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Physics Student Textbook – Grade 10

Physics

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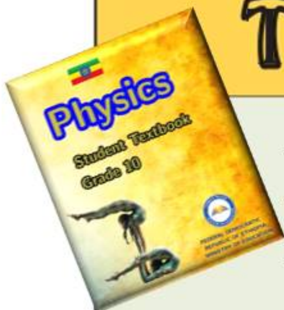

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Contents

Unit 1

Vector Quantities

Introduction

In science, particularly in physics, you try to make measurements as precise as possible. Several times in the history of science, precise measurements have led to new discoveries or important developments. Any number or sets of numbers used for a quantitative description of a physical phenomenon is called a physical quantity. Physical quantities can generally be divided in two groups: **scalars** and **vectors**. Scalars have only magnitudes while vectors have both magnitude and direction. The concepts of vectors and scalars help us in understanding physics of different natural phenomena. You will learn about this topics in this unit.

Brainstorming question:

List some physical quantities, and classify them as scalars and vectors.

By the end of this unit, you should be able to:

- *differentiate between scalar and vector quantities and give examples of each;*
- *demonstrate vectors representation graphically;*
- *add and subtract two vectors and resolve a vector into its components.*

1.1 Scalars and Vectors

Exercise 1.1

☞ What do you think are the differences between vectors and scalars?

Key concepts:

Scalars are quantities that has only magnitude while **Vectors** quantities that have both direction and magnitude.

Exercise 1.2

List other examples of vectors other than those discussed in the textbook.

By the end of this section, you should be able to:

- *define scalar and vector quantities;*
- *describe the difference between vector and scalar quantities;*
- *list some scalar and vector quantities.*

As discussed in the introduction, you classify physical quantities in two categories. In one case, you need only to state their magnitude with proper units and that gives their complete description. Take, for example, mass. If you say that the mass of a ball is 50 g, you do not have to add anything to the description of mass. Similarly, the statement that the density of water is 1000 kg/m^3 is a complete description of density. Such quantities are called scalars. A **scalar** quantity has only magnitude; no direction. **Time, distance, speed, length, volume, temperature, energy and power** are other examples of scalar quantities.

On the other hand, there are quantities which require both magnitude and direction for their complete description. A simple example is velocity. The statement that the velocity of a train is 100 km/h does not make much sense unless you also tell the direction in which the train is moving. Force is another such quantity. You must specify not only the magnitude of the force but also the direction in which the force is applied. Such quantities are called vectors. A **vector** quantity has both magnitude and direction. **Displacement, acceleration, momentum, impulse, weight and electric field strength** are other examples of vector quantities.

Section summary

- In physics, you deal generally with two kinds of quantities: scalars and vectors.
- Scalar are quantities that are specified only by their magnitude while vectors are quantities that are specified by their magnitude and direction.

Review questions

1. Explain how vector quantities differ from scalar quantities and give some examples for each.
2. Which of the following physical quantities are vectors and which are not: force, temperature, volume, velocity, age, weight?

1.2 Vector representations

By the end of this section, you should be able to:

- *identify the magnitude and direction of a vector;*
- *discuss how vectors can be represented graphically.*

Exercise 1.3

☞ How can you represent vectors?

Vector quantities are represented either algebraically or geometrically. Algebraically, they are represented by a bold letter as **A** or with an arrow over the letter, for example, $\vec{A}$. On the other hand, they are represented geometrically by an arrow that is drawn at a suitable scale. The initial point of arrow is called tail and the final point of the arrow is the head as it is indicated in Figure 1.1.

- The length of the arrow represents the vector magnitude if it is drawn in scale.
- The arrow head represents the vector direction.

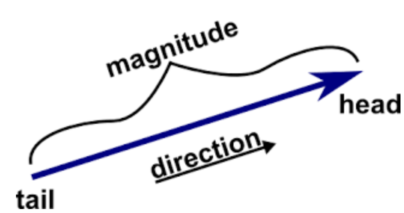


Figure 1.1 Head and tail of a vector

For example, a distance of 2.0 km, which is a scalar quantity, is denoted by 2.0 km, whereas a displacement of 2.0 km in some direction, which is a vector quantity, is denoted by **S** or $\vec{S}$. The magnitude is also indicated by placing the absolute value notation around the symbol that denotes the vector; so, you can write equivalently that $S \equiv |\mathbf{S}|$.

Key concepts

☞ Vectors are represented either algebraically or geometrically.

Two vectors are said to be equal if their magnitudes are equal and they point in the same direction. This means that all vectors which are parallel to each other, which have the same magnitude and point in the same direction are equal. Three vectors $\vec{A}$, $\vec{B}$ and $\vec{C}$ shown in Figure 1.2 are equal. Thus, you can say that $\vec{A} = \vec{B} = \vec{C}$. But $\vec{D}$ is not equal to $\vec{A}$.

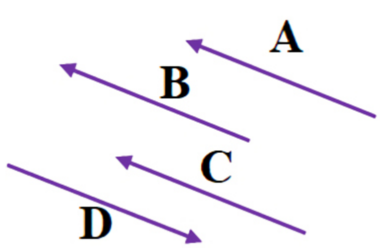


Figure 1.2 Three Vectors are equal but forth vector $\vec{D}$ is not equal

A vector (here $\vec{D}$) which has the same magnitude as $\vec{A}$ but has opposite direction, is called negative of $\vec{A}$, or $-\vec{A}$. Thus, $\vec{D} = -\vec{A}$.

Activity 1.1

By using a ruler, a protractor, and a square paper, graphically draw the following numerical vectors.

A. 10 cm , 60^o

B. 15 cm , 120^o

C. 3 cm , 30^o

Section summary

- Algebraically, a vector is represented by a bold face letter or an arrow over the letter.
- Geometrically, a vector is represented by an arrow where the length of the arrow represents magnitude and the arrow head represents the direction for the vector.

Review questions

- Give an example of a vector stating its magnitude, units and direction.
- Choose your own scale and draw arrows to represent the following vectors.:

  a) $\mathbf{s} = 40$ km North,

  b) $\mathbf{v} = 32$ m/s at an angle of 60^o above the horizontal.

1.3 Vector addition and subtraction

By the end of this section, you should be able to:

- *apply vector addition and subtraction techniques to solve real-life problems;*
- *define the term resultant vector.*

Exercise 1.4

Is it possible to add two vectors of equal magnitudes to get zero? Explain.

Different mathematical operations can be performed with vectors. You need to understand the mathematical properties of vectors, like addition and subtraction.

Addition of Vectors

When you add vectors, you need to add both a magnitude and a direction. The resultant of a number of vectors is the single vector whose effect is the same as the individual vectors acting together. In other words, the individual vectors can be replaced by the resultant where the overall effect is the same.

You should remember that only vectors of the same kind can be added. For example, two forces or two velocities can be added. But a force and a velocity cannot be added.

Key concepts:

Scalars and vectors can never be added.
For any two vectors to be added, they must be of the same nature.

If vectors **A** and **B** have a resultant **R**, this can be represented mathematically as,

$$\mathbf{R} = \mathbf{A} + \mathbf{B} \tag{1.1}$$

Let us consider a few special cases of addition of vectors.

- **When the Two Vectors are Parallel (Same Direction)**

If vectors **A** and **B** are parallel, then the magnitude of the resultant vector is the sum of the magnitudes of the two vectors. Hence, the magnitude of the resultant vector is

$$\mathbf{R} = \mathbf{A} + \mathbf{B} \tag{1.2}$$

Since the two vectors are in the same direction, the direction of the resultant vector is in the direction of one of the two vectors.

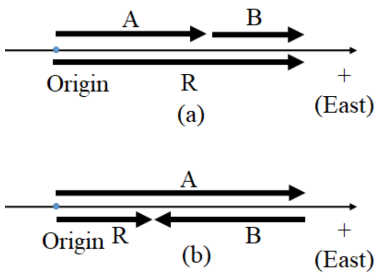


Figure 1.3 Resultant vector **R** of two vectors **A** and **B** when they are (a) same direction and (b) opposite direction .

- **When the Two Vectors are acting in Opposite Direction**
  If vectors $\vec{A}$ and $\vec{B}$ are parallel, then the magnitude of the resultant vector $\vec{R}$ is the difference of the magnitudes of the two vectors. Hence, the magnitude of the resultant vector is

$$\mathbf{R} = \mathbf{A} - \mathbf{B} \tag{1.3}$$

  Since the two vectors are in opposite directions with one another, the direction of the resultant vector is in the direction of the larger vector.

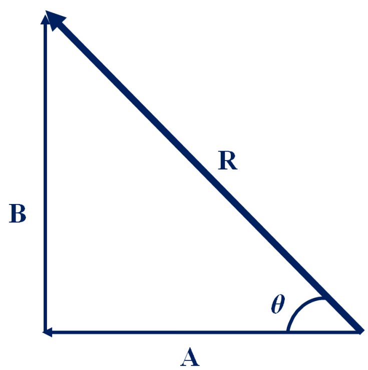


Figure 1.4 Two perpendicular vectors **A** and **B**; and its resultant vector **R**.

- **When the two vectors are perpendicular**
  If vectors $\vec{A}$ and $\vec{B}$ are perpendicular to each other, then the magnitude of the resultant vector is obtained using the Pythagoras theorem. Hence, the magnitude of the resultant vector is

$$R = \sqrt{A^2 + B^2} \tag{1.4}$$

  The direction of the resultant vector is obtained using the trigonometric equation:

$$\theta = tan^{-1}\left(\frac{B}{A}\right) \tag{1.5}$$

For example, the 4 N and 2 N forces can be added or subtracted to get the resultant force. That is, the net force is the result of adding up all the force vectors as shown in Figure 1.5.

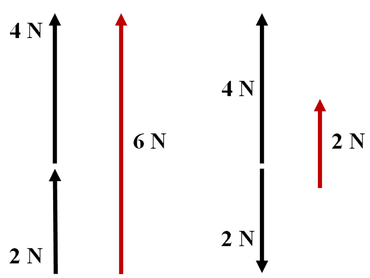


Figure 1.5 Addition and subtraction of two force vectors.

Note: The resultant of two vectors acting on the same point is maximum when the vectors are acting in the same direction and minimum when they operate in opposite directions.

Key concepts:

☞**Parallel vector:** Two vectors $\vec{A}$ and $\vec{B}$ are said to be parallel when they have same direction.

☞**Anti-parallel vectors:** Two vectors $\vec{A}$ and $\vec{B}$ are said to be anti-parallel when they have opposite directions.

Exercise 1.5

If two vectors $\vec{A}$ and $\vec{B}$ are perpendicular (an angle between them is 90^0), how you can find the sum of the two vectors?

Subtraction of Vectors

Vector subtraction is done in the same way as vector addition with one small change. You add the first vector to the negative of the vector that needs to be subtracted. As you discussed earlier, a negative vector has the same magnitude as the original vector, but points in the opposite direction. Subtracting vector **B** from vector **A**, which is written as, **A** - **B**, is actually equal to **A** + (**-B**).

As it is indicated in Figure 1.6, draw vector **-B** from the tip of **A** and join the tail of **A** with the tip of **-B**, then the resulting vector is the difference (**A** - **B**).

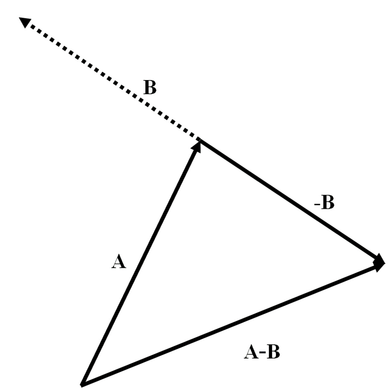


Figure 1.6 Subtraction of vector B from vector A

Example 1.1

Two vectors have magnitudes of 6 units and 3 units. What is the magnitude of the resultant vector when the two vectors are in the same direction, in opposite direction and perpendicular to each other.

Solution:

(a) When the two vectors are in the same direction, R = (6 + 3)units = 9 units.

(b) When the two vectors are in the opposite directions, R = (6 - 3)units = 3 units.

(c) When the two vectors are perpendicular to each other, $R = \sqrt{A^2 + B^2} = \sqrt{6^2 + 3^2} = 6.7 units$.

Exercise 1.6

If two vectors have equal magnitude, what are the maximum and minimum magnitudes of their sum?

Example 1.2

Two vectors have a length of 4 km and 3 km. What are the maximum and minimum magnitudes of their vector sum?

Solution: If the two vectors are in the same direction, the magnitude of their sum will be a maximum and will be 7 km. If the two vectors are in opposite directions, the magnitude of their sum will be a minimum and will be 1 km.

Section Summary

- Vector addition is a means of finding the resultant of a number of vectors.
- Subtraction of a vector is addition of the negative of a vector.

Review questions

1. What is meant by subtraction of vector?
2. What is meant by resultant vector?
3. Two vectors $\vec{A}$ and $\vec{B}$ have the same magnitude of 5 units and they start from the origin: $\vec{B}$ points to the north east and $\vec{A}$ points to the south west exactly opposite to vector $\vec{B}$. What would be the magnitude of the resultant vector? Why?
4. If two vectors have equal magnitude, what are the maximum and minimum magnitudes of their sum?
5. If three vectors have unequal magnitudes, can their sum be zero? Explain.

1.4 Graphical method of vector addition

By the end of this section, you should be able to:

- *describe the graphical method of vector addition;*
- *use the graphical method of vector addition to solve problems.*

Using the graphical method of vector addition, vectors are drawn to scale and the resultant is determined using a ruler and protractor. You next discuss the primary graphical techniques: the triangle method, the parallelogram method, and the polygon method.

Procedure for using graphical method of vector addition

- Decide on an appropriate scale. Record it on the diagram.
- Pick a starting point.
- Draw first vector with appropriate length and in the indicated direction.

- Draw the second and remaining vectors with appropriate length and direction.
- Draw the resultant based on the specific rule you are using.
- Measure the length of the resultant; use the scale to convert to the magnitude of the resultant.
- Use a protractor to measure the vector's direction.

Triangle method of vector addition

Triangle law of vector addition is used to find the sum of two vectors. This law is used to add two vectors when the first vector's head is joined to the tail of the second vector and then joining the tail of the first vector to the head of the second vector to form a triangle, and hence obtain the resultant sum vector. That's why the triangle law of vector addition is also called the head-to-tail method for the addition of vectors.

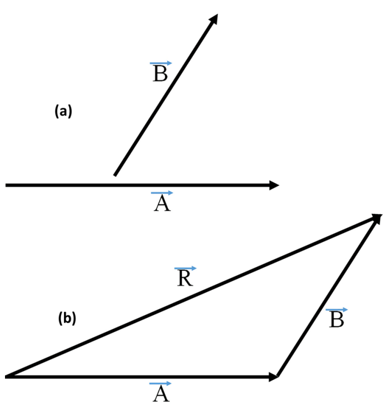


Figure 1.7 The triangle rule for the addition of two vectors.

Thus, if two vectors acting simultaneously on a body are represented both in magnitude and direction by two sides of a triangle taken in an order then the resultant sum vector (both magnitude and direction) of these two vectors is given by the third side of that triangle taken in the opposite order. This is the statement for the triangle law of vector addition.

Consider two vectors $\vec{A}$ and $\vec{B}$ shown in Figure 1.7 (a). To add these two vectors using the triangle method, the head of vector $\vec{A}$ should be joined to the tail of vector $\vec{B}$. Then, the resultant vector $\vec{R}$ has its tail at the tail of $\vec{A}$ and its head at the head of $\vec{B}$ as shown in Figure 1.7 (b).

$$\vec{R} = \vec{A} + \vec{B} \tag{1.6}$$

Activity 1.2

Consider adding two vectors $\vec{A}$ and $\vec{B}$ graphically. The two vectors are shown in Figure 1.8.

1. Select an appropriate scale. (Ex. 20 cm = 5 N)
2. Draw vector $\vec{A}$ to scale and in the proper direction.
3. Draw vector $\vec{B}$ to the same scale with its tail at the tip of $\vec{A}$ and in the proper direction.
4. The resultant vector $\vec{R} = \vec{A} + \vec{B}$ is the vector drawn from the tail of vector $\vec{A}$ to the tip of vector $\vec{B}$.
5. Measure the length of the resultant vector $\vec{B}$ using the selected scale and measure its direction with a protractor.

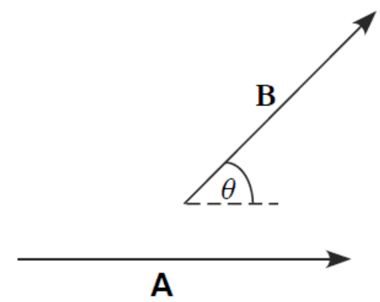


Figure 1.8 Two vectors $\vec{A}$ and $\vec{B}$.

Parallelogram method of vector addition

The vector addition may also be understood by the law of parallelogram. The parallelogram law of vector addition is used to add two vectors when the vectors that are to be added form the two adjacent sides of a parallelogram by joining the tails of the two vectors. Then, the sum of the two vectors is given by the diagonal of the parallelogram.

Thus, if two vectors are represented by the two adjacent sides (both in magnitude and direction) of a parallelogram drawn from a point, then their resultant sum vector is represented completely by the diagonal of the parallelogram drawn from the same point. This is the statement for the parallelogram law of vector addition

Suppose two vectors $\vec{A}$ and $\vec{B}$ are at the arbitrary positions shown in Figure 1.9 (a). Translate either one of them in parallel to the beginning of the other vector, so that after the translation, both vectors have their origins at the

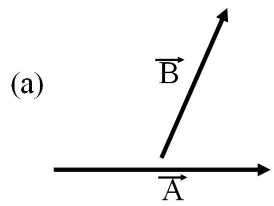
Key concepts

Graphically, vectors can be added using the triangle, parallelogram and polygon method of vector addition.

Activity 1.3

Repeat activity 1.2 using the parallelogram method of vector addition.

same point. Now, at the end of vector $\vec{A}$ we draw a line parallel to vector $\vec{B}$ and at the end of vector $\vec{B}$ we draw a line parallel to vector $\vec{A}$ (the dashed lines in Figure 1.9 (b)). In this way, we obtain a parallelogram. From the origin of the two vectors, we draw a diagonal of the parallelogram as shown in (Figure 1.9 (b)).The diagonal is the resultant $\vec{R}$ of the two vectors where



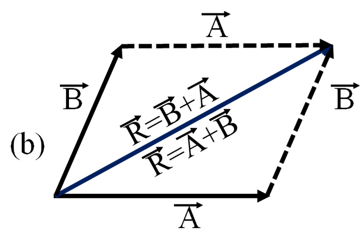


Figure 1.9 The Parallelogram rule for the addition of two vectors.

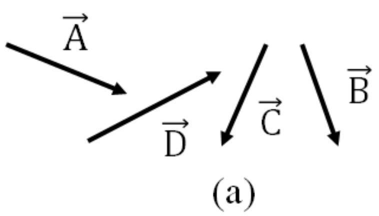
$$\vec{R} = \vec{A} + \vec{B} \tag{1.7}$$

Since vector addition is commutative,

$$\vec{A} + \vec{B} = \vec{B} + \vec{A} \tag{1.8}$$

Polygon method of Vector Addition

If more than two vectors are to be added, place them all head to tail to form a polygon. The resultant vector $\vec{R}$ is a vector drawn from the tail of the first vector to the head of the last vector.



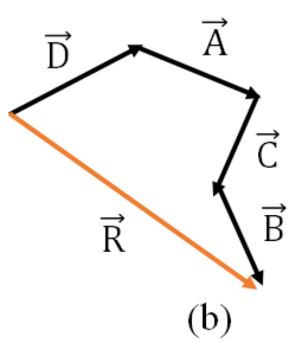


Figure 1.10 The polygon rule for the addition of vectors.

Suppose we want to draw the resultant vector $\vec{R}$ of four vectors $\vec{A}$, $\vec{B}$, $\vec{C}$, and $\vec{D}$ shown in Figure 1.10 (a). We select any one of the vectors as the first vector and make a parallel translation of a second vector to a position where the origin ("tail") of the second vector coincides with the end ("head") of the first vector. Then, we select a third vector and make a parallel translation of the third vector to a position where the origin of the third vector coincides with the end of the second vector. We repeat this procedure until all the vectors are in a head-to-tail arrangement like the one shown in (Figure 1.10 (b)). We draw the resultant vector $\vec{R}$ by connecting the origin ("tail") of the first vector with the end ("head") of the last vector. The end of the resultant vector is at the end of the last vector.

Thus, the resultant vector $\vec{R}$ is an arrow drawn from the tail of vector $\vec{D}$ to the head of vector $\vec{B}$, i.e., $\vec{R} = \vec{D} + \vec{A} + \vec{C} + \vec{B}$ as shown in Figure 1.10 (b). Because the addition of vectors is associative and commutative, we obtain the same resultant vector regardless of which vector we choose to be first, second, third, or fourth in this construction.

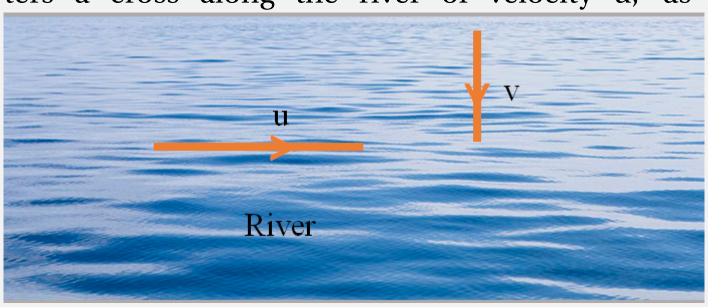
Section Summary

- Two non-parallel vectors are added by graphical means using the triangle method and the parallelogram methods. But for more than two vectors, the polygon method is used.

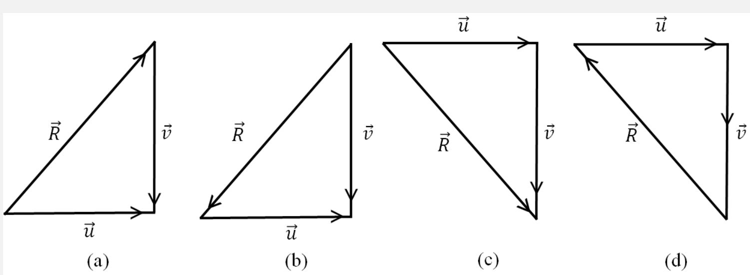
Review questions

1. Consider six vectors that are added tail-to-head, ending up where they started from. What is the magnitude of **R**?

2. A boat starts moving across a river at velocity v perpendicular to the river bank. The boat encounters a cross along the river of velocity u, as shown.



   Which vector diagram shows the resultant velocity v of the boat?



3. Vector **C** is 6 m in the x-direction. Vector **D** is 8 m in the y-direction. Use the parallelogram method to work out **C** + **D**.

Activity 1.4

Use the polygon method of vector addition to find the resultant vector R of the three vectors: $\vec{A} = 25.0m, 49.0^0$ north of east, $\vec{B} = 23.0m, 15.0^0$ north of east and $\vec{C} = 32.0m, 68.0^0$ south of east. Choose a reasonable scale.

1.5 Vector resolution

Exercise 1.7

Explain why a vector cannot have a component greater than its own magnitude.

By the end of this section, you should be able to:

- *resolve a vector into horizontal and vertical components;*
- *find the resultant of two or more vectors using the component method.*

In the previous discussion of vector addition, you saw that a number of vectors acting together can be combined to give a single vector (the resultant). In much the same way, a single vector can be broken down into a number of vectors when added give the original vector. These vectors which sum to the original are called components of the original vector. The process of breaking a vector into its components is called resolving into components.

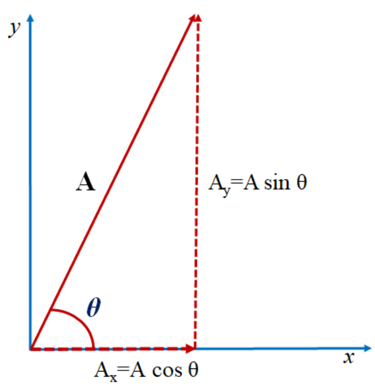


Figure 1.11 The horizontal (A_x) and vertical (A_y) components ofvector **A** .

Key points:

$sin\theta = \frac{A_y}{A}$

$cos\theta = \frac{A_x}{A}$

$tan\theta = \frac{A_y}{A_x}$

Suppose you have vector A as shown in Figure 1.11 and you need to find its components along x (horizontal component) and y-axes (vertical component). Let these components be called A_x and A_y respectively. Then, vector A can be written as:

$$\vec{A} = \vec{A}_x + \vec{A}_y \tag{1.9}$$

Simple trigonometry shows that:

$$A_x = Acos\theta \tag{1.10}$$

and

$$A_y = Asin\theta \tag{1.11}$$

where θ is the angle that **A** makes with the x - axis.

If the perpendicular components A_x and A_y of vector **A** are known, then **A** can also be found analytically. Thus, the magnitude of vector **A** and its direction in terms of its components are given by:

$$A = \sqrt{{A_x}^2 + {A_y}^2} \tag{1.12}$$

and the direction can be obtained using the equation

$$\theta = tan^{-1}\left(\frac{A_y}{A_x}\right) \tag{1.13}$$

Key concepts

Vectors can be resolved into components along a specified set of coordinates axes.

Example 1.3

A motorist undergoes a displacement of 250 km in a direction 30^o north of east. Resolve this displacement into its components.

Solution: Draw a rough sketch of the original vector. You can use trigonometry to calculate the magnitudes of the components (along north and along east) of the original displacement:

$$\begin{aligned} S_N &= (250)(sin30^o) \\ &= 125\ km \\ S_E &= (250)(cos30^o) \\ &= 216.5\ km \end{aligned}$$

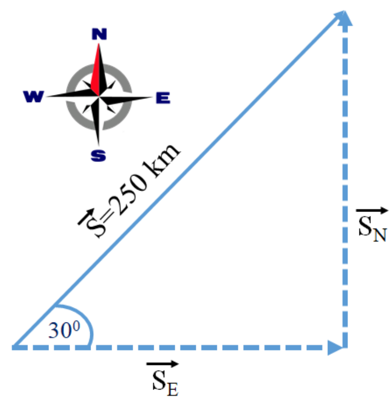


Figure 1.12 Resolving of resultant displacement.

Example 1.4

A boy walks 3 km due east and then 2 km due north. What is the magnitude and direction of his displacement vector?

Solution: You first make an overhead view of the boy's movement as shown in Figure 1.13. The magnitude of the displacement **S** is given by the Pythagorean theorem as follows:

$$S = [(3\ km)^2 + (2\ km)^2]^{1/2} = 3.61\ km$$

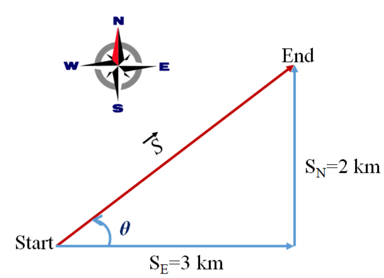


Figure 1.13 The magnitude and direction of the boy's motion.

The direction that this displacement vector makes relative to east is given by:

$$tan(\theta) = \frac{2\ km}{3\ km}$$
$$= 0.666...$$

Thus, $\theta = tan^{-1}(0.666...)=33.69^o$

Thus, the boy's displacement vector is 3.61 km with 56.31^o east of north, or 33.69^o north of east.

Exercise 1.8

a) Give an example of a nonzero vector that has a component of zero.
b) If two vectors are equal, what can you say about their components?

Section summary

- Any vector can be resolved into a horizontal and a vertical component.
- The combined effect of the horizontal and vertical components of the vector quantity is the same as the original vector.

Review questions

1. What is resolution of vector?
2. Draw simple vector diagrams and resolve them into their components.
   (a) 40 N at an angle of 30^o from the horizontal.
   (b) 10 m/s at an angle of 80^o from the horizontal.
   (c) 1900 km at an angle of 40^o from the vertical.
3. A car travels 10 km due north and then 5 km due west. Find graphically and analytically the magnitude and direction of the car's resultant displacement.
4. A girl walks 25.0^o north of east for 3.10 km. How far would she have to walk due north and due east to arrive at the same location?

Virtual Lab

On the soft copy of the book, click on the following link to perform virtual experiment on vector quantities unit under the guidance of your teacher.

1. Vector Addition PhET Experiment.

End of unit summary

- Scalar is a quantity specified only by its magnitude.
- Vectors is a quantity specified by its magnitude and direction.
- The vector is represented by an arrow drawn at a suitable scale where:
  - The arrow length represents the vector magnitude.
  - The arrow direction represents the vector direction.
- Two vectors $\vec{A}$ and $\vec{B}$ are said to be equal when they have equal magnitudes and same direction. For the two vectors $\vec{A}$ and $\vec{B}$, the resultant vector $\vec{R}$:
  - ⋆ $\vec{R} = \vec{A} + \vec{B}$ when the two vectors are in the same direction.
  - ⋆ $\vec{R} = \vec{A} - \vec{B}$ when the two vectors are in opposite directions.
- For two Vectors $\vec{A}$ and $\vec{B}$, $\vec{A} + \vec{B} = \vec{B} + \vec{A}$ is commutative property of vectors.
- The method of finding the components of vectors is called **resolving vector**.
  - When vector $\vec{A}$ is decomposed along the rectangular coordinate system, the horizontal component of $\vec{A}$ is $\vec{A}_x = Acos\theta$ and the vertical component $\vec{A}$ is $\vec{A}_y = Asin\theta$.

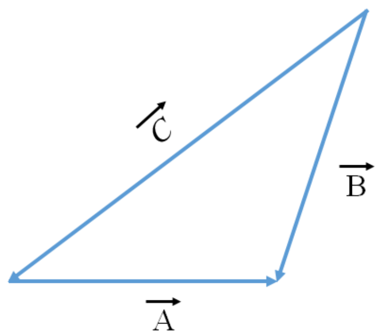


Figure 1.14 Magnitude and direction of three vectors

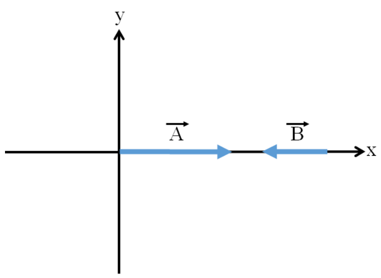


Figure 1.15 Magnitude and direction of two vectors

End of unit questions and problems

1. If two vectors have equal magnitudes, can their sum be zero? Explain.
2. Based on the three vectors in Figure 1.14, which of the following is true.
   (a) $\vec{A} + \vec{B} + \vec{C} = 0$
   (b) $\vec{A} = \vec{C} + \vec{B}$
   (c) $\vec{C} + \vec{A} = \vec{B}$
3. For the two vectors $\vec{A}$ and $\vec{B}$ with magnitude 6.8 cm and 5.5 cm in Figure 1.15, determine the magnitude and direction of:
   (a) $\vec{C} = \vec{A} + \vec{B}$
   (b) $\vec{C} = \vec{A} - \vec{B}$
   (c) $\vec{C} = \vec{B} - \vec{A}$
4. What is head to tail method?
5. List the head to tail methods of vector addition?
6. What is the parallelogram law of vector addition?
7. Explain the polygon law of vector addition?
8. Graphically determine the resultant of the following three vector displacements: 24 m, 36^o north of east; 18 m, 37^o east of north; and 26 m, 33^o west of south.
9. A car is driven 225 km west and then 98 km 45^o southwest. What is the displacement of the car from the point of origin (magnitude and direction)? Draw a diagram.
10. If $\vec{V}_x = 9.8$ m/s and $\vec{V}_y = 6.4$ m/s, determine the magnitude and direction of $\vec{V}$.

11. Three vectors A, B and C have a magnitude and direction of 21 unit north, 16 unit east and 26 unit south, respectively. Using a polygon method of vector addition, What will be the resultant vector?

Unit 2

Uniformly Accelerated Motion

Introduction

In grade 9, you have learned that uniform motion occurs when an object moves at a steady speed in a straight line. Most moving objects, however, do not display uniform motion. Any change in an object's speed or direction or both means that its motion is not uniform. This nonuniform motion, or changing velocity, is called accelerated motion. A car ride in a city at rush hour during which the car must speed up, slow down, and turn corners is an obvious example of accelerated motion. In this unit, you will learn about uniformly accelerated motion.

Brain storming question

In your everyday life, you come across a range of constant acceleration motions. Can you give two examples for such type of motion?

By the end of this unit, you should be able to:

- *know terms that are used to describe motion in one dimension;*
- *understand the different types of motions to describe physical phenomena;*
- *know the equation of motions that describe the motion of an object under uniform acceleration;*
- *solve motion problems using uniformly accelerated formulas;*
- *understand relative velocity in one dimension.*

2.1 Position and Displacement

By the end of this section, you should be able to:

- *define terms such as position, displacement, and distance;*
- *determine the total distance traveled by an object;*
- *describe the difference between distance and displacement;*
- *calculate the total displacement given the position as a function of time.*

Activity 2.1

While you are in the class room and learning physics lesson, can you describe your teacher's motion using position and displacement?

Key Concept

☞ Any measurement like position, distance and displacement must be made with respect to a reference frame.
☞ A frame of reference is a reference point combined with a set of directions.

Position

The most important idea when studying motion, is you have to know where you are. The word position describes your location (where you are). However, saying that you are here is meaningless, and you have to specify your position relative to a known reference point. For example, if you are 2 m from the doorway, inside your classroom then your reference point is the doorway. This defines your position inside the classroom. Note that you need a reference point (the doorway) and a direction (inside) to define your location.

A frame of reference or reference frame is reference point which serves as the origin for a coordinate system. The coordinate system can be up or down, inside or outside, left or right. For example, a boy is standing inside a train pulling out of a station. You are standing on the ground watching the train moving from left to right. To you, it looks as if the boy is moving from left to right. However, the boy is at rest relative to the train.

A position is a measurement of a location, with reference to an origin. Positions can therefore be negative or positive. The symbol s is used to indicate position. Position(s) has units of length for example cm, m or km. Depending on what reference point you choose, you can say that the school is 300 m from Kemal's house (with Kemal's house as the reference point or origin).

Exercise 2.1

Suppose you sitting on the chair and watching TV. Could this be an example of displacement or position?

Displacement

You know that distance is the total length of the path taken in going from the initial position (s_o) to the final position (s). Distance is a scalar. But the difference between the initial and final position vectors of a body is called its displacement. Basically, displacement is the shortest distance between the two positions and has a certain direction. Thus, displacement is a vector quantity. In Figure 2.1, distance is the length of dashed line while displacement is the straight-line distance from the starting point to the endpoint.

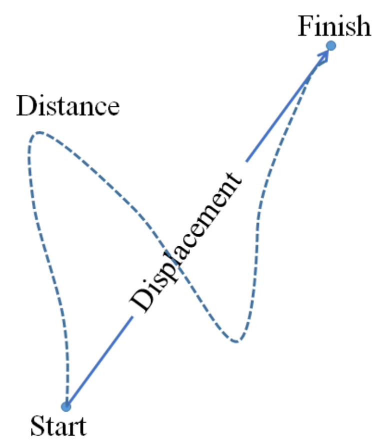


Figure 2.1 The possible distance and displacement of an object in motion between two points.

Activity 2.2

On a piece of graph paper, draw a scale map of your home and school area. Determine your displacement and estimate the distance you travel
(a) from home to school.
(b) from school to home.

If the initial position (s_o) from which an object moves to a second position (s) in a particular frame of reference, then the displacement $\vec{\Delta s}$ can be written as:

$$\vec{\Delta s} = s - s_o \tag{2.1}$$

In order to answer exercise 2.1, consider the motion of an object moving along a straight path. The object starts its journey from O which is treated as its reference point as shown in the Figure 2.2. Let A, B and C represent

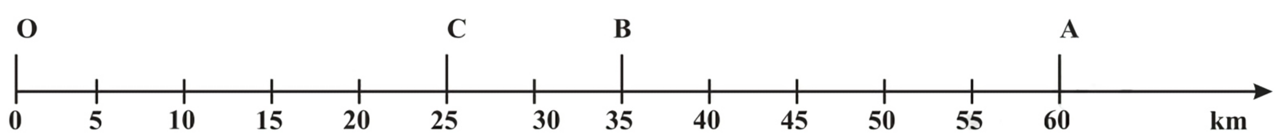


Figure 2.2 Positions of an object on a straight line path.

Exercise 2.2

Can the magnitude of the displacement of an object from its original position ever exceed the total distance moved? Explain.

the position of the object at different instants.

For motion of the object from O to A, the distance covered is 60 km and the magnitude of displacement is also 60 km. During its motion from O to A and back to B, the distance covered = 60 km + 25 km = 85 km while the magnitude of displacement = 60km - 25 km = 35 km. Thus, the magnitude of displacement (35 km) is not equal to the path length (85 km). Further, you will notice that the magnitude of the displacement for a course of motion may be zero but the corresponding distance covered is not zero. If you consider the object to travel back to O, the final position coincides with the initial position, and therefore, the displacement is zero. However, the distance covered in this journey is OA + AO = 60 km + 60 km = 120 km. Thus, the two different physical quantities (distance and displacement), are used to describe the overall motion of an object and to locate its final position with reference to its initial position at a given time.

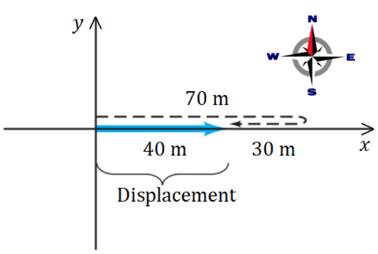


Figure 2.3 A person walks 40 m displacement

Example 2.1

A person walks 70 m east, and then 30 m west. Find the displacement?

Solution: The displacement of a person walking 70 m to the east and then turning around and walking back (west) a distance of 30 m as shown in Figure 2.3 is:. $\vec{\Delta s} = s - s_o = 70\ m\ - 30\ \ m$

$$\Delta\vec{s} = 40\ m\ east$$

The *displacement* is only 40 m since the person is now only 40 m from the starting point but the total *distance* traveled is 100 m.

Key Concepts:

☞ **Position** is a measurement of a location, with reference to an origin.

☞ **Distance** is the actual path that is travelled by a moving body.

☞ **Displacement** is defined as its change in position (final position minus initial position).

Section summary

- A description of motion depends on the reference frame from which it is described.
- Position is the location of an object compared to a reference frame (point).
- The distance an object moves is the length of the path along which it moves.
- Displacement is the difference between the initial and final positions of an object.

Review questions

1. Explain the difference between position and displacement.
2. Give an example that clearly show the difference among distance traveled, displacement and magnitude of displacement. Identify each quantity in your example.
3. A body travels a distance of 15m from A to B and then moves a distance of 20 m at right angles to AB. Calculate the total distance traveled and the displacement.

Activity 2.3

Walk from one corner of your classroom to its opposite corner along its sides. Measure the distance covered by you and magnitude of the displacement. What difference would you notice between the two in this case?

2.2 Average velocity and instantaneous velocity

By the end of this section, you should be able to:

- *define instantaneous and average velocity of a body in motion;*
- *describe the difference between average velocity and instantaneous velocity;*
- *solve problems related to the average velocity.*

Exercise 2.3

What is the difference between average velocity and instantaneous velocity?

Average velocity

In grade 9, you learnt that the rate of change of distance with time is called speed but the rate of change of displacement is known as velocity. Unlike speed, velocity is a vector quantity.

When an object travels a certain distance with different velocities, its motion is specified by its average velocity. The average velocity of a body is defined as the body displacement ($\vec{\Delta s}$) divided by the time interval (Δt) during which that displacement occurs. Let s_o and s be its positions at instants t_o and t, respectively.

Exercise 2.4

Can the average speed ever equal the magnitude of the average velocity? If "no," why not? If "yes," give an example.

Mathematically, you can express average velocity ($\vec{v_{av}}$) as:

$$\vec{v_{av}} = \frac{\vec{\Delta s}}{\Delta t} = \frac{s - s_o}{t - t_o} \qquad (2.2)$$

where $t - t_o$ is change in time, and to is the starting time which is obviously zero. The SI unit for average velocity is meters per second (m/s). But there are also many other units, such as km/h, mi/h (also written as mph) and cm/s in common use.

Key Concept

Velocity is the physical quantity that describes how a moving object's displacement changes.

The average speed of an object is obtained by dividing the total distance traveled by the total time taken:

$$\mathrm{v_{av}} = \frac{\text{total distance travelled}}{\text{total time taken}} \qquad (2.3)$$

If the motion is in the same direction along a straight line, the average speed is the same as the magnitude of the average velocity. However, this is always not the case.

Example 2.2

It takes you 10 min to walk with an average velocity of 1.2 m/s to the north from the bus stop to the museum entrance. What is your displacement?

Solution:

$\Delta t = 10\ min = 600$s

$v_{av} = 1.2\ \frac{m}{s}$ North $\quad \Delta s = ?$

$$\vec{\Delta s} = \vec{v_{av}} \times \Delta t = 1.2\ \frac{m}{s} \times 600\ s = 720\ m \quad north$$

This means the displacement has a magnitude of 720 m and a direction to the north.

Exercise 2.5

Consider the speedometer of a car. Does it provide information about speed or velocity?

Example 2.3

A passenger on the bus took 8 seconds to move 4 m to a seat on provided place forward. What is his average velocity?

Solution:

$\vec{\Delta s} = 4\ m, \quad \Delta t = 5\ s$

$v_{av} = ?$

$$\vec{v}_{av} = \frac{\vec{\Delta s}}{\Delta t} = \frac{4\ m}{5\ s} = 0.8\ m/s$$

The average velocity gives information based on initial point and final point of the passenger but you can't get information from average velocity whether he stops, goes slowly, or goes fast in the middle of his path. To know this, you can use another physical quantity which is called instantaneous velocity.

Example 2.4

A car travels at a constant 50km/h for 100 km. It then speeds up to 100km/h and is driven another 100 km. What is the car's average speed for the 200-km trip?

Solution: $s_1 = 100km, \quad v_1 = 50km/h \quad s_2 = 100km, \quad v_2 = 100km/h$

Total distance travelled = 200km

$$\Delta t_1 = \frac{s_1}{v_1}\frac{100km}{50km/h} = 2h$$

$$\Delta t_2 = \frac{s_2}{v_2} = \frac{100km}{100km/h} = 1h$$

v_{av} =?

$$\mathrm{v_{av}} = \frac{\text{total distance travelled}}{\text{total time taken}} = \frac{200\text{km}}{3\text{h}} = 66.7\text{km/h}$$

.

Note: Averaging the two speeds ($\frac{50km/h + 100km/h}{2}$) gives you a wrong answer which is 75km/h. The average speed of an object is obtained by dividing the total distance traveled by the total time taken. So that v_{av} = $66.7km/h$

Activity 2.4

☞ A student walks between two points of 30 m apart at a constant rate in a straight line taking 2 seconds to cover the distance. Another student walks between the same two points taking 4 seconds. Explain their difference.

☞ When one of the students walk at a constant velocity, what do you know about the displacement it moves each second?

Exercise 2.6

☞ Describe how the instantaneous velocity differs from the averag velocity?

Instantaneous velocity

Suppose the magnitude of your car's average velocity for a long trip was 20 m/s. This value, being an average, does not convey any information about how fast you were moving or the direction of the motion at any instant during the trip. Both can change from one instant to another. Surely there were times when your car traveled faster than 20 m/s and times when it traveled more slowly.

The instantaneous velocity **v** of the car indicates how fast the car moves and the direction of the motion at each instant of time. It is thus the rate of change in displacement as change in time approaches zero. Mathematically, the instantaneous velocity $\vec{v}$ of a body is given by

$$\vec{v} = \frac{s - s_o}{t - t_o} \quad when \quad t - t_o \quad approaches\,(\rightarrow)0 \tag{2.4}$$

The magnitude of the instantaneous velocity of a moving car is the reading of the speedometer.

Key Concept:

☞**Instantaneous velocity v** is the velocity at a specific instant in time (or over an infinitesimally small time interval).

Section summary

- Average velocity is change in displacement divided by time taken.
- Instantaneous velocity is the velocity of an accelerating body at a specific instant in time.
- The magnitude of instantaneous velocity is its instantaneous speed.

Review questions

1. How do you find the average velocity of an object in motion between two points?
2. Explain the difference between average speed and average velocity?
3. There is a distinction between average speed and the magnitude of average velocity. Give an example that illustrates the difference between these two quantities.
4. If an object has the instantaneous velocity of 20 m/s to east, what is its instantaneous speed?
5. A car moves with an average velocity of 48.0 km/h to the east. How long will it take him to drive 144 km on a straight highway?

6. An athlete runs 12 km to the north then turns and runs 16 km to the east in three hours.
   a) What is his/her displacement?
   b) Calculate his/her average velocity.
   c) Calculate average speed.

2.3 Acceleration

Exercise 2.7

1) If a body has constant velocity on straight level surface, what is the magnitude of its acceleration?
2) Does the direction of acceleration be in the direction of velocity itself?

By the end of this section, you should be able to:

- *explain acceleration in one dimension;*
- *distinguish between instantaneous acceleration and average acceleration;*
- *calculate average acceleration.*

While traveling in a bus or a car, you might have noticed that sometimes its speed increases and sometimes it slows down. That is, its velocity changes with time. The quantity that describes the rate of change of velocity in a given time interval is called acceleration. Any change in velocity whether positive, negative, directional, or any combination of these is acceleration. In everyday conversation, to accelerate means to speed up. Thus, the greater the acceleration is, the greater the change in velocity over a given time is.

Average acceleration

The magnitude of the average acceleration is defined by the change in an object's velocity divided by the time interval in which the change occurs.

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

$$\vec{a}_{av} = \frac{\Delta\vec{v}}{\Delta t} = \frac{v - v_o}{t - t_o} \tag{2.5}$$

Figure 2.4 Ethiopia-Djibouti high-speed train moving in a straight line.

Acceleration has dimensions of length divided by time squared. The SI units of acceleration is meters per second square, which is written as m/s^2.

Figure 2.4 shows a high-speed train leaving a station. Imagine that the train is moving to the right so that the displacement and the velocity are positive. The velocity increases in magnitude as the train moves faster. Therefore, the final velocity will be greater than the initial velocity, and $\Delta\mathbf{v}$ will be positive. When the change in velocity ($\Delta\mathbf{v}$) is positive, the acceleration is positive. On long trips with no stops, the train may travel for a while at a constant velocity. In this situation, because the velocity is not changing, $\Delta\mathbf{v} = 0$ m/s. When the velocity is constant, the acceleration is equal to zero. Imagine that the train, still traveling in the positive direction, slows down as it approaches the next station. In this case, the velocity is still positive, but the initial velocity is larger than the final velocity, so $\Delta\mathbf{v}$ will be negative. When $\Delta\mathbf{v}$ is negative, the acceleration is negative.

Key Concept

☞ Average acceleration is time rate change of velocity.
☞ The greater the acceleration, the greater the change in velocity over a given time.
☞ When an object slows down, its acceleration negative.

Instantaneous acceleration

The instantaneous acceleration is the acceleration at a particular instant. The instantaneous acceleration **a** that an object has at an instant time t is equal to the value that the average acceleration, calculated for an interval of time Δt which includes the instant t, approaches as the interval of time Δt gets smaller and smaller, i.e., as Δt approaches 0. As the time interval over which you are measuring the change in velocity gets smaller and smaller, the ratio of change in velocity to time interval as the time interval approach zero is instantaneous acceleration.

Therefore, instantaneous acceleration is defined as acceleration at a specific instant in time. Mathematically,

$$\mathbf{a} = \frac{\Delta \mathbf{v}}{\Delta t} \quad as \quad \Delta t \rightarrow \; 0. \tag{2.6}$$

For uniformly accelerated motion, the instantaneous acceleration has the same value as the average acceleration.

Exercise 2.8

☞ (a) If the velocity of an object is zero, does it mean that the acceleration is zero?

☞ (b) If the acceleration is zero, does it mean that the velocity is zero? Think of some examples.

Example 2.5

A car accelerates on a straight road from rest to $75 km/h$ in 5.0 s. What is the magnitude of its average acceleration?

Solution:

$v_0 = 0 \qquad v = 75 km/h \qquad \Delta t = 5.0S$

$a_{av} = ?$

$$\vec{a}_{av} = \frac{v - v_o}{t - t_o} = \frac{75 km/h - 0 km/h}{5.0s - 0s} = 15 \frac{km/h}{s}$$

This is read as "fifteen kilometers per hour per second" and means that, on average, the velocity changed by 15 km/h during each second. That is, assuming the acceleration was constant, during the first second the car's velocity increased from zero to 15 km/h. During the next second its velocity increased by another 15 km/h, reaching a velocity of 30 km/h at $t = 2.0s$,

and so on.
This result contains two different time units: hours and seconds. We usually prefer to use only seconds. To do so we can change km/h to m/s:

$$\frac{75km}{h} = (\frac{75km}{h})(\frac{1000m}{1km})(\frac{1h}{3600s}) = 21m/s$$

$$\vec{a}_{av} = \frac{\Delta\vec{v}}{\Delta t} = \frac{v - v_o}{t - t_o}$$

$$\vec{a}_{av} = \frac{21m/s - 0m/s}{5.0s - 0s} = 4.2\frac{m/s}{s} = 4.2m/s^2$$

Note that **acceleration** tells us how quickly the velocity changes, whereas **velocity** tells us how quickly the position changes.

Activity 2.5

☞ Discuss the concept of deceleration and negative acceleration.

Example 2.6

An automobile is moving to the right along a straight highway, which we choose to be the positive x axis.Then the driver steps on the brakes. If the initial velocity (when the driver hits the brakes) is 15m/s and it takes 5.0 s to slow down to 5m/s. What was the car's average acceleration?

Key Concept:

☞**Instantaneous acceleration a** is the average acceleration at a specific instant in time (or over an infinitesimally small time interval).

Solution: $v_0 = 15m/s \qquad v = 5m/s \qquad \Delta t = 5.0S$
a_{av}

Average acceleration is the change in velocity divided by the elapsed time.

$$\vec{a}_{av} = \frac{\Delta\vec{v}}{\Delta t} = \frac{v - v_o}{t - t_o}$$

$$\vec{a}_{av} = \frac{v - v_o}{t - t_o} = \frac{5m/s - 15m/s}{5.0s - 0s} = -2\frac{m/s}{s} = -2m/s^2$$

The negative sign appears because the final velocity is less than the initial velocity.

In this case, the direction of the acceleration is to the left (in the negative x direction) even though the velocity is always pointing to the right. You can say that the acceleration is to the left. The automobile is decelerating. But be careful: **deceleration** does not mean that the acceleration is necessarily negative.There is a deceleration whenever the magnitude of the velocity is decreasing; thus the velocity and acceleration points in opposite directions when there is deceleration.

Activity 2.6

☞ (a) Estimate your maximum running velocity, and estimate the average acceleration you undergo from rest to reach that velocity.
☞ (b) Design an experiment to check your estimates in (a). Include the equations you would use.
☞ (c) Get your design approved by your teacher, and then carry it out. Compare your results with your estimates.

Exercise 2.9

☞ For what type of motion does the average and instantaneous acceleration be the same?

Section summary

- Acceleration is the rate of change of velocity in a given time interval.
- Acceleration occurs whenever an object speeds up, slows down, or changes direction.
- There is a deceleration for an object in motion, when the magnitude of velocity is decreasing.

Review questions

1. Describe the similarities and differences between average acceleration and instantaneous acceleration.
2. A car moves along the x- axis. What is the sign of the car's acceleration if it is moving in the positive x direction with (a) increasing speed (b) decreasing speed?
3. A racehorse coming out of the gate accelerates from rest to

a velocity of 15.0 m/s due west in 1.80 s. What is its average acceleration?

4. A car is traveling at 14 m/s when the traffic light ahead turns red. The car decelerates and comes to a stop in 5.0 s. Calculate the acceleration of the car.

2.4 Equations of motion with constant acceleration

By the end of this section, you should be able to:

- *describe the nature of motion in a straight line;*
- *derive the equations of motion with constant acceleration;*
- *use appropriate equations of motion to solve motion-related problems;*

Exercise 2.10

Would you please list some examples of uniformly accelerated motion?

Exercise 2.11

If acceleration is constant, what do you think about velocity in a given equal interval of time?

If an object travels in a straight line and its velocity increases or decreases by equal amounts in equal intervals of time, the acceleration of the object is said to be uniform. Such type of motion is said to be a uniformly accelerated motion. A bicycle that slowly decreases its speed to stop and a ball dropped from the top of a ladder are some examples of uniformly accelerated motions.

When an object moves along a straight line with a uniform acceleration, it is possible to relate its velocity, acceleration during motion and the distance covered by it in a certain time interval by a set of equations known as the equations of motion. Since acceleration is constant, the average and instantaneous accelerations are equal. If an object's average acceleration during a time interval is known, the change in velocity during that time can be found. For convenience, you let the starting time $t_f = t$, where t is any arbitrary time. Also, you let $v_i = v_o$ (the initial velocity at time t = 0) and $\vec{v}_f = \vec{v}$ (the velocity at any time t). With this notation, you can express

$$\vec{a}_{av} = \frac{\vec{v} - \vec{v}_o}{t - t_o}$$

Since, average acceleration in a uniformly accelerated motion is the same as instantaneous acceleration, you can replace $\vec{a}_{av}$ by $\vec{a}$. Moreover, in 1-dimensional motion, direction can be indicated "-" or "+" signs. In this case, you can ignore the vector nature of symbols. Finally, replacing the vector notations by ordinary symbols, setting $t_o = 0$ and rearranging the result the result gives

$$v = v_o + at \tag{2.7}$$

This linear relationship enables us to find the velocity at any time t. You can make use of the fact that when the acceleration is constant (i.e., when the velocity varies linearly with time), the average velocity is given as:

$$v_{av} = \frac{v_o + v}{2} \tag{2.8}$$

To find the displacement as a function of time, you first let $x_i = x_0$(the initial position at time t = 0) and $s_f = s$ (the position at any time t). If the initial position is at the origin, $s_o = 0$, and hence $\Delta s = s$.

$$s = v_{av} t \tag{2.9}$$

Rearranging gives:

$$s = (\frac{v_o + v}{2})t$$

Substituting $v_o + at$ in place of v and making rearrangement gives:

$$s = v_0 t + \frac{1}{2}at^2 \tag{2.10}$$

Sometimes there are times when the time of motion is unknown. For such cases, you need to derive an equation that is independent of time as follows:

$$s = (\frac{v_o + v}{2})t = \left(\frac{v_o + v}{2}\right)\left(\frac{v - v_o}{a}\right) = \frac{v^2 - {v_o}^2}{2a} \tag{2.11}$$

Rearranging gives:

$$v^2 = {v_0}^2 + 2as \tag{2.12}$$

Key Concept:

☞ Uniform motion is a motion with a constant velocity while uniformly accelerated motion is motion with a constant acceleration.

Example 2.7

A car starts from rest and accelerates uniformly over a time of 5 seconds for a distance of 100 m. Determine the acceleration of the car.

Solution:

$v_0 = 0, \quad t = 5s, \quad$ and $s = 100m$

$a = ?$

$$s = v_o t + \frac{1}{2}at^2$$

$$a = \frac{2s}{t^2} = \frac{2 \times 100m}{25\ s^2} = 8\ m/s^2$$

Example 2.8

An airplane lands with an initial velocity of 70 m/s and then decelerates at $1.5m/s^2$ for 40 s. What is its final velocity?

Solution:

$v_o = 70m/s, \quad t = 40s, \quad$ and $a = -1.5m/s^2$

$v = ?$

$$v = v_o + at$$

$$v = 70m/s - 1.5m/s^2 \times 40s = 10\ m/s$$

The final velocity is much less than the initial velocity, as desired when slowing down, but is still positive.

Example 2.9

An automobile starts at rest and speeds up at 3.5 m/s^2 after the traffic light turns green. How far did the automobile take when it is traveling at 25 m/s?

Solution:

$v_o = 0,\qquad v = 25m/s,\qquad$ and $a = 3.5\ m/s^2$

$s = ?$

$$s = \frac{v^2 - {v_o}^2}{2a}$$

$$s = \frac{(25m/s)^2 - 0}{2 \times 3.5m/s^2} = 89.3m$$

Free fall

It is well known that, in the absence of air resistance, all objects dropped near the Earth's surface fall toward the Earth with the same constant acceleration under the influence of the Earth's gravity. A freely falling object is any object moving freely under the influence of gravity alone, regardless of its initial motion.

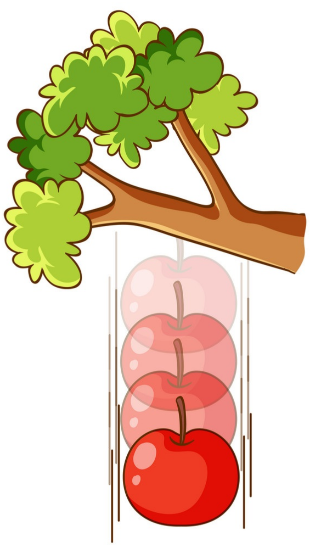


Figure 2.5 Freely falling of an apple with uniform acceleration due to gravity.

Activity 2.7

If you drop a piece of chalk and a paper at the same instant from the same height, which of them reaches the ground first? Explain your observation.

An object that is released from rest is falling freely once they are released. Any freely falling object experiences an acceleration directed downward, regardless of its initial motion.

You shall denote the magnitude of the free-fall acceleration by the symbol g. The value of g is maximum on the Earth's surface and decreases with increasing altitude from the surface. Furthermore, slight variations in g occur with changes in latitude. At the Earth's surface, the value of g is approximately $9.80m/s^2$.

If you neglect air resistance and assume that the free-fall acceleration does not vary with altitude over short vertical distances, then the motion of a freely falling object moving vertically is equivalent to motion in one dimension under constant acceleration. Therefore, the equations developed in the previous section for objects moving with constant acceleration can be applied. The only modification that you need to make in these equations for freely falling objects is to note that the motion is in the vertical direction (the y direction) rather than in the horizontal direction and that the acceleration is downward and has a magnitude of $9.80 m/s^2$. Thus, you replace a_y by $g = 9.80 m/s^2$.

Activity 2.8

As a freely falling body speeds up, what is happening to acceleration due to gravity?

The equation of motion can thus be modified as:

$$v = v_o + gt \tag{2.13}$$

$$h = v_o t + \frac{1}{2} g t^2 \tag{2.14}$$

$$v^2 = {v_0}^2 + 2gh \tag{2.15}$$

where v_0 is the initial velocity, h is the vertical height, g is acceleration due to gravity and t is the elapsed time.

Example 2.10

A mango fruit has fallen from a tree. Find its velocity and vertical height when it reached the ground if it took 1 s to reach the ground.

Solution:

$v_0 = 0$, $9 = 9.8 m/s^2$, and $t = 1s$

$h =$? and $v =$?

$$v = v_0 + gt = 0 + 9.8 m/s^2 \times 1s = 9.8 m/s$$

$$h = v_0 t + \frac{1}{2} g t^2 = \frac{1}{2} \times 9.8 m/s^2 \times 1s^2 = 4.9 m$$

Section summary

- The equation of motions at constant acceleration relates position, velocity, acceleration, and time.
- To describe the object with constant acceleration motion, identify the known quantities and choose the appropriate equations to solve for the unknowns. Either one or two of the acceleration constant motion equations are needed to solve for the unknowns, depending on the known and unknown quantities.

Review questions

1. What type of motion is experienced by a free-falling object?
2. A cyclist is traveling at 5.6 m/s when she starts to accelerate at 0.60 m/s^2 for a time interval of 4.0 s.
   (a) How far did she travel during this time interval?
   (b) What velocity did she attain?
3. A stone that starts at rest is in free fall for 8.0 s.
   (a) Calculate the stone's velocity after 8.0 s.
   (b) What is the stone's height covered during this time?

2.5 Graphical representation of uniformly accelerated motion

By the end of this section, you should be able to:

- *draw graphs of position-time, velocity-time and acceleration-time graph;*
- *explain the concept of instantaneous velocity using position-time graphs;*
- *distinguish between instantaneous acceleration and average acceleration using graphical method;*
- *draw velocity-time graph for a motion using the concept of instantaneous acceleration.*

Exercise 2.12

Would you remember the graphs of a uniform motion that you learnt in grade 9?

In your grade 9 physics, you learnt about the graphs of uniform motion. Figure **??** shows the summary of the graphs of a uniform motion.

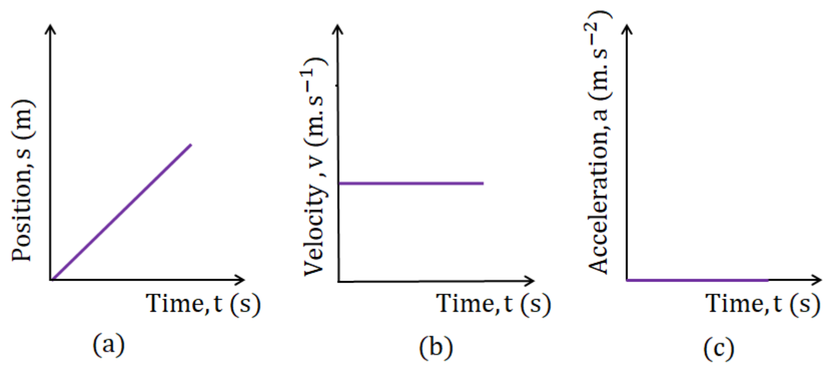


Figure 2.6 Graphs for motion at constant velocity (a) position vs. time (b) velocity vs. time (c) acceleration vs. time.

In this section, you will discuss about the graphs of a uniformly accelerated motion.

Position - time graph

A position-time graph is a graph that describes the motion of an object, with position x of a particle on the y-axis and the time on the x-axis. This graph will tell you the exact change in position of a body.

The position time relation for uniformly accelerated motion along a straight line is $s = v_o t + 1/2at^2$. Dependence of s on t^2 shows that it is a quadratic equation or quadratic function of t. So, the position-time graph for uniform accelerated motion is a parabola as shown in the Figure 2.7 (a).

As you learnt in grade 9, position-time graph slope represents the velocity of the object. Because the line is curved, however, its slope keeps changing. Thus, we must find the slope of the curved line. A tangent is a straight line that touches a curve at a single point and has the same slope as the curve at that point. Thus, choose a point on the curve and draw a tangent to the curve at that point as shown in the Figure 2.7(b). The slope of the tangent line is therefore an instantaneous velocity.

Key Concept

☞ The slope of the tangent to the graph of position versus time is velocity.

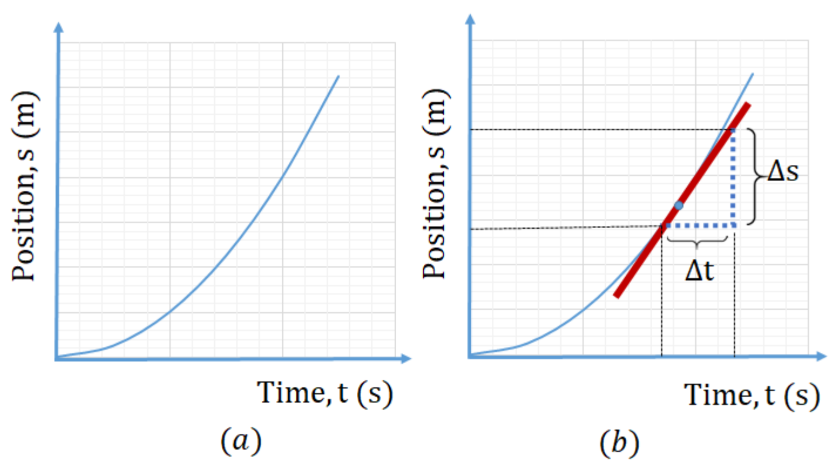


Figure 2.7 (a) The position-time graph in constant acceleration, (b) the slope of the tangent line at a particular point gives the instantaneous velocity.

You may recall from your mathematics studies that the slope of a line describes its steepness. Slope is determined by comparing the magnitude of the rise (the change between points on the y-axis) and the magnitude of the run (the change between the same points on the x-axis).

$$\text{Slope} = \frac{\text{rise}}{\text{run}} = \text{instantaneous velocity} \tag{2.16}$$

The instantaneous velocity of an object, at a specific point in time, is thus the slope of the tangent to the curve of the position-time graph of the object's motion at that specific time. That means, the magnitude of the velocity of an object at the point where the tangent line touches the graph is the slope of the tangent line.

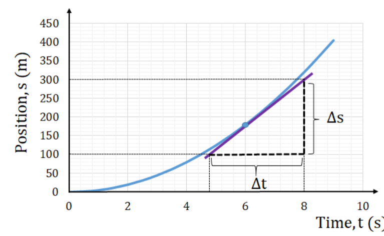


Figure 2.8 Position-time of the given problem.

Example 2.11

A car starts from rest and accelerate with the $10m/s^2$ for 10 s on the straight level road. Draw position- time graph and calculate the instantaneous velocity at 6 s.

Solution: :

$v_o = 0m/s$ $\quad a = 10m/s^2$ $\quad$ t=10s

Position-time graph?

v =?

a) Using equation of constant acceleration motion $s = 1/2at^2$. You have the following table, when $V_o = 0$.

Position (m)	0	5	20	45	80	125
Time(s)	0	1	2	3	4	5

b) Plot the position, s(m) on the y-axis and time, t (s) on the x-axis. And the graph is shown as in the Figure 2.8.

c) Draw the tangent line at the given time. The slope of the tangent line drown at 6 second of the x-axis coordinate, represent the instantaneous velocity at instant of 6 s. The slope of tangent line becomes:

$$Slope = \frac{\Delta \mathbf{s}}{\Delta t} = \frac{300\ m - 100\ m}{8\ s - 3\ s} = \frac{200\ m}{5\ s} = 66.7\frac{m}{s}$$

$\therefore V = 66.7m/s$

Exercise 2.13

☞ Suppose a truck accelerates with average accelerations of 20.0 m/s^2 starting from rest for 5.0 s. How far does it travel in this time? Draw position vs. time graph?

Velocity-time graph

A graph plotted with time along the X-axis and the velocity along the Y-axis is called the velocity-time graph. A velocity-time graph of the given motion shows how its velocity changes as it travels in a given time. If the particle starts from rest and experiences uniform acceleration, the velocity-time graph will be a straight line passing through the origin and having a positive slope (as shown in the Figure 2.9 (a)).

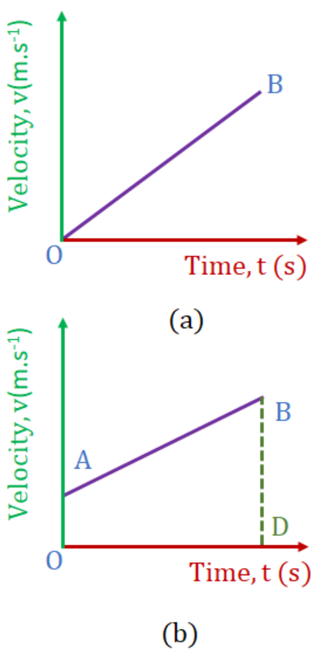


Figure 2.9 The velocity-time graph.

If the particle has an initial velocity the graph will be a straight line, but will not pass through the origin as shown in the Figure 2.9 (b). In Figure 2.9 (b), the ordinate OA gives the initial velocity and the ordinate BD gives the final velocity.

The velocity-time graph of a particle moving along a straight line with uniform acceleration may be used to measure the displacement of the particle and also the acceleration.

A) Area under the velocity-time graph

The area under the velocity-time graph gives the total displacement of the particle during the time interval.

Consider a particle moving along a straight line with uniform acceleration a. Let v_o be the velocity of the particle at the instant t = 0 and v at a later instant t. The velocity-time graph of such a motion is as shown in the Figure 2.10. The area under velocity time graph during the interval 0 to t is ABDO.

Area, ABDO = Area of rectangle ACDO Area of triangle ABC

$$
\begin{aligned}
Area, ABDO &= AO \times Ac + \frac{1}{2} \times AC \times BC \\
&= v_o t + \frac{1}{2} t(v - v_o) \\
&= v_o t + \frac{1}{2} a t^2 \\
&= displacement
\end{aligned}
$$

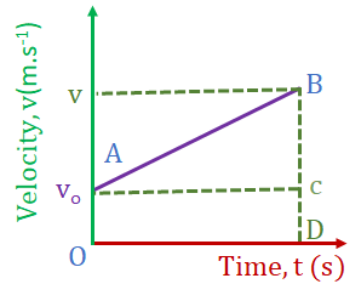


Figure 2.10 The area under velocity-time graph.

Thus, area under the v-t graph gives the displacement of the particle in that given time interval.

B) Slope of a velocity-time graph

The slope of the velocity-time graph gives the acceleration of the particle. Similarly, as said earlier, for a particle moving along a straight line with constant acceleration, the velocity-time graph will be a straight line inclined to the time axis as shown in the Figure 2.10. Let v_o be the velocity at t = 0 and v be the velocity after a time interval t.

Key Concept

☞ The area under the curve in a v - t graph is the change in position.

The acceleration,

$$a = \frac{v - v_o}{t} = \frac{BC}{Ac} = slope \quad (2.17)$$

That is, the slope of the v-t graph gives the acceleration of the particle.

Velocity-Time graph for uniform retardation

For a particle moving with uniform retardation or deceleration, the velocity-time graph will be a straight line having a negative slope as shown in the Figure 2.11. If the body is brought to rest, the graph will touch the time axis.

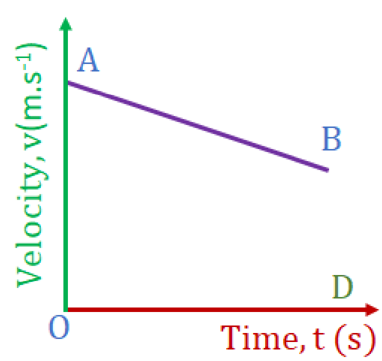


Figure 2.11 Velocity-Time graph for uniform retardation.

Velocity-Time graph for non-uniform motion

In the case of a particle moving with variable velocity, the velocity-time curve will be irregular in shape.

For example, consider a car starting from point A. Let it be moving along a straight line with uniform acceleration a during the time interval t_1 to t_2 and then start moving with uniform velocity during the interval of time t_2 to t_3. Thereafter, let the velocity of the car decrease uniformly and the car come to a stop at the instant t_4. The motion of the car can be represented by the v-t graph, as shown in the Figure 2.12. Then the area under the velocity-time graph gives the total displacement of the car.

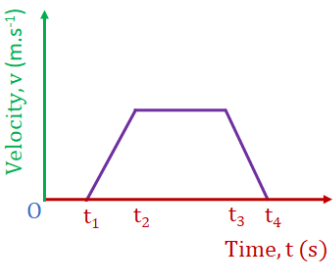


Figure 2.12 Velocity-Time graph for non-uniform motion.

Exercise 2.14

☞ What quantity is represented by the area under a velocity-time graph?

Example 2.12

The velocity vs. time graph is plotted in Figure 2.13 below. Calculate the total distance and displacement of the truck after 15 seconds.

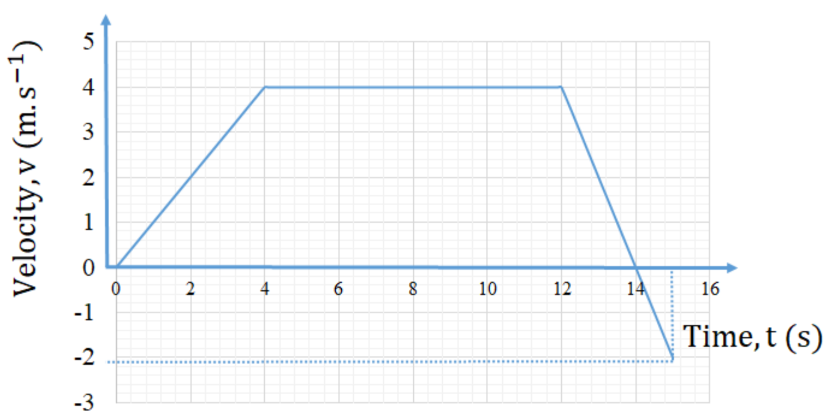


Figure 2.13 velocity- time graph.

Solution: : To calculate the total distance and total displacement you can use the area between velocity vs. graph.

s_1 = area of a triangle = $\frac{1}{2}(base) \times (height) = \frac{1}{2}(\Delta v) \times (\Delta t) = \frac{1}{2}(4m/s) \times (5s) = 10m$.

s_2 = area of a triangle = $(base) \times (height) = (\Delta v) \times (\Delta t) = (4m/s) \times (7s) = 28m$.

s_3 = area of a triangle = $\frac{1}{2}(base) \times (height) = \frac{1}{2}(\Delta v) \times (\Delta t) = \frac{1}{2}(4m/s) \times (2s) = 4m$.

s_4 = area of a triangle = $\frac{1}{2}(base) \times (height) = \frac{1}{2}(\Delta v) \times (\Delta t) = \frac{1}{2}(2m/s) \times (1s) = 1m$.
Thus, the total distance = $s_1 + s_2 + s_3 + s_4 = 43m$.
The total displacement = $s_1 + s_2 + s_3 - s_4$ (since velocity is negative) = 42 m in the positive direction.

Acceleration - time graph

Acceleration-time graph shows the acceleration plotted against time for a particle moving in a straight line. The acceleration-time plots acceleration values on the y-axis and time values on the x-axis. For a uniformly accelerated motion, acceleration is constant with time. Hence, acceleration time-graph will be a straight line parallel to the time axis. For a straight line parallel to the time axis, slope equals zero.

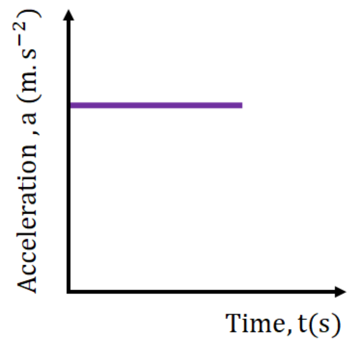


Figure 2.14 Acceleration-time graph.

An acceleration-time graph can be used to find the change of velocity during various time intervals. This is accomplished by determining the area under the line on the acceleration-time graph.

Exercise 2.15

☞ How long does it take a car to cross a 25.0 m wide intersection after the light turns green, if the car accelerates from rest at a constant acceleration of 2.0 m/s^2? Draw the acceleration-time graph.

In uniformly accelerated motion:

- Position-time equation is quadratic and hence the graph is parabolic.
- The slope of position-time graph is equal to the instantaneous velocity.
- Velocity-time equation is linear and hence the graph is a straight line.

Exercise 2.16

How does uniform acceleration motion differ from uniform motion?

- The slope of velocity-time graph is equal to the acceleration.

In general, graphs of motion in uniform acceleration are summarized in Figure 2.15.

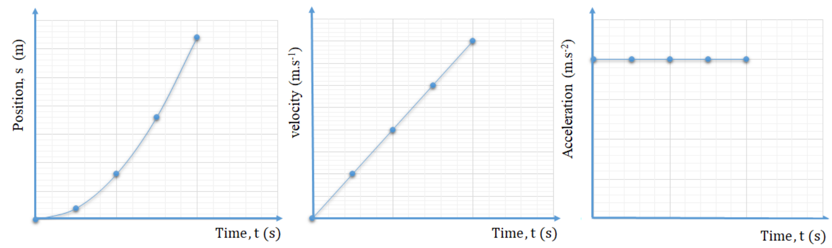


Figure 2.15 Graphs of motion in uniform acceleration.

Activity 2.9

The table below shows a set of position-time data for uniformly accelerated motion.

Position (m)	0	8	32	72	128
Time (s)	0	2	4	6	8

1. Plot a position-time graph.
2. Find the slopes of tangents at appropriate times.
3. Plot a velocity-time graph.
4. Plot an acceleration-time graph.
5. Determine the area under the line on the velocity-time graph and then on the acceleration-time graph. State what these two areas represent.

Section summary

- The position-time graph of a uniformly accelerated motion is a curve.
- The slope of the tangent to the graph of position-time is the instantaneous velocity.
- In a uniform motion, the graph of velocity-time is a horizontal straight line.

Review questions

1. What information can you obtain from a velocity-time graph?
2. Explain the relationship between slope and velocity-time graph.
3. The v-t graph below shows the motion of an air plane. Find the displacement of the airplane at $\Delta t = 1.0$ s and at $\Delta t = 2.0$s.

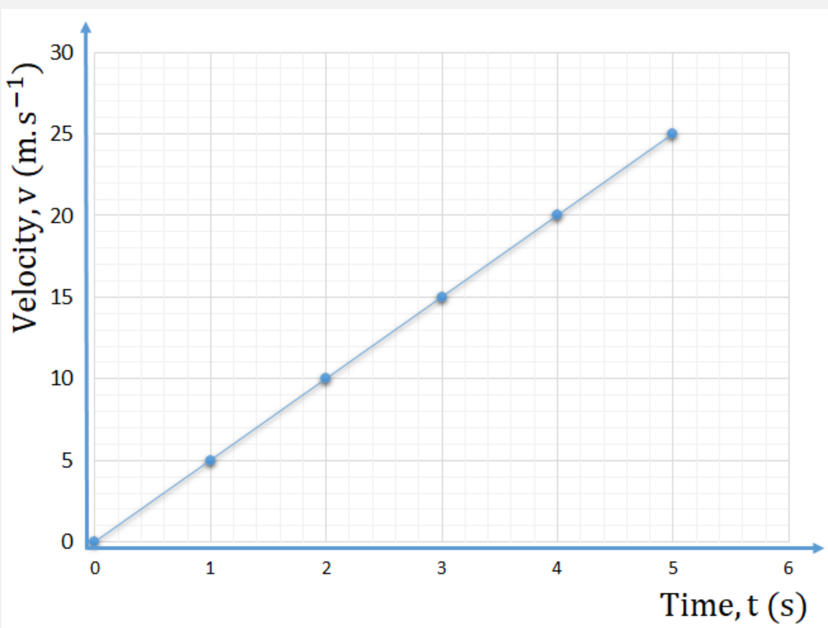


Figure 2.16 Velocity-time graph.

2.6 Relative velocity in one dimension

Exercise 2.17

What is meant by relative velocity in one dimension. Give an example?

By the end of this section, you should be able to:

- *explain relative velocity in 1-D using frame of reference;*
- *calculate the relative velocity.*

Any measurement of distance, speed, velocity and so on; must be made with respect to a reference frame, or frame of reference. When you say an object has a certain velocity, you must state its velocity with respect to a given reference frame.

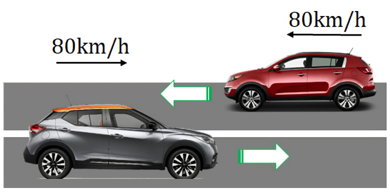


Figure 2.17 The two trains moving with same speed towards each other.

Next to this we look how observations made in different frames of reference are related to each other. For example, consider two cars approaching one another as in the Figure 2.17, each with a speed of 80 km/h with respect to the Earth. The observers on the Earth beside the train tracks will measure 80 km/h for the speed of each of the trains. Observers on either one of the trains (a different frame of reference) will measure a speed of 160 km/h for the train approaching them. Similarly, when one car traveling 90 km/h passes a second car traveling in the same direction 75 km/h at the first car has a speed relative to the second car 90 km/h-75 km/h = 15 km/h.

Let us consider an object A is moving at a speed with respect to the ground v_A and an object B is moving at a speed with respect to the ground v_B, the relative velocity of the v_A with respect to B (v_{AB}) or the relative velocity of the v_B with respect to A (v_{AB}) can be found:

a) when the two objects are approaching to each other:

$$v_{AB} = v_{BA} = v_A + v_B$$

b) when the objects are moving in the same direction:

$$v_{AB} = v_A - v_B$$

and

$$v_{BA} = v_B - v_A$$

Key Concept

☞ When the velocities are along the same line, simple addition or subtraction is sufficient to obtain the **relative velocity**.

Example 2.13

Car A is moving with a speed of 80 km/h while Car B is moving with speed of 65km/h following car A. Calculate the relative velocity of B with respect to A.

Solution: :

$$\vec{V}_A = 65 km/h$$

$$\vec{\mathrm{V}}_{\mathrm{B}} = 80 km/h$$

V_{BA}= ?

$$\vec{\mathrm{V}}_{\mathrm{BA}} = \vec{\mathrm{V}}_{\mathrm{B}} + \vec{\mathrm{V}}_{\mathrm{A}}$$
$$\vec{\mathrm{V}}_{\mathrm{BA}} = 65 km/h - 80 km/h$$
$$\vec{\mathrm{V}}_{\mathrm{BA}} = -15 km/h$$

This shows the car B is behind of car A by 15 km/h.

Section summary

- When you say that an object has certain velocity, you must state its velocity with respect to a given frame of reference.
- For a stationary frame of reference, if two objects are moving with velocities v_A and v_B, the relative velocity measured by an observer on one of the two objects approaching each other is the sum of the two velocities.

Review questions

1. A motorcycle traveling on the highway at a velocity of 120 km/h passes a car traveling at a velocity of 90 km/h. From the point of view of a passenger on the car, what is the velocity of

the motorcycle?

2. An automobile is moving at 80 km/h and a truck is moving at 60 km/h approaching an automobile. What is the relative velocity of an automobile with respect to a truck when the observer on the automobile measures it?

3. A thief is running away on a straight road on a jeep moving with a speed of 9 m/s. A police man chases him on a motor cycle moving at a speed of 10 m/s. If the instantaneous separation of jeep from the motor cycle is 100 m, how long does it take for the policemen to catch the thief?
   (a) 1 second
   (b) 19 seconds
   (c) 90 seconds
   (d) 100 seconds

Virtual Labs

On the soft copy of the book, click on the following link to perform virtual experiments on uniformly accelerated motion unit under the guidance of your teacher.

1. Forces and Motion: Basics PhET Experiment.

2. Moving-man PhET Experiment.

End of unit summary

- An object is in motion if it changes position relative to a reference point.

- For an object traveling at constant speed, its average speed is the same as its instantaneous speed.

- The direction of the acceleration is the direction of the change in the velocity and not the direction of the velocity itself.
- If an object is speeding up, its acceleration is positive; if an object is slowing down, its acceleration is negative.
- On velocity-time graph, a line sloping upward represents increasing speed, a line sloping downward represents decreasing speed, and a horizontal line represents zero acceleration or constant velocity.
- The summary of equations of motion at uniform acceleration are:

$v = v_o + at$	$v_{av} = \frac{(v_o+v)}{2}$
$s = (\frac{(v_o+v)}{2}t$	$S = v_o t + 1/2at^2$
$v^2 = {v_o}^2 + 2as$	$h = vot + 1/2gt^2$

- The relative velocity in one dimension is studied based on the reference frame.

End of unit questions and problems

1. How do intervals of constant acceleration appear on an acceleration-time graph?
2. How do intervals of constant acceleration appear on a velocity-time graph?
3. A truck on a straight road starts from rest, accelerating at $2m/s^2$ until it reaches a speed of 20 m/s. Then the truck travels for 20 s at constant speed until the brakes applied, are stopping the truck in a uniform manner in an additional 5 s. (a) how long is the truck in motion? (b) What is the average speed of the truck for the motion described?
4. If a student rides her bicycle in a straight line for 15 min with

an average velocity of 12.5 km/h south, how far has she ridden?

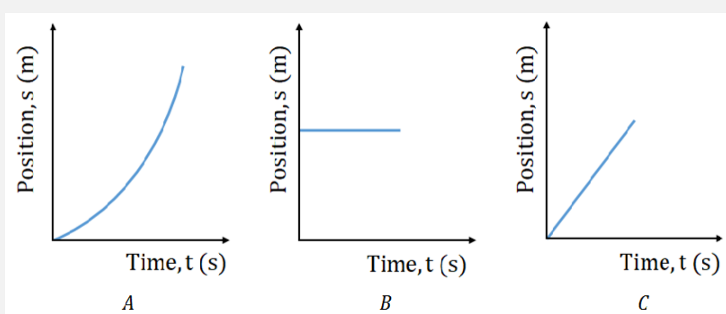
5. A race car travels on a racetrack at 44 m/s and slows at a constant rate to a velocity of 22 m/s over 11 s. How far does it move during this time?

6. A truck is traveling at 22 m/s when the driver notices a speed limit sign for the town ahead. He slows down to a speed of 14 m/s. He travels a distance of 125 m while he is slowing down. (a) Calculate the acceleration of the truck. (b) How long did it take the truck driver to change his speed?

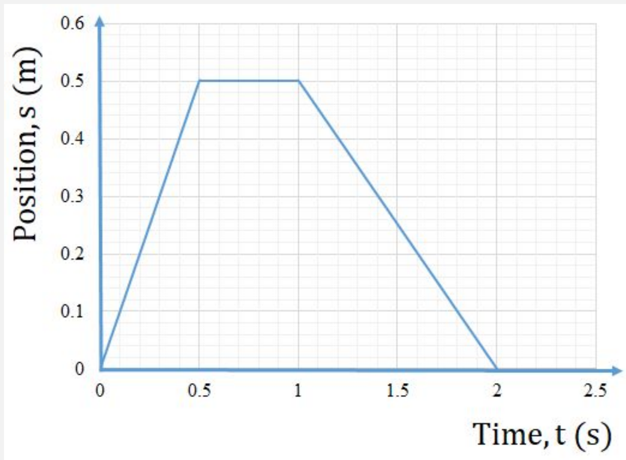
7. The velocity of a car changes over an 8 s time period as shown in the following table.
(a) Plot the v-t graph of the motion.
(b) What is the displacement of the car during the entire 8 s?
(c) Find the slope of the line between t = 0 s and t = 4 s? What does this slope represent?
(d) Find the slope of the line between t = 5 s and t = 7 s? What does this slope represent?

t (s)	0	1	2	3	4	5	6	7	8
s (m)	0	4	8	12	16	20	20	20	20

8. Which of the following graphs represent uniformly accelerated motion?



9. Given the position-time graph below, find the velocity-time graph.



10. A jet cruising at a speed of 1000 km/hr ejects hot air in the opposite direction. If the speed of the hot air with respect to the jet is 800 km/hr, then find its speed with respect to the ground.

Unit 3

Elasticity and Static Equilibrium of Rigid Body

Introduction

In grade 9 physics, you studied the effect of force on a body to produce displacement. The force applied on an object may also change its shape or size. Some objects regain their original shape and size whereas others do not. Such a behavior of objects depends on the microscopic structure of the material called **elasticity** and **plasticity**. In this unit, you will learn about the topics related to elasticity, plasticity, and static equilibrium of a rigid body.

Brainstorming question

What do you think are the important elastic and plastic properties of bridges and ladders?

By the end of this unit, you should be able to:

- *state elasticity and plasticity for an object;*
- *define density and specific gravity;*
- *explain stress and strain;*
- *demonstrate tensile strain and stress using local materials;*
- *state static equilibrium;*
- *apply first and second condition of equilibrium for a body in static equilibrium in everyday activity.*

Figure 3.1 Steel wire spring

Figure 3.2 The stretched rubber band.

Figure 3.3 The hammer force (an external force) applied on the nail which bent, showing permanent deformation of the nail.

3.1 Elasticity and plasticity

By the end of this section, you should be able to:

- *define elasticity and plasticity;*
- *explain the deformation of an object.*

A solid has a definite shape and size. In order to change (or deform) the shape or size of a body, a force is required. If you stretch a helical spring shown in Figure 3.1 by gently pulling its ends, the length of the spring increases slightly. When you leave the ends of the spring, it regains its original size and shape. The same is true for the rubber shown in Figure 3.2. When the force is applied to the rubber, it stretches and if the force is removed, it restores to its original position. But, if the external force applied on the solid material is large enough to permanently deform as shown in Figure 3.3, it can't regain its original shape.

The property of a body, by virtue of which it tends to regain its original size and shape when the applied force is removed, is known as elasticity and the deformation caused is known as elastic deformation.

However, if you apply force to a lump of putty or mud, they have no gross tendency to regain their previous shape, and they get permanently deformed. Such substances are called plastic and this property is called plasticity. Putty and mud are close to ideal plastics.

The elastic behavior of materials plays an important role in engineering design. For example, while designing a building, knowledge of elastic properties of materials like steel, concrete etc. is essential. The same is true in the design of bridges, automobiles, rope ways etc.

Key Concept

☞ **Deformation** is change of shape or size of an object.
☞ **Elastic deformation** is a reversible deformation; when the external forces that caused deformation are removed, it regains its original shape.
☞ **Plastic deformation** is non-reversible change of shape in response to applied external forces.

Activity 3.1

By using your two fingers, if you apply small force to the steel wire spring in Figure 3.2 and release it, does the spring regain its shape? Apply large force until it makes it straight line. What do you observe? Discuss in group.

Activity 3.2

The ball and the racket in the Figure below exert an equal force in opposite directions on each other. Are these two materials elastic or plastic?

Section summary

- External forces applied on an object cause deformation
- An object or material is elastic if it comes back to its original shape and size when the external force is removed.
- Based on the nature of the material and the magnitude of the external force applied, elasticity or plasticity can be observed.

Review questions

1. Define elasticity of a solid.
2. List some plastic materials in your locality.
3. Is the diving board shown in Figure 3.4 elastic or plastic?

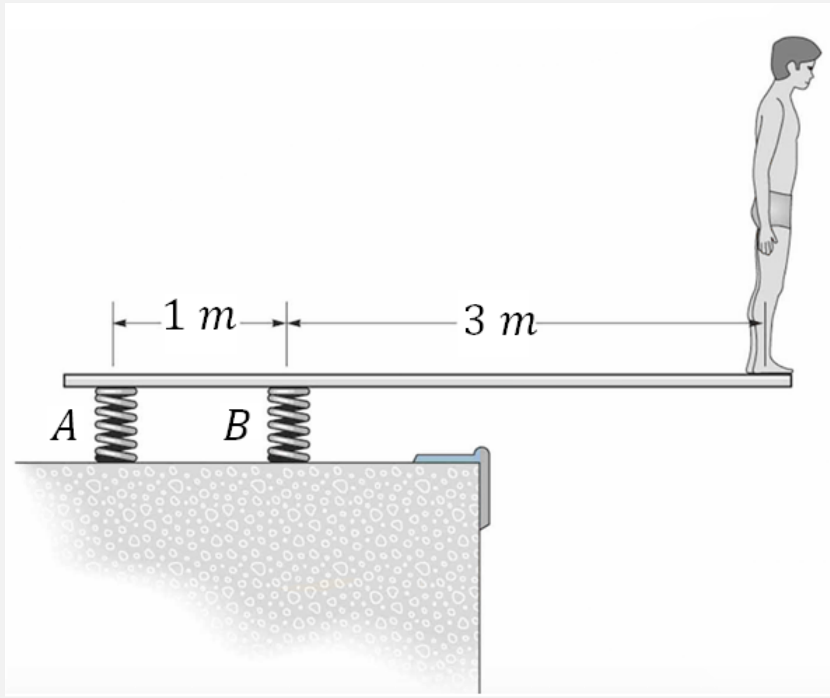


Figure 3.4 The diving board shown here is held by two supports at A and B; an athlete stands at one end.

4. Which statement is true about the direction of the forces exerted on the diving board shown in Figure 3.4?

   (a) Force at A is down and force at B is up.

   (b) Force at A is up and force at B is down.

   (c) Forces at both A and B are up.

   (d) Forces at both A and B are down.

3.2 Density and specific gravity

By the end of this section, you should be able to:

- *define density and specific gravity of an object;*
- *determine the density of an object;*
- *compare density of unknown object with a standard value.*

The **Density** of material shows the denseness of that material in a specific given area. It is essentially a measurement of how tightly matter is packed together. It is a unique physical property for a particular object. The principle of density was discovered by the Greek scientist Archimedes.

The density is usually represented by the Greek letter rho "ρ". A material's density is defined as its mass per unit volume.

Symbolically, it is given by the following equation:

$$\rho = \frac{m}{V} \tag{3.1}$$

The SI unit of density is kg/m^3. Sometimes densities are given in g/cm^3. The relation between them is given by: $1 kg/m^3 = 10^{-3} g/cm^3$.

Key Concept

Density is a characteristic property of any pure substance. For example, it is used in determining whether an object sinks or floats in a fluid.

The **specific gravity (SG)** or the relative density of a substance is defined as the ratio of the density of that substance to the density of reference substance, which is always water at 4.0^oC.

Activity 3.3

Suppose that a block of brass and a block of wood have exactly the same mass. If both blocks are dropped in a tank of water, which one floats and which one sinks? why?

Key Concept

☞Specific Gravity is a unitless quantity as it is the ratio of two densities.

Specific gravity is a ratio, it is a number without dimensions or units, and it is given by:

$$SG = \frac{\rho_{substance}}{\rho_{water}} \tag{3.2}$$

It is a dimensionless positive scalar quantity. For example the relative density of aluminum is 2.7. Its density is $2.7 \times 10^3 kgm^{-3}$. The densities and specific gravity of different substances are given in Table 3.1.

Activity 3.4

Suppose that you are given an iron and copper block. Determine the density of the two blocks by first measuring the masses and the volumes. Compare your result with the standard for iron $7.86g/cm^3$, and for copper $8.92g/cm^3$.

Table 3.1 Density and specific gravity of substance at 0^{o}C and 1 atm.

Material type	Material name	Density (Kg/m^3)	Relative density
Gas	Helium	0.179	1.79×10^{-4}
	Air	1.29	1.29×10^{-3}
	Carbon dioxide	1.98	1.98×10^{-3}
Liquid	Alcohol	7.9×10^2	0.79
	Gasoline	8.6×10^2	0.86
	Water (4^oC)	1×10^3	1
	Mercury	13.6×10^3	13.6
Solid	Glass (common)	$(2.4-2.8) \times 10^3$	2.5
	Aluminum	2.7×10^3	2.7
	Iron	7.86×10^3	7.86
	Copper	8.92×10^3	8.92
	Silver	10.5×10^3	10.5
	Uranium	19.07×10^3	19.07
	Gold	19.3×10^3	19.3

An object made of a particular pure substance such as pure gold, can have any size or mass, but the density will be the same for each.

Example 3.1

A mining worker gets an unknown mineral with a volume of $20cm^3$ and a mass of 54 g. Determine the density and the specific gravity of the mineral.

Solution:

$m = 60gm, \qquad V = 20cm^3$

$\rho = ?, \qquad SG = ?$

$$\begin{aligned} \rho &= \frac{m}{V} \\ &= \frac{54 \times 10{-}3Kg}{20 \times 10^{-6} m^3} \\ \therefore \ \rho &= 2.9 \times 10^3 kg/m^3 \\ SG &= \frac{\rho}{\rho_{water}} \\ &= \frac{2.7 \times 10^3 kg/m^3}{1 \times 10^3 kg/m^3} \\ \therefore \ SG &= 2.7 \end{aligned}$$

From table 3.1 above, this unknown rock is aluminium.

Example 3.2

What is the mass of a solid iron ball of radius 18 cm?

Solution:

$r = 18cm$

From table 3.1 above, the density of iron is $\rho = 7860kg/m^3$

$m = ?$

The volume of the sphere is given by: $\frac{4}{3}\pi r^3$. So that, the volume of Iron ball (V) becomes:

$$V = \frac{4}{3}(3.14)(0.18)m^3$$

$$V = 0.024m^3$$

From 3.1, you get $m = (\rho)(V)$ and it becomes:

$$m = (7860 kg/m^3)(0.024 m^3)$$

$$m = 188.64 kg$$

Section summary

- The density of a material is defined as the mass per unit volume.
- Specific gravity is the ratio of the density of the material to the density of water at $4^0 C$.

Review questions

1. What is the approximate mass of air in a living room of $5.6m \times 3.6m \times 2.4m$?
2. You have a sample of granite with density 2.8 g/cm^3. The density of water is 1.0 g/cm^3. What is the specific gravity of your granite?
3. Calculate the average density and specific gravity of the Earth given that the mass and radius of the Earth are $m_E = 5.98 \times 10^{24}$ kg and $R_E = 6.37 \times 10^6$ m, respectively.

Exercise 3.1

If you apply equal forces on a copper and silver wire of equal length and thickness, can they stretch equally? Explain.

3.3 Stress and Strain

By the end of this section, you should be able to:

- *define stress and strain;*
- *apply the formula of stress and strain to solve problems;*
- *apply physical concept of stress and strain on your daily life activity.*

You shall discuss the deformation of solid materials in terms of the concepts of stress and strain.

Stress

Stress is a quantity that describes the magnitude of forces that cause deformation. Stress is generally defined as force per unit area.

$$Stress = \frac{Force}{Area} \tag{3.3}$$

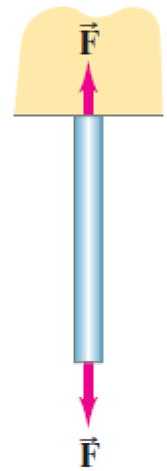


Figure 3.5 A rod clamped at one end stretched by applied force F.

Consider a rod of cross-sectional area A and original length L_0 that is clamped at one end, as shown in Figure 3.5. When an external force is applied perpendicular to the cross section, internal forces in the rod resist stretching, but the rod reaches an equilibrium situation in which its final length L is greater than L_0 and in which the external force is exactly balanced by internal forces. In such a situation, the rod is said to be stressed (thinner and longer) as shown in the Figure 3.6.

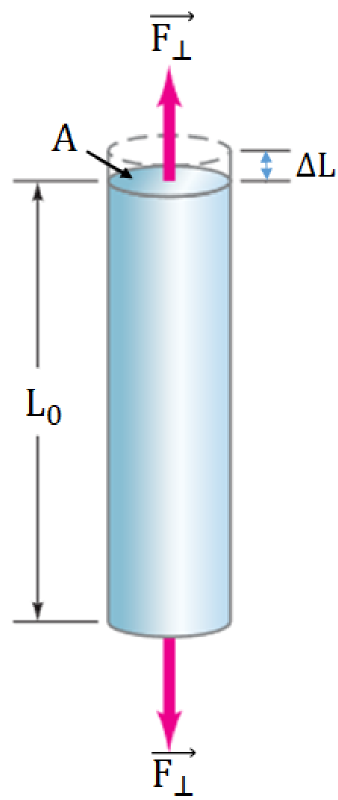


Figure 3.6 A rod stretched by an amount ΔL under the action of a force F.

On the other hand, when equal forces cause a compression of an object, we call it a compressive stress. As shown in the Figure 3.7, compressed (decreased in length) due to the equal forces applied on it. An object under compressive stress becomes thicker and shorter.

In either of these situations (Tension or compression), we define stress as the ratio of the perpendicular force ($F_\perp$) to the cross-sectional area (A) of the object being deformed.

$$\text{Tensile (or compressive) stress} = \frac{\mathrm{F}_\perp}{\mathrm{A}} \tag{3.4}$$

The unit of Tensile (or compressive) stress is N/m^2.

Key Concept

☞ **Stress** is a quantity that contains information about the magnitude of force causing deformation, defined as force per unit area.

Strain

Strain is a measure of how much the object is deformed due to applied force or stress. And it is given by:

$$\text{Tensile (or compressive) strain} = \frac{\Delta L}{L_0} \quad (3.5)$$

A strain is a dimensionless (no units) quantity because it is a ratio of two similar quantities. And is a measure of how much the object has been deformed. Stress is applied to the material by external agents, whereas strain is the material's response to the stress.

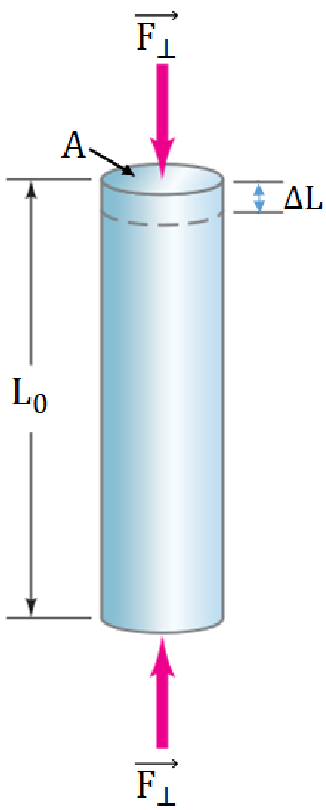


Figure 3.7 A rod compressed by an amount ΔL under the action of the forces acting inward.

Key Concept

☞ **Strain** is a dimensionless quantity that gives the amount of deformation of an object or medium under stress.

Exercise 3.2

- What is meant by tensile stress and compressive stress?
- What is the formula to calculate the compressive strain?

Example 3.3

1. Find the tensile stress when a force of 9.8 N acts over a cross-sectional area of $2 \times 10^{-3} m^2$.

Solution:

$F_\perp = 9.8$ N, $A = 2 \times 10^{-3} m^2$

Tensile stress = ?

Substituting the given values into the formula of tensile stress, we obtain:

$$\begin{aligned} Tensile\ stress &= \frac{F_\perp}{A} \\ &= \frac{9.8N}{2 \times 10^{-3} m^2} \\ &= 4.9 \times 10^3 N/m^2 \end{aligned}$$

Example 3.4

When a weight of $98N$ is suspended from wire of length $3m$ and diameter $0.4mm$, its length increases by $2.4cm$. Calculate tensile stress and tensile strain.

Solution:

$F = W = 98N$

$L_0 = 3m$

$D = 2r = 0.4mm$

$$A = \pi r^2 = (3.14)(0.2\times10^{-3}m^2)^2 = 6.28\times10^{-7}m^2$$

$$\Delta L = 2.4cm = 2.4\times10^2 m$$

Tensile stress=?

Tensile strain=?

Tensile stress and tensile strain becomes:

$$Tensile\ stress = \frac{F_\perp}{A} = \frac{mg}{A} = \frac{98N}{6.28\times10^{-7}m^2} = 1.56\times10^8 N/m^2$$

$$Tensile\ strain = \frac{\Delta L}{L_0} = \frac{2.4\times10^{-2}m}{3m} = 0.008$$

The amount of elongation of the wire due to the suspended load is 0.008.

Section summary

- The force per unit area acting on an object is the stress, and the resulting fractional change in length is the strain.
- Tensile (or compressive) stress causes elongation (or shortening) of the object and is due to an external forces acting along only one direction perpendicular to the cross-section.
- Tensile (or compressive) strain is the response of an object to tensile (or compressive) stress.

Activity 3.5

What type of stress are you applying when you press on the ends of a wooden rod? When you pull on its ends?

Review questions

1. The unit of stress is
   (a) Nm
   (b) N^2/m
   (c) N/m^2
   (d) $N-m$
2. A nylon string has a diameter of 2 mm, pulled by a force of 100 N. Calculate the tensile stress.
3. A load of 2.0 kg is applied to the ends of a wire 4.0 m long, and produces an extension of 0.24 mm. If the diameter of the wire is 2.0 mm, find the stress on the wire and the strain it produces.

3.4 Young's Modulus

Exercise 3.3

What did you know about Young's modulus of a material?

By the end of this section, you should be able to:

- *define Young's modulus;*
- *apply the formula of young's modulus to solve problems;*
- *demonstrate the tensile strain and stress using young's modulus from local materials.*

When the stress is sufficiently low, the deformation is directly proportional to the strain. The proportionality constant in this relation is called the **Young's modulus**. In the linear limit of low stress values, the general relation between stress and strain is:

$$Young's\ modulus = \frac{Stress}{Strain} \tag{3.6}$$

Consider a metallic rod of original length L_0 and cross sectional area A. When an external force $F_\perp$ is applied perpendicularly to the cross sectional

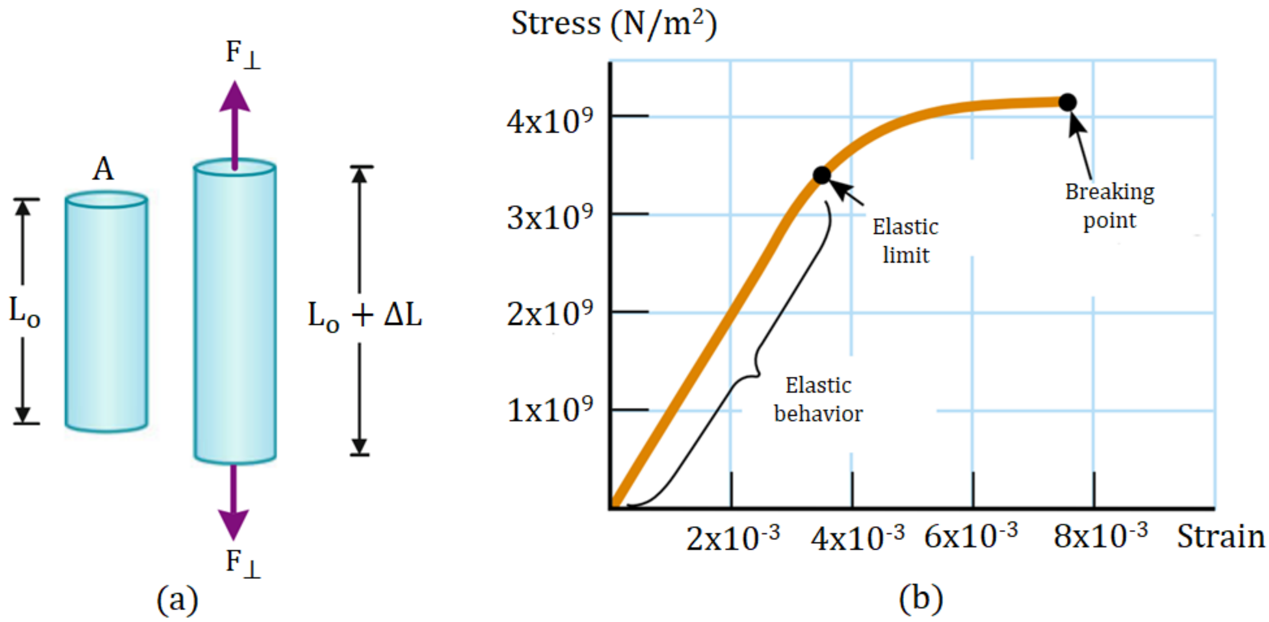


Figure 3.8 (a). A rod of length L_0 can be stretched by an amount ΔL after application of a tensile stress $F_\perp$. (b) The stress versus strain diagram for a ductile material.

area A of a rod, its length increases to a new length $L_0 + \Delta L$ as shown in the Figure3.8 (a). The relation between the tensile stress and the tensile strain is linear when the rod is in its elastic range. And Young's modulus is defined as:

$$\text{Young's modulus(Y)} = \frac{\text{Tensile stress}}{\text{Tensile strain}}$$

$$Y = \frac{\left(\frac{F_\perp}{A}\right)}{\left(\frac{\Delta L}{L_o}\right)} \tag{3.7}$$

Young's modulus is used to identify a solid which is stressed under either tension or compression. From this relation you can derive change in length by:

$$\Delta L = \frac{1}{Y}\frac{F}{A}L_0 \tag{3.8}$$

where L_0 is the original length of the object, A is the cross-sectional area, and ΔL is the change in length due to the applied force $F_\perp$. Y is a constant of proportionality known as the **elastic modulus**, or **Young's modulus**; its value depends only on the property of the material. Table 3.2 below shows the Young's modulus of different substances.

Figure 3.8 (b) shows a typical stress-strain curve for a ductile metal under a load, the relation between the tensile stress and the tensile strain is linear when the rod is in its elastic range (elastic behavior). When the stress exceeds its elastic limit, the rod is permanently deformed and it does not return to its original shape after the stress is removed. As the stress is increased even further, the rod reaches its breaking point.

Key Concept

☞ The **elastic limit** of the material is the stress value beyond which the material no longer behaves elasticity but becomes permanently deformed.

Table 3.2 Young's modulus of different substance in N/m^2

Substance	Young's modulus (N/m^2)
Tungsten	35×10^{10}
Steel	20×10^{10}
Copper	11×10^{10}
Brass	9.1×10^{10}
Aluminum	7.0×10^{10}
Glass	$6.5 - 7.8 \times 10^{10}$
Quartz	5.6×10^{10}
Water	-
Mercury	-

Activity 3.6

You have a shorter and a longer rod of the same material and apply equal force to each. Which one can be stretched more? Explain you result using young's modulus.

Exercise 3.4

A copper wire is 1.0 m long and its diameter is 1.0 mm. If the wire hangs vertically, how much weight must be added to its free end in order to stretch it 3.0 mm?

Example 3.5

A 1.60m long steel piano wire has a diameter of 0.20 cm. How great is the tension in the wire if it stretches 0.25 cm when tightened?

Solution:

$L_0 = 1.6m$

$$Y = 2 \times 10^{11} N/m^2$$

$$D = 0.2 \times 10^{-2} m$$

$$A = \pi r2 = (3.14)(0.0010m)^2 = 3.14 \times 10^{-6} m^2$$

Then

$$F = Y(\frac{\Delta L}{L_0})A$$

$$F = 2.0 \times 10^1 1 N/m^2 (\frac{0.0025m}{1.6m})(3.14 \times 10^{-6} m^2)$$

$$F = 980N$$

The large tension in all the wires in a piano must be supported by a strong frame.

Example 3.6

A pendulum consists of a big sphere of mass m = 30 kg hung from the end of a steel wire that has a length of 15 m, a cross-sectional area of $9 \times 10^{-6} m^2$, and Young's modulus of $200 \times 10^9 N/m^2$. Find the tensile stress on the wire and the increase in its length.

Solution:

$m = 30kg, \quad L_o = 15m, \; A = 9 \times 10^{-6} m^2, \quad Y = 200 \times 10^9 N/m^2$

Tensile stress and ΔL

The applied force on a wire must be equal to the weight of the sphere,

$$F_\perp = mg$$

The tensile stress will be

$$\begin{aligned} Tensile\ stress &= \frac{F_\perp}{A} \\ &= \frac{mg}{A} \\ &= \frac{30kg \times 9.8N/kg}{9 \times 10^{-6} m^2} \\ &= 3.27 \times 10^7 N/m^2 \end{aligned}$$

Key Concept

☞ When a force is applied on a material beyond its elastic limit, the material is permanently deformed.

Do you know? Thomas Young

(1773 - 1829, English) was English physician and physicist who described the elastic properties of a solid undergoing tension or compression in only one direction.

Using the value of Young's modulus, $Y = 200 \times 10^9 N/m^2$

Since Tensile strain = $\Delta L/L_o$ and $Y = \frac{\left(\frac{F_\perp}{A}\right)}{\left(\frac{\Delta L}{L_o}\right)}$, you can derive the expression for ΔL as

$$
\begin{aligned}
\Delta L &= \frac{1}{Y}\frac{F}{A}L_0 \\
&= \frac{3.27 \times 10^7 N/m^2}{200 \times 10^9 N/m^2} \times 15m \\
&= 2.45 \times 10^{-3} m \\
\therefore \Delta L &= 2.45mm
\end{aligned}
$$

Note that this large stress produces a relatively small change in length.

Section summary

- The relation between the tensile stress and the tensile strain is linear when the rod is in its elastic range.
- The ratio of the tensile stress and the tensile strain is called Young's Modulus(Y).
- Young's Modulus measures the resistance of a solid to a change in its length.

Review questions

1. What is Stress versus Strain diagram?
2. Under elastic limit, the stress is:
   (a) Inversely, proportional to strain
   (b) Directly proportional to strain
   (c) Square root of strain
   (d) Independent of strain
3. Define the following terms a) elastic limit, b) stress, c) strain, d) Young's Modulus

4. A 200-kg Load is hung on a wire having a length of 4.00 m, cross-sectional area $0.20 \times 10^{-5} m^2$, and Young's modulus $8.00 \times 10^{10} N/m^2$. What is its increase in length?

3.5 Static equilibrium

By the end of this section, you should be able to:

- *define static equilibrium of rigid body;*
- *state the first and second conditions of equilibrium;*
- *apply the first and second conditions for equilibrium to solve problems.*

A massive frame hung on a wall using two cables is in static equilibrium. A horizontal beam supported by a strut is also in static equilibrium. So, what is the definition of static equilibrium, and when do objects fall under this category?

Exercise 3.4

List an example of a body that is in static equilibrium from your surroundings.

Static equilibrium occurs when an object or a system remains at rest and does not tilt nor rotate. The word "static" means that the body is not in motion, while the term "equilibrium" indicates that all opposing forces are balanced. Thus, a system is in static equilibrium if it is at rest and all forces and other factors influencing the object are balanced.

When is a system or an object considered to be in static equilibrium? Two conditions need to be satisfied for a system is in static equilibrium: the first condition of equilibrium and the second condition of equilibrium.

Key Concept

☞ **Static equilibrium** is a type of equilibrium that occurs when a body is at rest and there is no net force or net torque acting on it.

3.5.1 First condition of equilibrium

The first condition of static equilibrium is related to translational equilibrium, which requires that the net force acting on the object should be zero. Remember that Newton's second law states that an object will not accelerate if the sum of all the forces acting on it is equal to zero,

$$F_1 + F_2 + F_3 + ...F_n = \vec{F_{net}} = 0 \qquad (3.9)$$

Key Concept

☞ The first condition of equilibrium states that the sum of the forces acting on a body must add up to zero.

Since force is a vector, both the magnitude and the direction of its components should also be considered. For example, a negative sign should be used if an object moves in the opposite direction. Therefore, for static equilibrium to be reached, the condition of static equilibrium should be fulfilled such that the component of the forces in all all dimensions are all equal to zero. Thus,

- For 1-D forces applied on an object (for instance,if the forces are along the x-axis), the first condition of equilibrium is given by:

$$\sum \vec{F}_x = 0$$

- For 2-D forces applied on an object, the first condition of equilibrium is given by:

$$\vec{\mathrm{F}_{\mathrm{net}}} = 0, \quad \text{so that} \quad \sum \vec{\mathrm{F}}_{\mathrm{x}} = 0 \quad \text{and} \quad \sum \vec{\mathrm{F}}_{\mathrm{y}} = 0 \qquad (3.10)$$

3.5.2 Second Condition of Equilibrium

For an object to be considered at rest, it is not enough that the net force acting on it is zero. Another factor that needs to be considered is its inability to tilt or rotate. If an object is said to be at rest and needs to remain at rest, the net torque applied to it should also be equal to zero,

$$\sum \vec{\tau} = \tau_{\vec{net}} = 0. \qquad (3.11)$$

It means that the clockwise torque acting on the object is also equal to the counter clockwise torque. This is rotational equilibrium, which is the second condition for static equilibrium.

Remember that torque is the twisting force or the amount of force that causes an object to rotate when it is applied to a certain distance from the axis of rotation. The axis of rotation or pivot point can be arbitrarily assigned, which means that any axis can be used to calculate torque as long as proper conventions are used. A door, for example, experiences torque when a force is applied to a certain distance from the hinge. It is influenced by two factors: the force applied and the location of the force relative to the pivot point. That is why torque is expressed as

$$\tau = Fr$$

where τ is torque in Nm, $\vec{F}$ is force in N and r is the lever distance or radius in m.

Torque is the product between the force, $\vec{F}$, and the radius, $\vec{r}$.

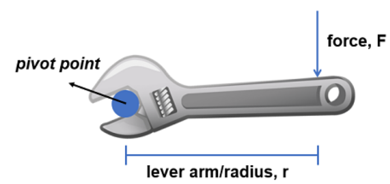


Figure 3.9 A force applied on one side of a nut makes it to rotate.

Rotational equilibrium, the second condition for static equilibrium, ensures that either there is no torque acting on the body or that the torques present are balanced and sum up to zero.

Key Concept

☞ The second condition necessary to achieve equilibrium is that the net external torque on a system must be zero.

Static Equilibrium Examples

Static equilibrium can be commonly observed in everyday life. Objects at rest are considered systems in static equilibrium, where both net force and net torque are zero. Two examples that demonstrate objects in static equilibrium are:

1. a book placed on top of a table
2. a balanced seesaw.

Static Equilibrium Example: Book at Rest

A book placed on top of a table is considered to be in static equilibrium. A free-body diagram, or a diagram showing all the forces acting on the object, can be used to check whether the object satisfies the two conditions of equilibrium.

As shown in Figure 3.10, the only forces acting on the book are gravity and normal force. Gravity acts downward, while normal force acts upward, perpendicular to the surface. The forces are also equal in magnitude but opposite in direction. Thus, the net force acting on the book is zero. There is also zero torque acting on the book, satisfying both the first and second conditions of static equilibrium.

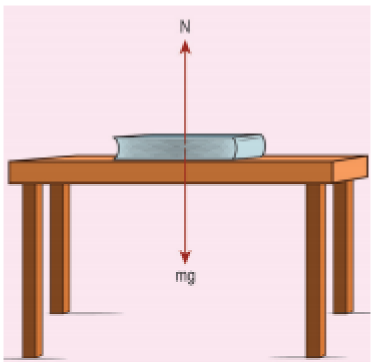


Figure 3.10 A book at rest on the top of a table.

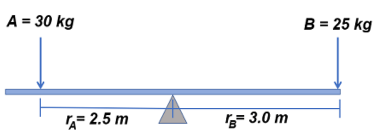


Figure 3.11 A balanced seesaw in static equilibrium.

A seesaw (shown in Figure 3.11) balanced by two children sitting on opposite sides is considered to be in static equilibrium. Consider a 6-m seesaw with negligible mass and a pivot point exactly at its center. Child A has a mass of 30 kg and sits 2.5 m away from the pivot point, while 25-kg child B sits 3.0 m away from the pivot point of the seesaw. To determine whether the seesaw is in static equilibrium, the two conditions for equilibrium should be satisfied.

Activity 3.7

A uniform meter stick supported at the 25-cm mark is in equilibrium when a 1-kg rock is suspended at the 0-cm end as shown in Figure 3.12. Is the mass of the meter stick greater than, equal to, or less than the mass of the rock? Explain your reasoning.

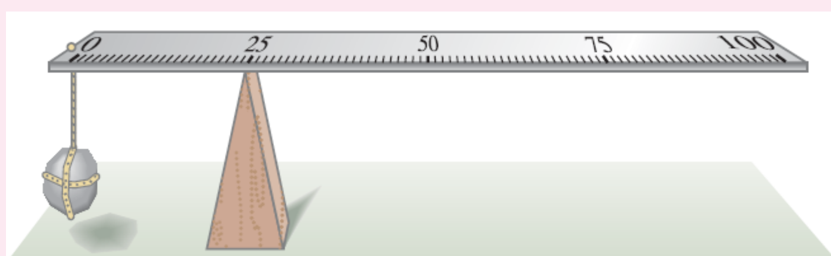


Figure 3.12 Suspended mass in eqiulibrium.

The following general procedure is recommended for solving problems that involve objects in equilibrium.

1. Choose one object at a time for consideration. Make a careful free-body diagram by showing all the forces acting on that object, including gravity and the points at which these forces act. If you aren't sure of the direction of a force, choose a direction; if the actual direction of the force (or component of a force) is opposite, your eventual calculation will give a result with a minus sign.

2. Choose a convenient coordinate system, and resolve the forces into their components. Using:

$$F_x = Fcos\theta \tag{3.12}$$

$$F_y = Fsin\theta \tag{3.13}$$

3. Using letters to represent unknowns, write down the **equilibrium equations** for the **forces**: and assuming all the forces act in a plane.

$$\sum F_x = 0 \tag{3.14}$$

$$\sum F_y = 0 \tag{3.15}$$

4. For the **torque equation**,

$$\sum \tau = 0 \tag{3.16}$$

   choose any axis perpendicular to the x y plane that might make the calculation easier. (For example, you can reduce the number of unknowns in the resulting equation by choosing the axis so that one of the unknown forces acts through that axis; then this force will have zero lever arm and produce zero torque, and so won;t appear in the torque equation.) Pay careful attention to determining the lever arm for each force correctly. Give each torque a + or - sign to indicate torque direction. For example, if torques tending to rotate the object counterclockwise are positive, then those tending to rotate it clockwise are negative.

5. **Solve** these equations for the unknowns. Three equations allow a maximum of three unknowns to be solved for. They can be forces, distances, or even angles.

Example 3.7

An object in Figure 3.13 is in static equilibrium. The a horizontal cord has a force of 30N. Find the force F of the cord and weight F_W of the object.

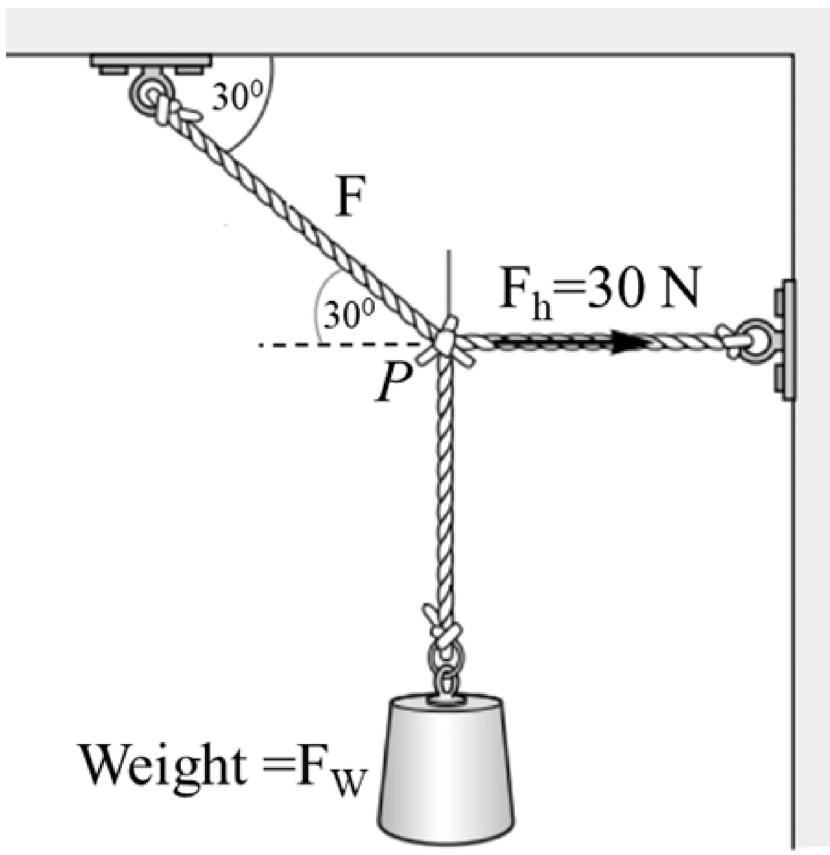


Figure 3.13 The cord extended between two poles.

Solution:

$F_x = 30N$

$F + ?$ and $F_W = ?$

a) Drawing free body diagram. All forces acting on the given mass on free body diagram as in the Figure 3.14

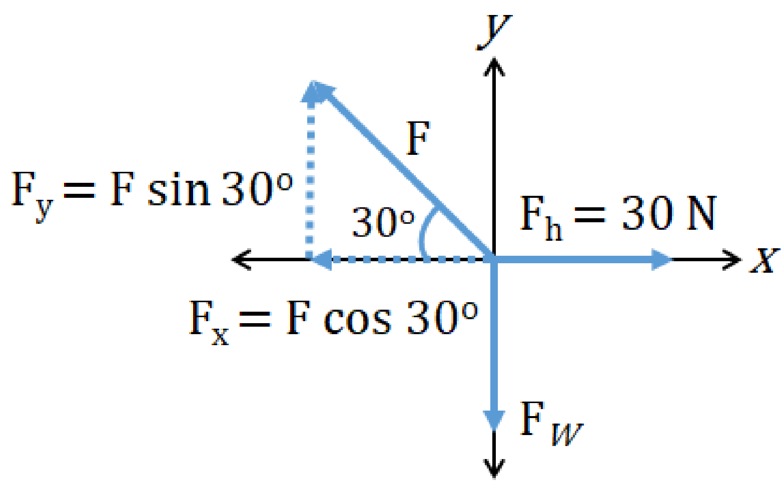


Figure 3.14 Free body diagram.

b) Resolving vectors in to their components. Only a force **F** due have components,

$$\mathbf{F}_x = F\ cos\ 30^0 = 0.86F$$

and

$$\mathbf{F}_y = F\ sin\ 30^0 = 0.5F$$

c)applying the first condition of equilibrium:

$\sum F_x = 0$ becomes $30\ N - F\ cos\ 30^o = 0$
$0.86\ F = 30\ N$

$$F = \frac{30\ N}{0.86} = 34.9\ N$$

$\sum F_y = 0$ becomes $F\ sin\ 30^o - F_W = 0$
$0.5\ F = F_W$ substituting the value of $F = 34.9$ N
$F_W = 0.5 \times 34.9\ N = 17.5N$

Example 3.8

A board of mass serves as a seesaw for two children, as shown in Figure 3.20. Child A has a mass of 30 kg and sits 2.5 m from the pivot point, P. At what distance x from the pivot must child B, of mass 25 kg, place herself to balance the seesaw?

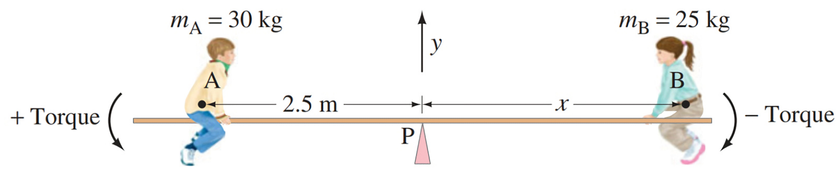


Figure 3.15 Two children on a seesaw.

Solution:

$m_A = 30kg,\qquad m_B = 25kg,\qquad x_B = 2.5m$

$x_A = x = ?$

Using the stated steps, you can solve it.

(a) **Draw free body diagram.** It is as shown below. The forces acting on the board are the forces exerted downward on it by each child, and the upward force exerted by the pivot and the force of gravity on the board which acts at the center of the uniform board.

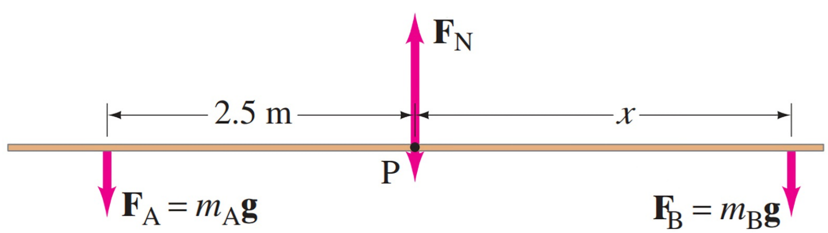


Figure 3.16 Free body diagram of seesaw board.

(b) **Coordinate system.** We choose y to be vertical, with positive upward, and x horizontal to the right, with origin at the pivot.

(c) Force equation. All the forces are in the y (vertical) direction, so

$$\sum \vec{F}_x = 0$$

$$\sum \vec{F}_y = 0$$

$$\vec{F}_N - m_A g - Mg - m_B g = 0$$

(d) **Torque equation.** Let us calculate the torque about an axis through the board at the pivot point, P. Then, the lever arms for the weight of the board are zero, and they will contribute zero torque about point P. Thus, the torque equation will involve only the forces F_A and F_B which are equal to the weights of the children. The torque exerted by each child will be mg times the appropriate lever arm, which here is the distance of each child from the pivot point. FA tends to rotate the board counterclockwise (+) and F_B clockwise (−) so the torque equation is

$$\sum \vec{\tau} = 0$$
$$m_A g(2.5m) - m_B g(x) + m_B g(0) + F_N(0) = 0$$
$$m_A g(2.5m) - m_B g(x) = 0$$

(e) **Solve.** We solve the torque equation for x and find

$$x = \frac{m_A}{m_B}(2.5m)$$
$$x = \frac{30kg}{25kg}(2.5m)$$
$$\therefore x = 3.0m$$

To balance the seesaw, child B must sit 3.0 m from the pivot point.

Section summary

- When an object is at rest (not moving) it is considered to be in static equilibrium.
- In the first condition of equilibrium, all external forces acting on the body balance out and their vector sum is zero.
- Torque is the product of the distance from the support or pivot (r) and the component of force perpendicular to the object.
- In second condition of equilibrium, the sum of all the torques (calculated about any arbitrary axis) must also be zero.

Review questions

1. Mention some examples of a rigid body that is in equilibrium in your surroundings.

2. Figure 3.17 shows three situations in which the same horizontal rod is supported by a hinge on a wall at one end and a cord at its other end.Without written calculation, rank the situations according to the magnitudes of (a) the vertical force on the rod from the hinge, and (b) the horizontal force on the rod from the hinge, greatest first.

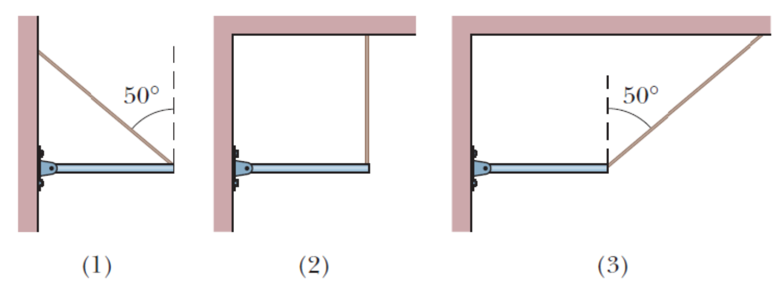


Figure 3.17 Horizontal rod tied with support in different ways.

3. The two children shown in Figure 3.18 are balanced on a see-saw of negligible mass. The first child has a mass of 26.0 kg and sits 1.60 m from the pivot(a) If the second child has a mass of 32.0 kg, how far is she from the pivot? (b) What is F_p, the supporting force exerted by the pivot?

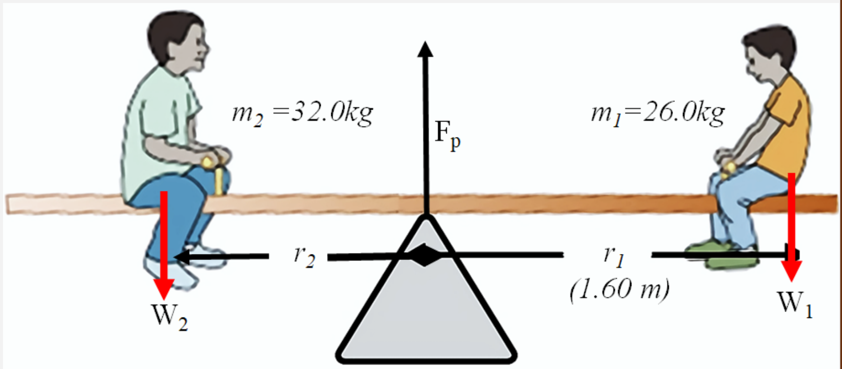


Figure 3.18

Virtual Labs

On the soft copy of the book, click on the following link to perform virtual experiments on elasticity and static equilibrium of a rigid body unit under the guidance of your teacher.

1. Density PhET Experiment.
2. Balancing Act PhET Experiment.

End of unit summary

- In elastic deformations with stress values lower than the proportionality limit, stress is proportional to strain.
- An object or material has plastic behavior when stress is larger than the elastic limit.
- Plastic behavior ends at the breaking point.
- The strength of the forces that cause deformation is expressed by stress.
- The extent of deformation under stress is expressed by strain, which is dimensionless.

- For a small stress, the relation between stress and strain is linear.
- The elastic modulus is the proportionality constant in this linear relation.
- Young's modulus (Y) = Tensile stress / Tensile strain.
- A body is in equilibrium when it remains either in uniform motion or at rest.
- Conditions for equilibrium require that the sum of all external forces acting on the body is zero (first condition of equilibrium), and the sum of all external torques from external forces is zero (second condition of equilibrium).

End of unit questions and problems

1. A force of 20 N at angle of 30^o to the horizontal and Force F_2 at an angle of 60^o to the horizontal applied on the object as shown in Figure 3.19 in the equilibrium. Calculate the magnitude of the force F and weight of the object.

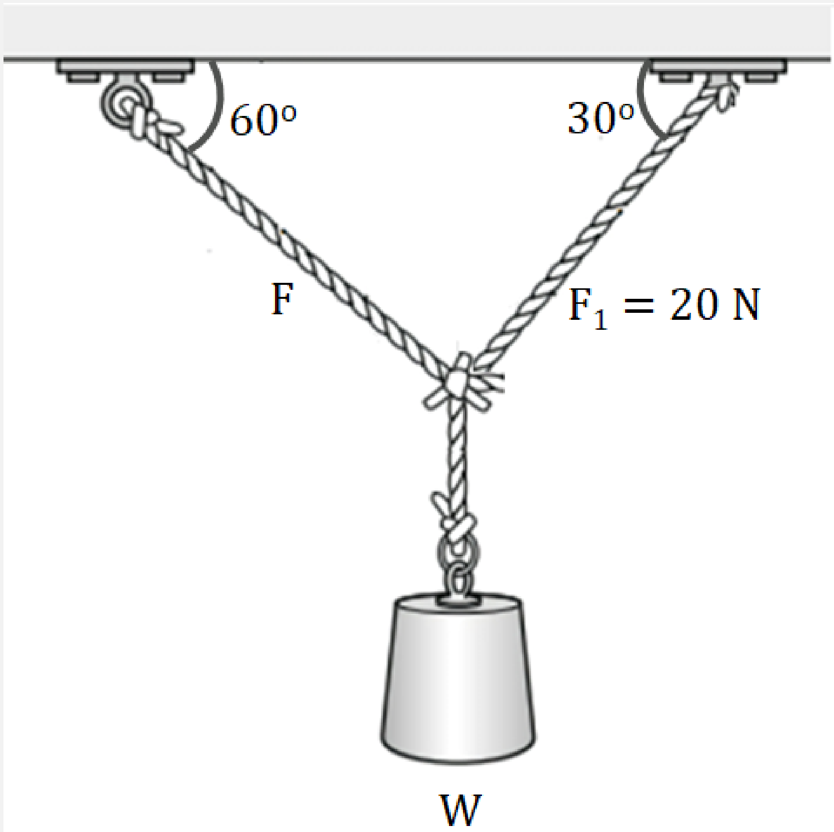


Figure 3.19 A cart in equilibrium.

2. Find the tension in the two cords shown in Figure 3.20. Neglect the mass of the cords, and assume that the angle is 33^o and the mass m is 190 kg.

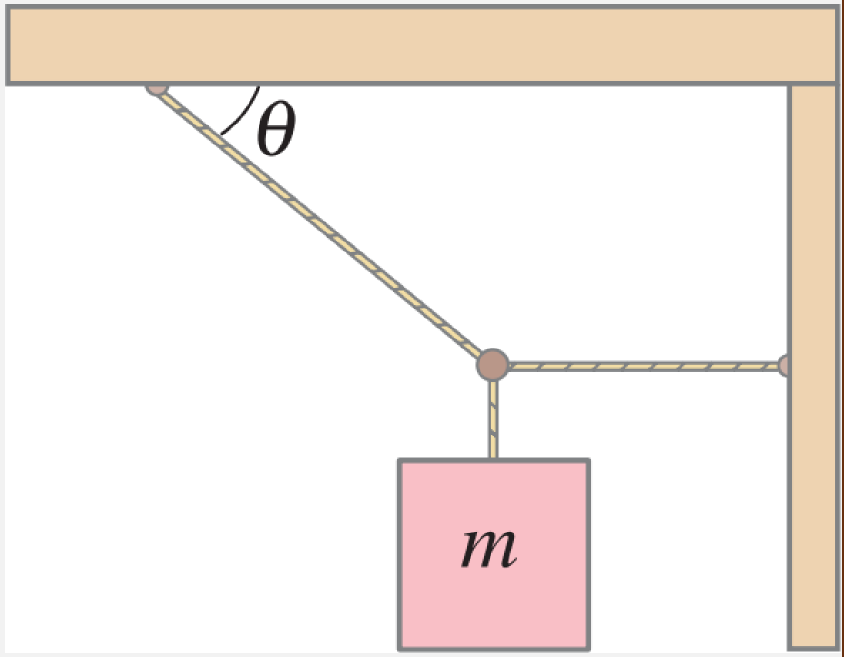


Figure 3.20 Suspended mass m.

3. The area of cross section of a steel wire ($Y = 2.0 \times 10^{11} N/m^2$) is $0.1 cm^2$. Calculate the force required to double its length.

4. A copper wire and a steel wire of the same diameter and length are connected end to end and a force is applied, which stretches their combined length by 1 cm. The two wires will have
(a) Different stresses and strains.
(b) The same stress and strain.
(c) The same strain but different stresses.
(d) The same stress but different strains.

5. A beam pivoted at one end has a force of 5.0N acting vertically upwards on it as shown in Figure 3.21. What is the weight of the beam?

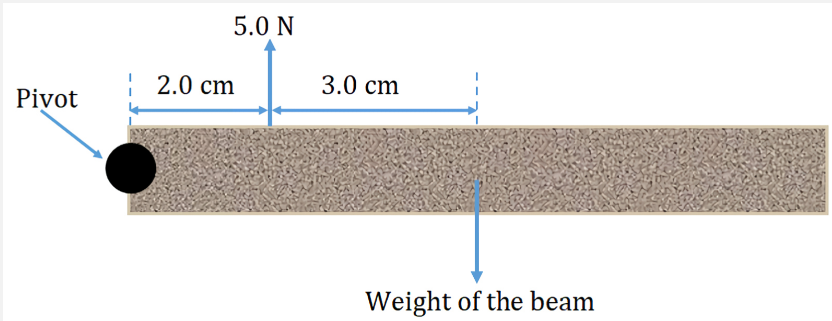


Figure 3.21 Different force applied on an object in equilibrium.

6. A metallic wire 4m in length and 1mm in diameter is stretched by putting a mass 4kg. Determine the elongation produced. Given that the Young's modulus of elasticity for the material of the wire is $13.78 \times 10^{10} N/m^{-2}$.

7. Two wires are made of the same metal. The length of the first wire is half that of the second and its diameter is double that of the second wire. If equal loads are applied on both wires, find the ratio of increase in their lengths?

Unit 4

Static and Current Electricity

Introduction

Physical phenomenon associated with the presence and flow of electric charge is known as electricity. In Ethiopia and elsewhere around the world, people depend on electricity to provide power for most appliances in the home, at work and out in the world in general. For example, lights, electric heating and electric stoves that you use in our home all depend on electricity to work. To realize just how big impact electricity has on our daily lives, just think about what happens when there is a power failure or load shedding. Thus, electricity has an important place in modern society. It is a controllable and convenient form of energy for a variety of uses in homes, schools, hospitals, industries and so on. In this unit, you shall attempt to look at topics which are related to electricity.

Brain storming question

Students, what constitutes electricity?

By the end of this unit, you should be able to:

- *understand the basic properties of electric charge;*
- *produce charges in different charging process and explain the charging process;*
- *have a conceptual understanding of Coulomb's law and the factors which effect electrical force;*
- *understand the concept of an electric field qualitatively and quantitatively;*
- *understand the concept of electric field lines;*
- *understand the relationship among voltage, current and resistance;*
- *describe arrangement of resistors in a combination circuit and its practical implications;*
- *apply the concept of electricity in solving problems in their real-life situations.*

4.1 Charges in Nature

By the end of this section, you should able to:

- *distinguish between the two types of electric charge;*
- *show that the total electric charge in an isolated system is conserved;*
- *use conservation of charge to calculate quantities of charge transferred between objects.*

Objects surrounding us (including people) contain large amounts of electric charge. There are two types of electric charge: positive charge and negative charge. Protons have a positive charge, and electrons have a negative charge. If the same amounts of negative and positive charge are brought together, they neutralize each other and there is no net charge.

Neutral objects contain positive and negative charges, but equal in numbers. However, if there is a little bit more of one type of charge than the other, then the object is said to be electrically charged.

Unit of Charge

The SI unit of electric charge is coulomb (C). The number of electrons in 1C of charge is 6.25×10^{18} electrons. You know that an electron possesses a negative charge of 1.6×10^{-19} C. In electrostatics, you often work with charge in microcoulombs ($1\mu C = 1 \times 10^{-6}$ C) and nano coulombs ($1nC = 1 \times 10^{-9}$ C).

Conservation of Charge

Electric charges are neither created nor destroyed, but are transferred from one material to another. This is called the law of conservation of charge. There are some practical examples of charge transfer from one material to another. For example, have you ever seen an old trick of comb and hair where your hair rises and sticks to the comb? This arises because of the simple conservation of charge, i.e., transfer of charge either from comb to hair or vice versa. Thus, the total charge in an isolated system never changes. By isolated we mean that no particles allowed to cross the boundary of the system.

Quantization of charge

The smallest charge that is possible to obtain is that of an electron or proton. The magnitude of this charge is denoted by e. Charge is said to be quantized when it occurs as the integral multiples of e. This is true for both negative and positive charges and is expressed as;

$$q = ne \tag{4.1}$$

where n is a positive or negative integer.

Exercise 4.1

When do you say that a body is charged positively?

Key Concept

☞ An object becomes negatively charged if it gains electrons and positively charged if it loses electrons.

Exercise 4.2

A conductor possesses a positive charge of 3.2×10^{-19} C. How many electrons does it have in excess or deficit (use: $e = 1.60 \times 10^{-19}$ C)?

Section summary

- There are two types of electric charges: positive and negative charges.
- Neutral Objects have equal number of positive and negative charges.
- The total electric charge in an isolated system, that is, the algebraic sum of the positive and negative charges present at any time, does not change.
- Electric charges are quantized, occurring only in discrete amounts.

Review questions

1. What are the different types of charges that exist in nature?
2. When do you say that a body is negatively charged?
3. What does the law of conservation of charges say?
4. What does it mean by quantization of a charge?
5. Write the properties of electric charges.

4.2 Methods of Charging a Body

By the end of this section, you should able to:

- *demonstrate different charging processes;*
- *explain the results of different charging processes.*

In the previous section, you discussed that charges are transferred from one body to another by a process known as charging. Charging is the process of electrifying bodies, i.e., removing from or adding charges to a body.

The following are the different methods of charging a body:

i Charging by rubbing

ii Charging by conduction

iii Charging by induction

Activity 4.1

Students, in groups, try to think of the different ways of charging a body?

Charging by rubbing

Charging by rubbing occurs when two different neutral materials are rubbed together and electric charges are transferred from one object to the other. Some materials are more likely to attract extra electrons (example silk) and become negatively charged while others are more likely to give electrons (example glass and ebonite rod) and become positively charged. This is because some kinds of atoms are more strongly attracted to electrons than others. For example, in Figure 4.1 (a), the hair and the comb are both neutral. When they are rubbed together, the atoms in the comb gain electrons and the atoms in the hair lose electrons (Figure 4.1 (b)). Due to this, the comb attracts tiny pieces of paper.

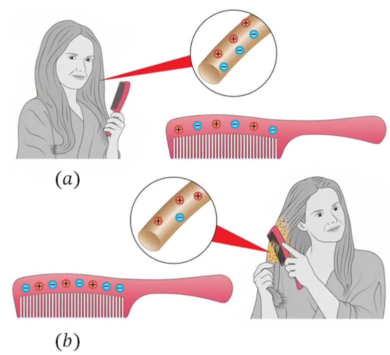


Figure 4.1 (a) The comb and the hair are both neutral. (b) After being rubbed together, the comb is negatively charged and the hair is positively charged.

Activity 4.2

Tear a piece of paper into several small pieces. Charge a plastic pen and two other objects by rubbing them on your hair or on some fabric. Bring each charged object near the pieces of paper.

(a) Describe what you observe, listing the three materials you charged.

(b) Why are the pieces of paper attracted to the charged object?

(c) Why do some pieces of paper fall off your charged objects after a short while?

(d) When using a conducting sphere with a large charge, the paper "jumps" off instead of falling. Explain why this happens.

Exercise 4.3

Charge an object by friction and bring it near a stream of smoke rising from a wooden splint. What do you see? Explain why it happens.

Charging by Conduction

Key Concept:

☞ Charging by rubbing leaves the two bodies with opposite sign of charges.

Charging by conduction involves the contact of a charged object to a neutral object. Suppose that a positively charged aluminum plate is touched to a neutral metal sphere. The neutral metal sphere (Figure 4.2 (i)) becomes charged as the result of being contacted by the charged aluminum plate.

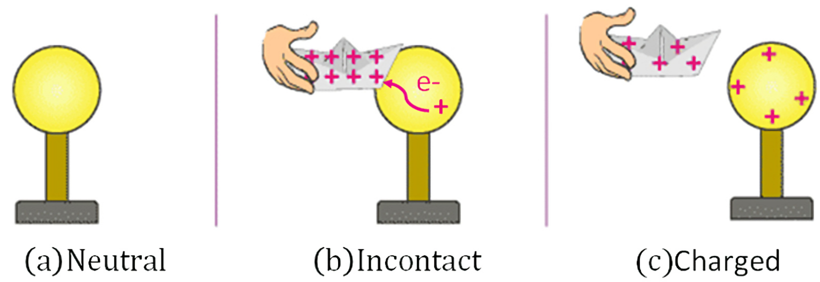


Figure 4.2 Charging by conduction.

The uncharged body is brought in contact with a charged metal sphere (Figure 4.2 (ii)) for a short time and then the bodies are separated. The metal sphere now has less excess negative charges and the body now has negative charges (Figure 4.2 (c)).

Key Concept:

☞ Charging by conduction leaves the charged body and the uncharged body with the same sign of charge but weaker in strength than the original object.

Charging by Induction

Charging by induction is a process where the charged object is held near to uncharged conductive material that is grounded on a neutrally charged material. The charge flows between two objects and the uncharged conductive material develop a charge with opposite polarity.

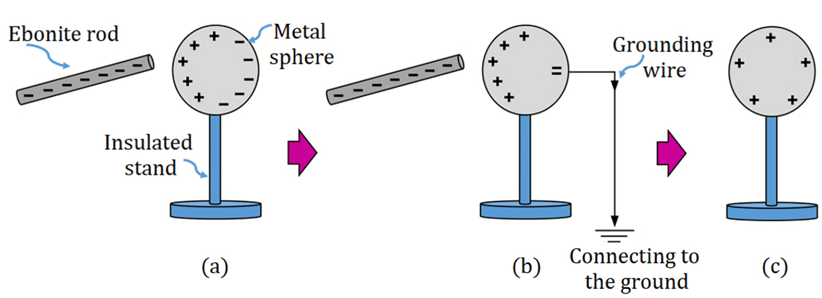


Figure 4.3 Charging by induction.

In Figure 4.3, a negatively charged ebonite rod is brought close to, but does not touch a neutral metal sphere. In the sphere, the free electrons closest to the rod move to the other side, as part (a) of the drawing indicates. As a result, the part of the sphere closer to the rod becomes positively charged and the opposite part becomes negatively charged. If the rod were removed, the free electrons would return to their original places, and the charged regions would disappear. Under most conditions the earth is a good electrical conductor. So when a metal wire is attached between the sphere and the ground, as in Figure 4.3 (b), some of the free electrons leave the sphere and distribute themselves over the much larger earth. If the grounding wire is then removed, followed by the ebonite rod, the sphere is left with a positive net charge, as part (c) of the picture shows.

Key Concept

☞ Charging by induction leaves the charged body and the uncharged body with the opposite sign of charge.

Section summary

- Charging is the process of supplying the electric charge (electrons) to an object or losing the electric charge (electrons) from an object.
- An uncharged object can be charged in different ways: charging by rubbing, charging by conduction and charging by induction.

Review questions

1. State the three methods of charging a body.
2. Describe how uncharged objects can be charged by contact and rubbing.

4.3 The electroscope

Exercise 4.4

Dear students, what do you think about the purpose of an electroscope?

By the end of this section, you should able to:

- *describe the function of an electroscope;*
- *use simple electroscope to detect charges;*
- *construct simple electroscope from locally available materials.*

The electroscope is a very sensitive instrument which can be used to detect the type of electric charge. It consists of a glass container with a metal rod inside which has two thin pieces of gold foil attached. The other end of the metal rod has a metal plate attached to it outside the glass container. A diagram of a gold leaf electroscope is shown in Figure 4.4.

Key Concept

☞ The collapsing or diverging of the leaf of the electroscope is used for detecting the presence of a charge on the body.

When a charged object, like the positively charged rod in the Figure 4.4 is brought close to (but not touching), the neutral metal plate of the electroscope, the negative charge in the gold foil, metal rod, and metal plate, would be attracted to the positive rod. Because the metal (gold is a metal too) is a conductor, the charge can move freely from the foil up the metal rod and onto the metal plate. There is now more negative charge on the plate and more positive charge on the gold foil leaves. This is called inducing a charge on the metal plate. It is important to remember that the electroscope is still neutral, the charges have just been induced to move to different parts of the instrument. The induced positive charge on the gold leaves forces them apart since like charges repel. This is how you can tell that the rod is charged.

If the rod is now moved away from the metal plate, the charge in the electroscope will spread itself out evenly again and the leaves will fall down again because there will no longer be an induced charge on them.

Section summary

- An electroscope is a device that is used to detect the presence of an electric charge on a body.

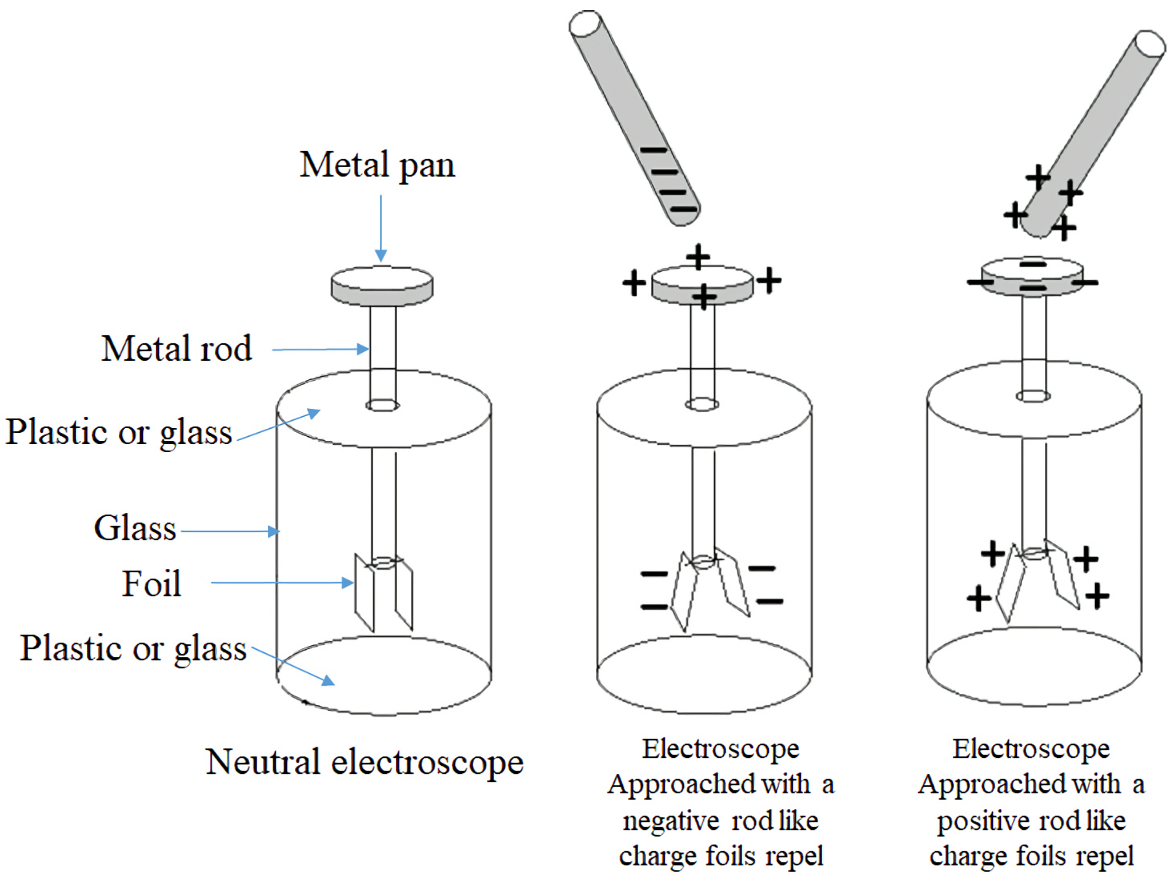


Figure 4.4 Charging an electroscope.

Review questions

1. What is the function of an electroscope?
2. How do you know that whether or not an electroscope is charged?

Activity 4.2

Based on what you learnt here, in groups, try to design/construct a simple electroscope using easily available materials.

4.4 Electrical Discharge

By the end of this section, you should able to:

- *express the nature of electric discharge;*
- *describe how lightning happens;*
- *list the importance of grounding.*

Exercise 4.5

Can a charged object become neutral again?

Key Concept

☞ Once an object is charged, the charges are trapped on it until they are given a path to escape. When electric charges are transferred very quickly, the process is called an electrical discharge. Sparks are an example of electrical discharge.

Activity 4.3

Students, lightning are a common experience during rainy season. But, how it is formed? Discuss in groups.

So far, you learnt about the techniques of charging a material. There is also a technique of removing the excess electric charges from the charged object. This process of removing electric charges from a charged body is called discharging. A charged body can be made to lose its charges by touching it with a conductor. When a body is discharged, it becomes neutral.

Lightning

Lightning is a very large electrical discharge caused by induction. In a thunderstorm, a charged area, usually negative, builds up at the base of a cloud (Figure 4.5 (a)). The negative charge at the base of the cloud creates a temporary positively charged area on the ground through the induction process (Figure 4.5 (b)). When enough charge has built up, a path of charged particles are formed (Figure 4.5 (c)). The cloud then discharges its excess electrons along the temporary path to the ground, creating a huge spark-lightning (Figure 4.5 (d)). This discharge also creates a rapid expansion of the air around it, causing thunder.

Air is normally an insulator. If it were not, lightning would occur every time that cloud formed. For lightning to happen, charges in the clouds must build up to the point where the air cannot keep the charges separated from the ground. Then, the air stops being an insulator and becomes a fair conductor, resulting in a lightning strike.

One way to avoid the damage caused by electric discharges is to make the excess charges flow harmlessly into Earth's surface. Earth is a donator

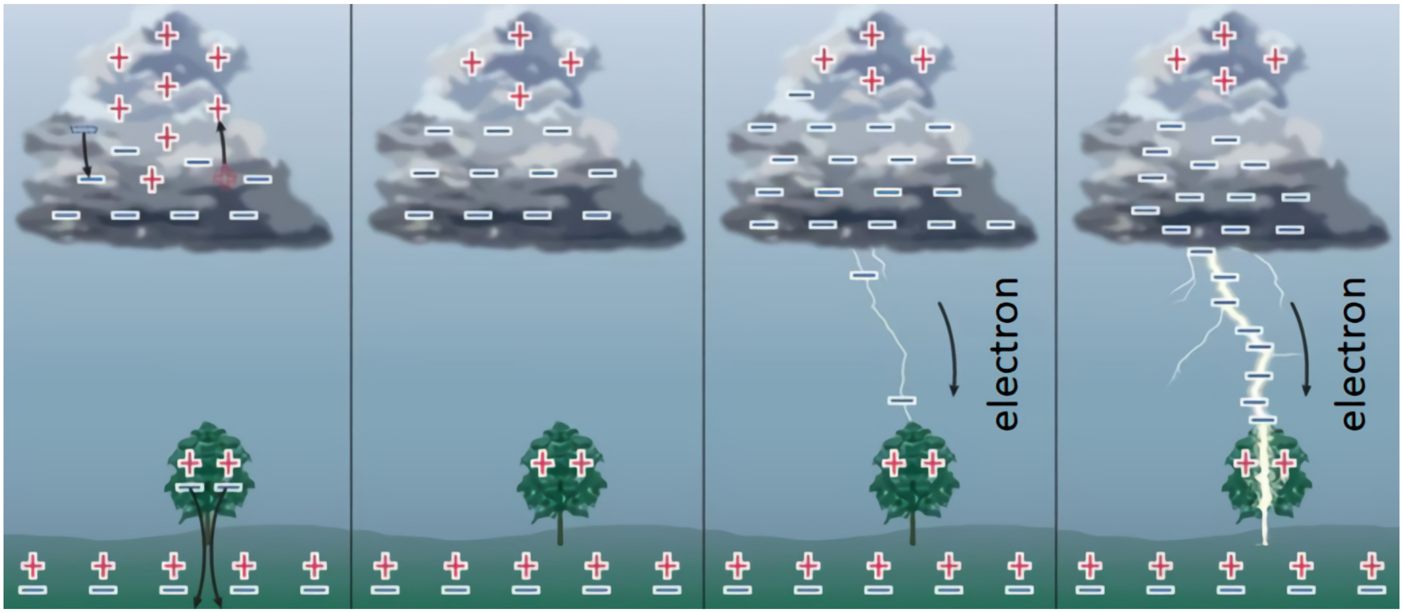


Figure 4.5 Lightning is an atmospheric electrical discharge.

or receiver of charge and is so large that overall it is not affected by the electron transfer of huge lightning strikes. So, it can absorb an enormous quantity of excess charge. As a result, the ground is always considered neutral.

Activity 4.4

Students, in your community, what did people do when they encounter a person struck by lightning? Have you observed while burying some parts of the person under the ground?

The process of providing a pathway to drain excess charge into earth is called grounding. The pathway is usually a conductor such as a wire or a pipe. You might have noticed lightning rods at the top of buildings and towers. A lightning conductor is often fitted to the top of a building to help to discharge the clouds safely. These rods are made of metal and are connected to metal cables that conduct electric charge into the ground if the rod is struck by lightning. The idea is that it should get struck before the building and conduct the surge of charge harmlessly to the earth.
Most lightning deaths and injuries occur outdoors. If you are outside and can see lightning or hear thunder, take shelter indoors immediately. If you cannot go indoors, you should take these precautions: avoid high places and open fields; stay away from tall objects such as trees, flag poles, or light towers; and avoid objects that conduct current such as bodies of water,

metal fences, picnic shelters, and metal bleachers.

Exercise 4.6

Have you heard about an individual's death through lightning?

It is very rare that people are struck by lightning and certainly you will not be struck while you are inside a car or in an airplane. The metal shell around you would divert charge away.

Section summary

- A lightning is a gigantic (very large) discharge between clouds and the earth, or between the charges in the atmosphere and the earth.

Exercise 4.7

Would you please add any other mechanisms that you know to make peoples safe from lightning?

Review questions

1. Describe the terms charging and discharging.
2. Explain what causes the lightning that is associated with a thunderstorm.
3. What is grounding?

4.5 Coulomb's law of electrostatics

Exercise 4.8

You might already know that like charges repel each other and unlike charges attract each other. But have you taken a minute to wonder how strong these forces are?

By the end of this section, you should able to:

- *state coulomb's laws of electrostatics;*
- *use coulomb's law to find the magnitude of electric force between two objects.*

The magnitude of the forces between charged spheres was first investigated quantitatively in 1785 by **Charles Coulomb** (1736-1806), a French scientist. He observed that the electrostatic force between the two charges is proportional to the product of the charges and is inversely proportional to the square of their distance apart.

Coulomb's law may be stated in mathematical terms as

$$F \propto q_1 q_2, \qquad F \propto \frac{1}{r^2} \tag{4.2}$$

$$F \propto \frac{q_1 q_2}{r^2}$$

where F is the magnitude of the electric force between the two charges q_1 and q_2, and r is the distance between the two charges.

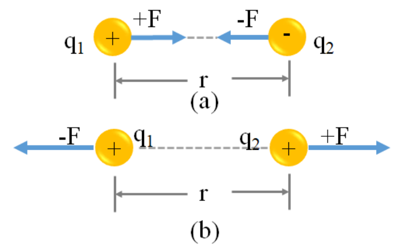


Figure 4.6 attractive and repulsive electrostatic force between two point charges.

You can turn the above expression of proportionality to equation by writing

$$F = k\frac{q_1 q_2}{r^2} \tag{4.3}$$

where, $k = \frac{1}{4\pi\epsilon_o} \approx 9\times 10^9 \frac{Nm^2}{C^2}$ is the electrostatic constant;

$\epsilon_o = 8.85\times 10^{-12}\frac{C^2}{Nm^2}$ is called permittivity of free space.

The SI unit of force is Newton. The electrostatic force is directed along the line joining the charges, and it is attractive if the charges have unlike signs and repulsive if the charges have like signs. Figure 4.6 shows the attractive and repulsive electrostatics forces.

Key Concept

☞ The electrostatic force exerted by a point charge on a test charge at a distance r depends on the charge of both charges, as well as the distance between the two.

Example 4.1

Charges $q_1 = 5.0\mu C$ and $q_2 = -12.0\mu C$ are separated by 30 cm on the x-axis. What is the force exerted by the positive charge on the negative charge?

Given: $q_1 = 5.0\mu C$, $q_2 = -12.0\mu C$, and $r = 30cm$

Required: $F = ?$

Solution:

Coulomb's law gives force on negative charge due to the positive charge as follows:

$$F = k\frac{q_1 q_2}{r^2} = \frac{9\times 10^9 \frac{Nm^2}{C^2}(5\times 10^{-6}C)(-12\times 10^{-6}C)}{(0.3m)^2} = -6.0N$$

The minus sign shows that the force is in the negative x-direction that is towards west. Therefore, it is a force of attraction.

Section summary

The force between two point charges is

- directly proportional to the magnitude of each charge.
- inversely proportional to square of the separation between their centers.
- directed along the line joining their centers.

Review questions

1. Two charges 1C and - 4C exists in air. What is the direction of force between them?
2. Two charges $q_1 = 2 \times 10^{-6}C$ and $q_1 = -4 \times 10^{-3}C$ are placed 30cm apart. Determine the magnitude and direction of the force that one charge exerts on the other

4.6 The electric field

Exercise 4.9

Students, what do you think is the definition for an electric field?

By the end of this section, you should able to:

- *state the meaning of an electric field;*
- *distinguish the elements that determine the strength of the electric field strength at a given location;*
- *show electric field lines diagrammatically;*
- *calculate the strength of an electric field.*

An electric field is a region where an electric charge experiences a force, just as a football field is an area where the game is played. Electric field lines are an excellent way of visualizing electric fields. They were first introduced by Michael Faraday.

The space around a charge or an arrangement of charges is different from space in which no charges are present. You can test whether a space has an electric field by bringing a small, point positive charge q_o into the space. If q_o experiences an electric force, then there is an electric field. If no force is experienced, then there is no electric field. For this reason, the small charge is called a test charge: it tests for the existence of electric fields. It has to be small so that its presence does not disturb the electric field it is trying to detect. Figure 4.7 shows the electric field lines of a positive and negative charged body.

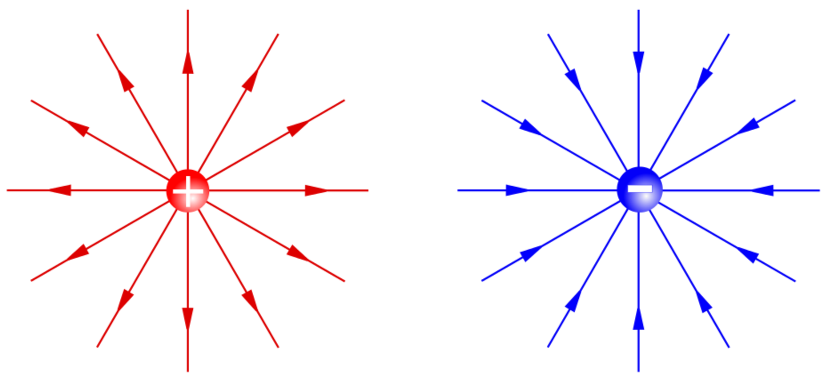


Figure 4.7 Electric field lines from positive and negative charges.

Key Concept

☞ A test charge is a positive electric charge whose charge is so small that it does not significantly disturb the charges that create the electric field.

Properties of electric field lines

- The field lines never intersect or cross each other.
- The field lines are perpendicular to the surface of the charge.
- The magnitude of charge and the number of field lines are proportional to each other.
- Field lines originate at a positive charge and terminate at a negative charge.
- The lines of force bend together when particles with unlike charges attract each other. The lines bend apart when particles with like charges repel each other. This is clearly indicated in Figure 4.8

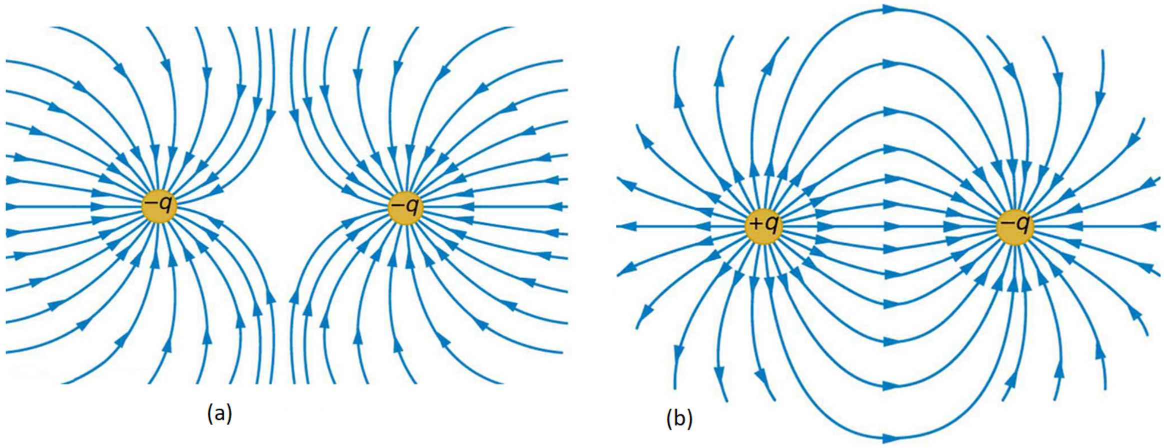


Figure 4.8 Electric field lines between (a) similar charges (b) opposite charges.

Electric Field Strength

Key Concept

☞ The magnitude of **E** is the force per unit charge and its direction is that of **F** (i.e., the direction of the force which acts on a positive charge).

The electric field strength at any point in space, **E** is equal to the force per unit charge exerted on a positive test charge. Mathematically,

$$\mathbf{E} = \frac{\mathbf{F}}{q} \qquad or \qquad \mathbf{F} = \mathbf{E}q \tag{4.4}$$

Thus, **E** is a vector. If q is positive, the electric field **E** has the same direction as the force acting on the charge. If q is negative, the direction of **E** is opposite to that of the force **F**. On the other hand, the SI unit of electric field is Newton per Coulomb ($\frac{N}{C}$).

Electric field strength due to a point charge

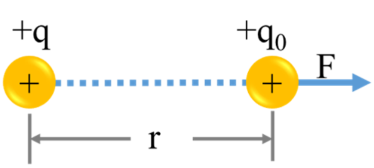


Figure 4.9 Electric field at a distance r from a charge.

In order to measure the electric field in a given region, you introduce a test charge and measure the force on it. However, you should realize that the test charge q_o exerts forces on the charge that produce the field, so it may change the configuration of the charges.

Since the electric field is force per unit charge, you divide the force by the charge q_o to obtain the field due to q at the location of q_o. That is

$$\mathbf{E} = \frac{\mathbf{F}}{q_o} = \frac{k\frac{q_o q}{r^2}}{q_o} = k\frac{q}{r^2} \qquad where F = k\frac{q_o q}{r^2} \tag{4.5}$$

The above equation gives the field arising due to the charge q at any location which is at a distance r from q. The direction of the field is taken as the direction of the force which is exerted on the positive charge. Thus, the electric field is radially outwards from a positive charge and radially in towards a negative point charge.

Just like the electric force, an electric field also obeys the superposition principle. Therefore, the field at a given point due to two or more charges is the vector sum of the fields of individual charges.

Exercise 4.10

☞ What is the direction of the electric field due to a positive pont charge?

Example 4.2

Calculate the strength and direction of the electric field E due to a point charge of 2.0 nC at a distance of 5.0 mm from the charge.

Solution:

Here $q = 2.00 \times 10^{-9}$ C and $r = 5.00 \times 10^{-3}$ m.
You can find the electric field created by a point charge by using the equation $E = k\frac{q}{r^2}$
Entering those values into the above equation gives

$$E = 9 \times 10^9 \frac{Nm^2}{C^2}\left(\frac{2.00 \times 10^{-9}C}{(5.00 \times 10^{-3}m)^2}\right) \approx 7.2 \times 10^5 \frac{N}{C}$$

This electric field strength is the same at any point 5.00 mm away from the charge q that creates the field. It is positive, meaning that it has a direction pointing away from the charge q.

Section summary

- A test charge is a positive electric charge whose charge is so small that it does not significantly disturb the charges that create the electric field.
- Electric field lines are directed radially outward from a positive charge and directed radially inward towards a negative charge.

Review questions

1. What are electric field lines?
2. What is the magnitude and direction of the force exerted on a 3.50μ C charge by a 250 N/C electric field that points due east?
3. Calculate the magnitude of the electric field 2.00 m from a point charge of 5.00 mC.

4.7 Electric circuits

By the end of this section, you should able to:

- *define what electric circuit is;*
- *describe the components of a simple circuit;*
- *sketch electric circuit diagram.*

Activity 4.5

What do you think about open and close circuits? Discuss in groups.

When a wire connects the terminals of the battery to the light bulb, as shown in Figure 4.10, charges built up on one terminal of the battery have a path to follow to reach the opposite charges on the other terminal. The charge that flows around a circuit is made up of electrons, which are negatively charged particles that are found orbiting the atoms that make up matter in the universe. The charges moving through the wire causes the filament to heat up and then gives light.

Together, the bulb, battery, switch, and wire form an electric circuit. Thus, an electric circuit is a path through which charges can flow. A schematic diagram for a circuit is sometimes called a circuit diagram.

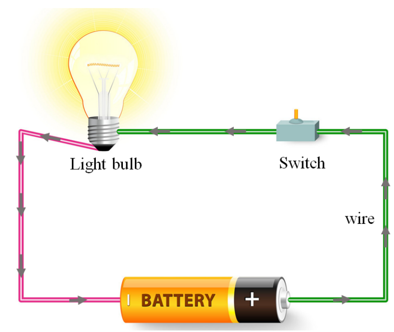


Figure 4.10 Simple electric circuit.

Any element or group of elements in a circuit that dissipates energy is called a load. A simple circuit consists of a source of potential difference and electrical energy, such as a battery, and a load like a bulb or group of bulbs. Because the connecting wire and switch have negligible resistance, you will not consider these elements as part of the load.

For the simple circuit shown in Figure 4.11 (a), a closed path is formed by wires connected to a light bulb and to a battery. As long as there is a closed path for electrons to follow, electrons can flow in a circuit. They move away from the negative battery terminal and toward the positive terminal. Thus, electric charge flows in the circuit as long as none of the wires, including the glowing filament wire in the light bulb, is disconnected or broken. Such a circuit is called a closed circuit.

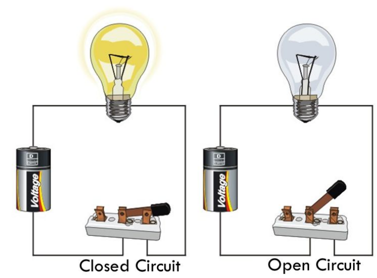


Figure 4.11 (a) Closed circuit (b) open circuit.

If the circuit is broken anywhere (or the switch is turned off), the charge stops flowing and the bulb does not glow. Thus, without a complete path, there is no charge flow and therefore no current. This situation is an open circuit. If the switch in Figure 4.11 were open, as shown in Figure 4.11(b), the circuit would be open, the current would be zero, and the bulb would not light up.

Key Concept

☞ A physical circuit is the electric circuit you create with real components. It consists of battery, wire, switch and load.

☞ A circuit diagram is a drawing which uses symbols to represent the different components in the physical circuit.

Electric circuits are incorporated into our lives in many different ways. They are used in nearly every type of item that uses electricity, from a phone to a lamp.

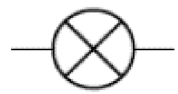
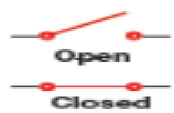
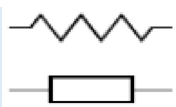
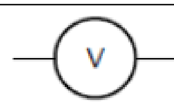
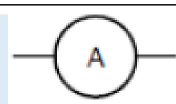
Components of electrical circuits

As you studied earlier, some common elements (components) which can be found in electrical circuits include light bulbs, batteries, connecting wires, switches, resistors, voltmeters and ammeters. You will learn more about these items in later sections, but it is important to know what their symbols are and how to represent them in circuit diagrams. Table 4.1 summarizes the symbol of electrical components.

Exercise 4.11

Students, what would happen to the lamp if the circuit is broken somewhere?

Table 4.1 Names of electrical components and their circuit symbols

Components	Symbol	Usage
Bulb or lump		bulb glows when charge moves through it
Battery		provides energy for charge to move
Switch		allows a circuit to be open or closed
Resistor		resists the flow of charge
Voltmeter		measures potential difference
Ammeter		measures current in a circuit
connecting lead		connects circuit elements together

Section summary

- The simplest electric circuit contains a source of electrical energy (such as a battery), an electric conductor (such as a wire connected to the battery) and a load (like lamps). Charges flow through a circuit.
- A closed path, or closed circuit, is needed for get electric charge to flow through the circuit.

Review questions

1. What does an electric circuit mean?
2. What is the name for the unbroken path that current follows?
3. What is the difference between open electric circuit and closed electric circuit?

4.8 Current, Voltage and Ohm's law

By the end of this section, you should able to:

- *define current, voltage and resistance;*
- *state Ohm's law;*
- *calculate current and solve problems involving Ohm's law.*

Dear students, if the electric charge flows through a conductor (for example, through a metallic wire), you say that there is an electric current in the conductor. In a torch, you know that the cells (or a battery, when placed in proper order) provide flow of charges or an electric current that makes the torch bulb to glow.

Exercise 4.12

Students, how would you explain what an electric current is?

The flow of charge particles or the rate of flow of electric charge through a point in a conducting medium is called electric current. The charge particles can be negative or positive.

Key Concept

☞ Electric current is defined as the rate of flow of electric charges.

Since electrons were not known at the time when the phenomenon of electricity was first observed, electric current was assumed to be the flow of positively charged particles. The current produced due to the flow of positively charged particles is called conventional current (or simply current) and it flows out from the positive terminal of the battery into the negative terminal. This was the convention chosen during the discovery of electricity. But this assumption was found wrong once the electron was discovered. So, in practice, the electric current is the flow of electrons (negatively charged particle). The flow of negatively charged particles is called electron current and it flows from the negative terminal of the battery to the positive terminal as shown in Figure 4.12.

However, the direction of current does not affect the properties of circuit as long as you keep it consistent. Therefore, the conventional current is taken as the standard current direction.

If a net charge ΔQ, flows across any cross-section of a conductor in time

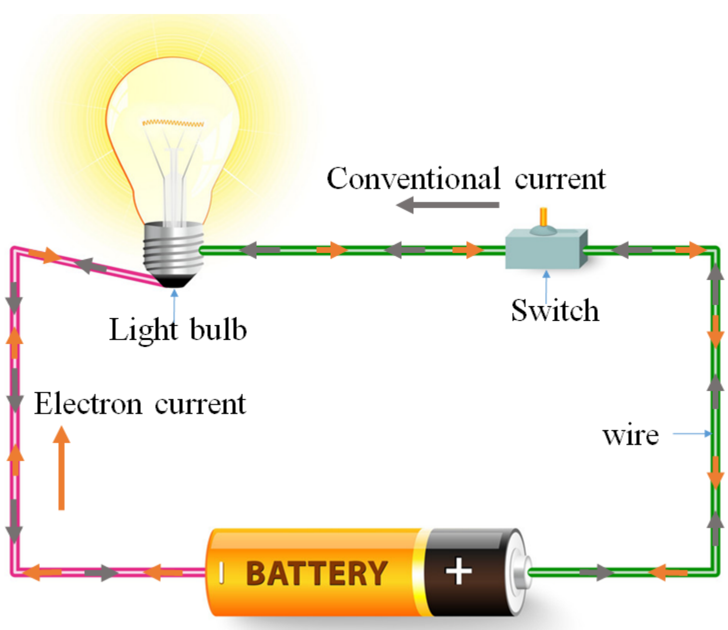


Figure 4.12 Conventional current and electron current.

Δt, then the current I, through the cross-section is

$$I = \frac{\Delta Q}{\Delta t} \tag{4.6}$$

The SI unit for the electric current is the ampere (A), named after the French scientist, **Andre-Marie Ampere (1775-1836)**. One ampere is constituted by the flow of one coulomb of charge per second, that is, 1 A = 1 C/s. Small quantities of current are expressed in milliampere ($1mA = 10^{-3}$A) or in microampere ($1\mu A = 10^{-6}$ A). An instrument used to measure electric current is called the ammeter.

Example 4.3

A current of 0.5 A is drawn by a filament of an electric bulb for 10 minutes. Find the amount of electric charge that flows through the circuit.

Given: $I = 0.5A$, and $\Delta t = 10min = 600s$

Required: $\Delta Q = ?$

Solution:

From the equation for current, you have

$$\Delta Q = I \times \Delta t = 0.5A \times 600s = 300C$$

Exercise 4.13

What makes electric charge to flow?

Potential Difference

Let us consider the analogy of flow of electric charge with the flow of water. Charges do not flow in a copper wire by themselves, just as water in a perfectly horizontal tube does not flow. If one end of the tube is connected to a tank of water kept at a higher level, such that there is a pressure difference between the two ends of the tube, water flows out of the other end of the tube. Thus, in a water circuit, a pump increases the gravitational potential energy of the water by raising the water from a lower level to a higher level.

For flow of charges in a conducting metallic wire, the electrons move only if there is a difference of electric pressure called the potential difference along the conductor. This difference of potential may be produced by a battery, consisting of one or more electric cells. A battery supplies energy to an electric circuit. When the positive and negative terminals in a battery are connected in a circuit, the electric potential energy of the electrons in the circuit is increased. As these electrons move toward the positive battery terminal, this electric potential energy is transformed into other forms of energy, just as gravitational potential energy is converted into kinetic energy as water falls.

Key Concept

☞ The voltage or potential difference in a circuit is a measure of the electrical potential energy of the electrons in the circuit. A battery supplies energy to an electric circuit by increasing the electric potential energy of electrons in the circuit.

A battery supplies energy to an electric circuit by converting chemical energy to electric potential energy. The chemical action within a cell generates the potential difference across the terminals of the cell, even when no current is drawn from it. When the cell is connected to a conducting circuit element, the potential difference sets the charges in motion in the conductor and produces an electric current. In order to maintain the current in a given electric circuit, the cell has to expend its chemical energy stored in it.

The electric potential difference between two points in an electric circuit carrying some current is defined as the work done to move a unit charge from one point to the other.

$$\Delta V = \frac{Work\ \ done\,(W)}{Charge\,(Q)} = \frac{W}{Q}$$

The SI unit of electric potential difference is volt (V), named after **Alessandro Volta (1745-1827)**, an Italian physicist. One volt is the potential difference between two points in a current carrying conductor when 1 joule of work is done to move a charge of 1 coulomb from one point to the other. Therefore,

$$1\text{Volt} = \frac{1\text{Joule's}}{1\text{Coulomb}}$$

$$[1V] = [1\frac{J}{C}] \tag{4.7}$$

The potential difference is measured by means of an instrument called the voltmeter.

Students, you might have seen when birds are sitting and even running along electric line wires high up in the air. There are times when these wires can be filled with dozens of birds. Since birds are not good conductors. That's one reason they don't get shocked when they sit on electrical wires. The energy bypasses the birds and keeps flowing along the wire instead.

There is another reason why birds can sit on a wire without getting shocked. There is no voltage difference in a single wire. For electrons to move there must be a difference in electrical potential. For example, energy flows from

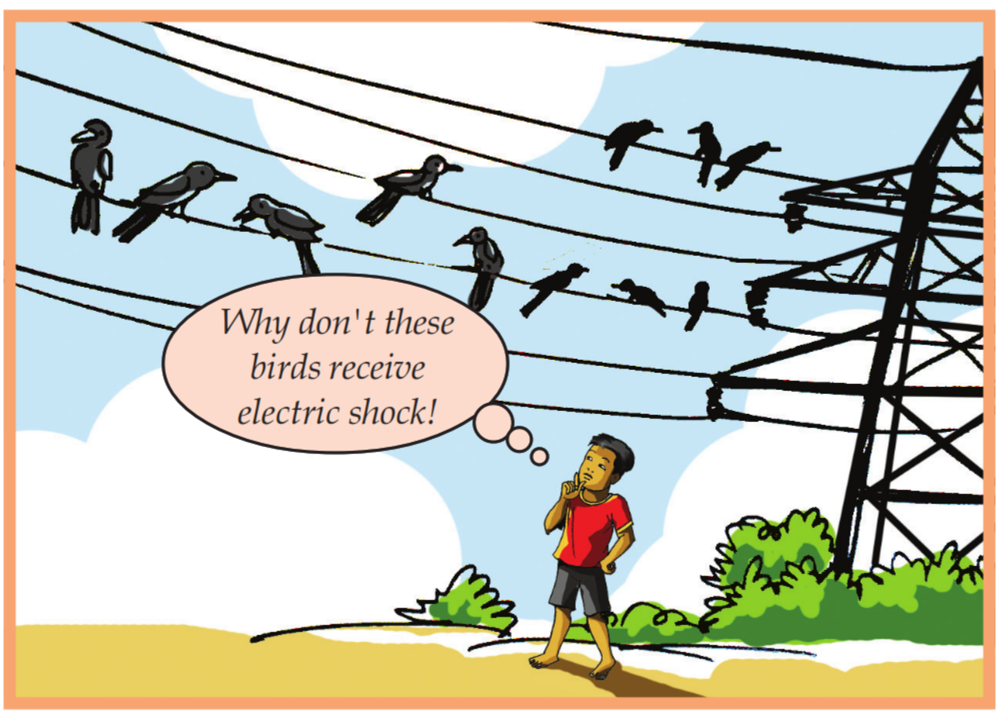


Figure 4.13 Birds on an electric cable.

Exercise 4.14

☞ How can birds sit on those wires in Fig. 4.13 and not get electric shock?

areas of high voltage to areas of low voltage. If it flows through a single power line at 35,000 volts, it will continue along the path of least resistance. That means it will bypass birds because there's no difference in electrical potential.

It would be a different story if a bird touched the ground while sitting on the wire. That would cause it to get shocked. This would also happen if a bird touched another wire with a different voltage. In these cases, the bird's body would become a path for electricity. It would move through the bird to reach either the ground or another place with a different voltage. This is why power lines tend to be high in the air with plenty of space between the wires.

Activity 4.6

Would I die if I touch a high voltage transmission line with one hand without having contact with the ground? If yes, then how can birds don't die when they sit on the line?

Example 4.4

How much work is done in moving a charge of 2C across two points having a potential difference 12 V?

Solution:
The amount of charge Q, that flows between two points at potential difference $\Delta V (= 12V)$ is 2 C. Thus, the amount of work W, done in moving the charge is

$$W = \Delta V Q = 12V \times 2C = 24J$$

Ohm's Law

Exercise 4.15

Is there a relationship between the potential difference across a conductor and the current through it?

In an electric circuit, charges do not flow freely. So the electrical current in a wire can be reduced by many factors including impurities in the metal of the wire that increases the resistance of the wire or collisions between the electrons and nuclei in the material. These factors create a resistance to the electrical current. Resistance is a description of how much a wire or other electrical component opposes the flow of charge through it.

In the 19th century, the German physicist **Georg Simon Ohm (1787-1854)** found experimentally that current through a conductor is proportional to the voltage drop across a current-carrying conductor.

In other words,

$$\Delta V \alpha I \tag{4.8}$$

$$or \quad \frac{\Delta V}{I} = constant = R \tag{4.9}$$

$$or \quad \Delta V = IR \tag{4.10}$$

This relationship is **called Ohm's law**. It can be viewed as a cause-and-effect relationship, with voltage being the cause and the current being the effect. Ohm's law is an empirical law like that for friction, which means that it is an experimentally observed phenomenon.

Exercise 4.16

Describe how the current in a circuit changes if the resistance increases and the voltage remains constant.

In the above expression, R is a constant for the given metallic wire at a given temperature and is called its resistance. It is the property of a conductor to resist the flow of charges through it. Thus, the motion of electrons through a conductor is retarded by its resistance. The units of resistance are volts per ampere, or V/A. You call a V/A an "ohm" which is represented by the uppercase Greek letter omega (Ω). Thus:

$$[1\Omega] = \left[1\frac{V}{A}\right]. \tag{4.11}$$

In many practical cases, it is necessary to increase or decrease the current in an electric circuit. In an electric circuit, a device called rheostat is often used to change the resistance in the circuit.

Ohm's law is an empirical relationship valid only for certain materials. Materials that obey Ohm's law, and hence have a constant resistance over a wide range of voltages, are said to be ohmic materials. Ohmic materials include good conductors like copper, aluminum, and silver. Materials hav-

Key Concept

☞ Resistance is a measure of how difficult it is for electrons to flow through a material.

ing resistance that change with voltage or current are nonohmic. Ohmic materials have a linear current-voltage relationship over a large range of applied voltages (Figure 4.14 (a)). Nonohmic materials have a nonlinear current-voltage relationship (Figure 4.14 (b)).

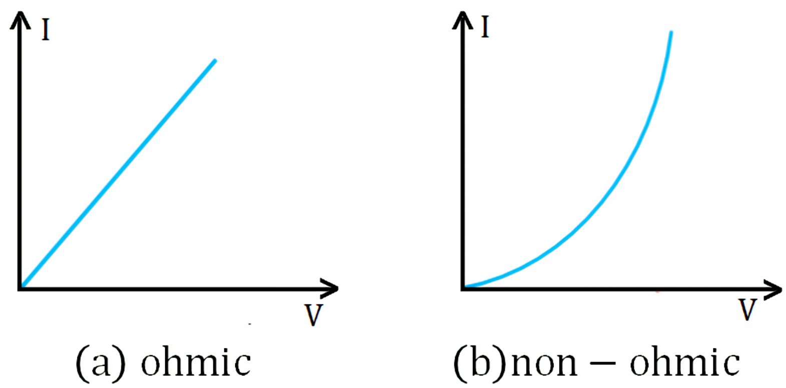


Figure 4.14 The current-voltage characteristics of (a) ohmic materials and (b) non-ohmic materials.

Exercise 4.17

Students, would you please think of an analogy for current, voltage and resistance?

The magnitude of the electric current depends on the material of the wire, length of the wire, area of cross section, and etc. The resistance of an ohmic conductor increases with length, which makes sense because the electrons going through it must undergo more collisions in a longer conductor. A smaller cross-sectional area also increases the resistance of a conductor, just as a smaller pipe slows the fluid moving through it. The resistance, then, is proportional to the conductor's length, and is inversely proportional to its cross sectional area A. Thus,

$$R \alpha \frac{l}{A} \tag{4.12}$$

$$or \qquad R = \rho \frac{l}{A} \tag{4.13}$$

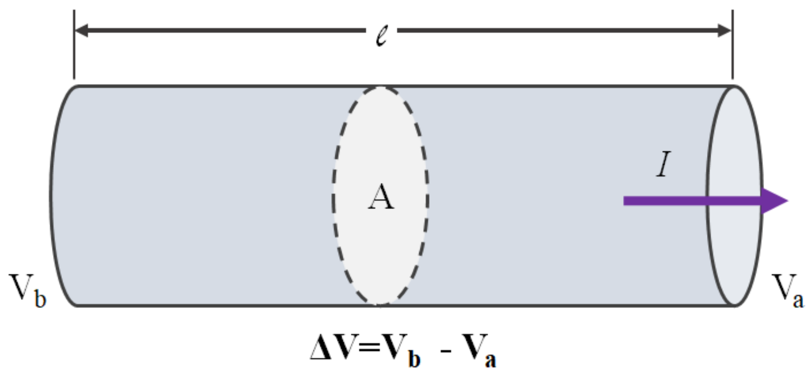


Figure 4.15 A uniform conductor of length l, and cross-sectional area A.

where the constant of proportionality, ρ, is called the resistivity of the material. Resistivity is the electrical resistance of a conducting material per unit length. In other words, it is the degree to which a conductor opposes the flow of electricity through itself, instead allowing the energy to flow out of the electrical circuit, most often as heat. The SI unit of resistivity is Ωm. It is a characteristic property of the material.

On the other hand, conductivity is the resistivity's reciprocal. So a high resistivity means a low conductivity, and a low resistivity means a high conductivity.

Exercise 4.18

Describe how the electric resistance of a wire changes as the wire becomes longer. How does the resistance change as the wire becomes thicker?

Example 4.5

How much current will an electric bulb draw from a 220 V source, if the resistance of the bulb filament is 1200Ω?

Solution:

$\Delta V = 220V$, and $\quad R = 1200\Omega$

$I = ?$

From Ohm's law, you have the current .

$$I = \frac{\Delta V}{R} = \frac{220V}{1200\Omega} = 0.18A$$

Note the difference of current drawn by an electric bulb and electric heater from the same 220 V source.

Example 4.6

The potential difference between the terminals of an electric heater is 60 V when it draws a current of 4 A from the source. What current will the heater draw if the potential difference is increased to 120 V?

Given: $\Delta V = 60V$, and $I = 4A$

Required: $R = ?$

Solution:

According to Ohm's law,

$$R = \frac{\Delta V}{I} = \frac{60V}{4A} = 15\Omega$$

When the potential difference is increased to 120 V, the current is given by

$$I = \frac{\Delta V}{R} = \frac{120V}{15\Omega} = 8A$$

The current through the heater becomes 8 A.

Example 4.7

Resistance of a metal wire of length 1m is 26Ω at $20^{o}C$. If the diameter of the wire is 0.3 mm, what will be the resistivity of the metal at that temperature?

Solution:

You are given the resistance R of the wire = 26Ω, the diameter d=0.3 mm=3×10^{-4}m, and the length l of the wire = 1 m.

Therefore, the resistivity of the given metallic wire is

$$\rho = \frac{RA}{l} = \frac{R\pi d^2}{4l}$$

Substitution of values in the above expression gives

$$\rho = 1.84 \times 10^{-6}\Omega m$$

The resistivity of the metal at $20^{o}C$ is $1.84 \times 10^{-6}\Omega m$. This is the resistivity of manganese.

Section summary

- Resistance is a property that resists the flow of electrons in a conductor. It controls the magnitude of the current. The SI unit of resistance is ohm (Ω).
- The potential difference, also referred to as voltage difference between two given points is the work in joules required to move one coulomb of charge from one point to the other.
- According to Ohm's law, the potential difference across the ends of a resistor is directly proportional to the current through it, provided its temperature remains the same.
- The resistance of a conductor depends directly on its length, inversely to its cross-sectional area, and also on the material of the conductor.

Review questions

1. What is the term used to state the flow of electric charge per unit time?
2. What is the relationship among voltage, current, and resistance in a circuit?
3. What is meant by the potential difference between two points is 1 V?
4. What are the factors that determine the resistance of a conductor?
5. Is the current flow larger or smaller through a thick wire or a thin wire of the same material when connected to the same source? Why?

6. Let the resistance of an electrical component remains constant while the potential difference across the two ends of the component decreases to half of its former value. What change will occur in the current through it?

4.9 Combination of resistors in a circuit

Exercise 4.19

How many different paths can electric current follow in a series circuit?

By the end of this section, you should able to:

- *draw a diagram that shows series and parallel connection of resistors;*
- *describe what happens to the current and potential difference when the resistors are connected in series and in parallel;*
- *calculate the equivalent resistance for a circuit of resistors in series, or in parallel;*
- *calculate the current in and potential difference across resistors connected in series and in parallel.*

Exercise 4.20

Students, if a series circuit containing mini-light bulbs is opened and some of the light bulbs are removed, what happens when the circuit is closed?

In this section, you consider simple circuits containing only resistors and batteries. Such circuits often contain a number of resistors connected in series or in parallel.

Resistors in Series

What if you wanted to watch TV and had to turn on all the lights, a refrigerator, and every other electrical appliance in the house to do so? That is what it would be like if all the electrical appliances in your house were connected in a series circuit.

A series circuit is a circuit that has only one path for the electric current to follow, as shown in Figure 4.16. If this path is broken, then the current no longer will flow and all the devices in the circuit stop working. As an example, if the entire string of lights went out when only one bulb burned out, then the lights in the string were wired as a series circuit.

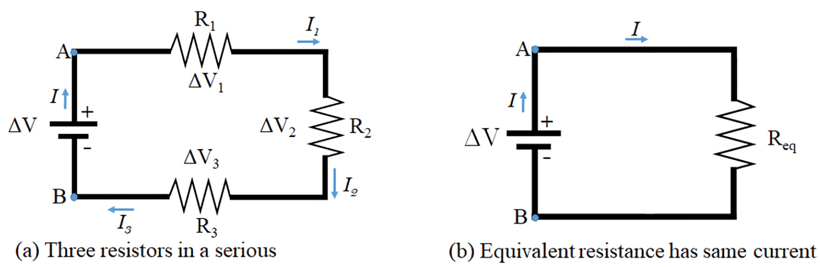


Figure 4.16 Series connection of three resistors.

Since charge is conserved, charges cannot build up or disappear at a point. As there is only one path for a charge to flow, the amount of charge entering and exiting the first resistor must equal the amount of charge that enters and exits the second resistor in the same time interval. Because the current is the amount of charge moving past a point per unit of time, the current in the first resistor must equal the current in the second resistor. This is true for any number of resistors arranged in series. When many resistors are connected in series, the current in each resistor is the same.

The potential difference across the battery, ΔV, must equal the sum of the potential differences across the load, $\Delta V_1 + \Delta V_2 + \Delta V_3$, where ΔV_1, ΔV_2, and ΔV_3 are the potential differences across R_1, R_2, and R_3 respectively. That is,

$$\Delta V = \Delta V_1 + \Delta V_2 + \Delta V_3 \tag{4.14}$$

Let I be the current through the circuit. The current through each resistor is also I. It is possible to replace the three resistors joined in series by an equivalent single resistor of resistance R_{eq}, such that the potential difference ΔV across it, and the current I through the circuit remains the same. Applying the Ohm's law to the entire circuit, you have

$$\Delta V = IR_{eq} \tag{4.15}$$

Key Concept

☞ Series describes two or more components of a circuit that provide a single path for current.

Exercise 4.21

What happens to the value of current when a number of resistors are connected in series circuit? What would be their equivalent resistance?

Key Concept

☞ In a series combination of resistors, the current is the same in every part of the circuit or the same current through each resistor.

$$IR_{eq} = \Delta V_1 + \Delta V_2 + \Delta V_3$$

Since $\Delta V_1 = IR_1, \Delta V_2 = IR_2, \Delta V_3 = IR_3,$

$$IR_{eq} = IR_1 + IR_2 + IR_3$$

$$\therefore R_{eq} = R_1 + R_2 + R_3 \tag{4.16}$$

Thus, when several resistors are joined in series, the resistance of the combination R_{eq} equals the sum of their individual resistances, R_1, R_2, R_3, and is thus greater than any individual resistance.

Key Concept

☞ The equivalent resistance in a series circuit is the sum of the circuit's resistances.

Resistors in Parallel

As discussed above, when a single bulb in a series light set burns out, the entire string of lights goes dark because the circuit is no longer closed. A wiring arrangement that provides alternative pathways for the movement of a charge is a parallel circuit. A parallel circuit is a circuit that has more than one path for the electric current to follow, as shown in Figure 4.17. The Figure shows the arrangement of three resistors joined in parallel with a combination of cells (or a battery). The current branches so that electrons flow through each of the paths.

Exercise 4.22

Explain why buildings are wired using parallel circuits rather than series circuits.

The bulbs of the decorative light set that you use in your home are arranged in parallel with each other. Thus, if one path is broken, electrons continue to flow through the other paths. Adding or removing additional devices in one branch does not break the current path in the other branches, so the devices on those branches continue to work normally. Houses, schools, and other buildings are wired using parallel circuits.

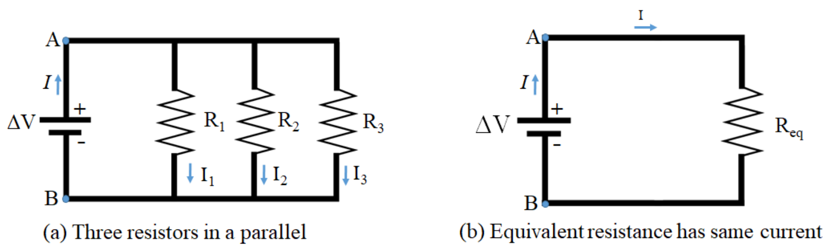


Figure 4.17 Parallel connections of three resistors.

Because charge is conserved, the sum of the currents in each bulb equals the current I delivered by the battery. This is true for all resistors in parallel.

$$I = I_1 + I_2 + I_3 ... \tag{4.17}$$

Therefore, the total current I, is equal to the sum of the separate currents through each branch of the combination.

Let R_{eq} be the equivalent resistance of the parallel combination of resistors. By applying Ohm's law to the parallel combination of resistors, you have

$$I = \frac{\Delta V}{R_{eq}}$$

Since $I = I_1 + I_2 + I_3$, by applying Ohm's law to each resistor, you have

$$\frac{\Delta V}{R_{eq}} = \frac{\Delta V_1}{R_1} + \frac{\Delta V_2}{R_2} + \frac{\Delta V_3}{R_3} \text{ where } I_1 = \frac{\Delta V}{R_1},\ I_2 = \frac{\Delta V}{R_2},\text{ and } I_3 = \frac{\Delta V}{R_3}$$

Because the potential difference across each bulb in a parallel arrangement equals the terminal voltage $\Delta V = \Delta V_1 = \Delta V_2 = \Delta V_3$, you can divide each side of the equation by ΔV to get the following equation.

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

Thus, the reciprocal of the equivalent resistance of a group of resistances joined in parallel is equal to the sum of the reciprocals of the individual resistances. An extension of this analysis shows that the equivalent resistance of two or more resistors connected in parallel can be calculated using the following equation.

Exercise 4.23

How does connecting devices in parallel affect the electric current in a circuit?

Key Concept

☞ Parallel describes two or more components of a circuit that provide separate conducting paths for current because the components are connected across common points or junctions. A parallel circuit has more than one path for current to follow.

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} ... + \frac{1}{R_n} \tag{4.18}$$

Example 4.8

In the circuit shown in Figure 4.18, find:

a) the equivalent resistance,

b) the current through each resistor.

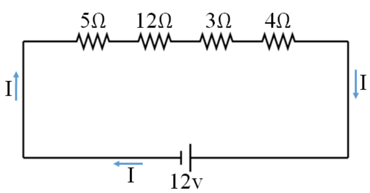


Figure 4.18 Circuit diagram for four resistors connected in series.

Solution:

$R_1 = 12\Omega, \quad R_2 = 3.0\Omega, \quad R_3 = 4.0\Omega, \quad R_4 = 5.0\Omega, \quad \Delta V = 12V$

$R_{eq} = ?, \quad I = ?$

a) All the four resistors are in series combination. So

$$R_{eq} = R_1 + R_2 + R_3 + R_4 = 12\Omega + 3.0\Omega + 4.0\Omega + 4.0\Omega = 24\Omega.$$

b) The current through all resistors in series circuit is the same. Thus, using Ohm's law,

$$I = \frac{\Delta V}{R} = \frac{\Delta V}{R_1} = \frac{12V}{24\Omega} = 0.50A$$

Example 4.9

In the circuit shown in Figure 4.19, find:

a) the equivalent resistance,

b) the current through the battery and each resistor.

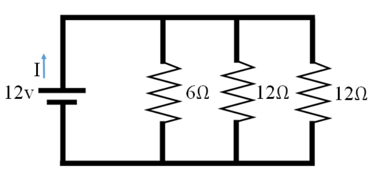


Figure 4.19 Circuit diagram for three resistors connected in parallel.

Solution:

$R_1 = 12\Omega, \quad R_2 = 12\Omega, \quad R_3 = 6.0\Omega, \quad \Delta V = 12V$

$R_{eq} = ?, \quad I = ?$

a) The three resistors are in a parallel combination. So

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{12\Omega} + \frac{1}{12\Omega} + \frac{1}{6.0\Omega} = \frac{1}{3.0\Omega}$$

$$\therefore R_{eq} = 3.0\Omega$$

Therefore, the equivalent resistance should be less than the smallest resistance as expected.

b) From Ohm's law, $I = \frac{\Delta V}{R_{eq}} = \frac{12V}{3.0\Omega} = 4.0A$

Since the voltage is constant in a parallel connection,

$$I_1 = \frac{\Delta V}{R_1} = \frac{12V}{12\Omega} = 1.0A$$
$$I_2 = \frac{\Delta V}{R_2} = \frac{12V}{12\Omega} = 1.0A$$
$$I_3 = \frac{\Delta V}{R_3} = \frac{12V}{6.0\Omega} = 2.0A$$

Resistors in a circuit may be connected in a variety of series-parallel combination. The general procedure for analyzing circuits with different series-parallel combination of resistors is to find the voltage across and the current through the various resistors as follows:

- Start from the resistor combination farthest from the voltage source, find the equivalent series and parallel resistances.
- Reduce the current until there is a single loop with one total equivalent resistance.
- Find the total current delivered to the reduced circuit using Ohm's law.
- Expand the reduced circuit in the reverse order to the above steps to find the currents and voltages for the resistors in each step.

Example 4.10

Find the equivalent resistance and the current across the 4.0Ω resistor shown in Figure 4.20.

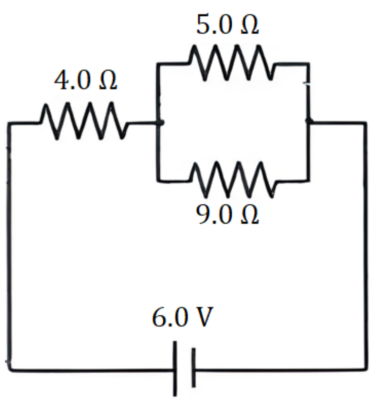


Figure 4.20 Circuit diagram for series-parallel combination of resistors.

Solution:

$R_1 = 4.0\Omega, \quad R_2 = 5.0\Omega, \quad R_3 = 9.0\Omega, \quad \Delta V = 6V$

$R_{eq} = ?, \quad I_{tot} = ?$

Since the 5.0Ω and 9.0Ω resistors are connected in parallel,

$$\frac{1}{R_{parallel}} = \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{5\Omega} + \frac{1}{9\Omega} = \frac{14}{45\Omega}$$

$$\therefore R_{parallel} = 3.21\Omega$$

Now the 4.0Ω and $R_{parallel}$ resistors are connected in parallel. Therefore,

$R_{eq} = 4.0\Omega + R_{parallel} = 4.0\Omega + 3.21\Omega = 7.21\Omega$

The current through the circuit can be calculated by

$$I = \frac{\Delta V}{R} = \frac{\Delta V}{R_eq} = \frac{6V}{7.21\Omega} = 0.830A.$$

This is equivalent with the value of the current across the 4.0Ω resistor as the 4.0Ω resistor is connected in parallel with $R_{parallel}$.

Section summary

- The formulae made about both series and parallel circuits are summarized in Table 4.2.

Table 4.2 Summary for a series and parallel circuits

Resistors in	**Series**	**Parallel**
Current	$I = I_1 = I_2 = I_3 = ... =$ same for each resistor	$I = I_1 + I_2 + I_3 + ... =$ sum of currents
Potential difference	$\Delta V = \Delta V_1 + \Delta V_2 + \Delta V_3 + ...$ = sum of potential differences	$\Delta V = \Delta V_1 = \Delta V_2 = \Delta V_3 = ...$ = same for each resistor
Equivalent resistance	$R_{eq} = R_1 + R_2 + R_3 + ... =$ sum of individual resistances	$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + ... =$ reciprocal sum of resistances

Review questions

1. Which type of circuit has more than one path for electrons to follow?

2. A 4.0 Ω resistor, an 8.0 Ω resistor, and a 12.0 Ω resistor are connected in series with a 24.0 V battery.
   a. Calculate the equivalent resistance.
   b. Calculate the current in the circuit.
   c. What is the current in each resistors?

3. A length of wire is cut into five equal pieces. The five pieces are then connected in parallel, with the resulting resistance being 2.00 Ω. What was the resistance of the original length of wire before it was cut up?

4. How can you tell that the headlights of the car are wired in parallel rather than in series? How would the brightness of the bulbs differ if they were wired in series across the same 12 V battery instead of in parallel?

4.10 Voltmeter and ammeter connection in a circuit

By the end of this section, you should able to:

- *list the devices used for measuring current and voltage;*
- *use voltmeter and ammeter to measure the voltage and current in an electric circuit, respectively;*
- *explain why an ammeter is connected in series and voltmeter is connected in parallel.*

As you have seen in previous sections, an electric circuit is made up of a number of different components such as batteries, resistors and light bulbs. There are devices that are used to measure the properties of these

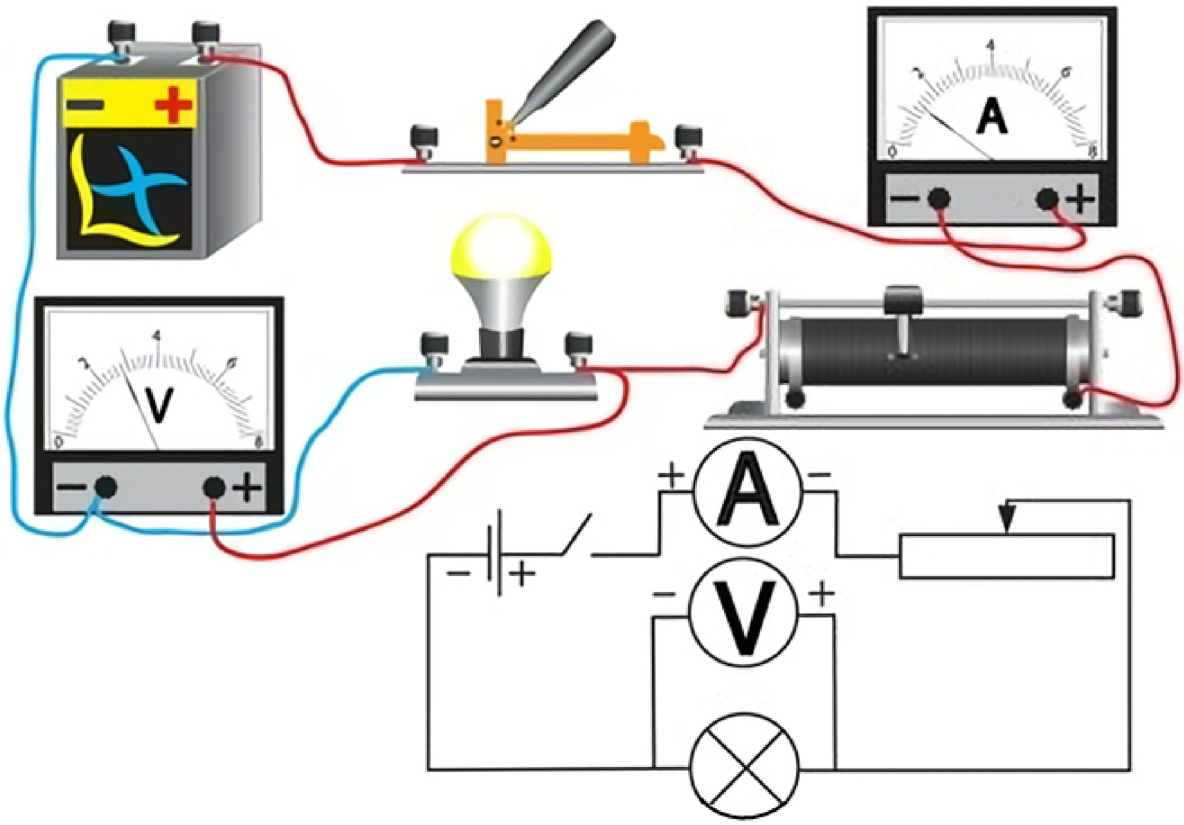


Figure 4.21 (a) Ammeter and voltmeter connection in a circuit. (b) Circuit diagram with ammeter and voltmeter.

components. These devices are called meters. Meters are of two types: analog and digital. Analog meters have a needle that swivels to point at numbers on a scale, as opposed to digital meters, which have numerical readouts similar to a hand-held calculator.

Voltmeter

A voltmeter is a device that is used to measure potential difference across a resistor or any other component of a circuit that has a voltage drop. In analogy with a water circuit, a voltmeter is like a meter designed to measure pressure difference. Voltmeters are connected in parallel with whatever device's voltage is to be measured.

A parallel connection is used because objects in parallel experience the same potential difference. Since the resistance of a voltmeter is high, it draws minimum current from the main circuit and, thus, the potential difference of the component that is going to be measured is not affected. If a voltmeter is connected in series, it would increase the equivalence resistance of the circuit and no current would flow through the circuit. Hence, it should be connected in parallel.

Figure 4.21 shows a voltmeter connected in parallel with a resistor. One lead of the voltmeter is connected to one end of the battery and the other lead is connected to the opposite end.

Key Concept

☞To measure the potential difference between the two points in a circuit, a voltmeter must be connected in parallel with the portion of the circuit on which the measurement is made.

(a) (b) (c)

Figure 4.22 (a) Analog voltmeter (b) Digital voltmeter (c) Voltmeter symbol.

Ammeter

An ammeter is a device that is used to measure the the flow of electric current in ampere. To measure the current of a circuit, the ammeter is connected in series in the circuit as shown in Figure 4.23 so that the same current that is there in the circuit flows through it and gets measured. Ammeter has low (nearly zero) resistance because you do not want to change the current that is flowing through the circuit. So its inclusion in series in the circuit does not change the resistance and hence the main current in the circuit. A series connection is used because objects in series have the same current passing through them. All of the current in this circuit flows through the meter.

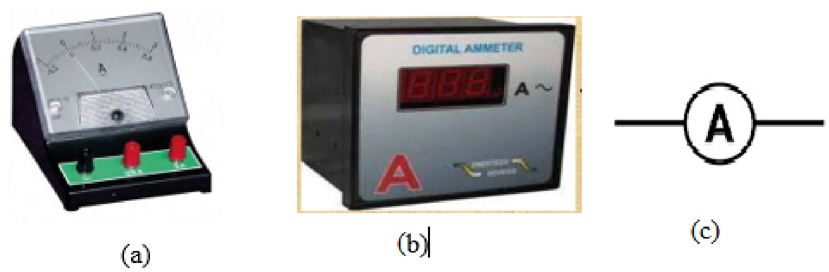


Figure 4.23 (a) Analog ammeter (b) A digital ammeter (c) Ammeter symbol.

Key Concept

☞Ammeters are connected in series with whatever device's current is to be measured.

If an ammeter is connected in parallel, it would draw most of the current and would get damaged. Hence, it must be connected in series.

Table 4.3 summarizes the use of each measuring instrument that you discussed and the way it should be connected to a circuit component.

Table 4.3 Summary of the use and connection of ammeter and voltmeter

Instrument	Measured Quantity	Proper Connection
Voltmeter	Voltage	In Parallel
Ammeter	Current	In Series

On the other hand, a multimeter is a measuring instrument that can measure multiple electrical properties. Figure 4.24 shows a digital multimeter, a convenient device, with a digital readout, that can be used to measure voltage, current, or resistance.

Figure 4.24 A multimeter used for measuring electrical properties.

Section summary

- Voltmeters measure voltage while ammeters measures current.
- Voltmeter is connected in parallel with the voltage source to receive full voltage and must have a large resistance to limit its effect on the circuit.
- An ammeter is connected in series to get the full current flowing through a branch and must have a small resistance to limit its effect on the circuit.

Review questions

1. Explain why a voltmeter is connected in parallel with a resistor.
2. Explain why an ammeter is connected in series with a resistor.
3. What will happen when you connect an ammeter in parallel and a voltmeter in a series circuit?
4. Suppose you are using a multimeter to measure current in a circuit and you inadvertently leave it in a voltmeter mode. What effect will the meter have on the circuit? What would happen if you were measuring voltage but accidentally put the meter in the ammeter mode?

Exercise 4.24

Students, have you ever had a mild electric shock?

4.11 Electrical safety in general and local context

By the end of this section, you should able to:

- *state the safety measures to be taken to protect us from electrical accidents or shocks.*

You probably felt only a mild tingling sensation of electric shock, but electricity can have much more dangerous effects. In some ways your body is like a piece of insulated wire. The fluids inside your body are good conductors of current. The electrical resistance of dry skin is much higher. Skin insulates the body like the plastic insulation around a copper wire. Your skin helps keep electric current from entering your body. A current can enter your body when you accidentally become part of an electric circuit. If direct body contact is made with an electrically energized part while a similar contact is made simultaneously with another conductive surface that is maintained at a different electrical potential, a current will flow, entering the body at one contact point, traversing the body, and then exiting at the other contact point, usually the ground.

Exercise 4.25

Students, try to identify what determines the damage caused to the human body by an electric shock.

Thus, a person can be electrocuted by touching a live wire while in contact with ground. Such a hazard is often due to frayed insulation that exposes the conducting wire. The ground contact might be made by touching a water pipe (which is normally at ground potential) or by standing on the ground with wet feet because impure water is a good conductor. Obviously, such situations should be avoided at all costs.

Key Concept

☞ The first precaution to take for personal safety is to avoid coming into contact with an electrical conductor that might cause a voltage across a human body or part of it, thus causing a current through the body which could be dangerous.

Electric shock can result in fatal burns, or it can cause the muscles of vital organs, such as the heart, to malfunction. The degree of damage to the body depends on the magnitude of the current, the length of time it acts, and the part of the body through which it passes. Currents of 5 mA or less can cause a sensation of shock, but ordinarily do little or no damage. If the current is larger than about 10 mA, the hand muscles contract and the person may be unable to let go of the live wire. If a current of about 100 mA passes through the body for just a few seconds, it can be fatal. Such large currents paralyze the respiratory muscles. The current that flows through the wires connected to a 60-W light bulb is about 0.5 A. This amount of current entering your body could be deadly. In some cases, currents of about 1 A through the body produce serious (and sometimes fatal) burns.

Fuse is the cheapest protection device in electrical circuit against short circuits and overloading of circuits. Fuse is a metal wire or thin metal strip which has the property of low melting point which is inserted into the electrical circuit as protective device. Fuse provides protection against excessive currents which can flow in circuit during short circuits. Under normal working condition the current flowing through the circuit is within safe limits but when fault occurs such as short circuit occurs or when load more than circuit capacity is connected to it, current exceeds the limiting value results in fuse wire gets heated up, melts and break the current. Thus fuse protects the machine or electrical equipment against the excessive currents. An automatic voltage regulator or stabilizer device that you use in your home uses a fuse to operate.

Figure 4.25 Fuse.

Figure 4.26 Voltage stabilizer.

As an additional safety feature for consumers, electrical equipment manufacturers now use electrical cords that have a third wire, called a case ground. To understand how this works, consider the drill being used in Figure 4.27. A two-wire device that has one wire, called the "phase" (or "hot" or "live") wire, is connected to the high-potential (220 V) side of the input power line and the second wire is connected to ground (0 V). If the high-voltage wire comes in contact with the case of the drill (Figure 4.27a), a short circuit occurs. In this undesirable circumstance, the pathway for the current is from the high-voltage wire through the person holding the drill and to Earth, a pathway that can be fatal. Protection is provided by a third wire, connected to the case of the drill (Figure 4.27b). In this case, if a short occurs, the path of least resistance for the current is from the high-voltage wire through the case and back to ground through the third wire. The resulting high current produced will blow a fuse or trip a circuit breaker before the consumer is injured.

Key Concept:

☞ A grounding plug (three-prong plug) uses a dedicated grounding wire to ground objects that may become conductors and thus dangerous. A polarized plug identifies the ground side of the line for use as a grounding safety feature.

Note: The color of wires represent electrical standards. In Ethiopia, the "phase" wire is red, yellow or blue, the ground wire is green yellowish, and

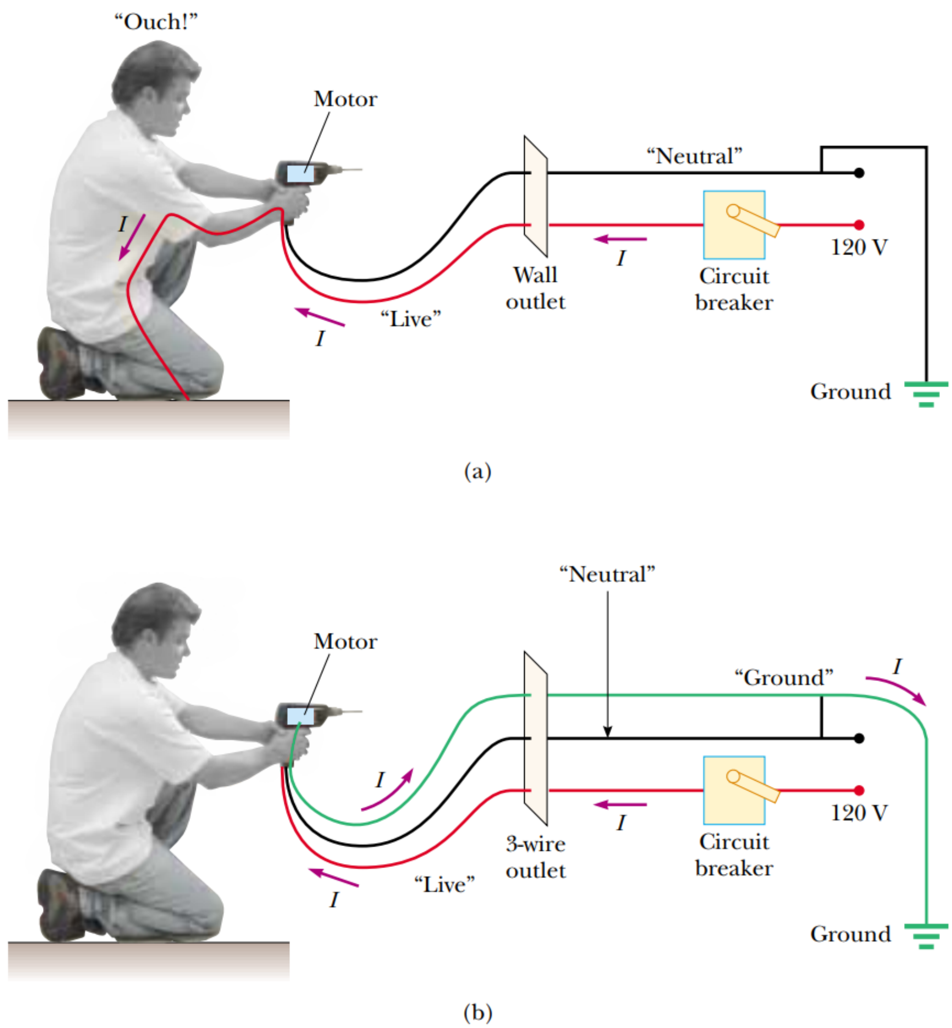


Figure 4.27 The "phase" wire, at 220 V, always includes a circuit breaker for safety. (a) When the drill is operated with two wires, the normal current path is from the "phase" wire, through the motor connections, and back to ground through the "neutral" wire. (b) Shock can be prevented by a third wire running from the drill case to the ground.

the neutral wire is black.

Special power outlets called ground-fault interrupters (GFIs) or residual current devices (RCD) are now being used in kitchens, bathrooms, basements, and other hazardous areas of new homes. They are designed to protect people from electrical shock by sensing small currents, approximately 5 mA and greater, leaking to ground. When current above this level is detected, the device shuts off (interrupts) the current in less than a millisecond.

In addition to these, the following are important safety tips to prevent electrical accidents or shocks.

- Never use appliances with frayed or damaged electric cords.
- Unplug appliances before working on them, such as when prying toast out of a jammed toaster.
- Avoid all water when using plugged-in appliances.
- Never touch power lines with anything, including kite string and ladders.
- Always respect warning signs and labels.

Section summary

- Safety of an electrical installation could be ensured by proper insulation, good earthling system and adopting adequate protection and control systems.
- Electrical hazards can cause burns, shocks and electrocution (death). You should follow proper Rules and Regulations to avoid accident.
- Qualified electricians are recommended to inspect electrical equipments. In damp locations, inspect electric cords and equipment in order to ensure they are in good condition; use a ground-fault circuit interrupter (GFCI).

Review questions

1. Identify the issues that determine the damage caused to the human body by an electric shock.
2. You are often advised to not flick electric switches with wet

hands, dry your hand first. You are also advised to never throw water on an electric fire. Why is this so?

4.12 Electric projects

By the end of this section, you should able to:

- *draw an electric circuit diagram consisting of battery, connecting wires, resistors, switch and bulb using their symbols;*
- *construct an electric circuit using wires, resistors, switch and bulb.*

You use electricity every day, but the electronic devices around you (like electric motors which move things including lifts and escalators, washing machines, food mixers and other home appliances) largely operate without being aware of how they do so. The "how" of these electronic devices working is answered by electrical circuits.

Exercise 4.26

Students, did you remember any electrical projects that you have undertaken? Is there any tips that you can share us from your experience?

As you already discussed in the previous sections, electrical circuits allow current to flow through our electronic devices to produce light, sound, and a variety of other effects. Of course, that is an easy statement to make but one that is much harder to explain or demonstrate. That is where classroom projects and lessons come in.

Thus, the best way to learn about circuits is through hands-on projects in which circuits are built and used. In this section, you will try to perform some simple electrical projects using the concepts that you have learnt earlier.

Project 4.1: A series lamp circuit

As you discussed earlier, in a series connection, components are connected end to end, so that current flows first through one lamp, then through the other. The lamps are strung together end to end.

One drawback of series connections is that if one component fails in a way that results in an open circuit, the entire circuit is broken and none of the components will work. So, if either one of the lamps in the series circuit burns out, neither lamp will work. That's because current must flow through both lamps for the circuit to be complete.

In this project, you will build a circuit that connects two lamps in series, a simple circuit like the one shown in Figure 4.28. The lamps are powered by a pair of AA batteries. Then, you will use your multimeter to measure the voltages at various points in the circuit.

Equipment's and materials:

- A small head screw driver

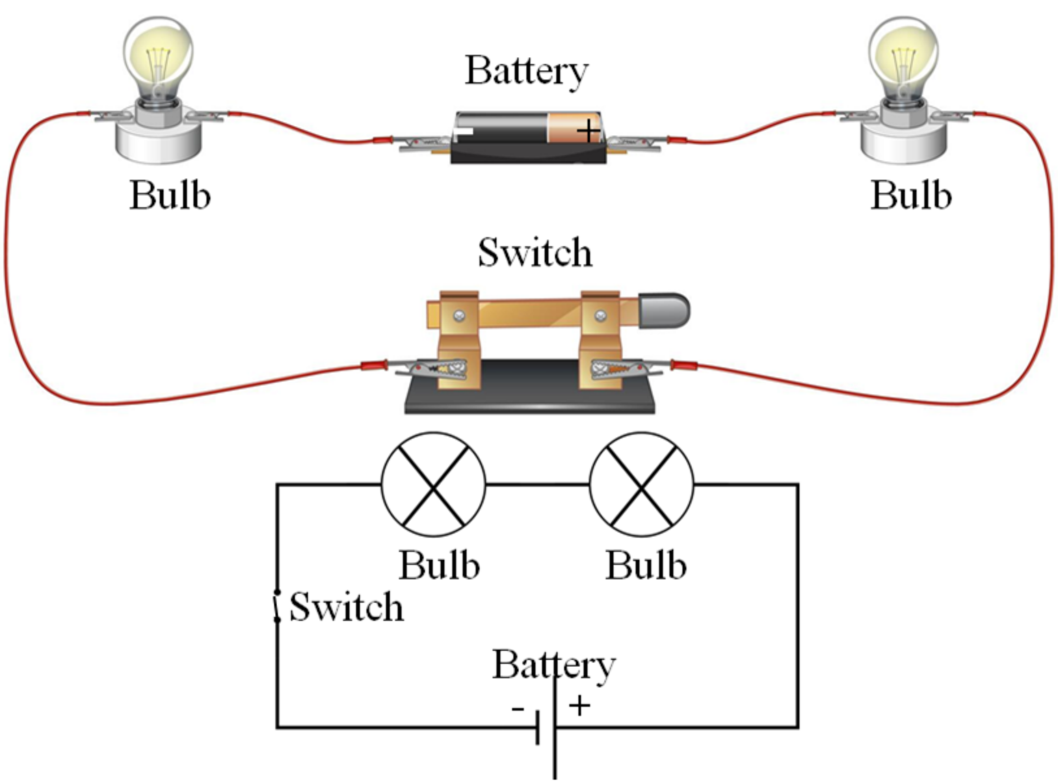


Figure 4.28 (a) Series Circuit (b) Series circuit diagram.

- Wire cutters
- Wire strippers
- A multimeter
- Two AA batteries
- One battery holder
- Two lamp holders
- Two 3V flashlight lamps
- One 6 inch length 22-gauge stranded wires

Steps

1. Cut a 6 inch length of wire and strip of 0.5 inch of insulation from each end.
2. Attach the red lead from the battery holder to one end of the terminals on one of the lamp holders.
3. Attach the black lead to one of the terminals on the other lamp holder.
4. Use the 6 inch wire to connect the unused terminal of the first lamp holder to the unused terminal of the second lamp holder.
5. Insert the batteries. Both lamps light. Notice that the lamps are dim. That's because in a series circuit made with two identical lamps, each of the two lamps sees only half the total voltage.
6. Remove one of the lamps from its holder. The other lamp goes out. This is because in a series circuit, a failure in any one component breaks the circuit so that none of the other components will work.
7. Replace the lamp you removed in step 6.

8. Set your multimeter to a DC voltage range that can read at least 3 volts.
   Note that you can measure the voltage seen by any component in a circuit by setting your multimeter to an appropriate voltage range and then touching the leads to both sides of the component.

9. Touch the leads to the two terminals on the first lamp holder. The mutlimeter should read approximately 1.5 V (If you are using an analog meter and the needle moves backwards, just reverse the leads).

10. Touch the leads to the terminals on the other lamp holder. Again the multimeter should read approximately 1.5V.

11. Touch the red lead of the meter to the terminal that the red lead from the battery is connected to and touch the black meter lead to the terminal that the black battery lead is connected to. This measure the voltage across both lamps combined. The meter will indicate 3V.

Project 4.2: A parallel lamp circuit

In the parallel connection, each lamp has its own direct connection to the battery. This arrangement avoids the if one fails they all fail nature of series connections. In a parallel connection, the components do not depend on each other for their connection to the battery. Thus, if one lamp burns out, the other will continue to burn.

In this project, you will build a circuit that connects two lamps in parallel like the one shown in Figure 4.29. The lamps are powered by a pair of AA batteries. You will use your multimeter to measure voltages within various points in the circuit.

Equipments and materials:

- A small head screw driver
- Wire cutters

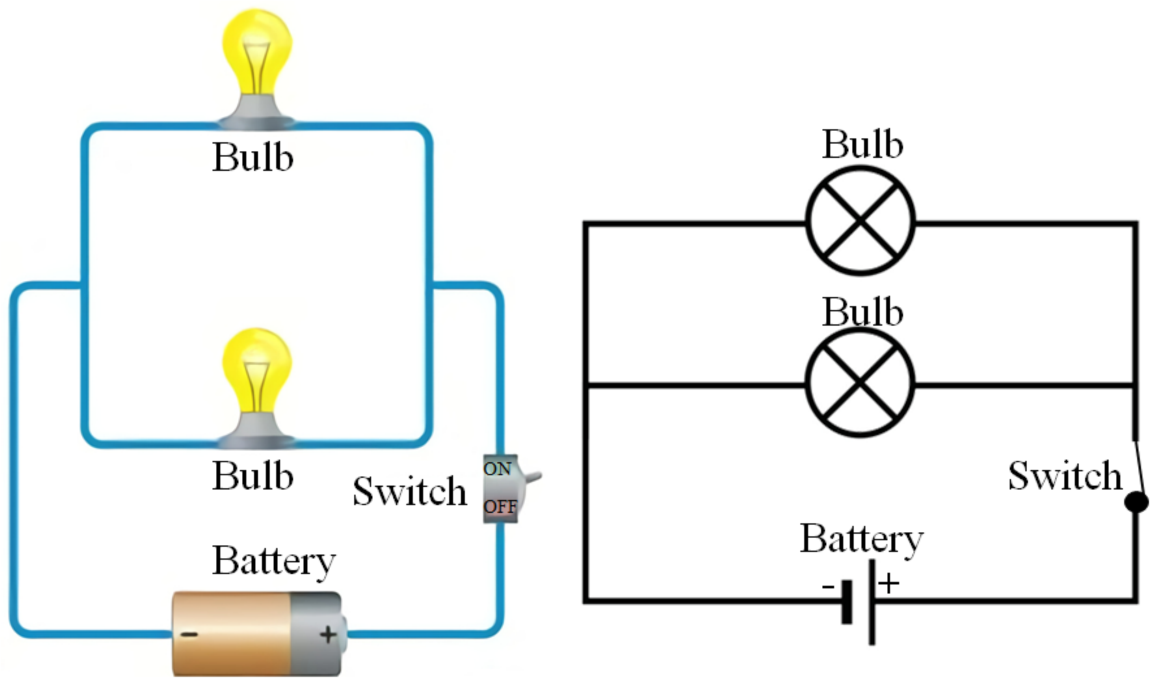


Figure 4.29 (a) Parallel Circuit (b) Parallel circuit diagram.

- Wire strippers
- A multimeter
- Two AA batteries
- One battery holder
- Two lamp holders
- Two 3V flashlight lamps
- Two 6 inch length 22-gauge stranded wires

Steps:

1. Cut two 6 inch lengths of wire and strip of 0.5 inch of insulation from each end.
2. Attach the red lead from the battery holder to one end of the terminals on the first lamp holder.

3. Attach the black lead to the other terminals on the first lamp holder.
4. Use the two wires to connect each of the terminals on the first lamp holder to the terminals on the second lamp holder. This wiring connects the two lamp holders in parallel.
5. Insert the batteries. The lamps light brighter than when you connected them in series in Project 4.1.
6. Remove one end of the lamps. Notice that the other lamp remains lit.
7. Replace the lamp you removed in step 6.
8. Set your multimeter to a DC voltage range that can read at least 3 volts.
9. Touch the leads of your multimeter to the two terminals on the first lamp holder. Make sure you touch the red meter lead to the terminal that the red battery lead is connected to and the black meter lead to the terminal that the black battery lead is attached to. Note that the voltage reads a full 3V.
10. Touch the meter leads to the terminals on the second lamp stand. Note that the voltage again reads 3V. When components are connected in parallel, the voltage is not divided among them. Instead, each component sees the same voltage. That is why the lamps light at full intensity in the parallel circuit.

Project 4.3: Electric house project

In this project, you will construct and wire a model house according to the requirements given below. You can use materials that are available in your locality.

The Building:

- Your team will design and construct an electric house with separate series, parallel, and complex circuits.
- The house you built will contain at least the following areas: one bedroom, one bathroom, a kitchen, a front door, and a living room/-dining room area.
- Each individual room will be illuminated by its own light.

Decorating

Your building is to be decorated neatly and should reflect the purpose of the room.

Wiring: To earn full point, each circuit below must be present and working in class:

Each house will be wired with 4 different circuits as follows:

- A single outside light with a switch.
- The living room area must have a "chandelier" with at least two lights in a series circuit with a switch.
- The house must have one parallel circuit consisting of a switch and at least three lights.
- The house must have one combination circuit consisting of two switches and at least three lights.

Specifics:

- Switches can be made from brads and paper clips.
- Your house will be powered by AAA, AA, D, or 9V batteries so make an obvious two leads to attach your battery to during testing if you do not supply your own batteries. You will need to use the AA, D,

and 9V in at least one circuit of your house. (You may not use the same battery for every circuit in your house)

- Each circuit must be able to work independently from the other.
- Insulated wire and lights will be provided.
- You will have access to scissors, wire cutters and wire strippers.

The Circuit Diagram:

You must provide one diagram for the complete circuit in your building. It must:

- be labeled and be complete including all electrical parts for each circuit;
- use accurate circuit symbols;
- be neat & drawn with a straight edge ruler;
- fill an entire piece of paper.

Virtual Labs

On the soft copy of the book, click on the following link to perform virtual experiments on static and current electricity unit under the guidance of your teacher.

1. Coulomb's Law PhET Experiment.
2. Circuit Construction Kit: DC - Virtual Lab PhET Experiment.
3. Circuit Construction Kit: DC PhET Experiment.
4. Charges and Fields PhET Experiment.
5. Balloons and Static Electricity PhET Experiment.
6. Ohm's Law PhET Experiment.

7. Resistance in a Wire PhET Experiment.

End of unit summary

- There are two types of charges in nature and they are called positive and negative charges.
- Charges with the same sign repel each other. Charges with opposite signs attract each other.
- Charging is the process of electrifying bodies, that is removing from or adding charges to a body.
- Electric charges can neither be created nor destroyed, but can be transferred from one material to the other.
- Charging by rubbing, charging by conduction, and charging by induction are the different methods of charging a body.
- An electroscope is a simple device used to study the properties of electric charges. It enables us to determine both the sign of the charge and the magnitude of the charge on a body. It can also be used to identify whether a given material is a conductor or an insulator.
- Lightning is formed when charged water drops of one sign (positive or negative) collect in one part of the cloud. There is electrostatic discharge (in the form of sparks) which jumps often from one cloud region to another, but sometimes from the cloud to earth.
- The force between two charges is given by Coulomb's law, which states that the force between two point charges is directly proportional to the product of the two charges and inversely proportional to the square of the distance between the two.

- The electric field defines the force per unit charge in the space around a charge distribution.
- Electric field lines start at positive charges and point away from positive charges. They end at negative charges and point toward negative charges.
- Electric-field lines never cross each other.
- Open circuits do not allow an electrical current to flow through the circuit. Closed circuits are complete and allow electricity to flow through.
- Current through a given area of a conductor is the net charge passing per unit time through the area.
- To maintain a constant current, you must have a closed circuit in which an external force moves electric charge from lower to higher potential energy. The work done per unit charge by the source in taking the charge from lower to higher potential energy (i.e., from one terminal of the source to the other) is called the voltage difference between the two terminals of a source in a closed circuit.
- Ohm's law: The electric current I flowing through a substance is proportional to the voltage ΔV across its ends, i.e., $\Delta V \alpha I$ or $\Delta V = RI$, where R is called the resistance of the substance. The unit of resistance is ohm: 1 Ω = 1 V A^{-1}.
- The resistance R of a conductor depends on its length l and cross-sectional area A through the relation, $R = \rho \frac{l}{A}$; where ρ called resistivity which is a property of the material and depends on temperature and pressure.
- Total resistance R of n resistors connected in series is given by $R = R_1 + R_2 + ... + R_n$

- Total resistance R of n resistors connected in parallel is given by $\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + ... + \frac{1}{R_n}$.
- Ammeter is a device used to measure the current in a circuit. It is connected in series to the element through which the current flows. Resistance of an ideal ammeter is zero.
- Voltmeter is a device used to measure the potential difference in the circuit. It is connected in parallel to the element through which potential drop is to be measured. Resistance of an ideal voltmeter is infinite.
- Precaution must be taken when working near electricity or electrical equipments.

End of unit questions and problems

1. Describe how you can know charged bodies attract or repel each other.
2. Why the inside of a car or building is a safe place to shelter during storm?
3. State Coulomb's law.
4. What are essential parts of an electroscope? Draw an electroscope and label it.
5. State the law of conservation of charge .
6. Explain about the different methods of charging a body.
7. List electric safety rules]].
8. Two charges $q_1 = 2\mu C$ and $q_2 = -4\mu C$ are placed 20cm apart. Determine the magnitude and direction of the force that one charge exerts over the other.

9. Two spheres; 4.0 cm apart, attract each other with a force of 1.2×10^{9} N. Determine the magnitude of the charge on each, if one has twice the charge (of the opposite sign) as the other.

10. Two equal charges of magnitude 1.1×10^{7} C experience an electrostatic force of 4.2×10^{4} N. How far apart are the centres of the two charges?

11. Discuss the use of a lightning conductor that is often fitted to the top of a building?

12. Why isn't a bird sitting on a high-voltage power line electrocuted? Compare this with the situation in which a large bird hits two wires simultaneously with its wings.

13. How is a voltmeter connected in the circuit to measure the potential difference between two points?

14. List one way electric current is similar to water current and one way it is different.

15. How does the current in a circuit change if the voltage is doubled and the resistance remains unchanged?

16. A copper wire has diameter 0.5 mm and resistivity of $1.6 \times 10^{-8} \Omega$ m. What will be the length of this wire to make its resistance 10 Ω? How much does the resistance change if the diameter is doubled?

17. If aluminium and copper wires of the same length have the same resistance, which has the larger diameter? Why?

18. The values of current I flowing in a given resistor for the corresponding values of potential difference V across the resistor are given below.

I (amperes)	0.1	0.2	0.3	0.4	0.5
V (volts)	1.5	3.0	4.5	6.0	7.5

Plot a graph between V and I, and calculate the resistance of that resistor.

19. When a 12 V battery is connected across an unknown resistor, there is a current of 2.5 mA in the circuit. Find the value of the resistance of the resistor.

20. A battery of 9 V is connected in series with resistors of 0.2 Ω, 0.3 Ω, 0.4 Ω, 0.5 Ω, and 12 Ω. How much current would flow through the 12 Ω resistor?

21. How many 176 Ω, resistors (in parallel) are required to carry 5 A on a 220 V line?

22. Show how you would connect three resistors, each having a resistance 6 Ω, so that the combination has a resistance of (i) 9 Ω, (ii) 4 Ω.

23. Why is the series arrangement not used for domestic circuits?

24. How does the resistance of a wire vary with its area of cross-section?

25. Why copper and aluminium wires are usually employed for electricity transmission?

26. You are often advised to not flick electric switches with wet hands, dry your hand first. You are also advised to never throw water on an electric fire. Why is this so?

27. Why is the resistance of wet skin so much smaller than dry, and why do blood and other bodily fluids have low resistances?

28. What determines the severity of a shock? Can you say that a certain voltage is hazardous without further information?

29. In view of the small currents that cause shock hazards and the larger currents that circuit breakers and fuses interrupt, how do they play a role in preventing shock hazards?

30. Suppose you plug an electric heater into the wall outlet. As soon as you turn it on, all the lights in the room go out. Explain what must have happened.

31. Why is it dangerous to use a fuse that is rated 30 A in a circuit calling for a 15 A fuse?

Unit 5

Magnetism

Introduction

Magnetism is an interaction that allows certain kinds of objects, which are called 'magnetic' objects, to exert forces on each other without physically touching. Humans have known about magnetism for thousands of years. For example, lodestone is a magnetized form of the iron oxide mineral magnetite. It has the property of attracting iron objects. Today magnetism plays many important roles in our lives. In this unit, you will learn about some of the fundamental concepts related to a magnet, magnetic field and magnetic force including its simple applications.

By the end of this unit, you will be able to:

- *understand the nature and characteristics of magnets;*
- *understand what is meant by the magnetic field;*
- *understand the concepts related to magnetic force;*
- *solve problems related to magnetism;*
- *appreciate simple applications of magnetism in your everyday life.*

Brain storming question:

Students, can you list the different ways in which magnetism has played a part in your life today?

5.1 Magnet

Exercise 5.1

Students, most probably you have been familiar with a magnet. How could you define it? When was a magnet first discovered?

By the end of this section, you will be able to:

- *identify various types of magnets based on their physical shapes;*
- *describe the properties of magnets.*

Magnet has always been a thing of awesome use for humans as they play an important role in a wide range of devices that you use in your daily life. According to history, the use of magnets was discovered by the ancient Greeks during the period of Greek civilization. They found stones which were able to attract iron and nickel like other substances. This naturally occurring stones which was discovered then is called as 'lodestone'. This is something like a magnet.

A magnet is a material or object that produces a magnetic field which is responsible for a force that pulls or attracts on other materials. Magnets attract objects made of iron or steel, such as nails and paper clips. Magnets also can attract or repel other magnets.

Figure 5.1 Magnets of different shapes.

Magnets can be made in various shapes and creates its own persistent magnetic field. The magnets that are commonly available in different shapes are those indicated in Figure 5.1. These magnets of different shapes are used in various appliances used at home like tape recorder, radio, motor, door-bell, head phones, etc. They are used in these appliances to either hold or separate, control, elevate (lift) substances, changing electrical energy to mechanical energy (motors, loudspeakers) or mechanical to electrical energy (generators and microphones).

Types of Magnets

There are three types of magnets. These are:

1. **Permanent Magnet:** are made up of magnetic material (such as steel) that is magnetized and has its own magnetic field. They are

known as permanent magnets because they do not lose their magnetic property once they are magnetized. However, the strength depends upon the nature of the material used in its creation.

The following are the ways to demagnetize the permanent magnets:

- Exposing magnets to extreme temperatures.
- The magnetic attraction between the magnet's atoms gets loosen when they are hammered.
- Stroking one magnet with the other in an inappropriate manner will reduce the magnetic strength.

Permanent magnets are used in the speakers, mobile phones, cars, generators, television, sensors etc.

2. **Temporary Magnet:** can be magnetized in the presence of a magnetic field. When the magnetic field is removed, these materials lose their magnetic property. Iron nails and paper-clips are examples of the temporary magnet.

3. **Electromagnets:** consist of a coil of wire wrapped around the metal core made from iron. When the coil of wire conducts a current, a magnetic field is generated making the material behave like a magnet. The strength of the magnetic field can be controlled by controlling the electric current. Electromagnets are used in the generators, motors, transformers, loudspeakers, MRI machines, magnetic locks etc.

Properties of magnet

The following are the basic properties of magnet:

- When a magnet is dipped in iron filings, you can observe that the iron filings cling to the end of the magnet as the attraction is maximum at the ends of the magnet. These ends are known as poles of the magnets.

Key Concept:

☞ Magnetic properties exist when the material is magnetized.
☞ Every magnet has two poles: North and South. Like poles repel and unlike poles attract each other.

- Magnetic poles always exist in pairs. Thus, when a magnet is cut into two pieces, both the pieces will have the North Pole and the South Pole.
- Whenever a magnet is suspended freely in mid-air, it always points towards north-south direction. Pole pointing towards geographic north is known as the North Pole and the pole pointing towards geographic south is known as the South Pole.
- Like poles repel while unlike poles attract.
- The magnetic force between two magnets is greater when the distance between these magnets is lesser.

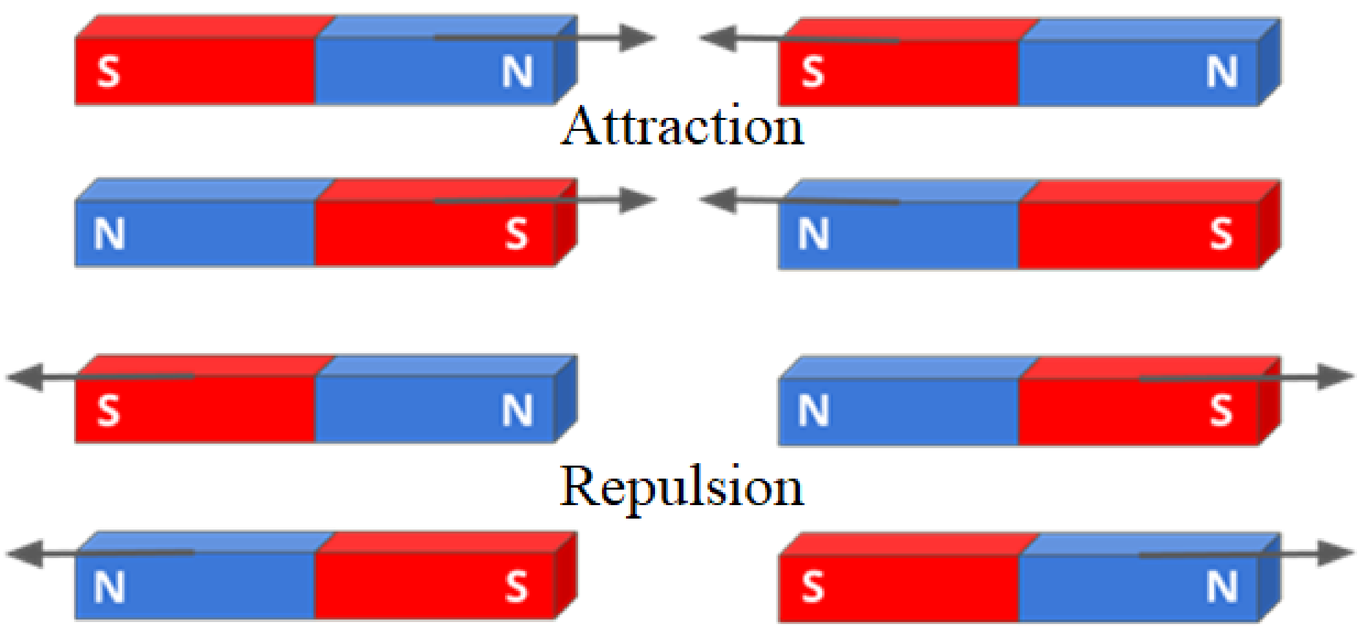


Figure 5.2 Properties of magnetic poles.

Section summary

- A magnet has a north pole and a south pole.
- Like magnetic poles repel each other; unlike poles attract each other.

Review questions

1. What is a magnet? List its properties.
2. How a magnet loses its magnetic properties?
3. State the rule for magnetic attraction and repulsion.
4. Describe how a temporary magnet differs from a permanent magnet.
5. What are magnetic poles? Does magnetic monople exist?
6. If you broke a magnet into two, would you have isolated north and south poles? Explain.

5.2 Magnetic Field

By the end of this section, you will be able to:

- *describe what a magnetic field is;*
- *state the properties of magnetic lines of force;*
- *draw magnetic field lines around magnets.*

The magnetic field is a field produced by the magnet or electric charges in motion. The magnetic field is the region around a magnetic material or moving electric charge within which the force of magnetism acts. Magnetic fields are represented using magnetic field lines. It is a visual tool used to visualize the direction and the strength of the magnetic field.

Magnetic field lines can be drawn using a compass needle. The compass needle should be placed on a piece of paper near the magnet. Check the direction in which the compass needle points and mark the direction. Move the compass needle to different positions and mark the directions. Joining the points shows the magnetic field lines.

Properties of Magnetic Field Lines

Some important properties of magnetic field lines are listed below:

- Magnetic field lines never intersect with each other.
- Magnetic field lines form a closed-loop.
- Magnetic field lines appear to emerge or start from the north pole and merge or terminate at the south pole.
- Inside the magnet, the direction of the magnetic field lines is from the south pole to the north pole.
- The closeness or density of the field lines is directly proportional to the strength of the field. In areas where the magnetic field is strong, the field lines are closer together. Where the field is weaker, the field lines are drawn further apart.
- The magnetic field is stronger at the poles because the field lines are denser near the poles.
- Magnetic field has both direction and magnitude at any point on the field. Therefore, magnetic field is represented by a vector.

Exercise 5.2

Can you observe magnetic field through our naked eyes?

Exercise 5.3

Students, what are the similarities and differences between an electric field and a magnetic field?

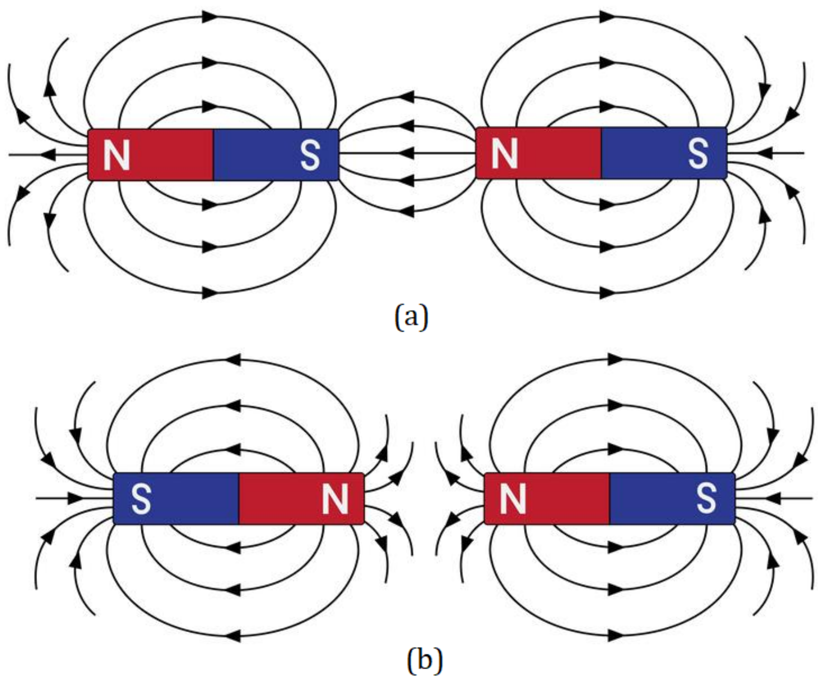


Figure 5.3 Magnetic field lines plot for a bar magnet.

Activity 5.1

Field around a pair of bar magnets

☞ Take two bar magnets and place them a short distance apart such that they are repelling each other.

☞ Place a sheet of white paper over the bar magnets and sprinkle some iron filings onto the paper.

☞ Give the paper a shake to evenly distribute the iron filings. In your exercise book, draw both the bar magnets and the pattern formed by the iron filings.

☞ Repeat the procedure for two bar magnets attracting each other and draw what the pattern looks like for this situation.

☞ Make a note of the shape of the lines formed by the iron filings, as well as their size and their direction for both arrangements of the bar magnet.

☞ What does the pattern look like when you place both bar magnets side by side?

Exercise 5.4

Determine where the field around a magnet is the strongest and where it is the weakest.

Key Concept

☞ Magnetic field lines are imaginary lines used to represent magnetic fields. They describe the direction of the magnetic field and the strength of the magnetic field.

As already said, opposite poles of a magnet attract each other and bringing them together causes their magnetic field lines to converge (come together). Like poles of a magnet repel each other and bringing them together causes their magnetic field lines to diverge (bend out from each other).

Section summary

- A magnet is surrounded by a magnetic field that exerts forces on other magnets.
- Magnetic field lines exit from the north pole of a magnet and enter its south pole.
- Magnetic field lines always form closed loops.

Review questions

1. Draw a small bar magnet and show the magnetic field lines as they appear around the magnet. Use arrows to show the direction of the field lines.
2. Draw the magnetic field between two like magnetic poles and then between two unlike magnetic poles. Show the directions of the fields.
3. Determine where the field around a magnet is the strongest and where it is the weakest.
4. Explain magnetic field using the concept for magnetic field lines.
5. Write down the properties of magnetic field lines.

5.3 The earth's magnetic field and the compass

By the end of this section, you will be able to:

- *describe the earth's magnetic field;*
- *explain the origin of the Earth's magnetic field and its importance for the life on Earth.*

Exercise 5.5

Students, does the earth have a magnet? What do you think?

Earth's Magnetic Field

Earth has a huge magnet that produces a magnetic field. The origin of Earth's magnetic field is thought to be deep within Earth in the outer core layer. One theory is that movement of molten iron in the outer core is responsible for generating Earth's magnetic field. The shape of Earth's magnetic field is similar to that of a huge bar magnet tilted about 11^0 from

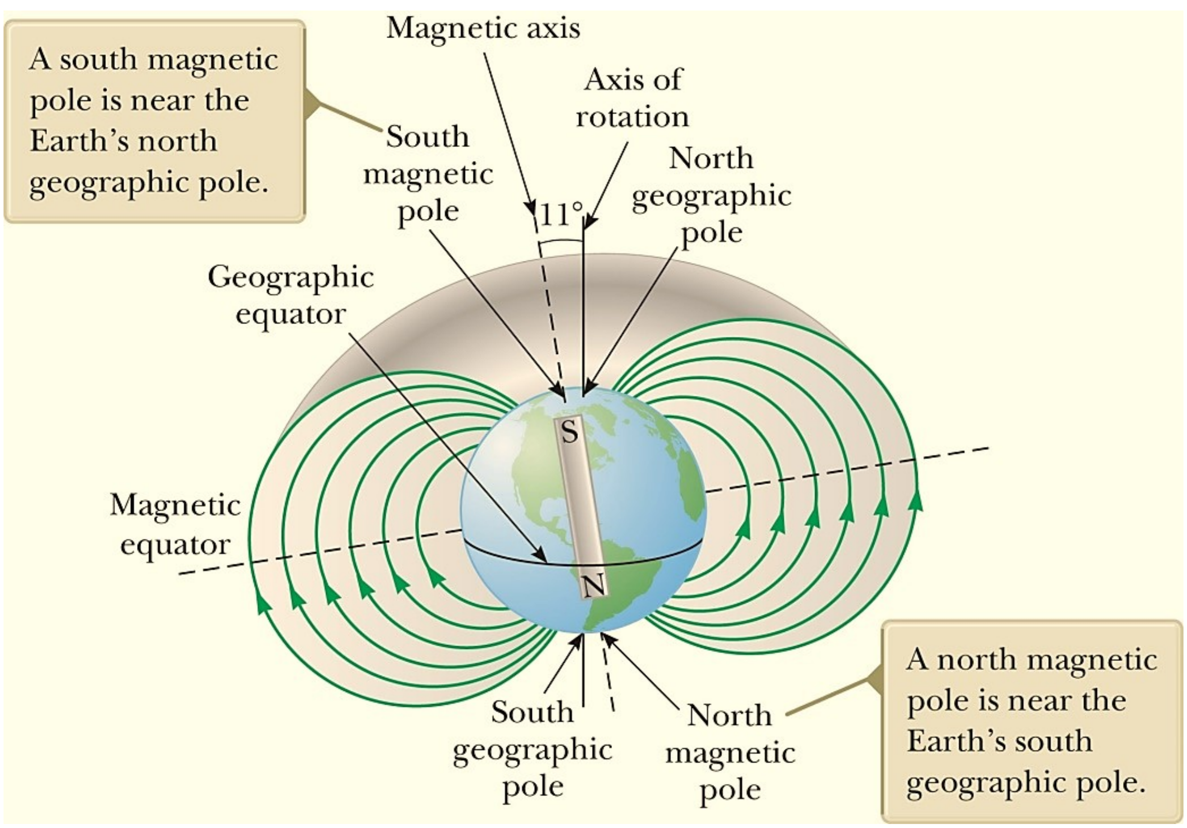


Figure 5.4 Earth's magnetic field.

Earth's geographic north and south poles.

In Figure 5.4, you can see a representation of the earth's magnetic field which is very similar to the magnetic field of a giant bar magnet. So the earth has two sets of north poles and south poles: geographic poles and magnetic poles.

Key Concept:

☞Earth is surrounded by a magnetic field similar to the field around a bar magnet.

Another interesting thing to note is that if you think of the earth as a big bar magnet, and you know that magnetic field lines always point from north to south, then the compass tells us that what you call the magnetic north pole is actually the south pole of the bar magnet.

A compass

A compass is an instrument which is used to find the direction of a magnetic field. It can do this because a compass consists of a small metal needle which is magnetized itself and which is free to turn in any direction. Therefore, in the presence of a magnetic field, the needle is able to line up in the same direction as the field.

Exercise 5.6

Students, have you ever seen a compass? If so what do you think is the purpose of a compass?

Compasses are mainly used in navigation to find direction on the earth. This works because the earth itself has a magnetic field which is similar to that of a bar magnet shown above. The compass needle aligns with the magnetic field direction and points north (or south). Once you know where north is, you can figure out any other direction. A picture of a compass is shown in Figure 5.5.

Figure 5.5 Compass

Earth's magnetic field also causes a compass needle to rotate. The north pole of the compass needle points toward Earth's magnetic pole that is in the north. This magnetic pole is actually a magnetic south pole. Earth's magnetic field is like that of a bar magnet with the magnet's south pole near Earth's north pole.

Some animals can detect magnetic fields, which helps them orientate themselves and find direction. Animals which can do this include pigeons, bees, Monarch butterflies, sea turtles and fish.

Section summary

- Earth is surrounded by a magnetic field similar to the field around a bar magnet.

Review questions

1. What is the evidence for the existence of the earth's magnetic field?
2. Explain why a compass will show you which direction is magnetic north.

5.4 Magnetic field of a current carrying conductor

By the end of this section, you should be able to:

- *describe the factors through which a magnetic field due to current carrying conductor depends on;*
- *Calculate the magnetic field of a current-carrying conductor.*

Current is generally defined as the rate of flow of charge. You already know that stationary charges produce an electric field which is proportional to the magnitude of the charge. However, moving charges produce magnetic fields which are proportional to the current and hence, a current carrying conductor produces magnetic effect around it. This magnetic field is generally attributed to the sub-atomic particles in the conductor, for example, the moving electrons in the atomic orbitals.

Exercise 5.7

List factors affecting the strength of magnetic field around a straight current carrying conductor.

Magnetic field due to a current-carrying conductor depends on the current in the conductor and distance of the point from the conductor. The **Biot-Savart Law**, named after French scientists Jean-Baptiste Biot and

Felix Savart, is an equation that describes the magnetic field created by a current-carrying wire, and allows you to calculate its strength at various points.

According to this law, the magnetic field strength **B** is proportional to the current and is inversely proportional to the distance r from the wire.

$$\mathbf{B} = \frac{\mu_0 I}{2\pi r} \tag{5.1}$$

where, $\mu_0 = 4\pi \times 10^{-7}\ \frac{Tm}{A}$ refers to the permeability of free space, I is the magnitude of the current I, and r is the distance from the source current to the magnetic field. The SI unit for magnetic field strength **B** is called the Tesla (T) after the eccentric but brilliant inventor Nikola Tesla (1856 - 1943).

Another smaller unit, called the gauss (G), where $1\ G = 10^{-4}$ T is sometimes used. The strongest permanent magnets have fields near 2T; superconducting electromagnets may attain 10 T or more. Earth's magnetic field on its surface is only about 5×10^{-5} T, or 0.5 G.

Activity 5.2

Sketch the magnetic field pattern of a steady electric current flowing in a long straight wire.

The equation gives us the magnitude of the magnetic field. But a magnetic field is a vector, so what about the direction? The magnetic field created by a current-carrying wire takes the form of concentric circles and is perpendicular to the wire. But you have to be able to figure out if those circles point clockwise or counter-clockwise. To do that, you use a right-hand rule. If you wrap your right hand's fingers around the wire with your thumb pointing in the direction of the current, then the direction in which the fingers would curl will give the direction of the magnetic field. In Figure 5.6, the blue concentric lines represent the magnetic field lines.

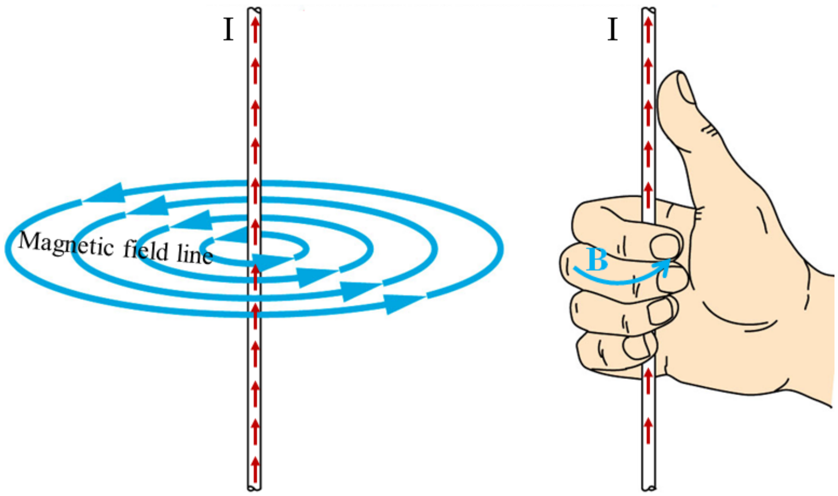


Figure 5.6 Magnetic field around a current carrying conductor

Thus, a current in a long straight wire produces a magnetic field with circular field lines as may be verified by sprinkling iron fillings on a board normal to the wire.

Generally speaking, the magnetic field produced due to a current-carrying conductor has the following characteristics:

- It encircles the conductor.
- It lies in a plane perpendicular to the conductor.
- Reversal in direction of current flow reverses the direction of the field.

Key Concept:

☞A wire carrying electric current will produce a magnetic field with closed field lines surrounding the wire.

Example 5.1

An infinitely long wire has a current of 3A passing through it. Calculate the magnetic field at a distance 2cm away from the wire.($\mu_0 = 4\pi \times 10^{-7}\ \frac{Tm}{A}$)

Solution:

For infinitely long wires, the formula for the magnetic field is $B = \frac{\mu_0 I}{2\pi r}$. The magnetic field is calculated using our given values.

$$B = \frac{\mu_0 I}{2\pi r} = \frac{(4\pi \times 10^{-7}\ \frac{Tm}{A}) \times (3A)}{2\pi \times (0.02m)} = 3 \times 10^{-5} T$$

The direction of the magnetic field can be determined using the right hand rule.

Section summary

- A magnetic field exists around any wire that carries current.
- The strength of the magnetic field is directly proportional to the magnitude of current and is inversely proportional to the distance of the point from the wire.
- The direction of the magnetic field can be obtained using the right hand rule.

Review questions

1. What will be the strength of the magnetic field if the distance from the current carrying conductor is very large?
2. What are the factors through which a magnetic field due to current carrying conductor depends on?

5.5 Magnetic force on a moving charge in a uniform magnetic field

Exercise 5.8

Students, what is the mechanism by which one magnet exerts a force on another?

By the end of this section, you should be able to:

- *describe the effects of magnetic fields on moving charges;*
- *determine the magnitude and direction of a magnetic force on a moving charge.*

The answer to exercise 5.8 is related to the fact that all magnetism is caused by current, the flow of charge. Magnetic fields exert forces on moving charges, and so they exert forces on other magnets, all of which have moving charges.

The magnitude of the magnetic force **F** on a charge q moving at a speed v in a magnetic field of strength B is given by:

$$\mathbf{F} = qvBsin\theta \qquad (5.2)$$

where θ is the angle between the directions of v and B. This force is often called the Lorentz force. In fact, this is how you define the magnetic field strength B in terms of the force on a charged particle moving in a magnetic field.

Key Concept:

☞ Any moving charged particle creates its own magnetic field and is affected when it moves through another magnetic field.

The direction of the magnetic force **F** is perpendicular to the plane formed by v and B, as determined by the right-hand rule, which is illustrated in Figure 5.7. It states that, to determine the direction of the magnetic force on a positive moving charge, you point the thumb of the right hand in the direction of **v**, the fingers in the direction of B, and a perpendicular to the palm points in the direction of **F**.

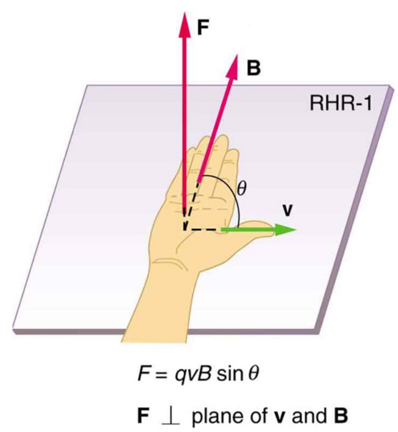


Figure 5.7 Right hand rules for a magnetic force on a moving charge.

Example 5.2

Determine the magnetic force of 50 C charged particles moving with the velocity of 3m/s in the same direction to a magnetic field of magnitude 1T.

Solution:
Given, q= 50C, v= 3m/s, B= 1T and $\theta = 0^o$. The magnitude of the force is obtained by

$$\mathbf{F} = qvBsin\theta = 50C \times 3m/s \times 1T \times sin0^o = 0$$

Section summary

- The force a magnetic field exerts on a charged particle depends on the velocity and charge of the particle and the strength of the field.
- The magnetic force is perpendicular to the plane formed by v and **B**.

Review questions

1. Is it possible for the magnetic force on a charge moving in a magnetic field to be zero?
2. An electron moves at 7.5×10^{6} m/s perpendicular to Earth's magnetic field at an altitude where the field strength is $1.0 \times 10^{-5}\,T$. Calculate the magnetic force.

5.6 Magnetic force on a current carrying conductor

Exercise 5.9

Students, in the previous section, you have learnt how a magnetic field exerts a force on moving charges. What about the magnetic field around the current carrying conductor? Does it produce a force?

By the end of this section, you should be able to:

- *state the relationship between magnetic force, current and magnetic field;*
- *calculate the magnetic force on a current carrying conductor in a magnetic field;*
- *determine the direction in which a current carrying wire experiences a force in an external magnetic field.*

The force on a current carrying wire is similar to that of a moving charge as expected since a charge carrying wire is a collection of moving charges. A current-carrying wire feels a force in the presence of a magnetic field. These forces are transmitted to the material of the conductor, and the conductor as a whole experienced a force distributed along its length. The electric motor and the moving coil galvanometer both depend on their operation on the magnetic force on conductor carrying currents.

Consider a conductor (wire) of length L and charge q which is due to electric current I. If this conductor is placed in a magnetic field of magnitude B which makes an angle with the velocity of charges (current) in the conductor, the force exerted on a single charge q is

$$\mathbf{F} = ILBsin\theta \tag{5.3}$$

The force on a current-carrying conductor is:

i) always perpendicular to the plane containing the conductor and the direction of the field in which it is placed and

ii) greatest when the conductor is at right angles to the field.

The direction of the magnetic force on a current carrying wire in a magnetic field can be found using the right hand rule: Point the fingers of your right hand in the direction of **B**. Point your thumb in the direction of the conventional current in the wire. The palm of your hand then faces or pushes in the direction of the force acting in the wire, as illustrated in Figure 5.8.

Key Concept:

☞ When a current-carrying conductor lies in a magnetic field, magnetic force is exerted on the moving charges within the conductor.

Example 5.3

A wire 25 cm long is at right angles to a 0.30T uniform magnetic field. The current through the wire is 6.0 A. What is the magnitude of the force on the wire?

Solution:

$$F = ILBsin\theta = 6A \times 0.25m \times 0.3T \times sin90^o = 0.45N$$

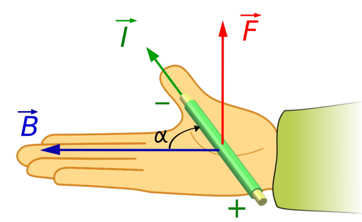


Figure 5.8 Right hand rules for a magnetic force on a current carrying conductor.

Section summary

- When a current-carrying wire is placed in a magnetic field, there exists a force on the wire that is perpendicular to the plane formed by the field and the wire.

Review questions

1. Explain how the magnetic force is produced on current carrying conductor in a magnetic field.
2. List the factors that affect the magnitude of the force experienced by a current-carrying wire.
3. Describe how to use the right-hand rule to determine the direction of a magnetic field around a straight current-carrying wire.
4. A wire of length 400 m is in a 0.20 T magnetic field. If a 2.5 N force acts on the wire, what is the value of the current in the wire?

5.7 Magnetic force between two parallel current carrying conductors

Exercise 5.10

explain how to determine the direction of the magnetic forces between two parallel conductors?

By the end of this section, you will be able to:

- *describe the effects of the magnetic force between two conductors.*
- *explain how parallel wires carrying currents can attract or repel each other.*

You have learnt that a conductor carrying a current produces magnetic field. Further, you also learnt that an external magnetic field will exert a force on a current carrying conductor.

When two wires carrying a current are placed parallel to each other, their

magnetic fields will interact, resulting in force acting between the wires. The magnitude of the force acting on each wire is equal, but the directions are opposite. This is true even if the conductors carry currents of different magnitudes.
Now, you will need to consider two cases for two parallel current carrying conductors.

1. When current in both conductors are in the same direction. you will need to draw a diagram to get a clear idea about the particular situation. Here, you have two parallel current carrying conductors, separated by a particular distance d, such that one of the conductors is carrying a current I_1 and the other is carrying I_2, which are in same direction. The direction of magnetic force is indicated in the figure and is found using the right hand rule. In this case two forces are acting towards each other. Therefore, you can say that they are attractive. Therefore you can conclude that if the current in the two

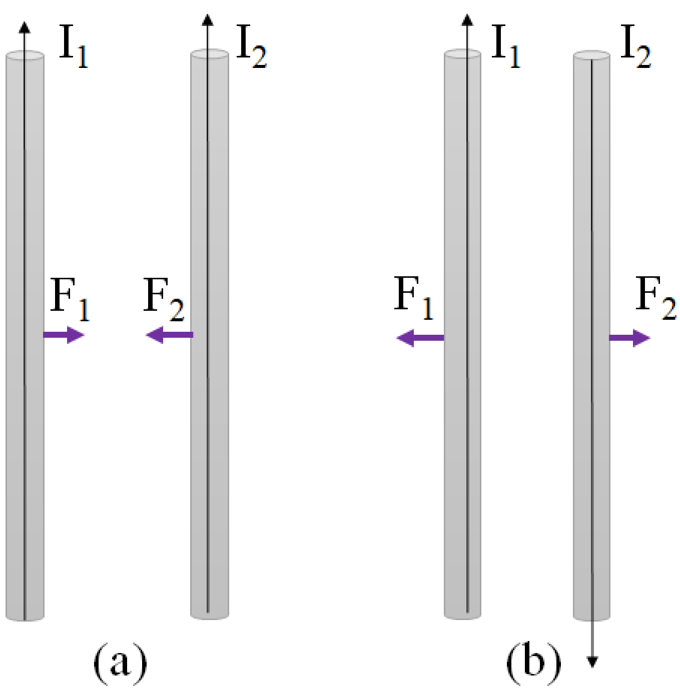


Figure 5.9 Magnetic force between two parallel conductors.

conductors placed parallel are in the same direction, the force acting on them will be experienced as attractive.

2. When current in the two conductors are in the opposite direction. You will need to draw a diagram to get a clear idea about the particular situation. Here, you have two parallel current carrying conductor, separated by a particular distance d, such that one of the conductors is carrying a current I_1 and the other is carrying I_2 , but in opposite direction. The direction of magnetic force is indicated in the figure and is found using the right hand rule. In this case two forces are acting opposite to each other. So you can say that they are repulsive. Therefore, you can conclude that if the current in the two conductors placed parallel are in the opposite direction, the force acting on them will be experienced as repulsive.

Key Concept

☞ If the two conductors carry current in the same direction, the wires attract each other. If the two wires carry currents in opposite directions, they repel each other.

Activity 5.3

Practice right hand rule and determine the direction of force in Figure 5.9.

Section summary

- The force between two parallel current carrying conductors is attractive if the currents are in the same direction, repulsive if they are in opposite directions.

Review questions

1. Two parallel wires carrying currents in the same direction attract each other. Why?
2. Is the force attractive or repulsive between the hot and neutral lines hung from power poles? Why?

5.8 Applications of magnetism

By the end of this section, you will be able to:

- *describe some applications of magnetism.*

Rare earth magnets play a significant role in a wide range of devices including simple toys, computers, credit cards, Magnetic Resonance Imaging

Figure 5.10 MRI scanning machine.

(MRI) machines, and business equipment. The following sections deal with some of the applications of magnetism.

> **Exercise 5.11**
>
> Students, what do you think are the applications of the magnetism that you learnt earlier?

Health and Medicine

Magnets are found in some commonly used medical equipment such as Magnetic Resonance Imaging machines. MRIs use powerful magnetic fields to generate a radar-like radio signal from inside the body, using the signal to create a clear, detailed picture of bones, organs and other tissue. An MRI magnet is very strong - thousands of times more powerful than common magnets. Another medical use for magnets is for treating cancer. A doctor injects a magnetically-sensitive fluid into the cancer area and uses a powerful magnet to generate heat in the body. The heat kills the cancer cells without harming healthy organs.

In the Home

Though it may not be obvious, most homes contain many magnets. Refrigerator magnets hold papers, bottle openers, and other small items to the metal refrigerator door. A pocket compass uses a magnetic needle to show which way is north. The dark magnetic strip on the backside of a credit card stores data in much the same way as a computer's hard drive does. Vacuum cleaners, blenders and washing machines all have electric motors that work by magnetic principles. You also find magnets in phones, doorbells, shower curtain weights and children's toys.

Computers and Electronics

Many computers use magnets to store data on hard drives. Magnets alter the direction of magnetic material on a hard disk in segments that then represent computer data. Later, computers read the direction of each segment of the magnetic material to "read" the data. The small speakers found in computers, televisions, and radios also use magnets; inside the speaker, a wire coil and magnet convert electronic signals into sound vibrations.

Electric Power and Other Industries

Magnets offer many benefits to the industrial world. Magnets in electric generators turn mechanical energy into electricity, while some motors use magnets to convert electricity back into mechanical work. In recycling, electrically-powered magnets in cranes grab and move large pieces of metal, some weighing thousands of pounds. Mines use magnetic sorting machines to separate useful metallic ores from crushed rock. In food processing, magnets remove small metal bits from grains and other food. Farmers use magnets to catch pieces of metal that cows eat out in the field. The cow swallows the magnet with its food; as it moves through the animal's digestive system it traps metal fragments.

Compasses and Navigation

In historic times, magnets had a supernatural thriller to them due to the fact human beings didn't virtually recognize the technology at the back of how they work. However, the early Chinese are believed to have first used them in magnetic compasses for navigation purposes. They found out magnets could direct needles and correlated with the north pole, and used that information to navigate. The early compasses have been created with lodestone because present-day magnets were no longer invented yet.

Figure 5.11 Magnetic compass used for navigation.

Lodestone comes from the mineral magnetite and is the handiest obviously-occurring magnet. Modern day day magnets, like neodymium magnets and uncommon earth magnets, are crafted from a complicated process in which some of the metals are forged together. This technique helps to cause them to stronger and extra suitable for a way they are used today. Therefore, lodestone in comparison to sturdy uncommon earth magnets is weaker.

Section summary

- Magnetism has a number of applications from health to navigation.

Review question

- List other applications of magnetism not discussed here.

Virtual Labs

On the soft copy of the book, click on the following link to perform virtual experiments on magnetism unit under the guidance of your teacher.

1. Magnet and Compass PhET Experiment.
2. Generator PhET Experiment.
3. Magnets and Electromagnets PhET Experiment.

End of unit summary

- Every magnet has two poles: north and south. These are inseparable. Like poles repel each other and unlike poles attract each other.
- The Earth also has a magnetic field.
- A compass needle can be used to find the magnetic north pole and help us find our direction.
- A current-carrying conductor produces a magnetic field around it. The right-hand rule is used to determine the direction of the magnetic field.
- When a current carrying conductor is placed in the magnetic field, it experiences a magnetic force.
- The magnitude of magnetic force on a moving charge q in a magnetic field B is given by $\mathbf{F} = qvBsin\theta$, where θ is the angle between the directions of v and B.
- The force between conductors is attractive when the currents flow in the same direction in the two conductors. When, the two conductors carrying currents in opposite direction, they repel each other.

End of unit questions and problems

1. What is a magnet?
2. How do magnets and their properties influence everyday life?
3. Describe what is meant by the term magnetic field.
4. Much like the static Electric force, there is a magnetic force between two magnets. How are the magnetic and electric forces similar? How are they different?
5. What happens to the poles of a magnet if it is cut into pieces?
6. What happens when like magnetic poles are brought close together?
7. What happens when unlike magnetic poles are brought close together?
8. Draw the shape of the magnetic field around a bar magnet.
9. Explain how a compass needle indicates the direction of a magnetic field.
10. Compare the magnetic field of the Earth to the magnetic field of a bar magnet.
11. Explain the difference between the geographical North Pole and the magnetic north pole of the Earth.
12. Draw magnetic field lines for two similar magnetic poles and two dissimilar magnetic poles.
13. A wire 0.50 m long carrying a current of 8.0 A is at right angles to a uniform magnetic field. The force on the wire is 0.40 N. What is the strength of the magnetic field?

14. The current through a wire 0.80 m long is 5.0 A. The wire is perpendicular to a 0.60 T magnetic field. What is the magnitude of the force on the wire?

15. An electric wire in the wall of a building carries a current of 25 A vertically upward. What is the magnetic field at a distance of 10 cm from the wire?

16. Determine the magnitude and direction of magnetic force on an electron traveling $8.75 \times 10^5\, m/s$ horizontally to the east in a vertically upward of magnetic field 0.75T.

Unit 6

Electromagnetic Waves and Geometrical Optics

Introduction

Light is one form of electromagnetic wave. Light lets us see things and is responsible for our visual contact with our immediate environment. It enables us to admire and adore various beautiful manifestations of nature. You can use light rays to model mirrors, lenses, telescopes, microscopes, and prisms. The study of how light interacts with materials is **optics**. When dealing with light rays, you are usually interested in the shape of a material and the angles at which light rays hit it. This kind of optics is referred to as geometrical optics. This unit deals with Electromagnetic waves and geometrical optics.

Activity 6.1

Students, do you remember the definition of wave that you learnt in grade 9? Try to discuss in group and tell your definition of wave to your teacher.

Exercise 6.1

What are the different types of waves?

Key Concept:

☞ EM is a wave that consists of oscillating electric and magnetic fields, which radiate outward from the source at the speed of light.

☞ EM waves can travel through empty space.

By the end of this unit, you should be able to:

- *understand the concept of Electromagnetic waves;*
- *understand the properties and transmission of light in various media and their applications;*
- *investigate the properties of light through experimentation and illustration using diagrams and optical instruments;*
- *predict the behavior of light through the use of ray diagrams;*
- *appreciate the contributions of optics in our day to day life.*

6.1 Electromagnetic (EM) waves

By the end of this section, you should be able to:

- *describe the propagation of EM waves;*
- *state sources of EM waves.*

A wave transfers energy from one place to another without transferring matter. Does your definition of a wave agree with the following proper meaning of a wave? If so, that is good.

How do waves transfer energy? Waves, such as water waves and sound waves, transfer energy by making particles of matter move. The energy is passed along from particle to particle as they collide with their neighbors.

Depending on their medium of propagation, waves are categorized into mechanical waves and EM waves.

- Mechanical waves are the types of waves that use matter to transfer energy. However, mechanical waves can't travel in almost empty space between the Earth and the Sun.

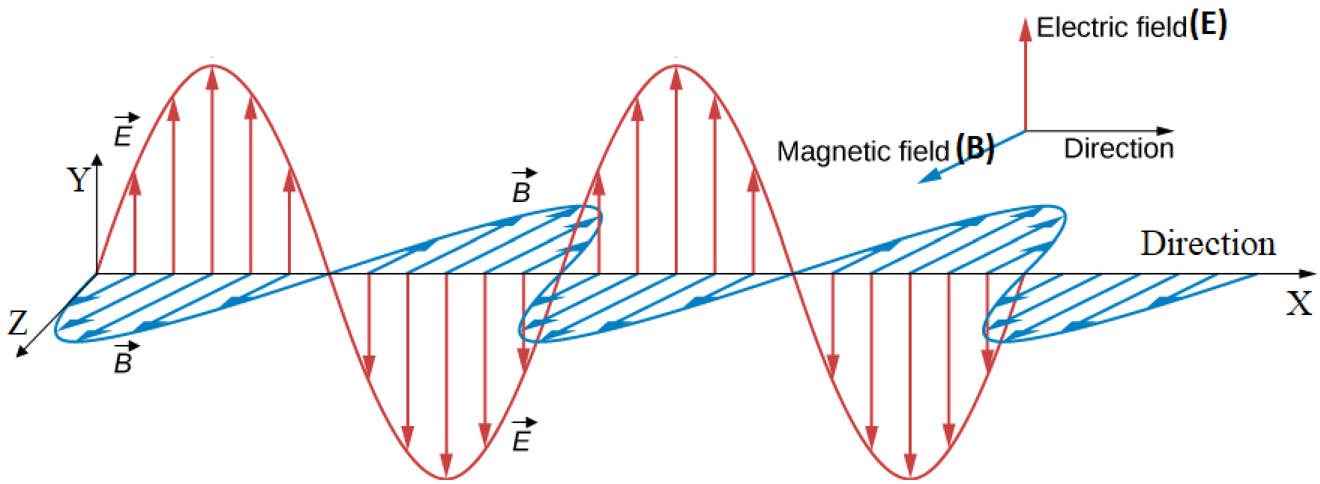


Figure 6.1 Electric field and magnetic field in an EM wave.

- An EM wave is a wave that can travel through empty space or through matter. How is such a wave produced? EM waves are produced by charged particles, such as electrons, that move back and forth or vibrate. It is thus made of electric and magnetic fields as shown in Figure 6.1. Both parts are called fields and vibrate at right angles to the wave motion.

As you learnt in grade 9, all EM waves are transverse waves. Did you recall the differences between transverse and longitudinal waves? For transverse waves, the direction of oscillation is perpendicular to the direction of propagation of waves. On the other hand, for a longitudinal wave, the direction of oscillation is parallel to the direction of propagation of the wave.

Recall that a wave on a rope is a transverse wave that causes the rope to move at right angles to the direction the wave is traveling. An EM wave traveling through matter also can cause matter to move at right angles to the direction the wave is moving.

Like all waves, an EM wave has a frequency and a wavelength. The number of times the electric and magnetic parts vibrate each second is the frequency of the wave. The wavelength is the distance between the crests or troughs of the vibrating electric or magnetic parts.

Radiant Energy from the Sun

The Sun emits EM waves that travel through space and reach Earth. The energy carried by EM waves is called radiant energy. Almost 92 % of the radiant energy that reaches Earth from the Sun is carried by infrared and visible light waves. Infrared waves make you feel warm when you sit in sunlight, and visible light waves enable you to see. A small amount of the radiant energy that reaches Earth is carried by ultraviolet waves. These are the waves that can cause sunburn if you are exposed to sunlight for too long.

Section summary

- EM waves are transverse waves made of vibrating electric and magnetic fields.

Review questions

1. Explain how an EM wave propagates.
2. Do EM waves need a medium to travel through?
3. Describe the properties of EM waves.

6.2 EM Spectrum

Exercise 6.2

Students, what do you know about the EM spectrum?

By the end of this section, you should be able to:

- *describe what an EM spectrum is;*
- *describe and explain the differences and similarities of the EM spectrum;*
- *describe the uses and dangers of EM spectrum.*

As shown in Figure 6.2, an EM spectrum is the complete range of EM wave

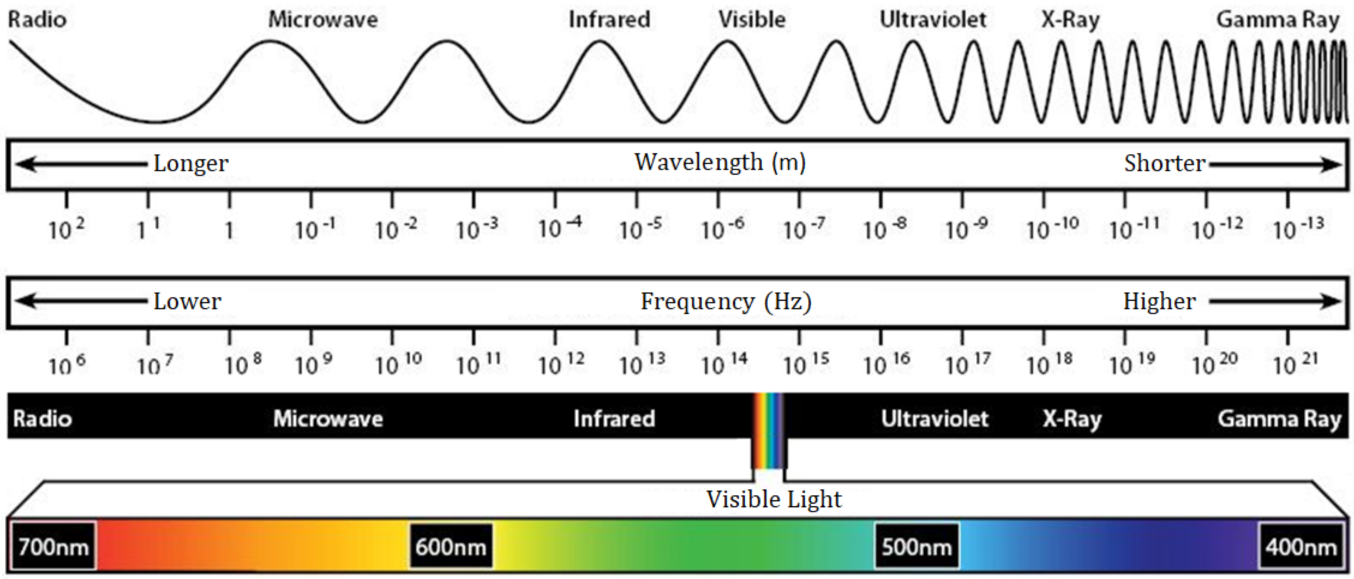


Figure 6.2 The EM spectrum.

frequencies and wavelengths. At one end of the spectrum, the waves have low frequency, long wavelength, and low energy. At the other end of the spectrum, the waves have high frequency, short wavelength, and high energy. All of the waves, from radio waves to visible light to gamma rays, are the same kind of waves. They differ from each other only by their frequencies, wavelengths, and energy.

Key Concept

☞ The EM spectrum consists of the following types of radiation: radio waves, microwaves, infrared, visible, ultraviolet, X-rays, gamma-rays. Gamma-rays have the highest energy and are the most penetrating, while radio waves have the lowest energy and are the least penetrating.

You briefly describe these different types of EM waves, in order of decreasing wavelengths.

Radio waves

Radio waves are made by various types of transmitter, depending on the wavelength. They are also given off by stars, sparks and lightning, which is why you hear interference on your radio in a thunderstorm. They have the lowest frequencies in the EM spectrum ranging from 500 kHz to about 1000 MHz and have a wavelength from around 1m to thousands of meters long.

They are used mainly for communications purposes like police radio communications, military aircraft radios and television transmissions. On the other hand, large doses of radio waves are believed to cause cancer, leukaemia and other disorders.

Microwaves

Microwaves are basically extremely high frequency radio waves, and are made by various types of transmitter. In a mobile phone, they're made by a transmitter chip and an antenna; in a microwave oven, they're made by a "magnetron". Their wavelength is usually a couple of centimetres. Stars also give off microwaves.

Microwaves cause water and fat molecules to vibrate, which makes the substances hot. Thus, you can use microwaves to cook many types of food. Mobile phones use microwaves, as they can be generated by a small antenna. They are also used by traffic speed cameras, and for radar, which is used by aircraft, ships and weather forecasters.

Prolonged exposure to microwaves is known to cause "cataracts" in your eyes, which is a clouding of the cornea. So don't make a habit of pressing your face against the microwave oven door to see if your food's ready. Microwaves from mobile phones can affect parts of your brain as you are holding the transmitter right by your head. The current advice is to keep calls short. People who work on aircraft carrier decks wear special suits which reflect microwaves, to avoid being "cooked" by the powerful radar units in modern military planes.

Infrared waves

Infrared waves are just below visible red light in the EM spectrum. You probably think of Infra-red waves as heat, because they're given off by hot objects, and you can feel them as warmth on your skin. Infra-Red waves are also given off by stars, lamps, flames and anything else that's warm including you.

Infrared waves are used for many tasks, for example, remote controls for TVs and video recorders, and physiotherapists use heat lamps to help heal sports injuries. Infrared waves are used to see objects in the dark. Police helicopters track criminals at night, using cameras which can see in the dark. Night sights for weapons sometimes use a sensitive infrared detector. Weather forecasters use satellite pictures to see what's heading our way. Some of the images they use are taken using infrared cameras cameras, because they show cloud and rain patterns more clearly.

The danger from too much infrared radiation is very simple: it makes you hot.

Visible Light

Our eyes can detect only a tiny part of the EM spectrum, called visible light. It runs from about 4×10^{14} Hz to about 7×10^{14} Hz or a wavelength range of about 700 - 400 nm. Visible light emitted or reflected from objects around us provides us information about the world. Our eyes are sensitive to this

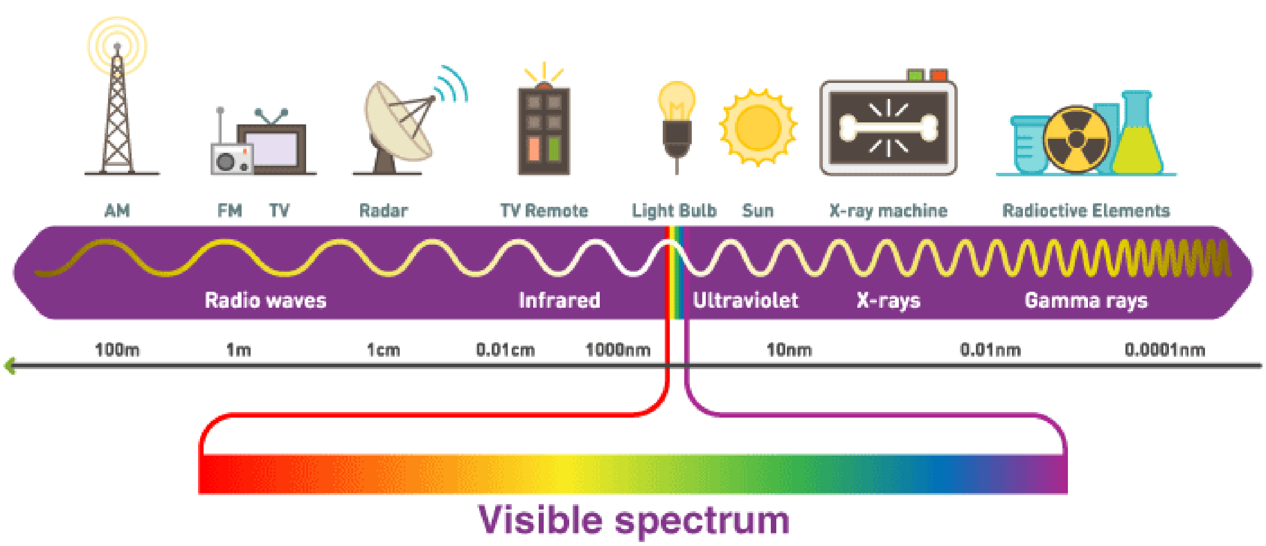


Figure 6.3 Visible spectrum.

range of wavelengths. The color of the visible spectrum was discussed in detail in section 6.8 of this unit.
You use light to see things. As the Sun sends so much light towards our planet, we've evolved to make use of those particular wavelengths in order to sense our environment.

Too much light can damage the retina in your eye. This can happen when you look at something very bright, such as the Sun. Although the damage can heal, if it's is too bad it'll be permanent.

Ultraviolet rays

Ultraviolet (UV) rays covers wavelengths ranging from about 4×10^{-7} m (400 nm) down to 6×10^{-10} m (0.6 nm). UV radiation is produced by special lamps and very hot bodies. The sun is also an important source of UV light. But fortunately, most of it is absorbed in the ozone layer in the atmosphere at an altitude of about 40 to 50 km.

Uses for UV light include getting a sun tan, detecting forged bank notes in shops, and hardening some types of dental filling. You also see UV lamps in discos, where they make your clothes glow. When you mark your possessions with a security marker pen, the ink is invisible unless you shine a UV lamp at it. UV rays can be used to kill microbes. Hospitals use UV lamps to sterilize surgical equipment and the air in operating theaters. Food and drug companies also use UV lamps to sterilize their products. Suitable doses of Ultraviolet rays cause the body to produce vitamin D, and this is used by doctors to treat vitamin D deficiency and some skin disorders.

Large doses of UV can damage the retinas in your eyes, so it's important to check that your sunglasses will block UV light. If your sunglasses don't block UV, you will actually get more ultra-violet light on your retinas than if you didn't wear them. Large doses of UV cause sunburn and even skin cancer. Fortunately, the ozone layer in the Earth's atmosphere screens us from most of the UV given off by the Sun.

X-rays

X-rays are very high frequency waves, and carry a lot of energy. They will pass through most substances, and this makes them useful in medicine and industry to see inside things. X-rays are given off by stars, and strongly by some types of nebula. When you use X-rays, you make them by firing a beam of electrons at a "target". If you fire the electrons with enough energy, X-rays will be produced.

X-rays are used by doctors to see the inside parts of a patient. X- Rays are also used in airport security checks, to see inside your luggage. They are also used by astronomers - many objects in the universe emit X-rays, which you can detect using suitable radio telescopes.

X-Rays can cause cell damage and cancers. This is why Radiographers in hospitals stand behind a shield when they X-ray their patients.

Gamma rays

Gamma rays are given off by stars, and by some radioactive substances. They are extremely high frequency waves, and carry a large amount of energy. They pass through most materials, and are quite difficult to stop - you need lead or concrete in order to block them out.

Because Gamma rays can kill living cells, they are used to kill cancer cells without having to resort to difficult surgery. This is called "Radiotherapy", and works because cancer cells can't repair themselves like healthy cells can when damaged by gamma rays. In industry, radioactive "tracer" substances can be put into pipes and machinery, then you can detect where the substances go. This is basically the same use as in medicine. Gamma rays kill microbes, and are used to sterilize food so that it will keep fresh for longer. This is known as "irradiated" food. Gamma rays are also used to sterilize medical equipment.

Gamma rays cause cell damage and can cause a variety of cancers. They cause mutations in growing tissues, so unborn babies are especially vulnerable.

Section summary

- The EM spectrum is made up of a broad range of frequencies of EM radiation.
- Each type of the EM spectrum have their own benefits and side effects.

Review questions

1. Mention one source of EM waves.
2. Arrange the following types of EM radiation in order of increasing frequency: infrared, X-rays, ultraviolet, visible, gamma.
3. Discuss on the use of each type of EM spectrum.
4. Describe the dangers of each type of EM spectrum.

Exercise 6.3

Does light require a medium to travel?

Key Concept

☞ As light is an EM wave, it can travel in a vacuum as well as through materials such as air, water, and glass.

6.3 Light as a wave

By the end of this section, you should be able to:

- *illustrate the propagation of light;*
- *describe the medium of propagation of light;*
- *describe the speed of light waves.*

In the previous section, you learnt that light is a form of EM wave. Light is, thus, another type of wave that carries energy. The light that humans can see a is called 'visible light'.

Medium of propagation of light

Like other waves, light waves can travel through matter. But light waves are different from water waves and sound waves. This is because light is an EM wave and it can pass through a vacuum. That is why you can see light from the moon, distant stars, and galaxies.

Exercise 6.4

Students, how do you know that light travels through a vacuum?

Speed of light

An EM wave, including visible light, is special because, no matter what the frequency, it all moves at a constant velocity (in vacuum) which is known as the speed of light.

The speed of light has the symbol c and is:

$$c = 2.99792458 \times 10^8\ m/s \approx 3.00 \times 10^8\ m/s \tag{6.1}$$

In reality, nothing travels faster than the speed of light. Thus, in empty space, light travels at a speed of about 300,000 km/s. Light travels so fast that light emitted from the Sun travels 150 million km to Earth in only about eight and a half minutes. Even though light travels incredibly fast, stars other than the Sun are so far away that it takes years for the light they emit to reach Earth.

However, when light travels in matter, it interacts with the atoms and molecules in the material and slows down. As a result, light travels fastest in empty space, and travels slowest in solids. In glass, for example, light travels about 197,000 km/s.

Key Concept

☞ EM waves in general and light in particular travel with a speed of $3.00 \times 10^8\ m/s$ in a vacuum.

Because all EM waves in a vacuum have the same speed of light, c, it follows that f and λ are related as follows:

$$c = f\lambda \tag{6.2}$$

where c is speed of light in vacuum, λ is wavelength of the EM wave and f is the frequency of the EM wave. Thus, as the frequency of an EM wave increases, its wavelength decreases.

Example 6.1

Find the frequency of red light, with a wavelength of 700 nm.

Solution:
You can obtain the frequency by rearranging $c = f\lambda$ to yield

$f = c/\lambda = (3\times10^{8}\ \text{m/s})/(700\times10^{-9}\ \text{m}) = 4.29\times10^{14}$ Hz.

Example 6.2

An FM radio station broadcasts electromagnetic radiation at a frequency of 103.4 MHz. Calculate the wavelength of this radiation.

Solution:
Since $c = f\lambda$,

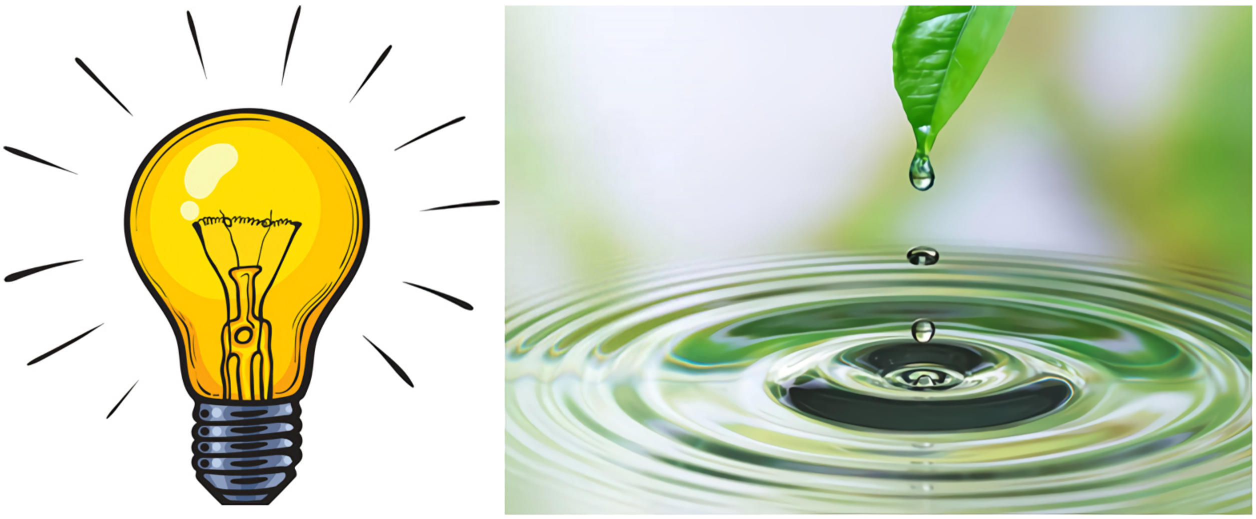
$\lambda = c/f = (3\times10^{8}\ \text{m/s})/(103.4\times10^{6}\text{Hz}) = 2.9\text{m}$

Exercise 6.5

Students, if you drop a rock on the smooth surface of a pond, what would happen?

Propagation of light

A source of light, such as a light bulb, gives off light rays that travel away from the light source in all directions, just as the rock hitting the pond causes waves to form in the water as in Figure 6.4 (b). But while the water waves spread out only on the surface of the pond, light waves spread out in all directions from the light source.



(a) (b)

Figure 6.4 (a) Light moves away in all directions from a light source, (b) Ripples spread out on the surface of water.

To understand about the direction of propagation of a wave, look at light entering a room through a small opening in a wall. You will note the motion of dust particles, which essentially provide simple evidence that light travels in a straight line. An arrow headed straight line represents the direction of propagation of light and is called a ray.

Exercise 6.6

Students, how is light propagated?

Light rays are drawn using straight lines and arrow heads and are used to show the path that light travels. A collection of rays is called a beam. Light rays are, thus, narrow beam of light that travel in a straight line. You can use the idea of a light ray to indicate the direction that light travels. A ray diagram is a drawing that shows the path of light rays. In Figure 6.5, the light rays from the object enter the eye and the eye sees the object.

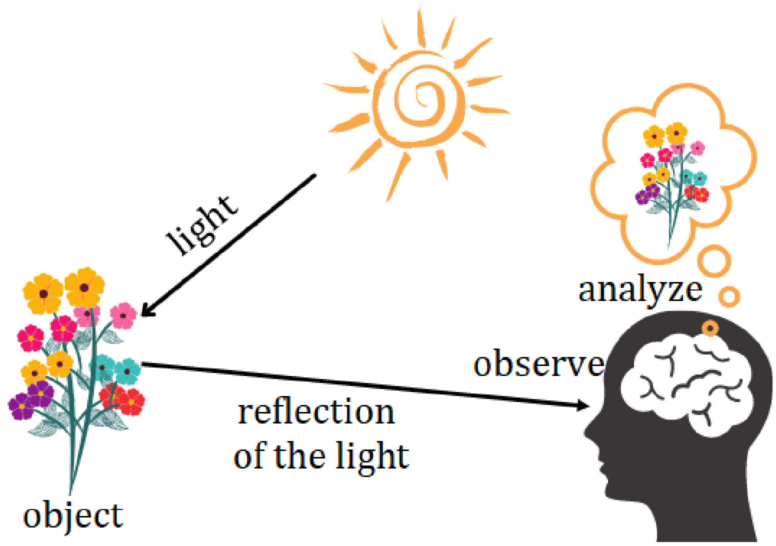


Figure 6.5 Light rays from the object to the eyes.

The most important thing to remember is that you can only see an object when light from the object enters our eyes. The object must be a source of light (for example, a light bulb) or else it must reflect light from a source (for example, the moon), and the reflected light enters our eyes.

Section summary

- Light travels in all directions from its source, in straight lines with arrows to show the path of light.
- Light rays are not real. They are merely used to show the path that light travels.
- Like all forms of EM waves, light can travel through empty space, as well as through matter.
- In vacuum, light travels with a speed of $3.00 \times 10^8\ m/s$.

Review questions

1. Are light rays real? Explain.

2. Give evidence to support the statement: "Light travels in straight lines". Draw a ray diagram to prove this.

3. Explain how an EM wave propagates.

4. Do EM waves need a medium to travel through?

5. What is the speed of light? What symbol is used to refer to the speed of light? Does the speed of light change?

6. Calculate the frequency of an EM wave with a wavelength of 400 nm.

6.4 Laws of reflection & refraction

By the end of this section, you should be able to:

- *state laws of reflection and refraction;*
- *solve problems based on the laws of reflection and refraction;*
- *identify area of application of these laws in your locality and/or elsewhere.*

Exercise 6.7

Dear students, when you smile into a mirror, you see your own face smiling back at you. Do you know the reason behind it?

Reflection of light

When you look in a mirror, you see your image because of the reflection of light rays on the mirror. The incoming light ray is called the incident ray. The light ray moving away from the surface is the reflected ray. The most important characteristic of these rays is their angles in relation to the reflecting surface. These angles are measured with respect to the normal of the surface. The normal is an imaginary line perpendicular to the surface. The angle of incidence, θ_i, is measured between the incident ray and the surface normal. The angle of reflection, θ_r, is measured between the reflected ray and the surface normal. This is shown in Figure 6.6.

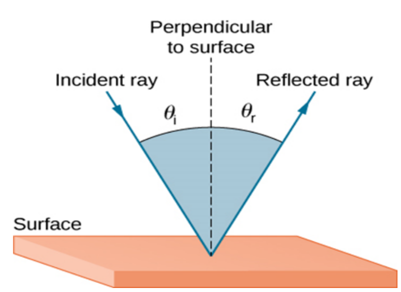


Figure 6.6 A light ray strikes a surface and is reflected.

When a light ray strikes a surface and is reflected, as in Figure 6.6, the

Key Concept

☞ Reflection is the change in direction of light rays at a surface that causes it to move away from the surface.

reflected ray obeys the law of reflection. According to the law of reflection,

i. $\theta_i = \theta_r$ and

ii. The incident ray, the normal to the mirror at the point of incidence and the reflected ray, all lie in the same plane.

These laws of reflection are applicable to all types of smooth, shiny surfaces like calm water, glass, and even polished metal.

Specular Reflection and Diffuse Reflection

The reflection of light from a smooth shiny surface, as in Figure 6.7 (a), is referred to as specular reflection. Notice that all the reflected light moves in the same direction. In contrast, if a surface is rough, as in Figure 6.7 (b), the reflected light is sent out in a variety of directions, giving rise to diffuse reflection. For example, when the surface of a road is wet, the water creates a smooth surface, and headlights reflecting from the road undergo specular reflection.

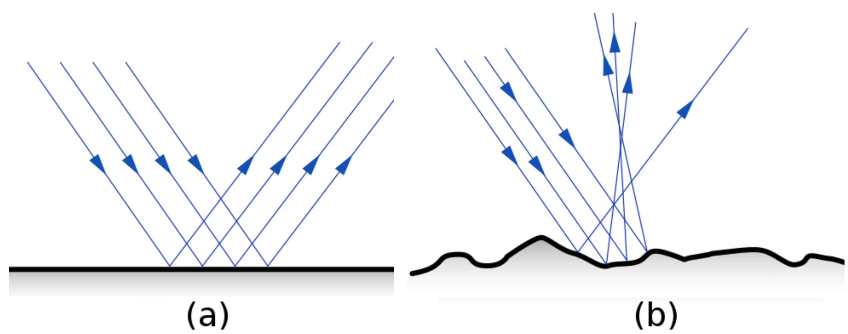


Figure 6.7 Specular and diffuse reflection.

Exercise 6.8

The law of reflection is true for any surface. Does this mean that when parallel rays approach a surface, the reflected rays will also be parallel?

Refraction of Light

Students, in the first part of this section, you studied light reflecting off various surfaces. Light seems to travel along straight-line paths in a transparent medium. In this subsection, you will learn about the refraction of light. Let us start our discussion by considering the case of the apparent displacement of a pencil partly immersed in water using the following activity.

Figure 6.8 Refraction of light.

Activity 6.2

1. Fill a large, opaque drinking glass or cup with water.
2. Place a pencil in the water at an angle.
3. Looking directly down into the cup from above, and observe the straw where it touches the water as shown in Figure 6.8.
4. Placing yourself so that the pencil angles to your left or right, slowly back away about 1 m. Observe the pencil as it appears above, at and below the surface of the water.
5. Describe the pencil's appearance from above.
6. Compare the pencil's appearance above and below the water's surface in step 4.

Students, have you noticed how the light reaching you from the portion of the pencil inside water seems to come from a different direction, compared to the part above water. This makes the pencil appear to be displaced at the interface. These observations indicate that light does not travel in the same direction in all media.

Exercise 6.9

What happens when light passes through a medium? Does it still move along a straight line path or change its direction?

Like all waves, the speed of light is dependent on the medium in which it is travelling. When light moves from one medium into another (for example, from air to glass), the direction of propagation of light in the second medium changes. This phenomenon is known as refraction of light. Refraction is therefore the bending of light as it moves from one optical medium to another.

Glass, water, ice, diamonds, and quartz are all examples of transparent media through which light can pass. The speed of light in each of these materials is different. The speed of light in water, for instance, is less than the speed of light in air; the speed of light in glass is less than the speed of light in water. When light moves from a material in which its speed is higher to a material in which its speed is lower, such as from air to glass, the ray is bent toward the normal, as shown in Figure 6.9 (a). If the ray moves from a material in which its speed is lower to one in which its speed is higher, as in Figure 6.9 (b), the ray is bent away from the normal. If the incident ray of light is parallel to the normal, then no refraction (bending) occurs in either case.

Key Concept

☞ Refraction is the bending of light as it travels from one medium to another.

☞ Refraction occurs when light's velocity changes.

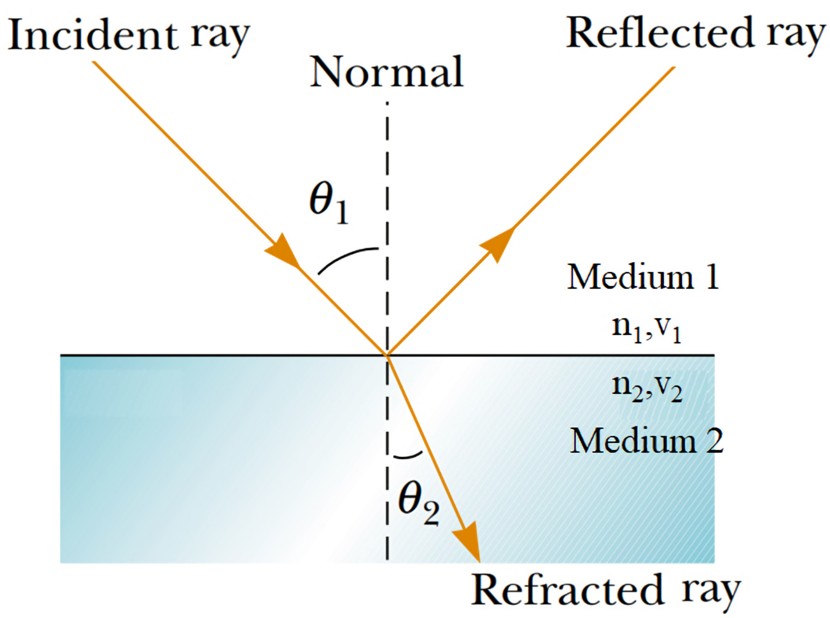


Figure 6.9 (a) When light moves from air to glass the refracted ray is bent toward the normal, (b) whereas the path of the light ray moving from glass into air is bent away from the normal.

Exercise 6.10

What causes light to bend?

The following are the laws of refraction of light.

- The incident ray, the refracted ray and the normal to the interface of two transparent media at the point of incidence, all lie in the same plane.

- The ratio of the sine of the angle of incidence and sine of the angle of refraction is constant.This law is also known as Snell's law of refraction. If θ_1 is the angle of incidence and θ_2 is the angle of refraction as shown in Figure 6.10, then,

$$\frac{sin\theta_1}{sin\theta_2} = constant \tag{6.3}$$

This constant value is called the refractive index of the second medium with respect to the first. Let us study about refractive index in some detail.

The Refractive Index

Exercise 6.11

Why does light travel faster through air than water?

The speed of light and the degree of bending of the light depends on the refractive index of material through which the light passes. You can think of the refractive index as a measure of how difficult it is for light to get through a material.

Consider a ray of light traveling from medium 1 into medium 2, as shown in Figure 6.10. Let v_1 be the speed of light in medium 1 and v_2 be the speed of light in medium 2. The refractive index of medium 2 with respect to medium 1 is given by the ratio of the speed of light in medium 1 and the speed of light in medium 2. This is usually represented by the symbol n_{21} which is expressed in an equation form as.

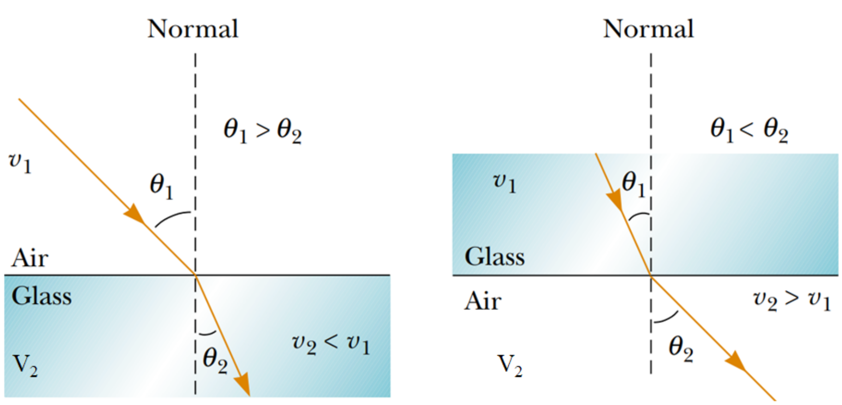


Figure 6.10 Ray showing the refraction of light between different medium..

$$n_{21} = \frac{\text{speed of light in medium 1}}{\text{speed of light in medium 2}} = \frac{v_1}{v_2} \tag{6.4}$$

By the same argument, the refractive index of medium 1 with respect to medium 2 is represented as n_{12}. It is given by

$$n_{12} = \frac{\text{speed of light in medium 2}}{\text{speed of light in medium 1}} = \frac{v_2}{v_1} \tag{6.5}$$

If medium 1 is vacuum or air, then the refractive index of medium 2 is considered with respect to vacuum. This is called the absolute refractive index of the medium. It is simply represented as n. If c is the speed of light in vacuum and v is the speed of light in the medium, then, the refractive index of the medium n is given by:

Key Concept

☞ The absolute refractive index of a material is the ratio of the speed of light in a vacuum to its speed in the medium.

$$n = \frac{\text{speed of light in vacuum}}{\text{speed of light in medium}} = \frac{c}{v} \tag{6.6}$$

The refractive index of different materials is given in table 6.1. From the table you can see that the refractive index of water, $n_w = 1.33$. This means that the ratio of the speed of light in air and the speed of light in water is equal to 1.33.

Table 6.1 Absolute refractive index of some material medium

Material medium	Refractive index	Material medium	Refractive index
Air	1.0003	Canada Balsam	1.53
Ice	1.31		
Water	1.33	Rock salt	1.54
Alcohol	1.36		
Kerosene	1.44	Carbon disulphide	1.63
Fused quartz	1.46	Dense flint glass	1.65
Turpentine oil	1.47	Ruby	1.71
Benzene	1.5	Sapphire	1.77
Crown glass	1.52	Diamond	2.42

In Figure 6.10 above, if a light ray is incident on the surface between these materials with an angle of incidence θ_1, the refracted ray passes through the second medium with an angle of refraction θ_2.

Snell's Law that was discussed above can be written as:

$$n_1 sin\theta_1 = n_2 sin\theta_2 \quad (6.7)$$

where n_1=refractive index of material 1, n_2 =refractive index of material 2, θ_1 =angle of incidence and θ_2 =angle of refraction.

Remember that angles of incidence and refraction are measured from the normal, which is an imaginary line perpendicular to the surface.

Example 6.3

If a light ray with an angle of incidence of 35^o passes from water to air, find the angle of refraction using Snell's Law.

Solution:

As depicted in Table 6.1, the refractive index is 1.33 for water and about 1 for air. You know the angle of incidence, so you are ready to use Snell's Law.

$$n_1 sin\theta_1 = n_2 sin\theta_2$$

$$1.33 \times sin35^o = 1 \times sin\theta_2$$

$$sin\theta_2 = 1.33 \times 0.57 \qquad = 0.763$$

$$\therefore \theta_2 = sin^{-1}(0.763) = 49.7^o$$

Since the light ray passes from a medium of high refractive index to a medium of low refractive index, the light ray is bent away from the normal.

Exercise 6.12

Students, what happens to the refracted ray when the angle of incidence is increased?

Total Internal reflection

When light passes from a dense medium (larger index of refraction) to a less dense (smaller index of refraction) medium, for example, from water to air, the refracted ray bends away from the normal, as in Figure 6.8 (a). As the angle of incidence increases, the angle of refraction also increases. When the angle of incidence reaches a certain value, called the critical angle θ_c, the angle of refraction is 90^o. Then the refracted ray points along the surface as shown in Figure 6.11 (b). When the angle of incidence exceeds the critical angle, as in Figure 6.11 (c), there is no refracted light. All the incident light is reflected back into the medium from which it came, a phenomenon called total internal reflection.

For total internal reflection to take place, the following two conditions must be satisfied.

- Light must travel from an optically denser medium (i.e., a medium having a high refractive index) to an optically rarer medium (i.e., a medium having a lower refractive index). It does not occur when light propagates from a less denser to a denser medium, for example, from air to water.

- The angle of incidence in the denser medium must be greater than the critical angle.

Now you shall learn how to derive the value of the critical angle for two given media. The process is fairly simple and involves just the use of Snell's Law that you have already studied. To recap, Snell's Law states:

$$n_1 sin\theta_1 = n_2 sin\theta_2 \tag{6.8}$$

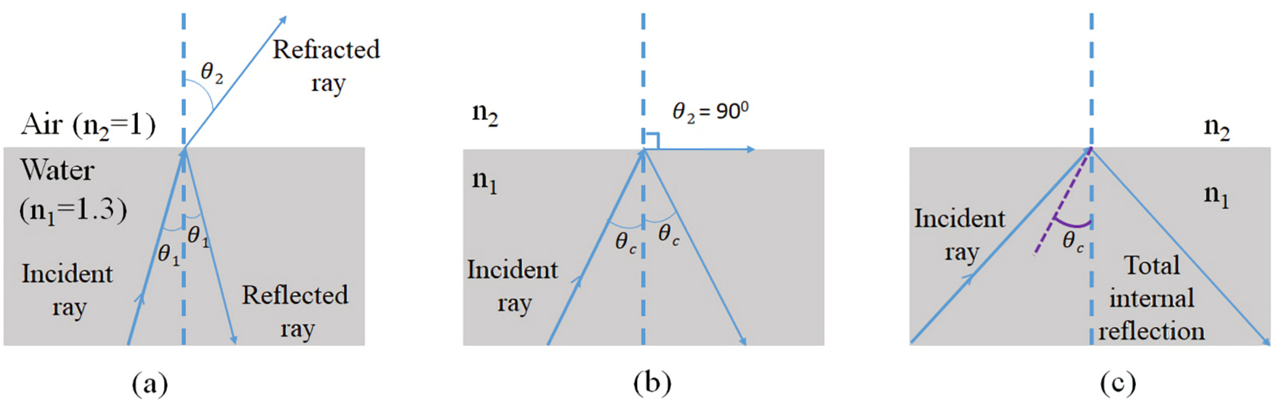


Figure 6.11 The critical angle and total internal reflection.

For total internal reflection, you know that the angle of incidence is the critical angle (i.e., $\theta_1 = \theta_c$). You also know that the angle of refraction at the critical angle is 90^o(i.e., $\theta_c = 90^o$). You can then write Snell's law as:

$$n_1 sin\theta_c = n_2 sin 90^o$$

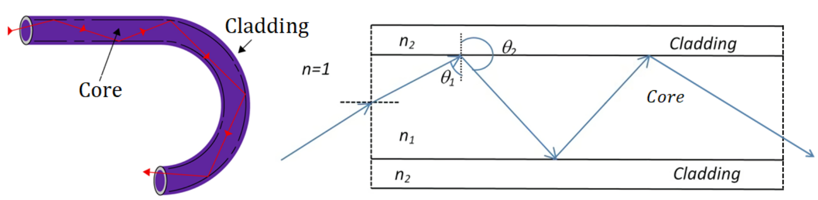
Solving for θ_c gives:

$$sin\theta_c = \frac{n_2}{n_1}(1)$$

$$\therefore \ \theta_c = sin^{-1}\left(\frac{n_2}{n_1}\right)$$

Total internal reflection is a powerful tool since it can be used to confine light. One of the most common applications of total internal reflection is in fibre optics. Optical fibres are usually thinner than a human hair. The construction of a single optical fibre is shown in Figure 6.12. When light is incident on one end of the fibre at a small angle, it undergoes multiple total internal reflections along the fibre. The light finally emerges with undiminished intensity at the other end. Even if the fibre is bent, this process is not affected.

Optical fibres are most common in telecommunications, because information can be transported over long distances, with minimal loss of data. The minimized loss of data gives optical fibres an advantage over conventional cables. Data is transmitted from one end of the fibre to another in the form of laser pulses.



(a) A light in glass fiber pipe

(b) Light emerging from a bundle of glass fibers.

Figure 6.12 Light is guided along a fiber by multiple internal reflections.

Optic fibres are also used in medicine in endoscopes. The main part of an endoscope is the optical fibre. Endoscopes are used to examine the inside of a patient's stomach, by inserting the endoscope down the patient's throat. Other medical applications of optical fibers' are in neurosurgery and study of bronchi.

Example 6.4

A particular glass has an index of refraction of n= 1.52. What is the critical angle for total internal reflection for light leaving the glass and entering air, for which n =1.00?

Solution:
You know that

$$\theta_c = sin^{-1}\left(\frac{n_2}{n_1}\right) = sin^{-1}\left(\frac{1}{1.52}\right) = 42^o$$

The Dispersion of Light: Prisms and Rainbows

Exercise 6.13

How could the white light of the sun give us various colors of the rainbow?

Before discussing about the dispersion of light, let us first go back to the refraction of light through a prism. The inclined refracting surfaces of a glass prism show exciting phenomenon. Let us find it out through through the following activity.

Activity 6.3

☞ Take a thick sheet of cardboard and make a small hole or narrow slit in its middle.

☞ Allow sunlight to fall on the narrow slit. This gives a narrow beam of white light.

☞ Now, take a glass prism and allow the light from the slit to fall on one of its faces as shown in Figure 6.13.

☞ Turn the prism slowly until the light that comes out of it appears on a nearby screen.

☞ What do you observe? You will find a beautiful band of colors. Why does this happen?

Key Concept

☞The prism can split the incident white light into a band of colors.

Notice the colors that appear at the two ends of the color band. What is the sequence of colors that you see on the screen? The various colors seen are Violet, Indigo, Blue, Green, Yellow, Orange and Red, as shown in Figure 6.13. The acronym VIBGYOR will help you to remember the sequence of colors.

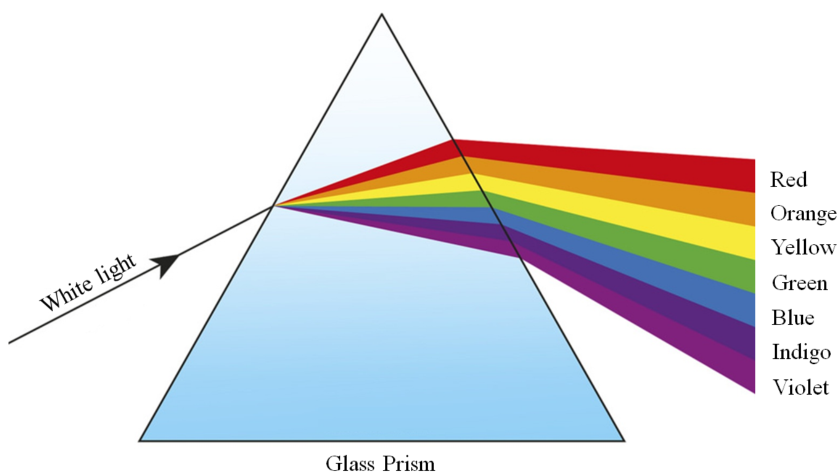


Figure 6.13 Dispersion of white light by a glass prism.

The band of the colored components of a light beam is called its spectrum. The splitting of light into its component colors is called dispersion. You have seen that white light is dispersed into its seven-color components by a prism. Why do you get these colors? Different colors of light bend through different angles with respect to the incident ray, as they pass

Figure 6.14 Rainbow in the sky.

through a prism. The red light refracts the least while the violet refracts the most. Thus, the rays of each color emerge along different paths and thus become distinct. It is the band of distinct colors that you see in a spectrum.

The rainbow is a familiar example of dispersion, in this case the dispersion of sunlight. A rainbow is a natural spectrum appearing in the sky after a rain shower (Figure 6.14). It is caused by dispersion of sunlight by tiny water droplets, present in the atmosphere. A rainbow is always formed in a direction opposite to that of the Sun. The water droplets act like small prisms. They refract and disperse the incident sunlight, then reflect it internally, and finally refract it again when it comes out of the raindrop. Due to the dispersion of light and internal reflection, different colors reach the observer's eye.

Section summary

1. Light rays reflect off surfaces. The incident ray shines in on the surface and the reflected ray is the one that bounces off the surface. The surface normal is the perpendicular line to the surface where the light strikes the surface.

2. The angle of incidence is the angle between the incident ray and the surface normal, and the angle of reflection is the angle between the reflected ray and the surface normal.

3. The law of reflection states the angle of incidence is equal to the angle of reflection and that the incident, the reflected and the normal lie in the same plane.

4. Specular reflection takes place when parallel rays fall on a surface and they leave the object as parallel rays.

5. Diffuse reflection takes place when parallel rays are reflected in different directions.

6. Refraction is the bending of light that occurs because light travels at different speeds in different materials. It obeys the laws of refraction.

7. Refractive index is a material property that describes how the material affects the speed of light travelling through it.

8. Total internal reflection takes place when light is reflected back into the medium because the angle of incidence is greater than the critical angle. The critical angle is the angle of incidence where the angle of reflection is 90^o. The light must shine from a dense to a less dense medium.

9. A prism can be used to split the incident white light into a band of visible colors.

Review questions

1. A ray of light strikes a surface at 25^o to the surface. Draw a ray diagram showing the incident ray, reflected ray and surface normal. Find the angle of reflection.
2. State the law of reflection.
3. Explain how light is reflected from rough and smooth surfaces.
4. State Snell's Law.
5. Describe what is meant by the refractive index of a medium.
6. A ray of light strikes the interface between air and diamond. If the incident ray makes an angle of 30^o with the interface, calculate the angle made by the refracted ray with the interface.
7. A ray of light traveling in air enters obliquely into water. Does the light ray bend towards the normal or away from the normal? Why?
8. You are given kerosene, turpentine and water. In which of these does the light travel fastest? Use the information given in table 6.1.
9. A ray of light travels from silicon to water. If the ray of light in the water makes an angle of 69^o to the surface normal, what is the angle of incidence in the silicon?
10. What are the conditions that must be satisfied for total internal reflection to occur?
11. Define what is meant by the critical angle when referring to total internal reflection. Include a ray diagram to explain the concept.
12. Why a Diamond Sparkles?

13. Will light traveling from diamond to silicon ever undergo total internal reflection?

14. When white light strikes a prism, which color of light is refracted the most and which is refracted the least?

6.5 Mirrors and lenses

By the end of this section, you should be able to:

- *apply the laws of reflection and refraction;*
- *describe image formation as a consequence of reflection and refraction;*
- *perform calculations based on the law of reflection and refraction;*
- *distinguish between real and virtual images;*

In this section, you shall study about the different types of mirrors and lenses. You will use the laws of reflection to understand how mirrors form images while you will use the laws of refraction to understand the images formed by lenses.

Exercise 6.14

Did you glance in the mirror before leaving for school this morning?

Mirror

A mirror is a reflective surface that does not allow the passage of light and instead bounces it off, thus producing an image. Plane and spherical mirrors are the different types of mirrors.

Exercise 6.15

How does a plane mirror form an image?

Plane Mirrors

Anu mirror that has a flat reflective surface is called a plane mirror.

Image Formation by a Plane Mirror

If you place a candle in front of a plane mirror, you see two candles. The actual, physical candle is called the object and the picture you see in the mirror is called the image. The object is the source of the incident rays. The image is the picture that is formed by the reflected rays. In a plane mirror, your image looks much the same as it would in a photograph.

In order to understand how plane mirror forms an image, let us do the following activity.

Activity 6.4

1. Stand one step away from a large mirror.
2. What do you observe in the mirror? This is called your image.
3. What size is your image? Bigger, smaller or the same size as your actual size?
4. How far is your image from you? How far is your image from the mirror?
5. Is your image upright or upside down?
6. Take one step backwards. What does your image do? How far are you away from your image?
7. Lift your left arm. Which arm does your image lift?

What did you notice from the above activity? The formation of an image by a plane mirror is illustrated in the diagram below. The object is the blue arrow and you locate the image by finding the position where at least two rays intersect after leaving the same point on the object (arrow head) and reflect off the mirror.

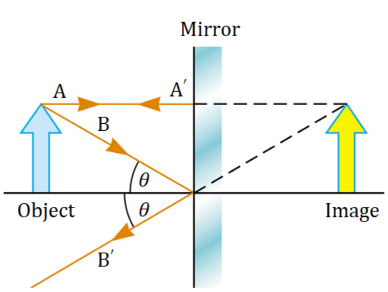


Figure 6.15 Image formation in the plane mirror.

The rays that originate from the arrow head are labeled A and B while the reflected rays are labeled A' and B'. The ray (A) that leaves the arrow head and hits the mirror at an angle of incidence of zero reflects directly back (ray A'). Ray B hits the mirror at an angle and is reflected at an angle of reflection that is equal to the angle of incidence (law of reflection); the reflected ray is labeled B'. Notice that the reflected rays A' and B' do not converge, but diverge (spread apart after reflection). In this case, the image is found by extending the reflected rays back to find the point where they appear to come from. The point where they intersect is then the location of the image of the arrow head (shown in yellow) as shown in Figure 6.14. This type of image is called a virtual image.

Thus, the image of an object in a plane mirror appears to be behind the mirror. You also find that the (virtual) image is located at the same distance behind the mirror as the object distance. Also the height of the image is identical to the height of the object, and is upright. The image size is the same as the object size and is upright. Although mirrors do not produce an inverted image, left and right are inverted. The image of a right hand is a left hand.

Number of images formed by two plane mirrors inclined to each other

If two plane mirrors are placed inclined to each other at an angle θ, the number of images formed by mirrors is

$$\approx \left(\frac{360^o}{\theta} - 1\right), \text{ if } \left(\frac{360^o}{\theta}\right) \text{ is an even integer.}$$

$$\approx \left(\frac{360^o}{\theta}\right), \text{ if } \left(\frac{360^o}{\theta}\right) \text{ is an odd integer.}$$

For example, there are 5 images formed by two mirrors at 60° angle.

Two mirrors inclined to each other at different angles may provide same number of images, e.g. for any value of θ between 90° and 120°, the number of maximum images formed is n = 3. This in turn implies that if θ is given, n is unique but if n is given, θ is not unique.

The number of images seen may be different from the number of images formed and depends on the position of observer relative to object and mirrors e.g., if $\theta = 120°$ maximum number of images formed will be 3 but number of images seen may be 1, 2 or 3 depending on the position of observer.

Uses of mirrors

Plane mirror is used

- in looking glasses,
- in construction of kaleidoscope, telescope, sextant, and periscope etc.,
- for seeing round the corners,
- as deflector of light etc.

Key Concept:

☞ The image created in a plane mirror has the following properties:

1. The image is virtual.
2. The image is the same distance behind the mirror as the object is in front of the mirror.
3. The image is laterally inverted. This means that the image is inverted from side to side.
4. The image is the same size as the object.
5. The image is upright.

Spherical Mirrors

Some mirrors are not flat. A spherical mirror is formed by the inside (concave) or outside (convex) surfaces of a sphere. Thus, a concave mirror has a surface that is curved inward, like the bowl of a spoon. Unlike plane mirrors, concave mirrors cause light rays to come together, or converge. A convex mirror, on the other hand, has a surface that curves outward, like the back of a spoon. Convex mirrors cause light waves to spread out, or diverge. Examples of a concave and a convex mirror are shown in Figure 6.16.

The following are some of the few important terms used to describe spherical mirrors.

- The centre of the sphere, of which the mirror is a part, is called the centre of curvature (C) of the mirror and the radius of this sphere defines its radius of curvature (R).
- The middle point P of the reflecting surface of the mirror is called its pole.
- The straight line passing through the center of curvature and pole is said to be the principal axis of the mirror.
- The circular outline (or periphery) of the mirror is called its aperture.

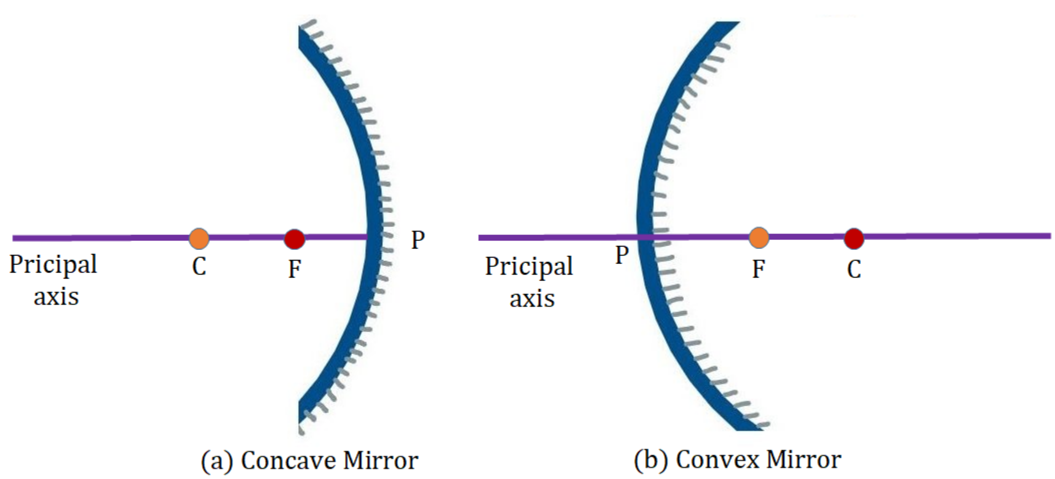


Figure 6.16 Spherical mirrors.

Aperture is a measure of the size of the mirror.

- A beam of light incident on a spherical mirror parallel to the principal axis converges to or appears to diverge from a common point after reflection. This point is known as principal focus (F) of the mirror.
- The distance between the pole and the principal focus gives the focal length (f) of the mirror.
- For spherical mirrors of small apertures, the radius of curvature is found to be equal to twice the focal length. You put this as $R = 2f$. This implies that the principal focus of a spherical mirror lies midway between the pole and center of curvature.

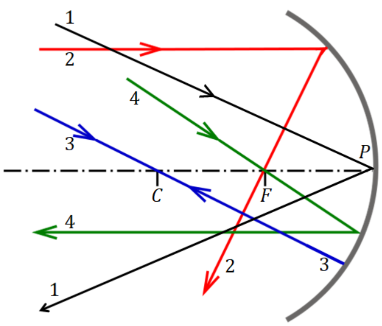


Figure 6.17 Rays used to form image by concave mirror

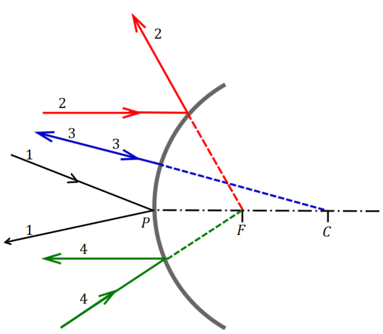


Figure 6.18 Rays used to form image by convex mirror

Representation of images formed by spherical mirrors using ray diagrams

You can study the formation of images by spherical mirrors by drawing ray diagrams. Consider an extended object, of finite size, placed in front of a spherical mirror. In order to locate the image of an object, any two of the following rays can be considered for locating the image for the sake of clarity of the ray diagram.

1. **Ray striking the pole:** The ray of light striking the pole of the mirror at an angle is reflected back at the same angle on the other side of the principal axis (Ray number 1 in Figure 6.17 and 6.18).
2. **Parallel ray:** For concave mirror, the ray parallel to the principal axis is reflected in such a way that after reflection it passes through the principal focus. But for a convex mirror, the parallel ray is so reflected that it appears to come from principal focus (Ray number 2 in Figure 6.17 and 6.18).
3. **Ray through center of curvature:** A ray passing through the center of curvature hits the mirror along the direction of the normal to

the mirror at that point and retraces its path after reflection (Ray number 3 in Figure 6.17 and 6.18).

4. **Ray through focus:** A ray of light heading towards the focus or incident on the mirror after passing through the focus returns parallel to the principal axis (Ray number 4 in Figure 6.17 and 6.18).

Remember that in all the above cases, the laws of reflection are followed. At the point of incidence, the incident ray is reflected in such a way that the angle of reflection equals the angle of incidence.

a) Image formation by Concave Mirror

The intersection of at least two reflected rays give the position of image of the point object. Any two of the following rays can be considered for locating the image. Using the above rules of image formation, the ray diagram for the image formed for different positions of an object are given in Figure 6.19.

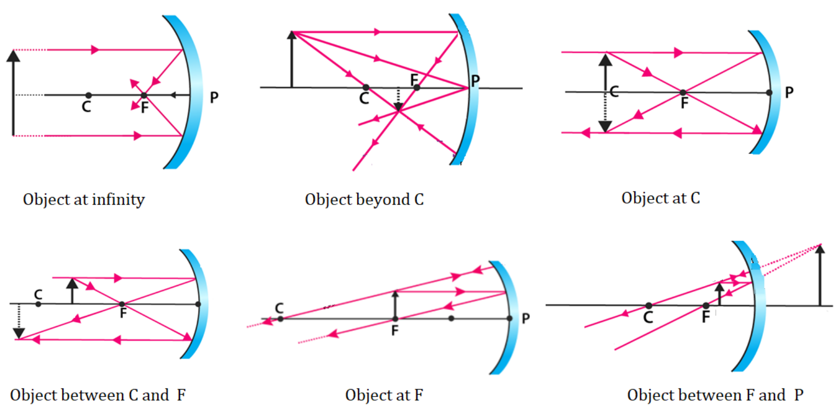


Figure 6.19 Formation of image by a concave mirror.

Exercise 6.16

How can you locate the image formed by a concave mirror for different positions of the object? Are the images real or virtual? Are they enlarged, diminished or have the same size?

Key Concept

☞The properties of the image produced by a concave mirror depend on the location of the object.

Activity 6.5

- Draw neat ray diagrams for each position of the object shown in Table 6.2.
- You may take any two of the rays mentioned in the previous section for locating the image.
- Compare your diagram with those given in Figure 6.19.
- Describe the nature, position and relative size of the image formed in each case.
- Tabulate the results in a convenient format.

Table 6.2 Image formation by a concave mirror for different positions of the object

Position of the object	Position of the image	Size of the image	Nature of the image
At infinity	At the focus F	Highly diminished, point-sized	Real and inverted
Beyond C	Between F and C	Diminished	Real and inverted
At C	At C	Same size	Real and inverted
Between C and F	Beyond C	Enlarged	Real and inverted
At F	At infinity	Highly enlarged	Real and inverted
Between P and F	Behind the mirror	Enlarged	Virtual and erect

Uses of concave mirrors

Concave mirrors are commonly used in torches, search-lights and vehicles headlights to get powerful parallel beams of light. They are often used as shaving mirrors to see a larger image of the face. The dentists use concave mirrors to see large images of the teeth of patients. Large concave mirrors are used to concentrate sunlight to produce heat in solar furnaces.

Exercise 6.17

Explain why concave mirrors are used in flashlights and automobile headlights.

Image formation by a Convex Mirror

You studied the image formation by a concave mirror. Now you shall study the formation of image by a convex mirror. Let's first illustrate this using an activity.

Activity 6.6:

- Take a convex mirror. Hold it in one hand.
- Hold a pencil in the upright position in the other hand.
- Observe the image of the pencil in the mirror. Is the image erect or inverted? Is it diminished or enlarged?
- Move the pencil away from the mirror slowly. Does the image become smaller or larger?
- Repeat this Activity carefully. State whether the image will move closer to or farther away from the focus as the object is moved away from the mirror?

Students, consider two positions of the object for studying the image formed by a convex mirror. First is when the object is at infinity and the second position is when the object is at a finite distance from the mirror. The ray diagrams for the formation of image by a convex mirror for these two positions of the object are shown in Figure 6.20 (a) and (b), respectively. The results are summarized in table 6.3.

Uses of convex mirrors

Convex mirrors are commonly used as rear-view (wing) mirrors in vehicles. These mirrors are fitted on the sides of the vehicle, enabling the driver to see traffic behind him/her to facilitate safe driving. Convex mirrors are

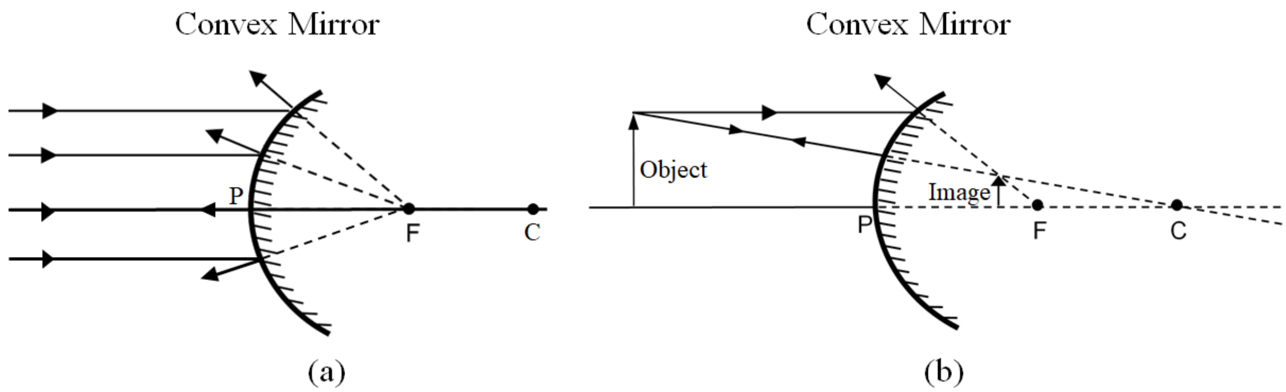


Figure 6.20 Formation of image by a convex mirror.

Table 6.3 Nature, position and relative size of the image formed by a convex mirror

Position of the object	Position of the image	Size of the image	Nature of the image
At infinity	At the focus F, behind the mirror	Highly diminished, point-sized	Virtual and erect
Between infinity and the pole P of the mirror	Between P and F, behind the mirror	Diminished	Virtual and erect

preferred because they always give an erect, though diminished, image. Also, they have a wider field of view as they are curved outwards. Thus, convex mirrors enable the driver to view much larger area than would be possible with a plane mirror.

Mirror Formula and Magnification

In spherical mirrors, the distance of the object from its pole is called the object distance (u). The distance of the image from the pole of the mirror is called the image distance (v). You already know that the distance of the principal focus from the pole is called the focal length (f).

There is a relationship between these three quantities given by the mirror formula which is expressed as

$$\frac{1}{v} + \frac{1}{u} = \frac{1}{f} \tag{6.9}$$

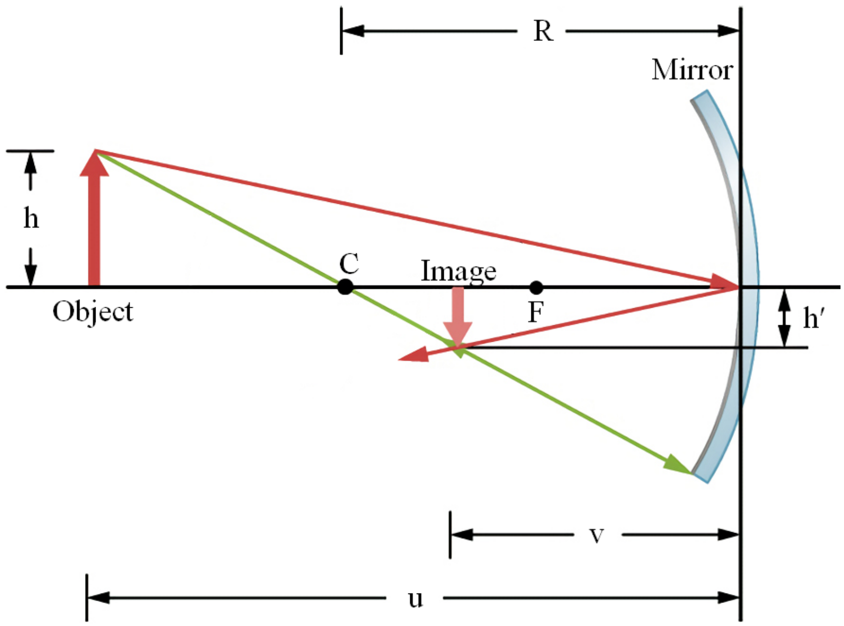


Figure 6.21 *u*, *v*, *f*, *h* and *h'* for a mirror.

On the other hand, the magnification produced by a spherical mirror gives the relative extent to which the image of an object is magnified with respect to the object size. Thus, the magnification m produced by a spherical mirror is given by

$$\mathrm{m} = \frac{\text{height ofthe image } (\mathrm{h}')}{\text{height of the object } (\mathrm{h})} = \frac{\mathrm{h}'}{\mathrm{h}} \tag{6.10}$$

The magnification m is also related to the object distance (u) and image distance (v). It can be expressed as:

$$\text{Magnification } (\mathrm{m}) = \frac{\mathrm{h}'}{\mathrm{h}} = -\frac{\mathrm{v}}{\mathrm{u}} \tag{6.11}$$

These formulas are valid for spherical mirrors for all positions of the object. While substituting the numerical values for u, v, f, and R in the mirror formula for solving problems, you must use the sign convention indicated

Table 6.4 Sign conventions for spherical mirrors

Quantity	**Positive when**	**Negative when**
object location, u	object is in front of mirror (real object)	object is in back of mirror (virtual object)
image location, v	image is in front of mirror (real image)	image is in back of mirror (virtual image)
image height, h’	image is upright	image is inverted
focal length, f	mirror is concave	mirror is convex
magnification, m	image is upright	image is inverted

in Table 6.4.

Example 6.5

A convex mirror used for rear-view on an automobile has a radius of curvature of 3.00 m. If a bus is located at 5.00 m from this mirror, find the position, nature and size of the image.

Solution:

Radius of curvature, R = - 3.00 m;

Object distance, u = + 5.00 m;

Image distance, v = ?

Height of the image, h’= ?

Focal length, $f = \frac{R}{2} = -\frac{3.00}{2} = -1.50m$ (as the principal focus of a convex mirror is behind the mirror)

$$\frac{1}{v} + \frac{1}{u} = \frac{1}{f},$$

$$\frac{1}{v} = \frac{1}{f} - \frac{1}{u} = -\frac{1}{1.50} - \frac{1}{+5.00} = \frac{-5.00 - 1.50}{7.50}$$

$$\therefore \quad v = \frac{-7.50}{6.50} = -1.15m$$

The image is 1.15 m at the back of the mirror.

$$Magnification \ (m) = \frac{h'}{h} = -\frac{v}{u} = -\frac{(-1.15m)}{5.00m} = +0.23$$

The image is virtual, erect and smaller in size by a factor of 0.23.

Example 6.6

An object, 6.0 cm in size, is placed at 25.0 cm in front of a concave mirror of focal length 15.0 cm. At what distance from the mirror should a screen be placed in order to obtain a sharp image? Find the nature and the size of the image.

Solution:

Object size, h = + 6.0 cm;

Object distance, u = + 25.0 cm;

Focal length, f = + 15.0 cm;

Image-distance, v = ?

Image-size, h' = ?

Since

$$\frac{1}{v}+\frac{1}{u}=\frac{1}{f},$$
$$\frac{1}{v}=\frac{1}{f}-\frac{1}{u}=\frac{1}{15.0}-\frac{1}{25.0}=\frac{5.00-3.00}{75}$$
$$\therefore \quad v=37.5m$$

The screen should be placed at 37.5 cm in front of the mirror. The image is real. Also,

$$Magnification\ (m)=\frac{h'}{h}=-\frac{v}{u}$$
$$h'=-\frac{hv}{u}=-\frac{(37.5cm)(6.0cm)}{(25.0cm)}=-6.0cm$$

Thus, the height of the image is - 6.0 cm. This implies that the image is inverted and enlarged.

Exercise 6.18

Have you ever touched the surface of a magnifying glass with your hand? Is it plane surface or curved? Is it thicker in the middle or at the edges?

Lenses

If you have ever used a microscope, telescope, binoculars, or a camera, you have worked with one or more lenses. A lens is a curved transparent material that is smooth and regularly shaped so that when light strikes it,

Exercise 6.19

What is a lens? How does it bend light rays?

the light refracts in a predictable and useful way.

A transparent material bound by two surfaces, of which one or both surfaces are spherical, forms a lens. This means that a lens is bound by at least one spherical surface. In such lenses, the other surface would be plane. A lens may have two spherical surfaces, bulging outwards. Such a lens is called a double convex lens. It is simply called a convex lens. It is thicker at the middle as compared to the edges. Convex lens converges light rays as shown in Figure 6.22 (a). Hence, convex lenses are also called converging lenses. Similarly, a double concave lens is bounded by two spherical surfaces, curved inwards. It is thicker at the edges than at the middle. Such lenses diverge light rays as shown in Figure 6.22 (b). Such lenses are also called diverging lenses. A double concave lens is simply called a concave lens.

Key Concept

☞Concave lenses, which cause light to diverge, and convex lenses cause light to converge.

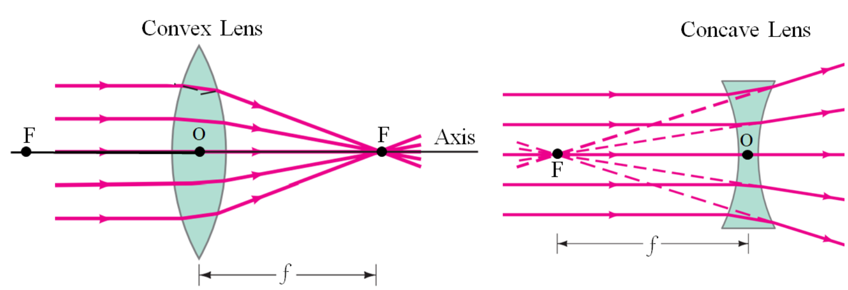


Figure 6.22 (a) Converging action of a convex lens, (b) diverging action of a concave lens.

A lens, either a convex lens or a concave lens, has two spherical surfaces. Each of these surfaces forms a part of a sphere. The centers of these spheres are called centers of curvature (C) of the lens. Since there are two centers of curvature, you may represent them as C_1 and C_2. An imaginary straight line passing through the two centers of curvature of a lens is called its principal axis. The central point of a lens is its optical center (O). A ray of light through the optical center of a lens passes without suffering any deviation. The effective diameter of the circular outline of a spherical lens is called its aperture.

In order to look for the phenomenon that happens when parallel rays of light are incident on a lens, try to do the following activity.

Exercise 6.20

What happens when parallel rays of light are incident on a lens?

Activity 6.7:

- Hold a convex lens in your hand. Direct it towards the Sun.
- Focus the light from the Sun on a sheet of paper. Obtain a sharp bright image of the Sun.
- Hold the paper and the lens in the same position for a while. Keep observing the paper. What happened? Why?

Caution: Do not look at the Sun directly or through a lens while doing this activity as it may damage your eyes.

The paper begins to burn producing smoke. It may even catch fire after a while. Why does this happen? The light from the Sun constitutes parallel rays of light. These rays were converged by the lens at the sharp bright spot formed on the paper. This caused the paper to burn.

In Figure 6.23 (a), several rays of light parallel to the principal axis are falling on a convex lens. These rays, after refraction from the lens, are converging to a point on the principal axis. This point on the principal axis is called the principal focus of the lens. On the other hand, in Figure 6.23 (b), several rays of light parallel to the principal axis are falling on a concave lens. These rays, after refraction from the lens, are appearing to diverge from a point on the principal axis. This point on the principal axis is called the principal focus of the concave lens.

If you pass parallel rays from the opposite surface of the lens, you get another principal focus on the opposite side. Letter F is usually used to represent principal focus. However, a lens has two principal foci. They are represented by F_1 and F_2. The distance of the principal focus from the optical center of a lens is called its focal length (f).

Image formation in lenses using ray diagrams

You can represent image formation by lenses using ray diagrams. Ray diagrams will also help us to study the nature, position and relative size of the image formed by lenses. For drawing ray diagrams in lenses, alike of spherical mirrors, you consider any two of the following rays:

1. A ray of light from the object, parallel to the principal axis, after refraction from a convex lens, passes through the principal focus on the other side of the lens, as shown in Figure 6.23 (a). In case of a concave lens, the ray appears to diverge from the principal focus located on the same side of the lens, as shown in Figure 6.23 (b).

2. A ray of light passing through a principal focus, after refraction from a convex lens, will emerge parallel to the principal axis. This is shown in Figure 6.23 (a). A ray of light appearing to meet at the principal focus of a concave lens, after refraction, will emerge parallel to the principal axis. This is shown in Figure 6.23 (b).

3. A ray of light passing through the optical center of a lens will emerge without any deviation. This is illustrated in Figure 6.23 (a) and Figure 6.23 (b).

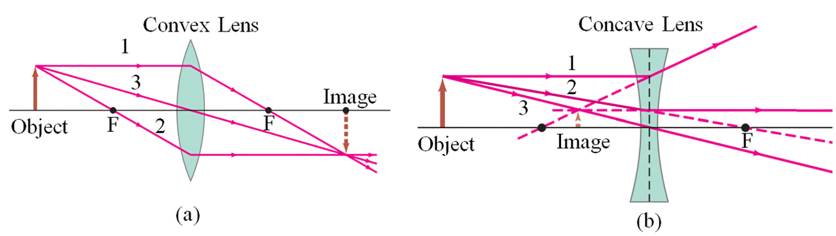


Figure 6.23 (a) Convex lens ray diagram. (b) Concave lens ray diagram.

Image formation by lenses

Lenses form images by refracting light. Let us study this for a convex lens first by doing the following activity.

Activity 6.8

Take a convex lens of some focal length.

- Draw five parallel straight lines, using chalk, on a long table such that the distance between the successive lines is equal to the focal length of the lens.
- Place the lens on a lens stand. Place it on the central line such that the optical center of the lens lies just over the line.
- The two lines on either side of the lens correspond to F and 2F of the lens respectively. Mark them with appropriate letters such as $2F_1, F_1, F_2$ and $2F_2$ respectively.
- Place a burning candle, far beyond $2F_1$ to the left. Obtain a clear sharp image on a screen on the opposite side of the lens.
- Note down the nature, position and relative size of the image.
- Repeat this activity by placing the object just behind $2F_1$, between F_1 and $2F_1$ at F_1, between F_1 and O. Note down and tabulate your observations.

What did you notice? Have you noticed as the nature, position and relative size of the image depends on the location of the object? The ray diagrams for the image formation in a convex lens for a few positions of the object are shown in Figure 6.24. Table 6.5 summarizes the nature, position and relative size of the image formed by convex lens for various positions of the object.

Exercise 6.21

How do lenses form images? What is their nature?

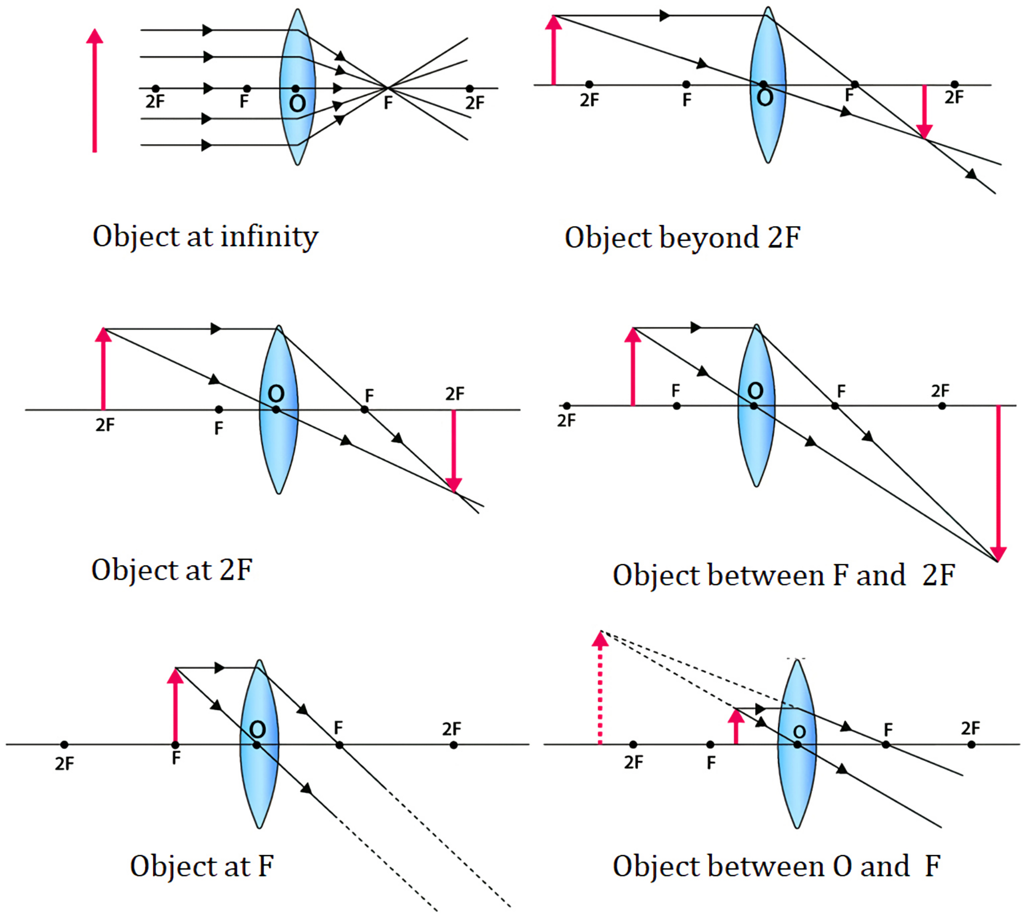


Figure 6.24 The position, size and the nature of the image formed by a convex lens for various positions of the object.

Let us now do an activity to study the nature, position and relative size of the image formed by a concave lens.

Table 6.5 Nature, position and relative size of the image formed by a convex lens for various positions of the object

Position of the object	Position of the image	Size of the image	Nature of the image
At infinity	At the focus F_2	Highly diminished, point-sized	Real and inverted
Beyond $2F_1$	Between F_2 and $2F_2$	Diminished	Real and inverted
At $2F_2$	At $2F_2$	Same size	Real and inverted
Between F_1 and $2F_1$	Beyond $2F_2$	Enlarged	Real and inverted
At Focus F_1	At infinity	Infinitely large or Highly enlarged	Real and inverted
Between focus F_1 and optical center O	On the same side of the lens as the object	Enlarged	Virtual and erect

Activity 6.9

- Take a concave lens. Place it on a lens stand.
- Place a burning candle on one side of the lens.
- Look through the lens from the other side and observe the image. Try to get the image on a screen, if possible. If not, observe the image directly through the lens.
- Note down the nature, relative size and approximate position of the image.
- Move the candle away from the lens. Note the change in the size of the image. What happens to the size of the image when the candle is placed too far away from the lens?.

What conclusion can you draw from this activity? A concave lens will always give a virtual, erect and diminished image, irrespective of the position of the object. The ray diagrams representing the image formation in a concave lens for various positions of the object are shown in Figure 6.25.

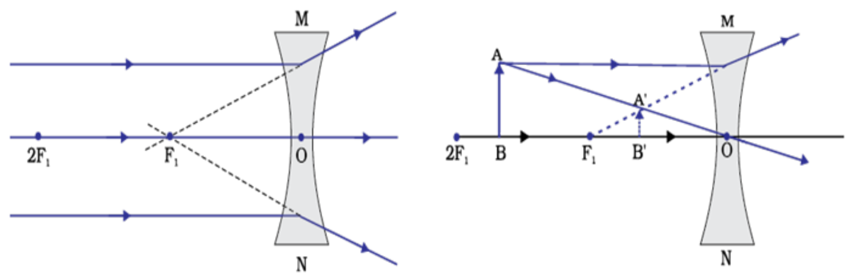


Figure 6.25 Image formed by a concave lens.

The summary of the above activity is given in table 6.6 below.

Table 6.6 Nature, position and relative size of the image formed by a concave lens for various positions of the object

Position of the object	Position of the image	Size of the image	Nature of the image
At infinity	At focus F_1	Highly diminished, point-sized	Virtual and erect
Between infinity and optical center O of the lens	Between focus F_1, and optical center O	Diminished	Virtual and erect

Lens Formula and Magnification

As there is a formula for spherical mirrors, there is also a formula for lenses. This formula gives the relationship between object distance (u), image-distance (v) and the focal length (f). It is expressed as

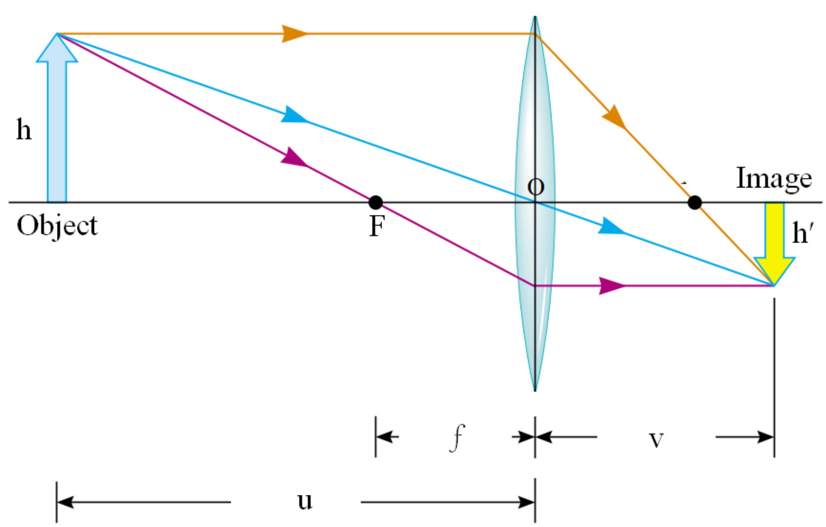


Figure 6.26 u, v and f in a lens.

$$\frac{1}{u}+\frac{1}{v}=\frac{1}{f} \tag{6.12}$$

The magnification produced by a lens, similar to that for spherical mirrors, is defined as the ratio of the height of the image (h') and the height of the object (h). Thus, the magnification (m) produced by the lens is given by,

$$m=\frac{h'}{h} \tag{6.13}$$

Magnification produced by a lens is also related to the object-distance u, and the image-distance v. This relationship is given by

$$Magnification\,(m)=\frac{h'}{h}=-\frac{v}{u} \tag{6.14}$$

The lens and magnification formula's given above are general and is valid in all situations for any spherical lens. While putting numerical values for solving problems relating to lenses in to the above equations, you need be careful in using the sign conventions indicated in Table 6.7.

Table 6.7 Sign conventions for lenses

Quantity	Positive when	Negative when
object location, u	object is in front of lens (real object)	object is in back of lens (virtual object)
image location, v	image is in back of lens (real image)	image is in front of lens (virtual image)
image height, h'	image is upright	image is inverted
focal length, f	converging lens	diverging lens
R_1 and R_2	center of curvature is in back of lens	center of curvature is in front of lens

Example 6.7

A concave lens has focal length of 15 cm. At what distance should the object from the lens be placed so that it forms an image at 10 cm from the lens? Also, find the magnification produced by the lens.

Solution:

A concave lens always forms a virtual, erect image on the same side of the object.
Image distance v = - 10 cm;
Focal length f = -15 cm;
Object distance, u = ?

$$Since \quad \frac{1}{v}+\frac{1}{u}=\frac{1}{f},$$
$$\frac{1}{u}=\frac{1}{f}-\frac{1}{v}=\frac{1}{-15.0}-\frac{1}{-10.0}=\frac{-2+3}{30}=\frac{1}{30}$$
$$\therefore \quad v=30cm$$

Thus, the object-distance is 30 cm.

$$Magnification \ (m)=-\frac{v}{u}=-\frac{-10}{30}=+0.33$$

The positive sign shows that the image is erect and virtual. The image is one-third of the size of the object

Example 6.8

A 2.0 cm tall object is placed perpendicular to the principal axis of a convex lens of focal length 10 cm. The distance of the object from the lens is 15 cm. Find the nature, position and size of the image. Also find its magnification.

Solution:
Height of the object, h = + 2.0 cm;
Focal length, f = + 10 cm;
Object distance, u = + 15 cm;
Image distance, v = ?
Height of the image, h'= ?
Since

$$\frac{1}{v}+\frac{1}{u}=\frac{1}{f},\frac{1}{v}=\frac{1}{f}-\frac{1}{u}=\frac{1}{10}-\frac{1}{15}=\frac{3-2}{30}$$
$$\therefore \quad v=+30cm$$

The positive sign of v shows that the image is formed at a distance of 30 cm on the other side of the optical center. The image is real and inverted.

$$Magnification\ (m) = \frac{h'}{h} = -\frac{v}{u}$$
$$h' = -\frac{hv}{u} = -(2)\frac{(30)}{(15)} = -6.0cm$$
$$Magnification(m) = -\frac{v}{u} = -\frac{+30}{+15} = -2$$

The negative signs of m and h' show that the image formed is inverted and real. It is formed below the principal axis. Thus, a real, inverted image, 4 cm tall, is formed at a distance of 30 cm on the other side of the lens. The image is two times enlarged.

Section summary

- The image formed by a plane mirror is virtual, erect and of the same size as that of the object, such that the object and its image appear to be equidistant from the mirror.
- A convex mirror is a diverging mirror in which the reflective surface bulges towards the light source. The image formed by convex mirrors is smaller than the object but gets larger as they approach the mirror.
- A concave mirror has a reflective surface that is curved inward and away from the light source. The image formed by a concave mirror shows different image types depending on the distance between the object and the mirror.
- A lens is any transparent material that is shaped in such a way that it will converge parallel incident rays to a point or diverge incident rays from a point.
- Converging lenses are thicker in the middle than on the edge and will bend incoming light rays towards the principal axis.

- Diverging lenses are thinner in the middle than on the edge and will bend incoming light rays away from the principal axis.

Review questions

1. List 5 properties of an image created by reflection from a plane mirror.
2. If a stool 0.5 m high is placed 2 m in front of a plane mirror, how far behind the plane mirror will the image be and how high will the image be?
3. Find the number of images formed by an object placed between two plane mirrors inclined at 30^o.
4. Define the principal focus of a concave mirror.
5. The radius of curvature of a spherical mirror is 20 cm. What is its focal length?
6. Name a mirror that can give an erect and enlarged image of an object.
7. Why is a convex mirror is preferred as a rear-view mirror in vehicles?
8. So far you studied the image formation by a plane mirror, a concave mirror and a convex mirror. Which of these mirrors will give the full image of a large object?
9. An object 1 cm high is placed 4 cm from a concave mirror. If the focal length of the mirror is 2 cm, find the position and size of the image. Is the image real or virtual? Calculate the magnification.
10. An object 2 cm high is placed 4 cm from a convex mirror. If the focal length of the mirror is 4 cm, find the position and

size of the image. Is the image real or virtual? Calculate the magnification.

11. A concave mirror produces three times magnified (enlarged) real image of an object placed at 10 cm in front of it. Where is the image located?

12. In each case, state whether a real or virtual image is formed by a convex lens:

    (a) Much further than 2F

    (b) Just further than 2F

    (c) At 2F

    (d) Between 2F and F

    (e) At F

    (f) Between F and O

13. An object stands 50 mm from a convex lens (focal length 40 mm). Use ray diagrams to determine the position of the image. Is it enlarged or minimized; upright or inverted?

14. An object 6 cm high is 10 cm from a concave lens. The image formed is 3 cm high. Find the focal length of the lens and the distance of the image from the lens.

15. An object is 20 cm from a concave lens. The virtual image formed is three times smaller than the object. Find the focal length of the lens.

6.6 Human eye and optical instruments

By the end of this section, you should be able to:

- *describe the human eye in relation to lenses;*
- *list simple optical instrument in use in your locality;*
- *explain the physics behind the operation of optical instruments.*

The Human eye

The human eye is one of the most valuable and sensitive sense organs. It enables us to see the wonderful world and the colors around us. Of all the sense organs, the human eye is the most significant one as it enables us to see the beautiful, colorful world around us.

Exercise 6.22

How does a human eye form an image?

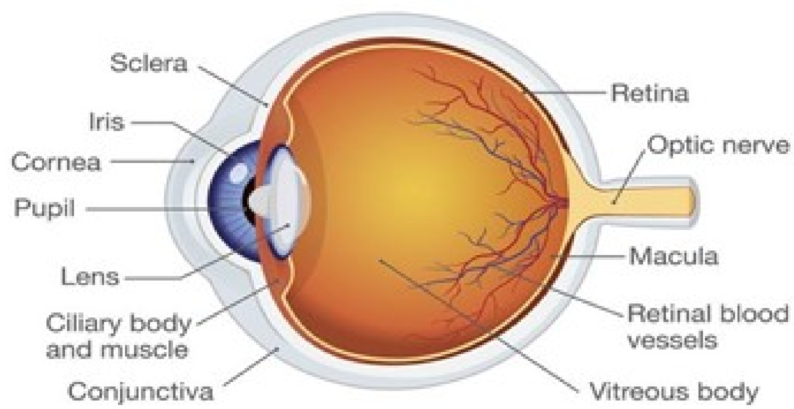


Figure 6.27 Basic elements of human eye.

The human eye is like a camera. Its lens system forms an image on a light-sensitive screen called the retina. Light enters the eye through a thin membrane called the cornea. It forms the transparent bulge on the front surface of the eyeball as shown in Figure 6.27.

The eyeball is approximately spherical in shape with a diameter of about 2.3 cm. Most of the refraction for the light rays entering the eye occurs at the outer surface of the cornea. The crystalline lens merely provides the finer adjustment of focal length required to focus objects at different distances on the retina. You find a structure called iris behind the cornea. Iris is a dark muscular diaphragm that controls the size of the pupil. The pupil regulates and controls the amount of light entering the eye. The eye lens forms an inverted real image of the object on the retina. The retina is a delicate membrane having enormous number of light-sensitive cells. The light-sensitive cells get activated upon illumination and generate electrical signals. These signals are sent to the brain via the optic nerves. The brain interprets these signals, and finally, processes the information so that you perceive objects as they are.

Key Concept

☞The human eye consists of a lens system that focuses images on the retina where the optic nerve transfers the messages to the brain.

Power of accommodation

The eye lens is composed of a fibrous, jelly-like material. Its curvature can be modified to some extent by the ciliary muscles. The change in the curvature of the eye lens can thus change its focal length. When the muscles are relaxed, the lens becomes thin. Thus, its focal length increases. This enables us to see distant objects clearly. When you are looking at objects closer to the eye, the ciliary muscles contract. This increases the curvature of the eye lens. The eye lens then becomes thicker. Consequently, the focal length of the eye lens decreases. This enables us to see nearby objects clearly. The ability of the eye lens to adjust its focal length is called accommodation. However, the focal length of the eye lens cannot be decreased below a certain minimum limit.

Exercise 6.23

Students, if you try to read a printed page by holding it very close to your eyes, what happens to the image you see?

If you try to read a printed page by holding it very close to your eyes, you may see the image being blurred or feel strain in the eye. To see an object comfortably and distinctly, you must hold it at about 25 cm from the eyes. For a young adult with normal vision, the near point is about 25 cm. The farthest point up to which the eye can see objects clearly is called the far point of the eye. It is infinity for a normal eye. You may note here a normal eye can see objects clearly that are between 25 cm and infinity.

Defects of vision and their correction

Key Concept

☞The minimum distance, at which objects can be seen most distinctly without strain, is called the least distance of distinct vision. It is also called the near point of the eye.

Exercise 6.24

Students, have you encountered peoples having defects in their vision?

Sometimes, the eye may gradually lose its power of accommodation. In such conditions, the person cannot see the objects distinctly and comfortably. The vision becomes blurred due to the refractive defects of the eye. There are mainly three common refractive defects of vision.

(a) Myopia/near-sightedness

A person with myopia can see nearby objects clearly but cannot see distant objects distinctly. A person with this defect has the far point nearer than infinity. Such a person may see clearly up to a distance of a few meters. In a myopic eye, the image of a distant object is formed in front of the retina and not at the retina itself (Figure 6.28 (a)) . This defect may arise due to (i) excessive curvature of the eye lens, or (ii) elongation of the eyeball. This defect can be corrected by using a concave lens of suitable power. A concave lens of suitable power will bring the image back on to the retina.This is illustrated in Figure 6.28 (b).

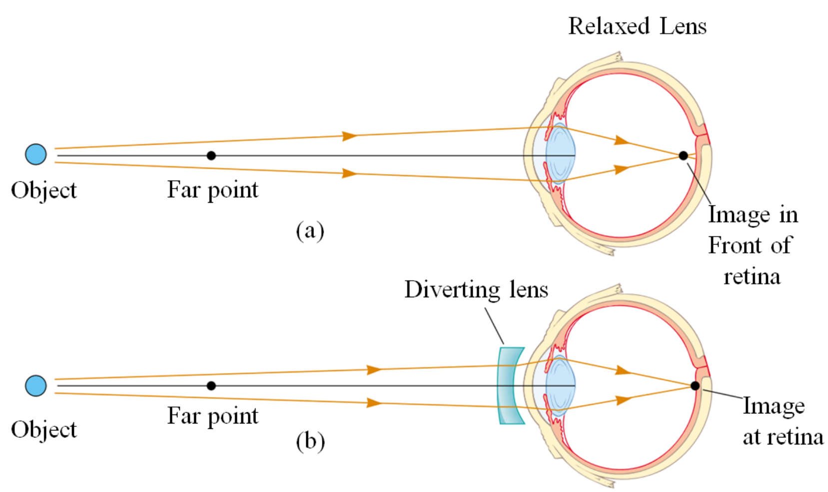


Figure 6.28 (a)Short-sightedness. (b) Short-sightedness corrected by diverging lens.

(b) Hypermetropia/far-sightedness

A person with hypermetropia can see distant objects clearly but cannot see nearby objects distinctly. The near point, for the person, is farther away from the normal near point (25 cm). Such a person has to keep a reading material much beyond 25 cm from the eye for comfortable reading. This is because the light rays from a close by object are focused at a point behind the retina as shown in Figure 6.29 (a). This defect arises either because (i) the focal length of the eye lens is too long, or (ii) the eyeball has become too small. This defect can be corrected by using a convex lens of appropriate power. Eye-glasses with converging lenses provide the additional focusing power required for forming the image on the retina. This is illustrated in Figure 6.29 (b).

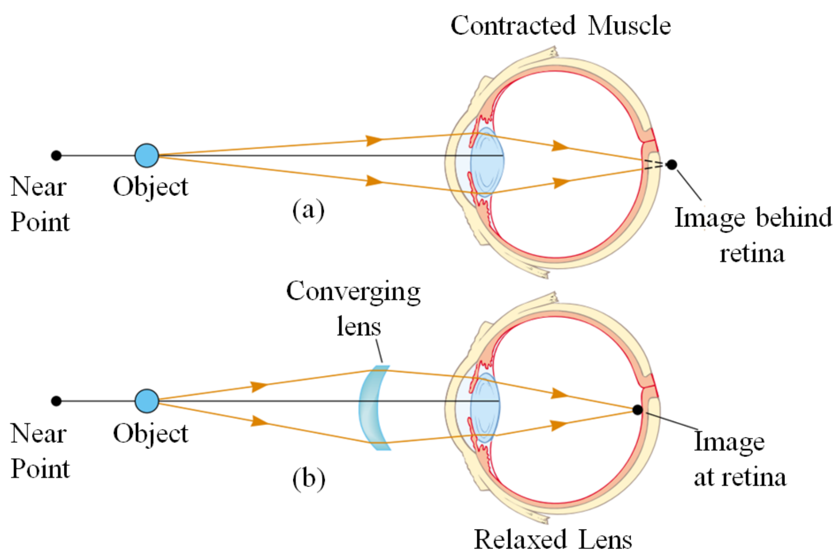


Figure 6.29 (a)Long-sightedness. (b) Long-sightedness corrected by converging lens.

(c) Presbyopia

The power of accommodation of the eye usually decreases with ageing. For most people, the near point gradually recedes away. They find it difficult to see nearby objects comfortably and distinctly without corrective eye-glasses. This defect is called Presbyopia. It arises due to the gradual weakening of the ciliary muscles and diminishing flexibility of the eye lens. Sometimes, a person may suffer from both myopia and hypermetropia. Such people often require bi-focal lenses. A common type of bi-focal lenses consists of both concave and convex lenses. The upper portion consists of a concave lens. It facilitates distant vision. The lower part is a convex lens. It facilitates near vision. Nowadays, it is possible to correct the refractive defects with contact lenses or through surgery.

Key Concept

☞ Myopia, hypermetropia and presbyopia are defects of vision. They can be corrected with an appropriate lens.

Students, do you know that our eyes can live even after our death? By donating your eyes after you die, you can light the life of a blind person.

Optical instruments

A number of optical devices and instruments have been designed utilizing reflecting and refracting properties of mirrors, lenses and prisms. Periscope, kaleidoscope, binoculars, camera, telescopes, microscopes are some examples of optical devices and instruments that are in common use. Our eye is, of course, one of the most important optical devices the nature has endowed us with. You have already studied about the human eye. You now go on to describe the principles of working of the microscope and the telescope.

Activity 6.9

Students, in group, please try to list the different types of optical instruments that you know.

Simple microscope

A simple magnifier or microscope is a converging lens of small focal length (Figure 6.30). In order to use such a lens as a microscope, the lens is held near the object, one focal length away or less, and the eye is positioned close to the lens on the other side. The idea is to get an erect, magnified and virtual image of the object at a distance so that it can be viewed comfortably, i.e., at 25 cm or more.

Exercise 6.25

Students, what do you think is a simple microscope?

Figure 6.30 A simple microscope.

Compound microscope

A simple microscope has a limited maximum magnification for realistic focal lengths. For much larger magnifications, one uses two lenses, one compounding the effect of the other. This is known as a compound microscope.

A compound microscope has, thus, more than one objective lens, each providing a different magnification. Figure 6.31 also shows how a microscope forms an image. An object, such as an insect, is placed close to a convex lens called the objective lens. This lens produces an enlarged image inside the microscope tube. The light rays from that image then pass through a second convex lens called the eyepiece lens. This lens further magnifies the image formed by the objective lens. By using two lenses, a much larger image is formed than a single lens can produce.

Key Concept

☞ The image formed by a magnifying glass is erect, magnified and virtual.

Key Concept

☞ The objective lens in a compound microscope forms an enlarged image, which is then magnified by the eyepiece lens.

Activity 6.10

Students, in groups try to discuss how a compound microscope magnifies objects. Infer how the image produced by a compound microscope would be different if the eyepiece lens were removed from the microscope.

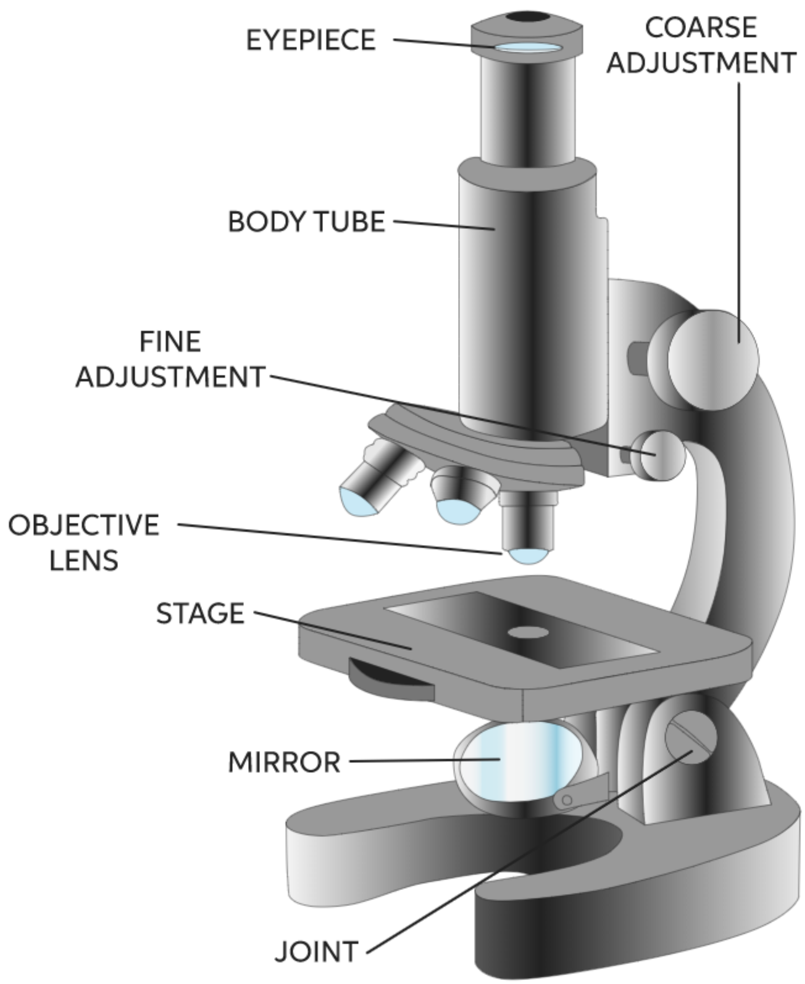


Figure 6.31 A compound microscope.

Exercise 6.26

Students, have you heard about the functions of a telescope?

Telescopes

Just as microscopes are used to magnify very small objects, telescopes are used to examine objects that are very far away. Much of what is known about the Moon, the solar system, and the distant universe has come from images and other information gathered by telescopes.

Two fundamentally different types of telescopes exist. The first type, the refracting telescope, uses a combination of lenses to form an image. The simplest refracting telescopes use two convex lenses to form an image of a distant object. Just as in a compound microscope, light passes through an objective lens that forms an image. That image is then magnified by an eyepiece, as shown in Figure 6.32. Like the compound microscope, the refracting telescope shown has an objective and an eyepiece. The two lenses are arranged so that the objective forms a real, inverted image of a distant object very near the focal point of the eyepiece.

Figure 6.32 Refracting telescopes use a large objective lens to gather light from distant objects.

An important difference between a telescope and a microscope is the size of the objective lens. The main purpose of a telescope is not to magnify an image. A telescope's main purpose is to gather as much light as possible from distant objects. The larger an objective lens is, the more light can enter it. This makes images of faraway objects look brighter and more

Exercise 6.27

What do you think are the differences between telescope and compound microscope? Would you please try to think of how telescopes make distant objects visible?

Exercise 6.28

Explain why the objective lens of a refracting telescope is much larger than the objective lens of a compound microscope.

detailed when they are magnified by the eyepiece. With a large enough objective lens, it's possible to see stars and galaxies that are many trillions of kilometers away. Figure 6.32 shows a refracting telescope.

Key Concept

☞ A refracting telescope is made from an objective lens and an eyepiece. The objective lens forms an image that is magnified by the eyepiece.

The second type, reflecting telescope, can be made much larger than refracting telescopes. Reflecting telescopes have a concave mirror instead of a concave objective lens to gather the light from distant objects. As shown in Figure 6.33, the large concave mirror focuses light onto a secondary mirror that directs it to the eyepiece, which magnifies the image.

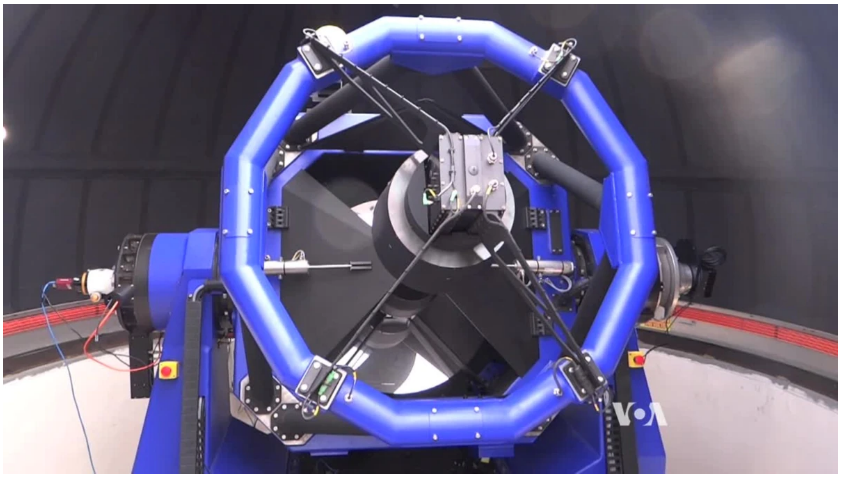


Figure 6.33 Reflecting telescopes gather light by using a concave mirror.

Exercise 6.29

Explain why the concave mirror of a reflecting telescope can be made much larger than the objective lens of a refracting telescope.

Because only the one reflecting surface on the mirror needs to be made carefully and kept clean, telescope mirrors are less expensive to make and maintain than lenses of a similar size. Also, mirrors can be supported not only at their edges but also on their backsides. They can be made much larger without sagging under their own weight.

Key Concept:

☞ Light entering the telescope tube is reflected by a concave mirror onto the secondary mirror. An eyepiece is used to magnify the image formed by the concave mirror.

Section summary

- The simple defects of vision, i.e., long and short sight, are attributed to the inability of the eye lens to focus images of near and far objects on the retina. Simple lenses enable these defects to be corrected.
- The function of optical instruments is to extend the performance of the human eye in a variety of ways.
- The magnifying glass creates an enlarged, erect and virtual image of an object placed closer to the lens than the focal point.
- The compound microscope is an instrument for looking at very small objects by using an objective to produce an enlarged real intermediate image which is then further enlarged by an eyepiece used as a magnifying glass.
- The telescope is an instrument for looking at distant objects. A large objective lens (in the refracting telescope) or concave mirror (in the reflecting telescope) collects light from the object to form a reduced real intermediate image at the focus. As in the microscope, this image is enlarged by an eyepiece acting as a magnifying glass.

Review questions

1. What is meant by power of accommodation of the eye?
2. A person with a myopic eye cannot see objects beyond 1.2 m distinctly. What should be the type of the corrective lens used to restore proper vision?
3. What is the far point and near point of the human eye with normal vision?
4. A student has difficulty reading the blackboard while sitting

in the last row. What could be the defect the child is suffering from? How can it be corrected?

5. List other optical instruments that you are familiar with and discuss how it works.
6. Why is a normal eye not able to see clearly the objects placed closer than 25 cm?
7. What is the difference between simple and compound microscopes?
8. Distinguish between the refracting and reflecting telescope.
9. A person needs a lens of power -5.5 dioptres for correcting his distant vision. For correcting his near vision he needs a lens of power +1.5 dioptre. What is the focal length of the lens required for correcting (i) distant vision, and (ii) near vision?
10. What type of telescope is there in Entoto Observatory center? What is its purpose?

6.7 Primary colors of light and human vision

Exercise 6.30

Students, which of the colors of visible light spectrum are considered as the primary colors of light?

By the end of this section, you should be able to:

- *list the primary colors of light;*
- *describe the relation of primary color and human vision.*

Light travels into the eye to the retina, located on the back of the eye. The retina is covered with millions of light receptive cells called cones (which are sensitive to color) and rods (which are more sensitive to intensity). When these cells detect light, they send signals to the brain. Most people have three kinds of cone cells, and every color stimulates more than one cone. Their combined response produces a unique signal for each color, and millions of different colors can be distinguished this way. These cells, working in combination with connecting nerve cells, give the brain enough information to interpret and name colors. You are able to "see" an object when light from the object enters your eyes and strikes these photoreceptors.

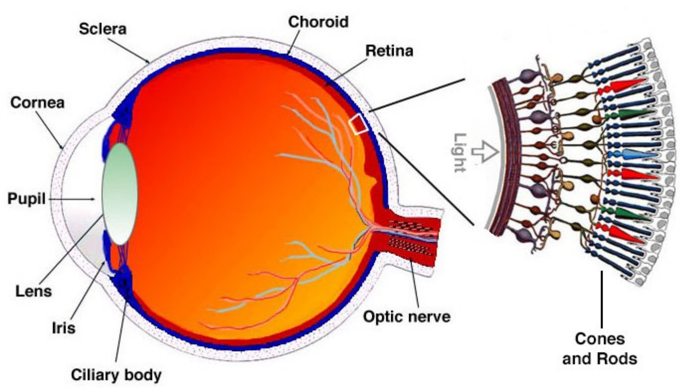


Figure 6.34 Rod and cone cells in the retina of the eye detect light and send signals to the brain.

Different wavelengths of light are perceived as different colors. For example, light with a wavelength of about 400 nm is seen as violet, and light with a wavelength of about 700 nm is seen as red. However, it is not typical to see light of a single wavelength. You are able to perceive all colors because there are three sets of cones in your eyes: one set that is most sensitive to red light, another that is most sensitive to green light, and a third that is most sensitive to blue light.

Key Concept

☞Light receptors within the eye transmit messages to the brain, which produces the familiar sensations of color.

The colors red, green, and blue are classically considered the primary colors because they are fundamental to human vision. All other colors of the visible light spectrum can be produced by properly adding different combinations of these three colors. Moreover, adding equal amounts of red, green, and blue light produces white light and, therefore, these colors are also often described as the primary additive colors.

Key Concept

☞ Red, green and blue are the primary colors.

Section summary

- Red, green and blue are the primary colors of light.
- Rods and cones are the two major types of light-sensing cells (photoreceptors) in the retina.

Review questions

1. List the three primary colors of light.
2. What are the two types of photoreceptor found in the retina of the human eye called and which type is sensitive to colors?

Exercise 6.31

Students, what do you think is the definition of color addition?

6.8 Color addition of light

By the end of this section, you should be able to:

- *recognize how additive colors affect the color of light;*
- *add primary colors.*

Key Concept

☞ Combinations of two of the primary colors follow the rules of additive color mixing so as to produce the secondary colors of light: cyan, magenta, and yellow.

The additive color system reproduces colors by adding the primary colors of light: red, green, and blue. All the colors that can be produced by a three-color additive system are combinations of these three primary colors. When mixed together in various proportions, the additive color primaries of red, green, and blue give us the range of colors that you see. So red, green and blue are therefore called the additive primary colors.

The addition of the primary colors of light can be demonstrated using a light box. The light box illuminates a screen with the three primary colors: red, green and blue. The lights are often in the shape of circles. The result of adding two primary colors of light is easily seen by viewing the overlap of the two or more circles of primary light. The different combinations of colors produced by red, green and blue are shown in Figure 6.35.

In the areas where two primary colors overlap, a secondary color appears. When overlapped, green and blue create cyan. Blue and red produce magenta. Red and green produce yellow.
Thus,

Red + Green = Yellow
Red+ Blue = Magenta
Blue + Green = Cyan

Yellow, magenta and cyan are sometimes referred to as **secondary colors of light** since they can be produced by the addition of equal intensities of two primary colors of light. When added in equal proportions, red, green, and blue result in white light. The absence of all three colors results in black.

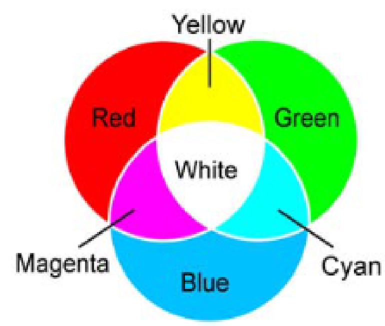


Figure 6.35 The different combinations of colors produced by the primary colors of light.

The addition of these three primary colors of light with varying degrees of intensity will result in the countless other colors that you are familiar (or unfamiliar) with. So, all the other colors can be produced by different combinations of red, green and blue.
blue light-emitting phosphors.

Principles of color addition have important applications to color television, color computer monitors and on-stage lighting at the theaters. A digital projector also works using the additive systems. Each of these applications involves the mixing or addition of colors of light to produce a desired appearance.

Section summary

- The combination of primary colors produce white color.
- All the other colors can be produced by different combinations of red, green and blue.

Review questions

1. What color did you get when you add red and blue, red and green, green and blue?
2. What type of applications did color addition have?

Exercise 6.32

Students, what do you think is the definition of color subtraction?

6.9 Color subtraction of light using filters

By the end of this section, you should be able to:

- *describe color subtraction of light using filters.*

The previous lesson focused on the principle of color addition. In this section, you will learn about color subtraction. The colors that are absorbed are 'subtracted' from the reflected light that is seen by the eye. A black objects absorbs all colors where as a white object reflects all colors. A blue objects reflects blue and absorbs all other colors. The primary and secondary colors of light for the substractive colors are opposite to the colors addition as shown in Figure 6.36.

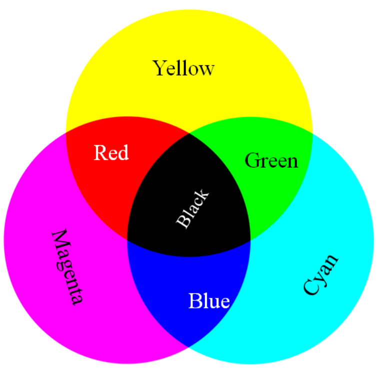


Figure 6.36 Color subtraction.

The following illustrates the process of color subtraction.

Cyan - Blue = (Green + Blue) - Blue = Green
Yellow - Green = (Red + Green) - Green = Red
Magneta - Red = (Red + Blue) - Red = Blue

Key Concept

☞ The subtractive primary colors are obtained by subtracting one of the three additive primary colors from white light.

Yellow, magenta and cyan are considered as the subtractive primary colors while red, green and blue are the secondary subtractive colors. On the other hand, the complimentary colors are the colors that are absorbed by the subtractive primaries. Cyan's complement is red; magenta's complement is green; and yellow's compliment is blue.

Pigments are substances which give an object its color by absorbing certain frequencies of light and reflecting other frequencies. For example, a red pigment absorbs all colors of light except red which it reflects. Paints and inks contain pigments which give the paints and inks different colors. A filter is also defined as a substance or device that prevents certain things from passing through it while allowing certain other things to pass. Color filters allow only certain colors of light to pass through them by absorbing all the rest. When white light shines on a red filter, for example, the orange, yellow, green, blue, and violet components of the light are absorbed by the filter allowing only the red component of the light to pass through to the other side of the filter.

The following shows the color subtraction of light using filters or pigments.

i. Yellow filter (or a pigment) absorbs blue light and transmits red and green light. Red and green light together are seen as yellow.

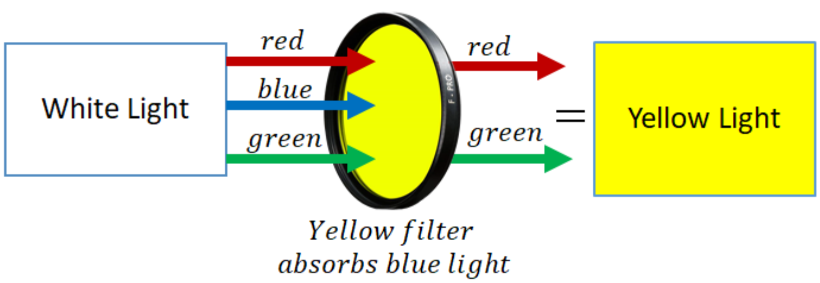


Figure 6.37 Color subtraction using yellow filter.

ii. Magenta filter absorbs green light and transmits red and blue light. Blue and red light together are seen as magenta.

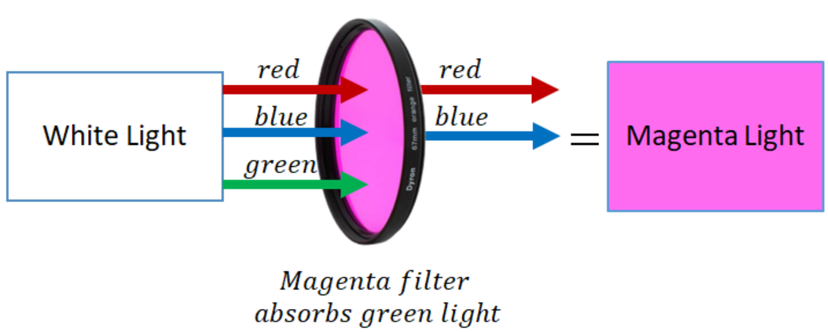


Figure 6.38 Color subtraction using magneta filter.

iii. Cyan filter (or pigment) absorbs red light and transmits blue and green light. Blue and green light together are seen as cyan.

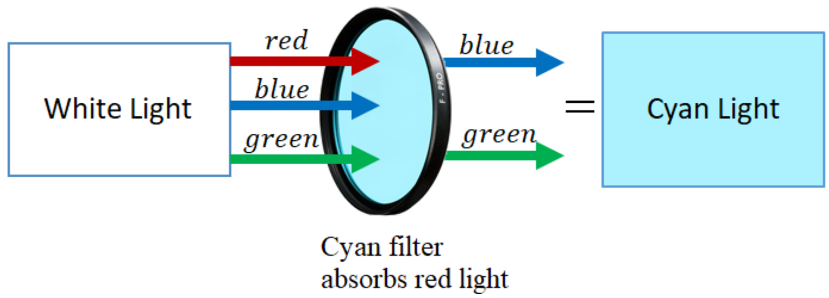


Figure 6.39 Color subtraction using cyan filter.

iV. Yellow filter (or a pigment) absorbs blue and Magenta filter (or a pigment) absorbs green and reflect the red light.

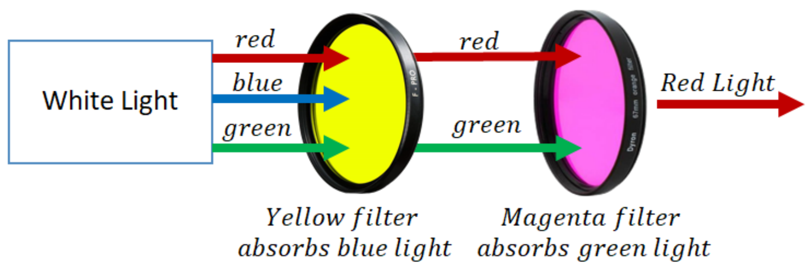


Figure 6.40 Color subtraction Using yellow and magneta filters.

V. Yellow filter (or a pigment) absorbs blue and cyan filter (or a pigment) absorbs red and reflect the green light.

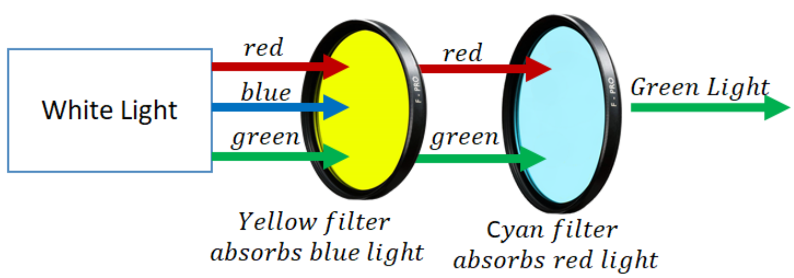


Figure 6.41 Color subtraction using yellow and cyan filters.

Vi. Magenta filter (or a pigment) absorbs green and Cyan filter (or a pigment) absorbs red and reflect the blue light.

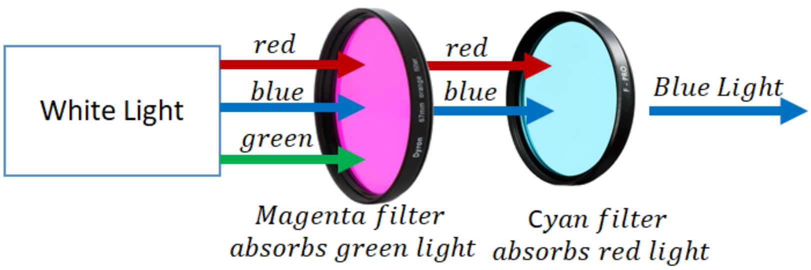


Figure 6.42 Subtraction using magneta and cyan filters

When you mix colors using paint, or through the printing process, you are using the subtractive color method. Subtractive color mixing means that one begins with white and ends with black; as one adds color, the result gets darker and tends to black.

Section summary

- Subtractive primary colors filter out all light when combined.
- Pigments can be produced by combining subtractive colors (magenta, yellow, and cyan).

Review questions

1. What colors of light are absorbed by a green pigment?
2. Which combination of colors of light gives magenta?
3. Which combination of colors of light gives cyan?
4. If yellow light falls on an object whose pigment absorbs green light, what color will the object appear?
5. If yellow light falls on a blue pigment, what color will appear?

Virtual Labs

On the soft copy of the book, click on the following link to perform virtual experiments on electromagnetic waves and geometrical optics unit under the guidance of your teacher.

1. Geometric Optics PhET Experiment.
2. Bending Light PhET Experiment.
3. Color Vision PhET Experiment.
4. Radio Waves & Electromagnetic Fields PhET Experiment.

Unit summary

- The ray model of light describes the path of light as straight lines.
- The speed of light in a vacuum is $2.99792458 \times 10^8\, m/s = 3.00 \times 10^8\, m/s$. The speed of light is different in different materials.
- Like all forms of electromagnetic waves, light can travel through vacuum as well as through matter.
- EM spectrum, the entire distribution of EM radiation according to frequency or wavelength. The entire EM spectrum, from the lowest to the highest frequency (longest to shortest wavelength), includes all radio waves (e.g., commercial radio and television, microwaves, radar), infrared radiation, visible light, ultraviolet radiation, X-rays, and gamma rays.
- Reflecting surfaces obey the laws of reflection. The refracting surfaces obey the laws of refraction.
- A light ray travelling obliquely from a denser medium to a rarer medium bends away from the normal. A light ray bends towards the normal when it travels obliquely from a rarer to a denser medium.

- The refractive index of a transparent medium is the ratio of the speed of light in vacuum to that in the medium.
- Mirrors and lenses form images of objects. Images can be either real or virtual, depending on the position of the object.
- The focal length of a spherical mirror is equal to half its radius of curvature.
- A compound microscope uses a convex objective lens to form an enlarged image that is further enlarged by an eyepiece.
- A refracting telescope uses a large objective lens and an eyepiece lens to form an image of a distant object.
- A reflecting telescope uses a large concave mirror that gathers light and an eyepiece lens to form an image of a distant object.
- The human eye mainly senses Red, Green and Blue, and the brain interprets combinations of these into all the colors you see.
- The most common set of primary colors is red, green and blue. When red, green and blue light are mixed or added together with the proper intensity, white light is obtained.
- Additive color synthesis occurs when three light zones (red, green, and blue) are mixed with optimum intensity and then white light is generated. Additive color synthesis: green + red = yellow, blue + red = magenta, blue + green = cyan.
- Subtractive synthesis occurs by mixing the basic material colors (cyan, magenta and yellow). If all three colors are mixed, a black color is created. They are mixed with: yellow + magenta = red, yellow + cyan = green, magenta + cyan = blue.

End Unit questions

1. You are looking at a burning candle. Draw the path of light that enables you to see that candle.
2. Explain why you need to protect yourselves from ultraviolet radiation from the Sun.
3. List some advantages and disadvantages of using X-rays.
4. Write a short essay on a type of electromagnetic waves. You should look at uses, advantages and disadvantages of your chosen radiation.
5. List the EM spectrum in order of increasing wavelength.
6. Do the reflected rays that contribute to forming the image from a plane mirror obey the law of reflection?
7. The image formed by a concave mirror is observed to be virtual, erect and larger than the object. Where should be the position of the object?
8. You wish to obtain an erect image of an object, using a concave mirror of focal length 15 cm. What should be the range of distance of the object from the mirror? What is the nature of the image? Is the image larger or smaller than the object? Draw a ray diagram to show the image formation in this case.
9. Name the type of mirror used in the following situations.
   (a) Headlights of a car.
   (b) Side/rear-view mirror of a vehicle.
   (c) Solar furnace. Support your answer with reason.
10. A concave lens of focal length 15 cm forms an image 10 cm from the lens. How far is the object placed from the lens? Draw the ray diagram.

11. An object is placed at a distance of 10 cm from a convex mirror of focal length 15 cm. Find the position and nature of the image.

12. The magnification produced by a plane mirror is +1. What does this mean?

13. An object 5.0 cm in length is placed at a distance of 20 cm in front of a convex mirror of radius of curvature 30 cm. Find the position of the image, its nature and size.

14. An object of size 7.0 cm is placed at 27 cm in front of a concave mirror of focal length 18 cm. At what distance from the mirror should a screen be placed, so that a sharp focused image can be obtained? Find the size and the nature of the image.

15. One-half of a convex lens is covered with a black paper. Will this lens produce a complete image of the object? Verify your answer experimentally. Explain your observations.

16. An object 5 cm in length is held 25 cm away from a converging lens of focal length 10 cm. Draw the ray diagram and find the position, size and the nature of the image formed.

17. A convex lens produces a virtual image which is four times larger than the object. The image is 15 cm from the lens. What is the focal length of the lens?

18. Compare and contrast primary light colors and primary pigment colors.

19. Determine the colors that are reflected from an object that appears black.

20. What color do the following shirts appear to the human eye when the lights in a room are turned off and the room is completely dark? A) red shirt B) blue shirt C) green shirt

21. The cover of a book appears to have a magenta color. What colors of light does it reflect and what colors does it absorb?

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