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Physics Student Textbook – Grade 10

Physics

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Grade 10

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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:

- *understand the differences between scalar and vector quantities;*
- *demonstrate vectors representation graphically;*
- *know how to add and subtract two or more vectors graphically;*
- *resolve a single vector into its components.*

1.1 Scalars and Vectors

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.*

Exercise 1.1

☞ From what you learnt in grade 9, what do you think are the differences between vectors and scalars?

Key concepts

☞ **Scalars** are quantities that have only magnitude whereas **Vectors** are quantities that have both direction and magnitude.

Exercise 1.2

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

As discussed in the introduction, physical quantities can be classified into two categories. Physical quantities that fall in the first category are those that can be completely specified by a number together with an appropriate unit of measurement. For instance, it makes perfectly good sense to say that the length of an object is 1.42 m or that the mass of an object is 12.21 kg. You do not have to add anything to the description of length or mass. Similarly, the statement that the density of water is 1000 kg/m^3 is a complete description of density. Quantities that can be specified in this simple and straightforward way are called scalar quantities. Thus, scalar quantities are physical quantities that can be completely specified by a single number together with an appropriate unit of measurement. Time, distance, speed, length, volume, temperature, energy and power are other examples of scalar quantities.

On the other hand, quantities that fall in the second category are those 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 algebraically and graphically;*
- *discuss about the different types of vectors.*

Exercise 1.3

☞ How can you represent vectors?

In the previous section, you learnt that vectors are represented both in magnitude and direction. On the other hand, vector quantities are represented either algebraically or geometrically. Algebraically, they are represented by a bold letter as $\boldsymbol{A}$ or with an arrow over the letter, for example, $\vec{A}$. For example, a displacement can be represented by the expression $\boldsymbol{S} = 50\ km$, Southwest. $S = 50\ km$ designates only the magnitude of the vector. The magnitude is also indicated by placing the absolute value notation around the symbol that denotes the vector; so, you can write equivalently that $S \equiv |\boldsymbol{S}|$.

On the other hand, vectors are represented geometrically by an arrow, or an arrow-tipped line segment. Such an arrow having a specified length and direction shows the graphical representation of a vector. You will use this representation when drawing vector diagrams. 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 arrow is drawn to scale so that its length represents the magnitude of the vector, and the arrow points in the specified direction of the vector. Hence,

Figure 1.1 Head and tail of a vector.

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

Thus, in order to draw a vector accurately, you must specify a scale and include a reference direction in the diagram. To do this, you need a ruler to measure and draw the vectors to the correct length. The length of the arrow should be proportional to the magnitude of the quantity being represented. So you must decide on a scale for your drawing. For example, you might let 1 *cm* on paper represent 2 *N* (1 cm represents 2 *N*), a force of 20 *N* towards the East would be represented as an arrow 10 *cm* long. A scale allows us to translate the length of the arrow into the vector's magnitude. The important thing is to choose a scale that produces a diagram of reasonable size. A reference direction may be a line representing a horizontal surface or the points of a compass.

Key concepts

☞ Vectors are represented either algebraically or geometrically.

The following are the procedures that you might use for drawing vectors graphically.

1. Decide upon a scale and write it down.
2. Determine the length of the arrow representing the vector by using the scale.

3. Draw the vector as an arrow. Make sure that you fill in the arrow head.

4. Fill in the magnitude of the vector.

Example 1.1

Draw the vector, 16 *km* East, to scale by indicating the scale that you have used:

Solution

First, let us decide upon a scale. Let 1 *cm* represent 4 *km*. So if 1 $cm = 4$ *km*, then 16 $km = 4$ *cm* and the direction is in the East. Using this information, you can draw the vectors as arrows as follows.

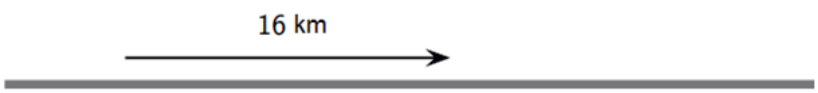


Figure 1.2 A scaled diagram for a vector with a magnitude of 16 *km*.

On the other hand, the following are some of the different types of vectors.

1. **Zero vector or Null vector:** a vector with zero magnitude and no direction.

2. **Unit Vector:** vector that has magnitude equal to one.

3. **Equal vectors:** vectors that have the same magnitude and same direction.

4. **Negative of a vector:** a vector that have the same magnitude but opposite direction with the given vector.

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.

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

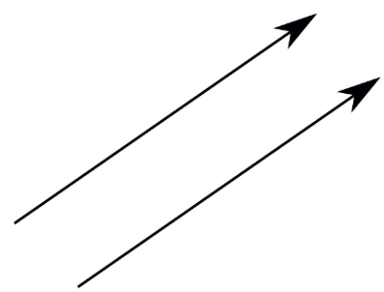


Figure 1.3 Two equal vectors.

Review questions

1. Give an example of a vector stating its magnitude, units and direction.

2. Choose your own scale and draw arrows to represent the following vectors:
   A) $\vec{A} = 40\ \ km$ North,
   B) $\vec{B} = 32\ \ m/s$ making an angle of 60^o with the horizontal.

3. Discuss the different types of vectors.

1.3 Vector addition and subtraction

Exercise 1.4

Is it possible to add two vectors in the same way as you did in scalars? Explain.

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

- *explain how to add and subtract vectors;*
- *define the term resultant vector.*

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

Key concepts

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

Addition of Vectors

The addition of scalar quantities is non problematic, it is a simple arithmetic sum. For example, the total mass of 2 kg plus 3 kg is 5 kg. The increase in temperature from 5^oC to 12^oC is 7^oC. However, like scalars, you cannot add two vectors. This is because when two vectors are added, you need to take account of their direction as well as their magnitude. Of course, 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.

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.

If vectors $\vec{A}$ and $\vec{B}$ have a resultant $\vec{R}$, this can be represented mathematically as,

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

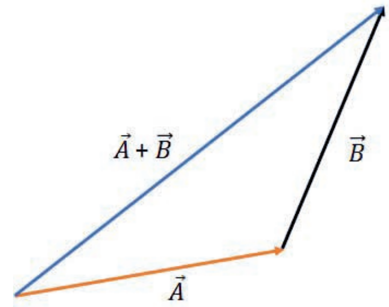


Figure 1.4 Addition of vectors $\vec{A}$ and $\vec{B}$.

Subtraction of Vectors

Vector subtraction is a straight forward extension of vector addition. If you want to subtract $\vec{B}$ from $\vec{A}$, written $\vec{A}-\vec{B}$, you must first define what is meant by subtraction. As it is discussed in the previous section, the negative of vector $\vec{B}$ is defined to be $-\vec{B}$; that is, graphically the negative of any vector has the same magnitude but opposite in direction as shown in Figure 1.5. In other words, $\vec{B}$ has the same length as $-\vec{B}$, but points in the opposite direction. Essentially, you just flip the vector so that it points in the opposite direction.

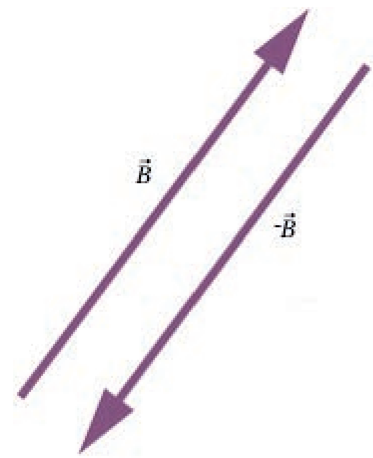


Figure 1.5 Vector $\vec{B}$ and the negative of Vector $\vec{B}$.

The subtraction of vector $\vec{B}$ from vector $\vec{A}$ is then simply defined to be the addition of $-\vec{B}$ to $\vec{A}$. That is,

$$\vec{A} - \vec{B} = \vec{A} + (-\vec{B}) \tag{1.2}$$

Note that vector subtraction is the addition of a negative vector. The order of subtraction does not affect the results. Hence, as it is indicated in Figure 1.6, draw vector $-\vec{B}$ from the tip of $\vec{A}$ and join the tail of $\vec{A}$ with the tip of $-\vec{B}$, then the resulting vector is the difference ($\vec{A}$ - $\vec{B}$).

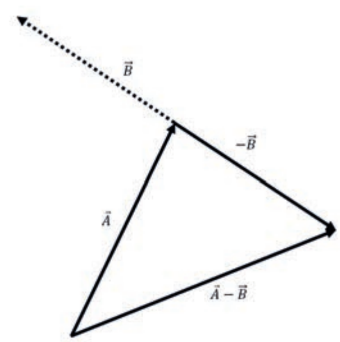


Figure 1.6 Subtraction of $\vec{B}$ from $\vec{A}$.

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.

Exercise 1.5

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

Review questions

1. What is meant by subtraction of vector?
2. What is meant by resultant vector?

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.*

You can add or subtract vectors using the algebraic or graphical method of vector addition. You will learn about the algebraic method in your grade 11 physics. In this section, you will learn about the graphical method of vector addition and subtraction.

As discussed above, one method for adding vectors involves manipulating their graphical representations on paper. So using the graphical method of vector addition, vectors are drawn to scale and the resultant is determined using a ruler and protractor. The following is the discussion of the primary graphical techniques: the triangle method, the parallelogram method, and the polygon method.

Key concepts

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

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.

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 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.

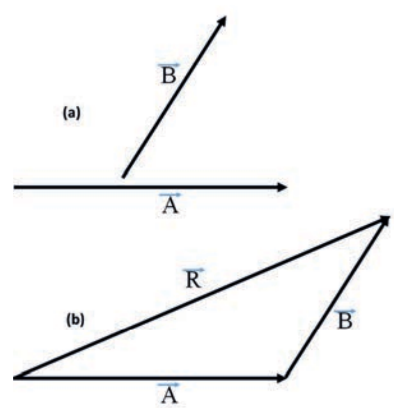


Figure 1.7 The triangle rule for the addition of two vectors.

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). This is written as:

$$\vec{R} = \vec{A} + \vec{B} \tag{1.3}$$

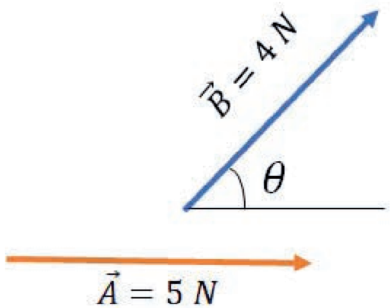


Figure 1.8 Two vectors $\vec{A}$ and $\vec{B}$.

Activity 1.2

Consider adding two vectors $\vec{A}$ and $\vec{B}$ graphically. The two vectors are shown in Figure 1.8. Using the above procedure of vector addition, add these two vectors using the triangle law of vector addition if the angle θ is 30^o.

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 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

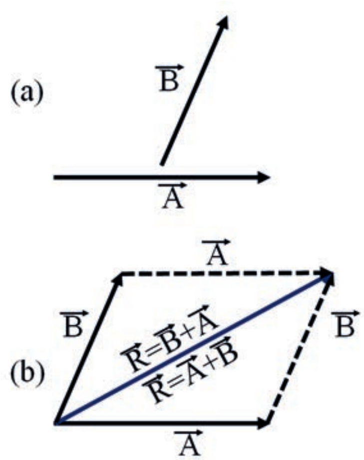


Figure 1.9 The Parallelogram rule for the addition of two vectors.

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

$$\vec{R} = \vec{A} + \vec{B} \tag{1.4}$$

Activity 1.3

Repeat activity 1.2 using the parallelogram method of vector addition.

Since vector addition is commutative,

$$\vec{A} + \vec{B} = \vec{B} + \vec{A} \tag{1.5}$$

Polygon method of vector addition

This law is used for the addition of more than two vectors. According to this law, if you have a large number of vectors, place the tail end of each successive vector at the head end of previous one. The resultant of all vectors can be obtained by drawing a vector from the tail end of first to the head end of the last vector.

Suppose you 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). You 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, you 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. You repeat this procedure until all the vectors are in a head-to-tail arrangement like the one shown in (Figure 1.10 (b)). You 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.

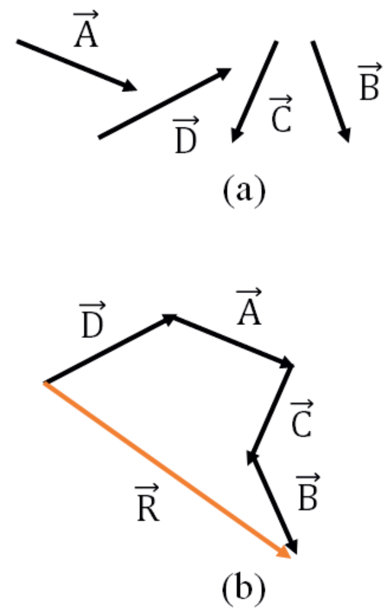


Figure 1.10 The polygon rule for the addition of vectors.

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, you obtain the same resultant vector regardless of which vector you choose to be first, second, third, or fourth in this construction.

Activity 1.4

Use the polygon method of vector addition to find the resultant vector $\vec{R}$ 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.

Note: You will follow the same procedure during the subtraction of vectors. Let us now consider a few special cases of addition of vectors.

1. **When the two vectors are in the same direction (parallel to each other)**

If vectors $\vec{A}$ and $\vec{B}$ are parallel, then the magnitude of the resultant vector $\vec{R}$ is the sum of the magnitudes of the two vectors. Hence, the magnitude of the resultant vector is

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

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.

Key concepts

To determine the resultant of two vectors acting:
☞in the same direction, add the given vectors and take the common direction.
☞in opposite directions, get the difference and take the direction of the vector with the greater value.

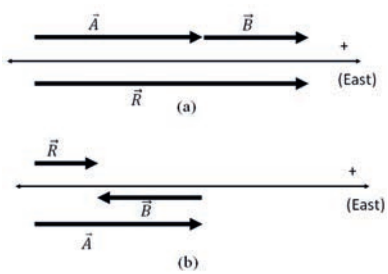


Figure 1.11 Resultant vector $\vec{R}$ of two vectors $\vec{A}$ and $\vec{B}$ when they are (a) same direction and (b) opposite direction.

2. **When the two vectors are acting in opposite directions**
   If vectors $\vec{A}$ and $\vec{B}$ are anti-parallel (i.e., in opposite direction), 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

$$|R| = |A - B| \tag{1.7}$$

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.

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 act in opposite directions.

3. **When the two vectors are perpendicular**
   If vectors $\vec{A}$ and $\vec{B}$ are perpendicular to each other as shown in 1.12, then the magnitude of the resultant vector $\vec{R}$ is obtained using the

Pythagoras theorem. Hence, the magnitude of the resultant vector is

$$|R| = \sqrt{A^2 + B^2} \tag{1.8}$$

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

$$\theta = tan^{-1}\left(\frac{B}{A}\right) \tag{1.9}$$

Note: You can compare the result you obtain in each of the three cases with a ruler and protractor. Surely, you will obtain similar result.

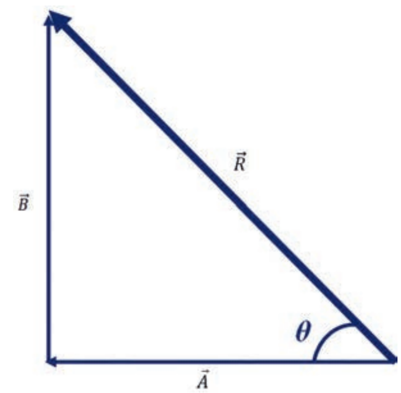


Figure 1.12 Two perpendicular vectors $\vec{A}$ and $\vec{B}$; and its resultant vector $\vec{R}$.

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 (a) in the same direction, (b) in opposite direction and (c) perpendicular to each other?

Solution:
You are given with two vectors of magnitudes 6 *units* and 3 *units*.

(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,
$|R| = \sqrt{A^2+B^2} = (\sqrt{6^2+3^2})\ units = 6.7\ units.$

Please compare the result you obtained here with the value you obtained with the direct measurement by a ruler.

Exercise 1.6

If two vectors $\vec{A}$ and $\vec{B}$ are perpendicular, how you can find the sum of the two vectors?

Section Summary

- Two vectors can be added by graphical means using the triangle and the parallelogram method. But for more than two vectors, the polygon method is used.

Review questions

1. 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?

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

3. If three vectors have unequal magnitudes, can their sum be zero? Explain.

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

5. Vector $\vec{C}$ is 6 m in the x-direction. Vector $\vec{D}$ is 8 m in the y-direction. Use the parallelogram method to work out $\vec{C} + \vec{D}$.

1.5 Vector resolution

Exercise 1.7

What do you think is vector resolution?

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.

Placing vectors in a coordinate system that you have chosen makes it possible to decompose them into components along each of the chosen coordinate axes. In the rectangular coordinate system shown in Figure 1.13, vector $\vec{A}$ is broken up or resolved into two component vectors. One, A_x, is parallel to the x-axis, and the other, A_y, is parallel to the y-axis.

The horizontal and vertical components can be found by two methods: graphical method and simple trigonometry. Let us look at them one by one.

Graphical method of vector resolution:

The following are the steps that you follow to resolve a vector graphically.

1. Select a scale and draw the vector to scale in the appropriate direction.
2. Extend x- and y-axes from the tail of the vector to the entire length of the vector and beyond.
3. From the arrow head of the vector, construct perpendicular projections to the x- and the y-axes.
4. Draw the x-component from the tail of the vector to the intersection of the perpendicular projection with the x-axis. Label this component as A_x.
5. Draw the y-component from the tail of the vector to the intersection of the perpendicular projection with the y-axis. Label this component as A_y.
6. Measure the length of the two components and use the scale to determine the magnitude of the components.

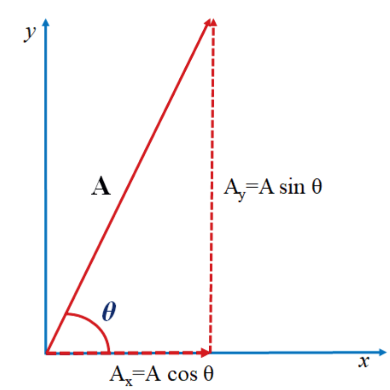


Figure 1.13 The horizontal (A_x) and vertical (A_y) components of vector $\vec{A}$.

Trigonometric method of vector resolution:

The trigonometric method of vector resolution relies on an understanding of the sine, cosine, and tangent functions. You can find the components by using trigonometry. The components are calculated according to these equations, where the angle θ is measured counterclockwise from the positive x-axis.

$$\cos\theta = \frac{\text{Adjacent side}}{\text{hypotenuse}} = \frac{A_x}{A} \implies A_x = A\cos\theta \tag{1.10}$$

and

$$\sin\theta = \frac{\text{Opposite side}}{\text{hypotenuse}} = \frac{A_y}{A} \implies A_y = A\sin\theta \tag{1.11}$$

You can see that the original vector is the sum of the two component vectors.

$$\vec{A} = \vec{A}_x + \vec{A}_y \tag{1.12}$$

Because A_x and A_y are at a right angle (90^o), the magnitude of the resultant vector can be calculated using the Pythagorean Theorem.

$$|A| = \sqrt{A_x{}^2 + A_y{}^2} \tag{1.13}$$

To find the angle or direction of the resultant, recall that the tangent of the angle that the vector makes with the x-axis is given by the following.

$$\theta = tan^{-1}\left(\frac{A_y}{A_x}\right) \quad \text{where } \tan\theta = \frac{\text{Opposite side side}}{\text{Adjacent side}} = \frac{A_y}{A_x} \tag{1.14}$$

Key concepts

Vectors can be resolved into components along a specified set of coordinate's axes.

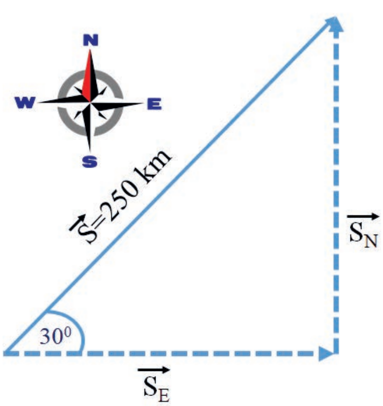


Figure 1.14 Resolving of resultant displacement.

Example 1.2

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:

$$S_N = (250)(sin\, 30^o) = 125\ km$$
$$S_E = (250)(cos\, 30^o) = 216.5\ km$$

Please check your answer with the graphical method, i.e., with ruler and protractor.

Example 1.3

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 1.15. The magnitude of the displacement $|S|$ is given by the Pythagorean theorem as follows:

$$|S| = [(3\ km)^2 + (2\ km)^2]^{1/2} = 3.6\ km$$

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

$$tan\,\theta = \frac{2\ km}{3\ km} = 0.666$$

Thus,

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

Hence, the boy's displacement vector is 3.61 km with 56.31^o East of North, or 33.69^o North of East.

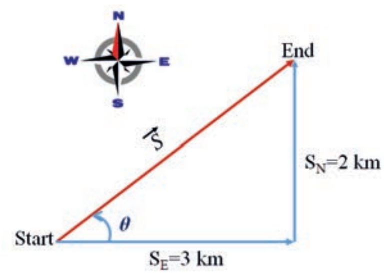


Figure 1.15 The magnitude and direction of the boy's motion.

Please check your answer with the graphical method, i.e., with ruler and protractor.

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.

Exercise 1.8

Could a vector ever be shorter than one of its components? Could it be equal in length to one of its components? Explain.

Review questions

1. What is resolution of a 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 vector.
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 head represents the vector direction.

- Vector addition is nothing but finding the resultant of a number of vectors acting on a body while vector subtraction is addition of the negative of a vector.
- The sum of two or more vectors is called the resultant. The resultant of two vectors can be found using either the parallelogram method or the triangle method. For more than two vectors, one can use the polygon method of vector addition.
- 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 $\vec{A}_x = A\cos\theta$ and the vertical component of $\vec{A}$ is $\vec{A}_y = A\sin\theta$.

End of unit questions and problems

1. A vector drawn 15 *mm* long represents a velocity of 30 *m/s*. How long should you draw a vector to represent a velocity of 20 *m/s*?
2. A vector that is 1 *cm* long represents a displacement of 5 *km*. How many kilometers are represented by a 3 *cm* vector drawn to the same scale?
3. Describe how you would add two vectors graphically.
4. Which of the following actions is permissible when you are graphically adding one vector to another? A) move the vector B) rotate the vector C) change the vector's length.
5. In your own words, write a clear definition of the resultant of two or more vectors.

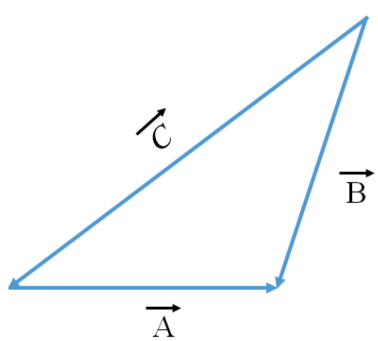


Figure 1.16 Magnitude and

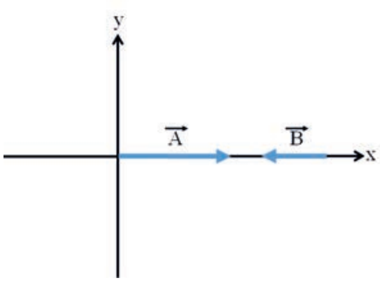


Figure 1.17 Magnitude and direction of two vectors

6. Explain the method you would use to subtract two vectors graphically.

7. You walk 30 *m* South and 30 *m* East. Find the magnitude and direction of the resultant displacement both graphically and algebraically.

8. A hiker walks 14.7 *km* at an angle 35^o East of South. Find the East and North components of this walk.

9. If two vectors have equal magnitudes, can their sum be zero? Explain.

10. Based on the three vectors in Figure 1.16, which of the following is true?

    (a) $\vec{A}+\vec{B}+\vec{C}=0$

    (b) $\vec{A}=\vec{C}+\vec{B}$

    (c) $\vec{C}+\vec{A}=\vec{B}$

11. For the two vectors $\vec{A}$ and $\vec{B}$ with magnitude 6.8 *cm* and 5.5 *cm* in Figure 1.17, determine the magnitude and direction of:

    (a) $\vec{R}=\vec{A}+\vec{B}$

    (b) $\vec{R}=\vec{A}-\vec{B}$

    (c) $\vec{R}=\vec{B}-\vec{A}$

12. Three vectors $\vec{A}$, $\vec{B}$ and $\vec{C}$ have a magnitude and direction of 21 *unit* North, 16 *unit* East and 26 *unit* South, respectively. Graphically determine the resultant of these three vectors?

13. If $\vec{v}_x = 9.8$ *m/s* and $\vec{v}_y = 6.4$ *m/s*, determine the magnitude and direction of $\vec{v}$.

Unit 2

Uniformly Accelerated Motion

Introduction

In your grade 9 Physics, you have learnt 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 causes the motion of an object to become non uniform. This non uniform 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 uniformly accelerated motion;*
- *understand the different types of motions used 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 distance and displacement traveled by an object;*
- *describe the difference between distance and displacement.*

Position

Exercise 2.1

Can two objects be at the same distance from a single point while being in different positions? Why or why not?

To describe the motion of an object, you must first be able to describe its position, or where it is at any particular time. 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. So, you need to specify its position relative to a convenient frame of reference. A frame of reference is an arbitrary set of axes from which the position and motion of an object are described.

To visualize position for objects moving in a straight line, you can imagine the object is on a number line. The object may be placed at any point on the number line in the positive numbers or the negative numbers. It is common to choose the original position of the object to be on the zero mark as shown in Figure 2.1. In making the zero mark the reference point, you have chosen a frame of reference. The exact position of an object is the separation between the object and the reference point.

Key Concept

☞ The location of an object in a frame of reference is called position.

Position is thus the location of an object with reference to an origin. It can be negative or positive. It has units of length: centimeter (cm), meter (m) or kilometer (km). For example, depending on that reference point you choose, you can say that the new constructed school is 300 m from Kemal's house (with Kemal's house as the reference point or origin).

Displacement

From your grade 9 Physics, you know that distance is the total length of the path taken in going from the initial position to the final position. 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 the dashed line, while displacement is the straight-line distance from the starting point to the endpoint.

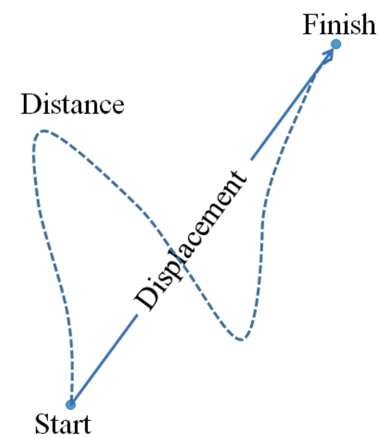


Figure 2.1 The possible distance and displacement of an object in motion between two points.

Activity 2.1

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:

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

Exercise 2.2

What is the difference between distance and displacement?

In order to answer exercise 2.2, 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 Figure 2.2. Let A, B, and C represent the position of the object at different instants.

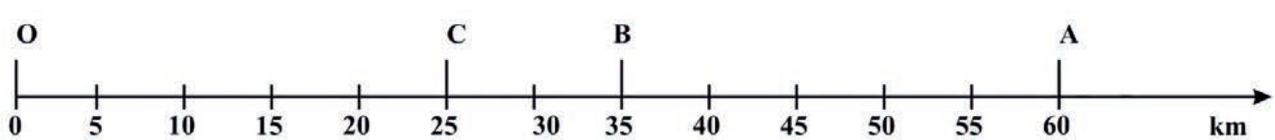


Figure 2.2 Positions of an object on a straight line path.

Exercise 2.3

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

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 = 60 *km* - 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.

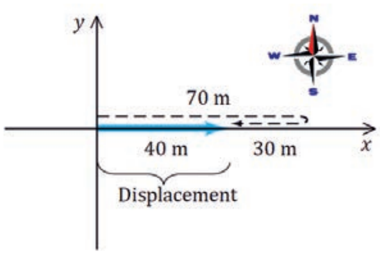


Figure 2.3 A person walking 70 *m* East and then 30 *m* West.

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: $\vec{\Delta s} = s - s_o = 70\ \ m\ \ - 30\ m$ as both vectors are in an opposite direction with one another. Thus,

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

The displacement is only 40 *m* since the person is now only 40 *m* from the starting point but the total distance traveled is 70 *m* + 30 *m* = 100 *m*.

Key Concepts

- Distance is the actual path that is travelled by a moving body, where as displacement is the 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 shows the difference among distance traveled, displacement, and magnitude of displacement. Identify each quantity in your example.
3. A body travels a distance of 15 m 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 2.2

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 2.4

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

Average velocity

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

Key Concept

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

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's 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. You can express average velocity ($\vec{v_{av}}$) mathematically as:

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

where $t - t_o$ is change in time, and t_o is the starting time which is commonly zero.

Exercise 2.5

☞ Does the speedometer of a car measure speed or velocity?

The SI unit for average velocity is meters per second (m/s or $m\ s^{-1}$). But there are also many other units, such as kilometer per hour (km/h), miles per hour (mi/h (also written as mph)) and centimeter per second (cm/s) in common use.

Exercise 2.6

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

☞ In which situation will the instantaneous velocity and average velocity of an object be the same?

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

$$\mathrm{v_{av}} = \frac{\text{total distance travelled}}{\text{total time taken}} = \frac{\mathrm{s_{tot}}}{\mathrm{t_{tot}}} \tag{2.3}$$

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.

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.

Key Concept

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

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

$$\vec{v} = \frac{s - s_o}{t - t_o} \text{ when } \mathrm{t - t_o} \text{ approaches } 0 \qquad (2.4)$$

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

Figure 2.4 A fatal car accident.

Road traffic accidents are among the main causes of mortality in Ethiopia. Speed is still the most common factor in fatal road accidents, accounting for more than half of all road deaths each year. Figure 2.4 shows one of the fatal car crash where at least 5 people were died and 17 others injured after a minibus collided with a parked car somewhere in Ethiopia. It may not seem like much, but driving even a few kilometers per hour above the speed limit greatly increases the risk of an accident. Speed limits are used to set the legal maximum or minimum speed at which road vehicles may travel on a given stretch of road. They are generally indicated on a traffic sign reflecting the maximum or minimum speed permitted that is expressed usually in kilometers per hour (*km/h*). Speed limits are being started to be monitored by traffic officers in the various streets and roads of our country. Speed limits are used to regulate the speed of vehicles in certain places and it also controls the flow of traffic. It is also observed to minimize accidents from happening.

Exercise 2.7

☞ Can you imagine the things that would happen if a driver does not obey the speed limits set and are moving in uniformly accelerated motion?

Example 2.2

It takes you 10 *minutes* 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:

You are given with $\Delta t = 10\ minutes = 600\ s$ and $v_{av} = 1.2\ \frac{m}{s}$, North.
You want to find Δs.

Since

$$\vec{v}_{av} = \frac{\vec{\Delta s}}{\Delta t}, \qquad \vec{\Delta s} = \vec{v_{av}} \times \Delta t = 1.2\ \frac{m}{s} \times 600\ s = 720\ m,\ \ North$$

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

Example 2.3

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

Solution:

You are given $\vec{\Delta s} = 4\ m\ \ and\ \ \Delta t = 8\ s$.
What you want to find is V_{av}.

The average velocity is thus

$$\vec{v}_{av} = \frac{\vec{\Delta s}}{\Delta t} = \frac{4\ m}{8\ s} = 0.5\ m/s$$

Example 2.4

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

Solution:

You are given $s_1 = 100\ km,\ v_1 = 50\ km/h,\ s_2 = 100\ km,\ v_2 = 100\ km/h.$ In order to find the average speed, you first need to find the total distance traveled and total time taken.

Thus, the total distance traveled is $100\ km + 100\ km = 200\ km$. The total time taken is $t_1 + t_2$ where

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

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

The car's average speed is thus

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

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

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?

Exercise 2.8

Cheetahs, the world's fastest land animals, can run up to about 125 km/h. A cheetah chasing an impala runs 32 m north, then suddenly turns and runs 46 m west before lunging at the impala. The entire motion takes only 2.7 s.

(a) Determine the cheetah's average speed for this motion.

(b) Determine the cheetah's average velocity.

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.

Exercise 2.9

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?

2.3 Acceleration

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

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

When you watch the first few seconds of a liftoff, a rocket barely seems to move. With each passing second, however, you can see it move faster until it reaches an enormous speed. How could you describe the change in the rocket's motion? When an object changes its motion, it is accelerating.

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. That is,

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

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

where v_o is the initial velocity of an object and v is the final velocity of an object at instants t_o and t, respectively. In this equation, $t - t_o$ is the length of time over which the motion changes. In SI units, acceleration has units of meters per second squared (m/s^2).

The direction of average acceleration is the direction of change in velocity. If an object speeds up, the acceleration is in the direction that the object is moving. You get on a bicycle and begin to pedal. The bike moves slowly at first, and then accelerates because its speed increases. When the speed of an object increases, it is said to be accelerating. On the other hand, if an object slows down, the acceleration is opposite to the direction that the object is moving. This is commonly referred to as deceleration. In Figure 2.5, a light train in Addis Ababa, Ethiopia, decelerates as it comes into a station. Thus, the train is accelerating in a direction opposite to its direction of motion.

Key Concept

☞ Acceleration occurs whenever an object speeds up, slows down, or changes direction.

Figure 2.5 A decelerating light train.

When you speed up, your final speed will always be greater than your initial speed. So subtracting your initial speed from your final speed gives a positive number. As a result, your acceleration is positive when you are speeding up. When you slow down, the final speed is less than the initial speed. Because your final speed is less than your initial speed, your acceleration is negative when you slow down.

Exercise 2.10

☞ What do you mean by an instantaneous acceleration for an object in motion?

Instantaneous acceleration

Key Concept

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

The object moving in a straight line may undergo an increase, or decrease in acceleration or it may move with a uniform acceleration or zero acceleration. Thus, in such cases, the average acceleration does not describe the motion of the object at every instant. The average acceleration only provides the mean value of the acceleration instead of the actual acceleration of the object during the motion while the instantaneous acceleration gives the exact acceleration at every instant during the motion.

Instantaneous acceleration is a quantity that tells us the rate at which an object is changing its velocity at a specific instant in time anywhere along its path. Hence, instantaneous acceleration a, or acceleration at a specific instant in time, is obtained using the same process discussed for instantaneous velocity. That is, you calculate the average velocity between two points in time separated by Δt and let Δt approach zero. You see that average acceleration $\mathbf{a} = \frac{\Delta \mathbf{v}}{\Delta t}$ approaches instantaneous acceleration as Δt approaches zero. The instantaneous acceleration is, thus mathematically expressed as,

$$a = \frac{\Delta \mathbf{v}}{\Delta t} \text{ as } \Delta t \text{ approaches } 0. \quad (2.6)$$

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

Exercise 2.11

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

Example 2.5

A car accelerates on a straight road from rest to 75 km/h in 5 s. What is the magnitude of its average acceleration?

Solution:
You are given with $v_0 = 0$, $v = 75\ km/h$ and $\Delta t = 5\ s$.
You want to find the average acceleration.

The average acceleration can be calculated by

$$\vec{a}_{av} = \frac{v - v_o}{t - t_o} = \frac{75\ km/h - 0\ km/h}{5\ s - 0s} = 15\ \frac{km/h}{s}.$$

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 = 2.0 s, and so on. This result contains two different time units: hours and seconds. You usually prefer to use only seconds. To do so, you can change *km/h* to *m/s*:

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

Exercise 2.12

☞ Think about the greatest accelerations you have experienced. Where did they occur? Did they involve speeding up or slowing down? What effects did they have on you?

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

$$\vec{a}_{av} = \frac{21\ m/s - 0m/s}{5\ s - 0s} = 4.2\ \frac{m/s}{s} = 4.2\ m/s^2$$

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

Exercise 2.13

☞ Discuss the concept of deceleration and negative acceleration.

Example 2.6

An automobile is moving to the right along a straight highway, which you 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 15 *m/s* and it takes 5.0 *s* to slow down to 5 *m/s*, what was the car's average acceleration?

Solution:

In this example, you are given with $v_0 = 15\ m/s,\ v = 5\ m/s$ and $\Delta t = 5.0\ s$. The required quantity is average acceleration.

Average acceleration can thus be calculated using the formula time.

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

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

The negative sign appears because the final velocity is less than the initial velocity. Thus, 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. That is the automobile is decelerating. But be careful: **deceleration** does not mean that acceleration is necessarily negative.There is a deceleration whenever the magnitude of the velocity is decreasing; thus, the velocity and acceleration point in opposite directions when there is a deceleration.

Activity 2.3

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

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.
- Instantaneous acceleration is the acceleration of the object at a specific instant during the motion.

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 race horse 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:

- *derive the equations of motion with constant acceleration;*
- *use appropriate equations of motion to solve motion-related problems.*

Exercise 2.14

How can you derive the equations of a uniformly accelerated motion?

If an object travels in a straight line and its velocity increases or decreases by equal amounts at 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. If an object's average acceleration during a time interval is known, the change in velocity during that time can be calculated. For convenience, you let the starting time $t_f = t$, where t is any arbitrary time. Also, let $\vec{v}_o$ be the initial velocity at time $t_o = 0$ and $\vec{v}$ be 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 acceleration is constant in a uniformly accelerated motion, the average and instantaneous accelerations are the same. So, you can replace $\vec{a}_{av}$ by $\vec{a}$. Moreover, in one-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 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 s_0 be the initial position at time $t_0 = 0$ and $s_f = s$ be the position at any time t. If the initial position is at the origin, $s_o = 0$, and hence $\Delta s = s$. So from the expression of average velocity, you can write s as

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

Substituting equation 2.8 into 2.9 gives:

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

Again 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

☞ Equations of uniformly accelerated motions are used to solve problems involving constant acceleration.

Example 2.7

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

Solution:

You are given with $v_o = 0$, $t = 5\ s$, and $s = 100\ m$.

The required quantity is acceleration, a.

From the expression for displacement, i.e.,

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

By making $v_o = 0$, you can easily derive and solve for a as

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

Substitution gives

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

Example 2.8

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

Solution:

You are given with $v_o = 70\ m/s,\ t = 40\ s,$ and $a = -1.5\ m/s^2$.
You want to find the final velocity, v.

You can find for the final velocity using the formula

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

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 travel when it was traveling at 25 *m/s*?

Solution:
In this example, you are given with $v_o = 0,\ v = 25\ m/s,$ and $a = 3.5\ m/s^2$.
You are asked to find the displacement, s.

You can find s using the equation

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

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.

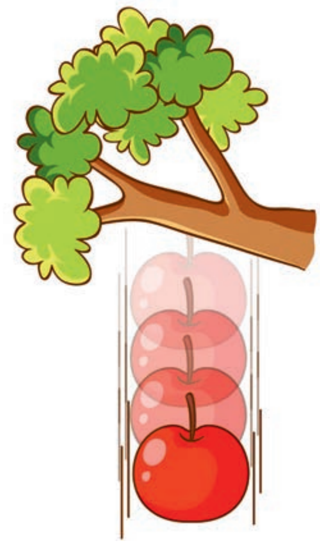


Figure 2.6 The freely falling of an apple with uniform acceleration due to gravity.

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

Activity 2.4

Suppose you hold a book in one hand and a flat sheet of paper in another hand. You drop them both and they fall to the ground. Explain why the falling book is a good example of free fall, but the paper is not.

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 9.80 m/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 derived above for objects moving with constant acceleration can be applied. The only modification that you need to make in these equations is to replace the acceleration 'a' of the equations with 'g' and the distance 's' with the height 'h' since the vertical distance of the freely falling bodies is known as height 'h'.

The equation of motion can thus be modified as:

$$v = v_o + gt \quad (2.13)$$

$$h = v_o t + \frac{1}{2} g t^2 \quad (2.14)$$

$$v^2 = {v_0}^2 + 2gh \quad (2.15)$$

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

Exercise 2.15

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

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:

You are given with $v_0 = 0$, $g = 9.8\ m/s^2$, and $t = 1\ s$.
The required quantities are final velocity and height.

You can find the velocity using the equation

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

On the other hand, the vertical height can be calculated using the equation

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

Section summary

- Uniformly accelerated equations are equations that are used to solve problems involving constant acceleration.
- The five quantities or variables commonly encountered in the uniformly accelerated motion equations are displacement, time, initial velocity, final velocity, and constant acceleration.
- Since the freely falling bodies with uniformly accelerated motion, the equations of motion derived for bodies under uniform acceleration can be applied to the motion of freely falling bodies by substituting 'a' by 'g' and 's' by 'h'.

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 is dropped from the top of a building is in free fall for 8.0 s.
   (a) Calculate the stone's velocity when it reaches the ground.
   (b) What is the height of the building from which the stone had been dropped?

2.5 Graphical representation of uniformly accelerated motion

Exercise 2.16

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

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

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

In your grade 9 physics, you learnt about the graphs of uniform motion. Figure 2.7 shows the summary of the graphs of a uniform motion.

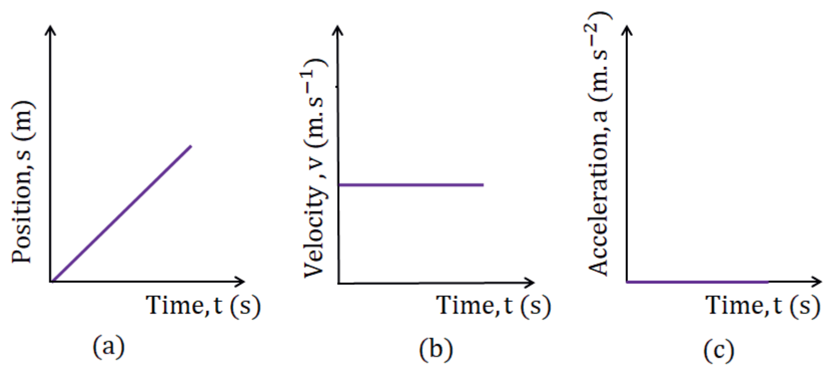


Figure 2.7 Graphs for motion at constant velocity (a) position-time (b) velocity-time (c) acceleration-time.

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 the position *s* 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 equation 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 uniformly accelerated motion is a parabola, as shown in Figure 2.8 (a).

Exercise 2.17

How does uniform acceleration motion differ from uniform motion?

As you learnt in grade 9, position-time graph's slope represents the velocity of the object. Because the line is curved, however, its slope keeps changing. Thus, you 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 Figure 2.8(b). The slope of the tangent line is therefore an instantaneous velocity.

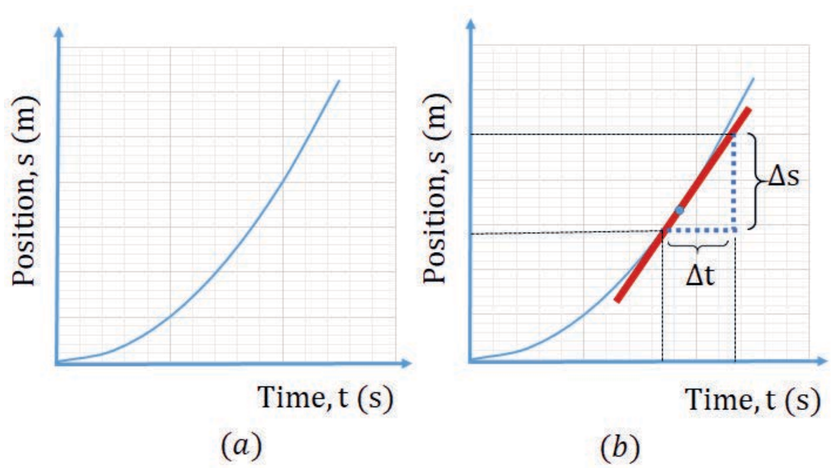


Figure 2.8 (a) The position-time graph with constant acceleration, (b) the slope of the tangent line at a particular point gives the instantaneous velocity.

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).

$$\text{Slope} = \frac{\text{rise}}{\text{run}} = \frac{\Delta s}{\Delta t} = \text{instantaneous velocity} \qquad (2.16)$$

Key Concept

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

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.

Example 2.11

A car starts from rest and accelerates at a 10 m/s^2 for 10 s on the straight, level road. Draw a position-time graph and calculate the instantaneous velocity at 4 s.

Solution:

In this example, you are given $v_o = 0\ m/s,\ a = 10\ m/s^2$, and $t = 10\ s$.

To draw the position-time graph, first solve for s using the equation $s = \frac{1}{2}at^2$ for the different values of t. Record and compare the result you obtained with the following table.

Position (m)	0	5	20	45	80	125	180
Time (s)	0	1	2	3	4	5	6

Then plot the position on the y-axis and time on the x-axis. The graph is shown as in the Figure 2.9.

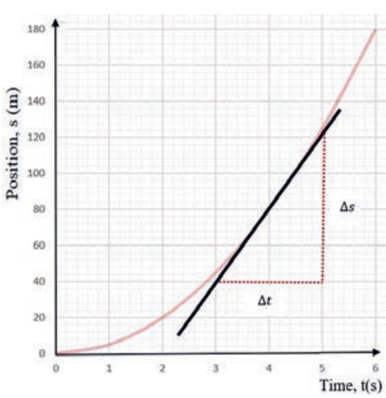


Figure 2.9 Position-time of the given problem.

On the other hand, to find the instantaneous velocity, draw the tangent line at the given time. The slope of the tangent line drawn at 4 s of the x-axis coordinate represents the instantaneous velocity at instant of 4 s. The slope of tangent line becomes:

$$Slope = \frac{\Delta s}{\Delta t} = \frac{120\ m - 40\ m}{5\ s - 3\ s} = \frac{80\ m}{2\ s} = 40\ \frac{m}{s}$$

Thus, the instantaneous velocity is 40 m/s.

Activity 2.5

☞ Suppose a truck accelerates with average accelerations of 20.0 m/s^2 starting from rest for 5.0 *s*.

a) How far does it travel in this time? Draw position-time graph?

b) Draw the tangent line at different point on the graph.

c) Find the slope of each tangent line that you draw.

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. The velocity-time graph of the given motion shows how its velocity changes as it travels over 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 Figure 2.10 (a)).

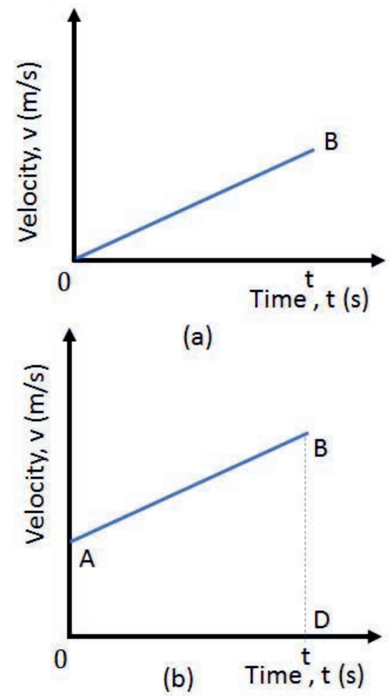


Figure 2.10 The velocity-time graph.

If the particle has an initial velocity, the graph will be a straight line, but will not pass through the origin as shown in Figure 2.10 (b). In Figure 2.10 (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 velocity-time graph

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 shown in Figure 2.11. The area under the velocity-time graph during the interval 0 to t is ABDO.

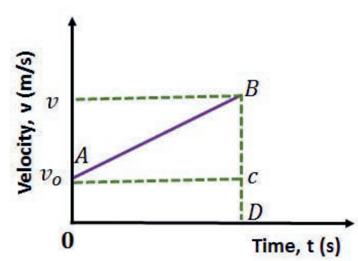


Figure 2.11 The area under velocity-time graph.

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

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

Key Concept

☞ The area under the curve in a velocity-time graph is the change in position or displacement.

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

B) Slope of a velocity-time graph

As discussed 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 Figure 2.11. Let v_o be the velocity at $t_o = 0$ and v be the velocity after a time interval t.

The acceleration,

$$a = \frac{v - v_o}{t} = \frac{BC}{Ac} = slope \tag{2.17}$$

That is, the slope of the velocity-time graph gives the acceleration of the particle.

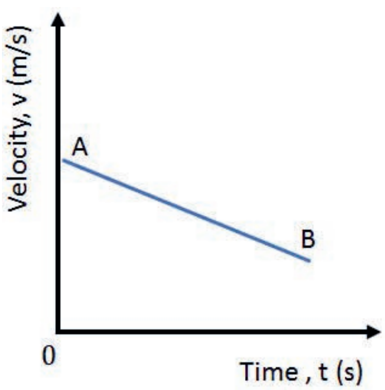


Figure 2.12 Velocity-time graph for uniform retardation.

Let us now consider two special cases.

1. Velocity-time graph for uniform retardation

For a particle moving with uniform retardation or deceleration, the velocity-time graph will be a straight line with a negative slope, as shown in Figure 2.12. If the body is brought to rest, the graph will touch the time axis.

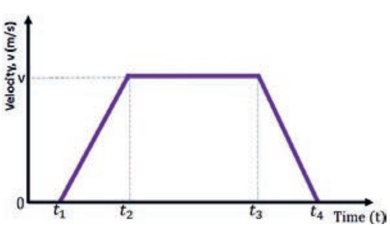


Figure 2.13 Velocity-time graph for non uniform motion.

2. 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 O. 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 velocity-time graph, as shown in Figure 2.13. Then the area under the velocity-time graph gives the total displacement of the car.

Example 2.12

The velocity-time graph of a certain motion is plotted in Figure 2.14 below. Calculate the total distance and displacement of the truck after 15 *s*.

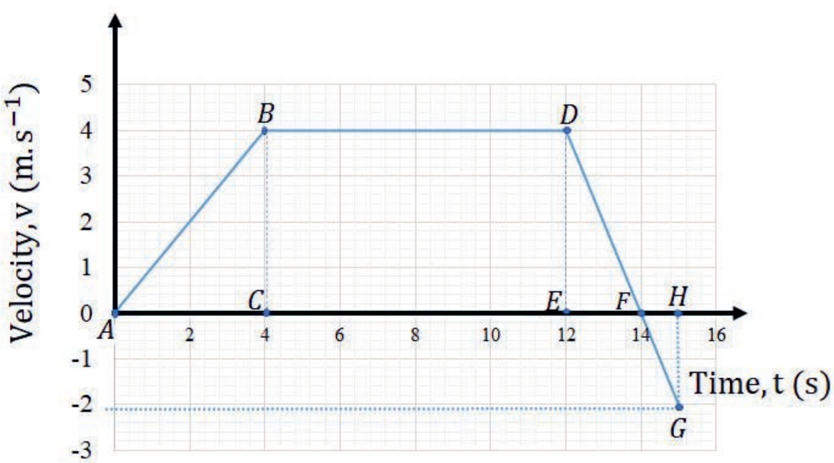


Figure 2.14 Velocity-time graph.

Exercise 2.18

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

Solution:

To calculate the total distance and total displacement, you have to find the area under velocity-time graph.

$$s_1 = \text{area of a triangle ACB}$$
$$= \tfrac{1}{2}(base) \times (height) = \tfrac{1}{2}(\Delta t) \times (\Delta v) = \tfrac{1}{2}(4\ s) \times (4\ m/s) = 8\ m.$$
$$s_2 = \text{area of rectangle CBDE}$$
$$= (base) \times (height) = (\Delta t) \times (\Delta v) = (8\ s\ m/s) \times (4\ m/s) = 32\ m.$$
$$s_3 = \text{area of a triangle EDF}$$
$$= \tfrac{1}{2}(base) \times (height) = \tfrac{1}{2}(\Delta t) \times (\Delta v) = \tfrac{1}{2}(2\ s) \times (4\ m/s) = 4\ m.$$
$$s_4 = \text{area of a triangle EHG}$$
$$= \tfrac{1}{2}(base) \times (height) = \tfrac{1}{2}(\Delta t) \times (\Delta v) = \tfrac{1}{2}(1\ s) \times (2\ m/s) = 1\ m.$$

Thus, the total distance is $s_1 + s_2 + s_3 + s_4 = 45\ m$.

On the other hand, the total displacement is $s_1 + s_2 + s_3 - s_4$ (since velocity is negative) = 44 m in the positive direction.

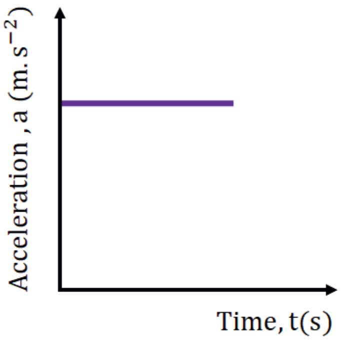


Figure 2.15 Acceleration-time graph.

Acceleration-time graph

The acceleration-time graph shows the acceleration graph 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, the 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.

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

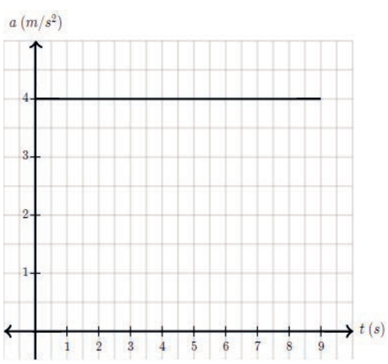


Figure 2.16 Acceleration-time graph of the given problem.

Example 2.13

For the acceleration-time graph shown in Figure 2.16, find the change in velocity of an object.

Solution:

In this example, the change in velocity can be obtained by finding the area under the acceleration-time graph. Thus,

$$\text{area} = \text{base} \times \text{height} = 9\ s \times 4\ m/s^2 = 36\ m/s$$

Hence, the change in velocity of the moving object is 36 m/s.

Activity 2.6

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. By plotting the position-time graph, find the slopes of tangents at appropriate times.
2. By plotting the velocity-time graph, determine the area under the graph. State what this area represent.
3. Also plot the acceleration-time graph and determine the area under the graph. State what this area represent.

Section summary

In a uniformly accelerated motion:

- The position-time equation is quadratic, and hence the graph is parabolic as shown in Figure 2.17 (a).
- The slope of the tangent line (at a point) of the position-time graph is equal to the instantaneous velocity at that time.
- The velocity-time equation is linear and hence the graph is a straight line as shown in Figure 2.17 (b).
- The slope of velocity-time graph is equal to the acceleration while the area under the graph is the displacement.
- The acceleration-time graph is a straight line parallel to the time axis as shown in Figure 2.17 (c).
- The area under acceleration-time graph is the change in velocity of an object.

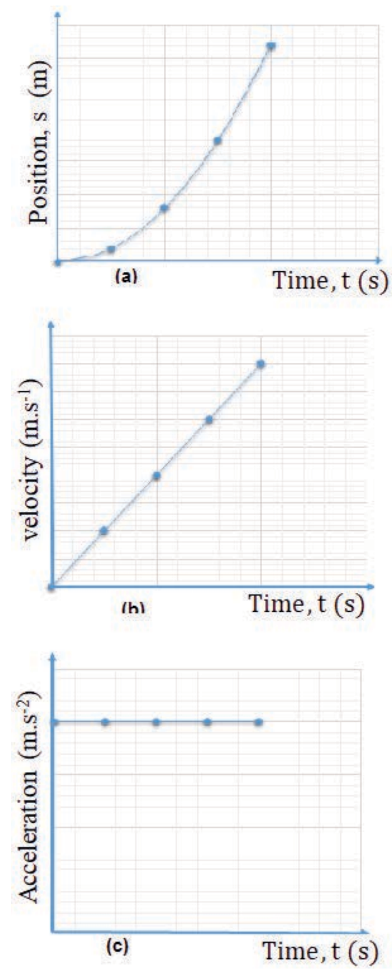


Figure 2.17 Graphs of motion in uniform acceleration.

Review questions

1. In a uniformly accelerated motion, state what each of the following represents:
   (a) the slope of a tangent on a position-time graph.
   (b) the slope of a line on a velocity-time graph.
   (c) the area under the line on an acceleration-time graph.

2. The velocity-time 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.

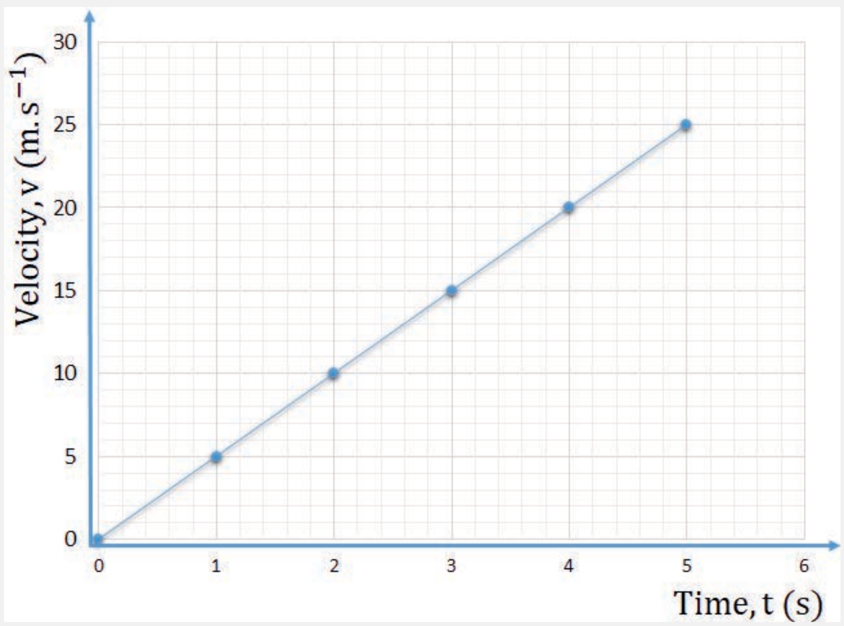


Figure 2.18 Velocity-time graph.

Exercise 2.19

☞ 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.

2.6 Relative velocity in one dimension

Exercise 2.20

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 one-dimension using a 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. In everyday life, when you measure the velocity of an object, the reference frame is taken to be the ground or the earth. For example, if you are traveling in a train and the train, is moving at a speed of 100 *km/h*, then your speed according to another passenger sitting on that train is zero. According to him, you are not moving. But if someone observes you from outside the train, standing on the ground, according to him, you are moving at 100 *km/h* as you are on the train and the train is moving at 100 *km/h*. Hence, the motion observed by the observer depends on the location (frame) of the observer. This type of motion is called relative motion.

The relative velocity of object A with respect to object B is the rate of change of position of the object A with respect to the object B. If v_A and v_B be the velocities of objects A and B with respect to the ground, then

- The relative velocity of A with respect to B is $v_{AB} = v_A - v_B$.
- The relative velocity of B with respect to A is $v_{BA} = v_B - v_A$.

Key Concept

☞ Relative velocity is the velocity of an object with respect to another object or observer.

In one-dimensional motion, objects move in a straight line. So there are only two possible cases: objects are moving in the same direction or in opposite directions. Thus, while using the above expressions, the signs of velocities needs to be the same (say, positive) for bodies that are moving in the same direction. But if they are moving in opposite directions, one of the velocities (say to the right) should be positive while the other one becomes negative. Thus, if the two objects are moving in the same direction, the magnitude of the relative velocity of one object with respect to another is equal to the difference in magnitude of two velocities. But if the two objects are moving in opposite directions, the above expression becomes

- $v_{AB} = v_A - (-v_B) = v_A + v_B$
- $v_{BA} = -v_B - v_A = -(v_A + v_B)$ if object A is moving to the right and object B is moving to the left.

Thus, for objects that are moving in opposite directions, the magnitude of relative velocity of one object with respect to other is equal to the sum of magnitude of their velocities.

Example 2.14

Two cars, A and B are traveling with the same speed of 100 *km/h* in opposite directions, as in the Figure 2.19 (a). Find the relative velocity of car A with respect to car B and the relative velocity of car B with respect to car A.

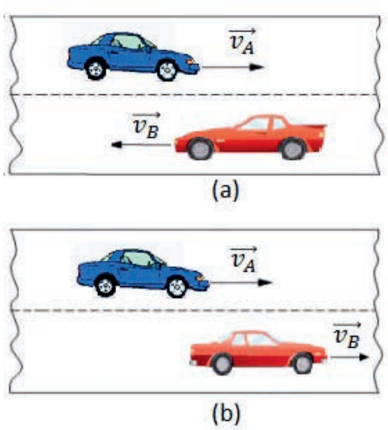


Figure 2.19 Two cars moving (a) in opposite directions (b) in same direction.

Solution:

In this example, suppose that right is positive and left is negative. So you are given v_A = 100 *km/h* and v_B = - 100 *km/h*.

- The relative velocity of A with respect to B is $v_{AB} = v_A - v_B$ $= [100 - (-100)]\ km/h = 100 + 100\ km/h = 200\ km/h$.
- The relative velocity of B with respect to A is $v_{BA} = v_B - v_A$ $= [(-100) - 100]\ km/h = -200\ km/h$.

Thus, when objects are moving in the opposite directions, the magnitude of the relative velocity between them is the sum of the velocities of the objects.

In the same question, if both bodies are moving in the same direction (say to the right) as in the Figure 2.19 (b) with the same speed, then

- The relative velocity of A with respect to B is $v_{AB} = v_A - v_B$ $= [100 - 100]\ km/h = 0 km/h$.
- The relative velocity of B with respect to A is $v_{BA} = v_B - v_A$ $= [100 - 100]\ km/h = 0\ km/h$.

That means A is at rest with respect to B, and B is at rest with respect to A; but both are moving at 100 *km/h* with respect to the ground. This shows that, when objects are moving in the same direction, the magnitude of the relative velocity between them is equal to the difference between the magnitude of their velocities.

Section summary

- When you say that an object has certain velocity, you must state its velocity with respect to a given frame of reference.
- If two objects are moving in the same direction, the magnitude of relative velocity of one object with respect to another is equal to the difference in magnitude of two velocities. On the other hand, if they are moving in opposite directions, the magnitude of relative velocity of one object with respect to other is equal to the sum of magnitude of their velocities.

Exercise 2.21

Why do a car coming in the opposite direction while travelling in a car seems to come at a very large speed?

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?

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.
- Distance is the length of the path taken by an object whereas displacement is simply the distance between where the object started and where it ended up.
- Average velocity is defined as the change in position (or displacement) over the time of travel while instantaneous velocity is the velocity of an object at a single point in time and is calculated by the slope of the tangent line.
- Average acceleration is the change in velocity divided by the elapsed time; instantaneous acceleration is acceleration at a given point in time.
- For uniformly accelerated motion, the position-time graph is a parabola. On the other hand, the velocity-time graph is an inclined line while the acceleration-time graph is a straight line parallel to the time axis.
- The summary of the equations of motion at uniform acceleration are:

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

- Relative velocity is the velocity of an object in relation to another object. It is a measure of how fast two objects are moving with respect to each other.

End of unit questions and problems

1. A runner travels around rectangular track with length 50 m and width 20 m. After traveling around the rectangular track twice, the runner back to its starting point. Determine the distance and displacement of the runner.

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 2 m/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 minutes 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?

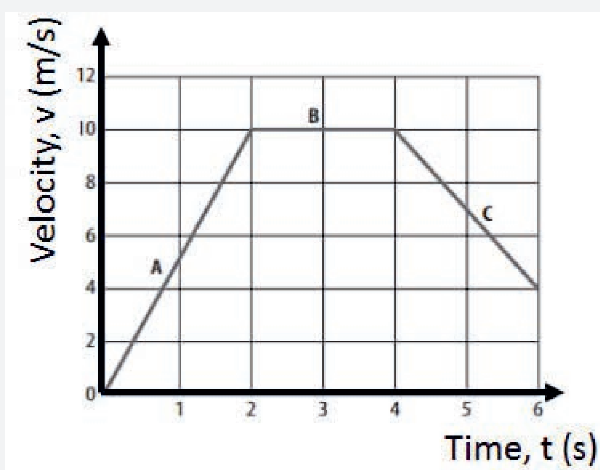
7. A rock is dropped from a bridge. What happens to the magnitude of the acceleration and the speed of the rock as it falls? [neglect friction]

8. A brick is dropped from rest from a height of 4.9 *m*. How long does it take the brick to reach the ground?

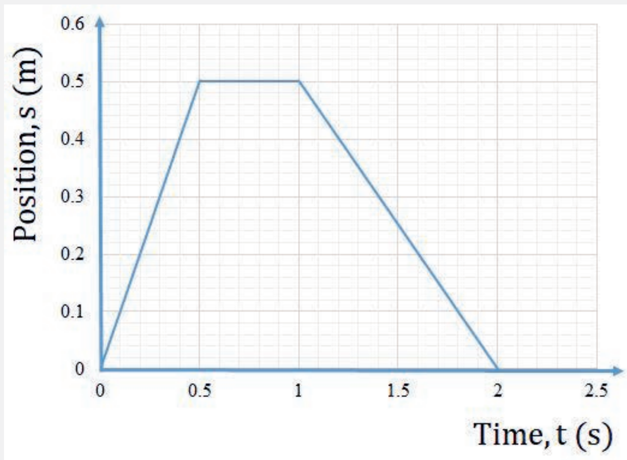
9. The velocity of a car changes over an 8 *s* time period as shown in the following table.
   (a) Plot the velocity-time graph of the motion.
   (b) What is the displacement of the car during the entire 8 *s*?
   (c) Find the slope of the line between t = 0 *s* and t = 4 *s*? What does this slope represent?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

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

10. For the motion described by the velocity-time graph below,
   A) What is the acceleration between 0 and 2 *s*?
   B) During what time period does the object have a constant speed?
   C) What is the displacement of the motion?

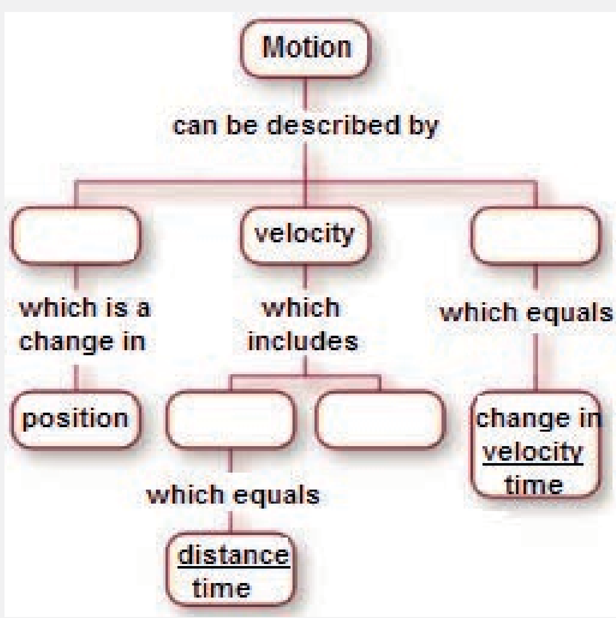


11. Given the position-time graph below, find the velocity-time graph.



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

13. Copy and complete the following concept map on motion.



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:

- *understand the differences between elasticity and plasticity for an object;*
- *describe density and specific gravity;*
- *comprehend the concept of stress and strain;*
- *know that Young modulus is the ratio of the stress to the strain of an object;*
- *understand the physical conditions of static equilibrium;*
- *apply the conditions of equilibrium for a body in static equilibrium in everyday activity.*

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 rigid body generally means a hard solid object having a definite shape and size. However, in reality, all bodies can be stretched, compressed and bent. Even the appreciably rigid steel bar can be deformed when a sufficiently large external force is applied on it. You may have seen iron rods at construction sites. This means that all practical solid bodies are never perfectly rigid. 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. Such a force is called a deforming force. 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.

Figure 3.1 Helical spring

Figure 3.2 Spring pen.

You might have experienced the use of such a spring in some materials like the one shown in Figure 3.2. Pressing the pen cap allow the writing point to come out of the pen casing (with a click sound). On pressing it again the writing point goes back inside the pen casing. Two points are to be noted here are:

- The spring inside the pen gets deformed on pushing the pen cap.
- It regains the original shape once the deforming force is removed.

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

If a body regains its original shape and size after the removal of deforming force, it is said to be elastic and the property is called elasticity. The deformation caused is known as elastic deformation. Examples: rubber, metals and steel ropes. However, if you apply force to a lump of putty, or potters clay, they have no gross tendency to regain their previous shape; they tend to get permanently deformed. If a body does not regain its original shape and size after removal of the deforming force, it is said to be plastic body and the property is called plasticity.

Plastic deformation is defined as the persistent deformation or change in the shape of a solid body caused by a sustained force. This happens when a great amount of tension is applied to a material. Plastic deformation is permanent and irreversible. Plasticity is the ability to be permanently formed or molded.

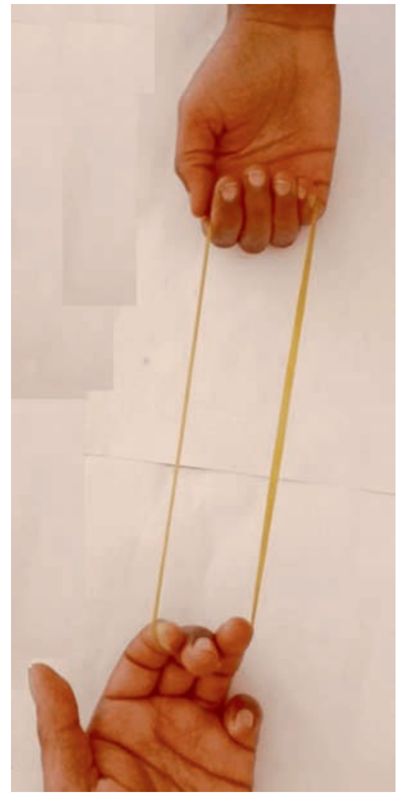


Figure 3.4 Stretched rubber band.

Activity 3.1

A rubber band shown in Figure 3.4 gets stretched when you apply force on it. However, it (almost) regains the original shape once the force is removed. But does it always come back to its original shape and size irrespective of the magnitude of force? Discuss in group.

Students, have you observed that elastic bodies show the property of elasticity up to a certain value of deforming force? If you go on increasing the deforming force, then a stage is reached when on removing the force, the body will not return to its original state. The maximum deforming force up to which a body retains its property of elasticity is called elastic limit of the material of the body. Beyond the elastic limit, the solid does not regain its original shape and size.

Key Concept

☞ Elastic limit is the property of a body whereas elasticity is the property of material of the body. All materials are elastic up to a certain deformation; then they turn plastic. Springs lose their springiness if subjected to large external force and tend to become plastic.

The elastic limit of ductile material is the beginning point of plastic deformation. The elastic limit of a solid is the utmost amount to which it may be stretched without permanently changing size or form. If the tension is placed beyond the elastic limit, the substance will deform plastically. Plastic deformation occurs in ductile materials such as metals (for example, copper) when the distortion surpasses the elastic limit. Plastic deformation is vital in the manufacture of new goods utilizing heat or pressure treatments as well as molding.

Activity 3.2

A slingshot used to shoot a body involves the uses of rubber bands. The body, placed at the centre of the band, is drawn back as far as possible and released, thus striking the target with a great impact. If you replace the rubber used with a cotton cord, would it still work in the same way?

Elastic behavior of materials plays an important role in our day to day life. The following are some of the practical applications of elasticity.

1. The metallic parts of machinery are never subjected to a stress beyond elastic limit; otherwise they will get permanently deformed.

2. The thickness of the metallic rope used in the crane in order to lift a given load is decided from the knowledge of elastic limit of the material of the rope and the factor of safety.

3. The bridges are declared unsafe after long use because during its long use, a bridge undergoes quick alternating strains continuously. It results in the loss of elastic strength.

4. Maximum height of a mountain on earth can be estimated from the elastic behavior of earth.

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.

Review questions

1. Define elasticity and plasticity.
2. List some plastic materials in your locality.
3. The body will regain its previous shape and size only when the deformation caused by the external forces is within a certain

limit. What is that limit?

3.2 Density and specific gravity

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

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

Exercise 3.1

Do you know the reason why oil floats on water or why iron needles sink while giant iron ships float on water?

Activity 3.3

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 $7.86 g/cm^3$ and for copper $8.92 g/cm^3$.

Density

Density is defined as the mass of an object per unit of its volume. You can also state it as the ratio between mass and volume. Thus density is the measure of the fact that how much mass of the object is contained in the unit volume of the substance. It also helps us in determining the compactness of the substance.

Density is represented using the symbol, "ρ". The density of a substance can thus be calculated using the formula:

$$\rho = \frac{m}{V} \quad (3.1)$$

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

Temperature and pressure are the two common factors affecting the density of the substance. Other general factors such as size, mass as well as arrangement of atoms in the substance also widely affect the density of the material.

Here are a few everyday examples of density.

Key Concept

☞ Density is a characteristic property of any pure substance. It is used in determining whether an object sinks or floats in a fluid.

- Rock sinks in the water, while wood, being less dense than the water, floats on the surface.
- Oil is less dense than water. It rises to the surface in cases of an oil spill in the ocean creating an oil slick on the surface of the water.

Specific gravity

Specific gravity is defined as the ratio of the density of the given substance to that of a standard substance (generally this standard substance is water at 4 ^oC but not for all). While considering water at 4^oC as a reference or standard parameter for comparison, a question arises why water is taken at 4 ^0C only, and not at 0 ^oC or 100 ^oC which is its freezing and boiling points, respectively. This is because at 4 ^oC, water has the highest density and not at 0 ^oC or 100 ^oC. That is the reason why it is common to use the density of water at 4 ^oC as a reference point.

The specific gravity (SG) of a substance can thus be calculated using the expression:

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

Since specific gravity is the ratio of two like terms, i.e., density of two substances, it is a unitless quantity. As discussed earlier, with change in temperature and pressure, the density of an object is affected and hence affecting the specific gravity of the given substance.

Key Concept

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

The following are some of the applications of specific gravity.

- Geologists and mineralogists use the concept of specific gravity in determining the mineral content of the rock.
- You apply the concept of specific gravity in comparing the purity of the newly found gem with the standard one.
- Specific gravity helps us in urinalysis and extracting the contents information of the urine.

Table 3.1 Density and specific gravity of substance at 0 ^oC 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.

Activity 3.4

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?

Example 3.1

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

Solution:

In this example, you are given with $m = 60\ g\ and\ V = 20cm^3$.

The required quantities are density and specific gravity.

The density can be calculated using the formula

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

Substitution gives

$$\rho = \frac{54 \times 10{-}3\ kg}{20 \times 10^{-6}\ m^3} = 2.9 \times 10^3\ kg/m^3$$

The specific gravity can be calculated by

$$SG = \frac{\rho_{substance}}{\rho_{water}} = \frac{2.7 \times 10^3\ kg/m^3}{1 \times 10^3\ kg/m^3} = 2.7$$

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:
You are given with $r = 18\ cm$. Moreover, from table 3.1 above, the density of iron is $\rho = 7860\ kg/m^3$.
You want to find the mass m.

From equation 3.1, you get $m = (\rho)(V)$. To use this formula , you first have to find the volume of the sphere. The volume of the sphere is given by $\frac{4}{3}\pi r^3$. Hence, the volume of iron ball (V) is thus:

$$V = \frac{4}{3}(3.14)((0.18)\ m)^3 = 0.024\ m^3$$

So the mass 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 a substance that is taken as a standard.

Review questions

1. What is the approximate mass of air in a living room of 5.6 $m \times$ 3.6 $m \times 2.4$ m?

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 3.2

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.*

From the previous discussion, you observed that a change in shape due to the application of a force is known as a deformation. Even very small forces are known to cause some deformation. Deformation is experienced by objects or physical media under the action of external force, for example; this may be squashing, squeezing, ripping, twisting, shearing, or pulling the objects apart. In the language of physics, two terms describe the forces on objects undergoing deformation: stress and strain.

Stress

Stress is a quantity that describes the magnitude of forces that cause deformation. If the magnitude of deforming force is F and it acts on area A, stress is generally defined as force per unit area.

Key Concept

☞ Stress is a quantity that is proportional to the force causing deformation; more specifically, stress is the external force acting on an object per unit cross-sectional area.

$$\text{Stress} = \frac{\text{Force}}{\text{Area}} = \frac{F}{A} \qquad (3.3)$$

The SI unit of stress is N/m^2.

When forces pull on an object and cause its elongation, like the stretching of an elastic band, you call such stress a tensile stress. When forces cause a compression of an object, you call it a compressive stress. When an object is being squeezed from all sides, like a submarine in the depths of an ocean, you call this kind of stress a bulk stress (or volume stress). In other situations, the acting forces may be neither tensile nor compressive, and still produce a noticeable deformation. For example, suppose you hold a book tightly between the palms of your hands, then with one hand you press and-pull on the front cover away from you, while with the other hand you press-and-pull on the back cover toward you. In such a case, the deforming forces act tangentially to the object's surface and you call them 'shear' forces and the stress they cause is called shear stress.

Exercise 3.3

What is meant by tensile stress and compressive stress?

Strain

An object or medium under stress becomes deformed. The quantity that describes this deformation is called strain. Strain is given as a fractional change in either length (under tensile stress) or volume (under bulk stress) or geometry (under shear stress).

Key Concept

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

Therefore, strain is a dimensionless number. Strain under a tensile stress is called tensile strain, strain under bulk stress is called bulk strain (or volume strain), and that caused by shear stress is called shear strain. Their equations are given as follows.

- **Tensile/Linear strain:** If on application of a longitudinal deforming force, the length L_o of a body changes by ΔL as in Figure 3.5, then

$$\text{Tensile (or compressive) strain} = \frac{\Delta \mathrm{L}}{\mathrm{L}_0} \tag{3.4}$$

- **Volumetric strain:** If on application of the deforming force, the volume V_o of the body changes by ΔV without change of shape of the body as in Figure 3.6, then

$$\text{Volumetric strain} = \frac{\Delta \mathrm{V}}{\mathrm{V}_0} \tag{3.5}$$

- **Shearing strain:** When the deforming forces are tangential, the shearing strain is given by the angle through which a line perpendicular to the fixed plane is turned due to deformation. This is shown in Figure 3.7. Then, you can write

$$\text{Shearing strain} = \frac{\Delta x}{L_0} \tag{3.6}$$

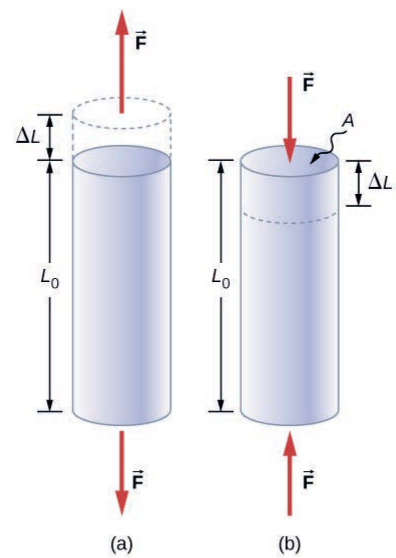


Figure 3.5 An object under (a) tensile stress (b) compressive stress.

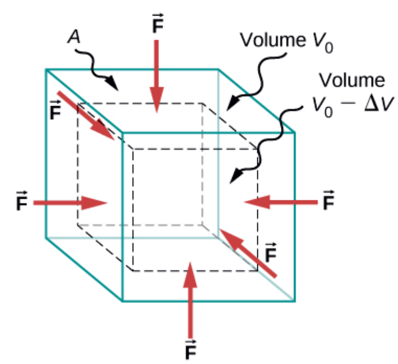


Figure 3.6 An object under volume strain.

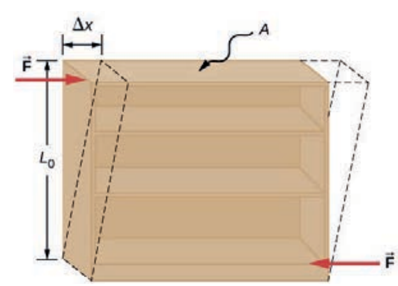


Figure 3.7 An object under shear stress.

In 1678, Robert Hooke obtained the stress-strain curve experimentally for a number of solid substances and established a law of elasticity known as Hooke's law. According to this law, within elastic limit, stress is directly proportional to corresponding strain.

$$\text{Stress} \propto \text{Strain}$$

$$\implies Stress = k \times Strain \tag{3.7}$$

This constant of proportionality K is a measure of elasticity of the substance and is called modulus of elasticity. As strain is a dimensionless quantity, the modulus of elasticity has the same dimensions (or units) as stress. Its value is independent of the stress and strain but depends on the nature of the material.

You can also see from the above equation that when an object is characterized by a large value of elastic modulus, the effect of stress is small. On the other hand, a small elastic modulus means that stress produces large strain and noticeable deformation. For example, a stress on a rubber band produces larger strain (deformation) than the same stress on a steel band of the same dimensions because the elastic modulus for rubber is two orders of magnitude smaller than the elastic modulus for steel. The elastic modulus for tensile stress is called the Young modulus; that for the bulk stress is called the bulk modulus; and that for shear stress is called the shear modulus.

Example 3.3

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:
You are given with $F = 9.8\ N$ and $A = 2 \times 10^{-3}\ m^2$.
You want to find the tensile stress.

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

$$\text{Tensile stress} = \frac{F}{A} = \frac{9.8N}{2 \times 10^{-3}\ m^2}$$
$$= 4.9 \times 10^3\ N/m^2$$

Example 3.4

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

Solution:
You are given with $F = W = 98\ N$, $L_0 = 3\ m$, $D = 2r = 0.4\ mm$. The area of the wire can be calculated by

$$A = \pi r^2 = (3.14)(0.2 \times 10^{-3}\ m^2)^2 = 6.28 \times 10^{-7}\ m^2$$

$$\Delta L = 2.4\ cm = 2.4 \times 10^2\ m$$

You want to find the tensile stress and tensile strain.

The tensile stress is thus obtained by:

$$\text{Tensile stress} = \frac{F}{A} = \frac{mg}{A} = \frac{98\ N}{6.28 \times 10^{-7}\ m^2} = 1.56 \times 10^8\ N/m^2$$

On the other hand, the tensile strain can be obtained by:

$$\text{Tensile strain} = \frac{\Delta L}{L_0} = \frac{2.4 \times 10^{-2}\ m}{3\ m} = 0.008$$

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. Review the relationship between stress and strain. Can you find any similarities between the two quantities?
2. Can compressive stress be applied to a rubber band?
3. A nylon string that has a diameter of 2 mm is pulled by a force of 100 N. Calculate the tensile stress.
4. 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 The Young Modulus

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

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

Exercise 3.4

What did you know about the Young modulus of a material?

Activity 3.6

Suppose you have a copper wire and you stretch it and there is an increase in its length. On removing the stretching force, the wire does not regain its original length. Can you calculate the Young modulus in this situation?

In the previous section, you have learnt that there are three kinds of elastic modulus. The elastic modulus for tensile stress is called the Young modulus; that for the bulk stress is called the bulk modulus; and that for shear stress is called the shear modulus. In this section, you will study about the the Young modulus.

The Young modulus is the elastic modulus when deformation is caused by either tensile or compressive stress. Experimental observation show that for a given material, the magnitude of the strain produced is same whether the stress is tensile or compressive. The ratio of tensile (or compressive) stress to the longitudinal strain is known as the the Young modulus of the material; it is denoted by the symbol Y.

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

Since strain is a dimensionless quantity, the unit of the Young modulus is the same as that of stress i.e., Nm^2 or Pascal (Pa).

The relation between the tensile stress and the tensile strain is linear when

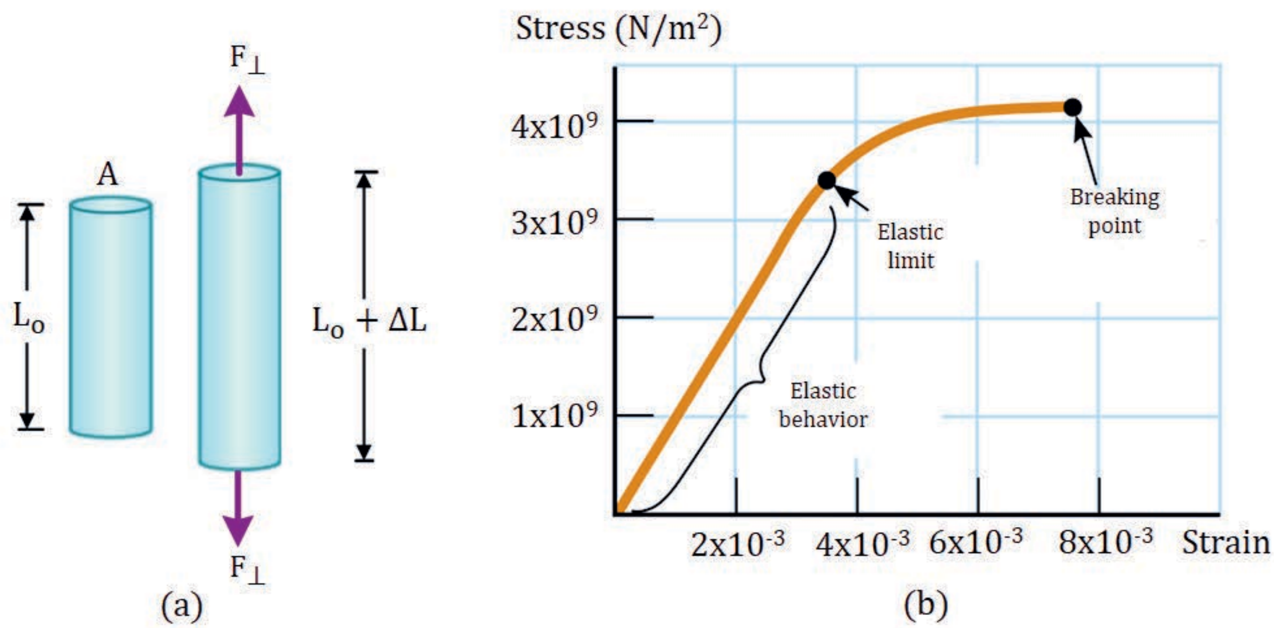


Figure 3.8 (a). A rod of length L_0 can be stretched by an amount ΔL after application of a tensile stress $F_\perp$. (b) The stress versus strain diagram for a ductile material.

the rod is in its elastic range.

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 area A of a rod, its length increases to a new length $L_0 + \Delta L$ as shown in the Figure 3.8 (a). The Young modulus is thus

$$Y = \frac{\left(\frac{F_\perp}{A}\right)}{\left(\frac{\Delta L}{L_o}\right)} \tag{3.8}$$

If the wire of radius r is suspended vertically with a rigid support and a mass m hangs at its lower end, then $A = \pi \times r^2$ and $F = mg$.

$$Y = \frac{mg \times L_o}{\pi r^2 \Delta L} \tag{3.9}$$

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

Key Concept

☞The Young modulus is a property of the material that tells us how easily it can stretch and deform and is defined as the ratio of tensile stress to tensile strain.

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.

Table 3.2 below shows the Young modulus of different substances.

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

Substance	Young 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	-

You can notice that for metals the Young moduli are large. Therefore, these materials require a large force to produce a small change in their length. The value of Young modulus is maximum for steel and thus steel is more elastic in comparison to other materials mentioned in the table. For the same change in length, steel requires a large amount of force. To increase the length of a thin steel wire of $0.1 cm^2$ cross-sectional area by 0.1 percent, a force of 2000 I is required. The force required to produce the same strain in Aluminium, brass and copper wires, having the same cross-sectional area, are 690 N, 900 N and 1100 N, respectively. It means that steel is more elastic than copper, brass and aluminium. It is for this reason that steel is preferred in heavy-duty machines and in structural designs. Wood, bone, concrete and glass have rather small values for their Young moduli.

Exercise 3.5

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?

The Young modulus is relevant only for solids since only solids can have well defined lengths and shapes.

Example 3.5

A 1.60 *m* 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:
In this example, you are given with $L_0 = 1.6\ m,\ Y = 2 \times 10^{11}\ N/m^2\ and\ D = 0.2 \times 10^{-2}$.
The required quantity is the tension or force on the wire.

From the formula of Young modulus, you can derive the expression for F as

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

where

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

Thus,

$$F = 2.0 \times 10^{11}\ N/m^2(\frac{0.0025\ m}{1.6\ m})(3.14 \times 10^{-6}\ m^2)$$

$$F = 980\ N$$

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

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.

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 the Young modulus of $200 \times 10^9\ N/m^2$. Find the tensile stress on the wire and the increase in its length.

Solution:
You are given with $m = 30\ kg,\ L_o = 15\ m,\ A = 9 \times 10^{-6}\ m^2$, and $Y = 200 \times 10^9\ N/m^2$.
You need to find the tensile stress and ΔL.

The tensile stress can be calculated by

$$\text{Tensile stress} = \frac{F}{A} = \frac{mg}{A}$$

Substitution gives

$$\text{Tensile stress} = \frac{30\ kg \times 9.8\ N/kg}{9 \times 10^{-6}\ m^2} = 3.27 \times 10^7\ N/m^2$$

In the above equation, the applied force on a wire must be equal to the weight of the sphere, i.e., $F = mg$.

On the other hand, from the expression of the Young modulus, $Y = \frac{\left(\frac{F}{A}\right)}{\left(\frac{\Delta L}{L_o}\right)}$, you can derive the expression for ΔL as

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

Substitution gives

$$\Delta L = \frac{3.27 \times 10^7\ N/m^2}{200 \times 10^9\ N/m^2} \times 15\ m = 2.45 \times 10^{-3} m$$

$$\therefore \Delta L = 2.45\ mm$$

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 the Young Modulus.
- The Young Modulus measures the resistance of a solid to a change in its length.

Review questions

1. In the Young experiment, if the length of the wire and the radius are both doubled, what will happen to the value of the Young modulus?

2. A wire increases by 10^{-3} of its length when a stress of $1 \times 10^{8}\ Nm^{-2}$ is applied to it. Calculate the Young modulus of material of the wire.

3. A wire is stretched by 0.01 m by a certain force F. Another wire of same material whose diameter and length are double to the original wire is stretched by the same force. What will be its elongation?

4. A 200 kg load is hung on a wire having a length of 4.0 m, cross-sectional area $0.20 \times 10^{-5}\ m^2$, and the Young 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.*

Exercise 3.6

List examples of bodies that are in static equilibrium from your surroundings.

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?

Static equilibrium occurs when an object or a system remains at rest and

Exercise 3.7

When is a system or an object considered to be in static equilibrium?

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.

Two conditions need to be satisfied for a system to be in static equilibrium: the first condition of equilibrium and the second condition of equilibrium. Firstly, the net force acting upon the object must be zero. Secondly, the net torque acting upon the object must also be zero. In other words, both static translational and static rotational equilibrium conditions must be satisfied. You will now look at each of the two conditions one by one.

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 equilibrium states that for an object to remain in equilibrium, the net force acting upon it in all directions must be zero. Simply put, the above statement means that the body must not be experiencing acceleration. 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. In the form of an equation, the first condition of equilibrium is denoted as follows:

$$F_1 + F_2 + F_3 + \ldots F_n = \vec{F_{net}} = 0 \quad (3.10)$$

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 dimensions should be equal to zero. Thus,

- For one dimensional 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 two dimensional forces applied on an object, the first condition of equilibrium is given by:

$$\vec{F}_{net} = 0, \quad \text{so that} \quad \sum \vec{F}_x = 0 \quad \text{and} \quad \sum \vec{F}_y = 0 \tag{3.11}$$

The above condition is true for both static equilibrium, where the object's velocity is zero, and dynamic equilibrium, where the object moves at a constant velocity.

3.5.2 Second condition of equilibrium

If the body does not achieve equilibrium even though the first condition for equilibrium is satisfied, it is because it tends to rotate. This situation demands another condition in addition to the first condition for equilibrium. A body satisfies the second condition for equilibrium when the resultant torque acting on it is zero.

Key Concept

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

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. The magnitude of torque is thus given by the equation:

$$\tau = Fr\sin\theta$$

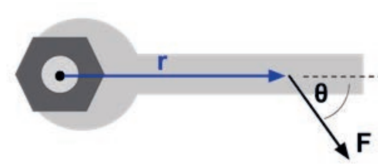


Figure 3.9 A force applied on one side of a nut at an angle makes it to rotate.

where τ is the symbol for torque in Nm, $\vec{F}$ is the magnitude of the force in N and r the distance from the pivot point to the point where the force is applied in m and θ is the angle between the force and the vector directed from the point of application to the pivot point.

If r is perpendicular to $\vec{F}$ like in Figure 3.10, the magnitude of the torque can be obtained by:

$$\tau = Fr$$

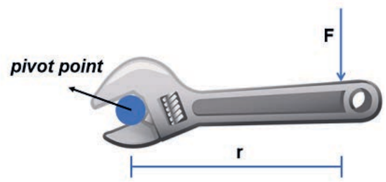


Figure 3.10 A force applied perpendicularly on one side of a nut makes it to rotate.

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. Mathematically it is represented as:

$$\sum \vec{\tau} = \tau_{\vec{net}} = 0. \quad (3.12)$$

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.

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. The following are examples that are used to demonstrate objects in static equilibrium.

1. A book placed on top of a table

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 or not the object satisfies the two conditions of equilibrium.

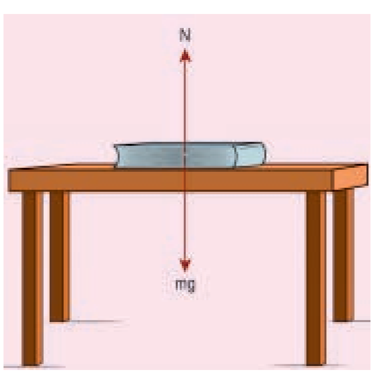


Figure 3.11 A book at rest on the top of a table.

As shown in Figure 3.11, the only forces acting on the book are gravity and normal force. Gravity acts downward, while normal force acts upward, perpendicular to the surface. Since the book is at rest, these two forces are equal in magnitude but opposite in direction. Thus, the net force acting on the book is zero. Taking a pivot at any point, you will get the vector sum of the torque due to these forces to be zero satisfying both the first and second conditions of static equilibrium.

2. A seesaw balanced by two children

A seesaw (shown in Figure 3.12) 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. If the girl has a mass of 30 *kg* and sits 2.5 *m* away from the pivot point, 25 *kg* boy has to sit 3.0 *m* away from the pivot point of the seesaw for a seesaw to become in static equilibrium. Thus, to determine whether the seesaw is in static equilibrium or not, the two conditions for equilibrium should be satisfied.

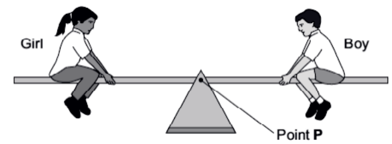
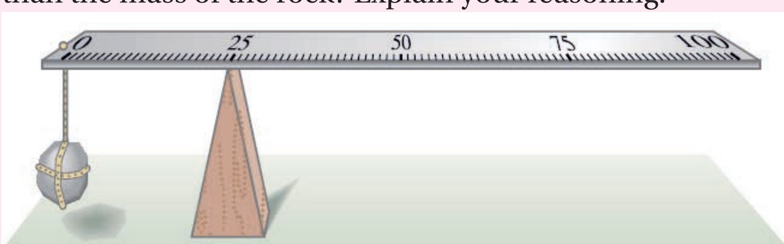


Figure 3.12 A balanced seesaw in static equilibrium.

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 the Figure below. Is the mass of the meter stick greater than, equal to, or less than the mass of the rock? Explain your reasoning.



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:

$$F_x = F cos\,\theta \tag{3.13}$$

$$F_y = F sin\,\theta \tag{3.14}$$

where θ is given in an anticlockwise direction from the positive x-axis.

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

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

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

4. For the **torque equation**,

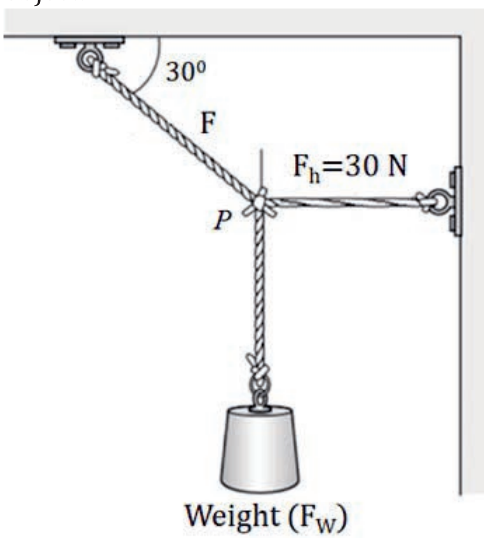
$$\sum \tau = 0 \tag{3.17}$$

Choose any axis perpendicular to the xy-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 shown in Figure below is in static equilibrium. The horizontal cord has a force of 30 N. Find the force F of the cord and weight F_W of the object.

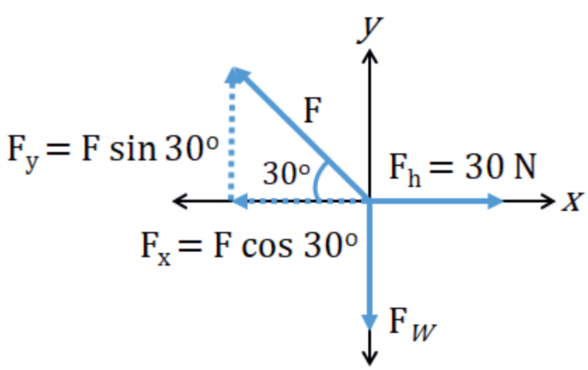


Solution:

You are given $F_W = F_x = 30\ N$.

What you want to find is F and F_W.

a) Drawing free body diagram: all forces acting on the given mass are indicated on the free body diagram shown in the Figure below.



b) Resolving vectors in to their components: the only force that have components is **F**. Hence,

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

and

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

c) By applying the first condition of equilibrium,

$$\sum F_x = 0 \quad \text{yields} \quad 30\ N - F\, cos\, 30^o = 0$$

$$0.86\ F = 30\ N$$

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

$$\sum F_y = 0 \quad \text{yields} \quad F\, sin\, 30^o - F_W = 0$$

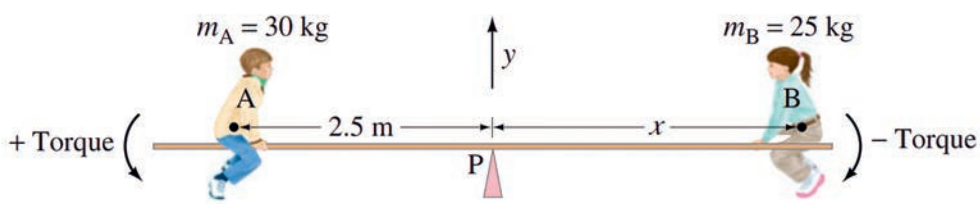
$$0.5\ F = F_W$$

Substituting the value of F into the above expression gives

$$F_W = 0.5 \times 34.9\ N = 17.5\ N$$

Example 3.8

A uniform board of mass 'M' serves as a seesaw for two children as shown in Figure below. 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

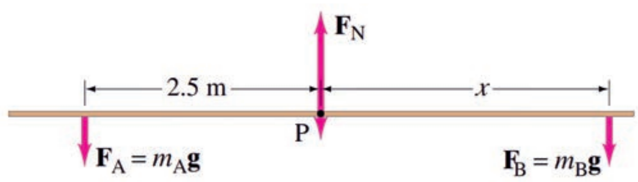


to balance the seesaw?

Solution:
You are given $m_A = 30\ kg,\ m_B = 25\ kg,$ and $x_A = 2.5\ m$.
The required quantity is the value of $x_B = x$.

You can easily solve this problem using the above stated steps.

(a) **Draw free body diagram.** 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. This is indicated in the Figure shown below.



(b) **Coordinate system.** You 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,

$$\sum \vec{F}_x = 0$$
$$\sum \vec{F}_y = 0 \quad \Longrightarrow \quad \vec{F}_N - m_A g - Mg - m_B g = 0$$

(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 is the distance of each child from the pivot point. F_A tends to rotate the board counterclockwise (+) and F_B clockwise (−) so the torque equation is

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

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

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

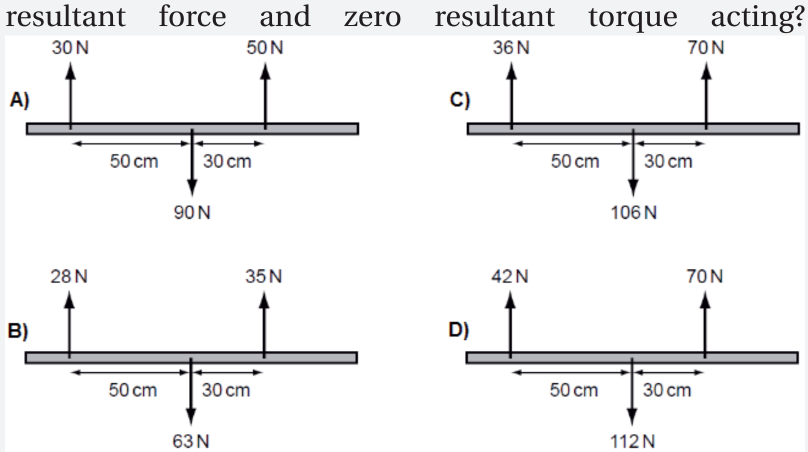
Thus, to balance the seesaw, child B must sit 3.0 m from the pivot point.

Section summary

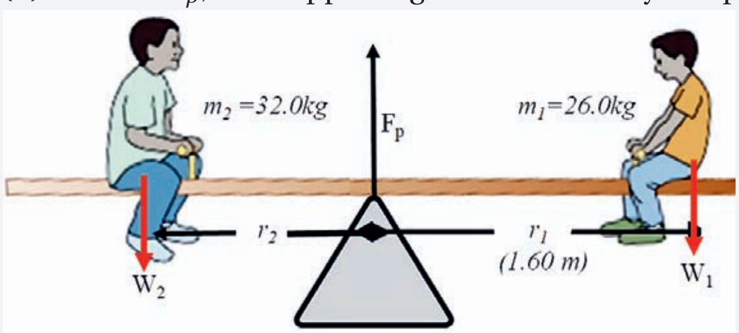
- Static equilibrium occurs when an object or a system remains at rest and does not tilt nor rotate.
- Two conditions need to be satisfied before a system is in static equilibrium: the first and second conditions of equilibrium.
- In the first condition of equilibrium, all external forces acting on the body balance out and their vector sum is zero.
- In second condition of equilibrium, the sum of all the torques (calculated about any arbitrary axis) must also be zero.
- Torque is the product of the distance from the support or pivot (r) and the component of force perpendicular to the object.

Review questions

1. What does static equilibrium mean?
2. What conditions are necessary for static equilibrium?
3. Mention some examples of a rigid body that is in static equilibrium in your surroundings.
4. Four beams of the same length each have three forces acting on them. Which beam has both zero resultant force and zero resultant torque acting?



5. The two children shown in the Figure below are balanced on a seesaw 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 he from the pivot?
   (b) What is F_p, the supporting force exerted by the pivot?



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

- Solids tend to regain their original shape and size once external deforming force is removed.
- The property of solids by virtue of which they regain their original shape and size even when the deforming forces are removed is called elasticity.
- The property of solids by virtue of which they do not regain

their original shape and size, even when the deforming forces are removed, is called plasticity.

- Beyond a limit, called elastic limit, the solid does not regain its original shape and size.
- Stress is a quantity that is proportional to the force causing a deformation; more specifically, stress is the external force acting on an object per unit cross-sectional area. The result of a stress is strain, which is a measure of the degree of deformation.
- Hooke's law states that within the elastic limit, the stress developed in a body is directly proportional to the strain.
- The Young 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. Define the term elasticity. Give examples of elastic and plastic objects.
2. You have a rock with a volume of 15 cm^3 and a mass of 45 g. What is its density?
3. A bar measures 12 mm x 20 mm x 1 m. It has a specific gravity of 2.78. Determine its mass.
4. A golden-colored cube is handed to you. The person wants you to buy it for 5000 *birr*, saying that is a gold nugget. From

a book you read that the density of gold is $19.3 g/cm^3$. You measure the cube and find that it is 2 *cm* on each side, and weighs 40 *g*. What is its density? Is it gold? Should you buy it?

5. Explain the terms stress, strain and Hooke's Law.

6. A wire is stretched 3 *mm* by a force of 150 *N*. Assuming the elastic limit is not exceeded, calculate the force that will stretch the wire 5 *mm*.

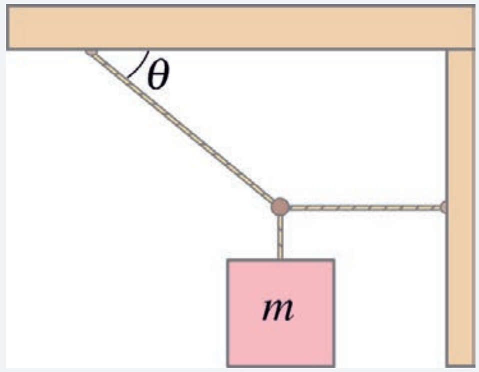
7. A circular rod of cross-sectional area $100 mm^2$ has a tensile force of 100 *kN* applied to it. Calculate the value for the stress in the rod.

8. A steel wire of length 6 *m* and diameter 0.6 *mm* is extended by a force of 60 *N*. The wire extends by 3 *mm*. Calculate:
   a) the applied stress.
   b) the strain on the wire.
   c) the Young Modulus of the steel.

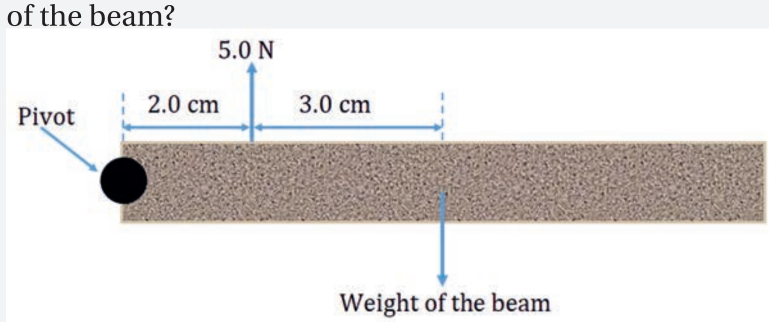
9. A wire increases by 10^{-3} of its length when a stress of $1x10^8 Nm^{-2}$ is applied to it. Calculate the Young modulus of the wire.

10. 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 the increase in their lengths?

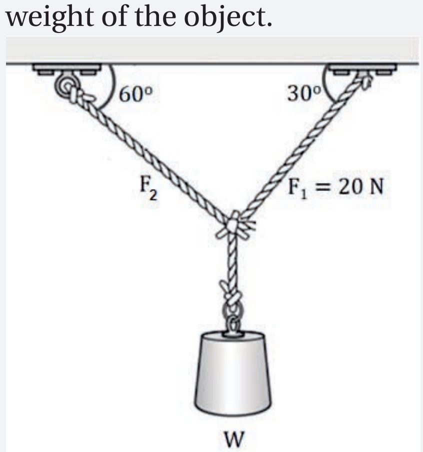
11. Find the tension in the two cords shown in the Figure below. Neglect the mass of the cords, and assume that the angle is 33^{o} and the mass *m* is 190 *kg*.



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



13. A force of 20 N at angle of 30 ^{o} to the horizontal and a force F_2 at an angle of 60 ^{o} to the horizontal are applied on an object as shown in the Figure below so as to make the object in equilibrium. Calculate the magnitude of the force F_2 and weight of the object.



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 your 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. 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, industries and so on. In this unit, you will learn topics related to electricity.

Brain storming question

What constitutes electricity?

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

- *understand the basic properties of electric charge;*
- *explain the charging and discharging processes;*
- *have a conceptual understanding of an electrical force;*
- *understand the concept of an electric field;*
- *understand the relationship among voltage, current and resistance;*
- *describe arrangement of resistors in a circuit;*
- *apply the concept of electricity in solving real life problems.*

4.1 Charges in Nature

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

- *distinguish between the two types of electric charges;*
- *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. Positive and negative charges are present in neutral objects, but their numbers are equal. 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.

Exercise 4.1

When do you say that a body is charged positively?

Unit of Charge

The SI unit of electric charge is Coulomb (C). One coulomb ($1\ C$) of charge is carried by 6.25×10^{18} electrons. An electron possesses a negative charge of $1.6 \times 10^{-19}\ C$. In electrostatics, you often work with charge in micro Coulombs ($1 \mu C = 1 \times 10^{-6}\ C$) and nano coulombs ($1 nC = 1 \times 10^{-9}\ C$).

Key Concept

☞ If an object gains electrons, it becomes negatively charged; if it loses electrons, it becomes positively charged.

Conservation of Charge

During electrification, 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 the old comb and hair trick where your hair rises and sticks to the comb? This arises because of the simple conservation of charge, i.e., the transfer of charge either from the comb to the hair or vice versa. Thus, the total charge in an isolated system never changes. By isolated, you mean that no particles are 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;

$$q = ne \quad \text{where } n \text{ is positive or negative integer.} \tag{4.1}$$

Section summary

- There are two types of electric charges: positive and negative.
- 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.

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)?

4.2 Methods of Charging a Body

By the end of this section, you should be 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, by removing or adding charges.

Activity 4.1

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

The following are the different methods of charging a body:

i Charging by rubbing

ii Charging by conduction

iii Charging by induction

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, such as silk are more likely to attract extra electrons and become negatively charged, where as others, such as glass and ebonite rod, are more likely to give electrons 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.

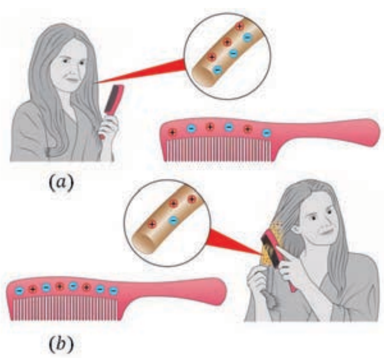


Figure 4.1 (a) The comb and the hair are both neutral. (b) After being rubbed together, the comb is negatively charged and the hair is positively charged.

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.

Charging by Conduction

Charging by conduction occurs when a charged object make contact with a neutral object. Figure 4.2 depicts the use of a positively charged aluminum plate being touched by a neutral metal sphere. A positively charged aluminum plate has an excess of protons. When looked at from an electron perspective, a positively charged aluminum plate has a shortage of electrons. So when the positively charged aluminum plate is touched to the neutral metal sphere (Figure 4.2 (b)), countless electrons on the metal sphere migrate towards the aluminum plate. There is a mass migration of electrons until the positive charge on the aluminum plate-metal sphere system becomes redistributed. Having lost electrons to the positively charged aluminum plate, there is a shortage of electrons on the sphere

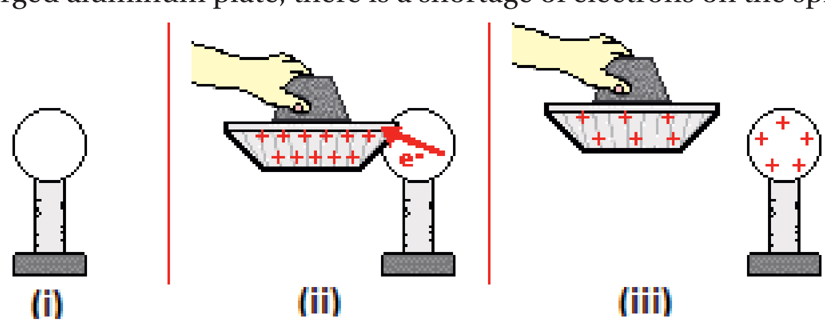


Figure 4.2 Charging by conduction.

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.

Key Concept

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

Key Concept

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

and an overall positive charge as shown in Figure 4.2 (c). The aluminum plate is still charged positively; only it now has less excess positive charge than it had before the charging process began. This process is called charging by conduction, or "by contact" and the two rods end up with the same sign on charge.

Charging by Induction

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

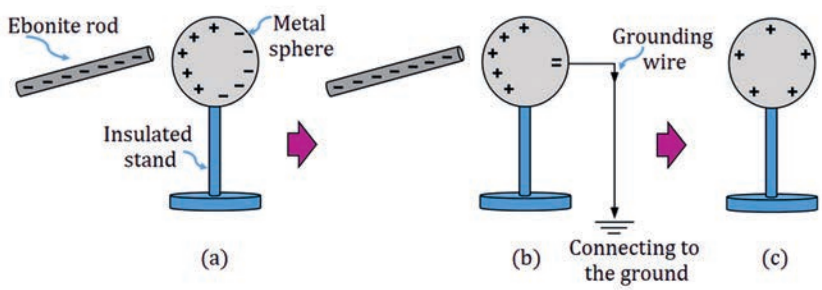


Figure 4.3 Charging by induction.

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, conduction and 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

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

- *describe the function of an electroscope;*
- *use a simple electroscope to detect charges;*
- *make a simple electroscope out of locally available materials.*

The electroscope is a very sensitive instrument which can be used to detect the type of electric charge, to identify whether an object is charged or not, to measure the quantity of charge and to know whether an object is conductor or insulator. It consists of a glass container with a metal rod inside that 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.

When a charged object, like the positively charged rod in Figure 4.4 is brought close to (but not touching), the neutral metal plate of the elec-

Exercise 4.4

What do you think about the purpose of an electroscope?

Key Concept

☞ For detecting the presence of a charge on the body, you use the collapsing or diverging of the leaf of the electroscope.

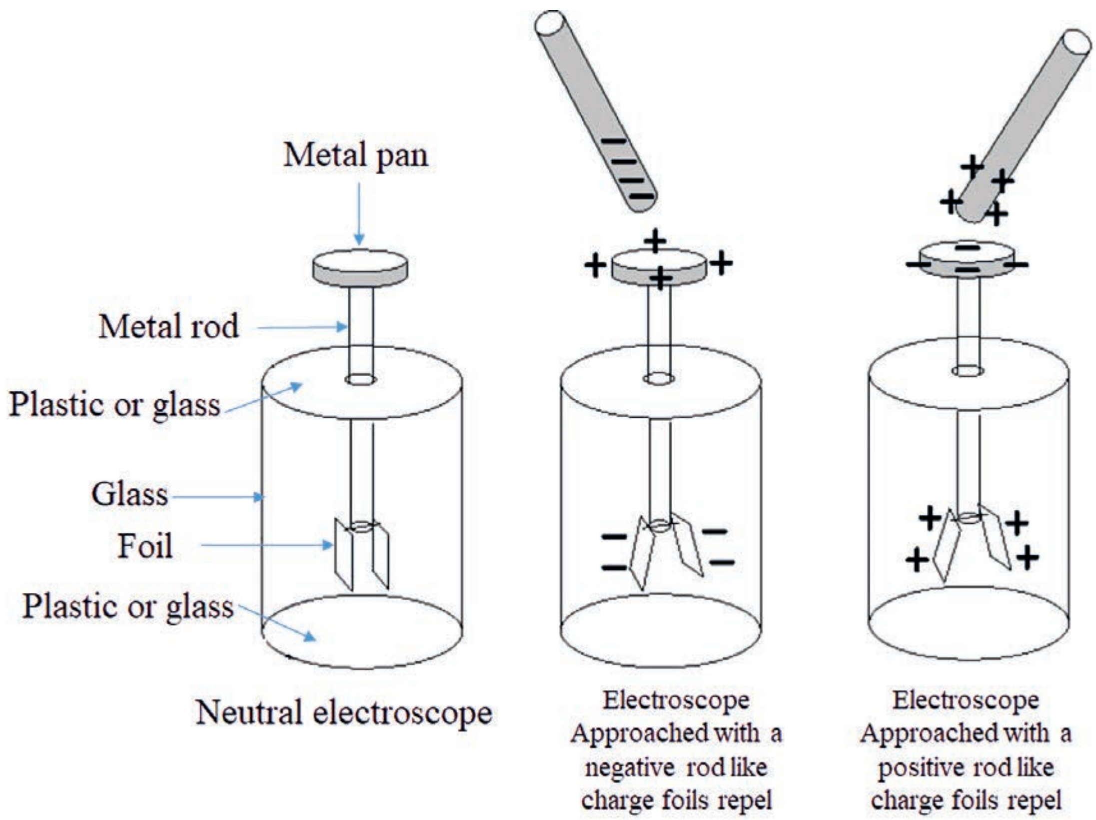


Figure 4.4 Charging an electroscope.

troscope, the negative charge in the gold foil, metal rod, and metal plate would be attracted to the positively charged rod. The charge can move freely from the foil up the metal rod and onto the metal plate because the metal (gold is a metal too) is a conductor. 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.

When the rod is now moved away from the metal plate, the charge in the electroscope spreads out evenly again, and the leaves will fall down again because there is no longer 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.

Review questions

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

Activity 4.3

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

Exercise 4.5

Can a charged object become neutral again?

4.4 Electrical Discharge

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

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

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.

So far, you have learnt about the techniques of charging a material. There is also a technique for removing the excess electric charges from the charged objects. 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 is formed (Figure 4.5 (c)). The cloud then discharges its excess electrons along the temporary path to the ground, creating a huge spark (Figure 4.5 (d)). This discharge also causes a rapid expansion of the air around it, causing thunder.

Activity 4.4

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

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 them 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 the Earth's surface. The Earth is a donator 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 4.5

In your community, what did people do when they encountered a person struck by lightning? Have you observed that they bury some parts of the person's (usually below the neck) i the ground?

The process of providing a pathway to drain excess charge into the 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

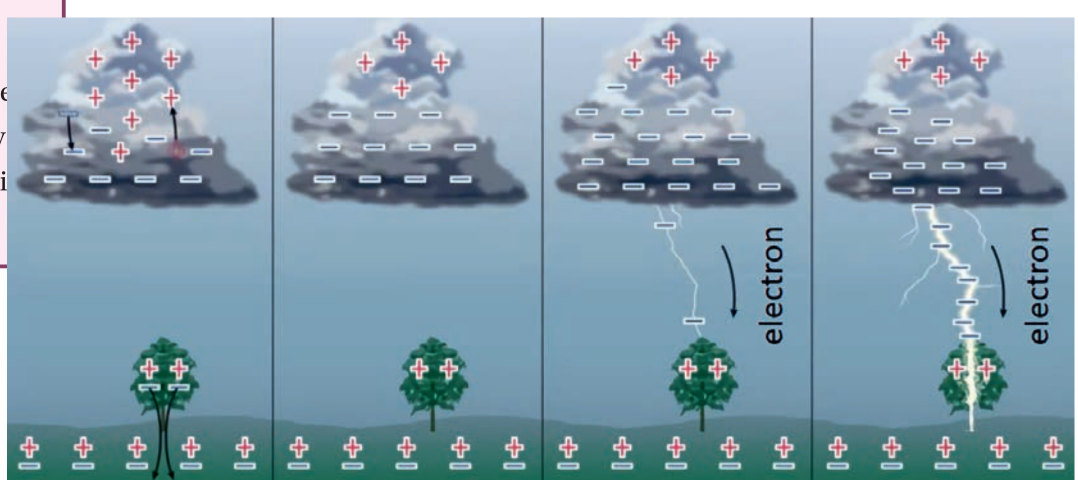


Figure 4.5 Lightning is an atmospheric electrical discharge.

to help 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 into the Earth's surface.

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.

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 charges away.

Exercise 4.6

Have you ever heard of someone being killed by lightning?

Exercise 4.7

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

Section summary

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

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?

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?

4.5 Coulomb's law of electrostatics

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

- *state Coulomb's laws of electrostatics;*
- *find the magnitude of electric force between two charges using Coulomb's law.*

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.

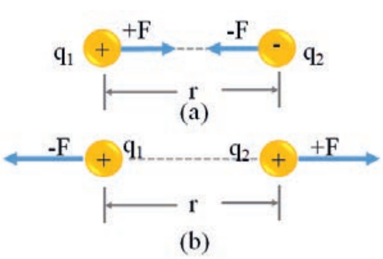


Figure 4.6 (a) Attractive and (b) repulsive electrostatic force between two charges.

Coulomb's law can 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.

You can convert the above proportionality expression to an 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.

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.

The SI unit of force is the 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 electrostatic forces.

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 magnitude of the force exerted by the two charges?

Solution:

You are given $q_1 = 5.0\mu C$, $q_2 = -12.0\mu C$ and $r = 30\ cm$.
You want to find the magnitude of the force F.

Using Coulomb's law,

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

Since the two charges are of opposite sign, the force between the charges is an attractive force.

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

4.6 The electric field

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

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

Exercise 4.9

What do you think is the definition for 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 differ 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 positively and negatively charged body.

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.

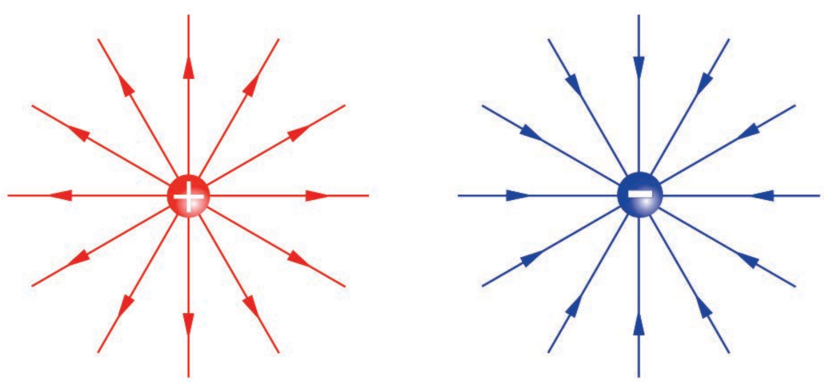


Figure 4.7 Electric field lines from positive and negative charges.

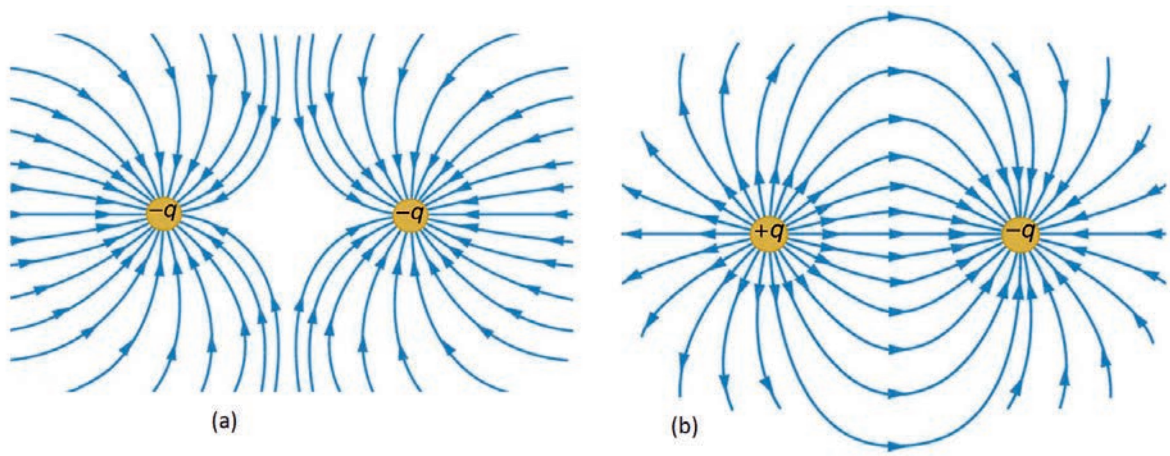


Figure 4.8 Electric field lines between (a) similar charges (b) opposite charges.

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 the 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

Key Concept

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

Electric Field Strength

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

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

Thus, $\vec{E}$ is a vector. If q is positive, the electric field $\vec{E}$ has the same direction as the force acting on the charge. If q is negative, the direction of $\vec{E}$ is opposite to that of the force $\vec{F}$. 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

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.

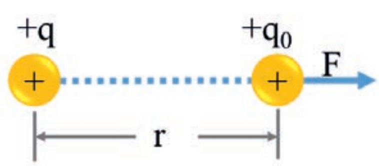


Figure 4.9 Electric field at a distance *r* from a charge.

Exercise 4.10

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

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

$$E = \frac{F}{q_o} = \frac{k\frac{q_o q}{r^2}}{q_o} = k\frac{q}{r^2} \quad \text{where} \quad \mathrm{F} = \mathrm{k}\frac{\mathrm{q_o q}}{\mathrm{r}^2} \qquad (4.5)$$

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 that is exerted on the positive charge. Thus, the electric field extends radially from a positive charge and inwards from a negative point 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:

In this example $q = 2.00 \times 10^{-9}\ C$ and $r = 5.00 \times 10^{-3}\ m$.
You want to find the magnitude and direction of the electric field.

You can find the electric field created by a point charge using the equation

$$E = k\frac{q}{r^2}$$

Substituting 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 is an electric field line?
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

Activity 4.6

What do you think are the differences between an open and closed circuits? Discuss in groups.

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

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

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 carried by electrons. The charges moving through the wire cause the filament to heat up and then give off light.

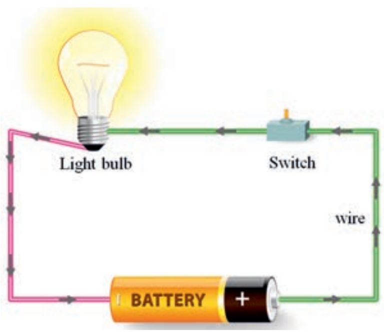


Figure 4.10 Simple electric circuit.

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.

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.

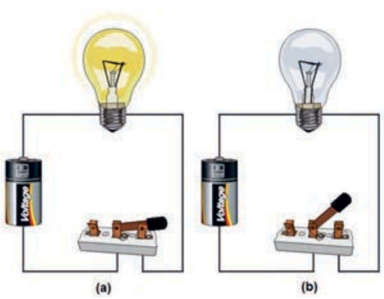


Figure 4.11 (a) Closed circuit (b) open circuit.

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, are disconnected or broken. Such a circuit is called a closed circuit.

Key Concept

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

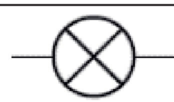
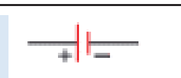
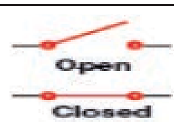
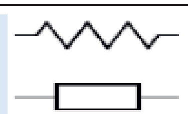
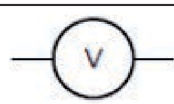
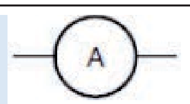
If the circuit is broken anywhere (or the switch is turned off), the charge stops flowing and the bulb does not glow. Thus, without a complete path, there is no charge flow and therefore no current. This situation is an open circuit. If the switch in Figure 4.11 were open, as shown in Figure 4.11(b),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

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) that 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 symbols of electrical components.

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

Exercise 4.11

What would happen to the lamp if the circuit is broken somewhere?

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 making electric charge to flow through the circuit.

Review questions

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

4.8 Current, Voltage, and Ohm's Law

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

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

Exercise 4.12

How would you explain what an electric current is?

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.

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. 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 to be wrong once the electron was discovered. So, in practice, the electric current is the flow of electrons (negatively charged particles). Electron current is the flow of negatively charged particles from the negative terminal of the battery to the positive terminal, as shown in Figure 4.12. However, the direction of the current does not affect the properties of the 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 Δt, then the current I, through the cross-section is

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

Key Concept

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

The SI unit for 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 ($1 mA = 10^{-3}$ A) or in

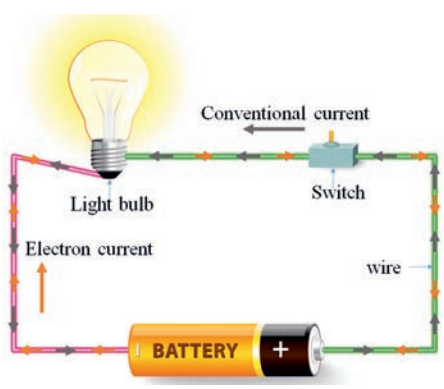


Figure 4.12 Conventional current and electron current.

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.

Solution:
You are given $I = 0.5\ A$, and $\Delta t = 10$ minutes $= 600\ s$.
You want to find the net charge, ΔQ.

From the equation for current, you have

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

Potential Difference

Exercise 4.13

What makes electric charges to flow?

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 the 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 of 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.

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.

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.

The electric potential difference (V) 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.

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

The SI unit of electric potential difference is the volt (V), named after **Alessandro Volta (1745-1827)**, an Italian physicist. One volt $(1\ V)$ is the potential difference between two points in a current-carrying conductor when 1 Joule $(1\ J)$ of work is done to move a charge of 1 coulomb $(1\ C)$ from one point to the other. Therefore, $1\ V = 1\ \frac{J}{C}$.On the other hand, potential difference is measured by means of an instrument called the voltmeter.

Exercise 4.14

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

You might have seen birds sitting and even running along electric line wires high in the air. There are times when these wires can be filled with dozens of birds. Since birds are not good conductors, that is 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 on a single wire. There must be a difference

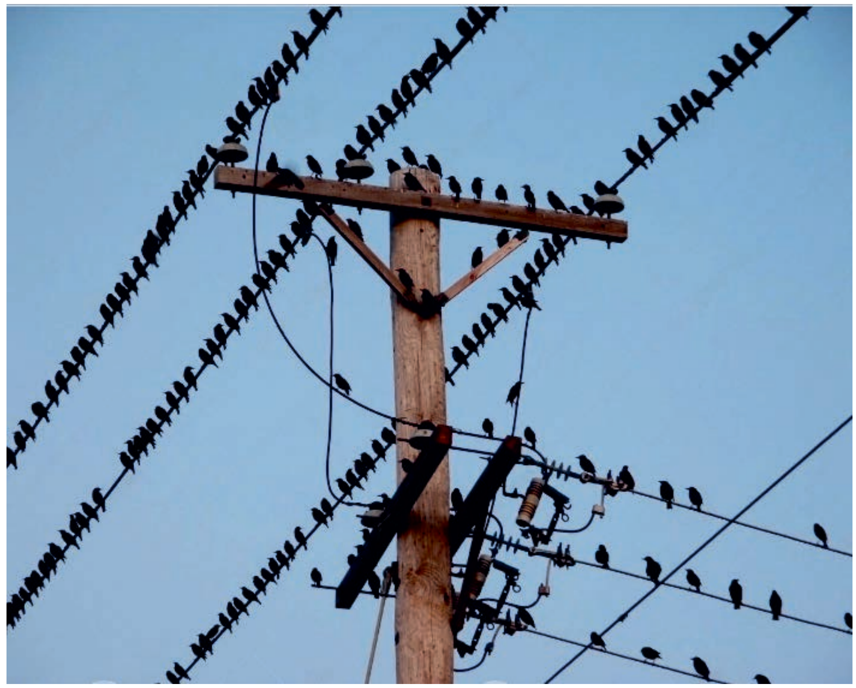


Figure 4.13 Birds on an electric cable.

in electrical potential for electrons to move. For example, energy flows from 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 is no difference in electrical potential.

Activity 4.7

Would you be harmed if you touch one of the wires of a high-voltage transmission line just like birds without having contact with the ground? If yes, then how can birds not die when they sit on such lines?

It would be a different story if a bird is connected to the ground through some means (like a tree) 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.

Example 4.4

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

Solution:
In this example, you are given with $V = 12\ V$ and $q = 2C$.
What you want to find is the work done.

The amount of work W, done in moving the charge is

$$W = VQ = 12\ V \times 2\ C = 24\ J$$

Ohm's Law

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,

$$V\ \alpha\ I$$

In an equation form,

$$\frac{V}{I} = R \quad or \quad V = IR \tag{4.7}$$

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.

In the above expression, R is a constant for the given metallic wire at a

Exercise 4.15

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

Exercise 4.16

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

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 $\frac{V}{A}$. You call a $\frac{V}{A}$ an "ohm", which is represented by the uppercase Greek letter omega (Ω). Thus, $1\ \Omega = 1\ \frac{V}{A}$.

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

Key Concept

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

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 voltage, are said to be ohmic materials. Ohmic materials include good conductors like copper, aluminum, and silver. Ohmic materials have a linear current-voltage relationship over a large range of applied voltages (Figure 4.14 (a)). Non-ohmic materials have a nonlinear current-voltage relationship (Figure 4.14 (b)).

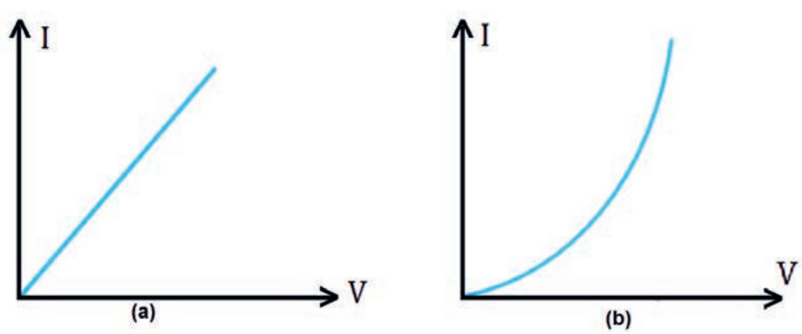


Figure 4.14 The current-voltage characteristics of (a) ohmic materials and (b) non-ohmic materials.

Exercise 4.17

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,

$$R \, \alpha \, \frac{L}{A}$$

$$R = \rho \frac{L}{A} \tag{4.8}$$

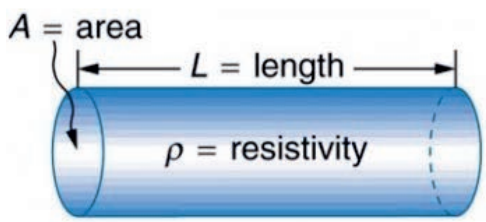


Figure 4.15 A uniform conductor of length L, and cross-sectional area A.

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 resistivity's reciprocal. So a high resistivity means a low conductivity, and a low resistivity means a high conductivity.

Exercise 4.18

For the same crossection of a wire, describe how the electric resistance of a wire changes as the wire becomes longer. How does the resistance change as the wire becomes thicker for the same length of a wire?

Example 4.5

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

Solution:

You are given $V = 220\ V$ and $R = 1200\ \Omega$.

You want to find the value for the current, I.

From Ohm's law, current can be calculated by:

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

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?

Solution:

You are given $V = 60\ V$ and $I = 4\ A$.
What you want to find is the resistance, R.

According to Ohm's law,

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

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

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

The current through the heater becomes 8 A.

Example 4.7

The resistance of a metal wire of length 1 m is 26 Ω at 20 ^oC. 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 = 26 Ω, the diameter d = 0.3 mm = $3 \times 10^{-4}\ m$, and the length L of the wire = 1 m. You want to find the resistivity.

From the expression of the resistance, 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 ^oC 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 an 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. Will current flow more easily 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?

Exercise 4.19

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

Exercise 4.20

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?

4.9 Combination of resistors in a circuit

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

- *draw a diagram that shows series and parallel connections 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 and potential difference across resistors connected in series and parallel.*

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

Students, 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.

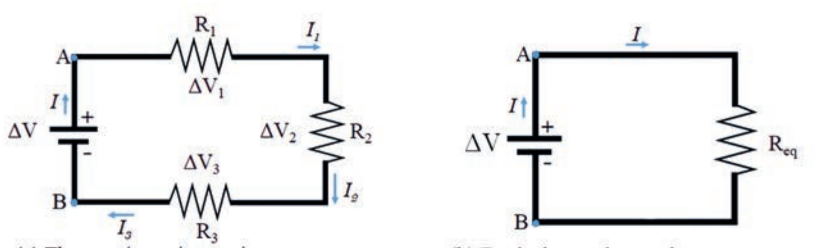
Key Concept

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

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 will no longer flow and all the devices in the circuit will 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.

Exercise 4.21

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



(a) Three resistors in a serious (b) Equivalent resistance has same current

Figure 4.16 Series connection of three resistors.

Since charge is conserved, charges cannot build up or disappear at one 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.

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.

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

$$V = V_1 + V_2 + V_3 \tag{4.9}$$

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 V across it, and the current I through the circuit remain the same. Applying Ohm's law to the entire circuit, you have

$$V = IR_{eq}$$

By making use of equation 4.9,

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

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

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

$$\therefore R_{eq} = R_1 + R_2 + R_3 \tag{4.10}$$

Key Concept

☞ The equivalent resistance in a series circuit is the sum of the circuit's resistances.

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.

Resistors in Parallel

Exercise 4.22

Explain why buildings are wired using parallel circuits rather than series circuits.

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.

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.

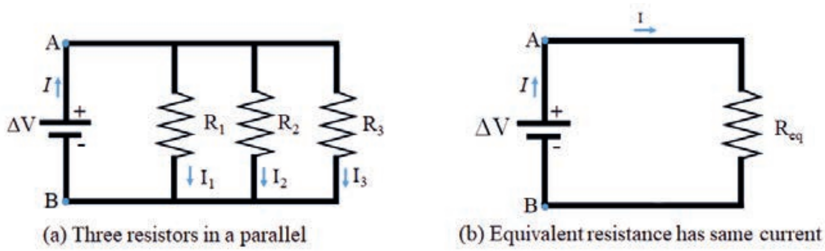


Figure 4.17 Parallel connections of three resistors.

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.

$$I = I_1 + I_2 + I_3 \ldots \tag{4.11}$$

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

$$I = \frac{V}{R_{eq}}$$

Since $I = I_1 + I_2 + I_3$, applying Ohm's law to each resistor gives you

$$\frac{V}{R_{eq}} = \frac{V_1}{R_1} + \frac{V_2}{R_2} + \frac{V_3}{R_3}$$

where $I_1 = \frac{V}{R_1}$, $I_2 = \frac{V}{R_2}$, and $I_3 = \frac{V}{R_3}$

Because the potential difference across each bulb in a parallel arrangement equals the terminal voltage $V = V_1 = V_2 = V_3$, you can divide each side of the equation by V to get the following equation.

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}$$

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 the current to follow.

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.

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} ... + \frac{1}{R_n} \tag{4.12}$$

Example 4.8

In the circuit shown in Figure 4.18, find:

a) the equivalent resistance,

b) the current through each resistor.

Solution:

You are given $R_1 = 12\ \Omega,\ R_2 = 3.0\ \Omega,\ R_3 = 4.0\ \Omega,\ R_4 = 5.0\ \Omega\ and\ V = 12\ V$.
The required quantities are R_{eq} and I.

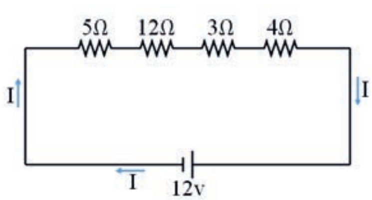


Figure 4.18 Circuit diagram for four resistors connected in series.

a) Since all the four resistors are in series combination,

$$R_{eq} = R_1 + R_2 + R_3 + R_4 = 12\ \Omega + 3.0\ \Omega + 4.0\ \Omega + 4.0\ \Omega = 24\ \Omega.$$

b) The current through all resistors in a series circuit is the same. Thus, using Ohm's law,

$$I = \frac{V}{R} = \frac{V}{R_1} = \frac{12V}{24\ \Omega} = 0.50\ A$$

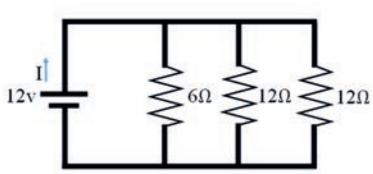


Figure 4.19 Circuit diagram for three resistors connected in parallel.

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.

Solution:

The given quantities are $R_1 = 12\ \Omega,\ R_2 = 12\ \Omega,\ R_3 = 6.0\ \Omega$ and $V = 12\ V$.

The required quantities are R_{eq} *and* I.

a) The three resistors are in a parallel combination. So

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{12\ \Omega} + \frac{1}{12\ \Omega} + \frac{1}{6.0\ \Omega} = \frac{1}{3.0\ \Omega}$$

$$R_{eq} = 3.0\ \Omega$$

Therefore, the equivalent resistance should be less than the smallest resistance as expected.

b) From Ohm's law,

$$I = \frac{V}{R_{eq}} = \frac{12\ V}{3.0\ \Omega} = 4.0\ A$$

Since the voltage is constant in a parallel connection,

$$I_1 = \frac{V}{R_1} = \frac{12\ V}{12\ \Omega} = 1.0\ A$$
$$I_2 = \frac{V}{R_2} = \frac{12\ V}{12\ \Omega} = 1.0\ A$$
$$I_3 = \frac{V}{R_3} = \frac{12\ V}{6.0\ \Omega} = 2.0\ A$$

On the other hand, resistors in a circuit may be connected in a variety of series-parallel combinations. The general procedure for analyzing circuits with different series-parallel combinations 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 of 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 4.0 Ω resistor shown in Figure 4.20.

Solution:

You are given $R_1 = 4.0\ \Omega,\ R_2 = 5.0\ \Omega,\ \ R_3 = 9.0\ \Omega$, and $V = 6\ V$.
You want to find the value for R_{eq} and I.

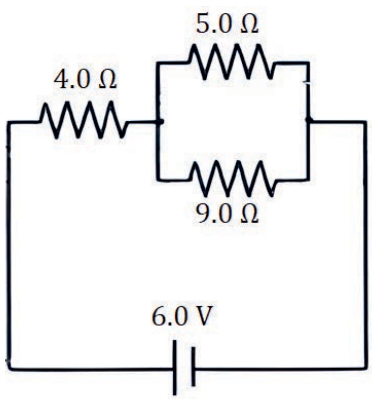


Figure 4.20 Circuit diagram for series-parallel combination of resistors.

Since the 5.0 Ω and 9.0 Ω resistors are connected in parallel,

$$\frac{1}{R_{parallel}} = \frac{1}{R_2} + \frac{1}{R_3} = \frac{1}{5\ \Omega} + \frac{1}{9\ \Omega} = \frac{14}{45\ \Omega}$$

$$R_{parallel} = 3.21\ \Omega$$

Now the 4.0 Ω 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

$$I = \frac{V}{R} = \frac{V}{R_{eq}} = \frac{6\ V}{7.21\ \Omega} = 0.830\ A.$$

This is equivalent to the value of the current across the 4.0 Ω resistor as the 4.0 Ω 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	$V = V_1 + V_2 + V_3 + ... =$ sum of potential differences	$V = V_1 = V_2 = V_3 = ... =$ 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 be 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 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.

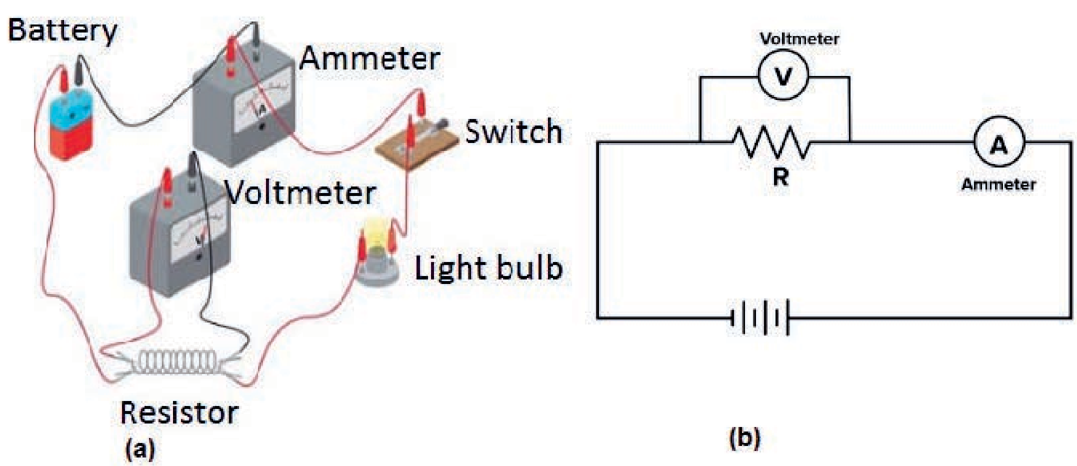


Figure 4.21 (a) Ammeter and voltmeter connection in a circuit. (b) Circuit diagram with ammeter and voltmeter.

Voltmeter

A voltmeter is a device that is used to measure potential differences 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 differences.

To measure the potential difference between 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 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 it. Hence, it should be connected in parallel. Figure 4.21 shows a voltmeter is 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.

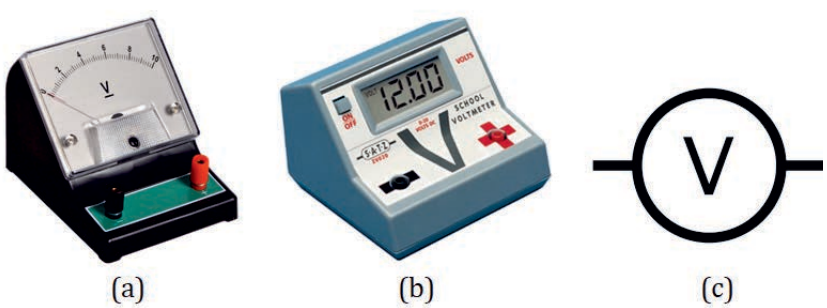


Figure 4.22 (a) Analog voltmeter (b) Digital voltmeter (c) Voltmeter symbol.

Ammeter

An ammeter is a device that is used to measure the the flow of electric current in amperes. To measure the current of a circuit, the ammeter shown in Figure 4.23 is connected in series in the circuit so that the same current that is in the circuit flows through it and gets measured. Ammeter

Key Concept

☞ Voltmeters are connected in parallel with whatever device's voltage is to be measured.

Exercise 4.24

How do we connect the ammeter and voltmeter in an electrical circuit? Draw a circuit diagram in order to justify your answer. What will be happening if the positions of these instruments are interchanged? Specify the reasons.

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 a series have the same current passing through them. All of the current in this circuit flows through the meter.

(a) (b) (c)

Figure 4.23 (a) Analog ammeter (b) A digital ammeter (c) Ammeter symbol.

If an ammeter is connected in parallel, it would draw most of the current and get damaged. Hence, it must be connected in series.

Key Concept

☞Ammeters are connected in series with whatever device's current is to be measured.

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 an ammeter and a voltmeter

Instrument	Measured Quantity	Proper Connection
Voltmeter	Voltage	In Parallel
Ammeter	Current	In Series

On the other hand, 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 Multimeter used for measuring electrical properties.

Section summary

- Voltmeters measure voltage and 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. In Figure 4.25, there are four positions available for the placement of meters.
   a)Which position(s) would be appropriate for placement of an ammeter?
   b) Which position(s) would be appropriate for placement of a voltmeter?

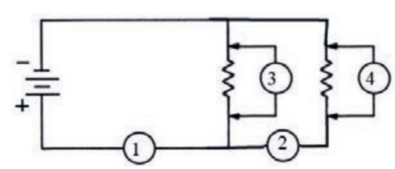


Figure 4.25 Ammeter and voltmeter connection in a circuit.

c) Which position could hold an ammeter that would read the total current through the circuit?
d) Which position could hold a voltmeter that would read the total voltage drop through the circuit?

5. Suppose you are using a multimeter to measure current in a circuit and you inadvertently leave it in 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 ammeter mode?

Exercise 4.25

Have you ever had a mild electric shock?

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 that could be dangerous.

4.11 Electrical safety in general and local context

By the end of this section, you should be 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 from the 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.

A person can be electrocuted by touching a live wire while in contact with the 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.

Exercise 4.26

Try to identify what determines the damage caused to the human body by an electric shock.

Electric shock can result in fatal burns or 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.

Figure 4.26 A Fuse.

A fuse is the cheapest protection device in an electrical circuit against short circuits and overloading of circuits. A fuse is a metal wire or thin metal strip that has the property of having low melting point which is inserted into the electrical circuit as protective device. A fuse provides protection against excessive currents which can flow in circuit during short circuits. Under normal working conditions, the current flowing through the circuit is within safe limits, but when fault occurs, such as a short circuit occurs, or when load greater than the circuit capacity is connected to it, the current exceeds the limiting value, resulting in a fuse wire that gets heated up, melts, and breaks the current. Thus, fuse protects the machine or electrical equipment against excessive currents. An automatic voltage regulator or stabilizer device that you use in your home uses a fuse to operate.

Figure 4.27 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 4.28. 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 4.28 (a)), 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 4.28 (b)). In this case, if a short occurs, the path of least resistance for the current is from the

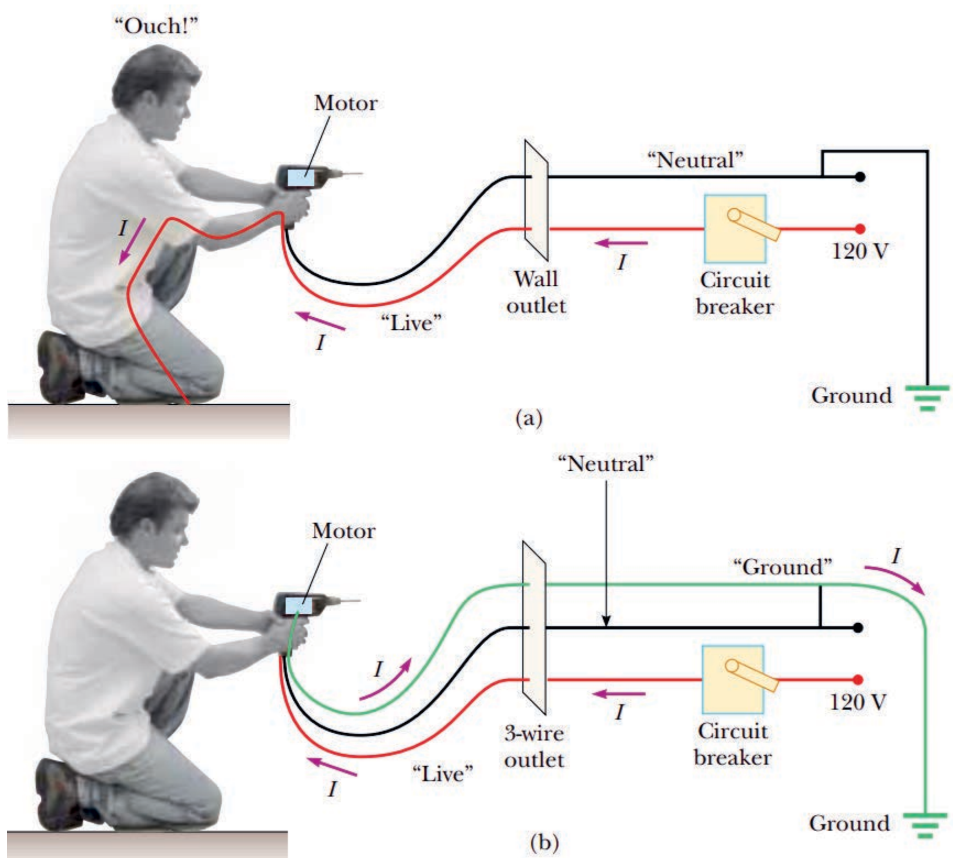


Figure 4.28 The "phase" wire, at 220 V, always includes a circuit breaker for safety. (a) When the drill is operated with two wires, the normal current path is from the "phase" wire, through the motor connections, and back to ground through the "neutral" wire. (b) Shock can be prevented by a third wire running from the drill case to the ground.

high-voltage wire through the case and back to ground through the third wire. The resulting high current will blow a fuse or trip a circuit breaker before the consumer is injured.

Note: The color of wires represents electrical standards. In Ethiopia, the "phase" wire is red, yellow, or blue, and the ground wire is greenish-yellowish, and the neutral wire is black.

Key Concept

☞ A grounding plug (a 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.

Special power outlets called ground-fault interrupters (GFIs) or residual current devices (RCDs) 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 factors that determine the damage caused to the human body by an electric shock.
2. You are often advised not to flick electric switches with wet hands; you have to dry your hands 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 be able to:

- *draw an electric circuit diagram consisting of a battery, connecting wires, resistors, a switch, and a 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 that move things including lifts and escalators, washing machines, food mixers and other home appliances) largely operate without your being aware of how they do so. The "how" of these electronic devices working is answered by electrical circuits.

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.

Exercise 4.27

Did you remember any electrical projects that you have undertaken? Is there any tips that you can share us from your experience?

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 and 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 is because current must flow through both lamps for the circuit to be complete.

In this project, you will build a simple circuit that connects two lamps in series, like the one shown in Figure 4.29. 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 and materials:

- A small head screw driver

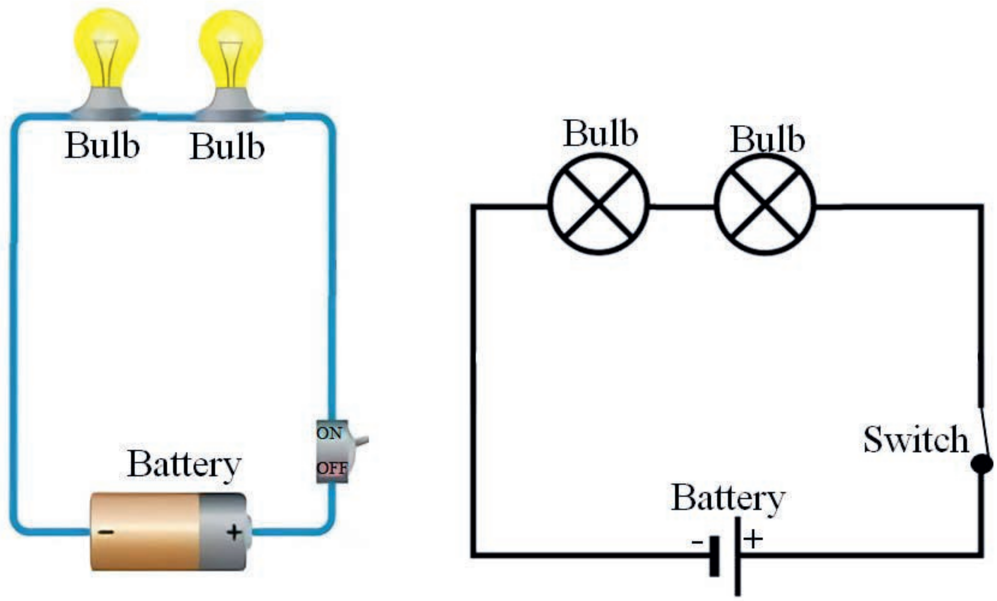


Figure 4.29 (a) Series circuit (b) Series circuit diagram.

- Wire cutters
- Wire strippers
- A multimeter
- Two AA batteries
- One battery holder
- Two lamp holders
- Two 3 V flashlight lamps
- One 6-inch length of 22-gauge stranded wires.

Steps

1. Cut a 6 inch length of wire and strip 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. This makes both lamps to lit. Notice that the lamps are dim. This is 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. This makes 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 V. *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 1.5 V.

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 3 V.

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 light.

In this project, you will build a circuit that connects two lamps in parallel like the one shown in Figure 4.30. The lamps are powered by a pair of AA batteries. You will use your multimeter to measure voltages at various points in the circuit.

Equipments and materials:

- A small head screw driver
- Wire cutters
- Wire strippers

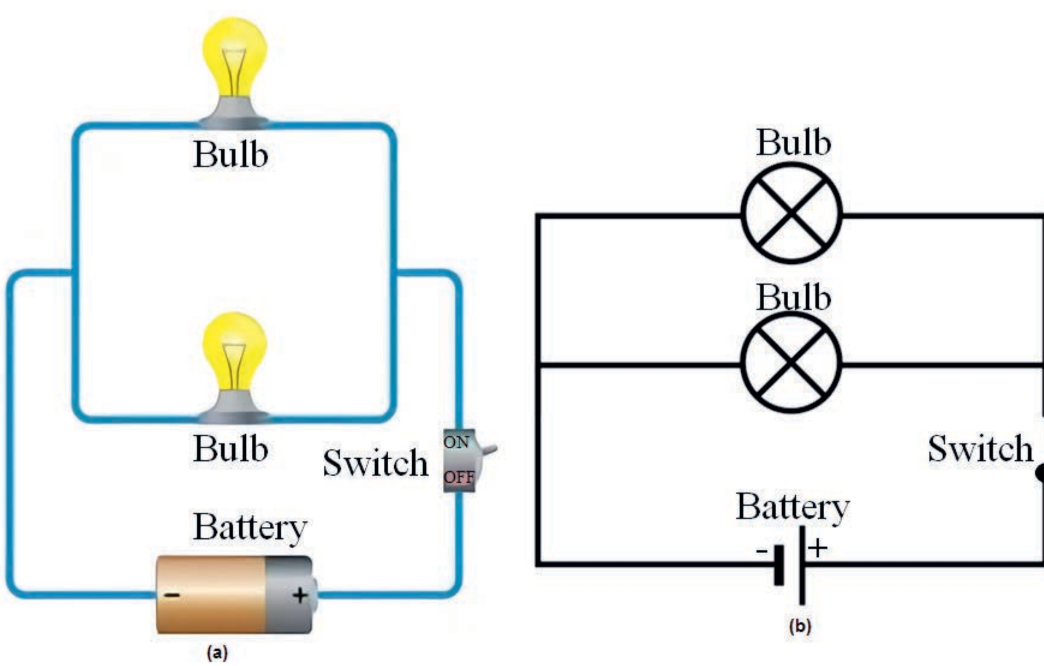


Figure 4.30 a) Parallel Circuit b) Parallel circuit diagram.

- A multimeter
- Two AA batteries
- One battery holder
- Two lamp holders
- Two 3 V 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. This makes 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 V.
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 3 V.

10. Touch the meter, which leads to the terminals on the second lamp stand. Note that the voltage again reads 3 *V*. 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, in groups, you will construct and wire a model house according to the requirements given below. You can use materials that are available in your area.

The Building:

- Your group will design and construct an electric house with separate series, parallel, and complex circuits.
- The house you build 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 a full point, each circuit below must be completed. Each house will be wired with 4-hour 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 9 V batteries, so make two obvious 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 9 V 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 others.
- 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 and 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 magnitude of 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 in 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 them.
- The 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 V across its ends, i.e., $V \alpha I$ or $V = RI$, where R is called the resistance of the substance.
- 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.
- The equivalent resistance R of n resistors connected in series is given by $R = R_1 + R_2 + ... + R_n$
- The equivalent resistance R of n resistors connected in parallel is given by $\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + ... + \frac{1}{R_n}$.
- An 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.
- A 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.
- 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 20 *cm* 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 $1.2 \times 10^9\ N$. Determine the magnitude of the charge on each to see if one has twice the charge (of the opposite sign) as the other.
10. Two equal charges of magnitude $1.1 \times 10^7\ C$ experience an electrostatic force of $4.2 \times 10^4\ N$. 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 is not 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 magnets, that 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.

Brain storming question:

Can you list the different ways in which magnetism has played a part in your life today?

By the end of this unit, you should 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.*

5.1 Magnet

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

- *identify various types of magnets based on their physical shapes;*
- *describe the properties of magnets.*

Exercise 5.1

Most probably, you have been familiar with a magnet. How could you define it? When was a magnet first discovered?

Magnets have always been an awesome thing for humans, as they play an important role in a wide range of devices that you use in your daily life. The use of magnets was discovered by the ancient Greeks during the period of Greek civilization. They found stones that were able to attract iron and nickel like other substances. This naturally occurring stone 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 that is responsible for a force that pulls or attracts other materials. Magnets attract objects made of iron or steel, such as nails and paper clips. Magnets can also attract or repel other magnets.

Figure 5.1 Magnets of different shapes.

Magnets can be made in various shapes and create their 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 a tape recorder, radio, motor, door-bell, head phones, etc. They are used in these appliances to either hold or separate, control, elevate (lift) substances, by changing electrical energy into mechanical energy (motors, loudspeakers) or mechanical into electrical energy (generators and microphones).

Types of Magnets

There are three categories of magnets. These are:

1. **Permanent Magnets:** 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 on the nature of the material used in its creation. Permanent magnets are used in speakers, mobile phones, cars, generators, televisions, sensors, etc.

The following are the ways to demagnetize the permanent magnets:

- Exposing magnets to extreme temperatures.
- The magnetic attraction between the magnet's atoms gets loose when they are hammered.
- Striking one magnet with the other in an inappropriate manner will reduce the magnetic strength.

2. **Temporary Magnet:** can be magnetized in the presence of a magnetic field. When the magnetic field is removed, these materials lose their magnetic properties. Iron nails and paper-clips are examples of temporary magnets.

3. **Electromagnets:** consist of a coil of wire wrapped around a metal core made of 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 generators, motors, transformers, loudspeakers, MRI machines, magnetic locks, etc.

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.

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 greatest at the ends of the magnet. These ends are known as the poles of the magnets.
- Magnetic poles always exist in pairs. Thus, when a magnet is cut into two pieces, both pieces will have the North Pole and the South Pole.

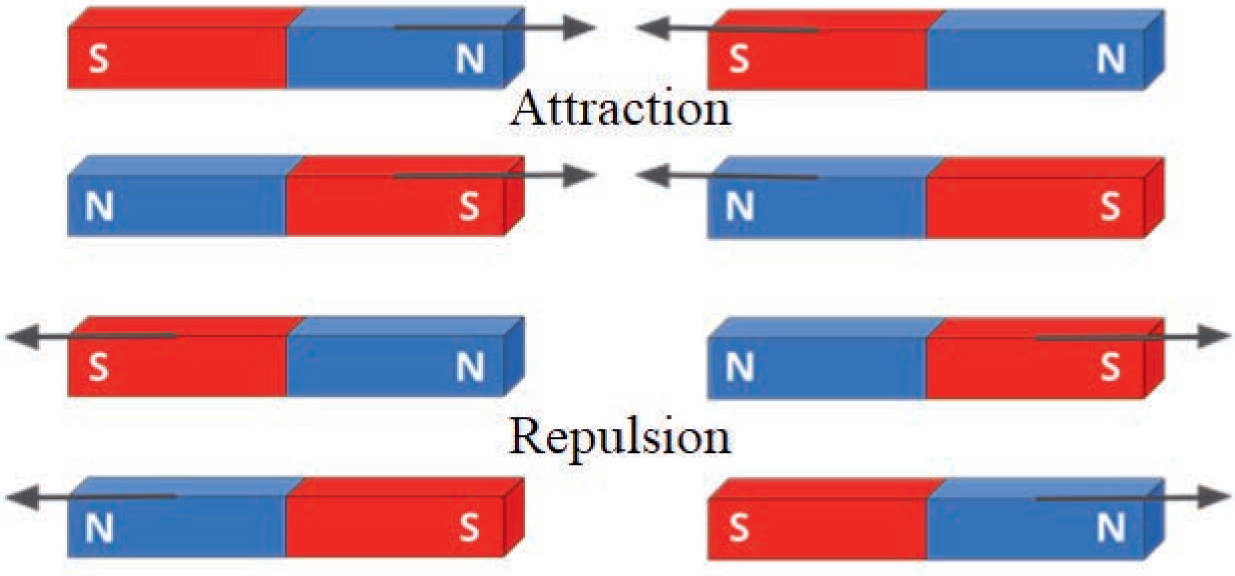


Figure 5.2 Properties of magnetic poles.

- Whenever a magnet is suspended freely in mid-air, it always points in a North-South direction. The 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 them is smaller.

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 could 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 mono-pole 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 should be able to:

- *describe what a magnetic field is;*
- *state the properties of magnetic lines of force;*
- *draw magnetic field lines around magnets.*

AS you learnt in unit 4, an electric field is a region where an electric charge experiences an attraction or repulsion force on other electric charge in the given region. In the same manner, a magnetic field is a field produced by the magnet or electric charges in motion. So it is the region around a magnetic material or moving electric charge within which the force of magnetism acts. Magnetic fields are represented by using magnetic field lines. It is a visual tool used to visualize the direction and strength of the magnetic field.

Exercise 5.2

Can you observe magnetic field lines through our naked eyes? Are they similarities between magnetic field lines and electric field lines?

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. The lines joining the points shows the magnetic field lines.

Properties of magnetic field lines

In order to understand about the properties of magnetic field lines, try to perform the following activity.

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 in this situation.

☞ Make a note of the shape of the lines formed by the iron filings as well as their size and direction for both arrangements of the bar magnet.

☞ What does the pattern look like when you place both bar magnets side by side?

Exercise 5.3

What are the similarities and differences between an electric field and a magnetic field?

What did you observe from the above activity?You have noticed that opposite poles of a magnet attract each other and bringing them together causes their magnetic field lines to converge (come together). On the other hand, like poles of a magnet repel each other and bringing them together causes their magnetic field lines to diverge (bend out from each other).

The following is some more list of some important properties of magnetic field lines.

- Magnetic field lines never intersect with each other.
- Magnetic field lines form a closed-loop.
- Outside a magnet, magnetic field lines appear to emerge or start from the North pole and merge or terminate at the South pole. Inside a 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. In a place 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.

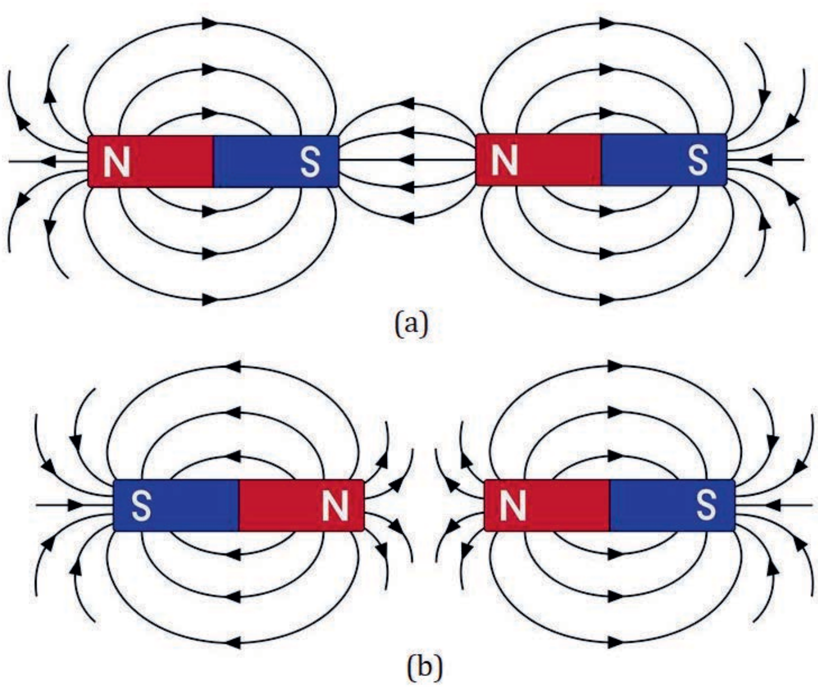


Figure 5.3 Magnetic field lines plot for a bar magnet.

The following is the discussion of the similarities and differences between electric and magnetic fields.

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.

Exercise 5.5

What are the similarities and differences between an electric field and a magnetic field?

Similarities between magnetic and electric fields

- Electric fields are produced by two kinds of charges, positive and negative. Magnetic fields are associated with two magnetic poles: North and South, although they are also produced by charges (moving charges).
- Like poles repel, but unlike poles attract each other.
- The electric field points in the direction of the force experienced by a positive charge. The magnetic field points in the direction of the force experienced by the North pole.

Differences between magnetic and electric fields

- Positive and negative charges can exist separately. The north and south poles always come together. Single magnetic poles, known as magnetic monopoles, have been proposed theoretically, but a magnetic monopole has never been observed.
- Electric field lines have definite starting and ending points. Magnetic field lines are continuous loops. Outside of a magnet, the field is directed from the North Pole to the South Pole. Inside a magnet, the field runs from south to north.

Section summary

- Magnetic field lines are the imaginary lines around a magnet which gives us the pattern of magnetic field of the magnet.
- Magnetic field lines don't start or end. They form a closed loop. They flow from North pole to South pole outside the magnet, while they flow from South pole to North pole inside the magnet.

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 the magnetic field using the concept of 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 should 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 5.6

Does the Earth have a magnet? What do you think?

Earth's Magnetic Field

As you learnt in the previous section, the magnetic field is the region around a magnetic material or a moving electric charge. Earth has a huge magnet that produces a magnetic field. The origin of the Earth's magnetic field is thought to be deep within the Earth in the outer core layer. The Earth's magnetic field, also known as the geomagnetic field, is the magnetic field that extends from the Earth's interior out into space and causes a compass needle to rotate. The movement of molten iron in the outer core is responsible for generating the Earth's magnetic field. The shape of the Earth's magnetic field, is similar to that of a huge bar magnet tilted about 11^o from the 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 and South poles: geographic poles and magnetic poles.

Key Concept

☞ The 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.

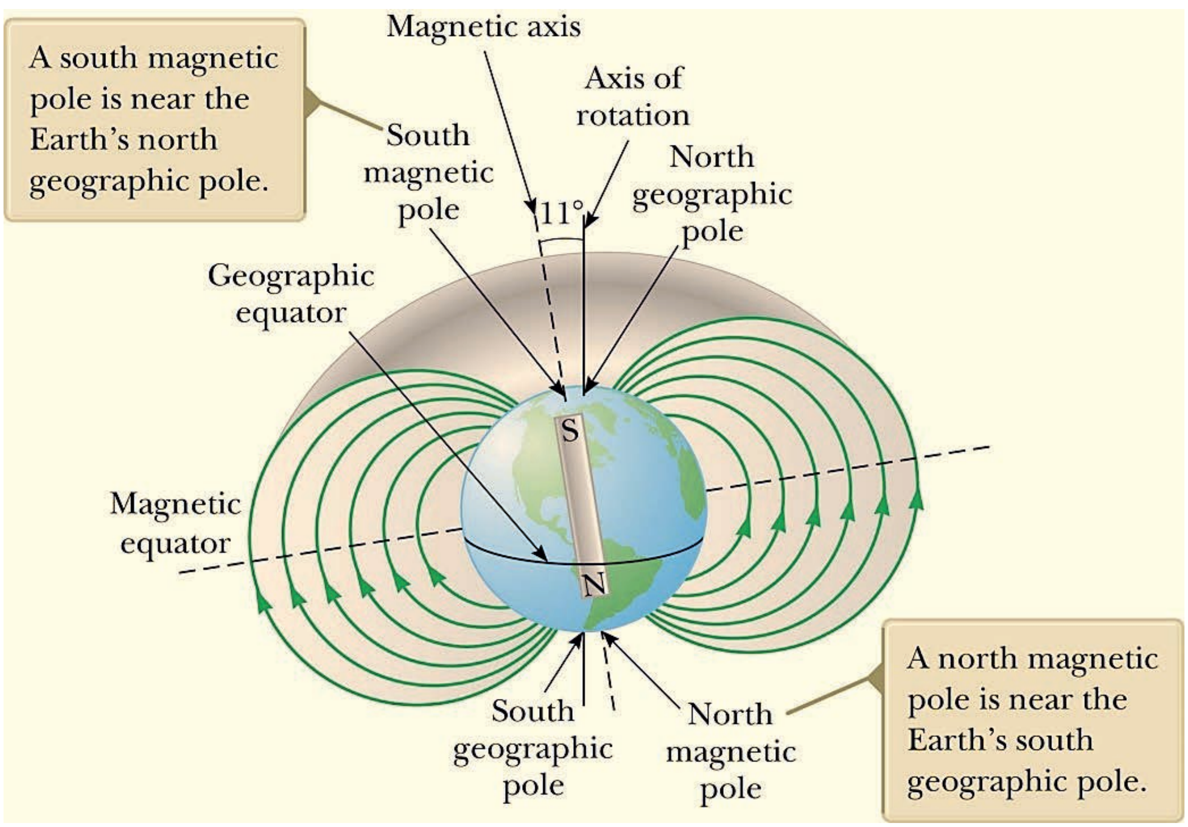


Figure 5.4 Earth's magnetic field.

A compass

A compass is an instrument that is used to find the direction of a magnetic field. It can do this because a compass consists of a small metal needle that is magnetized itself and that 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 5.7

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 directions on the Earth. This works because the Earth itself has a magnetic field which is similar to that of a bar magnets, as discussed above. The compass needle aligns with the magnetic field direction and points North (or South). Once you know where the North is, you can figure out any other direction. A picture of a compass is shown in Figure 5.5.

Figure 5.5 Compass.

The Earth's magnetic field also causes a compass needle to rotate. The North pole of the compass needle points toward the Earth's magnetic pole, which is in the North. This magnetic pole is actually the 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 orient themselves and find directions. Animals that 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.*

Exercise 5.8

List factors affecting the strength of magnetic field around a straight 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. Moving charges also produce magnetic fields which are proportional to the current, and hence, a current-carrying wire produces a 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.

As discussed above, a moving charge (or current), produces a magnetic field. Figure 5.6 shows a long, straight section of wire carrying a current I. Since there is current present in the wire, a magnetic field is produced around the wire and is composed of closed concentric circles, as represented by the gray loops in Figure 5.6.

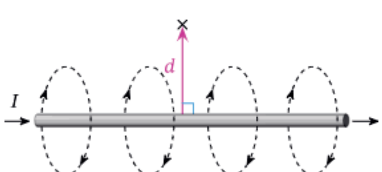


Figure 5.6 Magnetic field around a current-carrying wire.

The strength of a magnetic field, B, some distance d away from a straight wire carrying a current, I, can be found using the equation

$$B = \frac{\mu_o I}{2\pi d} \tag{5.1}$$

where, $\mu_o = 4\pi \times 10^{-7}\ \frac{Tm}{A}$ refers to the permeability of free space, I is the magnitude of the current, and d 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 $2\ T$; superconducting electromagnets may attain $10\ T$ or more. The Earth's magnetic field on its surface is only about $5 \times 10^{-5}\ T$ or $0.5\ G$.

Activity 5.2

Sketch the magnetic field pattern of a steady electric current flowing in a long straight wire.

It should be noted that the distance d must be measured perpendicular to the wire. A perpendicular distance measurement is shown in Figure 5.6. The strength of the field, B, decreases as the distance away from the wire, d, increases.

Since magnetic field is a vector quantity, you need to also determine the direction of the magnetic field. The direction of 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 5.7, the concentric lines represent the magnetic field lines.

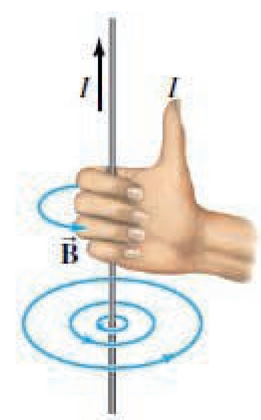


Figure 5.7 Right-hand rule for a magnetic field around a current-carrying wire.

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.
- A change in the direction of the current flow reverses the direction

of the field.

Key Concept

☞ A wire carrying an 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 3 A passing through it. Calculate the magnetic field at a distance of 2 cm from the wire ($\mu_0 = 4\pi \times 10^{-7} \frac{Tm}{A}$).

Solution:

In this example, you are given with $I3\ A\ \ and\ \ d = 2\ cm$.

You want to find the magnitude and direction of a magnetic field.

For infinitely long straight wire, the formula for the magnetic field is

$$B = \frac{\mu_0 I}{2\pi d}$$

Substituting the given values into the equation gives

$$B = \frac{(4\pi \times 10^{-7}\ \frac{Tm}{A}) \times (3\ A)}{2\pi \times (0.02\ m)} = 3 \times 10^{-5}\ T$$

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 on which a magnetic field due to a current-carrying conductor depends?

5.5 Magnetic force on a moving charge placed in a uniform magnetic field

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.*

When a charged particle passes through a uniform magnetic field, a magnetic force is exerted on them. If a charged particle is in motion in a magnetic field with a speed or velocity (v), in the magnetic field ($\vec{B}$), then it will feel a force which is magnetic force ($\vec{F}$). At the rest position, these particles are unaffected by the magnetic fields, but as they begin to move, the magnetic field pushes at them. Note that a uniform or steady magnetic field is the region or field where it has equal magnitude of strength and same direction at each point.

Exercise 5.9

What is the mechanism by which one magnet exerts a force on another?

Consider a positively charged particle that is moving in a uniform magnetic field. Then, the magnitude of the force (magnetic force) is directly proportional to the magnitude of the charge, the component of the velocity which is acting perpendicular to the direction of this field and the magnitude of the generated magnetic field.

Key Concept

☞ Any moving charged particle creates its own magnetic field and is affected when it moves through another magnetic field.

$$F = qvBsin\,\theta \tag{5.2}$$

Here, q is the magnitude of the charge, v$\sin\theta$ is the component of the velocity that is acting perpendicular to the direction of magnetic field and the B is the magnitude of the applied magnetic field.

The magnitude of the force becomes zero, when the speed or velocity of the particle and the magnetic field are parallel to each other, and reaches maximum when the velocity of the particle and the magnetic field are perpendicular to each other.

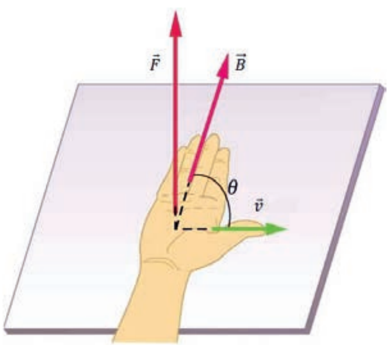


Figure 5.8 Right-hand rule for a magnetic force on a moving charge.

The direction of the magnetic force $\vec{F}$ is perpendicular to the plane formed by $\vec{v}$ and $\vec{B}$, as determined by the right-hand rule, which is illustrated in Figure 5.8. 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 $\vec{v}$, the fingers in the direction of $\vec{B}$, and a perpendicular to the palm points in the direction of $\vec{F}$.

Example 5.2

Determine the magnitude of the magnetic force of a 50 C charged particles moving with the velocity of 3 m/s in the same direction to a magnetic field of magnitude 1 T.

Solution:

You are given q= 50 C, v= 3 m/s, B = 1 T and $\theta = 0^o$.

The required quantity is The magnitude of the magnetic force.

The magnitude of the force is obtained by

$$\mathbf{F} = qvB\sin\theta = 50\ C \times 3‘m/s \times 1\ T \times \sin 0^o = 0$$

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 $\vec{v}$ and $\vec{B}$.

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 $7.5 \times 10^6\ m/s$ 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 wire

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.*

Exercise 5.10

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 wire? Does it produce a force?

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 experiences a force distributed along its length. The electric motor and the moving coil galvanometer both depend on their

Key Concept

☞ When a current-carrying wire lies in a magnetic field, magnetic force is exerted on the moving charges within the conductor.

operation on the magnetic force on wire carrying-currents.

Consider a wire of length L where an electric current I flow through the wire as shown in Figure 5.9. If this wire is placed in a magnetic field of magnitude B, the magnitude of the force is directly proportional to the current I in the wire, to the magnetic field B (assumed uniform), and to the length of wire exposed to the magnetic field. The force also depends on the angle between the current direction and the magnetic field as shown in Figure 5.9, being proportional to. Thus, the force on a wire carrying a current I with length in a uniform magnetic field B is given by:

$$F = ILB sin\theta \tag{5.3}$$

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 $\vec{B}$. 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 on the wire, as illustrated in Figure 5.10.

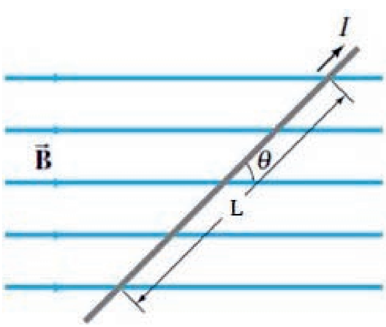


Figure 5.9 Current-carrying wire in magnetic field.

In general, 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.

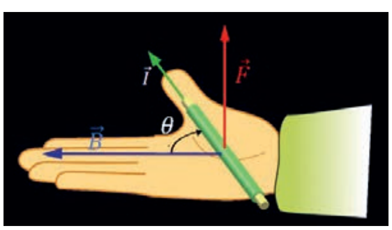


Figure 5.10 Right hand rule for a magnetic force on a current-carrying conductor.

Example 5.3

A wire 25 cm long is at right angles to a 0.30 T uniform magnetic field. The current through the wire is 6.0 A. What is the magnitude of the force on the wire?

Solution:

In this example, you are given $L = 25\ cm = 0.25\ m$, $B = 0.3\ T$, $\theta = 90^o$ and $I = 6\ A$.

You want to find the magnitude of the force.

The magnitude of the magnetic force can be calculated by

$$F = ILB\sin\theta = 6\ \text{A} \times 0.25\ \text{m} \times 0.3\ \text{T} \times \sin 90^{o} = 0.45\ \text{N}.$$

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 a current-carrying wire in a magnetic field.
2. List the factors that affect the magnitude of the force a current-carrying wire experiences.
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 wires

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

- *describe the effects of the magnetic force between two wires.*
- *explain how parallel wires carrying-currents can attract or repel each other.*

Exercise 5.11

Explain how to determine the direction of the magnetic forces between two parallel wires?

In section 5.4, you have learnt that a wire carrying a current produces magnetic field. Further, you also learnt that an external magnetic field will exert a force on a current-carrying wire.

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 wires carry currents of different magnitudes.

Now, you will need to consider two cases for two parallel current-carrying wires.

1. When current in both wires are in the same direction, you will need to draw a diagram to get a clear idea of the particular situation. Here, you have two parallel current-carrying wires, separated by a particular distance d, such that one of the wires is carrying current I_1 and the other is carrying I_2, which are in the same direction. The direction of magnetic force is indicated in Figure 5.11 (a) and is found using the right hand rule. In this case, two forces are acting toward each other. Therefore, you can say that they are attractive. Therefore, you can conclude that if the current in the two wires placed parallel is in the same direction, the force acting on them will be perceived as attractive.

2. When the current in the two wires is going in opposite directions,

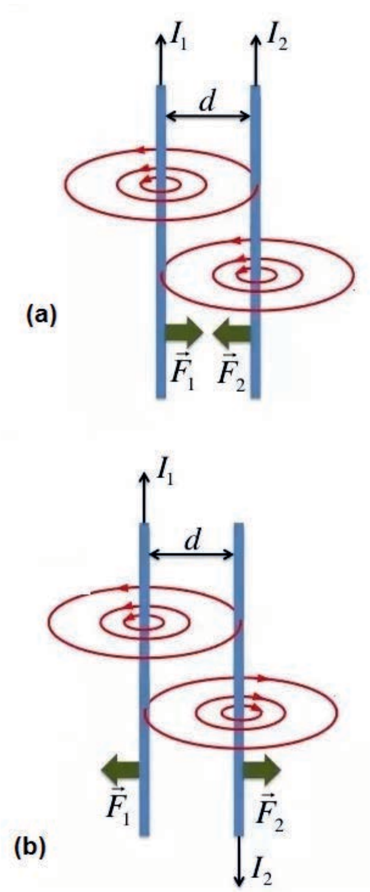


Figure 5.11 Magnetic force between two parallel wires carrying currents (a) in the same direction (b) in opposite directions.

you will need to draw a diagram to get a clear idea of the particular situation. Here, you have two parallel current-carrying wires, separated by a particular distance d, such that one of the wires is carrying current I_1 and the other is carrying I_2, but in opposite directions. The direction of magnetic force is indicated in Figure 5.11 (b) and is found using the right hand rule. In this case, two forces are acting in opposition to each other. Thus, you can say that they are repulsive. Therefore, you can conclude that if the current in the two conductors placed parallel is in the opposite directions, the force acting on them will be perceived 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.

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 phase and neutral lines hung from power poles? Why?

Activity 5.3

Practice the right-hand rule and determine the direction of force in Figure 5.11.

5.8 Applications of magnetism

Exercise 5.12

What do you think are the applications of the magnetism?

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

- *describe some applications of magnetism.*

Magnets play a significant role in a wide range of devices including simple toys, computers, credit cards, Magnetic Resonance Imaging (MRI) machines, and business equipment. The following is a discussion of some of the applications of magnetism.

Health and medicine

Magnets are found in some commonly used medical equipment such as MRIs. It uses 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

Figure 5.12 MRI scanning machine.

to show which way is north. The dark magnetic strip on the back 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 on magnetic principles. You also find magnets in phones, doorbells 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 foods. 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.

Figure 5.13 Magnetic compass used for navigation.

Compasses and Navigation

Peoples use magnetic compasses for navigation purposes. They found out magnets could direct needles and correlate with the North pole, and they used that information to navigate. The early compasses were created with lodestone because magnets were not yet longer invented. Lodestone comes from the mineral magnetite and is the handiest obviously-occurring magnet. Modern 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 $F = \text{qvBsin}\,\theta$.
- The magnitude of the magnetic force on a wire carrying a current I with length in a uniform magnetic field B is given by $F = ILBsin\,\theta$.
- The force between conductors is attractive when the currents flow in the same direction in the two wires. When the two wires are carrying currents in opposite directions, 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? What about when unlike magnetic poles are brought close together?

7. Draw the shape of the magnetic field around a bar magnet.

8. Explain how a compass needle indicates the direction of a magnetic field.

9. Compare the magnetic field of the Earth to the magnetic field of a bar magnet.

10. Explain the difference between the geographical North Pole and the magnetic North pole of the Earth.

11. Draw magnetic field lines for two similar magnetic poles and two dissimilar magnetic poles.

12. 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?

13. 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?

14. 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?

15. 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 0.75 T.

Unit 6

Electromagnetic Waves and Geometrical Optics

Introduction

Light is one form of an 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 called **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 topics related to Electromagnetic waves and geometrical optics.

Brainstorming Activity

Do you remember the definition of wave that you learnt in grade 9? Try to discuss in group and tell your answer of wave to your teacher.

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.*

Exercise 6.1

What are the different types of waves?

A wave transfers energy from one place to another without transferring matter. 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.

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.

- Mechanical waves are the types of waves that use matter to transfer energy. They cannot travel in almost empty space between the Earth and the Sun.
- An EM wave is a wave that can travel through empty space or through matter. They 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. Thus, EM waves are transverse waves as you learnt in grade 9. In transverse waves, the direction of oscillation is perpendicular to the direction of propagation of waves while in 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.

Exercise 6.2

Did you recall the differences between transverse and longitudinal waves?

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.

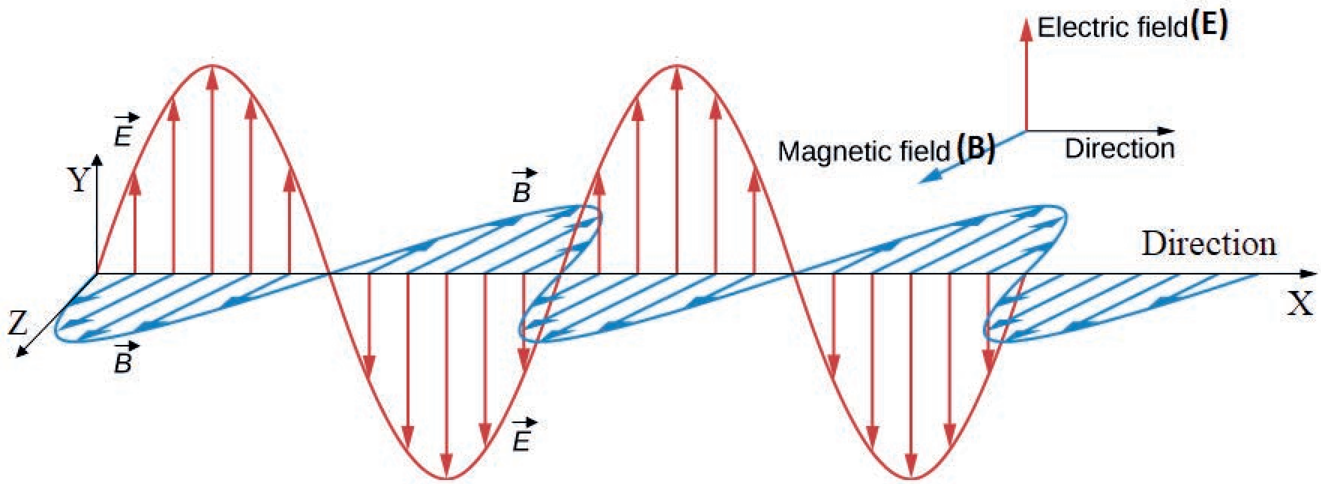


Figure 6.1 Electric field and magnetic field in an EM wave.

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 the 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

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 spectrum's of EM waves;*
- *describe the uses and dangers of the spectrum's of EM waves.*

Exercise 6.3

What do you know about the EM spectrum?

As shown in Figure 6.2, an EM spectrum is the complete range of EM wave frequencies and wavelengths. At one end of the spectrum, the waves have a low frequency, a long wavelength, and low energy. At the other end of the spectrum, the waves have a high frequency, a short wavelength, and high energy. All of the waves, from radio waves to visible light to gamma rays, are the same kind of wave. They differ from each other only by their frequencies, wavelengths, and energies.

You briefly describe these different spectrum's of EM wave, in order of decreasing wavelengths.

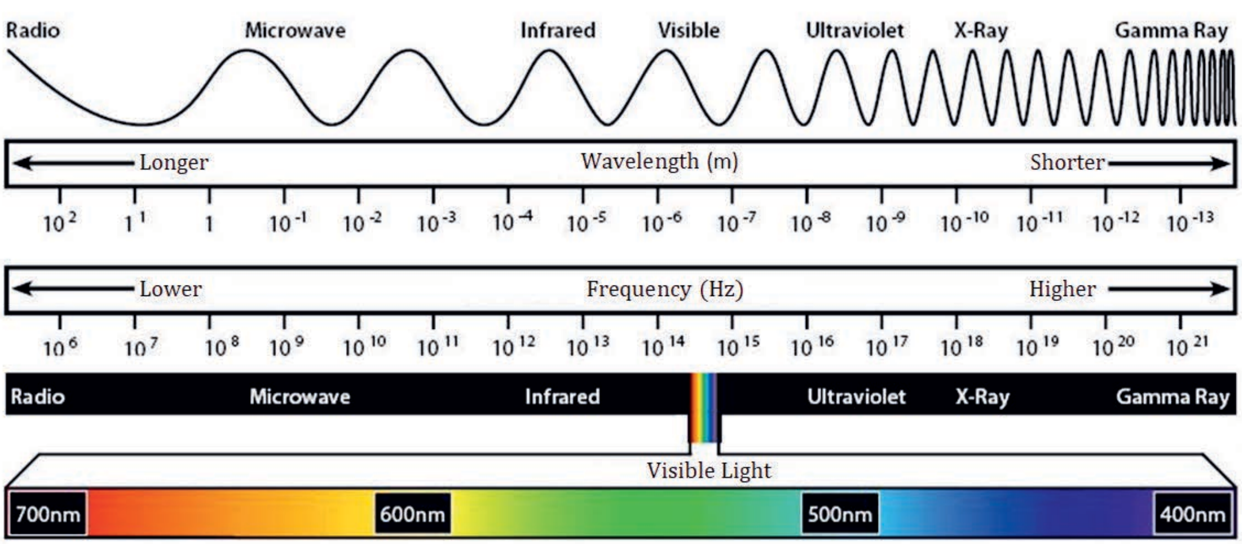


Figure 6.2 The EM spectrum.

Radio waves

Radio waves are made by various types of transmitters, 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 a wavelength of around 1 meter to thousands of meters.

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.

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.

Microwaves

Microwaves are basically extremely high-frequency radio waves, and are made by various types of transmitters. In a mobile phone, they are made by a transmitter chip and an antenna; in a microwave oven, they are made by a "magnetron". Their wavelength is usually a couple of centimeters. 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, which 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 do not make it a habit of pressing your face against the microwave oven door to see if your food is 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. To avoid being harmed by the powerful radar units in modern military planes,people who work on aircraft carrier decks wear special suits which reflect microwaves.

Infrared waves

Infrared waves are just below visible red light in the EM spectrum. You probably think of Infrared waves as heat because they are given off by hot objects and you can feel them as warmth on your skin. Infrared waves are also given off by stars, lamps, flames and anything else that is warm including you.

Infrared waves are used for many tasks, for example, as 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 that can see in the dark. Night sights for weapons sometimes use a sensitive infrared detector. Weather forecasters use satellite pictures to see what is heading our way. Some of the images they use were taken using infrared cameras, because they show cloud and rain patterns more clearly.

Exercise 6.4

What are the uses and dangers of each of the EM spectrum?

The danger from too much infrared radiation is very simple: it simply makes you hot.

Visible Light

Our eyes can detect only a tiny part of the EM spectrum called visible light. The frequency of visible light ranges between about 4×10^{14} *Hz* to 7×10^{14} *Hz*. Its wavelength in vacuum ranges between about 700 *nm* and 400 *nm*. Visible light, emitted or reflected from objects around us gives us with information about the world. The color of the visible spectrum will be 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, you have 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

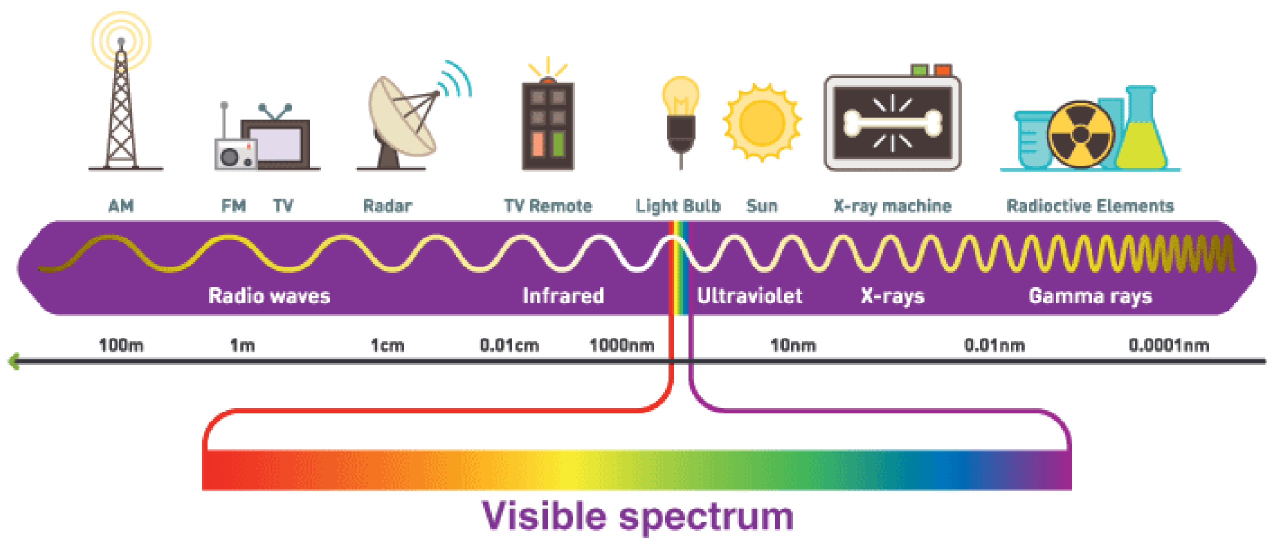


Figure 6.3 Visible spectrum.

can heal, if it is too bad, it will 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 UV 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 is important to check that your sunglasses will block UV light. If your sunglasses do not block UV, you will actually get more UV light on your retinas than if you did not 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 as 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 cannot 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 and hence, 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, UV rays, visible light, and gamma.
3. Discuss on the use of each type of EM spectrum.
4. Describe the dangers of each type of EM spectrum.

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.*

Exercise 6.5

Does light require a medium to travel?

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 is called a 'visible light'.

Medium of propagation of light

Like other waves, light waves can travel through matter. Although it travels through matter, it is different from waves like water 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.

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.

Speed of light

An EM wave, including light, is special because, no matter what the frequency, it all moves at a constant velocity (in a vacuum), which is known as the speed of light. The speed of light has the symbol c and is equal to $2.99792458 \times 10^8\ m/s \approx 3.00 \times 10^8\ m/s$.

In reality, nothing travels faster than the speed of light. Thus, in empty space, light travels at a speed of about 300,000 *kilometers*. 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.

Exercise 6.6

How do you know that light travels through a vacuum?

On the other hand, when light travels through matter, it interacts with the atoms and molecules in the material and slows down. As a result, light travels fastest in empty space, and slowest in solids. In glass, for example, light travels about 197,000 *km/s*.

Because all EM waves in a vacuum have the same speed c (i.e., speed of light), it follows that:

$$c = \lambda \times f \tag{6.1}$$

where λ is the wavelength of the EM wave, and f is the frequency of the EM wave. Thus, the greater the frequency of an EM wave, the smaller its wavelength becomes.

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.

Example 6.1

Find the frequency of red light with a wavelength of 700 *nm*.

Solution:
You are given that $\lambda = 700\ nm$ and $c = 3.00 \times 10^8\ m/s$. You are asked to find the frequency.

You can obtain the frequency by rearranging the formula $c = \lambda \times f$, to yield

$$f = \frac{c}{\lambda} = \frac{3 \times 10^8\ m/s}{700 \times 10^{-9} m} = 4.29 \times 10^{14} Hz$$

Example 6.2

An FM radio station broadcasts EM radiation at a frequency of 103.4 *MHz*. Calculate the wavelength of this radiation.

Solution:
In this example, you are given $f = 103.4\ MHz$ and $c = 3.00 \times 10^8\ m/s$. What you want to find is the wavelength, λ.

From the expression $c = \lambda \times f$, you can easily derive for λ. Thus,

$$\lambda = \frac{c}{f} = \frac{3 \times 10^8\ m/s}{103.4 \times 10^6 Hz} = 2.9\ m$$

Propagation of light

Exercise 6.7

If you drop a rock on the smooth surface of a pond, what would happen?

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). However, while the water waves spread out only on the surface of the pond, light waves spread out in all directions from the light source as it is indicated in Figure 6.4 (a).

To understand the direction of propagation of a light 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 6.8

How is light propagated?

Light rays are drawn using straight lines with arrow heads and are used to show the path that light travels. A collection of rays is called a beam. Light rays are, therefore, narrow beams of light that travel in a straight line. You can use the idea of a light ray to indicate the direction through which 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.

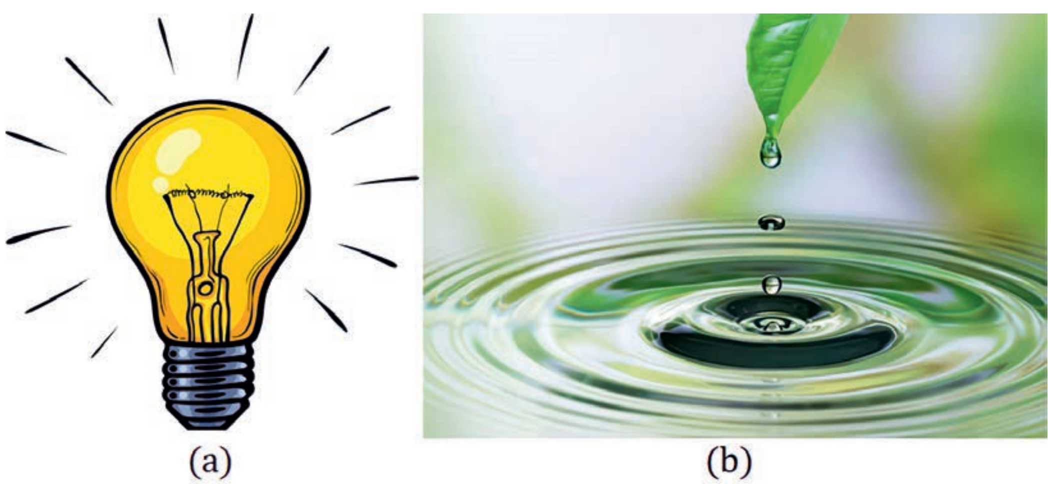


Figure 6.4 (a) Light moves away in all directions from a light source, (b) Ripples spread out on the surface of water.

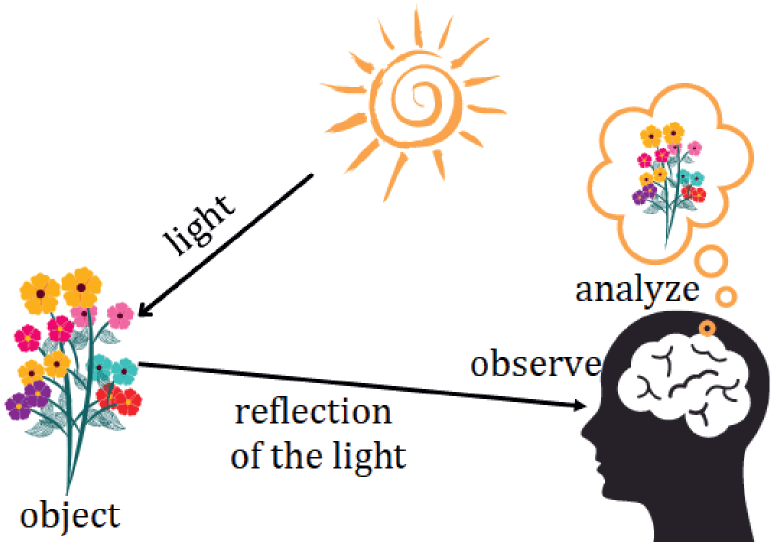


Figure 6.5 Light rays from the object to the eyes.

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 light 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 6.9

When you smile infront of 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. Thus, when a ray of light approaches a smooth polished surface and the light ray bounces back, it is called the reflection of light. 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

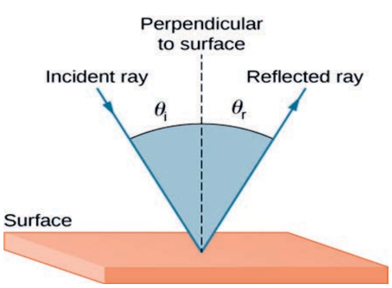


Figure 6.6 A light ray strikes a surface and is reflected.

and the surface normal. This is shown in Figure 6.6.

When a light ray strikes a surface and is reflected, as in Figure 6.6, the 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 are applicable to all types of reflections, i.e., specular and diffuse reflection. The following is the discussion of the distinction between these two types of reflection.

Key Concept

☞ Reflection is the change in direction of light rays at a surface that causes them to move away from the surface.

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. In this type of reflection, 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.

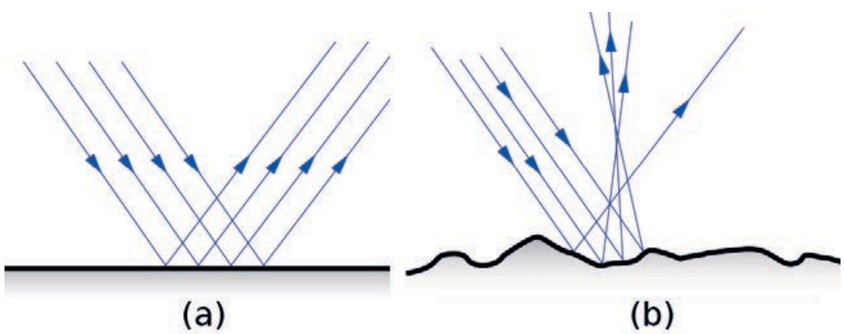


Figure 6.7 (a) Specular and (b) diffuse reflection.

Exercise 6.10

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

In the first part of this section, you studied light reflecting off various surfaces. Light seems to travel along straight-lines in a transparent medium.

In this subsection, you will learn about the refraction of light. Let us start our discussion by considering the apparent displacement of a pencil partly immersed in water using the following activity:

Figure 6.8 Refraction of light.

Activity 6.1

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, 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.

Exercise 6.11

What happens when light passes through a medium? Does it still move along a straight line path or change its direction?

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.

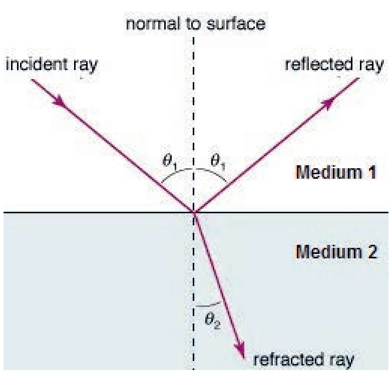


Figure 6.9 Ray showing the refraction of light.

Like all waves, the speed of light is dependent on the medium through which it is traveling. 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 the 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 6.10 (a). On the other hand, if the ray moves from a material in which its speed is lower to one in which its speed is higher, as in Figure 6.10 (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.

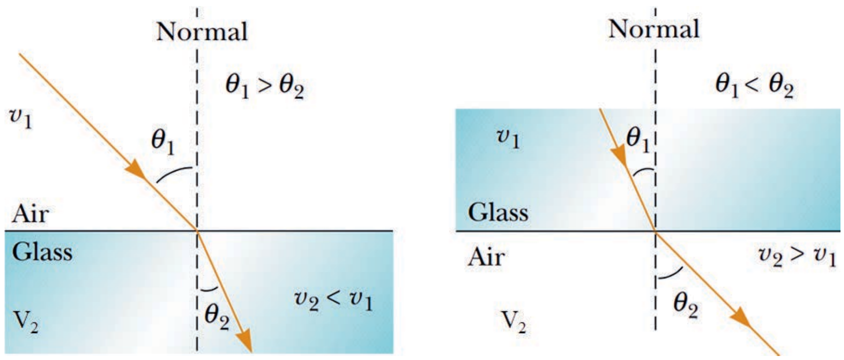


Figure 6.10 Bending of a light ray (a) toward the normal and (b) away from the normal.

Key Concept

☞ Refraction is the bending of light as it travels from one medium to another.

☞ Refraction occurs when light's velocity changes.

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 to the 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 6.11, then,

$$\frac{sin\,\theta_1}{sin\,\theta_2} = constant \tag{6.2}$$

This constant value is called the refractive index of the second medium with respect to the first. Let us study refractive index in some detail.

Exercise 6.12

Explain why light bends when it passes from one medium to another.

The Refractive Index

Exercise 6.13

Why does light travel faster through air than water?

The speed of light and the degree of bending of the light depend on the refractive index of the 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 6.11.

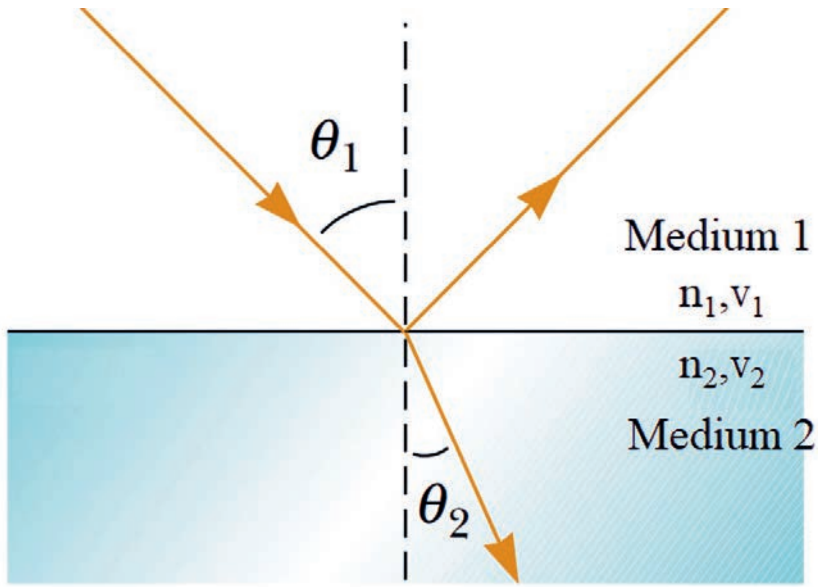


Figure 6.11 Ray showing the refraction of light between different medium.

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 as:

$$n_{21} = \frac{\text{speed of light in medium 1}}{\text{speed of light in medium 2}} = \frac{v_1}{v_2} \qquad (6.3)$$

By the same argument, the refractive index of medium 1 with respect to medium 2 is represented as n_{12} and it is given by

$$n_{12} = \frac{\text{speed of light in medium 2}}{\text{speed of light in medium 1}} = \frac{v_2}{v_1} \qquad (6.4)$$

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 (or simply the refractive index) of the medium. It is simply represented as n. If c is the speed of light in a vacuum and v is the speed of light in the medium, then, the refractive index of the medium n is given by:

$$n = \frac{\text{speed of light in vacuum}}{\text{speed of light in medium}} = \frac{c}{v} \qquad (6.5)$$

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.

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 vacuum to the speed of light in water is equal to 1.33.

Table 6.1 Absolute refractive index of some material mediums

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 6.11 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 which was discussed above can thus be written as follows:

$$n_1 sin\,\theta_1 = n_2 sin\,\theta_2 \qquad (6.6)$$

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 are also given the value of the angle of incidence, i.e., 35^o. So you can use Snell's law to find the value for the angle of refraction.

$$n_1 sin\,\theta_1 = n_2 sin\,\theta_2$$

$$1.33 \times sin\,35^o = 1 \times sin\,\theta_2$$

$$sin\,\theta_2 = 1.33 \times 0.57 = 0.763$$

$$\therefore \theta_2 = sin^{-1}(0.763) = 49.7^o$$

In this example, 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 6.14

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 medium (smaller index of refraction), for example, from water to air, the refracted ray bends away from the normal, as in Figure 6.10 (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 6.12 (b). When the angle of incidence exceeds the critical angle, as in Figure 6.12 (c), there is no refracted light. All the incident light is reflected back into the medium from which it came,

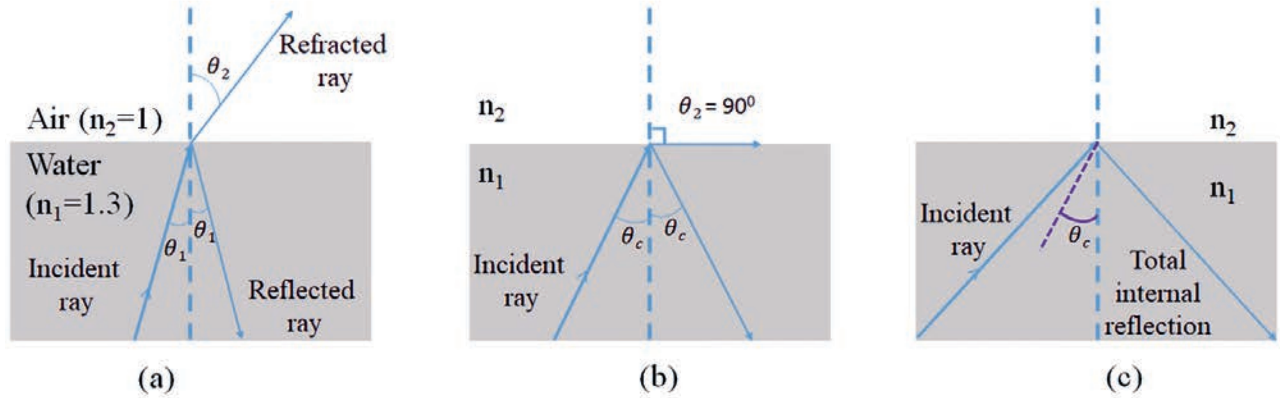


Figure 6.12 The critical angle and total internal reflection.

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 dense 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:

$$n_1 sin\,\theta_1 = n_2 sin\,\theta_2 \qquad (6.7)$$

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 6.13. 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.

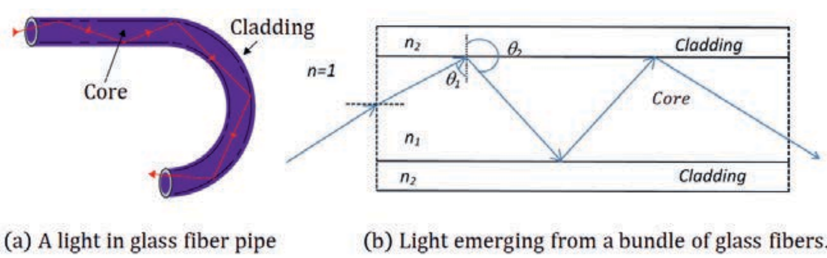


Figure 6.13 Light is guided along a fibre by multiple internal reflections.

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.

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 fibres' are in neurosurgery and the study of the 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 are given $n_1 = 1.52$ and $n_2 = 1.00$.
Using the expression for θ_c,

$$\theta_c = sin^{-1}\left(\frac{n_2}{n_1}\right) = sin^{-1}\left(\frac{1}{1.52}\right) = 42^o$$

The Dispersion of Light: Prisms and Rainbows

Before discussing 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 phenomena. Let us find it out through the following activity.

Activity 6.2

☞ 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 6.14.
☞ 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?

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 6.14. The acronym VIBGYOR will help you to remember the sequence of colors.

Exercise 6.15

How could the white light of the sun give us various colors of the rainbow?

Key Concept

☞The prism can split the incident white light into a band of colors.

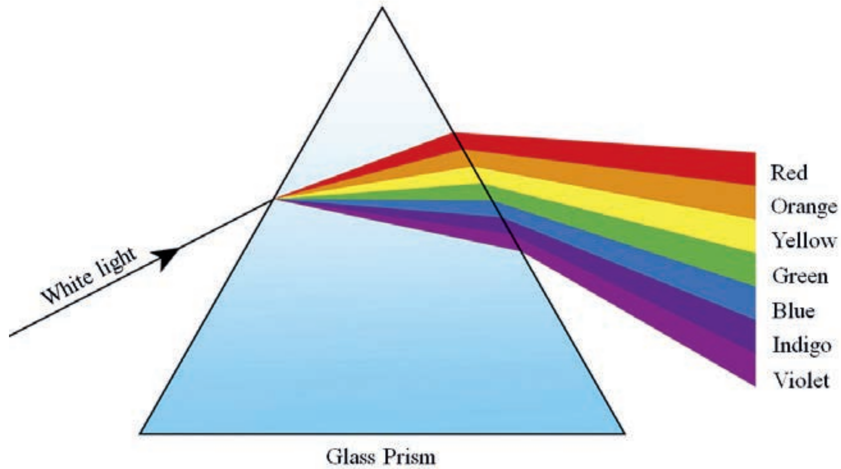


Figure 6.14 Dispersion of white light by a glass prism.

The band of colored components in 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 have these colors? Different colors of light bend at different angles with respect to the incident ray, as they pass through a prism. The red light refracts the least, while the violet light 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.

Figure 6.15 Rainbow in the sky.

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 6.15). It is caused by the 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 traveling 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 6.16

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 two types of mirrors.

Plane Mirrors

Exercise 6.17

How does a plane mirror form an image?

A 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 will 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 a plane mirror forms an image, let us do the following activity.

Activity 6.3

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 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 Figure 6.16. 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 reflecting off the mirror.

The rays that originate from the arrow head are labeled A and B, while the reflected rays are labeled A' and B'. 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 6.16. This type of image is called a virtual image.

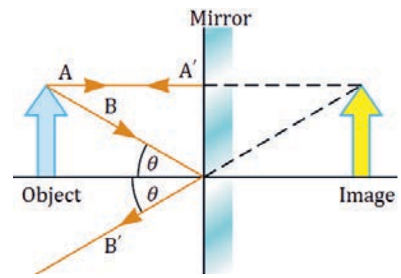


Figure 6.16 Image formation in the plane mirror.

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.

Key Concept

The image formed by a plane mirror is:
- ☞ virtual.
- ☞ the same distance behind the mirror as the object is in front of the mirror.
- ☞ laterally inverted. This means that the image is inverted from side to side.
- ☞ the same size as the object.
- ☞ upright.

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, 5 images are formed by two mirrors at a 60° angle. Two mirrors inclined to each other at different angles may provide the same number of images. Fore example, 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.

On the other hand, the number of images seen may be different from the number of images formed and depends on the position of the observer relative to the object and mirrors. For instance, if θ= 120°, the maximum number of images formed will be 3 but the number of images seen may be 1, 2 or 3 depending on the position of the observer.

Uses of plane mirrors

A plane mirror is used

- in looking glasses,
- in construction of kaleidoscope, telescope, sextant, and periscope,
- for seeing round the corners,
- as deflector of light, etc.

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 6.17.

The following are some of the few important terms used to describe spherical mirrors.

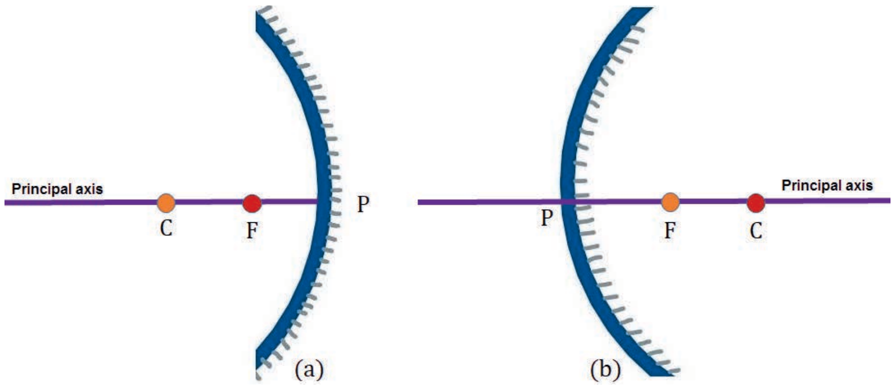


Figure 6.17 Spherical mirrors.

- The center of the sphere, of which the mirror is apart is called the center 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 the pole is said to be the principal axis of the mirror.
- The circular outline (or periphery) of the mirror is called its aperture. 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.

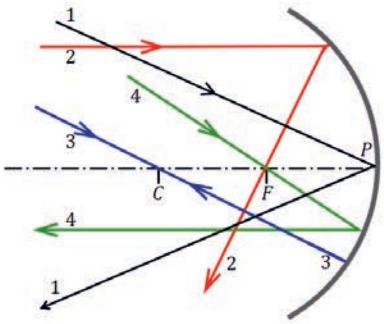


Figure 6.18 Rays used to form image by concave mirror.

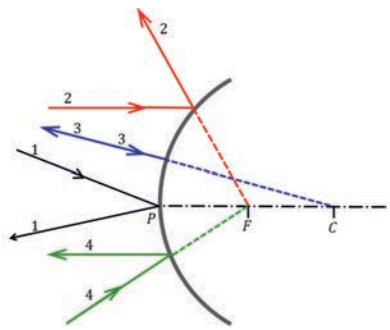


Figure 6.19 Rays used to form image by convex mirror.

Exercise 6.18

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?

Ray diagrams used to form images by spherical mirrors

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.

1. **Ray striking the pole:** A 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 Figures 6.18 and 6.19).

2. **Parallel ray:** For a concave mirror, the ray parallel to the principal axis is reflected in such a way that after reflection it passes through the principal focus (Ray number 2 in Figure 6.18). But for a convex mirror, the parallel ray is so reflected that it appears to come from the principal focus (Ray number 2 in Figure 6.19).

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 Figures 6.18 and 6.19).

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 Figures 6.18 and 6.19).

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 a concave mirror

The intersection of at least two of the above four reflected rays gives the position of the image of the object. Thus, any two of the above rays can be considered for locating the image. Using the above rules of ray diagrams, the image formed for the different positions of an object is given in Figure 6.20.

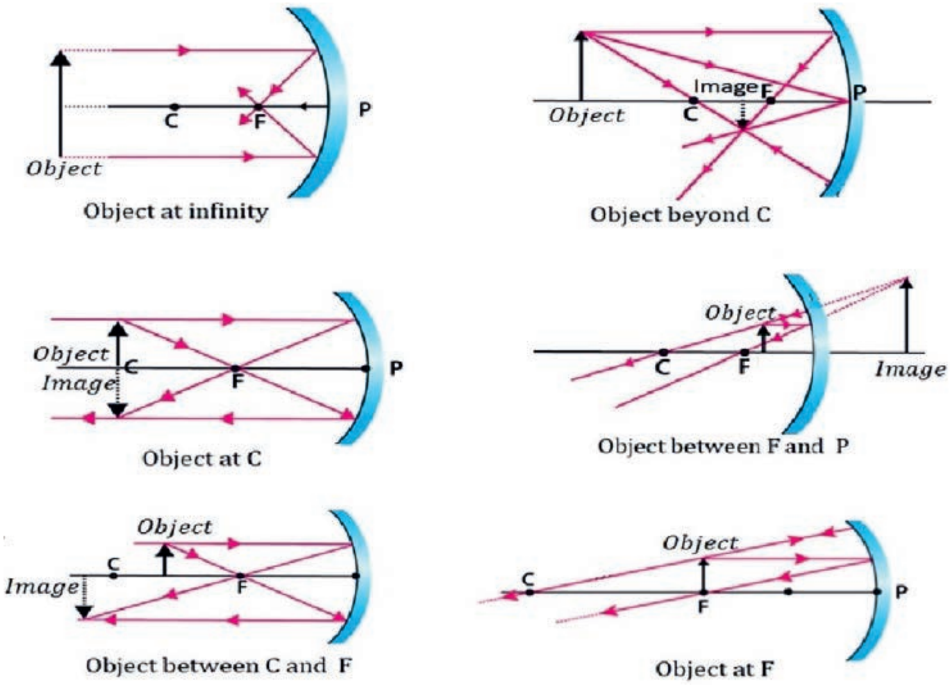


Figure 6.20 Formation of an image by a concave mirror.

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

Activity 6.4

- Draw neat ray diagrams for each position of the object shown in Figure 6.20.
- You may choose any two of the rays mentioned in the previous sub section for locating the image.
- Compare your diagram with those given in Figure 6.20.
- Describe the nature, position, and relative size of the image formed in each case.
- Tabulate the results in a convenient format.

Key Concept

☞ The properties of the image produced by a concave mirror depend on the location of the object.

Exercise 6.19

Explain why concave mirrors are used in flash lights and automobile headlights.

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 their patients. Large concave mirrors are used to concentrate sunlight to produce heat in solar furnaces.

b) Image formation by convex mirror

You studied the formation of the image using a concave mirror. Now you shall study the formation of images by a convex mirror. Let us first illustrate this using an activity.

Activity 6.5

- 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.

What did you noticed from this activity? Consider two positions of the object when studying the image formed by a convex mirror. The first position is when the object is at infinity and the second is when the object is at a finite distance from the mirror. The ray diagrams for the formation of an image by a convex mirror for these two positions of the object are shown in Figure 6.21 (a) and (b), respectively. The results are summarized in table 6.3.

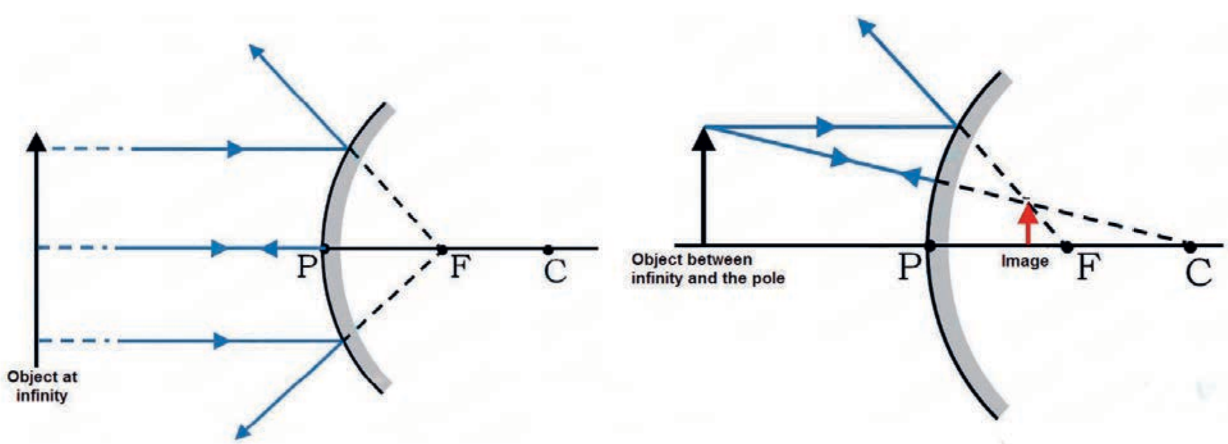


Figure 6.21 Formation of an image by a convex mirror.

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

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 or her to facilitate safe driving. Convex mirrors are 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 a 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

$$\frac{1}{v} + \frac{1}{u} = \frac{1}{f} \tag{6.8}$$

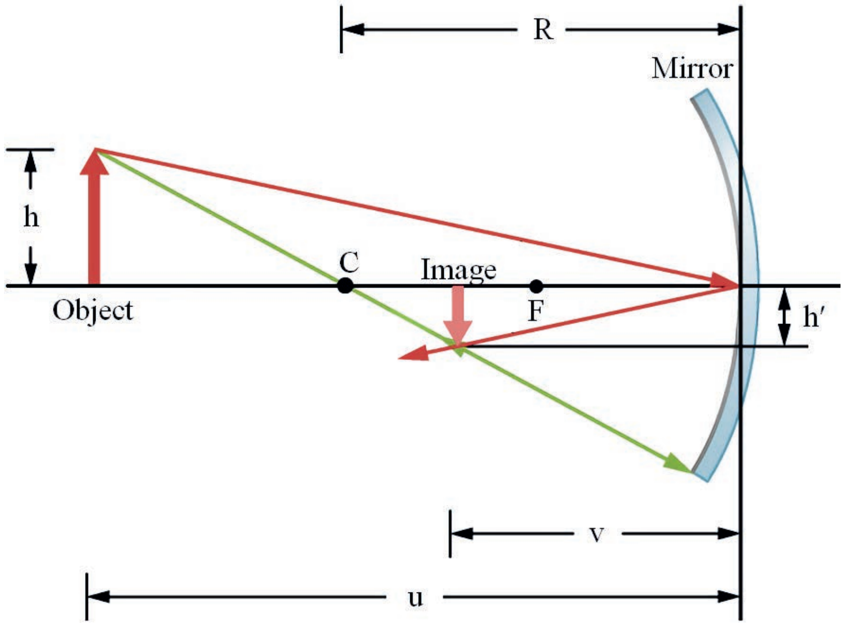


Figure 6.22 *u*, *v*, *f*, *h* and *h'* for a mirror.

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's size. Thus, the magnification *m* produced by a spherical mirror is given by

$$m = \frac{\text{height ofthe image (h}')}{\text{height of the object (h)}} = \frac{h'}{h} \quad (6.9)$$

The magnification *m* is also related to the object distance (u) and image distance (v). It can be expressed as

$$\text{Magnification (m)} = \frac{h'}{h} = -\frac{v}{u} \quad (6.10)$$

These formulas are valid for spherical mirrors in 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 in Table 6.4.

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

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:

You are given radius of curvature, R = - 3.00 m and object distance, u = + 5.00 m; The focal length is $f = \frac{R}{2} = -\frac{3.00}{2} = -1.50m$ (as the principal focus of a convex mirror is behind the mirror).

You want to find the value for the image distance, v and height of the image, h'.

Using the mirror equation,

$$\frac{1}{v} + \frac{1}{u} = \frac{1}{f},$$

$$\frac{1}{v} = \frac{1}{f} - \frac{1}{u} = -\frac{1}{1.50} - \frac{1}{+5.00} = \frac{-5.00 - 1.50}{7.50}$$

$$\therefore \quad v = \frac{-7.50}{6.50} = -1.15m$$

Therefore, the image is 1.15 m at the back of the mirror.

$$\text{Magnification } (m) = \frac{h'}{h} = -\frac{v}{u} = -\frac{(-1.15m)}{5.00m} = +0.23$$

The image is thus 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 15.0 *cm* focal length. At what distance from the mirror should a screen be placed in order to obtain a sharp image? Determine the nature and the size of the image.

Solution:

The given quantities are object size, $h = +6.0$ *cm*, object distance, $u = +25.0$ *cm* and focal length, and $f = +15.0$ *cm*.

You are asked to find the image distance, v and image size, h'.

$$\text{Since} \quad \frac{1}{v} + \frac{1}{u} = \frac{1}{f},$$

$$\frac{1}{v} = \frac{1}{f} - \frac{1}{u} = \frac{1}{15.0} - \frac{1}{25.0} = \frac{5.00 - 3.00}{75}$$

$$\therefore \quad v = 37.5\ m$$

The screen should be placed at 37.5 *cm* in front of the mirror. The image is real. Also,

$$\text{Magnification } (m) = \frac{h'}{h} = -\frac{v}{u}$$

Solving for h' gives

$$h' = -\frac{hv}{u} = -\frac{(37.5\ cm)(6.0\ cm)}{(25.0 cm)} = -6.0\ cm$$

Thus, the height of the image is - 6.0 *cm*. The negative sign implies that the image is inverted and enlarged.

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 piece of transparent material that is smooth and regularly shaped so that when light strikes it, the light refracts in a predictable and useful way.

Exercise 6.20

What is a lens? How does it bend light rays?

A transparent material bound by two surfaces of which one or both 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

Exercise 6.21

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?

Key Concept

☞ Concave lenses, cause light to diverge, and convex lenses cause light to converge.

Exercise 6.22

What happens when parallel rays of light are incident on 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 lenses converge light rays, as shown in Figure 6.23 (a). Hence, convex lenses are also called converging lenses. Similarly, a double concave lens is bounded by two inwardly curved spherical surfaces. It is thicker in the edges than at the middle. Such lenses diverge light rays as shown in Figure 6.23 (b) and are also called diverging lenses. A double concave lens is simply called a concave lens.

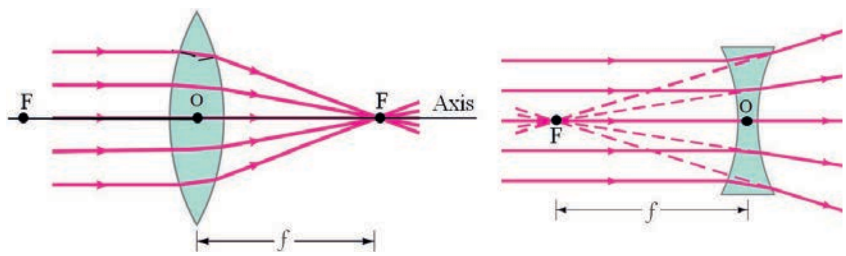


Figure 6.23 (a) Converging action of a convex lens, (b) diverging action of a concave lens.

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 the 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.

Activity 6.6

- 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 directly at the Sun or through a lens while performing this activity as it may cause damage to your eyes.

The paper begins to burn producing a 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 traveling 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. The letter F is usually used to represent the 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).

Ray diagrams used to form image in lenses

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, like those 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 6.24 (a). In the 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 6.24 (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 6.24 (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 6.24 (b).

3. A ray of light passing through the optical center of a lens will emerge without any deviation. This is illustrated in Figure 6.24 (a) and Figure 6.24 (b).

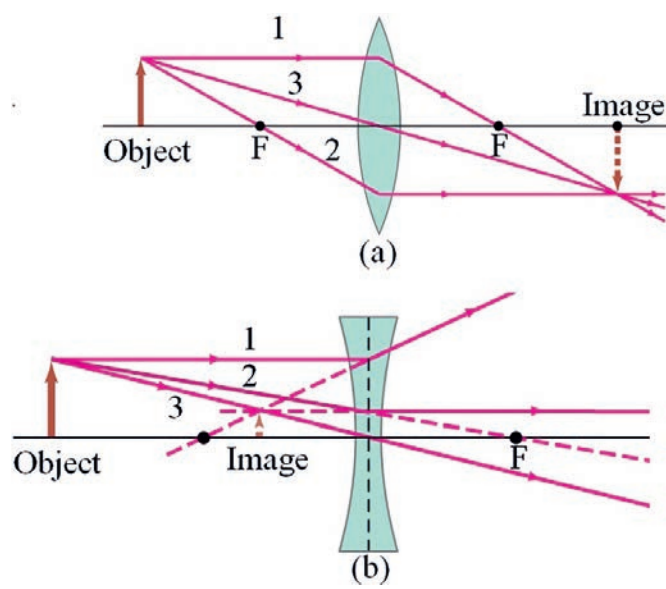


Figure 6.24 Ray diagram for (a) Convex lens (b) Concave lens.

(a) Image formation by convex lenses

Lenses form images by refracting light. Let us study this for a convex lens first by doing the following activity.

Exercise 6.23

How do lenses form images? What is their nature?

Activity 6.7

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 the appropriate letters, for example, $2F_1, F_1, F_2$ and $2F_2$ respectively.
- Place a burning candle, far beyond $2F_1$ to the left. Obtain a clear sharp image on the opposite side of the lens on a screen.
- 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 that the nature, position, and relative size of the image depend 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 6.25. Table 6.5 summarizes the nature, position, and relative size of the image formed by a convex lens for various positions of the object.

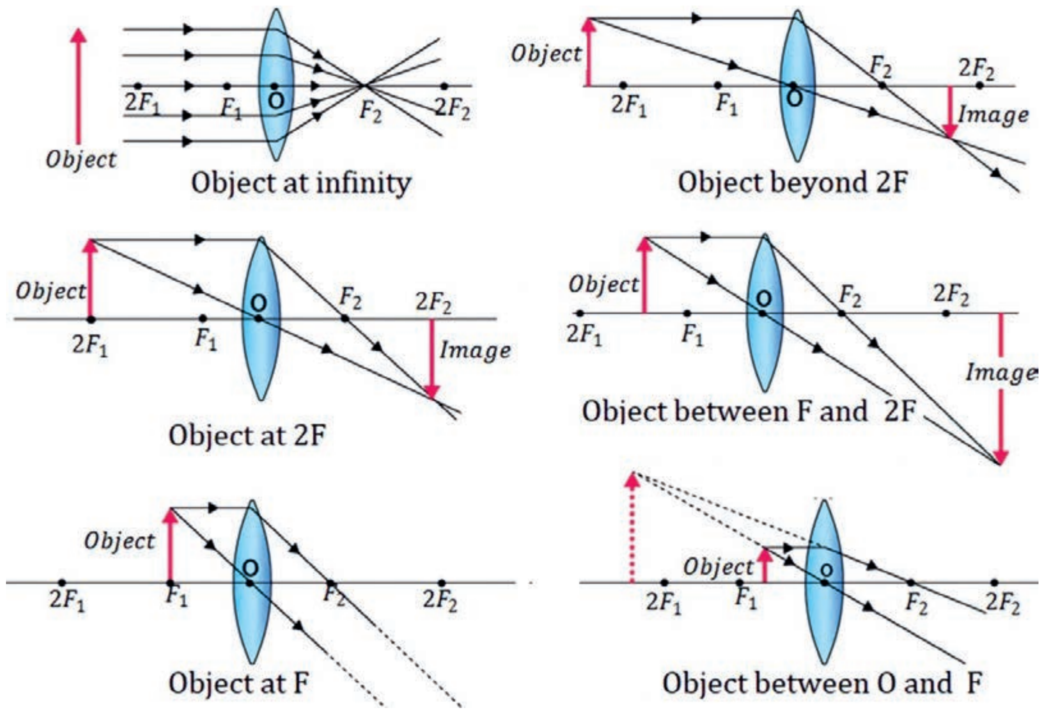


Figure 6.25 The position, size and nature of the image formed by a convex lens for various positions of the object.

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

(b) Image formation by concave lenses

Let us now do an activity to study the nature, position and relative size of the image formed by a concave lens.

Activity 6.8

- 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 conclusions 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 6.26.

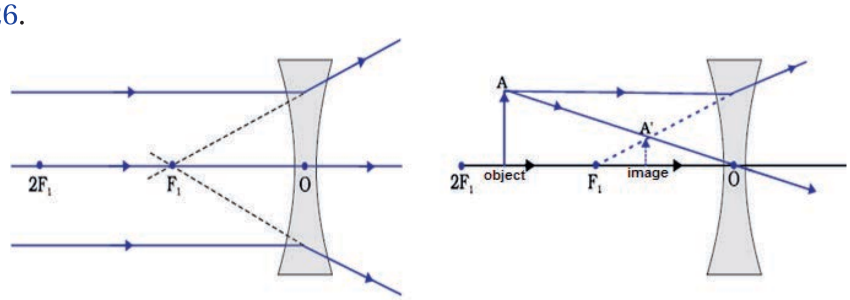


Figure 6.26 Image formed by a concave lens.

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 an equation for spherical mirrors, there is also a similar equation for lenses. This equation gives the relationship between object distance (u), image distance (v) and the focal length (f). It is expressed as

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f} \tag{6.11}$$

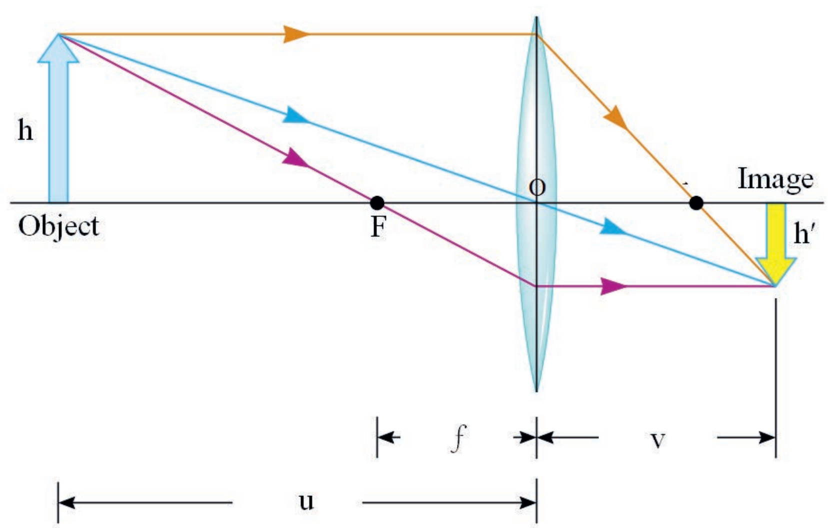


Figure 6.27 u, v and f in a lens.

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,

$$m = \frac{h'}{h} \tag{6.12}$$

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

The magnification produced by a lens is also related to the object distance u, and the image distance v. This relationship is given by

$$m = \frac{h'}{h} = -\frac{v}{u} \tag{6.13}$$

The above lens and magnification formula are general and is applicable to any spherical lens in any situations. While putting numerical values for solving problems relating to lenses into the above equations, you need to be careful to use the sign conventions indicated in table 6.7.

Example 6.7

A concave lens has a focal length of 15 *cm*. At what distance from the lens should the object be placed so that it forms an image at 10 *cm* from the lens? Also, find the magnification produced by the lens.

Solution:

In this example, image distance v = - 10 *cm* and focal length f = -15 *cm*.
You want to find the value for the object distance, u and magnification, m.

$$Since \quad \frac{1}{v} + \frac{1}{u} = \frac{1}{f},$$

$$\frac{1}{u} = \frac{1}{f} - \frac{1}{v} = \frac{1}{-15.0} - \frac{1}{-10.0} = \frac{-2+3}{30} = \frac{1}{30}$$

$$\implies v = 30\ cm$$

Thus, the object distance is 30 *cm*.

$$\text{Magnification } (m) = -\frac{v}{u} = -\frac{-10}{30} = +0.33$$

The positive sign shows that the image is erect and virtual. The image is one-third the size of the object.

Thus, a concave lens always forms a virtual, erect image on the same side of the object.

Example 6.8

A 2.0 *cm* tall object is placed perpendicular to the principal axis of a convex lens of 10 *cm* focal length. 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:
You are given height of the object, $h = +\,2.0$ *cm*, focal length, $f = +\,10$ *cm* and object distance, and $u = +\,15$ *cm*.
The required quantity is the value for the image distance, v and 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.

$$\text{Magnification } (m) = \frac{h'}{h} = -\frac{v}{u}$$

$$\implies h' = -\frac{hv}{u} = -(2)\frac{(30)}{(15)} = -6.0cm$$

$$\text{Thus, the magnification is } (m) = -\frac{v}{u} = -\frac{+30}{+15} = -2.$$

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.
- The lens which is thick in the middle and thin at the edges is called a convex lens whereas the lens which is thin in the middle and thick at the edges is called a concave lens.
- Convex lens is also known as a converging lens as it converges the parallel rays of light at a point after refraction.

- Concave lens is also known as diverging lens as it diverges the parallel beam of light after refraction.
- The type of image formed by a convex lens depends on the position of the object that can be placed at different positions in front of the lens. However, a concave lens always produces a virtual, erect and diminished images.
- The mirror as well as lens equation expresses the quantitative relationship between the object distance, the image distance and the focal length.

Review questions

1. List the five 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 preferred as a rear-view mirror in automobiles?
8. So far, you have 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 a three times magnified (enlarged) real image of an object placed 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 $2F_1$

    (b) Just further than $2F_1$

    (c) At $2F_1$

    (d) Between $2F_1$ and F_1

    (e) At F_1

    (f) Between F_1 and O.

13. An object stands 50 *mm* away 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.*

Exercise 6.24

How does a human eye form an image?

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.

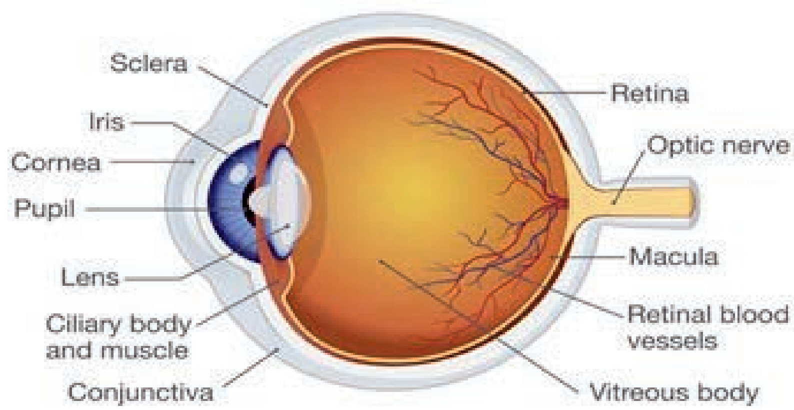


Figure 6.28 Basic elements of human eye.

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 6.28.

The eyeball is approximately spherical in shape with a diameter of about 2.3 *cm*. Most of the refraction of the light rays entering the eye occurs at the outer surface of the cornea. The crystalline lens merely provides the finer adjustment of the focal length required to focus objects at different distances on the retina. You find a structure called the 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 with an 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. The ciliary muscles can modify to some extent its curvatures. 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's 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's lens to adjust its focal length is called accommodation. However, the focal length of the eye's lens cannot be decreased below a certain minimum limit.

Exercise 6.25

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 that a normal eye can see objects clearly that are between 25 *cm* and infinity.

Key Concept

☞The minimum distance, at which objects can be seen most clearly without strain, is called the least distance of distinct vision. It is also called the near point of the eye.

Defects of vision and their correction

Exercise 6.26

Have you encountered peoples who have 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 6.29 (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 6.29 (b).

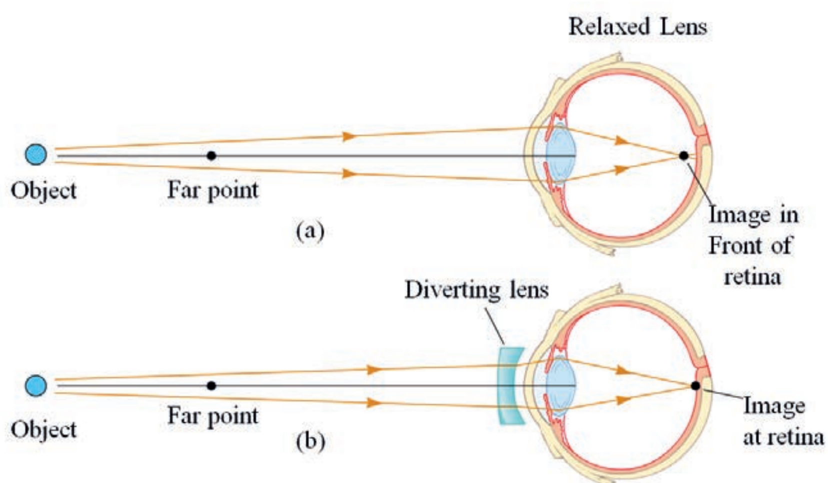


Figure 6.29 (a) Short-sightedness. (b) Short-sightedness corrected by diverging lens.

(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 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 6.30 (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 6.30 (b).

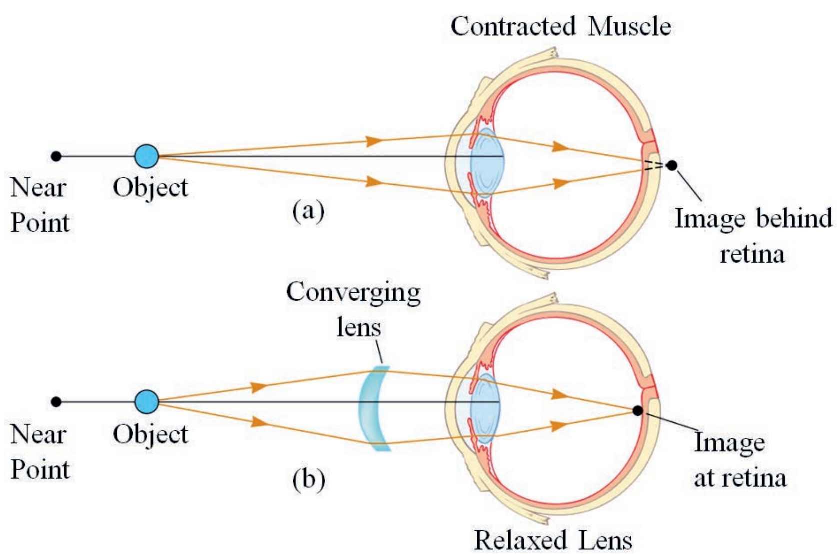


Figure 6.30 (a)Long-sightedness. (b) Long-sightedness corrected by converging lens.

Key Concept

☞ Myopia, hypermetropia and presbyopia are defects of vision. They can be corrected with an appropriate lens.

(c) Presbyopia

The power in accommodation of the eye usually decreases with age. For most people, the near point gradually recedes. Without corrective eye-glasses, they have difficulty seeing nearby objects comfortably and clearly. 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 lens 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.

Do you know that your 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

Activity 6.9

In group, please try to list the different types of optical instruments that you know.

A number of optical devices and instruments have been designed utilizing the reflecting and refracting properties of mirrors and lenses. Periscope, kaleidoscope, binoculars, camera, telescopes, and 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 that the nature has endowed us with. You have already studied the human eye. You now go on to describe the principles of operation of the microscope and the telescope.

Simple microscope

Exercise 6.27

What do you think is a simple microscope?

A simple magnifier or microscope is a converging lens of small focal length (Figure 6.31). 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.

Figure 6.31 A simple microscope.

Compound microscope

A simple microscope has a limited maximum magnification for realistic focal lengths. For much larger magnifications, one has to use two lenses, one compounding the effect of the other. This is known as a compound microscope.

A compound microscope has, therefore, more than one objective lens, each providing a different magnification. Figure 6.32 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.

Activity 6.10

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.

Key Concept

☞ The objective lens in a compound microscope forms an enlarged image, which is then magnified by the eyepiece lens.

Exercise 6.28

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 6.33. 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

Exercise 6.29

What do you think are the differences between a telescope and a compound microscope? Would you please try to think of how telescopes make distant objects visible?

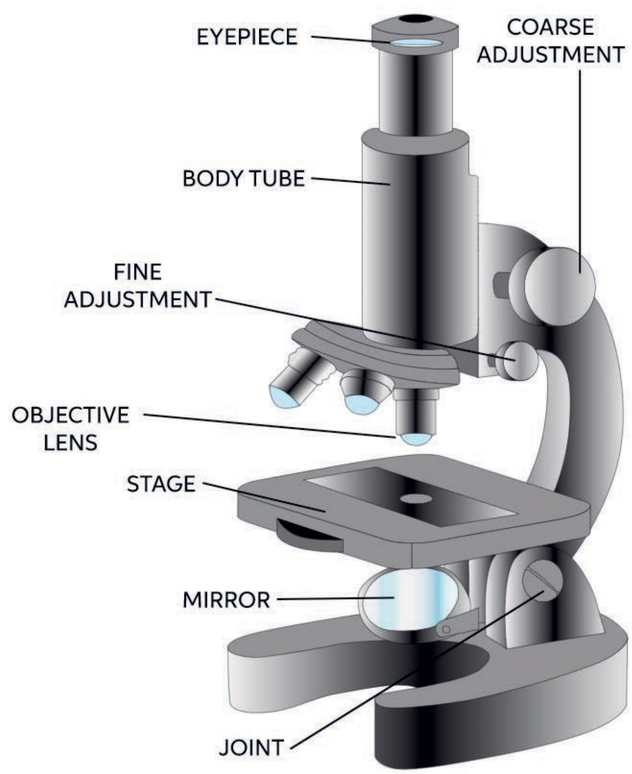


Figure 6.32 A compound microscope.

distant object very near the focal point of the eyepiece.

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 that can enter it. This makes images of far away objects look brighter and more detailed when they are magnified by the eyepiece. With a large enough objective lens, it is possible to see stars and galaxies that are many trillions of kilometers away. Figure 6.33 shows a refracting telescope.

The second type, the 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 6.34, the large concave mirror focuses light onto a secondary mirror that directs it to the eyepiece, which magnifies the image.

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.

Figure 6.33 Refracting telescope.

Exercise 6.30

Explain why the objective lens of a refracting telescope is much larger than the objective lens of a compound microscope.

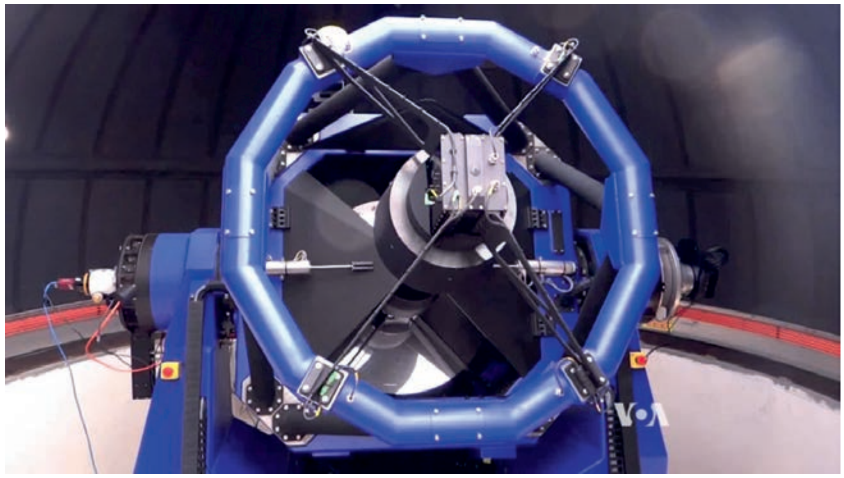


Figure 6.34 Reflecting telescopes gather light by using a concave mirror.

Exercise 6.31

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 the power of accommodation of the eye?
2. A person with a myopic eye cannot see objects beyond 1.2 m clearly. What should be the type of corrective lens used to restore proper vision?
3. What is the far and near points 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 they work.
6. Why is a normal eye not able to clearly see 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 6.32

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 between 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,

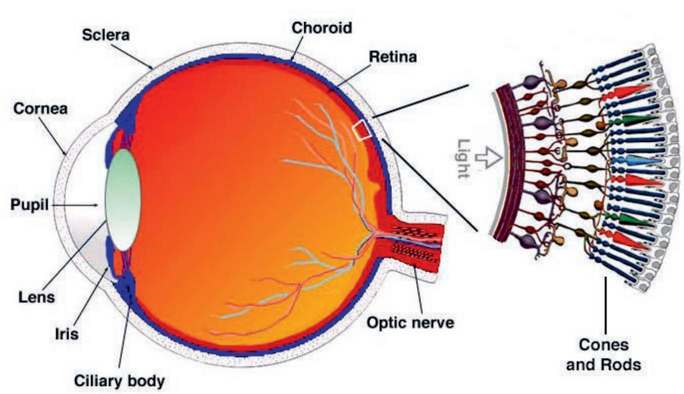


Figure 6.35 Rod and cone cells in the retina of the eye detect light and send signals to the brain.

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.

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 of red, green, and blue light 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 photoreceptors found in the retina of the human eye called, and which type is sensitive to colors?

6.8 Color addition of light

Exercise 6.33

What do you think is the definition of color addition?

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

- *recognize how additive colors affect the color of light;*
- *add primary colors.*

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.

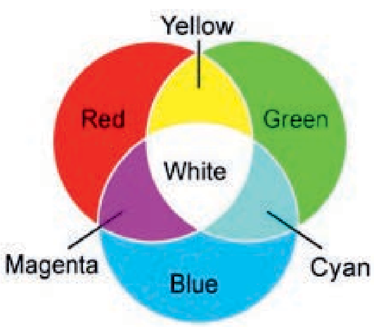


Figure 6.36 The different combinations of colors produced by the primary colors of light.

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 6.36.

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.

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.

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.

Color addition principles 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 the three primary colors of light with equal proportions produce white light.
- All the other colors of light can be produced by different combinations of red, green and blue.

Review questions

1. What colors did you get when you added red and blue, red and green, green and blue lights?
2. What type of applications did color addition of light have?

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.

Exercise 6.34

What do you think is the definition of color subtraction?

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 6.37. The following illustrates color subtraction.

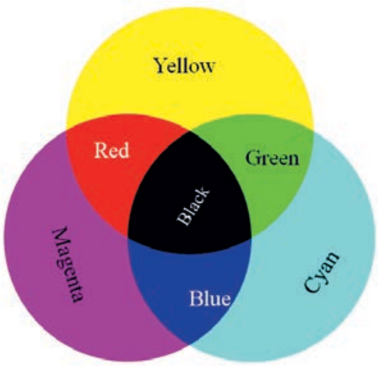


Figure 6.37 Color subtraction.

Cyan - Blue = (Green + Blue) - Blue = Green
Yellow - Green = (Red + Green) - Green = Red
Magneta - Red = (Red + Blue) - Red = Blue

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.

Key Concept

☞ The subtractive primary colors are obtained by subtracting one of the three additive primary colors from white light.

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.

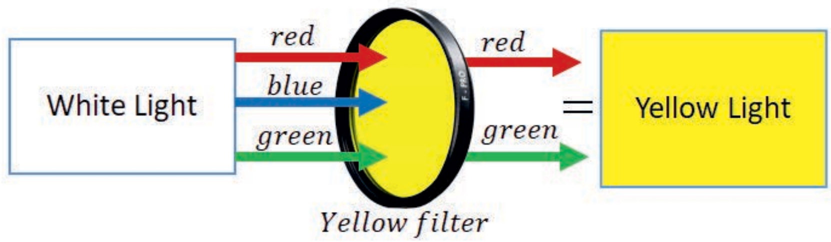


Figure 6.38 Color subtraction using yellow filter.

ii. Magenta filter (or a pigment) absorbs green light and transmits red and blue light. Blue and red light together are seen as magenta.

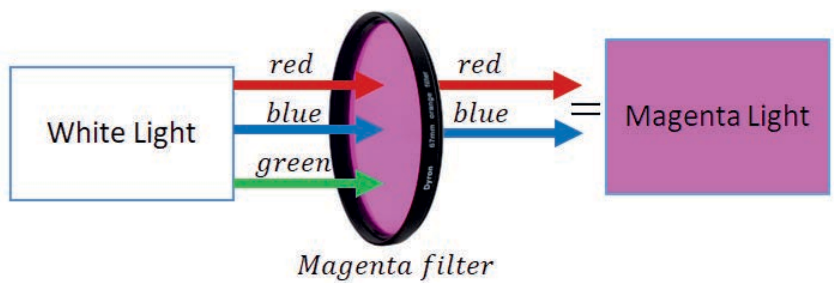


Figure 6.39 Color subtraction using magneta filter.

iii. Cyan filter (or pigment) absorbs red light and transmits blue and green light. Blue and green light together are seen as cyan.

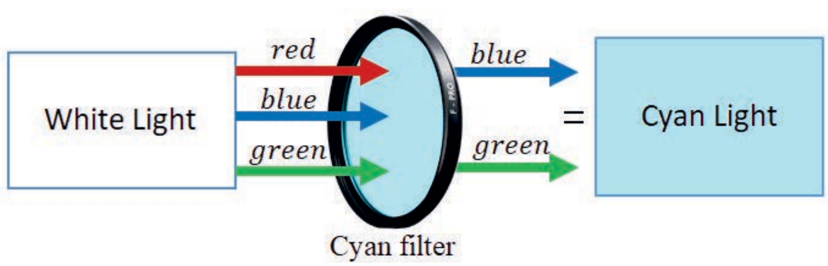


Figure 6.40 Color subtraction using cyan filter.

iv. Yellow filter (or a pigment) absorbs blue and Magenta filter (or a pigment) absorbs green and reflect the red light.

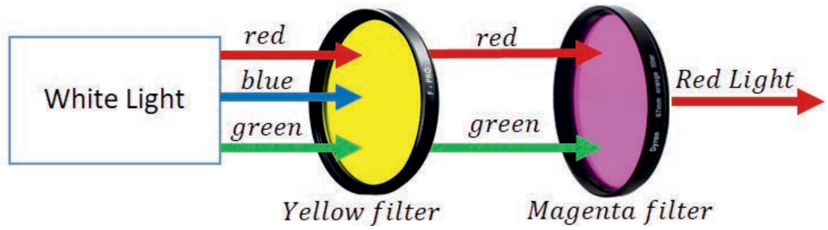


Figure 6.41 Color subtraction using yellow and magneta filters.

v. Yellow filter (or a pigment) absorbs blue and cyan filter (or a pigment) absorbs red and reflect the green light.

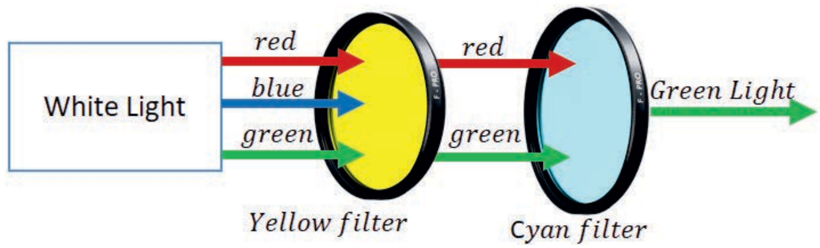


Figure 6.42 Color subtraction using yellow and cyan filters.

vi. Magenta filter (or a pigment) absorbs green and cyan filter (or a pigment) absorbs red and reflect the blue light.

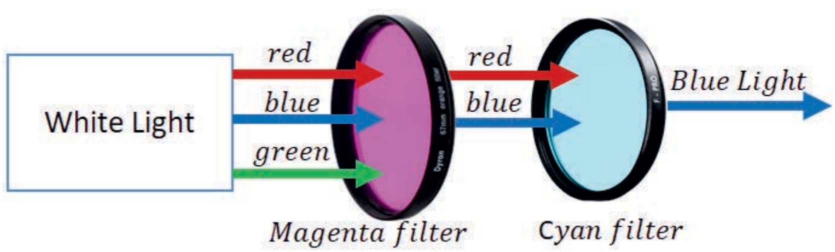


Figure 6.43 Subtraction using magneta and cyan filters.

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.

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.

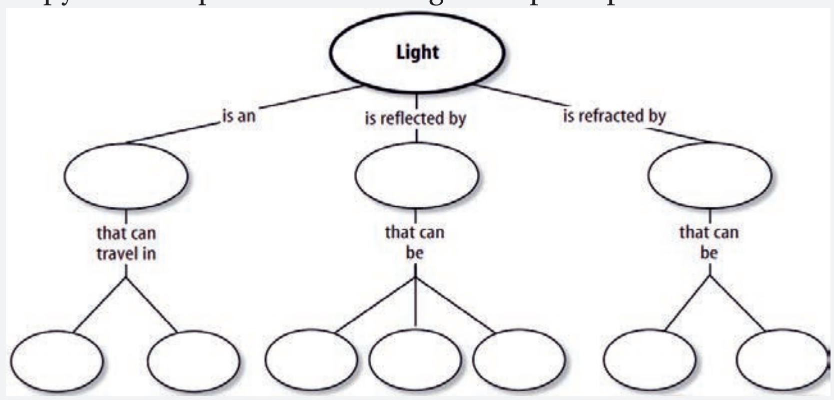
- Like all forms of electromagnetic waves, light can travel through vacuum as well as through matter.
- EM spectrum, the entire distribution of EM radiation according to frequency or wavelength. The entire EM spectrum, from the lowest to the highest frequency (longest to shortest wavelength), includes 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 a 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 the 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. Copy and complete the following concept map.



8. 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?

9. You wish to obtain an erect image of an object, using a concave mirror of 15 *cm* focal length. 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.

10. Name the type of mirror used in the following situations.
    (a) Headlights of a car.
    (b) Side/rear-view mirror of an automobile.
    (c) Solar furnace. Support your answer with reason.

11. 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.

12. An object is placed at a distance of 10 *cm* from a convex mirror of 15 *cm* focal length. Find the position and nature of the image.

13. The magnification produced by a plane mirror is +1. What does this mean?

14. 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 its size.

15. An object of size 7.0 *cm* is placed at 27 *cm* in front of a concave mirror of 18 *cm* focal length. 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.

16. 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.

17. 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 nature of the image formed.

18. 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?

19. Compare and contrast primary light colors and primary pigment colors.

20. Determine the colors that are reflected from an object that appears black.

21. 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.

22. The cover of a book appears to have a magenta color. What colors of light does it reflect and what colors does it absorb?