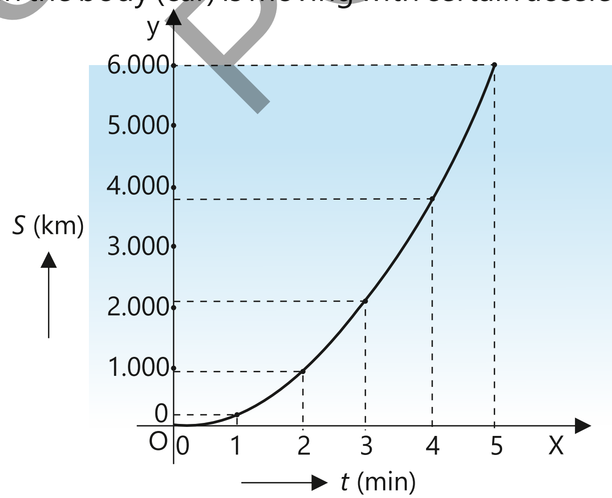


Fig. 2.10

2.7 Gradient of a Distance-Time Graph

The gradient is the measure of slope of a line.

Consider the distance-time graph of uniform speed again. Select any two values of time t_1 and t_2. Draw two vertical dotted lines at t_1 and t_2 on x-axis. These lines meet the graph at points P and Q. From these points draw horizontal lines to meet y-axis at S_1 and S_2 respectively as shown in Fig.2.11.

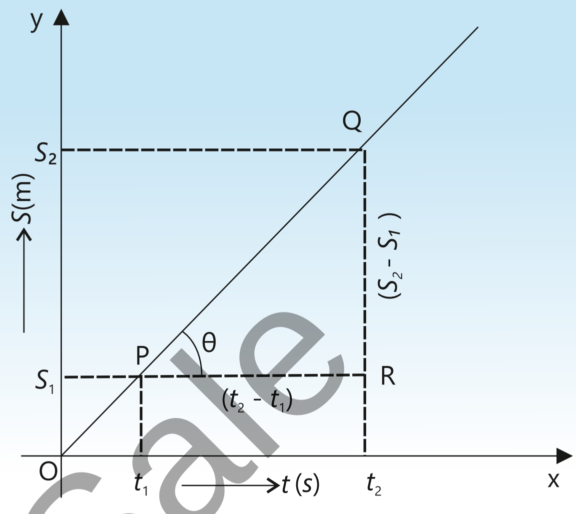


Fig. 2.11

Distance covered in this time interval is $S_2 - S_1 = S$

Time taken $t_2 - t_1 = t$

The slope or gradient of the graph is the measure of tangent θ of the triangle RPQ:

$$\text{Slope} = \frac{RQ}{PR}$$

$$\text{Slope} = \frac{S_2 - S_1}{t_2 - t_1} = \frac{S}{t}$$

From Eq. (2.1), $\frac{S}{t} = v_{av}$, the average speed during the time interval t.

Figure 2.17 shows that $\frac{S}{t} = \tan\theta$ = slope of graph line, therefore,

Gradient of the distance-Time graph is equal to the average speed of the body.

2.8 Speed-Time Graph

Suppose we can note the speed of the same car after every one second and record it in the table given below, we can draw the graph between speed v versus time t. This is called speed-time graph.

Table

Time t (s)	0	1	2	3	4	5
Speed v ($m\ s^{-1}$)	0	8	16	24	32	40

Take t along x-axis and v along y-axis. Scale can be selected as 1 s = 1 cm (x-axis)
and speed 10 m s^{-1} = 1 cm along y-axis.
Shape of the graph is shown in Fig. 2.12· It is a straight line rising upward. This shows that speed increases by the same amount after every one second. This is a motion with uniform acceleration. It is also evident from the table.

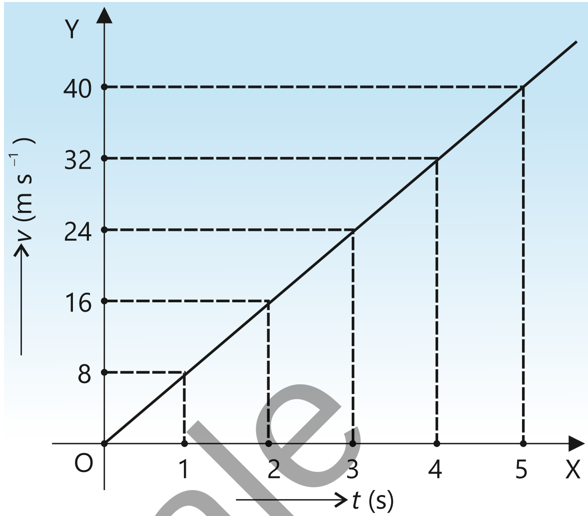


Fig. 2.12

2.9 Gradient of a Speed-Time Graph

Now consider the speed-time graph (Fig. 2.13). The speeds at times t_1 and t_2 are v_1 and v_2 respectively. The change in speed in a time interval $(t_2 - t_1)$ is $(v_2 - v_1)$. Therefore,

$$\text{Slope} = \frac{\text{Change in speed}}{\text{Total time taken}}$$

$$\text{or Slope} = \frac{(v_2 - v_1)}{(t_2 - t_1)}$$

$$\text{Slope} = \frac{\Delta v}{t}$$

But $\frac{\Delta v}{t} = a$, the average acceleration.

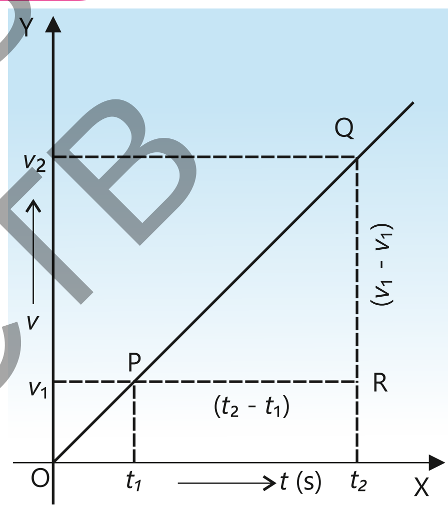


Fig. 2.13

Hence

Gradient of the speed-Time graph is equal to the average acceleration of the body.

This shows that when a car moves with constant acceleration, the velocity-time graph is a straight line which rises through same height for equal intervals of time.

2.10 Area Under Speed-Time Graph

The distance moved by an object can also be determined by using its speed-time graph. For example, figure 2.14 shows that the object is moving with constant speed v. For a time-interval t, the distance covered by the object as given by Eq. 2.1 is $v \times t$.

This distance can also be found by calculating the area under the speed-time graph. The area under the graph for time interval t is the area of rectangle of sides t and v. This area is shown shaded in Fig.2.14 and is equal to $v \times t$. Thus, area under speed-time graph up to the time axis is numerically equal to the distance covered by the object in time t.

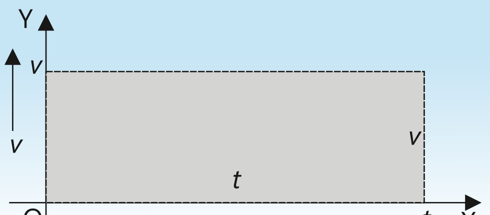


Fig. 2.14

Now consider another example shown in Fig. 2.15. Here, the speed of the object increases uniformly from 0 to v in time t. The average speed is given by

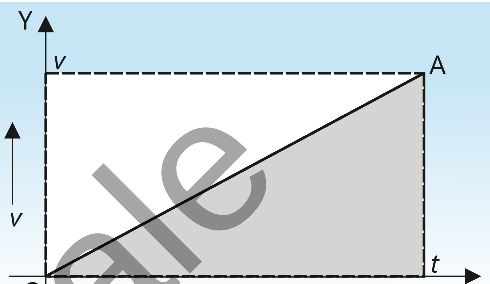


Fig. 2.15

$$v_{av} = \frac{0 + v}{2} = \frac{1}{2} v$$

Distance covered = average speed × time = $1/2\, v \times t$.

If we calculate the area under speed-time graph, it is equal to the area of the right-angled triangle shown shaded in Fig. 2.15. The base of the triangle is equal to t and the perpendicular is equal to v.

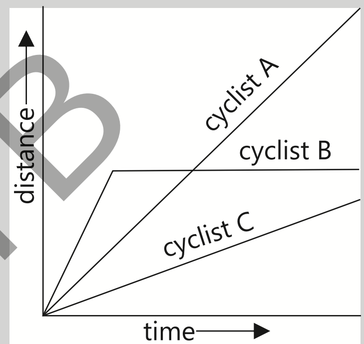
Area of a triangle = 1/2 (perpendicular × base)

= $1/2\,(v \times t)$

We see that this area is numerically equal to the distance covered by the object during the time interval t. Therefore, we can say that:

The area under the speed-time graph up to the time axis is numerically equal to the distance covered by the object.

Mini Exercise



The distance-time graph shows the motion of three cyclists.

(a) What does each line on the graph represent?

(b) Which cyclist travelled the most distance?

(c) Which cyclist travelled at the greatest speed? the lowest speed? at constant speed?

2.11 Solving Problems for Motion Under Gravity

Three equations of motion are used to solve problems for motion of bodies. If v_i is the initial velocity of the body, v_f is the final velocity, t is the time taken, S is the distance covered and a is the acceleration, then

$$v_f = v_i + at \quad \text{------------- (1)}$$

$$S = v_i t + \frac{1}{2} at^2 \quad \text{------------- (2)}$$

$$2aS = v_f^2 - v_i^2 \quad \text{------------- (3)}$$

While applying these equations, the following assumptions are made:

(i) Motion is always considered along a straight line

(ii) Only the magnitudes of vector quantities are used.

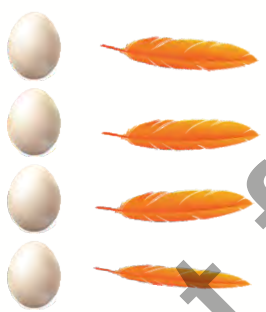
(iii) Acceleration is assumed to be uniform.

(iv) The direction of initial velocity is taken as positive. Other quantities which are in the direction of initial velocity are taken as positive. The quantities in the direction opposite to the initial velocity are taken as negative.

2.12 Free Fall Acceleration

When a body is falling freely under the action of gravity of the Earth, the acceleration acting on it is the gravitational acceleration and is denoted by g. The direction of gravitational acceleration is always downwards. Its value is 9.8 m s^{-2}, but for convenience we shall use the value of g as 10 m s^{-2}.

For Your Information!



Light and heavier objects when fall through vacuum, move side by side.

Since the freely falling bodies move vertically downwards in a straight line with uniform acceleration g, so the three equations of motion can be applied to the motion of such bodies. While applying equations of motion, the acceleration a is replaced by g. Thus, equations of motion for freely falling bodies can be written as:

$$v_f = v_i + gt \quad \text{-------------} \quad (1)$$

$$S = v_i t + \frac{1}{2} g t^2 \quad \text{-------------} \quad (2)$$

$$2gS = v_f^2 - v_i^2 \quad \text{-------------} \quad (3)$$

It should be remembered that while using these equations, the following points should be kept in mind:

(i) If a body is released from some height to fall freely, its initial velocity v_i will be taken as zero.

(ii) The gravitational acceleration g will be taken as positive in the downward direction. All other quantities will also be taken as positive in the downward direction. The quantities in the direction opposite to the acceleration will be taken as negative.

(iii) If a body is thrown vertically upward, the value of g will be negative and the final velocity will be zero at the highest point.

For Your Information!

Acceleration of free fall g is 10 m s^{-2} for all objects.

Example 2.5

An iron bob is dropped from the top of a tower. It reaches the ground in 4 seconds. Find: (a) the height of the tower (b) the velocity of the ball as it strikes the ground.

Solution

For freely falling body:

Initial velocity = v_i = 0

Acceleration = g = $10\ m\ s^{-2}$

Time = t = 4 s

Height (distance) = S = h = ?

Final velocity = v_f = ?

(a) According to second equation of motion,

$$S = v_i t + \frac{1}{2} g t^2$$

Putting the values, $h = 0 \times 4\ s + \frac{1}{2} \times 10\ m\ s^{-2} \times (4)^2\ s^2$

$h = 80\ m$

(b) From the first equation of motion, we have

$$v_f = v_i + gt$$

Putting the values, $v_f = 0 + 10\ m\ s^{-2} \times 4s = 40\ m\ s^{-1}$

EXERCISE

A Multiple Choice Questions

Tick (✓) the correct answer.

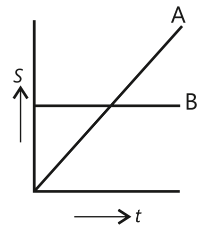
2.1 The numerical ratio of displacement to distance is:
(a) always less than one (b) always equal to one
(c) always greater than one (d) equal to or less than one

2.2 A ball is dropped from the top of a tower, the distance covered by it in the first second is:
(a) 5 m (b) 10 m (c) 50 m (d) 100 m

2.3 A body accelerates from rest to a velocity of $144\ km\ h^{-1}$ in 20 seconds. The distance covered by it is:
(a) 100 m (b) 400 m (c) 1400 m (d) 1440 m

2.4 A body is moving with constant acceleration starting from rest. It covers a distance S in 4 seconds. How much time does it take to cover one-fourth of this distance?
(a) 1 s (b) 2 s (c) 4 s (d) 16 s

2.5 The displacement time graphs of two objects A and B are shown in the figure. Point out the true statement from the following:

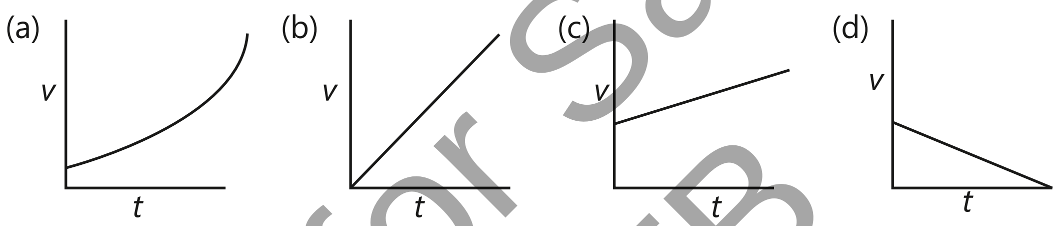


(a) The velocity of A is greater than B.
(b) The velocity of A is less than B.
(c) The velocity of A is equal to that of B.
(d) The graph gives no information in this regard.

2.6 Gradient of the speed-time graph is equal to:
(a) speed (b) velocity (c) acceleration (d) distance covered

2.7 Gradient of the distance-time graph is equal to the:
(a) speed (b) velocity (c) distance covered (d) acceleration

2.8 A car accelerates uniformly from 80.5 km h^{-1} at t = 0 to 113 km h^{-1} at t = 9 s. Which graph best describes the motion of the car?



B Short Answer Questions

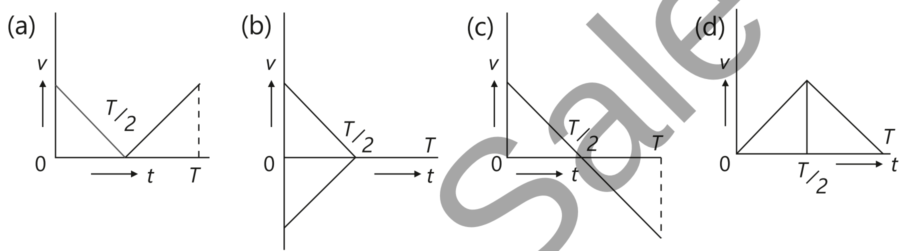
2.1 Define scalar and vector quantities.
2.2 Give 5 examples each for scalar and vector quantities.
2.3 State head-to-tail rule for addition of vectors.
2.4 What are distance- time graph and speed-time graph?
2.5 Falling objects near the Earth have the same constant acceleration. Does this imply that a heavier object will fall faster than a lighter object?
2.6 The vector quantities are sometimes written in scalar notation (not bold face). How is the direction indicated?
2.7 A body is moving with uniform speed. Will its velocity be uniform? Give reason.
2.8 Is it possible for a body to have acceleration? When moving with:
(i) constant velocity
(ii) constant speed

C Constructed Response Questions

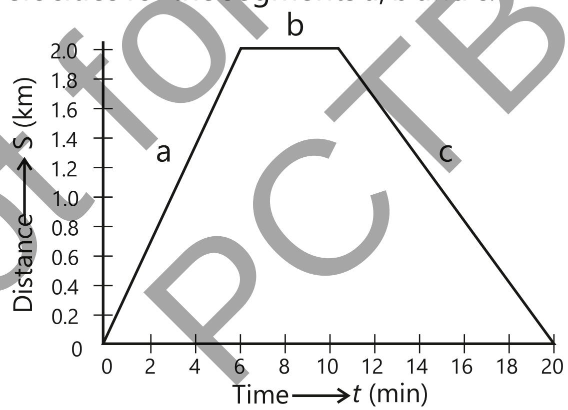
2.1 Distance and displacement may or may not be equal in magnitude. Explain this statement.

2.2 For a complete trip, average velocity was calculated. Its value came out to be positive. Is it possible that its instantaneous velocity at any time during the trip had the negative value? Give justification of your answer.

2.3 A ball is thrown vertically upward with velocity *v*. It returns to the ground in time *T*. Which of the following graphs correctly represents the motion? Explain your reasoning.



2.4 The figure given below shows the distance - time graph for the travel of a cyclist. Find the velocities for the segments a, b and c.



2.5 Is it possible that the velocity of an object is zero at an instant of time, but its acceleration is not zero? If yes, give an example of such a case.

D Comprehensive Questions

2.1 How a vector can be represented graphically? Explain.

2.2 Differentiate between:

(i) rest and motion

(ii) speed and velocity

2.3 What do gradients of distance-time graph and speed-time graph represent? Explain it by drawing diagrams.

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

2.5 How equations of motion can be applied to the bodies moving under the action of gravity?

E Numerical Problems

2.1 Draw the representative lines of the following vectors:

(a) A velocity of 400 m s^{-1} making an angle of 60° with x-axis.

(b) A force of 50 N making an angle of 120° with x-axis.

2.2 A car is moving with an average speed of 72 km h^{-1}. How much time will it take to cover a distance of 360 km? (5 h)

2.3 A truck starts from rest. It reaches a velocity of 90 km h^{-1} in 50 seconds. Find its average acceleration. (0.5 m s^{-2})

2.4 A motorcycle initially travelling at 18 km h^{-1} accelerates at constant rate of 2 m s^{-2}. How far will the motorcycle go in 10 seconds? (150 m)

2.5 A wagon is moving on the road with a velocity of 54 km h^{-1}. Brakes are applied suddenly. The wagon covers a distance of 25 m before stopping. Determine the acceleration of the wagon. (-4.5 m s^{-2})

2.6 A ball is dropped from the top of a tower. The ball reaches the ground in 5 seconds. Find the height of the tower and the velocity of the ball with which it strikes the ground. (125 m, 50 m s^{-1})

2.7 A cricket ball is hit so that it travels straight up in the air. An observer notes that it took 3 seconds to reach the highest point. What was the initial velocity of the ball? If the ball was hit 1 m above the ground, how high did it rise from the ground? (30 m s^{-1}, 46 m)

Chapter 3

Dynamics

Student Learning Outcomes

After completing this chapter, students will be able to:

- Illustrate that mass is a measure of the quantity of matter in an object
- Explain that the mass of an object resists change from its state of rest or motion (inertia)
- Describe universal gravitation and gravity. State Newton's Law of gravitation. (Include problems related to gravitation.)
- Define and calculate weight [Weight is the force exerted on an object having mass by a planet's gravity, and use $w = mg$]
- Define and calculate gravitational field strength [This includes being able to state that a gravitational field is a region in which a mass experiences a force due to gravitational attraction. Students should be able to define gravitational field strength (g) as force per unit mass use the equation gravitational field strength = weight/mass $g = w/m$ (and know that this is equivalent to the acceleration of free fall)]
- Represent the forces acting on a body using free body diagrams
- State and apply Newton's first law
- Identify the effect of force on velocity [It may change the velocity of an object by changing its direction of motion or its speed]
- Determine the resultant of two or more forces acting in the same plane.
- State and apply Newton's second law in terms of acceleration
- State and apply Newton's third law
- Explain with examples how Newton's third law describes pairs of forces of the same type acting on different objects
- Analyse the dissipative effect of friction
- Analyse the dynamics of an object reaching terminal velocity
- Differentiate qualitatively between rolling and sliding friction
- Justify methods to reduce friction.
- Define and calculate momentum
- Define and calculate impulse [Use the equation Impulse= $F\Delta t = m\Delta V$]
- Apply the principle of the conservation of momentum to solve simple problems in one dimension
- Define resultant force in terms of momentum.

In kinematics, we studied the motion of objects. If the position, velocity and acceleration were known at any time, then the position and velocity of the moving body at another time could be completely described. But one of the things left out of this discussion was the cause of acceleration produced in the body. If a stone is dropped from a height, it is accelerated downward. It is because the Earth exerts a force of gravity on the stone that pulls it down. When we drive a car or motorcycle, the engine exerts a force which produces acceleration. We will observe that whenever there is acceleration, there is always a force present to cause that acceleration. Dynamics is concerned with the forces that produce change in the motions of bodies.

3.1 Concept of Force

Fig. 3.1

A common concept of a force is a push or a pull that starts, stops or changes the magnitude and direction of velocity of a body. We come across many forces in our daily life. Some of them we apply on other bodies and some are acting on us. For example, when we open a door, we push or pull it by applying force. When we are sitting in a car, we push against the seat as the car turns round a corner.

Force transfers energy to an object. Take the example of a man who moves a wheelbarrow with its load. The man first applies force to lift it and then applies force to push it (Fig.3.1). He applies a different amount of force on each handle when turning the wheelbarrow around the corner in order to keep it from tipping over. The examples of forces acting on us are the force of gravity acting downward, the force of friction which helps us to walk on the ground and many others.

3.2 Forces in a Free- Body Diagram

External forces acting on an object may include friction, gravity, normal force, drag, tension in a string or a human force due to pushing or pulling.

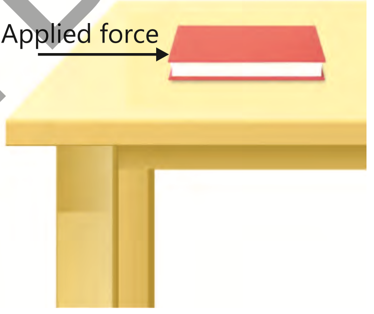


Fig. 3.2 (a)

Suppose a book is pushed over the surface of a table top as shown in Fig.3.2(a). Then how can we represent the forces acting on the body using free-body diagram?

Free-body diagrams are used to show the relative magnitudes and directions of all the forces acting on an object in a given situation. In other words, a free-body diagram is a special example of the vector diagrams.

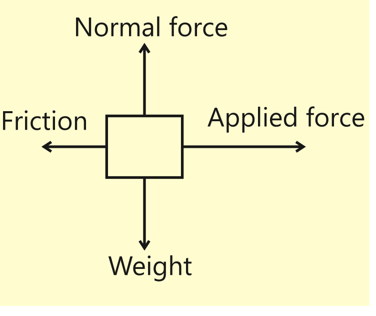


Fig. 3.2 (b)

Usually, the object is represented by a box and the force arrows are drawn outward from the centre of the box in the directions of forces as shown in Fig.3.2(b). The length of a force arrow (line) reflects the magnitude of the force and the arrow head indicates the direction in which the force acts. Each force is labelled to indicate the exact type of force.

3.3 Newton's Laws of Motion

Newton's First Law of Motion

Do You Know?

Sir Isaac Newton was born in Lincolnshire on January 4, 1643. The name of his famous book is "Principia Mathematica".

It is our common observation that a force is required to move or to stop a body. A book placed on a table remains there unless a force is applied to move it (Fig.3.3). A ball rolling on floor should continue to move with the same velocity in the absence of an applied force. But practically, we see that it is not true. The ball stops after covering some distance. In fact, an opposing force (friction) causes the ball to stop. Newton expressed such observations in his first law of motion which states that:

Fig. 3.3

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

When a fast-moving bus stops suddenly, the passengers tend to bend forward. It is because they want to continue their motion. On the other hand, when the bus starts moving quickly from rest, the passengers are pushed back against the seat. This time, the tendency of passengers is to retain their state of rest.

According to first law of motion, a bus moving on the road should continue its motion without any force exerted by the engine. But practically, we see that if the engine stops working, the bus comes to rest after covering some distance. It is because of the friction between the tyres of the bus and the road. All the bodies moving on the Earth are stopped by the force of friction. If you were in outer space and throw an object away where no force is acted upon it, the object would continue to move forever with constant velocity.

The first law of motion also provides us another definition of force which is stated as follows:

Force is an agency which changes or tends to change the state of rest or of uniform motion of a body.

In simple words, we can say that force causes acceleration.

Inertia

A net force is required to change the velocity of objects. For instance, a net force may cause a bicycle to pick up speed quickly. But when the same force is applied to a truck, any change in the motion may not be observed. We say that the truck has more inertia than a bicycle. The **mass** of an object is a measure of its inertia. The greater the mass of an object, the greater is its inertia.

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

As a result of the role of inertia in Newton's first law, this law is sometimes called as law of inertia.

A Demonstration of Property of Inertia

When the table cloth is pulled abruptly, the objects remain in their original position on the table.

Newton's Second Law of Motion

Newton's first law indicates that if no net force acts on an object, then the velocity of the object remains unchanged. The second law deals with the acceleration produced in a body when a net force acts upon it. Newton's second law can be stated as:

If a net external force acts upon a body, it accelerates the body in the direction of force. The magnitude of acceleration is directly proportional to the magnitude of force and is inversely proportional to the mass of the body.

If a net force of magnitude F acts on a body of mass m and produces an acceleration of magnitude a, then the second law can be written mathematically as:

$$a \propto F$$

and

$$a \propto \frac{1}{m}$$

So

$$a \propto \frac{F}{m}$$

or

$$a = (\text{constant})\,\frac{F}{m}$$

According to SI units, if $m = 1$ kg, $a = 1\ \text{m s}^{-2}$, $F = 1$ N, then the value of the constant will be 1. Therefore, the above equation can be written as:

$$a = 1 \times \frac{F}{m}$$

$$\text{or} \quad F = m\,a \qquad ....(3.1)$$

First law of motion provides the definition of force, i.e., a force produces an acceleration in a body. By the second law of motion ($F = ma$), we can calculate mathematically, the amount of force required to produce a certain amount of acceleration in a body of known mass. The SI unit of force is newton (N).

One newton is the force which produces an acceleration of 1 m s^{-2} in a body of mass 1 kg.

From Eq 3.1 $\qquad 1\text{ N} = 1\text{ kg m s}^{-2}$

Effect of Force on Velocity

Newton's second law also tells that a force can change the velocity of a body by producing acceleration or deceleration in it. As velocity is a vector quantity, so the change may be in its magnitude, direction or in both of them.

Newton's Third Law of Motion

Whenever there is an interaction between two bodies A and B, such that the body A exerts a force on body B, the force is known as action of A on B. In response to this action, the body B exerts a force on the body A. This force is known as reaction of B on A. For example, when we press a spring, the force exerted by our hand on the spring is action. Our hand also experiences a force exerted by the spring. This is the force of reaction (Fig.3.4). Newton expressed these action and reaction forces in his third law of motion. It is stated as:

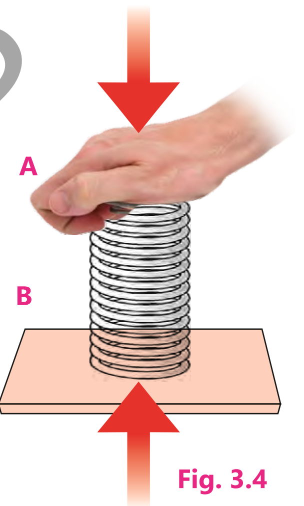


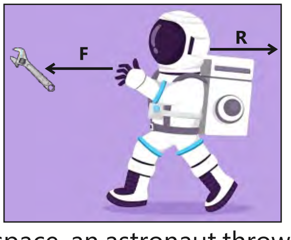
Fig. 3.4

For every action, there is always an equal and opposite reaction.

Since, action and reaction do not act on the same body but they act on two different bodies, so they can never balance each other. Thus, Newton's third law can also be expressed as follows:

If one body exerts a force on a second body, the second body also exerts an equal and opposite force on the first body.

Do You Know?



In space, an astronaut throws a wrench, as a reaction he moves in opposite direction.

Forces Act in Pairs

We have studied that forces act in pairs when two objects interact, i.e., action and reaction forces. We often notice a force that seems to make something happen but usually we do not notice the other force involved. Here are some examples of pairs of forces involved in accordance with Newton's third law of motion.

(i) Consider a block lying on a table as shown in Fig. 3.5.

The force acting downward on the block is the weight. The block exerts a downward force on the table equal to its weight **w**. The table also exerts a reaction force $\mathbf{F_n}$ on the block. The two forces on the block balance each other and the block remains at rest.

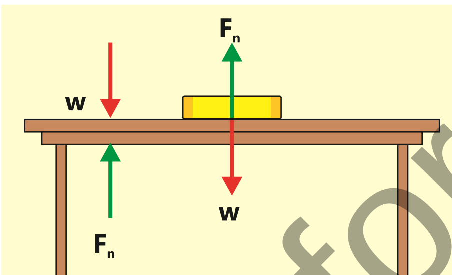


Fig. 3.5

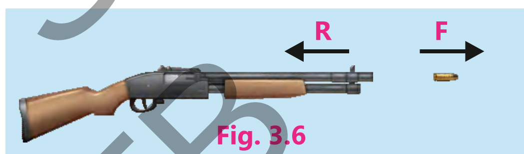


Fig. 3.6

(ii) When a bullet is fired from a gun, the bullet moves in the forward direction with a force **F**. This is the force of action. The gun recoils in the backward direction with a reaction force **R** (Fig. 3.6).

Mini Exercise

Look at the photographs below. Identify the pairs of forces acting in each photograph.

3.4 Mass and Weight

Commonly, we consider mass and weight as the same quantities but scientifically, mass and weight are two different quantities. When we say that the weight of this object is 5 kg, it is not true. In fact, 5 kg is the mass of the object. The simplest definition of mass is that it is a measure of the quantity of matter in a body. Scientifically, mass of a body can be defined as:

The characteristic of a body which determines the magnitude of acceleration produced when a certain force acts upon it is known as mass of the body.

Mass is a scalar quantity. It remains the same everywhere. Practically, mass is measured by an ordinary balance. The SI unit of mass is kilogram (kg).

Weight is a gravitational force acting on the object. It is a vector quantity directed downward, towards the centre of the Earth.

The weight of an object is equal to the force with which the Earth attracts the body towards its centre.

Gravitational Force

An apple falling down from a tree is one of the best examples of gravitational force (Fig. 3.7). When we throw an object upward, it is the gravitational force of the Earth that brings it back to the Earth. In fact, the gravitational force is an attractive force that exists among all bodies which have mass. It is a long-range force given by Newton's law of gravitation:

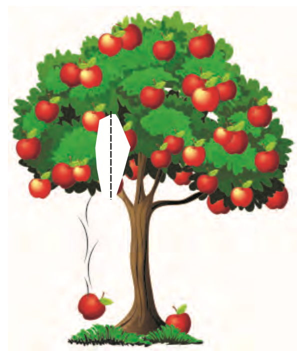


Fig. 3.7

$$F = G\frac{m_1 m_2}{r^2}$$

where m_1 and m_2 are two masses distant r apart and G is constant of gravitation. Its value is 6.67×10^{-11} N m^2 kg^{-2}. The Sun's gravitational force keeps the Earth and all other planets of our solar system in fixed orbits. Similarly, the gravitational force of the Earth keeps the moon in its orbit. It also keeps the atmosphere and oceans fixed to the surface of the Earth. Even an object resting on a surface exerts a downward force called its weight due to attractive force of the Earth also known as gravity.

Gravitational Field

The gravitational field is a space around a mass in which another mass experiences a force due to gravitational attraction. The gravitational field strength is defined as the gravitational force acting on unit mass. Thus, mass *m* on the surface of the Earth exerts a force known as its weight **w** given by **w** = *m* **g**, where **g** is the gravitational field strength. Its value is 10 N kg^{-1}.

As the value of **g** varies from place to place and also with altitude, therefore, the value of weight does not remain the same everywhere.

It varies from place to place according to variation in **g**. Though an object's weight may vary from one place to another, but at any particular location, its weight is proportional to its mass. Thus, we can conveniently compare the masses of two objects at a given location by comparing their weights. The weight cannot be measured by an ordinary balance. A spring balance can be used to measure the weight. The SI unit of weight is newton (N).

Example 3.1

A force of 7500 N is applied to move a truck of mass 3000 kg. Find the acceleration produced in the truck. How long will it take to accelerate the truck from 36 km h^{-1} to 72 km h^{-1} speed?

Solution

Mass of truck $= m = 3000$ kg

Force applied $= F = 7500$ N

Acceleration $= a = ?$

Initial speed $= v_i = 36$ km h^{-1}

$$= \frac{36 \times 1000 \text{ m}}{60 \times 60 \text{ s}} = 10 \text{ m s}^{-1}$$

Final speed $= v_f = 72$ km h^{-1} $= \dfrac{72 \times 1000 \text{ m}}{60 \times 60 \text{ s}} = 20 \text{ m s}^{-1}$

Time $= t = ?$

By Newton's second law, $F = ma$

or $a = \dfrac{F}{m}$

Putting the values, $a = \dfrac{7500 \text{ N}}{3000 \text{ kg}} = 2.5 \text{ m s}^{-2}$

Now, using first equation of motion,

$$v_f = v_i + at$$

or $$t = \frac{v_f - v_i}{a}$$

Putting the values, $$t = \frac{20\ \text{m s}^{-1} - 10\ \text{m s}^{-1}}{2.5\ \text{m s}^{-2}} = 4\ \text{s}$$

3.5 Friction

When a cricket ball is hit by the bat, it moves on the ground with a reasonably large velocity. According to Newton's first law of motion, it should continue to move with constant velocity. But, practically, we observe that it eventually stops after covering some distance. Does any force act on the ball in opposite direction that stops the ball? Yes, it is the force of friction between the ball and the ground that opposes the motion of the ball.

Dissipative Effect of Friction

Friction is a dissipative force due to which the energy is wasted in doing work to overcome against friction. The lost energy appears in the form of heat.

A very common example of energy dissipation is the rubbing of hands (Fig.3.8). When we rub our hands, heat is produced due to friction and our hands become warm. Similarly, the temperature of machines rises due to friction between its moving parts that can cause many problems. The tyres of vehicles also wear out after becoming too hot due to friction between tyres and road.

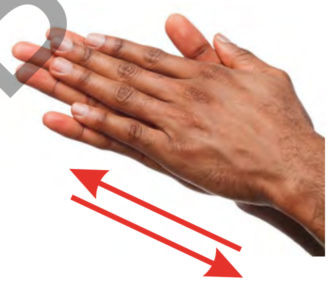


Fig. 3.8 Rubbing hands

Shooting of stars seen in the sky at night also happen due to friction of air. These are actually asteroids that enter the Earth's atmosphere. As they are moving, air resistance causes generation of heat. Their temperature becomes so high that they start burning and ultimately disintegrate.

Do You Know?

On a wet road, the water does not form wet layer between the tyre surface and the road surface due to the spaces in the tread pattern on the tyre. This reduces the chances of skidding of vechicles on wet roads.

Sliding Friction

The friction between two solid surfaces is called sliding friction which can be divided into two categories.

1. Static friction		2. Kinetic friction

Static Friction

Let us consider the motion of a block on a horizontal surface. The arrangement is shown in Fig. 3.9. When a weight is put in the pan, a force **F** = **T** equal to the sum of this weight and weight of the pan acts on the block. This force tends to pull the block. At the same time an opposing force appears that does not let the block move. This opposing force is the static friction $\mathbf{F}_S$.

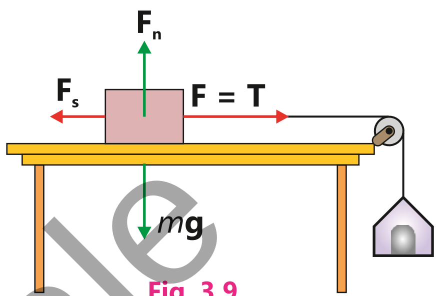


Fig. 3.9

Kinetic Friction

If we go on adding more weights in the pan one by one in small steps, a stage will come when the block starts sliding on the horizontal surface. This is the limit of static friction that is equal to the total weights including pan. When the block is sliding, friction still exists. It is known as kinetic friction.

For Your Information!

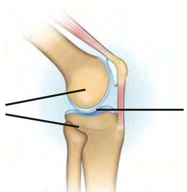
Some frogs can cling to a vertical surface, such as this leaf, because of the static friction between their feet and the surface.

Do You Know?

When a shuttle re-enters the Earth's atmosphere, the friction caused by the atmosphere raises the surface temperature of the shuttle to over 950°C.

Do You Know?

Friction in human joints is very low because our bodies contain a natural lubricating system. Consequently, though our bones rub against each other at the points as we move, yet bones do not normally wear out, even after many years of use.



Knee joint

Rolling Friction

The static and kinetic friction which we have studied so far is the sliding friction. There is another type of friction which is called rolling friction. When an object rolls over a surface, the friction produced is called rolling friction. The idea of rolling friction is associated with the concept of wheel. In our everyday life, we observe that a body with wheels faces less friction as compared to a body of the same size without wheels.

For Your Information!

Practically, the contact point is not perfectly circular; it becomes flat under pressure as shown in figure. This flat portion of the wheel has the tendency to slide against the surface and does produce a frictional force.

Ball bearings also play the same role as is played by the wheels. Many machines in industry are designed with ball bearings so that the moving parts roll on the ball bearing and friction is greatly reduced. The rolling friction is about one hundred times smaller than the sliding friction.

The reason for the rolling friction to be less than the sliding friction is that there is no relative motion between the wheel and the surface over which it rolls. The wheel touches the surface only at a point. It does not slide.

For Your Information!

A hovercraft is a kind of ship that can move over the surface of water and ground both. Air is ejected underneath by powerful fans forming a cushion of air. The hovercraft moves over the cushion of air which offers very small resistance.

Methods to Reduce Friction

The following methods are used to reduce friction:

(i) The parts which slide against each other are highly polished.

(ii) Since, the friction of liquids is less than that of solid surfaces, therefore, oil or grease is applied between the moving parts of the macl

(iii) As rolling friction is much less than the sliding friction, so sliding friction is converted into rolling friction by the use of ball bearings (Fig. 3.10) in the machines and wheels under the heavy objects.

Fig. 3.10

(iv) Frictional force does not act only among solids, high speed vehicles, aeroplanes and ships also face friction while moving through air or water. If the front of a vehicle is flat, it faces more resistance by air or water. Therefore, the bodies moving through air or water are streamlined to minimize air or water friction. In this case, the air passes smoothly over the slanting surface of vehicle. This type of flow of air is known as streamline flow. A streamline flow over the car is shown in Fig. 3.11. The vehicles designed pointed from the front are said to be streamlined.

Fig. 3.11 Streamline air flow over a speedy car

Terminal Velocity

When an object falls freely, it is accelerated by an amount g = 10 m s^{-2}. But practically the acceleration may be different. Air resistance plays an important role in determining how fast an object accelerates when it falls.

If we drop a cricket ball and a piece of Styrofoam of the same weight from a certain height, they will hit the ground at the same time only if there were no air resistance. Both would fall with the same acceleration g = 10 m s^{-2}. Practically, the ball in air, would drop faster. The Styrofoam having larger surface would face greater opposing force of the air and thus moves slowly.

Experiments have been made in this respect and it was found that the faster an object falls the more air resistance will be exerted on it. A speed is finally attained at which the upward force of air resistance balances the downward force of gravity. When this happens, the object stops accelerating. It keeps falling at a constant velocity. This constant velocity achieved by an object is called its terminal velocity. Even a heavy object like a meteorite does not gain an infinite velocity as it falls to the Earth.

This principle applies to paratroopers. Air resistance acting against the large surface area of a parachute allows for descent at a safer velocity (Fig.3.12).

Fig. 3.12
A paratrooper falling with terminal velocity

3.6 Momentum and Impulse

Suppose that a bicycle rider and a heavy truck are moving with the same speed, which one can be stopped easily, depends on the quantity of motion of the moving body. It is our common observation that quantity of motion in a moving body depends on its mass and velocity. Greater is the mass, the greater will be the quantity of motion. Similarly, greater is the velocity, the greater will be quantity of motion. This quantity of motion is called momentum and denoted by p. It is defined as:

The momentum of a moving body is the product of its mass and velocity.

Therefore, $\mathbf{p} = m \times \mathbf{v}$ .... (3.2)

Like velocity momentum is also a vector quantity. The SI unit momentum is ($kg\ m\ s^{-1}$). It can also be written as (N s).

When a ball is hit by a bat, the force is exerted on the ball for a very short interval of time. In such cases, it is very difficult to calculate the exact magnitude of the force. However, initial velocity $\mathbf{v}_i$ of the ball and final velocity $\mathbf{v}_f$ after collision can be found easily.

During a time interval Δt, the average acceleration **a** is given by

$$\mathbf{a} = \frac{\Delta \mathbf{v}}{\Delta t} = \frac{\mathbf{v}_f - \mathbf{v}_i}{\Delta t} \quad \text{......................................} \quad (3.3)$$

According to Newton's second law of motion, the value of average force acting during the interval Δt will be:

$$\mathbf{F} = m\mathbf{a} = m\left(\frac{\Delta \mathbf{v}}{\Delta t}\right)$$

or

$$\mathbf{F} \times \Delta t = m(\Delta \mathbf{v}) = m(\mathbf{v}_f - \mathbf{v}_i) \quad \text{......................................} \quad (3.4)$$

Equation (3.4) shows that **F** and Δt cannot be exactly known but their product which is equal to the change of momentum ($m\mathbf{v}_f - m\mathbf{v}_i$) can be calculated. For such cases, the product $\mathbf{F} \times \Delta t$ is called as **Impulse** of the force.

When a large force **F** acts on an object for a short interval of time, the impulse of the force is defined as the total change in momentum of the object.

Dividing both sides of Eq.3.4 by Δt, we have

$$\mathbf{F} = \frac{m(\Delta \mathbf{v})}{\Delta t} \quad \text{................}(3.5)$$

where $m(\Delta \mathbf{v})$ is the change in momentum $\Delta \mathbf{p}$. Equation (3.5) gives the value of force in terms of momentum i.e., force acting on an object is equal to the change in momentum of the object per unit time.

$$\mathbf{F} = \frac{\Delta \mathbf{p}}{\Delta t} \quad \text{................}(3.6)$$

Equation (3.6) suggests to define Newton’s second law of motion in terms of momentum i.e.,

The rate of change of momentum of a body is equal to the force acting on it.

The direction of change in momentum is that of the force.

Do you know?

A cricketer draws his hands back to reduce the impact of the ball by increasing the time.

For Your Information!

The arrow penetrates into the apple, and in response, the momentum of the apple changes. Conversely, the apple applies an opposing force to the arrow, and in response, the momentum of the arrow changes.

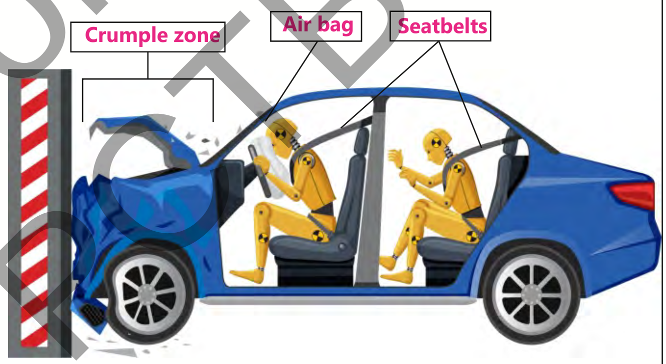
Packing of Fragile Objects

Fragile objects such as glassware may break easily due to jerks or by the direct impact with hard objects during their transportation.

To protect them soft, packing materials are used for these objects. These materials reduce the effect of quick change in momentum. Consequently, the force acting on the fragile objects is greatly reduced. Special materials like Styrofoam, corrugated cardboard sheets, bubble wrap are used for the packing of such objects.

Crumple Zones

A crumple zone of an automobile is a structural feature designed to compress during an accident to absorb deformation energy from the impact. Typically, crumple zones are located in front and behind of the main body of the vehicle.



Crumple zones work by managing crash energy absorbing within the outer parts of the vehicle, rather than being directly transmitted to the occupants. This is achieved by controlled weakling of outer parts (plastic bumpers, etc.) of the vehicle, while strengthening of the passenger cabin.

Example 3.2

A cricket ball of mass 160 g is hit by a bat. The ball leaves the bat with a velocity of 52 m s^{-1}. If the ball strikes the bat with a velocity of -28 m s^{-1} (opposite direction) before hitting, find the average force exerted on the ball by the bat. The ball remains in contact with the bat for 4×10^{-3} s.

Solution

Mass of ball $m = 160\text{ g} = 0.16\text{ kg}$

Initial velocity $v_i = -28\text{ m s}^{-1}$

Final velocity $v_f = 52\text{ m s}^{-1}$

Time of contact $t = 4 \times 10^{-3}\text{ s}$

Average force $F = ?$

From Eq. (3.6), we have

$$F = \frac{m(v_f - v_i)}{t}$$

Putting the values,

$$F = \frac{0.16\text{ kg }[52\text{ m s}^{-1} - (-28\text{ m s}^{-1})]}{4 \times 10^{-3}\text{ s}}$$

or $F = 3200\text{ N}$

3.7 Principle of Conservation of Momentum

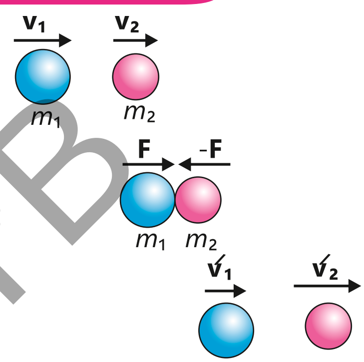


Fig. 3.13

The collection of objects is known as a 'system'. If no external force acts on any object of the system, it is known as isolated system. Consider a system of two balls of masses m_1 and m_2. Suppose that the balls are moving with velocities $\mathbf{v}_1$ and $\mathbf{v}_2$ along a straight line in the same direction. If $\mathbf{v}_1 > \mathbf{v}_2$, the balls will collide as shown in Fig. 3.13. If their velocities become $\acute{\mathbf{v}}_1$, and $\acute{\mathbf{v}}_2$ respectively after collision, then

Total momentum of the system before collision $= m_1\mathbf{v}_1 + m_2\mathbf{v}_2$

Total momentum of the system after collision $= m_1\acute{\mathbf{v}}_1 + m_2\acute{\mathbf{v}}_2$

The principle of conservation of momentum states that:

> If no external force acts on an isolated system, the final total momentum of the system is equal to the initial total momentum of the system.

This means that:

Total momentum of the system before collision = Total momentum of the system after collision

or $m_1\mathbf{v}_1 + m_2\mathbf{v}_2 = m_1\acute{\mathbf{v}}_1 + m_2\acute{\mathbf{v}}_2$

To explain this principle, let us consider the collision of two identical balls in which the second ball is at rest.

When there is collision of two balls, there is a transfer of momentum from one ball to another. The ball at rest gains momentum and starts moving whereas the striking ball slows down. If the balls are identical, we will observe that there is a total transfer of momentum. The striking ball comes to rest and the other ball starts moving with the same speed (Fig. 3.14). It means that second ball gains momentum equal to that lost by the first one. If the first ball stops after collision, the second ball moves with the momentum of the first ball. This suggests that the total momentum of the two balls after collision remains the same as total momentum before collision.

The principle of conservation of momentum is applicable not only to macro-objects but also for micro-objects like atoms and molecules.

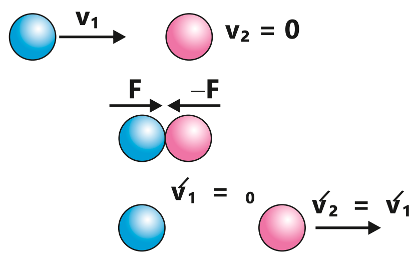


Fig. 3.14

Seatbelts

When a moving car stops suddenly, the passengers move forward toward the windshield. Seatbelts prevent the passengers from moving. Thus, chances of hitting the passengers against the windshield or steering wheel are reduced.

Example 3.3

A ball of mass 3 kg moving with a velocity of 5 m s^{-1} collides with a stationary ball of mass 2 kg and then both of them move together. If the friction is negligible, find out the velocity with which both the balls will move after collision.

Solution

Mass of first ball $= m_1 = 3$ kg

Velocity of first ball before collision $= v_1 = 5$ m s^{-1}

Mass of second ball $= m_2 = 2$ kg

Velocity of second ball before collision $= v_2 = 0$

Velocity of both the balls after collision $= v = ?$

Total mass of balls after collision $= m_1 + m_2$

By law of conversion of momentum,

Total momentum before collision = Total momentum after collision

or $$m_1 v_1 + m_2 v_2 = (m_1 + m_2) v$$

Putting the values,

$$3\text{ kg} \times 5\text{ m s}^{-1} + 0 = (3\text{ kg} + 2\text{ kg})\, v$$

$$15\text{ kg m s}^{-1} = 5\text{ kg} \times v$$

$$v = 3\text{ m s}^{-1}$$

EXERCISE

A Multiple Choice Questions

Tick (✓) the correct answer.

3.1 When we kick a stone, we get hurt. This is due to:
(a) inertia (b) velocity (c) momentum (d) reaction

3.2 An object will continue its motion with constant acceleration until:
(a) the resultant force on it begins to decrease.
(b) the resultant force on it is zero.
(c) the resultant force on it begins to increase.
(d) the resultant force is at right angle to its tangential velocity.

3.3 A ball with initial momentum p hits a solid wall and bounces back with the same velocity. Its momentum p' after collision will be:
(a) $p' = p$ (b) $p' = -p$ (c) $p' = 2p$ (d) $p' = -2p$

3.4 A particle of mass m moving with a velocity v collides with another particle of the same mass at rest. The velocity of the first particle after collision is:
(a) v (b) $-v$ (c) 0 (d) $-1/2$

3.5 Conservation of linear momentum is equivalent to:
(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

3.6 A large force acts on an object for a very short interval of time. In this case, it is easy to determine:
(a) magnitude of force (b) time interval
(c) product of force and time (d) none of these

3.7 A lubricant is usually introduced between two surfaces to decrease friction. The lubricant:
(a) decreases temperature (b) acts as ball bearings
(c) prevents direct contact of the surfaces (d) provides rolling friction

B Short Answer Questions

3.1 What kind of changes in motion may be produced by a force?

3.2 An object moves with constant velocity in free space. How long will the object continue to move with this velocity?

3.3 Define impulse of force.

3.4 When sitting in a car which suddenly accelerates from rest, you are pushed back into the seat, why?

3.5 The force expressed in Newton's second law is a net force. Why is it so?

3.6 How can you show that rolling friction is lesser than the sliding friction?

3.7 Define terminal velocity of an object.

3.8 An astronaut walking in space wants to return to his spaceship by firing a hand rocket. In what direction does he fire the rocket?

C Constructed Response Questions

3.1 Inflatable airbags are installed in the vehicles as safety equipment. In terms of momentum, what is the advantage of airbags over seatbelts?

3.2 When a cricket ball hits high, a fielder tries to catch it. While holding the ball he/she draws hands backward. Why?

3.3 When someone jumps from a small boat onto the river bank, why does the jumper often fall into the water? Explain.

3.4 Imagine that if friction vanishes suddenly from everything, then what could be the scenario of daily life activities?

D Comprehensive Questions

3.1 Describe Newton's laws of motion.

3.2 Define momentum and express Newton's 2nd law of motion in terms of change in momentum.

3.3 State and explain the principle of conservation of momentum.

3.4 Describe the motion of a block on a table taking into account the friction between the two surfaces. What is the static friction and kinetic friction?

3.5 Explain the effect of friction on the motion of vehicles in context of tyre surface and braking force.

E Numerical Problems

3.1 A 10 kg block is placed on a smooth horizontal surface. A horizontal force of 5 N is applied to the block. Find:

(a) the acceleration produced in the block.

(b) the velocity of block after 5 seconds. ($0.5\ m\ s^{-2}$, $2.5\ m\ s^{-1}$)

3.2 The mass of a person is 80 kg. What will be his weight on the Earth? What will be his weight on the Moon? The value of acceleration due to gravity of Moon is $1.6\ m\ s^{-2}$. (800 N, 128 N)

3.3 What force is required to increase the velocity of 800 kg car from $10\ m\ s^{-1}$ to $30\ m\ s^{-1}$ in 10 seconds? (1600 N)

3.4 A 5 g bullet is fired by a gun. The bullet moves with a velocity of $300\ m\ s^{-1}$. If the mass of the gun is 10 kg, find the recoil speed of the gun. ($-0.15\ m\ s^{-1}$)

3.5 An astronaut weighs 70 kg. He throws a wrench of mass 300 g at a speed of $3.5\ m\ s^{-1}$. Determine:

(a) the speed of astronaut as he recoils away from the wrench.

(b) the distance covered by the astronaut in 30 minutes.

($-1.5 \times 10^{-2}\ m\ s^{-1}$, 27 m)

3.6 A cyclist weighing 55 kg rides a bicycle of mass 5 kg. He starts from rest and applies a force of 90 N for 8 seconds. Then he continues at a constant speed for another 8 seconds. Calculate the total distance travelled by the cyclist.

(144 m)

3.7 A ball of mass 0.4 kg is dropped on the floor from a height of 1.8 m. The ball rebounds straight upward to a height of 0.8 m. What is the magnitude and direction of the impulse applied to the ball by the floor?

(4 N s, upward)

3.8 Two balls of masses 0.2 kg and 0.4 kg are moving towards each other with velocities $20\ m\ s^{-1}$ and $5\ m\ s^{-1}$ respectively. After collision, the velocity of 0.2 kg ball becomes $6\ m\ s^{-1}$. What will be the velocity of 0.4 kg ball?

($2\ m\ s^{-1}$)

Chapter 4

Turning Effects of Force

Student Learning Outcomes

After completing this chapter, students will be able to:

- Differentiate between like and unlike parallel forces.
- Analyse problems involving turning effects of forces [Student should know that moment of a force = force × perpendicular distance from the pivot and be able to use this in simple problems and give examples and applications of turning effects in real life]
- State what is meant by centre of mass and centre of gravity.
- Describe how to determine the position of the centre of gravity of a plane lamina using a plumb line
- Describe and identify states of equilibrium. [This includes the types, conditions and states of equilibrium and identifying their examples from daily life.]
- Analyse, qualitatively, the effect of the position of the centre of gravity on the stability of simple objects
- Propose how the stability of an object can be improved [by lowering the centre of mass and increasing the base area of the object]
- Illustrate the applications of stability physics in real life [Such as this concept is central to engineering technology such as balancing toys and racing cars
- Predict qualitatively the motion of rotating bodies [Describe qualitatively that, analogous to Newton's 1st law for transnational motion (, an object that is rotating will continue to do so at the same rate unless acted upon by a resultant moment (in which case it would begin to accelerate or decelerate its rotational motion)]
- Describe qualitatively motion in a circular path due to a centripetal force. (Use of the formula $F_c = \frac{mv^2}{r}$)
- Identify the sources of centripetal force in real life examples [e.g., tension in a string for a stone being swirled around, gravity for the Moon orbiting the Earth]

As we know, a force is a vector quantity, so it acts in a particular direction. We observe various effects of forces. Some forces produce acceleration or decelerating in a body, some tend to turn it around a point and some forces balance each other acting in opposite directions.

All those forces which act parallel to one another are known as parallel forces. The points of application of such forces may be different.

4.1 Like and Unlike Parallel Forces

If the parallel forces are acting in the same direction, then they are called like parallel forces and if their directions are opposite to one another, they are called unlike parallel forces. Three forces $\mathbf{F_1}$, $\mathbf{F_2}$ and $\mathbf{F_3}$ are shown in Fig. 4.1 acting on a rigid body at different points. Here, the forces $\mathbf{F_1}$ and $\mathbf{F_2}$ are like parallel forces but $\mathbf{F_2}$ and $\mathbf{F_3}$ are unlike parallel forces.

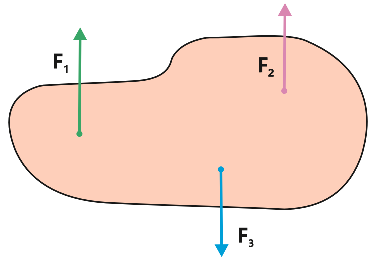


Fig. 4.1

4.2 Addition of Forces

In chapter 2, we have learnt about vectors and their representation. Remember that the resultant is the same for any order of addition of vectors. As forces are vectors, so forces can also be added by head-to-tail rule.

To determine the resultant of two or more forces acting in a plane, the following example will explain its method.

Example 4.1

Let us add three force vectors $\mathbf{F_1}$, $\mathbf{F_2}$ and $\mathbf{F_3}$ having magnitudes of 200 N, 300 N and 250 N acting at angles of 30°, 45°, 60° with *x*-axis. By selecting a suitable scale 100 N = 1 cm, we can draw the force vectors as shown in Fig. 4.2(a).

To add these vectors, we apply head-to-tail rule as shown in Fig. 4.2(b).

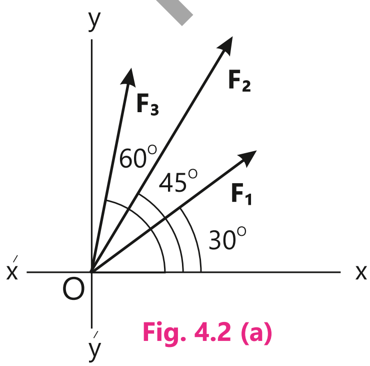


Fig. 4.2 (a)

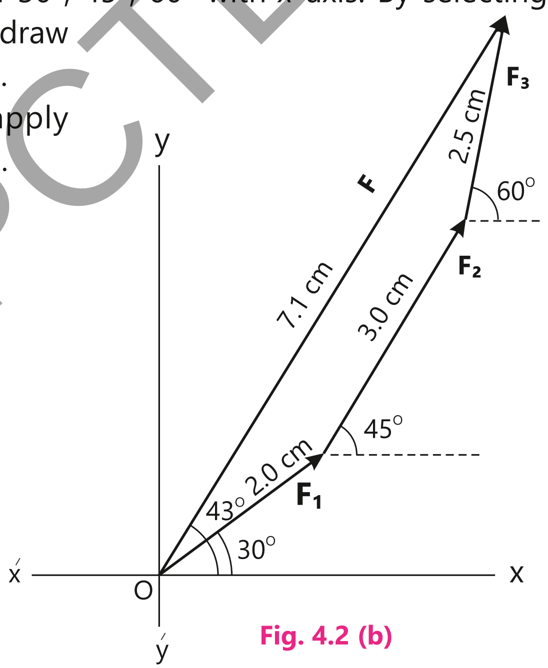


Fig. 4.2 (b)

Measured length of resultant force is 7.1 cm. According to selected scale, magnitude of the resultant force **F** is 710 N and direction is at an angle 43° with *x*-axis.

4.3 Turning Effect of a Force

We have learnt so far that a net force affects the liner motion of an object by causing it to accelerate. Since rigid objects can also rotate, so we need to extend our concept to the turning effect of a force. When we open or close a door, we apply force. This force rotates the door about its hinge. This is called turning effect of force. Similarly, we use turning effect of force when we open or close a water tap. Let us define some terms used in the study of turning effect of a force.

If the distance between two points of the body remains the same under the action of a force, it is called a **rigid body**.

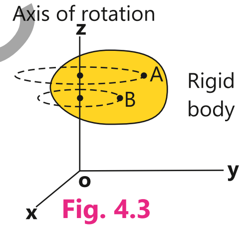
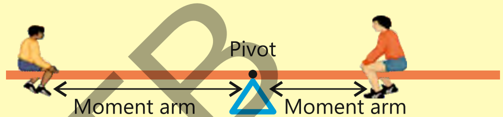


Fig. 4.3

During rotation, all the particles of the rigid body rotate along fixed circles as shown in Fig. 4.3. The straight line joining the centres of these circles is called **the axis of rotation**. In this case, it is OZ. To observe the turning effect of a force, let us perform an activity.

Activity 4.1

Take your class to play ground where a see-saw is available. Let a lighter child sits on the left side and the heavier one on the right side of the see-saw. The distances of both the children from the pivot should be equal. The force exerted by each child is equal to his weight acting downward. Does the heavier child move down? Yes, because he is exerting larger force. Now move the heavier child nearer to the pivot and the lighter child away from the pivot as shown in the figure. Ask the students what do they observe?



You will see that the see-saw tilts to the opposite direction and the lighter child moves down. This shows that the turning effect of a force does not depend only on its magnitude but also on the location where it acts. Therefore, we can say that the greater the force, the greater is its turning effect. Moreover, the larger the perpendicular distance of the force from the axis of rotation, the greater is its turning effect.

The line along which the force acts is called the line of action of the force.

The perpendicular distance of the line of action of a force from the axis of rotation is known as moment arm of the force or simply moment arm.

The moment arms of both the children are shown in the figure of activity 4.1. There are many other examples to observe the turning or rotational effect of a force. It is harder to open a door by pushing it at a point closer to the hinge as compared to push it at the handle (Fig. 4.4). That is why, door or window handles are always installed at larger distances from hinges to produce larger moment of force by applying less force. This makes the doors be opened or closed more easier. Similarly, it requires greater force to open a nut by a spanner if you hold it closer such as point A than point B (Fig. 4.5).

Fig. 4.4

Fig. 4.5

Moment of Force

The turning effect of a force is measured by a quantity known as moment of force or torque.

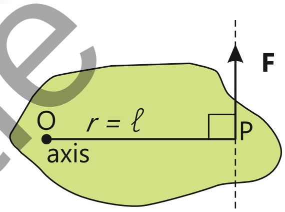


Fig. 4.6

Moment of a force or torque is defined as the product of the force and the moment arm.

The magnitude of torque is given by

$$\tau = F \times \ell \qquad ....(4.1)$$

Where τ (tau) is the torque and ℓ is the moment arm. In Fig. 4.6, the line of action of a force **F** is perpendicular to r, therefore, moment arm $\ell = r$. Remember that the torque of a force is zero when the line of action of a force passes through the axis of rotation, because its moment arm becomes zero. The torque is positive if the force tends to produce an anticlockwise rotation about the axis, and it is taken as negative if the force tends to produce a clockwise rotation. The SI unit of torque is newton metre (N m).

Do You Know?

Moment of force is applicable in the working of bottle opener. A small force applied at longer moment arm produces more torque while opening a bottle.

In many cases, the line joining the axis of rotation and point P where the force **F** acts, is not perpendicular to the force **F**. Therefore, OP will not be the moment arm for **F**. In such cases, we have to find a component of force **F** perpendiculars to OP = ℓ (Fig. 4.7), or we can find r the component of ℓ that is perpendicular to the (line of action) force **F** (Fig. 4.8).

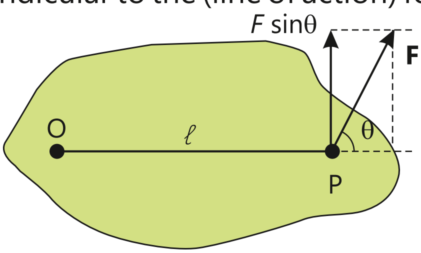


Fig. 4.7

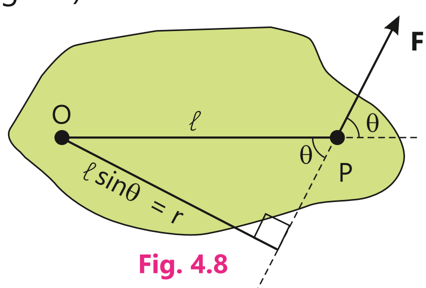


Fig. 4.8

For this, we need to know the method of finding rectangular components of a force or any vector. This is also called as resolution of Forces.

Couple

A couple is a special type of torque. We observe at many situations in our daily life, when two equal and opposite parallel forces produce torque. For example, while opening or closing a water tap, turning key in the lock, opening the lid of a jar and turning steering wheel of a motor car, we apply a pair of equal forces in opposite directions. The torque produced in this way in known as couple.

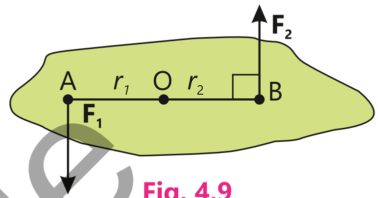


Fig. 4.9

When two equal and opposite parallel forces act at two different points of the same body, they form a couple.

Steering wheel of vehicles

While turning a vehicle, a couple is applied on the steering wheel. It is interesting to know that now-a-days, steering wheels of smaller diameter are installed in vehicles. The reason is that, most of the vehicles are provided with power steering in which a pump pushes hydraulic fluid to reduce the force needed to turn the wheels, resulting in effortless steering.

Example 4.2

A spanner 25 cm long is used to open a nut. If a force of 400 N is applied at the end of a spanner shown in Fig. 4.10, what is the torque acting on the nut?

Solution

Length of Spanner ℓ = 25 cm = 0.25 m

Force = $F = 400$ N

Torque $\tau = ?$

From Eq. (4.1), $\tau = F \times \ell$

Putting the values, $\tau = 400 \text{ N} \times 0.25 \text{ m} = 100 \text{ N m}$

Fig. 4.10

4.4 Resolution of Vectors

By head-to-tail rule, two or more vectors can be added to give a resultant vector. Its reverse process is also possible, i.e., a given vector can be divided into two or more parts. These parts are called as components of the given vector. If these components are added up, their resultant is equal to the given vector. To divide a force into its components is known as **resolution of a force**.

Usually, a force is resolved into two components which are perpendicular to each other. These are called its perpendicular or rectangular components of the force.

Let us resolve a force **F** into its perpendicular components. A force **F** acting on a body at an angle θ with x-axis is shown in Fig. 4.11(a). Imagine a beam of light is placed above the vector **F**. As the light falls perpendicularly to the x-axis, it will cast a shadow OA of vector **F** onto x-axis. We call this shadow as x-component of vector **F**. In the same way, if light is thrown perpendicular to y-axis, the shadow OB of vector **F** on y-axis is the y-component of **F**.

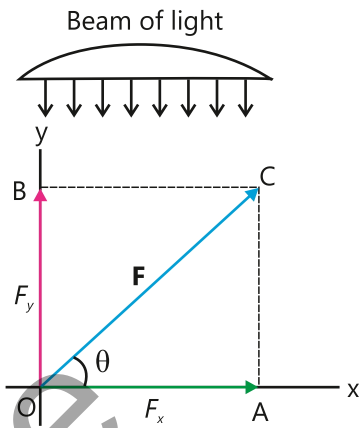


Fig. 4.11(a)

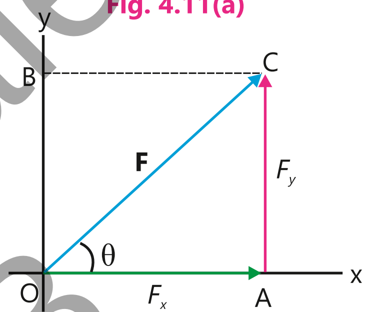


Fig. 4.11(b)

> A component of a vector is its effective value in a given direction.

The x and y components can be practically drawn simply by dropping perpendiculars from the tip of vector **F** onto x and y-axes respectively. The x-component of force **F** is denoted as F_x and y-component as F_y.

From Fig. 4.11(b), it is evident that **F** is the resultant vector of components F_x and F_y. Moreover, F_x and F_y are perpendicular to each other. Therefore, F_x and F_y are called perpendicular components of vector **F**.

The magnitudes of the perpendicular components can be found from the right angled triangle OAC in Fig. 4.11(b).

$$\frac{OA}{OC} = \cos\theta$$

Putting the values,

$$\frac{F_x}{F} = \cos\theta$$

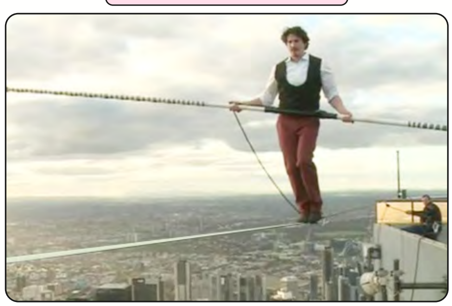
or $$F_x = F\cos\theta \qquad \text{...... (4.2)}$$

Similarly, $$\frac{AC}{OC} = \sin\theta$$

$$\frac{F_y}{F} = \sin\theta$$

or $$F_y = F\sin\theta \qquad \text{... .... (4.3)}$$

Do You Know?



A tight rope walker balances himself by holding a bamboo stick. This is an application of principle of moments.

4.5 Determination of a Force from its Prependicular Components

The magnitude and direction of a force can be found if its perpendicular components are known. Applying Pythagorean theorem to the right angled triangle OAC (Fig. 4.11-b).

$$(OC)^2 = (OA)^2 + (AC)^2$$

or

$$F^2 = F_x^2 + F_y^2$$

$$F = \sqrt{F_x^2 + F_y^2} \quad ....(4.4)$$

Hence, using Eq. (4.4) the magnitude F of the required vector **F** can be determined. The direction of **F** is given by

$$\tan\theta = \frac{F_y}{F_x} \quad ....(4.5)$$

or

$$\theta = \tan^{-1}\left(\frac{F_y}{F_x}\right)$$

By using table of trigonometric ratios or calculator, the value of θ can be determined.

Example 4.3

A force of 160 N is acting on a wooden box at an angle of 60° with the horizontal direction. Determine the values of its x and y components.

Solution

Magnitude of force $F = 160\ N$

Angle $\theta = 60°$

Using calculator, $\sin\theta = \sin 60° = 0.866$

$\cos\theta = \cos 60° = 0.5$

x-component is given by Eq. (4.2)

$$F_x = F\cos\theta$$

Putting the values, $F_x = 160\ N \times 0.5 = 80\ N$

y-component is given by Eq. (4.3)

$$F_y = F\sin\theta$$

Putting the values, $F_y = 160 N \times 0.866 = 138.6\ N$

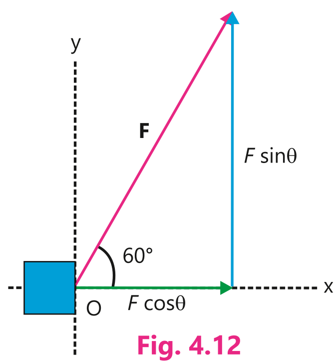


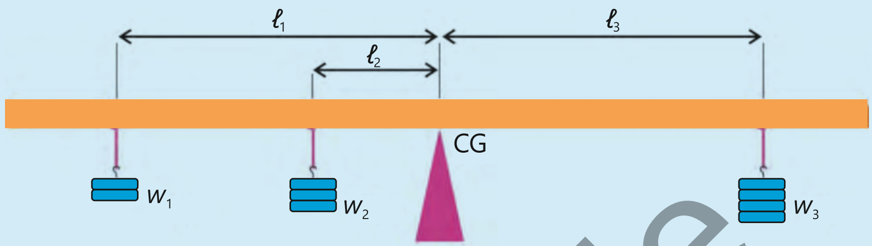
Fig. 4.12

4.6 Principle of Moments

To understand the principle of moments, let us perform an activity.

Activity 4.2

Balance a metre rule on a wedge at its centre of gravity such that the metre rule stays horizontal. Suspend two weights w_1 and w_2 on one side of the metre rule at distance ℓ_1 and ℓ_2 from the centre and a third weight w_3 on the other side at distance ℓ_3 until the rule is again balanced.



The weights w_1 and w_2 tend to rotate the rod anticlockwise about CG and the weight w_3 tends to rotate it clockwise. The values of the moments of the weights are $w_1 \times \ell_1$, $w_2 \times \ell_2$ and $w_3 \times \ell_3$. When the metre rule is balanced, then

Total anticlockwise moments = Total clockwise moments

$$w_1 \times \ell_1 + w_2\, \ell_2 = w_3 \times \ell_3 \quad \text{.................................(4.6)}$$

This is known as principle of moments, which is stated as:

When a body is in balanced position, the sum of clockwise moments about any point equals the sum of anticlockwise moments about that point.

Example 4.4

A metre stick is pinned at its one end O on a table so that it can rotate freely. One force of magnitude 18 N is applied perpendicular to the length of the stick at its free end. Another force of magnitude 60N is acting at an angle of 30° with the stick as shown in Fig. 4.13(a). At what distance from the end of stick that is pinned should the second force act such that the stick does not rotate?

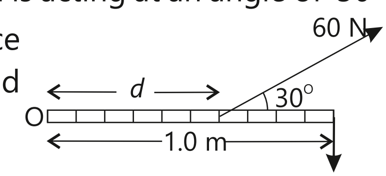


Fig 4.13(a)

Solution

Weight of the stick does not affect in the horizontal plane. Resolving force **F** of magnitude = 60 N into rectangular components that act at distance *d* from point O:

F_x = $60\text{ N} \times \cos 30^{\circ} = 60\text{ N} \times 0.866 = 51.96\text{ N}$

F_y = $60\text{ N} \times \sin 30^{\circ} = 60\text{ N} \times 0.5 = 30\text{ N}$

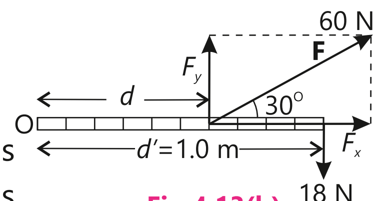


Fig 4.13(b)

As the component F_x passes through the axis of rotation, its torque is zero. Torque τ_1 of 30 N is positive and τ_2 of 18 N force is negative. The stick will not rotate when these two torques balance each others, i.e $\tau_1 = \tau_2$ or $F_y \times d = F_y' \times d'$

$$30\text{ N} \times d = 18\text{ N} \times 1\text{ m}$$

$$d = \frac{18\text{ N} \times 1\text{ m}}{30\text{ N}} = 0.6\text{ m}$$

4.7 Centre of Gravity and Centre of Mass

An object is composed of a large number of small particles. Each particle is acted upon by the gravitational force directed towards the centre of the Earth (Fig. 4.14-a). As the object is small as compared to the Earth, the value of g can be taken as uniform over all particles. Therefore, each particle experiences the same force mg. Since all these forces are parallel and act in the same direction, so their resultant as shown in Fig. 4.14(b) will be equal to the sum of all these forces .i.e,

Resultant force = $\sum mg$ where $\sum$ means the "sum of".

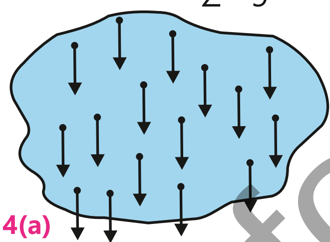


Fig. 4.14(a)
Gravitational force acting on various particles

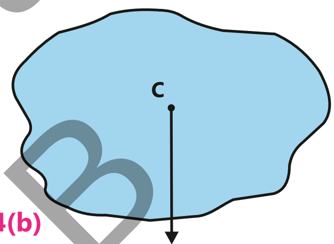


Fig. 4.14(b)
Resultant gravitational force

We know that the sum of the gravitational forces acting on all particles is equal to the total weight of the object $w = Mg$ Where $M = \sum m$ = mass of the object.

> Centre of gravity is that point where total weight of the body appears to be acting.

If a body is supported at its centre of gravity, it stays there without rotation. The centre of gravity of an object of regular shape lies at its geometrical centre. Centre of gravity of some geometrical shapes is given in Table 4.1.

Table 4.1

Object	Centre of Gravity
Square, Rectangle	Point of intersection of the diagonals
Triangle	Point of intersection of the medians
Round plate	Centre of the plate
Sphere	Centre of the sphere
Cylinder	Centre of the axis
Metre rule	Centre of the rod

Centre of Gravity of a Plane Lamina

For an irregular shaped plane lamina, the centre of gravity can be found by suspending it freely through different points (Fig. 4.15-a). Each time the object is suspended, its centre of gravity lies on the vertical line drawn from the point of suspension with the help of a plumb line. The exact position of the centre of gravity is at the point where two such lines cross each other as shown in Fig 4.15(b). The centre of gravity can exist inside a body or outside the body as is in case of a cup.

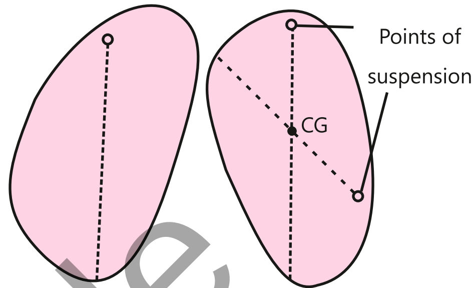


Fig. 4.15(a) **Fig. 4.15(b)**
Irregular shaped plane lamina

Centre of Mass

Newton's second law of motion is applicable to single particle or system of particles. Even when the parts of a system have different velocities and acceleration, there is still one point in the system whose acceleration could be found by applying second law. This point is called the centre of mass of the system.

For your information!

Centre of gravity of a bowl is outside the material.

> The centre of mass of a body is that point where the whole mass of the body is assumed to be concentrated.

Hence, the centre of mass behaves as if all the mass of the body or system is lying at that point. In the Fig. 4.16 given below, a rotating wrench slides along a frictionless floor. There is no resultant force on the wrench. Therefore, its centre of mass, shown by a yellow dot, follows a linear path with constant speed.

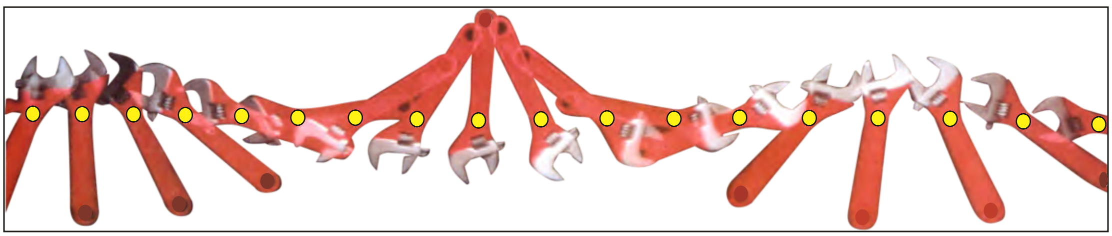


Fig. 4.16: Rotating wrench sliding along a frictionless floor

On the surface of the Earth, where *g* is almost uniform, the centre of mass of an object coincides with its centre of gravity.

4.8 Equilibrium

We have learnt how translatory and rotational motion can be caused due to the application of external forces. Now, we shall see how external forces can be balanced to produce no translational or rotational effects.

Do You Know?

This is a fascinating scene of equilibrium.

We know that if a number of forces act on a body such that their resultant is zero, the body remains at rest or continues to move with uniform velocity if already in motion. This state of the body is known as equilibrium, which can be stated as:

A body is said to be in equilibrium if it has no acceleration.

There are two types of equilibrium:

(i) Static equilibrium (ii) Dynamic equilibrium

A body at rest is in static equilibrium whereas a body moving with uniform velocity is in dynamic equilibrium.

An example of static equilibrium is a book lying on the table as shown in Fig. 4.17. Only two forces are acting on it. One is its weight $w = mg$ acting downward and the other is $\mathbf{F_n}$ the normal force that the table exerts upward on the book. Since the book is at rest so, it has zero acceleration. Therefore, the sum of all the forces acting on the book should be zero, so that the book is said to be in equilibrium. Hence

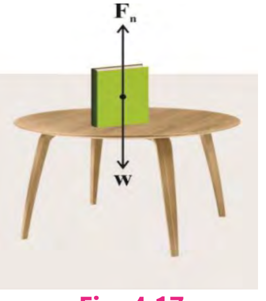


Fig. 4.17
Book is in static equilibrium

$$F_n - w = 0$$

or $$F_n = w$$

This means that forces can act on a body without accelerating it, provided these forces balance each other.

An electric bulb hanging from the ceiling of a room, a man holding a box, a beam held horizontal against a wall with the help of a rope and a hanging weight (Fig. 4.18), are all examples of static equilibrium.

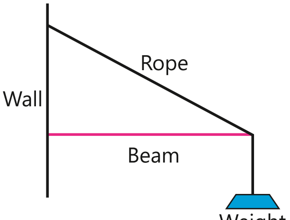


Fig. 4.18
A beam projected from a wall is also in static equilibrium

A good example of dynamic equilibrium is a paratrooper (Fig. 4.19). In a few second after the free fall, the parachute opens and a little later, the paratrooper starts descending with a uniform velocity. In this state, the force of gravity acting vertically downward on the paratrooper is balanced by the resistance of air on the parachute acting upward.

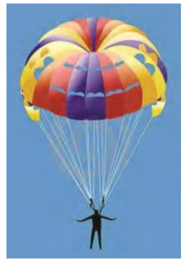


Fig. 4.19
A paratrooper is in dynamic equilibrium

4.9 Conditions of Equilibrium

There are two conditions of equilibrium:

First Condition of Equilibrium

By Newton's second law of motion, $F = ma$
If the body is in translational equilibrium, then $a = 0$, therefore, net force F should be 0 or $\sum F = 0$ ....(4.7)

This is the mathematical form of the first condition of equilibrium which states that:

Fascinating Freefall

A group of paratroopers making in a formation-an example of dynamic equilibrium.

> A body is said to be in translational equilibrium only if the vector sum of all the external forces acting on it is equal to zero.

In case a number of coplanar forces $\mathbf{F_1}$, $\mathbf{F_2}$, $\mathbf{F_3}$, ... having their resultant equal to $\mathbf{F}$, are acting on a body, these can be resolved into their rectangular components, and first condition of equilibrium can be then written as:

Along x-direction, $F_{1x} + F_{2x} + F_{3x} + ... = 0$

or $\sum F_x = 0$ ...... (4.8)

Similarly, along y-direction,

$F_{1y} + F_{2y} + F_{3y} + ... = 0$

or $\sum F_y = 0$ ......(4.9)

Thus, first condition of equilibrium can also be stated as:

> The sum of all the components of forces along x-axis should be zero and the sum of all the components of forces along y-axis should also be zero.

Second Condition of Equilibrium

The second condition of equilibrium implies to the rotational equilibrium which means that the body should not rotate under the action of the forces.

Consider the example of a rigid body in Fig.4.20. Two forces $\mathbf{F_1}$ and $\mathbf{F_2}$ of equal magnitude are acting on it. In case (a), both the forces act along the same line of action.

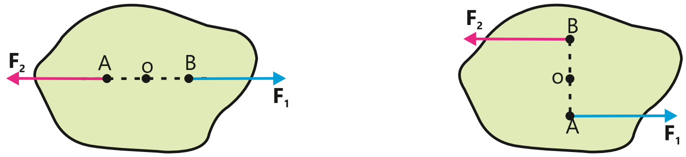


Fig. 4.20

In case (b), the lines of action of the two forces are different. Since magnitude of $\mathbf{F_1}$ and $\mathbf{F_2}$ are equal, so the resultant force is zero in both the cases. Thus, first condition of equilibrium is satisfied. But you can observe that in case (b), the forces are forming a couple which can apply torque to rotate the body about point O. Therefore, for a body to be completely in equilibrium, a second condition is also required. That is, no net torque should be acting. This is the second condition of equilibrium which can be stated as:

> The vector sum of all the torques acting on a body about any point must be zero.

Mathematically, we can write: $\sum \tau = 0$ ......(4.10)

Hence, a body will be in complete equilibrium when,

$$\begin{cases}\sum F_x = 0 \\ \sum F_y = 0\end{cases}$$

And $\sum \tau = 0$

Example 4.5

A picture is suspended by means of two vertical strings as shown in Fig 4.21. The weight of the picture is 5 N, and it is acting at its centre of gravity. Find the tension T_1 & T_2 in the two strings.

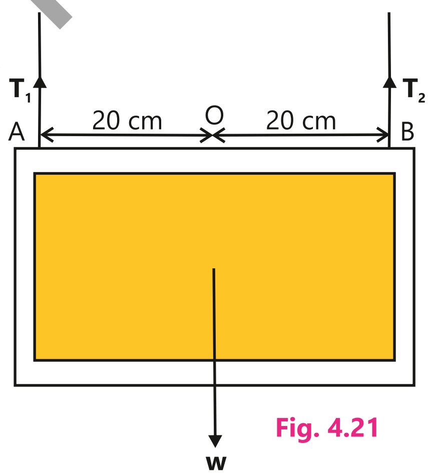


Fig. 4.21

Solution

Total upward force = $T_1 + T_2$

Total downward force = w = 5 N

Tensions in the strings, T_1 = ? and T_2 = ?

Since, there is no horizontal force, so $\sum F_x = 0$

Already $\sum F_x = 0$

Putting $\sum F_y = 0$

$T_1 + T_2 - w = 0$ ....(i)

Apply $\sum \tau = 0$, selecting point B as point of rotation. Here, torque τ_1 of T_1 is negative whereas torque τ_2 of w is positive about point B. T_2 produces zero torque as it passes through the point of rotation. Hence,

$$\tau_2 - \tau_1 = 0$$

or $$w \times BO - T_1 \times AB = 0$$

putting the values, $$w \times 0.2\ m - T_1 \times 0.4\ m = 0$$

or $$5\ N \times 0.2\ m - T_1 \times 0.4\ m = 0$$

or $$T_1 = \frac{5\ N \times 0.2\ m}{0.4\ m} = 2.5\ N$$

Putting the value of T_1 and w in Eq. (i), we have

$$2.5\ N + T_2 - 5\ N = 0$$

or $$T_2 = 2.5\ N$$

4.10 States of Equilibrium

An object is balanced when its centre of mass and its point of support lie on the same vertical line. Then forces on each side are balanced, and the object is said to be in equilibrium. There are three states of equilibrium in connection with stability of the balanced bodies.

Stable Equilibrium

A body is said to be in a state of stable equilibrium, if after a slight tilt, it comes back to its original position.

Stable equilibrium occurs when the torques arising from the rotation (tilt) of the object compel the body back towards its equilibrium position.

The cone shown in Fig 4.22(a) is in the state of stable equilibrium. Its weight **w** acting downward at the centre of gravity G and the reaction of the floor $\mathbf{F_n}$ acting upward, lie on the same vertical line. Since these forces are equal and in opposite direction, so they balance each other and both the conditions of equilibrium are satisfied.

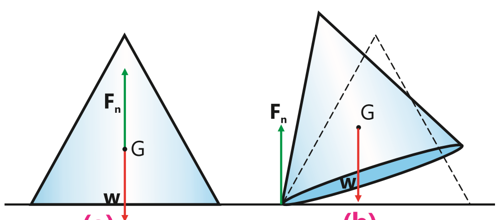


Fig. 4.22

As you try to push over the cone slightly, its centre of gravity is raised but it still remains above the base of the cone. The weight **w** and the normal force $\mathbf{F_n}$ do not remain in the same line but act like two unlike parallel forces. The cone does not remain in equilibrium. Unlike parallel forces produce a clockwise torque which brings the cone back to its original position. It is worth noting that the body remains in equilibrium as long its centre of mass lies within the base.

Unstable Equilibrium

Try to balance the cone on its tip. It is balanced for a moment because **w** and **F_n** lie along the same line. Even it is slightly tilted, it will not come back to its original position by itself. Rather it will fall downward, because its centre of mass no longer remains above the base. It topples over, because line of action of **w** no longer lies inside the base O (Fig. 4.23). In this case, centre of gravity is lowered on tilting and continues to fall further. It cannot rise up again because the anticlockwise torque produced by **w** moves it further downward.

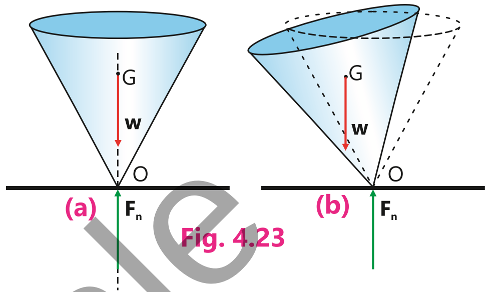


Fig. 4.23

A body is said to be in a state of unstable equilibrium, if after a slight tilt, it tends to move on further away from its original position.

Neutral Equilibrium

A cylinder resting on a horizontal surface (Fig. 4.24) shows the neutral equilibrium. If the cylinder is rotated slightly, there is no force or torque that brings it back to its original position or moves it away. As the cylinder rotates, the height of the centre of mass remains unchanged. In any position of the cylinder, its weight and reaction of the ground lie in the same vertical line.

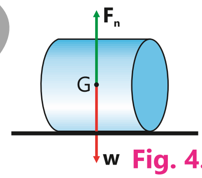


Fig. 4.24

A body is in neutral equilibrium, if it comes to rest in its new position after disturbance without any change in its centre of mass.

Other examples of neutral equilibrium are a ball rolling on a horizontal surfaces, or a cone resting on its curved surface (Fig.4.25).

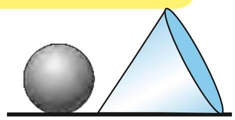


Fig. 4.25

4.11 Improvement of Stability

It is our daily life observation that a low armchair is more stable than a high chair because of its low centre of gravity. The position of centre of gravity is very important when we are talking about stability. A bus can be stable or unstable depending on how it is loaded. If the heavy loads are placed on the floor of the bus, its centre of gravity will be low. Now if it is disturbed slightly, a torque will bring it back to its original position.

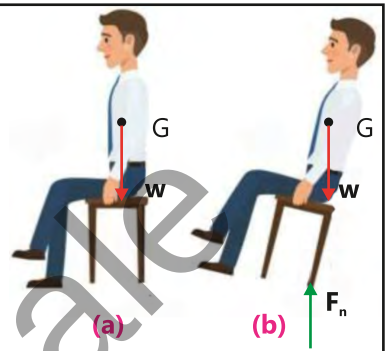
Interesting Information!


A double decker bus is being tilting to test its stability.

In this case, the bus is in stable equilibrium. If the same bus is loaded with steel sheets on the top, the centre of gravity be raised. It is now near to a state of unstable equilibrium. A couple will turn it over if it is slightly tilted. The same is the case of ships and boats. We can improve the stability of a system either by lowering the centre of gravity or by widening the base.

Interesting Information!

An unstable equilibrium is illustrated in this figure. A chair in normal position is quite stable (Fig. a) but it has been turned into an unstable position by tilting it back on its legs (Fig. b). In this tilted position, a couple is formed by its weight **w** and reaction $\mathbf{F_n}$ of the ground. This clockwise couple tends to overturn chair backward.



4.12 Application of Stability in Real Life

The concept of stability is widely applied to engineering technology especially in manufacturing racing cars and balancing toys.

As the racing cars are driven at very high speeds and also there are sharp turns in the track, therefore, the chances of the cars to topple over increase. To enhance the stability of racing cars, their centres of mass are kept as low as possible. There base areas are also increased by keeping the wheel outside of their main bodies. Balancing toys are also very interesting for both children and elders. Look at some balancing toys shown belows.

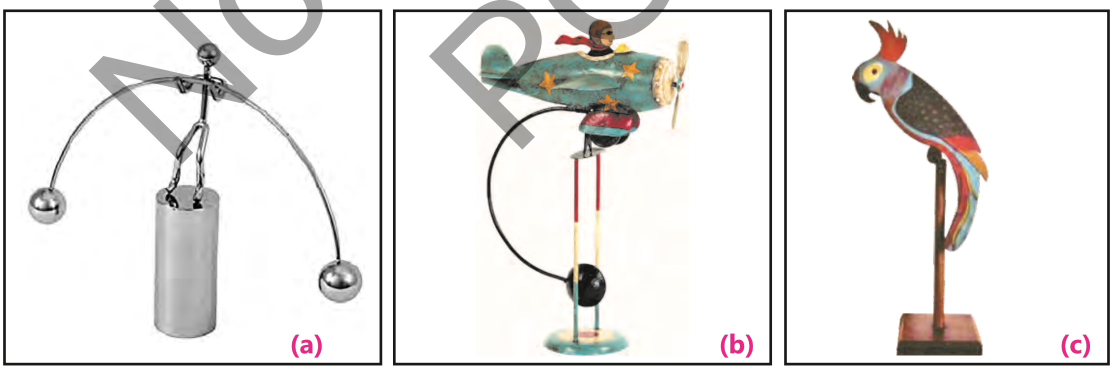


Fig. 4.26: Balancing toys

The physics behind these types of toys is that stability is built in with balancing toys. These toys are basically in completely stable state and their centres of gravity always remain below the pivot point. If the toys are disturbed in any direction, the centre of gravity is raised and it becomes unstable for a moment. It comes back to its initial stable position by lowering its centre of gravity.

The kids learn from these toys about stable systems and how they return to their state of initial rest position after being disturbed. Educational games on the basis of balancing toys have also been developed for the kids as shown in Fig 4.27.

Fig. 4.27

Interesting Information!

To enhance the stability of a racing car, its centre of mass is kept as low as possible. Its base area is also increased by keeping its wheels outside of its main body.

Rotational Motion Versus Translatinal Motion

Counterparts of velocity, acceleration, force and momentum in translational motion are angular velocity, angular acceleration, moment of force (torque) and angular momentum respectively in rotational motion. It suggests that the torque plays the same role in the rotational motion that is played by the force in the translational motion. Therefore, we are justified to predict that analogous to Newton's first law of motion, a rotating object will continue to do so with constant angular velocity unless acted upon by a resultant moment (torque). However, if a resultant torque is applied to rotating object, it will accelerate depending on the direction of the torque relative to the axis of rotation.

This fundamental principle enhances our understanding how objects move and interact with their environment whether in linear or rotational motion scenarios.

Motion in a Circle

When a body is moving along a circular path, its velocity at any point is directed along the tangent drawn at that point. Figure 4.28 shows that the direction of tangent at each point on a circle is different, therefore, the velocity of an object moving with uniform speed in a circle is changing constantly. Hence, a force perpendicular to the direction of motion is always required to keep the object moving with uniform speed in a circular path.

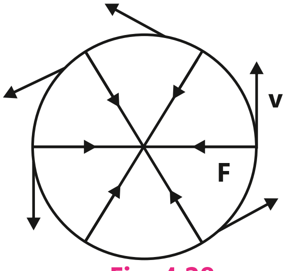


Fig. 4.28

It should be noted that **F** is essentially perpendicular to **v**. For an instance, if it is not perpendicular to **v**, the force **F** will have a component in the direction of **v**. This will change the magnitude of velocity. As the body moves with constant speed, so it is possible only if the component of force along **v** is $F\cos 90^\circ = 0$.

4.13 Centripetal Force

We have studied above that an object can move in a circular path with uniform speed only if a force perpendicular to its velocity is acting constantly on it. This force is always directed towards the centre of the circle. It is called centripetal force and can be defined as:

> The force that causes an object to move in a circle at constant speed is called the centripetal force.

For an object of mass m moving with uniform speed v in circle of radius r, the magnitude of centripetal force F_c acting on it can be calculated by using the relation:

$$F_c = \frac{mv^2}{r} \quad \text{.............(4.11)}$$

Example 4.6

A 150 g stone attached to a string is whirled in a horizontal circle at a constant speed of 8 m s^{-1}. The length of string is 1.2 m. Calculate the centripetal force acting on the stone. Neglect effects of gravity.

Solution

Mass of stone $= m = 150\text{ g} = 0.15\text{ kg}$
Speed of stone $= v = 8\text{ m s}^{-1}$
Radius of circle $= r = 1.2\text{ m}$
Centripetal force $= F_c = ?$

Using Eq.4.11, $F_c = \frac{mv^2}{r}$

Putting the values, $F_c = \frac{0.15\text{ kg} \times (8\text{ m s}^{-1})^2}{1.2\text{ m}} = 8\text{ N}$

Sources of Centripetal Force

We have learnt that centripetal force has to be supplied if the body is to be maintained in its circular path. What could be the sources of centripetal force?

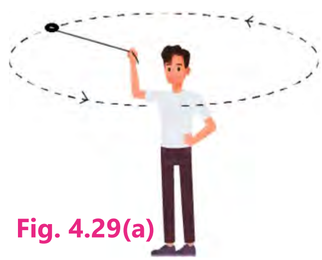


Fig. 4.29(a)
A stone whirled in a circle by a string

If we tie a stone to one end of a string and whirl it from the other end, we will have to exert a force on the stone through the string (Fig 4.29-a). If we release the string when it is at any point P, the stone will fly off along the tangent (PQ) to the circle. Then, it will move along the same straight line with constant velocity unless an unbalanced force acts upon it.

In fact, the tension **T** in the string was providing the stone the necessary centripetal force to keep it along the circular path (Fig 4.29-b). When we release the string we stop applying force on the stone and hence it moves in a straight line.

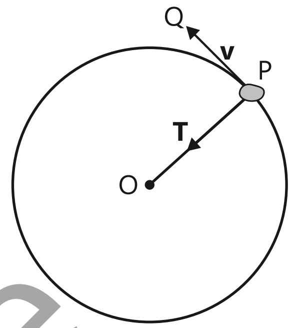


Fig. 4.29 (b)

Now consider the case of the moon which moves around the Earth at constant speed. The gravity of the Earth provides the necessary centripetal force to keep it in its orbit. Same is the case of satellites orbiting the Earth in circular paths with uniform speed. The gravitational pull of the Earth provides centripetal force.

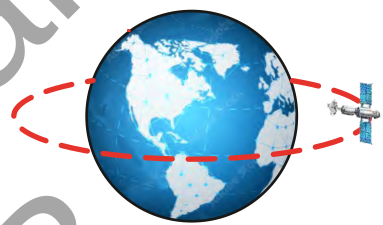


Fig. 4.30
A satellite orbiting the Earth

One of the real life examples is a washing machine dryer. A dryer is a metallic cylinderical drum with many small holes in its walls. Wet clothes are put in it. When the cylinder rotates rapidly, friction between clothes and drum walls provides necessary centripetal force. As the water molecules are free to move, so they cannot get the required centripetal force to move in circular paths and escape from the drum through the holes. This results into quick drying of clothes.


Fig. 4.31
Washing machine

Another interesting example is that of a cream separator. In a cream separator, milk is whirled rapidly.

Cream seperator
Fig. 4.32

The lighter particles of cream experience less centripetal force and gather in the central part of the machine. The heavier particles of milk need greater centripetal force to keep their circular motion in circles of small radius *r*. In this way, they move away towards the walls.

EXERCISE

A Multiple Choice Questions

Tick (✓) the correct answer.

4.1 A particle is simultaneously acted upon by two forces of 4 and 3 newtons. The net force on the particle is:

(a) 1 N (b) between 1 N and 7 N (c) 5 N (d) 7 N

4.2 If $\mathbf{F}_1$ and $\mathbf{F}_2$ are the forces acting on a body and τ is the torque produced in it, the body will be completely in equilibrium, when:

(a) $\sum \mathbf{F} = 0$ and $\sum \tau = 0$ (b) $\sum \mathbf{F} = 0$ and $\sum \tau \neq 0$

(c) $\sum \mathbf{F} \neq 0$ and $\sum \tau = 0$ (d) $\sum \mathbf{F} \neq 0$ and $\sum \tau \neq 0$

4.3 A Shopkeeper sells his articles by a balance having unequal arms of the pans. If he puts the weights in the pan having shorter arm, then the customer:

(a) loses (b) gains (c) neither loses nor gains (d) not certain

4.4 A man walks on a tight rope. He balances himself by holding a bamboo stick horizontally. It is an application of:

(a) law of conservation of momentum

(b) Newton's second law of motion

(c) principle of moments

(d) Newton's third law of motion

4.5 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

4.6 A cylinder resting on its circular base is in:

(a) stable equilibrium (b) unstable equilibrium

(c) neutral equilibrium (d) none of these

B Short Answer Questions

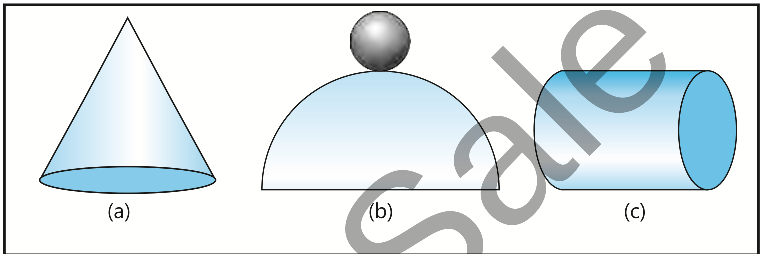
4.1 What are rectangular components of a vector and their values?

4.2 What is the line of action of a force?

4.3 Define moment of a force. Prove that $\tau = rF\sin\theta$, where θ is angle between **r** and **F**.

4.4 With the help of a diagram, show that the resultant force is zero but the resultant torque is not zero.

4.5 Identify the state of equilibrium in each case in the figure given below.



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

4.7 What are two basic principles of stability in physics which are applied in designing balancing toys and racing cars?

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

C Constructed Response Questions

4.1 A car travels at the same speed around two curves with different radii. For which radius the car experiences more centripetal force? Prove your answer.

4.2 A ripe mango does not normally fall from the tree. But when the branch of the tree is shaken, the mango falls down easily. Can you tell the reason?

4.3 Discuss the concepts of stability and centre of gravity in relation to objects toppling over. Provide an example where an object's centre of gravity affects its stability, and explain how altering its base of support can influence stability.

4.4 Why an accelerated body cannot be considered in equilibrium?

4.5 Two boxes of the same weight but different heights are lying on the floor of a truck. If the truck makes a sudden stop, which box is more likely to tumble over? Why?

D Comprehensive Questions

4.1 Explain the principle of moments with an example.

4.2 Describe how could you determine the centre of gravity of an irregular shaped lamina experimentally.

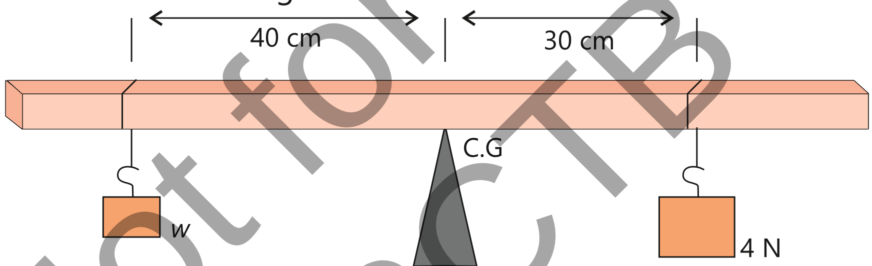
4.3 State and explain two conditions of equilibrium.

4.4 How the stability of an object can be improved? Give a few examples to support your answer.

E Numerical Problems

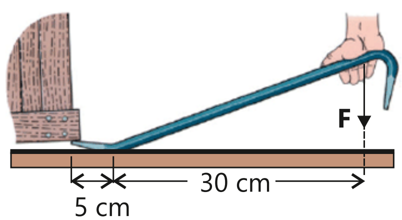
4.1 A force of 200 N is acting on a cart at an angle of 30° with the horizontal direction. Find the x and y-components of the force. (173.2 N, 100 N)

4.2 Two weights are hanging from a metre rule at the positions as shown in the given figure. If the metre rule is balanced at its centre of gravity (C. G), find the unknown weight *w*. (3 N)



4.3 A see-saw is balanced with two children sitting near either end. Child A weighs 30 kg and sits 2 metres away from the pivot, while child B weighs 40 kg and sits 1.5 metres from the pivot. Calculate the total moment on each side and determine if the sea-saw is in equilibrium. (60 N)

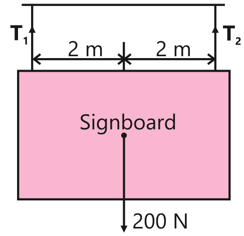
4.4 A crowbar is used to lift a box as shown in the given figure. If the downward force of 250 N is applied at the end of the bar, how much weight does the other end bear? The crowbar itself has negligible weight. (1500 N)



4.5 A 30 cm long spanner is used to open the nut of a car. If the torque required for it is 150 N m, how much force *F* should

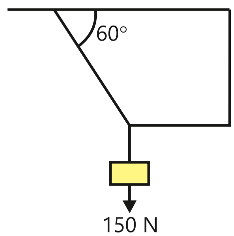
be applied on the spanner as shown in the figure given below. (500 N)

4.6: A signboard is suspended by means of two steel wires as shown in the given figure. If the weight of the board is 200 N, what is the tension in the strings? (100 N, 100 N)



4.7: One girl of 30 kg mass sits 1.6 m from the axis of a see-saw. Another girl of mass 40 kg wants to sit on the other side, so that the see-saw may remain in equilibrium. How far away from the axis, the other girl may sit? (1.2 m)

4.8: Find the tension in each string as shown in the given figure, if the block weighs 150 N. (86.6 N, 173.2 N)



Chapter 5 Work, Energy And Power

Student Learning Outcomes

After completing this chapter, students will be able to:

- Define work done.
- Use the equation work done = force × distance moved in the direction of the force $W = F \times S$ to solve problems
- Define energy as the ability to do work
- Explain that energy may be stored [Such as in gravitational potential, chemical, elastic (strain), nuclear, electrostatic, and internal (thermal) energies]
- Prove that Kinetic Energy = $\frac{1}{2} mv^2$ [use of equations of motion not needed; proof through kinematic graphs will suffice]
- Prove and use the formula for gravitational potential energy
- Use the formulas for kinetic and gravitational potential energy to solve problems involving simple energy conversions [make use of the conversion of energy from one form to the other, including cases involving loss of energy to the surroundings]
- Describe how energy is transferred and stored during events and processes [e.g. work done during transfer by mechanical work done, electrical work done, and heat]
- State and apply the principle of the conservation of energy
- Differentiate between and list renewable and non-renewable energy sources
- Describe advantages and disadvantages of methods of energy generation [limited to whether it is renewable, when and whether it is available, and its impact on the environment]
- Define and calculate power [As work done per unit time and also as energy transferred per unit time. This also includes applying the equations: (a) power= work done/time taken $P = W/t$ (b) power = energy transferred/time taken
- Define and calculate efficiency [including: (a) (%) efficiency = (useful energy output)/(total energy input) (x 100%) (b) (%) efficiency = (useful power output)/(total power input) (x 100%)]
- Apply the concept of efficiency to simple problems involving energy transfer
- State that a system cannot have an efficiency of 100% due to unavoidable energy losses that occur.

Work and energy are important concepts in physics as well as in our everyday life. Commonly the word 'work' covers all sort of activities whether mental or physical. If a girl is studying (Fig. 5.1) or a man is standing (Fig. 5.2) with a load of bricks on his head, we say that they are doing work. But according to physics, work has a specific definition. Work is said to be done when a force acts on an object and moves it through some distance.

Fig. 5.1

The concept of energy is closely associated with that of work, when work is done by one system on another, energy is transferred between the two systems.

In this chapter, we will define work, energy, power and efficiency and show how they are related to one another.

Fig. 5.2

5.1 Work

Force and distance are two essential elements of work. When a constant force acting on a body moves it through some distance, we say that 'the force has done work'.

> Work is defined as the product of magnitude of force and the distance covered in the direction of force.

Consider a block of wood lying on a table (Fig. 5.3). If we exert a force F on the block to move it through a distance S in the direction of force, then the work W done by the force is:

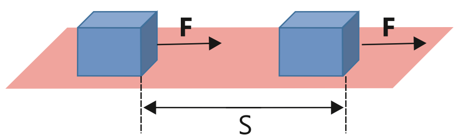


Fig. 5.3

Work = Magnitude of force × Distance

or $W = F \times S$ .... (5.1)

From Eq. (5.1), it can be concluded that if some force is acting on a body but there is no displacement, then no work is done. For example, a man is pushing hard a wall but the wall remains fixed in its place. In this case, the man is doing no work (Fig. 5.4).

Similarly, if a force acting on the body is zero and the body is moving with uniform velocity, work will be zero.

As $F = 0$ so $W = 0 \times S = 0$

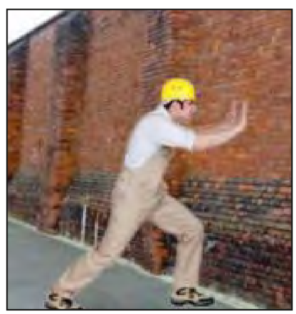


Fig. 5.4

What will be the work done when a force is acting on a body making an angle θ with the direction of motion? In this case, work is done due to the component of force which is acting along the direction of motion (Fig. 5.5).

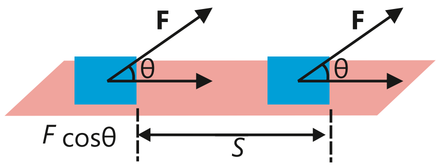


Fig. 5.5

Resolving the force F into its components, we have the component $F\cos\theta$ that acts in the direction of motion. Therefore,

$$W = (F\cos\theta)\,S$$

or $$W = FS\cos\theta \quad \ldots\ldots (5.2)$$

If θ is zero, $\cos 0° = 1$, then

$$W = FS\,(1) = FS$$

This is the case when force and distance covered are in the same direction. Now if θ = 90°, then cos 90° = 0 which means the force has zero component in the direction of motion. Thus,

Fig. 5.6

$$W = FS\,(0) = 0$$

This is the case when force is perpendicular to the displacement. Look at Fig. 5.6, it suggests that if a person carries a bag to some distance, this work is zero, because the force applied to hold the load is upward which is perpendicular to the displacement.

The work done to push an object is the same whether the object moves north to south or east to west, provided the magnitude of force and the distance moved are not changed. Work does not convey any directional information, so it is a scalar quantity.

Calculation of Work Done by Graph

When a constant force F acts through a distance S, the event can be plotted on a force-distance graph as shown in Fig. 5.7. If the force and distance covered are in the same direction, the work done is $F \times S$.

Clearly the shaded area in the figure is also $F \times S$. Hence, the area under a force-distance curve can be taken to represent the work done by that force.

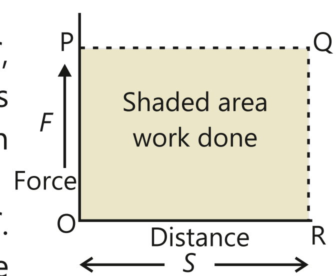


Fig. 5.7

Units of Work

The SI unit of work is joule (J).

One joule work is done when a force of one newton acting on a body moves it through a distance of one metre in its own direction.

From Eq. (5.1)

$$1\,J = 1\,N \times 1\,m$$

or $$1\,J = N\,m$$

Bigger units are also used like $1\,kJ = 10^3\,J$ and $1\,MJ = 10^6\,J$

Example 5.1

Find the work done by a 65 N force in pulling the suitcase (Fig. 5.8) for a distance of 20 metres.

Solution

Force applied $F = 65\,N$

Distance covered $S = 20\,m$

Angle from the figure $\theta = 30^\circ$

Work $W = ?$

Using Eq. 5.2,

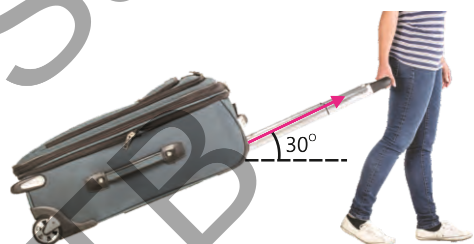


Fig. 5.8

$$W = FS\cos 30^\circ$$
$$W = 65\,N \times 20\,m \times 0.866$$
$$W = 1125.8\,N\,m = 1125.8\,J$$

5.2 Energy

Our body cannot move unless we have energy from food. A car would not run without the energy it obtains from burning fuel. Machines in the factories cannot run without consuming energy supplied by electricity. Any change in motion requires energy. When we say that a certain body has energy, we mean that it has the ability of doing work.

Energy can be defined as the ability of a body to do work.

When someone does work, energy of the body has to be spent. In fact, energy is transferred to the body on which work is done. In other words, the energy is transferred from one system to another. For example,

For Your Information!

A stretched bow stores energy, which is transferred to the arrow as it is shot. Some bows store enough energy to shot an arrow even 1 km away.

when you do work pushing a swing, chemical energy in your body is transferred to the swing and appears as energy of the motion of the swing.

Like work, energy is a scalar quantity. Its SI unit is joule (J).

When one joule work is done on a body, the amount of energy spent is one joule.

There are many forms of energy. Electrical energy, chemical energy, nuclear energy, heat energy and light energy are some well-known forms which we shall study later on. There are two basic forms of energy:

(i) Kinetic energy

(ii) Potential energy

The combination of these two types of energies is called mechanical energy.

Kinetic Energy

The kinetic energy of a body is the energy that a body possesses by virtue of its motion.

To find out how much kinetic energy a moving body possesses, an opposite force can be applied on the body to stop its motion. Then the work done by the force will be equal to the kinetic energy of the body. i.e., Kinetic energy (E_k) = Work done (W)

Suppose a body of mass m is moving with velocity v. An opposing force F acting on the body through a distance S brings it to rest. Then,

$E_k = \text{Work done} = F \times S$

As $F = ma$ and $S = v_{av} \times \text{time} = \left(\frac{v + 0}{2}\right)t = \frac{v}{2} \times t$

Hence, $E_k = ma \times \frac{vt}{2} = \frac{1}{2}\, ma \times vt$

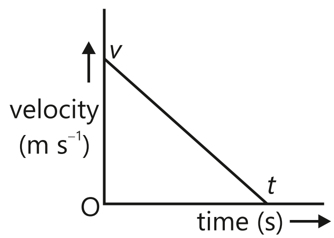


Fig. 5.9

Using velocity-time graph (Fig 5.9), the acceleration 'a' is given by its slope.

Hence, $a = \frac{v}{t}$, the slope is negative as the velocity and force are in opposite direction.

Thus $\quad E_k = \frac{1}{2}\, m \left(\frac{v}{t}\right) vt$

or $\quad E_k = \frac{1}{2}\, mv^2 \qquad$ -------- (5.3)

Example 5.2

A truck of mass 3000 kg is moving on a road with uniform velocity of 54 km h^{-1}.

Determine its kinetic energy.

Solution

Mass of the truck $m = 3000$ kg
Velocity $v = 54$ km h^{-1} = 15 m s^{-1}
Kinetic energy E_k = ?

Putting the values,

$$E_k = \frac{1}{2}mv^2 = \frac{1}{2} \times 3000\ \text{kg} \times (15)^2\ \text{m}^2\ \text{s}^{-2}$$

$$E_k = 337500\ \text{J} = 337.5\ \text{kJ}$$

For Your Information!

- The work done by the single beat of human heart is 0.5 J.
- The energy content of the nuclear bomb dropped on Hiroshima, Japan, in the second world war was 8.0×10^{13} J.
- The energy output of a power station in one year is 10^{16} J.

Potential Energy

In the previous section, we have seen that the work done on a body is used to increase its kinetic energy. Sometimes, the work done on a body does not increase its kinetic energy, rather it is stored in the body as **potential energy**.

Potential energy is defined as the energy that a body possesses by virtue of its position or deformation.

Do You Know?

The train is changing potential energy every moment in the roller coaster.

Forms of Potential Energy

There are many forms of potential energy. As mentioned above, the energy possessed by an object by virtue of its position relative to the Earth is known as **gravitational potential energy**.

The energy stored in a compressed or stretched spring is called **elastic potential energy** and the potential energy in the chemicals of a battery is called **chemical potential energy**, which is changed to electrical energy by chemical reactions. **Thermal or internal energy** is released by burning fossil fuels i.e. coal, oil or gas through chemical reactions.

Nuclear energy is the hidden energy in the nuclei of atoms. When they are broken, energy is released in the form of heat and some other radiations. This is called nuclear fission.

If the block shown in Fig. 5.10 is lifted to a height *h* above the ground, then the block would have potential energy in that raised position. Therefore, it has the ability to do work whenever it is allowed to fall. How should potential energy be measured? Because

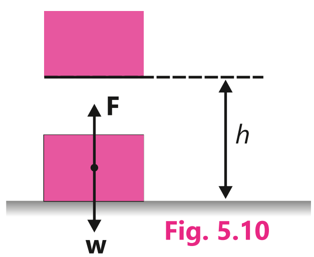


Fig. 5.10

work is done on the block to put it into the position where it has potential energy, therefore, we can say that the work done is stored in it as potential energy. Thus, **potential energy** E_p is given by

$$E_p = \text{Work done to put the block in elevated position}$$

The applied force necessary to lift the block with constant velocity is equal to weight w of the block and since $w = mg$, therefore, potential energy of the block at height h becomes,

$$E_p = wh$$

or $$E_p = mgh \qquad .... (5.4)$$

Fig. 5.11 Waterfall

The most obvious example of gravitational potential energy is a waterfall (Fig. 5.11), water at the top of the fall has potential energy. When the water falls to the bottom, it can be used to run turbines to produce electricity and thus can do work.

For Your Information!

According to Einstein's theory of relativity, matter and energy are interchangeable under certain conditions. The loss of some mass in nuclear reactions may transform into energy production and similarly energy may be converted into material particles. Hence, now we have conservation of mass and energy rather that conservation of each separately.

Example 5.3

A ball of mass 180 g was thrown vertically upward to a height of 12 m. Find the potential energy gained by the ball.

Solution

Mass of ball $m = 180\text{ g} = 0.18\text{ kg}$

Height $h = 12\text{ m}$

P.E. gained $E_p = ?$

$g = 10\text{ m s}^{-2}$

From Eq. (5.4) $E_p = mgh$

Putting the values

$$E_p = 0.18\text{ kg} \times 10\text{ m s}^{-2} \times 12\text{ m} = 21.6\text{ J}$$

5.3 Conservation of Energy

The study of various forms of energy and the transformation of one kind of energy into another has led to a very important principle known as the principle of conservation of energy. Formally, it is stated as:

Energy cannot be created or destroyed. It may be transformed from one form to another, but the total amount of energy never changes.

During energy transfer process, some energy seems to be lost and not accounted for in calculations. This loss of energy is due to work done against friction of the moving parts in the process. This energy appears as heat and is dissipated in the environment. This energy does not remain available for doing some useful work and may be called waste energy.

A process of energy conversion and conservation can be described with the given example.

Let a body of mass m be at rest at a point A above the height h from the ground (Fig.5.12). Its total energy *P.E.* is *mgh*,

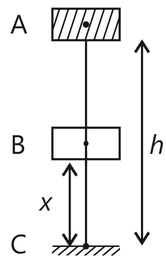


Fig. 5.12

$$E_p = mgh$$

and $$E_k = 0$$

Then the body is allowed to drop to point B at a height x from the ground. The body loses potential energy and gains kinetic energy as it gets speed while falling down. Assuming air resistance negligible.

$$E_p = mg\,(h - x)$$

The loss of potential energy will appear as the gain in kinetic energy, hence, at point B

$$E_k = mgx$$

Total energy at B $\quad E = mg\,(h - x) + mgx \;=\; mgh$

Just before hitting the ground at point C, the whole of potential energy is changed into kinetic energy. Thus,

$$E_p = 0 \quad \text{and} \quad E_k = mgh$$

Thus, total energy remains the same as *mgh*. On hitting the ground, this energy is dissipated as heat and sound in the environment.

5.4 Renewable and Non-Renewable Sources

The resources of energy which are replaced by new ones after their use are called renewable energy source. On the other hand, non-renewable sources are those, which are depleted with the continuous use. Once they run out, they are not easily replaced by new ones. Sources such as hydroelectricity, solar energy, wind energy, tidal energy, wave energy and geothermal energy are renewable. These are replaced by new ones. For example, snow fall and rain fall are continuous processes. Therefore, water supply to the reservoirs of dams for generation of hydroelectric power will never end up. Likewise, solar energy will remain available forever. Same is the case with wind and tidal energy. These are not going to run out in future.

Non-renewable sources include fossil fuels and nuclear energy. The remnants of plants and animals buried under the Earth took millions of years to change into fossil fuels. These fuels are in limited quantity. Once they are used up, it will take further millions of years to form new ones. Similarly, fuels for the nuclear energy are also limited.

As the need for energy is increasing day by day, there is need to develop other non- traditional renewable energy sources.

5.5 The Advantages and Disadvantages of Methods of Energy Production

The production of hydroelectric power is more economical and pollution free. The solar power, wind, tidal and wave power need more initial cost but they do not produce pollution and are also economical as well. On the other hand, power generation by fossil fuels and nuclear fuel adds to the pollution of environment. Burning of fossil fuels produces smoke, carbon dioxide gas and heat (Fig. 5.13. They enhance direct pollution to atmosphere. Windmills are very noisy. Some people think that wind turbines spoil the beauty of landscape.

Fig. 5.13

Do You Know?

Burning fossil fuels release five billion tonnes of carbon dioxide into the atmosphere every year.

Nuclear power generators are also run by steam produced by nuclear heat energy. Heat itself is a form of pollution. Moreover, there is always danger of leakage of the radioactive radiation which is harmful to living bodies. People living around nuclear plants are always at risk. The disposal of nuclear waste is another problem for the nuclear power generation. However, any form of waste energy ends up as thermal energy that goes to the environment. Thus, thermal pollution is increasing day by day causing global warming.

5.6 Power

In many cases, the time to do work is as important as the amount of work done. Suppose you walk up to a height '*h*' through upstairs (Fig. 5.14). You do work, because you are lifting your body up the stairs. If you run up, you can reach the same height in a shorter time interval.

Fig. 5.14

The work done is the same in either case, because the net result is that you lifted up the same weight *w* to the same height *h*. But you know that if you run up the stairs, you would be more tired than you walked up slowly. In fact, there is a difference in the rate at which work is done. We say that you expend more energy when you go up the stairs rapidly than when you go slowly.

The concept of power can also be explained with another example of an electric motor or a water pump. A bigger motor draws more water during the same interval of time as compared to a smaller one. It is said that the power of bigger motor is greater than that of smaller one.

> Power is defined as the time rate of doing work.

Mathematically,

$$Power = \frac{Work}{Time}$$

If *W* is the work done in time *t*, then

$$P = \frac{W}{t} \quad .... (5.5)$$

Power of any agency can also be defined as energy transferred per unit time.

Units of Power

Since both work and time are scalar quantities, so according to Eq.(5.5) power is also a scalar quantity. The SI unit of powers is watt (W).

One watt is the work done at the rate of one joule per second.

$$1\ W = \frac{1\ J}{1\ s} \quad \text{or} \quad 1\ J\ s^{-1}$$

Bigger Units of power are:

$$1\ kW = 10^3\ W$$

$$1\ MW = 10^6\ W$$

In British engineering system, the unit of power used is horse-power (hp). The horse power is defined as:

$$1\ hp = 746\ W$$

Do You Know?

Appliance	Av. Power (watts)
Energy saver	23
Tube light	40
Electric fan	80
Bulb	100
T.V.	200
Washing machine	250
Refrigerator	600
Electric iron	1000
Toaster	1000
Microwave oven	1200
Air conditioner	2500

Example 5.4

A 1000 kg car moving with an acceleration of 4 m s^{-2} covers a distance of 50 m in 5 seconds. What is the power generated by its engine?

Solution

Mass of car m = 1000 kg

Acceleration a = 4 m s^{-2}

Distance S = 50 m

Time taken t = 5 s

Power P = ?

First, we shall determine the force applied by Newton's second law.

$$F = ma = 1000\ kg \times 4\ m\ s^{-2} = 4000\ N$$

From Eq. (5.1), Work, $W = FS$

Or $W = 4000\ N \times 50\ m = 2.0 \times 10^5\ J$

From Eq. (5.5), $P = \frac{W}{t}$

Putting the values of W and t, we have

$$P = \frac{2.0 \times 10^5\ J}{5\ s} = 4 \times 10^4\ W = 40\ kW$$

For Your Information!

The watt is named in honour of James Watt (1736-1819), a Scottish engineer who perfected the steam engine.

5.7 Efficiency

The efficiency of a working system tells us what part of the energy can be converted into the required useful form of energy and what part is wasted out of the energy available.

The available energy for conversion is usually called the input energy and the energy converted into the required form is known as the output energy.

The efficiency of a system is defined as:

Do You Know?

Activity	Average Efficiency (%)
Diesel engine	35
Petrol engine	25
Electric motor	80
Bicycle	15

For Your Information!

A machine with its output equal to input is called an ideal machine with efficiency 100%.

The ratio of useful output energy and the total input energy is called the efficiency of a working system.

or $$\text{Efficiency} = \frac{\text{Useful output energy}}{\text{Total input energy}}$$

Efficiency is often multiplied by 100 to give percentage efficiency. Thus,

$$\text{Percentage Efficiency} = \frac{\textit{Useful output energy}}{\textit{Total input energy}} \times 100$$

It can also be given as:

$$\text{Percentage Efficiency} = \frac{\textit{Useful power output}}{\textit{Total power input}} \times 100 \quad \text{..........} \quad (5.6)$$

It is found that the energy output is always less than the energy input. During any conversion of energy, some energy is wasted in the form of heat. No device has yet been invented that may convert all the input energy into required output. That is why a system cannot have an efficiency of 100 %. As the energy losses are inevitable in the working of a machine, hence, an ideal or perpetual machine cannot be constructed.

Example 5.5

A block weighing 120 N is dragged up a slope with a force of 100 N to lift it up a height of 10 m. If the slope is 20 m long, calculate the efficiency of the system.

Solution

Weight of block	$W = 120\ \text{N}$
Force applied	$F = 100\ \text{N}$
Distance	$S = 20\ \text{m}$
Height	$h = 10\ \text{m}$

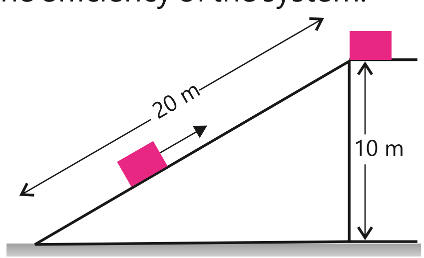


Fig. 5.15

% Efficiency = ?

Work done to lift the block up is:

$$W = F \times S = 100\ \text{N} \times 20\ \text{m} = 2000\ \text{J}$$

Now, total input energy = work done on the block = 2000 J

Useful output energy = Gravitational potential energy gained = *wh*

$$= 120\ \text{N} \times 10\ \text{m} = 1200\ \text{J}$$

$$\text{Percentage Efficiency} = \frac{\textit{Useful output energy}}{\textit{Total input energy}} \times 100$$

$$= \frac{1200\ \text{J}}{2000\ \text{J}} \times 100 = 60\%$$

EXERCISE

A Multiple Choice Questions

Tick (✓) the correct answer.

5.1 Work done is maximum when the angle between the force *F* and the displacement *d* is:

(a) 0° (b) 30° (c) 60° (d) 90°

5.2 A joule can also be written as:

(a) $kg\ m\ s^{-2}$ (b) $kg\ m\ s^{-1}$ (c) $kg\ m^2 s^{-3}$ (d) $kg\ m^2 s^{-2}$

5.3 The power of a water pump is 2 kW. The amount of water it can raise in one minute to a height of 5 metres is:

(a) 1000 litres (b) 1200 litres (c) 2000 litres (d) 2400 litres

5.4 A bullet of mass 0.05 kg has a speed of 300 $m\ s^{-1}$. Its kinetic energy will be:

(a) 2250 J (b) 4500 J (c) 1500 J (d) 1125 J

5.5 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

5.6 The magnitude of momentum of an object is doubled, the kinetic energy of the object will:

(a) double (b) increase to four times

(c) reduce to one-half (d) remain the same

5.7 Which of the following is not renewable energy source?

(a) Hydroelectric energy (b) Fossil fuels

(c) Wind energy (d) Solar energy

B Short Answer Questions

5.1 A slow-moving car may have more kinetic energy than a fast-moving motorcycle. How is this possible?

5.2 A force F_1 does 5 J of work in 10 s. Another force F_2 does 3 J of work in 5 s. Which force delivers greater power?

5.3 A woman runs up a flight of stairs. The gain in her gravitational potential energy is 4500 J. If she runs up the same stairs with twice the speed, what will be her gain in potential energy?

5.4 What is power? Define the unit used for it.

5.5 Differentiate between renewable and non-renewable energy sources.

C Constructed Response Questions

5.1 Can the kinetic energy of a body ever be negative?

5.2 Which one has the greater kinetic energy; an object travelling with a velocity v or an object twice as heavy travelling with a velocity of ½ v?

5.3 While playing cricket on a street, the ball smashes a window pane. Describe the energy changes in this event.

5.4 A man rowing boat upstream is at rest with respect to the shore. Is he doing work?

5.5 A cyclist goes downhill from the top of a steep hill without pedalling and takes it to the top of the next hill.

(i) Draw a diagram of what happened.

(ii) Analyse this event in terms of potential and kinetic energy. Label your diagram using these terms.

5.6 Is timber or wood renewable source of heat energy? Comment.

D Comprehensive Questions

5.1 What is meant by kinetic energy? State its unit. Describe how it is determined.

5.2 State the law of conservation of energy. Explain it with the help of an example of a body falling from certain height in terms of its potential energy and kinetic energy.

5.3 Explain what is meant by efficiency of a machine. How is it calculated? Why there is a limit for the efficiency of a machine?

E Numerical Problems

5.1 A force of 20 N acting at an angle of 60° to the horizontal is used to pull a box through a distance of 3 m across a floor. How much work is done?

(30 J)

5.2 An engine raises 100 kg of water through a height of 80 m in 25 s. What is the power of the engine?

(3200 W)

5.3 A body of mass 20 kg is at rest. A 40 N force acts on it for 5 seconds. What is the kinetic energy of the body at the end of this time?

(1000 J)

5.4 A 0.14 kg ball is thrown vertically upward with an initial velocity of 35 m s^{-1}. Find the maximum height reached by the ball.

(61.25 m)

5.5 A girl is swinging on a swing. At the lowest point of her swing, she is 1.2 m from the ground, and at the highest point she is 2.0 m from the ground. What is her maximum velocity and where?

(4 m s^{-1}, at the lowest position)

5.6 A person pushes a lawn mower with a force of 50 N making an angle of 45° with the horizontal. If the mower is moved through a distance of 20 m, how much work is done?

(707 J)

5.7 A box of mass 10 kg is pushed up along a ramp 15 m long with a force of 80 N. If the box rises up a height of 5 m, what is the efficiency of the system?

(41.7%)

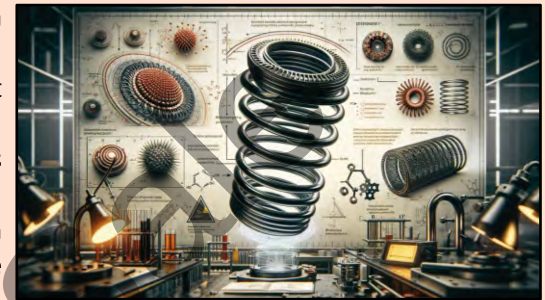
5.8 A force of 600 N acts on a box to push it 5 m in 15 s. Calculate the power.

(200 W)

Chapter 6 Mechanical Properties of Matter

Student Learning Outcomes

After completing this chapter, students will be able to:



- Illustrate that forces may produce a change in size and shape of an object.
- Define and calculate the spring constant [apply the equation, spring constant = force/extension $k = F/x$ to solve problems involving simple springs]
- Sketch, plot and interpret load–extension graphs for an elastic solid and describe the associated experimental procedures.
- Define and use the term 'limit of proportionality' for a load-extension graph [Including identifying this point on the graph (an understanding of the elastic limit is not required)]
- Define and calculate density.
- Define and calculate pressure [As force per unit area. Use the equation pressure = force/area $P = F/A$ to solve simple problems]
- Describe how pressure varies with force and area in the context of everyday examples
- Describe how pressure at a surface produces a force in a direction at right angles to the surface [can make reference to experiments to verify this principle]
- Justify that the atmosphere exerts a pressure.
- Describe that atmospheric pressure decreases with the increase in height above the Earth's surface.
- Explain that changes in atmospheric pressure in a region may indicate a change in the weather.
- Analyse the workings and applications of a liquid barometer
- Justify and analyse quantitatively how pressure varies with depth in a liquid
- Describe the working and applications of a manometer
- Define and apply Pascal's law [Apply Pascal's law to systems such as the transmission of pressure in hydraulic systems with particular reference to the hydraulic press and hydraulic brakes on vehicles.]

You have learnt in lower classes that every thing around us is made up of matter. The matter normally exists in solid, liquid and gaseous states. These states are due to attractive force that exists between the atoms and molecules. We have already studied some basic properties of matter. In this chapter, we will discuss mechanical properties of matter that are of vital importance of a material for various useful purposes in technology and engineering. The main contents included in this chapter are: deformation of solids due to some applied force, density and pressure.

6.1 Deformation of Solids

We have observed that an external force applied on an object can change its size or shape. Such a force is known as deforming force. For example, an appropriate force applied to a spring can increase its length called extension or cause compression thus reducing its length. If this force is removed, the spring will restore its original size and shape. Similarly, stretched rubber strip or band comes to its original shape and size on removing the applied force.

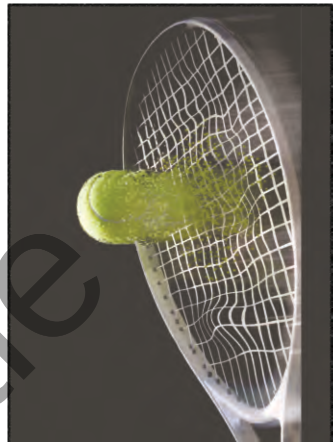


Fig. 6.1

When a tennis ball is hit by a racket, the shapes of tennis ball and also racket strings are distorted or deformed (Fig. 6.1). They regain their original shape after bouncing of the ball by the racket. An object is said to be elastic, if after removal of the deforming force, it restores to its original size and shape. This property of the material is known as elasticity. Due to this property, we can determine the strength of a material and the deformation produced under the action of a force.

For Your Information!

Some materials such as clay dough or plasticine do not return to their original shape after the removal of the deforming force. They are known as inelastic materials.

Most of the materials are elastic up to a certain limit known as elastic limit. Beyond the elastic limit, the change becomes permanent. The object or material does not regain its original shape or size even after the removal of the deforming force.

6.2 Hooke's Law

If a force F is applied on a spring to stretch or compress it, the extension or compression x has been found directly proportional to the applied force within the elastic limit. Thus,

$$F \propto x$$

or $$F = kx$$ or $$k = \frac{F}{x} \quad \text{........ (6.1)}$$

where k is the constant of proportionality and is known as spring constant. In fact, it is a measure of stiffness of the spring. The greater the value of spring constant, the greater will be the stiffness or strength of the spring. Its unit is N m^{-1}.

A graph of force against extension is a straight line passing through the origin. If the applied force or load exceeds the elastic limit of the spring, it is permanently deformed and its graph will no longer remain linear. The gradient or slope of force-extension graph is a measure of spring constant *k*.

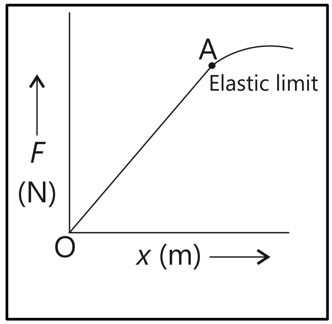


Fig. 6.2

Hooke's law also holds when a force is applied to a straight thin wire or a rubber band within its elastic limit.

Quick Quiz

1. If the above experiment is repeated with a stiffer spring (high value of *k*), what will be the effect on the graph?
2. How can you find the value of unknown weight using this experiment?

6.3 Density

If you take equal volumes of different substances and weigh them by a balance, you will find that each of them has a different mass. That is, one centimetre cube of wood may weigh only 0.7 g but made of iron will weigh 8.0 g. Why is it so? You know that all substances are composed of molecules. The molecules of different substances are different in size and mass. The inter-molecular spacing is also different.

The mass of equal volume of various substances actually is the mass of the total number of molecules present in that volume. Naturally, the substance whose molecules are densely packed and also which are heavy will weigh more than others.

For Your Information!

Packing foam or polythene has a very low density.

Density of a substance is defined as its mass per unit volume.

$$\text{Density} = \frac{\text{Mass}}{\text{Volume}} \quad \text{............ (6.2)}$$

The SI unit of density is kg m^{-3}. Other unit also in use is g cm^{-3}. Table 7.1 shows the density of some substances.

Table 7.1

Substance	Density (kg m^{-3})
Air	1.3
Patrol	800
Water	1000
Concrete	2400
Aluminum	2700
Steel	7800
Lead	11400
Gold	19300
Osmium	22600

The architects and engineers take special care of the density of the building material to be used in designing and constructing roads, bridges and buildings. The density of building material is essential for estimating the strength required in foundations and supporting pillars.

Example 6.1 The length, breath and thickness of an iron block are 3 cm, 2 cm, 2 cm respectively. Calculate the density of iron if the mass of block is 94 g.

Solution

Length = 3 cm, Breath = 2 cm,

Thickness = 2 cm, Mass = 94 g, Density = ?

Using Eq. 6.2 $$\text{Density} = \frac{\text{Mass}}{\text{Volume}}$$

where Volume $= \text{Length} \times \text{Breadth} \times \text{Thickness}$

$= 3\text{ cm} \times 2\text{ cm} \times 2\text{ cm} = 12\text{ cm}^3$

$$\text{Hence, Density} = \frac{94\text{ g}}{12\text{ cm}^3} = 7.8\text{ g cm}^{-3}$$

Thus, density of iron $= 7800\text{ kg m}^{-3}$

6.4 Pressure

If a wooden rod has a flat end, it will be very difficult to push it into ground. On the other hand, if it has a pointed end, it can be easily pushed into the ground. In the first case, the applied force is spread over a large area, whereas in the second case, the force is concentrated on a small area. The force applied on the rod will exert greater pressure in the second case than in the first one.

> Pressure is defined as the force exerted normally on unit area of an object.

If F is the force acting normally on a surface of area A, then pressure P on the surface is given by

$$P = \frac{F}{A} \quad \text{............} \quad (6.3)$$

For Your Information!

Immiscible liquids of different densities form layers when they are mixed.

Quick Quiz

How will you measure the volume if the object is lighter than the liquid?

For Your Information!

Density is a test to know the purity of a substance.

Quick Quiz

By which property can you identify a silver spoon and a stainless steel spoon?

For Your Information!

The force in both the pictures is same, equal to weight of the bag. In right hand picture, the area of contact is the greater than in the left hand picture. We say that the pressure is less in the right hand picture.

For Your Information!

Sports boots for football and hockey have studs on their soles. They reduce the area in contact between your feet and the ground. This increases the pressure and your feet grip the surface more firmly.

The area A on which the force acts is usually referred as contact area. Equation (6.3) shows that for a certain force, the pressure can be very large if the contact area A is small.

In the system international, the unit of pressure is N m^{-2} and is called pascal (Pa).

Daily Life Examples

Fig. 6.3 Chopper

1. The edge of the blade of a chopper is made very sharp. When we apply force on the handle of the chopper to cut an object, the pressure on the object, at the contact surface, due to its small area becomes very high and the object is easily cut (Fig. 6.3).
2. The top of a thumb pin is flat but the end of the pin is very sharp. So, the contact area is very small. When we apply a force at the top, the pressure at the end of pin is so high that it pierces into the wooden board (Fig. 6.4).
3. When we walk on ground, we exert a force on it due to which we experience a reaction force. When the ground is flat, this reaction force is spread over the whole area of the foot and the pressure due to reaction force is not painful. But when we walk on pebbles, the contact area is reduced. Then the pressure due to reaction force becomes so high that it becomes painful.
4. Heavy animals like elephant have thick legs and large flat feet so that due to large contact area, pressure becomes less otherwise, their bones would not tolerate the pressure.

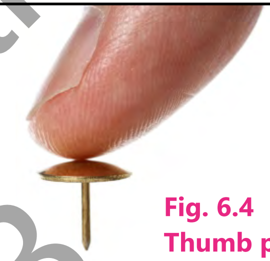


Fig. 6.4 Thumb pin

Brain Teaser!

Why a bulldozer has large pillar tracks instead of wheels?

6.5 Pressure in Liquids

We have learnt in the lower classes that liquids exert pressure in all directions. Moreover, liquid pressure increases with depth.

Let us determine the pressure at a certain depth of a liquid. Figure. 6.8 shows a container of liquid. Consider an area A in the liquid at depth h. The force acting on this area is equal to the weight of the liquid column over surface A. The volume of this liquid is $V = Ah$. If ρ is the density of liquid, then mass m of the liquid column will be:

$$m = \rho V = \rho A h$$

Therefore, force acting on area A will be

$F = mg = \rho Ahg$

The pressure P at area A will be,

$$P = \frac{F}{A} = \frac{\rho Ahg}{A}$$

Or $$P = \rho gh \quad \text{.....................(6.4)}$$

Equation 6.4 shows that pressure in a liquid increases with depth. The value of pressure depends on the depth and density of the liquid.

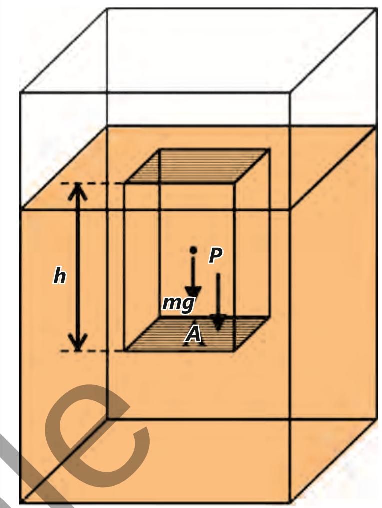


Fig. 6.5 Pressure in a liquid

Pressure produces force at right angle to the surface. A force or its component that is parallel to the surface, does not contribute to pressure. The pressure, by definition, is only contributed by the normal component of the force. That is, the forces in a liquid that push directly against the surface and add up to a net force is perpendicular to the surface. If there is a hole in the surface of the liquid container, the liquid spurts at right angle to the surface before curving downward due to gravity.

Example 6.2

Calculate the pressure of column of mercury 76 cm high. Density of mercury is 13.6×10^3 kg m^{-3}.

Solution

Density $\rho = 13.6 \times 10^3$ kg m^{-3}

Height $h = 76$cm $= 76 \times 10^{-2}$m

$g = 10$ m s^{-2}

As Pressure $= \rho gh$

$\therefore$ $P = 13.6 \times 10^3 \text{ kg m}^{-3} \times 10 \text{ m s}^{-2} \times 76 \times 10^{-2} \text{ m}$

$P = 1.034 \times 10^5 \text{ kg m}^{-3} \times \text{m s}^{-2} \times \text{m}$

$P = 1.034 \times 10^5 \text{ N m}^{-2}$

$P = 1.034 \times 10^5$ Pa

For Your Information!

Some liquids under pressure can dissolve more gas than a liquid at a lower pressure. When we open a bottle of soda water, the pressure in the bottle is decreased. The liquid can no longer hold as much gas. The dissolved gas comes out of the solution and rises to the surface of the liquid in the form of bubbles.

Example 6.3

A cylindrical water tank 2 m deep has been built on the top of a building 20 m high. What will be the pressure of water at the ground floor when the tank is full? Density of water is 1000 kg m^{-3}. Take $g = 10$ m s^{-2}.

Solution

Height $h = 2 + 20 = 22\,m$

Density $\rho = 1000\ kg\,m^{-3}$

$g = 10\,m\,s^{-2}$

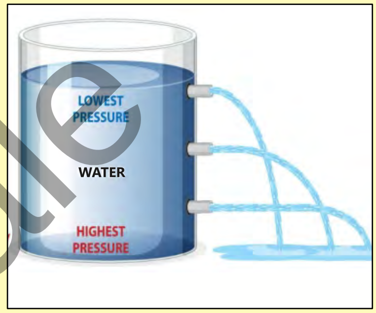
$P = \rho gh = 22\,m \times 1000\,kg\,m^{-3} \times 10\,m\,s^{-2}$

$= 220000\,Pa = 2.2 \times 10^5\,Pa$

Activity 6.1

Teacher should help the students to perform this activity and initiate discussion as per instructions:

i. Make three small holes at different heights in the side of a container as shown in the figure.
ii. Fill the container with water.
iii. Observe the water streams flowing out of the holes. It is initially normal to the surface.
iv. Which one of the streams hits the ground at larger distance?
v. At which position the liquid has more pressure?



You will observe that the stream from each hole, initially flows out normal to the surface before curving down due to gravity and the lowest hole has more pressure. It shows that liquid pressure increases with depth.

6.6 Atmospheric Pressure

The Earth is surrounded by a layer of air which we call atmosphere. We know that air is a mixture of gases. Their molecules are always in motion. They collide with one another and with all other objects coming in their way. Thus, they exert force on the objects. This force per unit area is the atmospheric pressure. Since the molecules of air have random motion, therefore, atmospheric pressure acts equally in all directions.

The atmosphere exerts pressure on the surface of the Earth and on everything on the Earth. This pressure is called atmospheric pressure.

Atmospheric pressure extends up to a height of about 100 kilometres. The density of air is not the same in the atmosphere. It decreases continuously with altitude.

Do You Know?

The pressure of 1 atmosphere is equivalent to placing a 1.0 kg mass (10 N weight) on an area of 1 cm^2.

We live at the bottom of the Earth's atmosphere which is a fluid that exerts pressure on our bodies. At sea level, the value of atmospheric pressure is about 1.013×10^5 Pa. This value is referred to as standard atmospheric pressure. It is an enormous pressure which can crush anything. We do not feel it because practically all the bodies have air inside them. As atmospheric pressure acts in all directions, so it balances the pressure inside.

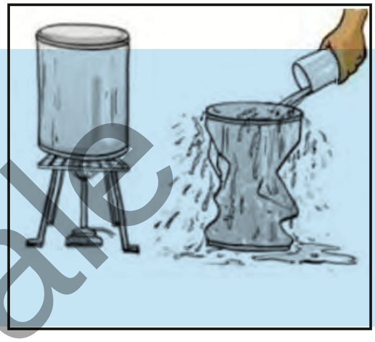
Evidence of Atmospheric Pressure

We can observe the force of the atmospheric pressure if we remove the inside air from a vessel as shown in the following activity.

Activity 6.2

The teacher should perform this activity in the class following the given instructions.

Boil some water in a tin can. When it is full of steam, remove it from the burner and close its mouth by an air tight cork. Then pour cold water over it. The can crumples as shown in the figure. Why does the tin crumples?



Variation of Atmospheric Pressure with Height

We have studied that pressure in a liquid increases with depth. At depth h, the pressure of liquid is given by

$$P = \rho g h$$

This formula is applicable to all the fluids. As the gases of the atmosphere are also fluid, therefore, the atmospheric pressure should be maximum on the ground at sea level. As we go up in the air, atmospheric pressure decreases. At a height of about 5 km, it falls to 55 kPa and at a height of 30 km, it falls to 1 kPa. By measuring the atmospheric pressure at a point in air, altitude of that point can be determined. The lower the atmospheric pressure, the greater is the altitude.

6.7 Measurement of Atmospheric Pressure

Atmospheric pressure is usually measured by the height of mercury column which it can support. Instruments which measure the atmospheric pressure are called barometers. A simple mercury barometer consists of a glass tube about one metre long that is closed at one end. It is completely filled with mercury, then it is inverted vertically in a dish of mercury. A metre scale is placed by the side of the tube to measure the height of mercury column (Fig. 6.6). The space in glass tube over the top of the mercury is completely empty. The pressure is almost

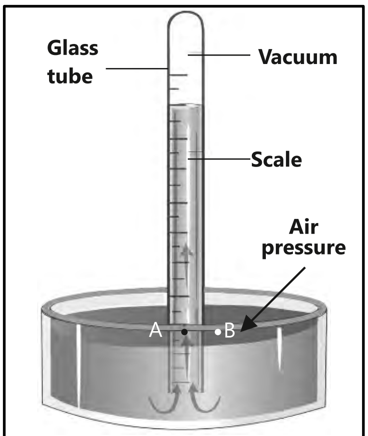


Fig 6.6 Barometer

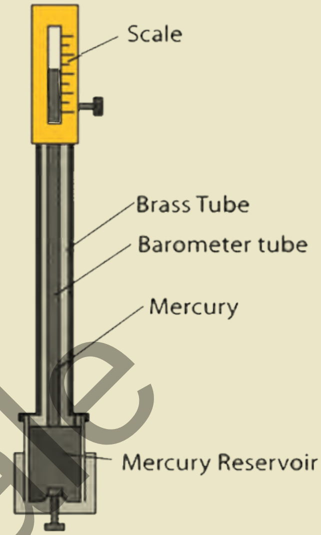
zero.

The pressure P, at point A in the mercury column is the same as at point B at the surface of mercury in the dish because both the points are at the same level. This is equal to the atmospheric pressure $P = \rho g h$ acting at the surface of mercury in the dish.

For Your Information!

Air pressure guage which is used to measure the pressure in motor car tyres.

For Your Information!



A Fortin's Barometer is used in laboratories to measure the atmospheric pressure.

If we put $P = 1.013 \times 10^5$ Pa at sea level, $\rho = 13.6 \times 10^3$ kg m^{-3} for mercury, the height of mercury column comes out to be 760 mm. By using this instrument, atmospheric pressure at any altitude in the air can be measured in terms of height of mercury column.

Quick Quiz

Would you exert more, same or less pressure on the ground if you stand on one foot instead of two feet?

Changes in Atmospheric Pressure as Weather Indicator

The atmospheric pressure does not always remain uniform but flactuates. By observing the variation, the meteorologists can forecast the weather conditions.

Quick Quiz

Can we use water in place of mercury to construct a barometer? Explain why.

Atmospheric pressure depends upon the density of air. At high altitudes, where the air is less dense, the atmospheric pressure falls down. Similarly, increase in the quantity of water vapours also decreases the density. Thus, atmospheric pressure becomes low in cloudy regions. Weather casters use this knowledge to predict rains. A fall in pressure often means that rain clouds are on the way and the rain is to follow.

6.8 Measurement of Pressure by Manometer

A simple manometer consists of a U-shaped glass tube which contains mercury. In the beginning, the atmospheric pressure at the two open ends of the tube is the same and hence, mercury level in the two arms remains same (Fig. 6.7). If on connecting a gas cylinder with short arm keeping the longer arm of the tube open, the mercury level in short arm is lower than that in the long arm (Fig. 6.8), then the unknown pressure is more than the atmospheric pressure. If the mercury level in the short arm is more than the long arm (Fig.6.9), then the unknown pressure is less than the atmospheric pressure.

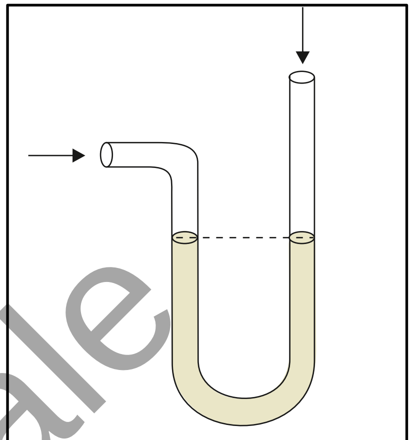


Fig. 6.7 manometer

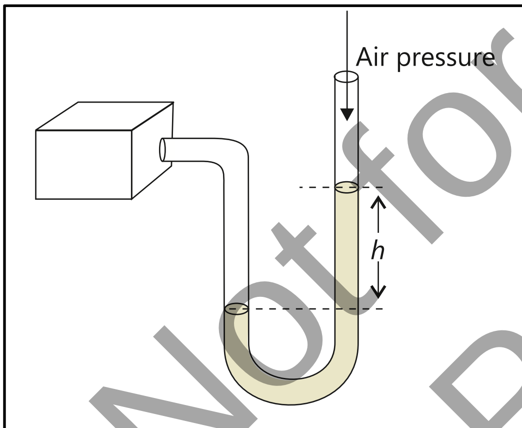


Fig. 6.8

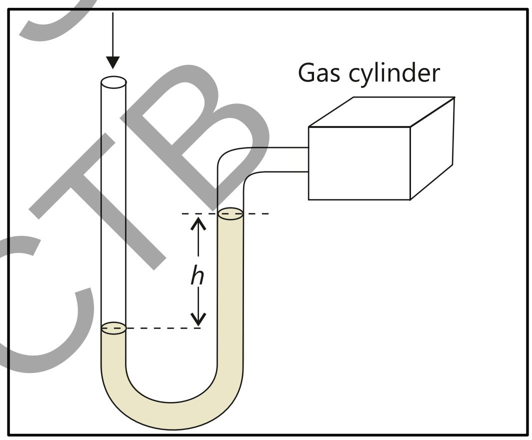


Fig. 6.9

6.9 Pascal's Law

When we inflate a balloon, we blow air in it with a certain pressure but the balloon blows uniformly from all sides. It means that the pressure applied at its mouth has been transmitted uniformly in all directions. Similarly, when a motorbike tyre is inflated, air pressure is applied at one point but the tyre is uniformly inflated from all sides. This indicates that pressure is transmitted to each part of the tyre.

Some Typical Pressures

Location	Pressure (Pa)
Sun's centre	2×10^{16}
Earth's centre	2×10^{11}
Deepest ocean trench	1.1×10^{18}
A motor tyre	2×10^{5}
Standard atmospheric	1.013×10^{5}
Blood pressure	1.6×10^{4}
On mount Everst	4×10^{4}
On mars	7×10^{2}

Activity 6.3

Teacher should demonstrate or help the students to perform by following the instructions given below:

(i) Fill a polythene shopping bag with water.

(ii) Poke several holes by using a pin on the bag.

(iii) Squeeze the bag gently.

(iv) What do you observe?

Squeezing the top of bag causes the water to squirt on in all directions. It means the pressure is transmitted equally throughout the liquid.

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

This is the statement of Pascal's law.

The technology of hydraulic systems is based on Pascal's law. Its main advantages are:

(i) Liquids do not absorb any of the supplied energy.

(ii) They are capable of moving much heavy loads and providing great forces due to incompressibility.

Some useful hydraulic systems are:

1. Hydraulic press
2. Car lift at service stations
3. Hydraulic brakes of vehicles

Hydraulic Press

Consider a specially designed container as shown in Fig. 6.10. In this container there are two cylinders joined by means of a pipe. The cross-sectional area of the smaller cylinder is A_1 and that of the larger one is A_2. The cylinders are filled with some incompressible liquid.

Suppose that the small piston is pressed down by applying a force F_1. The pressure $P = F_1 / A_1$ produced by small piston is transmitted equally to the large piston.

Due to this pressure P, a force F_2, will act on A_2, which is given by

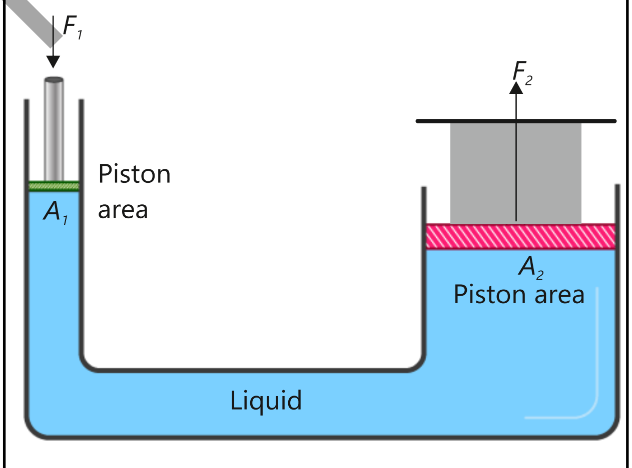


Fig. 6.10

$F_2 = PA_2$

Putting the value of P,

$$F_2 = \frac{F_1}{A_1} A_2 \quad \text{.........................} \quad (6.5)$$

Since $A_2 > A_1$, therefore, $F_2 > F_1$. The result indicates that a small force applied on the smaller piston, results into a large force on the larger piston. Such a system is known as **force multiplier**.

A hydraulic press works on this principle. Cotton bale or any other object to be compressed is placed over the larger piston. A force F_1 is applied on the smaller piston. The pressure P produced by smaller piston is transmitted equally to the larger piston. A much greater force F_2 acts on it. This force lifts the larger piston and compresses the cotton bale.

This principle is also used at service stations to lift cars for washing (Fig. 6.11).

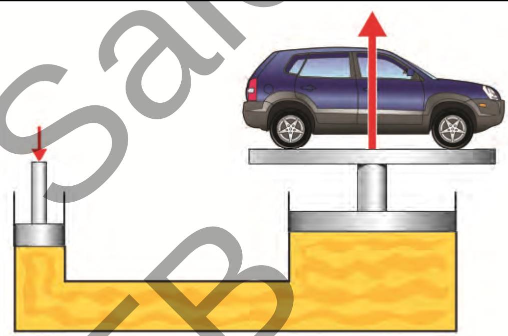


Fig. 6.11

Example 6.4

The diameters of the pistons of a hydraulic press are 5 cm and 25 cm respectively. A normal force of 160 N is applied on the smaller piston, what will be the pressure exerted by this force on the bigger piston? How much weight can be lifted by the other piston?

Solution

Let the areas of cross-sections of the pistons be A_1 and A_2 and their radii be r_1 and r_2 respectively.

Putting the values of $r_1 = \frac{5}{2}$ cm $= 2.5 \times 10^{-2}$ m $\quad r_2 = \frac{25}{2}$ cm $= 12.5 \times 10^{-2}$ m

$$A_1 = \pi r_1^2 \qquad \text{and} \qquad A_2 = \pi r_2^2$$

Force on the smaller piston $F_1 = 160$ N. Its pressure on the piston is

$$P = \frac{F_1}{A_1} = \frac{F_1}{\pi r_1^2}$$

If the weight lifted by the bigger piston is w, then according to the Pascal's law.

$$\frac{F_1}{A_1} = \frac{w}{A_2}$$

or $$w = \frac{F_1 A_2}{A_1} = \frac{F_1 \pi r_2^2}{\pi r_1^2} = \frac{F_1 \times r_2^2}{r_1^2}$$

Putting the values,

$$w = 160\ \text{N} \times (12.5 \times 10^{-2}\ \text{m})^2\ /\ (2.5 \times 10^{-2}\ \text{m})^2 = 4000\ \text{N} = 4\ \text{kN}$$

So, we can lift 4000 N weight by applying a force of 160 N on smaller piston.

Hydraulic Brakes

The brakes of some vehicles work on Pascal's law. In such type of brakes, cylinders with pistons are attached to the wheels. The brake pedal is attached to a master cylinder having smaller area of cross-section. Master cylinder is connected to all the larger cylinders attached to the wheel through pipes as shown in Fig. 6.12. Oil is filled in this system. When pedal is pushed down, the piston applies pressure on the liquid in the master cylinder. The liquid pressure is transmitted equally to all the larger pistons of other cylinders. This pressure causes these pistons to move outward pressing the brake pads towards brake discs or brake drums. Force of friction between the pads and discs or drums slows down the vehicle. When pressure is released from the pedal, the springs pull back the brake pads and wheels again turn freely.

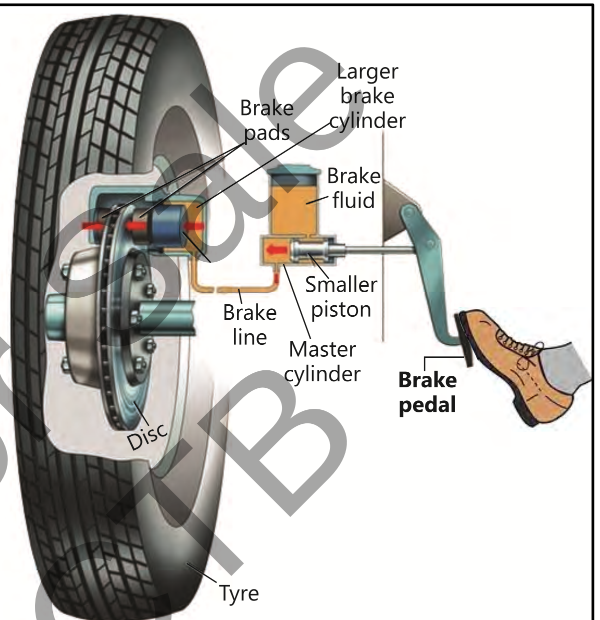


Fig. 6.12 Hydraulic brake system

EXERCISE

A Multiple Choice Questions

Tick (✓) the correct answer.

6.1. A wire is stretched by a weight *w*. If the diameter of the wire is reduced to half of its previous value, the extension will become:

(a) one half (b) double
(c) one fourth (d) four times

6.2. Four wires of the same material are stretched by the same load. Their dimensions are given below. Which of them will elongate most?
(a) Length 1 m, diameter 1 mm (b) Length 2 m, diameter 2 mm
(c) Length 3 m, diameter 3 mm (d) Length 4 m, diameter 0.5 mm

6.3. Two metal plates of area 2 and 3 square metres are placed in a liquid at the same depth. The ratio of pressures on the two plates is:
(a) 1:1 (b) $\sqrt{2} : \sqrt{3}$
(c) 2:3 (d) 4:9

6.4. The pressure at any point in a liquid is proportional to:
(a) density of the liquid
(b) depth of the point below the surface of the liquid
(c) acceleration due to gravity
(d) all of the above

6.5. Pressure applied to an enclosed fluid is:
(a) increased and applied to every part of the fluid
(b) diminished and transmitted to the walls of container
(c) increased in proportional to the mass of fluid and then transmitted to each part of the fluid
(d) transmitted unchanged to every portion of the fluid and walls of containing vessel

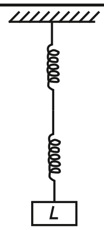
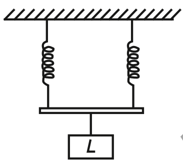
6.6. What is the force exerted by the atmosphere on a rectangular block surface of length 50 cm and breadth 40 cm? The atmospheric pressure is 100 kPa.
(a) 20 kN (b) 100 kN (c) 200 kN (d) 500 kN

B Short Answer Questions

6.1 Why heavy animals like an elephant have a large area of the foot?
6.2 Why animals like deer who run fast have a small area of the foot?
6.3 Why is it painful to walk bare footed on pebbles?
6.4 What is Hooke's Law? Does an object remain elastic beyond elastic limit? Give reason.
6.5 Distinguish between force and pressure.
6.6 What is the relationship between liquid pressure and the depth of the liquid?
6.7 What is the basic principle to measure the atmospheric pressure by a simple mercury barometer?
6.8 State the basic principle used in the hydraulic brake system of the automobiles.

C Constructed Response Questions

6.1. A spring having spring constant *k* hangs vertically from a fixed point. A load of weight *L*, when hung from the spring, causes an extension *x*, the elastic limit of the spring is not exceeded.
Some identical springs, each with spring constant *k*, are arranged as shown below:
For each arrangement, complete the table by determining:
(i) the total extension in terms of *x*.
(ii) the spring constant in terms of *k*.

Arrangement	Total Extension *x*	Spring constant (*k*) of the arrangement
		
		

6.2 Springs are made of steel instead of iron. Why?

6.3 How does water pressure one metre below the surface of a swimming pool compare to water pressure one metre below the surface of a very large and deep lake?

6.4 What will happen to the pressure in all parts of a confined liquid if pressure is increased in one part? Give an example from your daily life where such principle is applied.

6.5 If some air remains trapped within the top of the mercury column of the barometer which is supposed to be vacuum, how would it affect the height of the mercury column?

6.6 The end of glass tube used in a simple barometer is not properly sealed, some leak is present. What will be its effect?

6.7 Comment on the statement. "Density is a property of a material not the property of an object made of that material."

6.8 How the load of a large structure is estimated by an engineer?

D Comprehensive Questions

6.1 What is Hooke's law? Give three applications of this law.

6.2 Describe the working and applications of a simple mercury barometer and a manometer.

6.3 Describe Pascal's Law. State its applications with examples.

6.4 On what factors the pressure of a liquid in a container depend? How is it determined?

6.5 Explain that atmosphere exerts pressure. What are its applications? Give at least three examples.

E Numerical Problems

6.1 A spring is stretched 20 mm by a load of 40 N. Calculate the value of spring constant. If an object causes an extension of 16 mm, what will be its weight? ($2\ kN\ m^{-1}$, 32 N)

6.2 The mass of 5 litres of milk is 4.5 kg. Find its density in SI units. ($0.9 \times 10^3\ kg\ m^{-3}$)

6.3 When a solid of mass 60 g is lowered into a measuring cylinder, the level of water rises from $40\ cm^3$ to $44\ cm^3$. Calculate the density of the solid. ($15 \times 10^3\ kg\ m^{-3}$)

6.4 A brick measures 5 cm × 10 cm × 20 cm. If its mass is 5 kg, calculate the maximum and minimum pressure which the brick can exert on a horizontal surface. (1×10^4 Pa, 25×10^2 Pa)

6.5 What will be the height of the column in barometer at sea level if mercury is replaced by water of density $1000\ kg\ m^{-3}$, where density of mercury is $13.6 \times 10^3\ kg\ m^{-3}$ (10.3 m)

6.6 Suppose in the hydraulic brake system of a car, the force exerted normally on its piston of cross-sectional area of $5\ cm^2$ is 500 N. What will be the pressure transferred to the brake oil? What will be the force on the second piston of area of cross-section $20\ cm^2$? [$1.0 \times 10^6\ N\ m^{-2}$, 2000 N]

6.7 The area of cross-section of the small and large pistons of a hydraulic press is respectively $10\ cm^2$ and $100\ cm^2$. What force should be exerted on the small piston in order to lift a car of weight 4000 N? (400 N)

6.8 If the pressure in a hydraulic press is increased by an additional $10\ N\ cm^{-2}$, how much extra load will the output platform support if its cross-sectional area is $50\ cm^2$? (500 N)

6.9 The force exerted normally on the hydraulic brake system of a car, with its piston of cross sectional area $5\ cm^2$ is 500 N. What will be the:

(a) pressure transferred to the brake oil?

(b) force on the brake piston of area of cross section $20\ cm^2$?

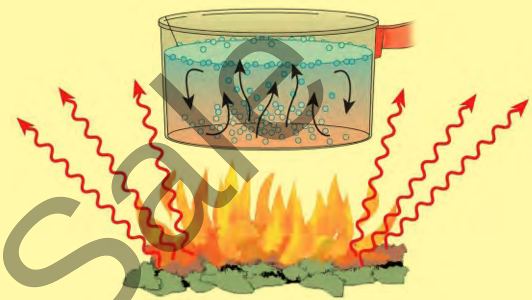
[(a) $1.0 \times 10^6\ N\ m^{-2}$, (b) 2000 N)]

Chapter 7

Thermal Properties of Matter

Student Learning Outcomes

After completing this chapter, students will be able to:



- Describe, qualitatively, the particle structure of solids, liquids and gasses [Including and relating their properties to the forces and distances between particles and to the motion of the particles (atoms, molecules, ions and electrons)].
- Describe plasma as a fourth state of matter [In which a significant portion of the material is made up of ions or electrons e.g. in stars, neon lights and lightning streamers].
- Describe the relationship between the motion of particles and temperature [including the idea that there is a lowest possible temperature (approx.-273°C), known as absolute zero, where the particles have least kinetic energy]
- State that an increase in the temperature of an object increases its internal energy
- Explain, with examples, how a physical property which varies with temperature may be used for the measurement of temperature
- Justify the need for fixed points in the calibration of thermometers [including what is meant by the ice point and steam point.]
- Illustrate what is meant by the sensitivity, range and linearity of thermometers.

Heat or thermal energy has always been the necessity of human beings, animals and plants in this world. Without heat, their existence would not have been possible. In the beginning, the Sun was the only source of light and heat. With the discovery of fire, a new era was started. The uses of heat produced from fire were increased day by day and contributed greatly to the comforts and facilities for the human being. Initially, the hot and cold objects were sensed by touching which was not a good standard to measure the degree of hotness of an object. So, man evolved different methods to measure it. After the invention of standard measuring devices, the temperature was also included in the list of basic physical quantities like mass, length and time.

This chapter begins with the introduction of kinetic molecular theory of particles of matter. It is due to the fact that temperature and heat or internal energy are associated with the motion of particles in the matter.

7.1 Kinetic Molecular Theory of Matter

According to this theory, matter is composed of very small particles called molecules which are always in motion. Their motion may be vibrational, rotational or linear. There exists a mutual force of attraction between the molecules known as intermolecular force. This force depends upon the distance between the molecules. It decreases with increasing distance between them.

The molecules possess kinetic energy due to motion and potential energy due to force of attraction. When a substance is heated, its temperature rises and its molecular motion becomes more vigorous which increases the kinetic energy of the molecules. Thus, the temperature of the substance depends upon the average kinetic energy of its molecules. In general, matter exists in three states solids, liquids and gases as shown in Fig. 7.1.

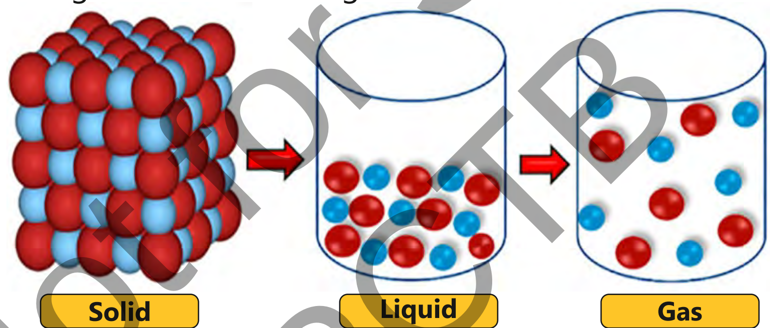


Fig. 7.1

Most of the properties of solids, liquids and gases can be explained on the basis of kinetic molecular theory of matter. In case of solids, the intermolecular forces are so strong that they keep the molecules bound. So, the molecules are held at fixed positions but still they show vibrational motion about their fixed points (Fig. 7.2). This is why, the solids have a definite shape and a definite volume.

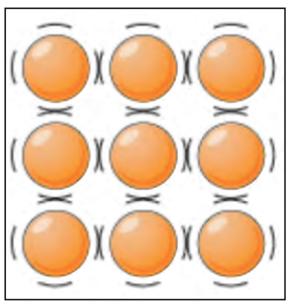


Fig. 7.2

In case of liquids, intermolecular force is so weak that it cannot hold the molecules at fixed positions and the molecules can slide over each other in random directions. A liquid, therefore, possesses a definite volume but has no definite shape. Due to flow of the molecules, it acquires the shape of the containing vessel.

Gas molecules are relatively far away from one another. Due to which, gas neither posseses a definite volume nor a definite shape.

Plasma

The plasma is a gas in which most of the atoms are ionized containing positive ions and electrons (Fig. 7.3-a). They are freely moving in the volume of the gas. Due to presence of positive ions and free electrons, plasma is the conducting state of matter. It allows electric current to pass through it. Since the gas in plasma state has properties which are quite different from ordinary gas, therefore, plasma is known as fourth state of matter. The Sun and the most of other stars are in plasma state. Plasma is also found in plasma TV and in gas discharge tubes (Fig. 7.3-b) when electric current passes through them. The plasma state also occurs during the early stages of lightning formation known as lightning streamers which are the conducting paths through the atmosphere due to ionized air molecules.

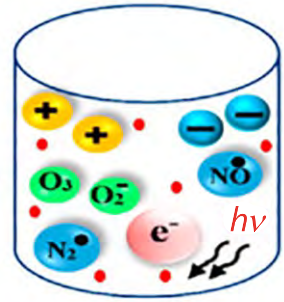


Fig. 7.3(a) Plasma


Fig. 7.3(b) Gas discharge tube

7.2 Temperature and Heat

When we touch ice, we feel cold. When we dip our fingers in warm water, we feel hot. Thus, by sense of touch we can tell which of the bodies is colder or hotter. A hotter body is said to be at higher temperature as compared to a colder body.

Temperature of a body is defined as degree of its hotness or coldness.

It is our common experience that when we heat a body, its temperature rises. Process of heating provides heat or **thermal energy** to the body which is the cause of the rise in temperature.

Fig. 7.4

The following activity will help to define temperature.

Activity 7.1

The teacher should arrange hot water in some tea cups, thermometers and metal spoons. Make groups of the students. Each group will put the spoon in the hot water and stir it. Ask them what do they feel. Does the other end of the spoon also become hot?

Do they observe that the spoon also gets hotter? It means heat is being transferred from the hot water to the spoon because the temperature of the water was higher than that of the spoon.

Thus

Temperature can be defined as a physical quantity which determines the direction of flow of thermal energy.

This means that thermal energy is transferred from one object to another due to temperature difference of the two bodies. Therefore, we can define heat as follows:

Heat is the energy which is transferred from one object to another due to difference of temperature between the two bodies.

Temperature and Internal Energy

We know that matter is composed of molecules which are always in motion. Molecules of a solid are vibrating about their fixed positions. The molecules of a liquid are sliding one over the other and those of gases are randomly moving. The molecules possess kinetic energy on account of their motion. Potential energy is also associated with molecules because of their attractive forces.

Fig. 7.5 The internal energy of air inside a hot-air balloon increases as the temperature increases.

The sum of kinetic and potential energies of the molecules of an object is called its internal energy.

When we heat a substance, its molecular motion becomes more vigorous which means an increase in its internal energy. As a result, temperature of the substance rises. The heat energy transferred to a body increases the internal energy of its molecules due to which its temperature rises.

Remember that, it is not true to say that a substance contains heat. The substance contains internal energy. The word heat is used only when referring to the energy actually in transit from hot to cold body.

7.3 Thermometers

Our sense of touch can tell us whether an object is hot or cold. It gives an idea about the object's temperature but we cannot measure the actual temperature of the body just by touching it. For the exact measurement of the hotness of a substance, we require an instrument called a thermometer.

Thermometers use some property of a substance, which changes appreciably with the change of temperature.

Basic Thermometric Properties

Some basic thermometric properties for a material suitable to construct a thermometer are the following:

1. It is a good conductor of heat.
2. It gives quick response to temperature changes.
3. It has uniform thermal expansion.
4. It has high boiling point.
5. It has low freezing point.
6. It has large expansivity (low specific heat capacity).
7. It does not wet glass.
8. It does not vapourize.
9. It is visible.

Liquid-in-Glass Thermometer

We know that liquids expand on heating. So, expansion in the volume of a liquid can be used for the measurement of temperature. This is known as liquid-in-glass thermometer. One such liquid which is commonly used in thermometers is mercury. Figure 7.6 shows a mercury thermometer. It is made of glass. It has a bulb at one end filled with mercury.

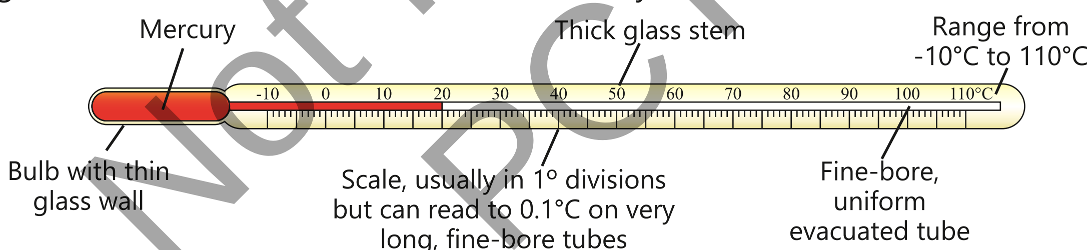


Fig. 7.6

When the temperature rises, the mercury expands and moves up through the narrow capillary tube in the form of a mercury thread. As shown in Fig. 7.6, the position of the end of thread reads the temperature. Mercury is opaque and can be easily seen due to its silvery colour. Alcohol is also a choice for the thermometric liquid, but it must be coloured to make it visible.

Point to Ponder!

Could we make mercury thermometer if expansion of glass would have been greater than mercury?

Brain Teaser!

(a) Why the walls of the thermometer bulb are thin?

(b) Why the inner bore must be narrow?

Temperature Scales

For the measurement of temperature, a scale is to be constructed which requires two reference temperatures called two fixed points. One is the steam point slightly above the boiling of water at standard atmospheric pressure. This corresponds to upper fixed point of the scale. The second fixed point is the melting point of pure ice or simply ice point. It is called the lower fixed point. Different scales of temperature have been constructed by assigning different numerical values to these fixed points. Three different scales are:

(i) Celsius or centigrade scale

(ii) Fahrenheit scale

(iii) Kelvin scale

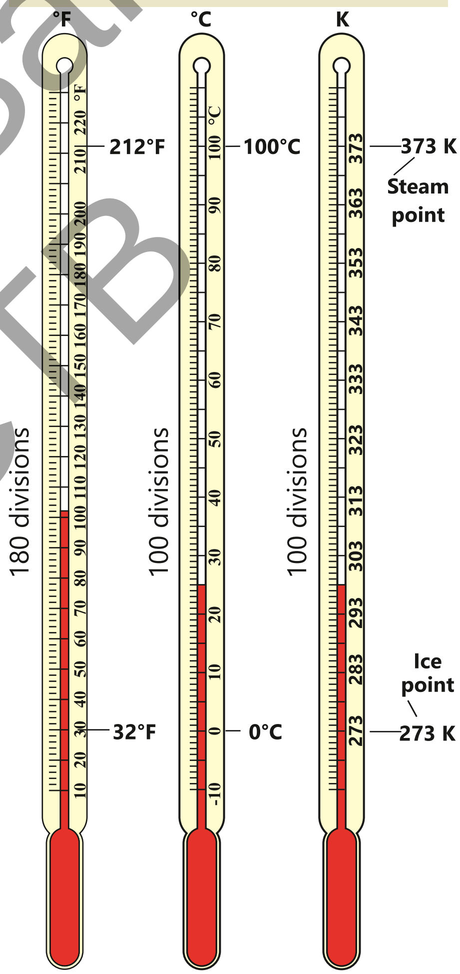
In Celsius or centigrade scale, the numerical values assigned to lower and upper fixed points are 0 and 100. As the difference between these values is 100, so the space between these points is divided into 100 equal parts. Each part is known as 1°C.

In Fahrenheit scale, the lower fixed point is labelled as 32 and upper as 212. As the difference between these two numbers is 180, so in this scale the space between these points is divided into 180 equal parts. Each part is known as 1°F. Celsius and Fahrenheit scales are generally used in ordinary life.

There is a third scale of temperature known as Kelvin scale or Absolute temperature scale. It is used in scientific measurements. In Kelvin scale, the lower and upper fixed points are labelled as 273 and 373. As the difference between these values is 100, so the width of 1 K is the same as that of 1°C. The zero point of this scale is the temperature at which the molecules

For Your Information!

The pressure of a given mass of gas increases with temperature. So, pressure of a gas is also a thermometric property which is used in gas thermometers. The resistance of a given length of wire also depends upon temperature. It increases with the increase in temperature. So, the resistance of a wire is also a thermometric substance and is used in platinum resistance thermometer.



Comparison of three scales of temperature
Fig. 7.7

of a substance cease to move. Their average kinetic energy becomes zero. This is known as absolute zero. Its value is -273.15 °C. For calculations, it is simply taken as -273 °C. Absolute zero is the lowest possible temperature ever to be in the whole universe. The matter does not exist below absolute zero temperature.

Conversion of Temperature from One Scale to Another

If the temperature of a body is T_c on Celsius scale, T_F on Fahrenheit scale and T_k on Kelvin scale, then these readings are related by the following formulae:

(i) Conversion of Celsius (centigrade) to Fahrenheit scale:

$$T_F = \frac{9}{5} \times T_C + 32 \quad \text{.......} (7.1)$$

(ii) Conversion of Fahrenheit to Celsius scale:

$$T_C = \frac{5}{9}(T_F - 32) \quad \text{.......} (7.2)$$

(iii) Relationship between Kelvin and Celsius scales:

$$T_k = T_C + 273 \quad \text{.......} (7.3)$$

Example 7.1

How much 30°C temperature would be on Fahrenheit and Kelvin scales?

Solution

Temperature $T_C = 30°C$

Using $T_F = \frac{9}{5} \times T_C + 32°$

$= \frac{9}{5} \times 30°C + 32° = 86°F$

Using $T_k = T_C + 273$

$= 30°C + 273 = 303K$

7.4 Sensitivity, Range and Linearity of Thermometers

A thermometer is evaluated by its three key characteristics that are sensitivity, range and linearity. They help determine the suitability of the thermometer for specific use ensuring accurate and reliable measurement of temperature.

Sensitivity

Sensitivity of a thermometer refers to its ability to detect small changes in the temperature of an object. For example, the minimum division on the scale of a thermometer is 1°C. The accuracy of its temperature measurement will be 1°C. On another thermometer the marks are 0.1°C apart. Hence, its accuracy will be up to 0.1°C and said to be more sensitive. Its measurement will be more precise than the measurement by a thermometer with an accuracy of 1°C.

Range

This refers to the span of temperature, from low to high, over which the thermometer can measure accurately. For example, a clinical thermometer designed for human body temperature has a narrow or short range, say from 35°C to 45°C. A long-range thermometer is usually used for science experiments in the laboratory with markings from –10°C to 110°C. The choice of liquid for thermometers put a lower and upper limit for the range of a thermometer. For example, Mercury freezes at -39°C and boils at 357°C. Hence, we can construct mercury in glass thermometers within this range. The marking scale depends on desired range of measurement. For extremely low temperatures, alcohol is used. Alcohol has a much lower freezing point about -112°C which increases its lower limit for the range but it has lower upper limit as it boils at 78 °C.

Linearity

This refers to a direct proportional relationship between the temperature and scale reading across entire range of measurement. A good linear thermometer should measure equal increments on the scale corresponding to equal change in the temperature. It means that marking on the scale should be evenly spaced over the whole range. High linearity means more consistent and proportional scale readings over the entire range to ensure accuracy of measurement.

EXERCISE

A Multiple Choice Questions

Tick (✓) the correct answer.

7.1 How do the molecules in a solid behave?
(a) Move randomly (b) Vibrate about their mean positions
(c) Rotate and vibrate randomly at their own positions
(d) Move in a straight line from hot to cold ends.

7.2 What type of motion is of the molecules in a gas?
(a) Linear motion (b) Random motion
(c) Vibratory motion (d) Rotatory motion

7.3 Temperature of a substance is:
(a) the total amount of heat contained in it
(b) the total number of molecules in it
(c) degree of hotness or coldness
(d) dependent upon the intermolecular distance

7.4 Heat is the:
(a) total kinetic energy of the molecules
(b) the internal energy
(c) work done by the molecules
(d) the energy in transit

7.5 In Kelvin scale, the temperature corresponding to melting point of ice is:
(a) zero (b) 32 (c) -273 (d) +273

7.6 The temperature which has the same value on Celsius and Fahrenheit scale is:
(a) -40 (b) +40 (c) +45 (d) -45

7.7 Which one is a better choice for a liquid-in-glass thermometer?
(a) Is colourless (b) Is a bad conductor
(c) Expand linearly (d) Wets glass

7.8 One disadvantage of using alcohol in a liquid-in-glass thermometer:
(a) it has large expansivity (b) it has low freezing point (-112°C)
(c) it wets the glass tube (d) its expansion is linear

7.9 Water is not used as a thermometric liquid mainly due to:
(a) colourless (b) a bad conductor of heat
(c) non-linear expansion (d) a low boiling point (100°C)

7.10 A thermometer has a narrow capillary tube so that it:
(a) quickly responds to temperature changes
(b) can read the maximum temperature
(c) gives a large change for a given temperature rise
(d) can measure a large range of temperature

B Short Answer Questions

7.1 Why solids have a fixed volume and shape according to particle theory of matter?

7.2 What are the reasons that gases have neither a fixed volume nor a fixed shape?

7.3 Compare the spacing of molecules in the solid, liquid and gaseous state.

7.4 What is the effect of raising the temperature of a liquid?

7.5 What is meant by temperature of a body?

7.6 Define heat as 'energy in transit'.

7.7 What is meant by thermometric property of a substance? Enlist some thermometric properties.

7.8 State the main scales used for the measurement of temperature.

7.9 What is meant by sensitivity of a thermometer?

7.10 What do you mean by the linearity of a thermometer?

7.11 What makes the scale reading of a thermometer accurate?

7.12 What does determine the direction of heat flow?

7.13 Distinguish between the heat and internal energy.

7.14 When you touch a cold surface, does cold travel from the surface to your hand or does energy travel from your hand to cold surface?

7.15 Can you feel your fever by touching your own forehead? Explain.

C Constructed Response Questions

7.1 Is kinetic molecular theory of matter applicable to the plasma state of matter? Describe briefly.

7.2 Why is mercury usually preferred to alcohol as a thermometric liquid?

7.3 Why is water not suitable for use in thermometers? Without calculations, guess what is equivalent temperature of 373 K on Celsius and Fahrenheit scales?

7.4 Mention two ways in which the design of a liquid-in-glass thermometer may be altered to increase its sensitivity.

7.5 One litre of water is heated by a stove and its temperature rises by 2°C. If two litres of water is heated on the same stove for the same time, what will be then rise in temperature?

7.6 Why are there no negative numbers on the Kelvin scale?

7.7 Comment on the statement. "A thermometer measures its own temperature."

7.8 There are various objects made of cotton, wood, plastic, metals, etc. In a winter night, compare their temperatures with the air temperature by touching them with your hand.

7.9 Which is greater: an increase in temperature 1°C or one 1°F?

7.10 Why would not you expect all the molecules in a gas to have the same speed?

7.11 Does it make sense to talk about the temperature of a vacuum?

7.12 Comment on the statement: "A hot body does not contain heat".

7.13 Discuss whether the Sun is matter.

D Comprehensive Questions

7.1 Describe the main points of particle theory of matter which differentiate solids, liquids and gases.

7.2 What is temperature? How is it measured? Describe briefly the construction of a mercury-in-glass thermometer.

7.3 Compare the three scales used for measuring temperature.

7.4 What is meant by sensitive, range and linearity of thermometers? Explain with examples.

E Numerical Problems

7.1 The temperature of a normal human body on Fahrenheit scale is 98.6°F. Convert it into Celsius scale and Kelvin scale.
(37°C, 310 K)

7.2 At what temperature Celsius and Fahrenheit thermometer reading would be the same? (-40°)

7.3 Convert 5°F to Celsius and Kelvin scale. (-15°C, 258 K)

7.4 What is equivalent temperature of 25°C on Fahrenheit and Kelvin scales?
(77°F, 298 K)

7.5 The ice and steam points on an ungraduated thermometer are found to be 192 mm apart. What temperature will be on Celsius scale if the length of mercury thread is at 67.2 mm above the ice point mark?
(35°C)

7.6 The length between the fixed point of liquid-in-glass thermometer is 20 cm. If the mercury level is 4.5 cm above the lower mark, what is the temperature on the Fahrenheit scale? (72.5°F)

Chapter 8

Magnetism

Student Learning Outcomes

After completing this chapter, students will be able to:

- Describe the forces between magnetic poles and between magnets and magnetic materials [Including the use of the terms north pole (N pole), south pole (S pole), attraction and repulsion, magnetised and unmagnetised]
- Describe induced magnetism
- Differentiate between temporary and permanent magnets
- Describe magnetic fields [as a region in which a magnetic pole experiences a force]
- State that the direction of the magnetic field at a point is the direction of the force on the N pole of a magnet at that point
- State that the relative strength of a magnetic field is represented by the spacing of the magnetic field lines
- Describe uses of permanent magnets and electromagnets
- Explain how materials can be magnetised and demagnetise [stroking method, heating, orienting in north-south direction and striking, use of a solenoid]
- Analyse applications of magnets in recording technology [and illustrate how electronic devices need to be kept safe from strong magnetic fields]
- State that soft magnetic materials (such as soft iron) can be used to provide shielding from magnetic fields

Almost all of us are familiar with a magnet because of its interesting properties. In lower classes, we have studied some of the properties. You might have also enjoyed a magnet attracting small pieces of iron.

8.1 Magnetic Materials

Some materials are attracted by the magnets. They are called magnetic materials. Some properties of the magnets are given below.

1. Magnetic Poles

If a bar magnet is suspended horizontally through a string and allowed to come to rest, it will point in north-south direction. The end of the magnet that points north is called the **north magnetic pole** (N) and rhe end that points south is the **south magnetic pole** (S) as shown in Fig. 8.1.

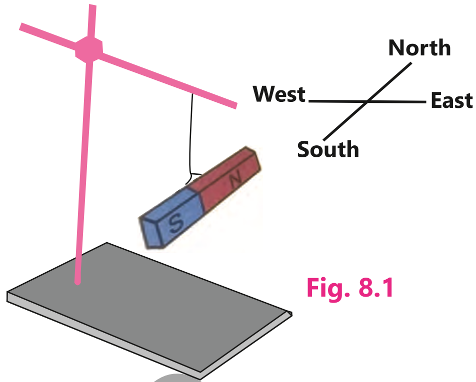


Fig. 8.1

2. Attraction and Repulsion of Magnetic Poles

When two freely suspended bar magnets are placed close to each other, the two north poles will repel each other (Fig. 8.2). So will the two south poles (Fig. 8.3).

However, if the north pole of one is placed near the south pole of the other, the poles will attract (Fig. 8.4 & Fig. 8.5). We can say that **Like poles repel and unlike poles attract**.

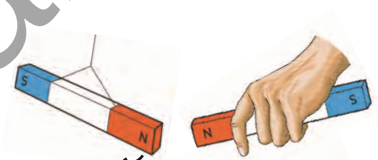


Fig. 8.2

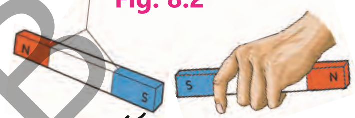


Fig. 8.3

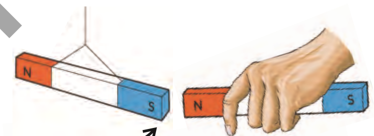


Fig. 8.4

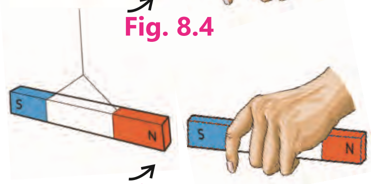


Fig. 8.5

3 . Identification of a Magnet

To identify whether an object is a magnet or simply a magnetic material, we can bring its one end close to any pole of a suspended bar magnet. If it is attracted, then we can conclude that the end of the object is either of opposite pole to that of the suspended magnet or it is simply a magnetic material. Then we should bring the same end of the object close to the other end of the suspended magnet. If the object is again attracted, it is not a magnet but it is a magnetic material.
If it is repelled by the other end of the suspended magnet, then the object is a magnet.

The repulsion between the like poles is a real test to identify a magnet.

4. Is Isolated Magnetic Pole Possible?

If we break a bar magnet into two equal pieces, can we get N-pole and S-pole separately? No, it is not possible. Each piece will have its two poles, i.e., N-pole and S-pole. Even if a magnet is divided into thousands pieces, each piece will be a complete magnet with its N, and S-poles (Fig.8.6).

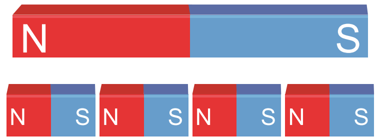


Fig. 8.6

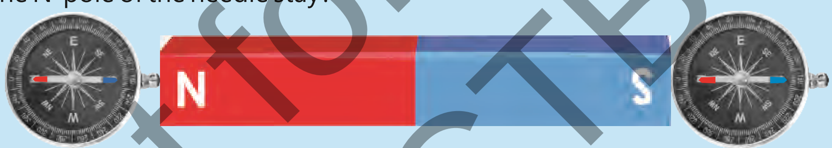
8.2 Induced Magnetism

Magnetic material such as iron or steel can be made a magnet. This is known as magnetization. In other words, we can say that magnetism has induced in it. You can perform an activity to observe this fact.

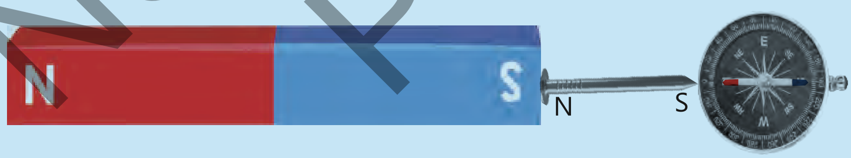
Activity 8.1

The teacher should facilitate each group to perform this activity as per instructions.

1. Take a magnetic compass. Put it on a table and see which end of its needle points north. The N-pole of the needle is usually coloured red.
2. Place a bar magnet on the table. Bring the compass near to its N-pole. In which direction does the N-pole of the needle stay?



3. Put the compass near to the S-pole of the bar magnet. In which direction does the N-pole of the needle stay this time?
4. Now place an iron nail having its head in contact with any pole of the bar magnet.



5. Put the compass near to the pointed end of an iron nail. Observe the direction in which N-pole of the needle settles. Has the nail become a magnet? Has magnetism been induced in it?
6. Take the bar magnet away from the nail. Again check the behaviour of the nail by bringing compass near to its ends. Does the magnetism vanish?

From the above activity, we conclude that the S-pole of the true magnet induces N-pole in the near end of the piece of iron (nail) while the far end of the iron piece becomes S-pole as shown in the figure.

It should be noted that the induced magnetism vanishes as the true magnet is removed.

8.3 Temporary and Permanent Magnets

Temporary magnets are the magnets that work in the presence of a magnetic field of permanent magnets. Once the magnetic field vanishes, they lose their magnetic properties. You have learnt something about a magnetic field in lower classes. In this chapter, we will study it in detail.

Usually, soft iron is used to make temporary magnets. Paper clips, office pins and iron nails can easily be made temporary magnets. Electromagnets are also good examples of temporary magnets. You have already learnt different uses of electromagnets.

Permanent magnets retain their magnetic properties forever. These are either found in nature or artificially made by placing objects made of steel and some special alloys in a strong magnetic field for a sufficient time. There are many types of permanent magnetic materials. For example cobalt, alnico and ferrite.

8.4 Magnetic Fields

When a magnet attracts a certain magnetic material, it exerts some force to do so. Similarly, when it attracts or repels a magnetic pole of another magnet, it exerts a force on it. This force can be observed up to a certain distance from the magnet that can be explained by the concept of magnetic field around the magnet.

A magnetic field is the region around a magnet where an other magnetic object experiences a force on it.

The pattern of a magnetic field around a bar magnet can be seen very easily by a simple experiment.

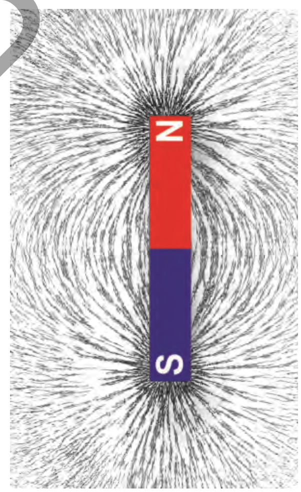


Fig. 8.7

If iron filings are sprinkled on a thin glass plate placed over a bar magnet, the filings become tiny magnets through magnetic induction. Now if the glass surface is gently tapped, the filings form a pattern. This pattern is known as the magnetic field pattern (Fig.8.7). This pattern can be better shown by lines that correspond to the path of the filings. These lines are called **magnetic lines of force**.

Magnetic lines of Force

The magnetic lines of force around a bar magnet can be drawn by using a small compass. The needle of the compass will move along the magnetic lines of force. Figure. 8.8 shows the magnetic lines of force around a bar magnet drawn by this method. The compass needle is symbolized by an arrow being the north pole (Fig. 8.9).

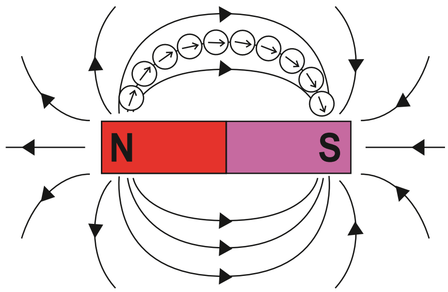


Fig. 8.8

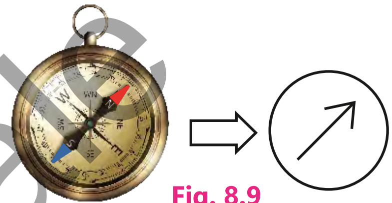


Fig. 8.9

The magnetic field at a point has both a magnitude and a direction.

The direction of the magnetic field at any point in space is the direction indicated by the N-pole of a magnetic compass needle placed at that point.

Figure. 8.8 also shows that the field lines appear to originate from the north pole and end on the south pole. Actually, the magnetic field extends in space all around the magnet but the figure shows the field in one plane only.

Strength of the Magnetic Field

The strength of the magnetic field is proportional to the number of magnetic lines of force passing through unit area placed perpendicular to the lines. Thus, the magnetic field is stronger in regions where the field lines are relatively close together and weaker where these are far apart. For example in Fig. 8.10, the lines are closest together near north and south poles indicating that the strength of the magnetic field is stronger in these regions. Away from the poles, the magnetic field becomes weaker.

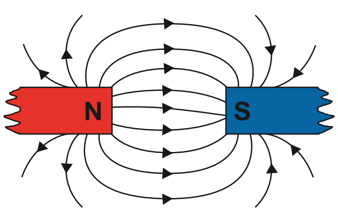


Fig. 8.10

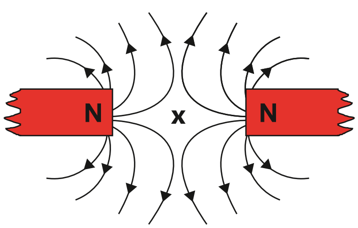


Fig. 8.11

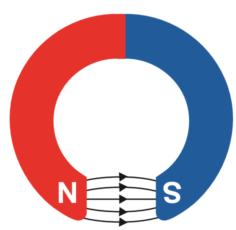


Fig. 8.12

In case the two magnets are placed close to each other, their combined magnetic field can also be drawn by using the compass needle. Figure. 8.10 and Fig. 8.11 show the patterns of the combined magnetic field of two magnets lying with different orientations. In Fig. 8.11, point '**x**' is called a neutral point because the field due to one magnet cancels out that due to the other magnet. Figure. 8.12 represents the field pattern of a horse-shoe magnet. The field is almost uniform between the poles except near the edges.

8.5 Uses of Permanent Magnets

There are many uses of permanent magnets such as:

1. They are the essential parts of D.C motors, A.C and D.C electric generators.
2. Permanent magnets are used in the moving coil loud-speakers.
3. These are very commonly used in door catchers.
4. Magnetic strips are fitted to the doors of refrigerators and freezers to keep the door closed tightly.
5. They are commonly used to separate iron objects from different mixtures. Flourmills use permanent magnets to remove iron nails, etc. from the grains before grinding.
6. In the medical field, they are used to remove iron splinters from the eyes.
7. A piece of permanent magnet is used to reset the iron pointer in a maximum and minimum thermometer.

8.6 Electromagnets

Electromagnets are also a kind of temporary magnets. The following activity will show how electromagnets can be made and tested.

When an electric current passes through the coil of wire, magnetic field is produced inside the coil that magnetizes the iron nail. As we have observed that the magnetic properties of an electromagnet are temporary, therefore, iron object remains a magnet as long as the electric current passes through the coil. When the current is stopped, it no longer remains a magnet.

An iron nail or a rod becomes a magnet when an electric current passes through a coil of wire around it. It is called an electromagnet.

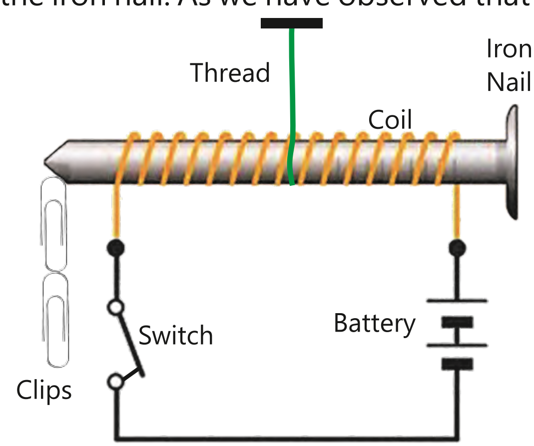


Fig. 8.13

If we increase the number of cells in the battery or increase the number of turns of the coil, we will observe that the strength of the magnetic field in each case increases. This will be indicated by the more number of clips held by the nail in these cases.

Uses of Electromagnets

Electromagnets are used in electric bell, telephone receiver, simple magnetic relay, circuit breaker, reed switches, cranes, tape recorder, maglev trains and many other devices. Functions of some of them are described below:

Magnetic Relay

This is a type of switch which works with an electromagnet. It is an input circuit which works with a low current for safety purpose. When it is turned ON it activates another circuit which works with a high current (Fig. 8.14).

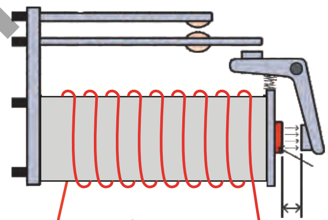


Fig. 8.14

Circuit Breaker

A circuit breaker is designed to pass a certain maximum current through it safely. If the current becomes excessive, it switches OFF the circuit. Thus, electric appliances are protected from burning. It is a replacement of fuse which was used for this purpose (Fig. 8.15).

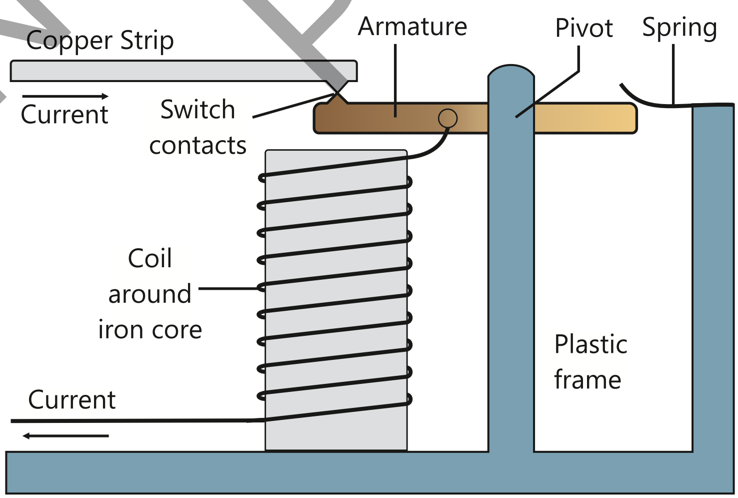


Fig. 8.15

Telephone Reciever

Varying electric current received from the other side is converted into sound by using an electromagnet fitted inside the receiver of a telephone (Fig. 8.16).

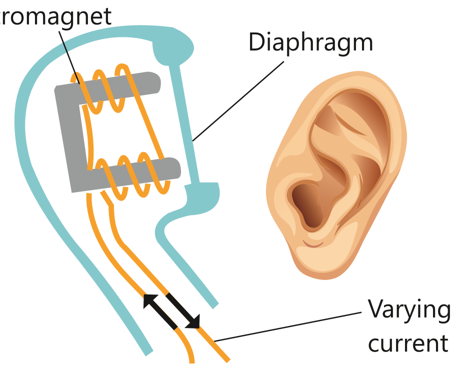


Fig. 8.16

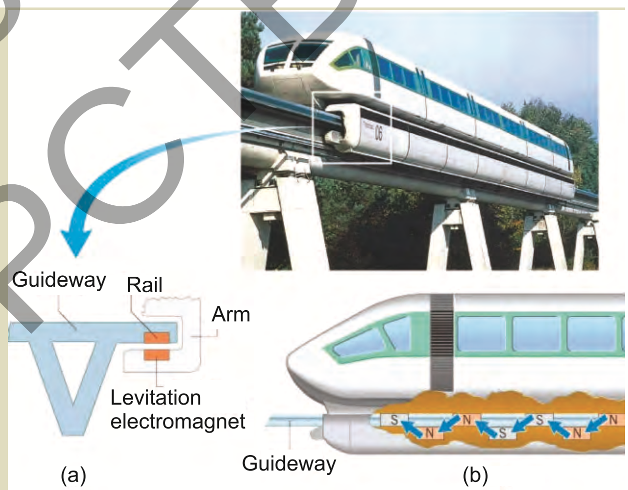
Electromagnetic Cranes

Huge electromagnets are used in cranes at scrapyards, steel works and on ships to lift iron and steel objects (Fig. 8.17).


Fig. 8.17

For Your Information!

A wonderful use of electromagnets can be seen in the **Maglev trains**. The maglev stands for a magnetically levitated train. A maglev uses forces that arise from induced magnetism to levitate or float a few centimetres above the guideway. That is why, it does not need wheels and faces no friction. In Japan, it is known as a bullet train that can run up to a speed of 400 km per hour.



As described above, magnetic levitative only lifts the train and does not move it forward. To push the train forward, propulsion electromagnets are installed along the guideway and train. The push and pull of these magnets moves the train forward.

8.7 Magnetisation and Demagnetisation

There are two methods used for magnetising a steel bar:

1. Stroking

In this method, magnetism is induced in a steel bar by using the magnetic field of a permanent magnet. The steel bar can be stroked in two ways:

(a) Single-Touch Method

A steel bar is placed on a horizontal surface. It is stroked from one end to the other several times in the same direction using the same pole (say N) of the permanent magnet. Every time the magnet is lifted up sufficiently high on reaching the other end of the bar (Fig. 8.18.

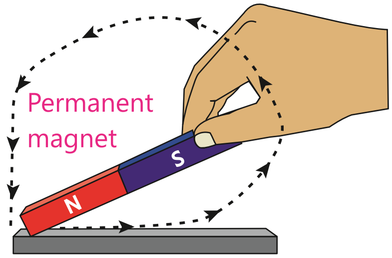


Fig. 8.18

(b) Double-Touch Method

In this method, stroking is done from the centre of the steel bar onwards with the unlike poles of two permanent magnets at the same time (Fig. 8.19). This method is more efficient than the first one.

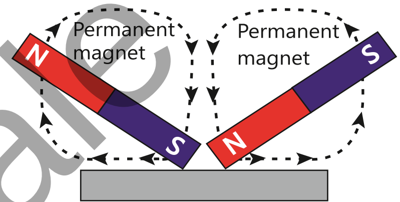


Fig. 8.19

In both the cases, the poles produced at the ends of magnetized steel bar after stroking are of the opposite polarity to that of the stroking pole.

2. Making a Magnet using Solenoid

In this method, a steel bar to be magnetised is placed inside a solenoid (long coil of wire) as shown in Fig. 8.20. The solenoid should have several hundred turns of insulated copper wire. When direct current is passed through the solenoid, the steel bar becomes a magnet. The polarity of the magnetised steel bar is found by applying **Right hand Grip rule** which is stated as:

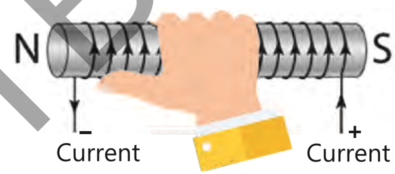


Fig. 8.20

> Grip the solenoid with the right hand such that fingers are curled along the direction of current (positive to the negative terminal of the battery) in the solenoid, then the thumb points to the N-pole of the bar end.

Demagnetisation of Magnets

1. Heating

Thermal vibrations tend to disturb the order of the domain. Therefore, if we heat a magnet strongly, the magnet loses its magnetism very quickly (Fig. 8.21).

Fig. 8.21

2. **Hammering**

If we beat a magnet, the domains lose their alignment and the magnet is demagnetised. It is also called hammering (Fig. 8.22).

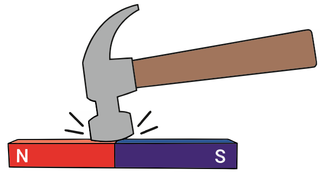


Fig. 8.22

3. **Alternating Current**

When an alternating current (A.C) is flowing through a long solenoid, a magnet moved out slowly from inside of the solenoid is demagnetised (Fig. 8.23).

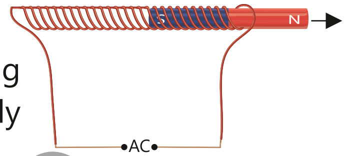


Fig. 8.23

8.8 Applications of Magnets in Recording Technology

Electromagnets have widely used in recording technology of sound, video and data in the form of electrical signals through magnetization of a magnetic material. Most common magnetic recording mediums are **magnetic tapes** and **disk recorders** which are used not only to reproduce audio and video signals but also to store computer data. These materials are usually coated with iron oxide. Some other recordings mediums are magnetic drums, ferrite cores and magnetic bubble memory. We will discuss the process of magnetic recording on tapes and disks in some detail.

Magnetic Tape Recording

Induced magnetism is used in the process of magnetic tape recording. Recording and playing head is a coil of wire wrapped around an iron core. The iron core has a horse-shoe shape with a narrow gap in between its two ends. Audio and video tapes are synthetic tapes coated with a layer of ferromagnetic material.

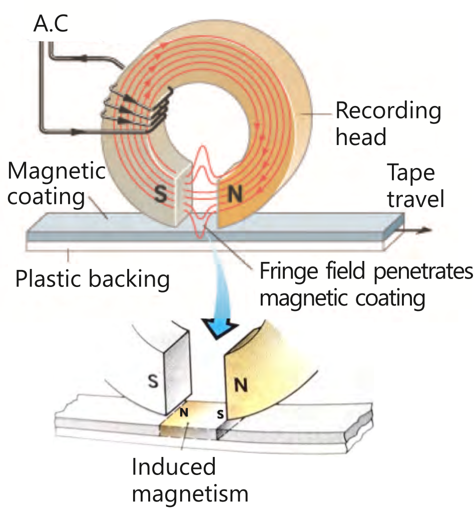


Fig. 8.24

Sound or picture is converted into electrical forms as varying currents. These currents are sent to the head that becomes an electromagnet with a N-pole at one end and a S-pole at the other end. The magnetic field lines pass through the iron core and cross the gap. Some of the field lines in the gap curved outward as shown in Fig. 8.24. The curved part of the magnetic field called as **fringe field** penetrates magnetic coating on the moving tape and induces magnetism in the coating. This induced magnetism is retained when the tape leaves the vicinity of the recording head. The reverse process changes the varying induced magnetism into varying current that onward is converted into sound or picture.

Hard Disk Recording

Hard disks are circular flat plates made of aluminium, glass or plastic and coated on both sides with iron oxide. Hard disks can store terabyte of information.

A magnetic head is a small electromagnet which writes a binary digit (1 or 0) by magnetising tiny spots on the spinning disk in different directions and reads digit by detecting the magnetisation direction of spots (Fig. 8.25). The term hard disk is also used to refer to the whole of a computer's internal data storage.

Fig. 8.25

Magnetic disk devices have an advantage over tapes recorders. A disk unit has the ability to read or write a recording instantly while locating a desired information on tape may take many minutes.

Electronic devices can be protected from strong magnetic effects by enclosing them in the boxes made of soft iron. We will describe it in detail in the next section.

8.9 Soft Iron as Magnetic Shield

Soft iron has high magnetic permeability. The permeability is the ability of a material to allow the magnetic flux or lines of force through it when the material is placed inside a magnetic field. When a piece of soft iron is put into a magnetic field, it generates a magnetic field due to magnetisation.

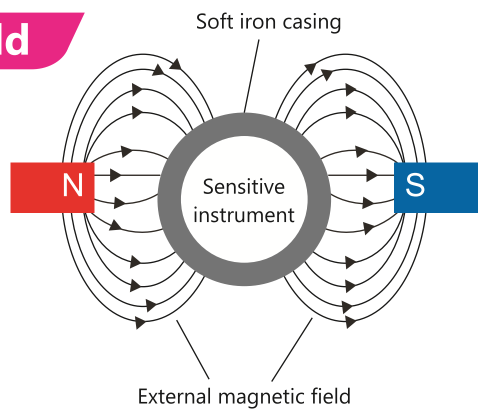


Fig. 8.26

If a sensitive magnetic device is enclosed in a casing of soft iron, the magnetic flux gets established in the soft iron rather than the device. Thus, the device is shielded from external magnetic field.

Figure 8.26 can explain this phenomenon well. A soft iron casing (shell) is placed inside a magnetic field produced by opposite poles of two bar magnets. Since the magnetic permeability of the iron shell is higher than that of air, so the magnetic flux is established in the soft iron. As a result, the device is protected from the magnetic field. Usually, the casing is made with rounded corners to facilitate the magnetic field line up easily.

Soft iron is generally used in the cores of transformers and electromagnets because of its high permeability. In case of an electromagnet, the core of soft iron can be easily magnetised when current is passed around it and quickly lost when current is stopped. That is why, electromagnets are widely used in electric bells, loud speakers, picking and releasing iron scraps by the cranes and in many more appliances. The sensitivity of a moving coil galvanometer is also increased by placing a soft iron core inside the coil.

EXERCISE

A Multiple Choice Questions

Tick (✓) the correct answer.

8.1 Which one of the following is not a magnetic material?
(a) Cobalt (b) Iron
(c) Aluminium (d) Nickel

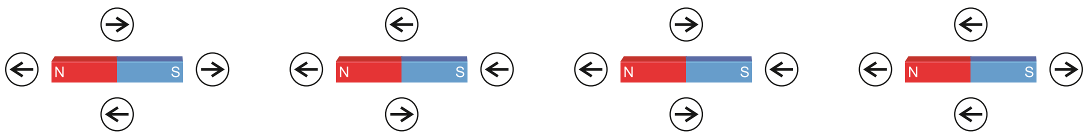
8.2 Magnetic lines of force:
a) are always directed in a straight line
(b) cross one another
(c) enter into the north pole
(d) enter into the south pole

8.3 Permanent magnets cannot be made by:
(a) soft iron (b) steel (c) neodymium (d) alnico

8.4 Permanent magnets are used in:
(a) circuit breaker (b) loudspeaker
(c) electric crane (d) magnetic recording

8.5 A common method used to magnetise a material is:
(a) stroking (b) hitting
(c) heating (d) placing inside a solenoid having A.C

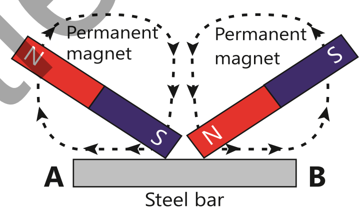
8.6 A magnetic compass is placed around a bar magnet at four points as shown in figure below. Which diagram would indicate the correct directions of the field?



(a) (b) (c) (d)

8.7 A steel rod is magnetised by double touch stroking method. Which one would be the correct polarity of the AB magnet?

(a) (b) (c) (d)



8.8 The best material to protect a device from external magnetic field is:
(a) wood (b) plastic (c) steel (d) soft iron

B Short Answer Questions

8.1 What are temporary and permanent magnets?

8.2 Define magnetic field of a magnet.

8.3 What are magnetic lines of force?

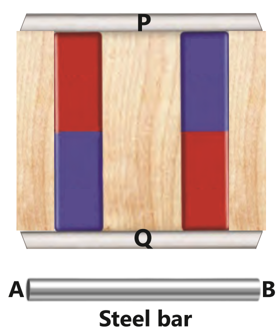
8.4 Name some uses of permanent magnets and electromagnets.

8.5 Which type of magnetic field is formed by a current-carrying long coil?

C Constructed Response Questions

8.1 Two bar magnets are stored in a wooden box. Label the poles of the magnets and identify P and Q objects.

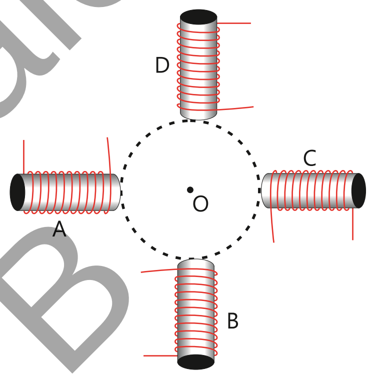
8.2 A steel bar has to be magnetised by placing it inside a solenoid such that end A of a bar becomes N-pole and end B becomes S-pole. Draw circuit diagram of solenoid showing steel bar inside it.



8.3 Two bar magnets are lying as shown in the figure. A compass is placed at the middle of the gap. Its needle settles in the north-south direction. Label N and S poles of the magnets. Justify your answer by drawing fields lines.

8.4 Electric current or motion of electrons produce magnetic field. Is the reverse process true, that is the magnetic field gives rise to electric current? If yes, give an example and describe it briefly.

8.5 Four similar solenoids are placed in a circle as shown in the figure. The magnitude of current in all of them should be the same. Show by diagram, the direction of current in each solenoid such that when current in anyone solenoid is switched OFF, the net magnetic field at the centre O is directed towards that solenoid. Explain your answer.



D Comprehensive Questions

8.1 How can you identify whether an object is a magnet or a magnetic material?

8.2 Describe the strength of a magnetic field in terms of magnetic lines of force. Explain it by drawing a few diagrams for the fields as examples.

8.3 A magnet attracts only a magnet. Explain the statement.

Glossary

Acceleration: Rate of change of velocity with time.

Accuracy: Relative measurement reflected by the number of significant figures.

Artificial Satellites: Objects moving in fixed circular orbits around the Earth.

Base Quantity: Such quantity, which can be expressed independently without the reference of any other quantity.

Base Units: The units in System International, which are seven in number.

Centre of Gravity: The point of body where its whole weight acts.

Centripetal Acceleration:

Acceleration produced by the centripetal force.

Centripetal Force: The force which keeps an object to move in a circular path.

Circular Motion: Motion of a body along a circular path.

Components of a Vector: Such vectors when added give the resultant vector.

Couple: When two equal and unlike parallel forces act at different points of a body, then they constitute a couple.

Density: Mass of unit volume of a substance.

Derived Quantity: A quantity which is expressed with reference to base quantities.

Derived Units: Units which can be derived from base units.

Displacement: The shortest distance between two points.

Dynamics: Study of motion of bodies under the action of forces.

Efficiency: Ratio of output and input.

Elastic Potential Energy: Energy of a compressed or stretched spring.

Elasticity: The property of the solids because of which they restore their original shape when external force ceases to act.

Electromagnet: A temporary magnet when electric current flows through a coil wrapped around an iron rod.

Energy: Ability of a body to do work.

Equilibrium: A state of a body which has no acceleration.

Force: The agent that changes or tends to change the state of a body.

Friction: The force that tends to prevent the bodies from sliding over each other.

Gravitational Field: The region around an object where its force of gravity acts.

Gravitational Force: Mutual force of attraction between the objects.

Gravitational Potential Energy: Energy of body due to its position in the gravitational field.

Heat: The form of energy, which is transferred from one place to another because of difference of temperature.

Horizontal Component: The component of a vector which is along horizontal or x-direction.

Hydraulic Brakes: Brakes working according to Pascal's law.

Hydraulic Press: A press that works under Pascal's law.

Hydroelectric Generation:

Conversion of kinetic energy of flowing water into electrical energy.

Inertia: The characteristic of a body due to which it resists against any change in its state.

Internal Energy: Total energy of molecules of an object.

joule: The unit of work in System International.

Kilowatt-hour: Work done in one hour at a rate of one kilowatt.

Kinematics: Study of motion of bodies without taking into consideration of the mass and forces.

Kinetic Energy: Energy of a body due to its motion.

Kinetic Friction: Friction during motion.

Least Count: The minimum measurement recorded by an instrument.

Light Year: The unit of distance for celestial bodies equal to 9.46×10^{15} m.

Like Parallel Forces: Forces acting along parallel lines in the same direction.

Limiting Friction: The maximum value of static friction.

Line of Action of a Force: The straight line along which the force acts.

Linear Motion: The motion of body along a straight line.

Mass: The characteristics of a body, which determines the acceleration produced by the application of a force.

Mechanics: The branch of Physics which deals with the study of motion of bodies.

Magnet: It attracts magnetic materials and stays north-south direction when suspended freely.

Magnetic Compass: A direction indicating device using a magnetic needle.

Magnetic Field: Space around a magnetic in which force is exerted on another magnet.

Momentum: The product of mass and velocity of a moving body.

Neutral Equilibrium: The condition of a body in which its centre of gravity neither rises nor lowers of its original position after disturbance.

Orbital Speed: A critical speed of a satellite in order to keep on moving around the Earth at a specific height.

Parallel Forces: Forces acting along the parallel lines.

Physical Quantities:

Measurable characteristics of objects.

Physics: That branch of Science, which explains the properties of matter, energy, space and time.

Plasma: A state of matter in which most of the atoms are ionized into positive ions and electrons.

Power: Rate of doing work.

Precision: Determined by the instrument used equal to its least count.

Prefix: Symbols added to a unit to write it by power of 10.

Pressure: Force exerted normally on unit area of an object.

Random Motion: Motion without any consideration of time and direction.

Perpendicular Components: The components of a vector which are mutually perpendicular to each other.

Resolution of a Vector: Division of a vector into its components.

Resultant Vector: Such a vector which shows the combined effect of two or more vectors.

Rolling Friction: The friction produced during the motion of one body over the other with the help of wheels.

Scalar Quantities: Quantities which can be specified by their magnitudes only.

Scientific Notation: The number written as power of ten or prefix in which there is only one non-zero digit before decimal.

Significant Figures: In a measurement, the correctly known digits and the first doubtful digit.

Sliding Friction: The friction between two surfaces sliding against each other.

Speed: Distance covered by a body in unit time.

Stable Equilibrium: The condition of a body in which it comes to its original condition after being disturbed.

Static Friction: The force of friction arising due to applied external force before motion of one body over the other.

Temperature: Degree of hotness or coldness of a body.

Tension: The force acting along a string

Thermometry: Art of measurement of temperature.

Torque: Product of force and its moment arm.

Uniform Acceleration: Equal changes in velocity in equal intervals of time.

Uniform Speed: Equal distances covered by a body in equal intervals of time.

Uniform Velocity: Equal changes in displacement in equal intervals of time.

Unlike Parallel Forces: Forces acting along parallel lines but in opposite directions.

Unstable Equilibrium: The condition of a body in which it does not come to its original condition after disturbance.

Vectors Quantities: Quantities which can be specified by magnitude as well as direction.

Velocity: Rate of change of displacement with time.

Vertical Component: The component of a vector which is along vertical or y-direction.

Vibratory Motion: The to and fro motion of a body about a fixed point.

Volume Expansion: Increase in volume.

Watt: The unit of power in System International.

Weight: The force with which the Earth pulls a body towards its centre.

Work: The product of force and the displacement in the direction of force.