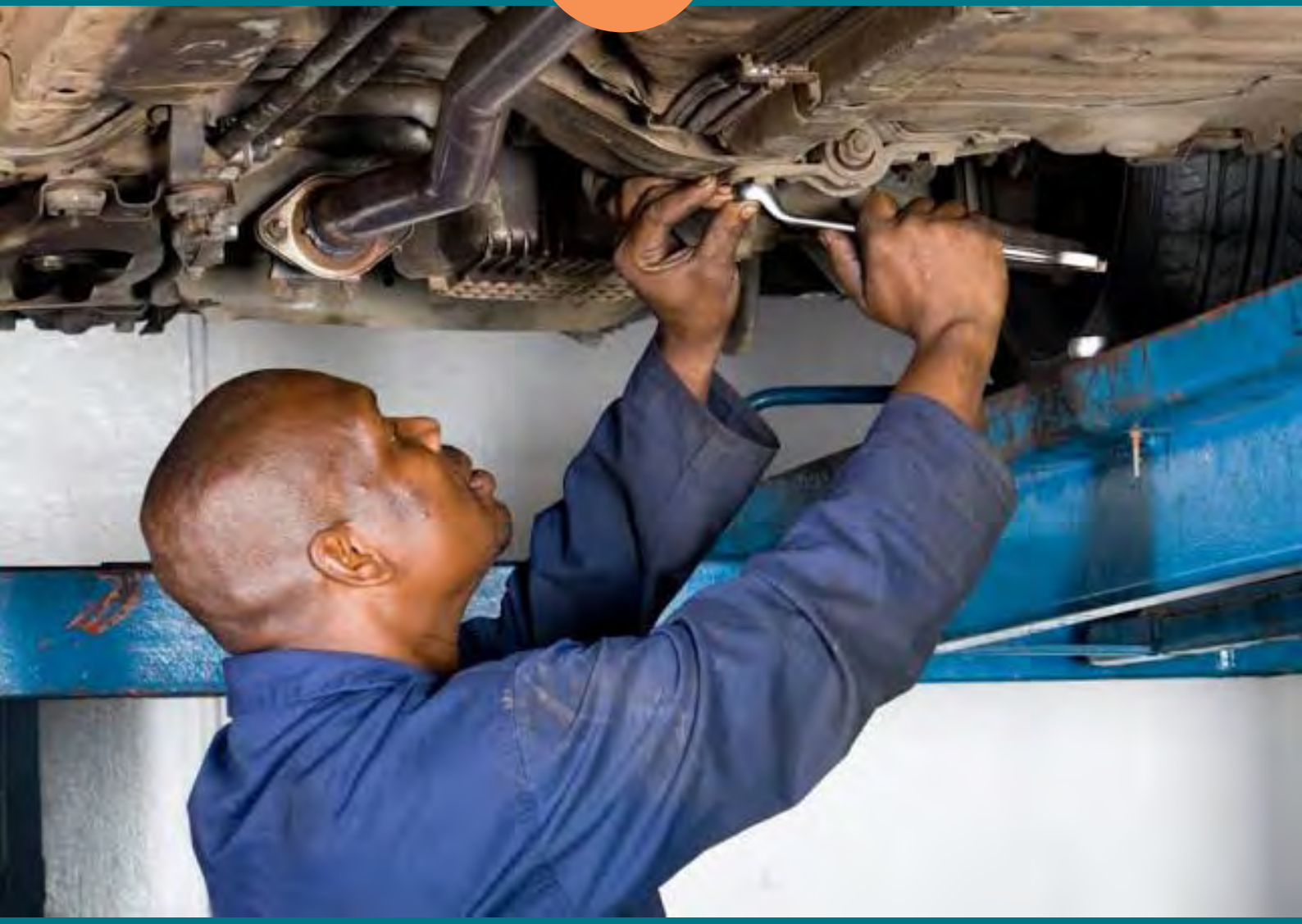
MINISTRY OF EDUCATION
GHANA ASSOCIATION OF SCIENCE TEACHERS

(GAST)

Physics

for Senior High Schools

Year 3



• Slyvester Affam • Believe Awadzi
• Yangy Kwabena Clifford

MINISTRY OF EDUCATION

GHANA ASSOCIATION OF SCIENCE TEACHERS

PHYSICS

For Senior High Schools

3

Slyvester Affam
Believe Awadzi
Yangy Kwabena Clifford

Ghana Education Service (GES)

(GAST)



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FOREWORD

Ghana's new Senior High School Curriculum aims to ensure that all learners achieve their potential by equipping them with 21st Century skills, knowledge, character qualities and shared Ghanaian values. This will prepare learners to live a responsible adult life, progress to further studies and enter the world of work. This is the first time that Ghana has developed a Senior High School Curriculum which focuses on national values, attempting to educate a generation of Ghanaian youth who are proud of our country and can contribute effectively to its development.

The Ministry of Education is proud to have overseen the production of these Learner Materials which can be used in class and for self-study and revision. These materials have been developed through a partnership between the Ghana Education Service, teacher unions (Ghana National Association of Teachers-GNAT, National Association of Graduate Teacher -NAGRAT and the Coalition of Concerned Teachers- CCT) and National Subject Associations. These materials are informative and of high quality because they have been written by teachers for teachers with the expert backing of each subject association.

I believe that, if used appropriately, these materials will go a long way to transforming our Senior High Schools and developing Ghana so that we become a proud, prosperous and values-driven nation where our people are our greatest national asset.

Haruna Iddrisu MP

Minister for Education

SECTION

1

DIMENSION, VECTORS, FLOTATION AND DEFORMATION



BASIC PHYSICS

INTRODUCTION

This section introduces you to the concepts of moments, equilibrium, and gravitation—foundational topics for understanding forces and their effects on motion and stability. You will explore the turning effect of forces (moments), the principle of moments, and conditions for equilibrium, including how to determine reactions at supports. The section also covers the centre of gravity, states of equilibrium, and applications of torque and couples in daily life. You will extend your understanding to gravitational fields, Newton's law of universal gravitation, and related quantities such as gravitational potential and escape velocity. Finally, you will study satellite motion, including orbital period and weightlessness in space. This section builds on prior learning from *Motion* and *Vectors* in Years One and Two and prepares you for applications in engineering, architecture, and space science.

KEY IDEAS

- **Acceleration due to Gravity**: Determined by a planet's mass and radius and decreases with increasing distance from the planet's surface.
- **Centre of Gravity**: The point where the entire weight of a body appears to act, influencing balance and stability.
- **Newton's Law of Universal Gravitation**: Every two masses attract each other with an equal and opposite force proportional to their masses and inversely proportional to the square of the distance between them.
- **Principle of Moments**: For a body in rotational equilibrium, the total clockwise moments equal the total anticlockwise moments about a pivot.
- **Satellite Motion and Weightlessness**: Satellites orbit due to gravitational pull, and weightlessness occurs because they are in continuous free fall.
- **Types of Equilibrium**: Bodies may be in stable, unstable, or neutral equilibrium depending on the centre of gravity's behaviour when slightly disturbed.

MOMENTS AND EQUILIBRIUM

Moments and Turning Effect of Forces

When you push a door near the hinges, it is harder to open. When you push the same door at the edge farthest from the hinges, it's much easier to open. The *force* you apply and the *distance* from the pivot (hinges) together determine how effective your push is.

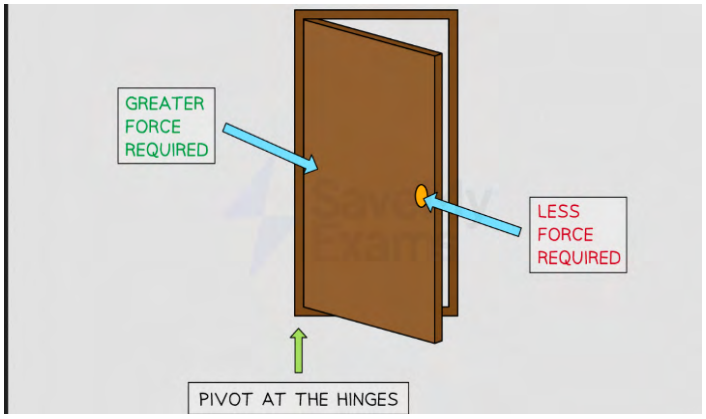


Figure 1.1: *Pushing a door at different points away from the hinge comes with different levels of ease of opening the door*

Again, in using a spanner (wrench) to loosen a nut,

1. If the nut is tight, using a longer spanner makes it easier to loosen.
2. The longer handle increases the distance from the pivot (nut), so for the same force, the moment is larger.
3. This is why mechanics sometimes add a pipe over a spanner to extend it — more distance, more turning effect.



Figure 1.2: *Holding a spanner at different lengths (X and Y) from the nut comes with different levels of ease of loosening the nut*

These examples show that forces can not only move objects in a straight line but can also cause them to turn about a pivot or fixed point. Can you think of two more examples of situations whereby turning effects are employed?

The turning effect of the force about a fixed point called the pivot or fulcrum is known as a **moment**. Moments are the rotational counterparts of forces and are important for understanding how objects turn or balance.

Factors Affecting Moment

The size of a moment depends on two factors: the magnitude of the force and the perpendicular distance from the pivot to the line of action of the force. This perpendicular distance is often called the **moment arm** or **lever arm**.

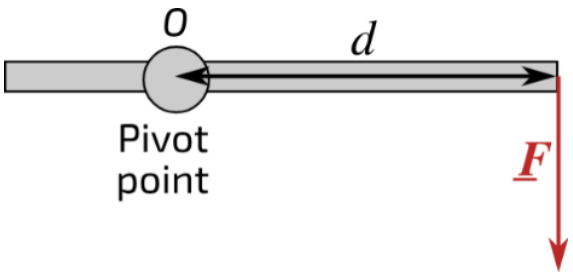


Figure 1.3: *A force F applied perpendicular to the distance d*

The mathematical expression for the moment M is

$$M = F \times d$$

where:

- F is the magnitude of the force (in newtons, N),
- d is the perpendicular distance from the pivot to the line of action of the force (in metres, m).

When the force is applied at angle θ to the body, the perpendicular component of the force is determined as Fsinθ and in that case, the moment of a force becomes Fsinθ × d.

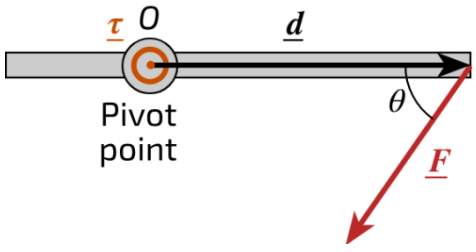


Figure 1.3: *A force F applied at angle θ to the distance d*

The S.I unit of a moment is newton-meter (Nm).

Moments Have Direction

They can be **clockwise** or **anticlockwise**. Conventionally, one direction is taken as positive (usually anticlockwise) and the other as negative.

The **net moment** on a body is the algebraic sum of all individual moments, taking their directions into account. Since a moment has both magnitude and direction, it implies that it is a vector quantity.

Centre of Gravity

If you balance a spoon or your centimetre rule on your finger at just the right spot, it stays level and does not tip to either side. The same thing happens with a seesaw plank when you find the exact point where it balances perfectly on its stand—it will not tilt or turn, and if you push it at that point, it will simply move straight without twisting.

This special point is called the **centre of gravity**. It is the point in a body where the weight appears to act. When a force is applied through the centre of gravity, the body does not rotate but moves in a straight line. A body supported at this point will remain balanced horizontally.

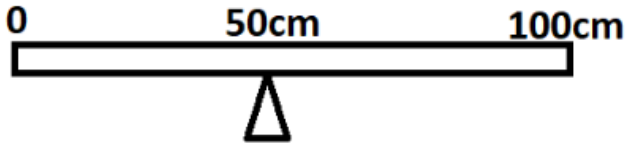


Figure 1.4: *A diagram of a uniform meter rule balanced at its centre of gravity, at the middle*

For bodies with regular shapes and uniform mass, the centre of gravity is assumed to act at the middle of the body and this can be determined by a process called the *balanced point method* as shown in Activity 1.3. That is, for example, if a regular object has a length of 20 cm, then its centre of gravity is considered to be at the 10 cm mark.

In the case of an irregular object, the centre of gravity cannot be located the middle of the body. The centre of gravity of an irregular object can be determined by a process called plumb-line method shown in Activity 1.3.

The centre of gravity helps to determine the balance point and the stability of a body.

EQUILIBRIUM

Imagine the door to your room is slightly open. You try to push it wider, but your brother pushes from the other side to stop you. If you both push with exactly the same strength, the door stays in the same position—it does not move in or out.

The same thing happens when two people of equal strength arm-wrestle and push equally hard—their hands remain locked in place without moving.

In both cases, the **forces are balanced**, and the **bodies** (the door and the wrestlers) **are in equilibrium**.

A body is said to be in equilibrium when several forces act on it but cause no movement or rotation. At equilibrium, the net force on the body is zero, and the net turning effect (moment) is also zero.

Types of Equilibrium

There are two main types of equilibrium and these are translational equilibrium and rotational equilibrium.

1. **Translational equilibrium**

   A body is said to be in translational equilibrium when the sum of forces acting on it is zero. That is there is no net force acting on the body either at rest or in motion with constant velocity. For example; A cup resting on a table (gravity pulls it down, the table pushes it up), also, a car moving in a straight line with a constant velocity (driving force from the engine is equal to the resistive forces).

2. **Rotational equilibrium**

   A body is in rotational equilibrium when the turning effects (moments) acting on it are balanced. In other words, the sum of the clockwise moments equals the sum of the anticlockwise moments, or the algebraic sum of all moments is zero. In this state, the body will not start rotating, and if it's already rotating, it will not speed up or slow down. For example:

   a. A metre rule balanced horizontally on a pivot, with equal weights placed at equal distances on opposite sides. Or different weights placed at different positions on either side.

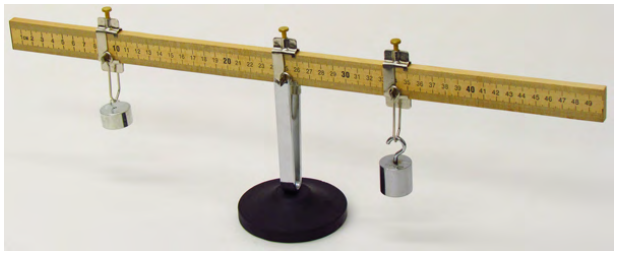


Figure 1.5: *A metre rule balanced by different weights on both sides at different lengths from the pivot.*

b. A see-saw with two people of different weights positioned at different distances from the pivot so that their moments are equal, or of equal weights at equal distances from the pivot, keeping the see-saw level.

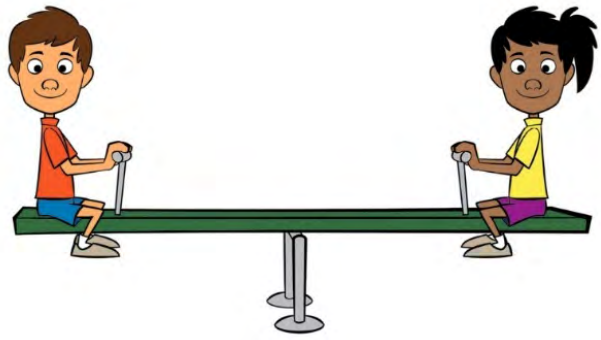


Figure 1.6: *Children of equal weights at equal distances from the pivot of a see-saw*

States of Equilibrium

Equilibrium can occur in different forms depending on how a resting body behaves when slightly disturbed or displaced. The forms in which equilibrium occurs is called the states of equilibrium. There are three states of equilibrium:

1. **Stable equilibrium**

   At times when a body is slightly disturbed, it returns to its original position after the disturbance is removed. The body at this state is said to be in a stable equilibrium.

   This happens because when the body is disturbed, its centre of gravity rises and gravity pulls it back to its lowest point which is the original position.

   Examples of stable equilibrium include:

   a. A book resting on a table on its broad base.

   b. A conical flask resting on its circular base.

   c. A cement block resting on its broad base.

2. **Unstable equilibrium**

   At times too when a body is slightly disturbed, it does not return to its original position but moves further away. At this state, the body is said to be in an unstable equilibrium. This happens because the centre of gravity falls when disturbed causing the body to assume a new position. The body at this state does not have a restoring force to return to its original position.

   Examples of unstable equilibrium are

   a. A cement block placed on its small base.

   b. A pen placed on its tip.

   c. A conical flask resting on its apex.

3. **Neutral equilibrium**

   There are instances where a body is slightly disturbed and the body rolls, assuming a new position when the disturbance is removed. The body at this state is said to be in a neutral equilibrium. This occurs because the centre of gravity stays at the same height and the body is equally balanced in any position. Examples of neutral equilibrium are:

   a. A cylinder rolling on its side.

   b. A ball on a flat horizontal surface.

   c. A conical flask rolling on its side.

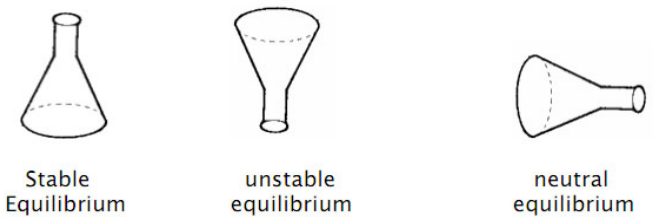


Figure 1.7: *States of equilibrium*

Principle of moment

For a body to be in equilibrium, the sum of clockwise moments about a pivot or fixed point must be equal to the sum of anticlockwise moments about that same point. That is Σ clockwise moment = Σ anticlockwise moment

Considering ***Figure 1.8,***

1. Force 1 will cause the bar to turn in an anticlockwise direction and it is applied at the distance 1 from the pivot point (tip of the red triangular fulcrum).
2. Hence anticlockwise moment = force 1 × distance 1
3. Force 2 will cause the bar to move in a clockwise direction and it is applied at the distance 2 from the pivot point.
4. Hence clockwise moment = force 2 × distance 2
5. If the wood (lever) remains in equilibrium under the influence of force 1 and force 2, then by the principle of moment, force 1 × distance 1 = force 2 × distance 2.
6. If the wood begins to rotate, the moments must not be balanced, i.e. force 1 × distance 1 ≠ force 2 × distance 2.

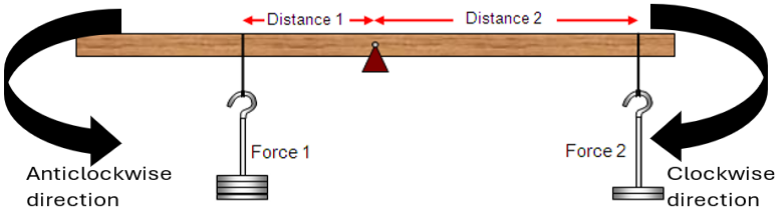


Figure 1.8: *A lever showing moments*

COUPLE AND TORQUE



Figure 1.9: *A cross wrench (cross spanner) used to loosen or tighten a nut.*

The image in ***Figure 1.9*** shows two forces, indicated by the red arrows, being applied to the cross-wrench. These forces are:

1. Equal and opposite. Thus, one force is pushing and the other is pulling.

2. parallel. That is, they act along parallel lines.
3. not on the same line. If you extend the arrows to visualise the line of action of the forces, they do not overlap.

Together, these two forces form **a couple** that causes the nut to rotate, either tightening or loosening it. The combination of these two forces is much more effective at producing a strong rotational effect than a single force would be.

A pair of equal and opposite forces that act on a body but do not share the same line of action is called a **couple**. They cause a body to turn or rotate.

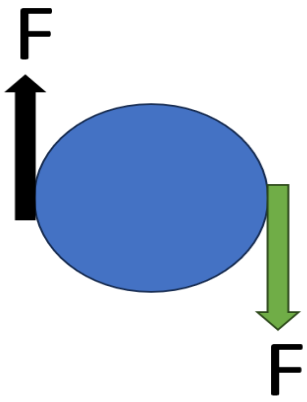


Figure 1.10: *A diagram showing couple of force acting on a body*

Other Real-life examples of couple

1. Opening a jar lid using both hands.
2. Turning the steering wheel with both hands.
3. Turning a key in a lock with the thumb and the first finger.
4. Turning a water tap/faucet

Torque

When a couple of forces act on a body, the body may turn or rotate. The turning effect of a couple is called a **torque (τ).** It is mathematically expressed as $\tau = F \times d$,

where F is the magnitude of one of the forces and d is the perpendicular distance between the forces.

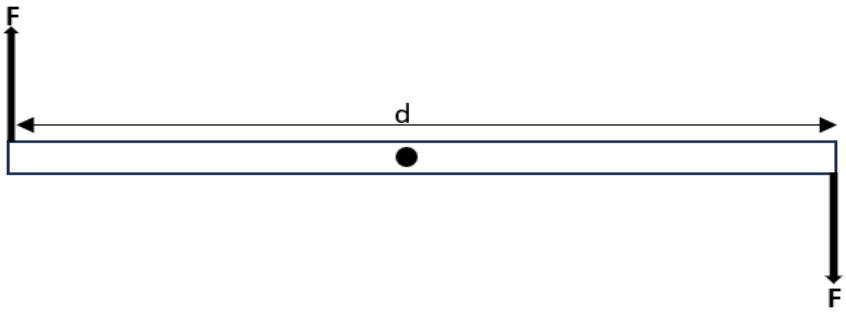


Figure 1.11: *A couple acting on a bar which will make the bar to rotate clockwise*

Calculating reactions at supports

When a beam or metre rule is placed on supports, the supports provide the beam with reaction forces to keep it in equilibrium. These reactions can be calculated by;

1. Identifying all the forces acting on the beam.
2. Applying the rotational equilibrium and translational equilibrium
3. Solve the equations simultaneously to find the unknown when necessary.
   (Refer to the solved problems for examples)

Real – world Applications of Moments and Equilibrium

The concept and principle of moments and equilibrium are widely used in many fields of life.

1. Levers and tools: Devices like spanners, scissors, crowbars nutcrackers etc use the principle of moments to increase or multiply forces.
2. Car jacks: The concept of moments is used to lift heavy loads with relatively small efforts.
3. Chairs, tables, shelves etc: These items are designed to be in a stable equilibrium so they do not easily tip over.
4. Bridges: Engineers ensure that the bridge is constructed in a way that it does not collapse under loads by carefully calculating the support reactions and the moments.

Activity 1.1 Factors That Affect Moment

Objective: To understand and experimentally demonstrate the factors that influence the magnitude and direction of a moment (turning effect).

What you need

1. Metre rule
2. A few weights of different known masses (e.g. 20g, 50g, 100g, or just use varying numbers of identical small weights)
3. String or paper clips (to suspend metre rule and to hang weights)
4. Sticky tape to secure string if needed

What to do

1. Set up the Lever: Suspend the metre rule using the string at its centre. Ensure that the rule hangs horizontally, or as close to this as possible. Use tape to secure the string if needed.
2. Explore Force Magnitude
   - **a.** Hang a small weight (e.g., 20 g) at a fixed distance from the pivot on one side (e.g. 30 cm mark). Observe the turning effect.
   - **b.** Now, keeping the distance the same, replace the 20g weight with a heavier one (e.g., 50g or 100g). Observe the change in turning effect.
   - **c.** Question: What happens to the turning effect when you increase the force (weight) while keeping the distance constant?
3. Explore Perpendicular Distance
   - **a.** Hang a fixed weight (e.g., 100g) at a short distance from the pivot (e.g., 10 cm mark). Observe the turning effect.
   - **b.** Now, keeping the weight the same, move it further away from the pivot (e.g., 30 cm, then 40 cm mark). Observe the change in turning effect.
   - **c.** Question: What happens to the turning effect when you increase the perpendicular distance from the pivot while keeping the force constant?
4. Explore Direction
   - **a.** Hang a weight on one side of the pivot. Observe the direction of rotation.
   - **b.** Now hang a weight on the *other* side of the pivot. Observe the direction of rotation.
   - **c.** Question: How does the side of the pivot where the force is applied affect the direction of the turning effect?

See Annex for expected observations.

Activity 1.2 Applying the Principle of Moments Using a Scenario

Objective: Use the principle of moments to understand how balance and rotation occur in everyday objects like a wheelbarrow or a seesaw. Sketch diagrams, identify forces, and explain how moments determine equilibrium.

What you need

1. Notebook or drawing paper
2. Pencil or pen
3. Ruler or straightedge (optional)
4. Coloured pencils or markers (optional for clarity)

What To do

1. Choose a Scenario: Imagine a person using a wheelbarrow to lift a load or sitting on one side of a seesaw with another person or weight on the other side.
2. Sketch the Diagram
   - **a.** Draw a simple side-view diagram of the chosen object (wheelbarrow or seesaw).
   - **b.** For a wheelbarrow, show:
     - **i.** The wheel (pivot point)
     - **ii.** The person applying force on handles
     - **iii.** The load inside the wheelbarrow
   - **c.** For a seesaw, show:
     - **i.** The pivot (fulcrum) in the middle
     - **ii.** People or weights on each side
3. Mark the Forces
   - **a.** Label the forces acting on the system:
     - **i.** Weight of the load or person (acting downward)
     - **ii.** Effort force applied by the person (wheelbarrow handles or seesaw rider)
     - **iii.** Reaction force at the pivot (wheel or fulcrum)

b. Indicate the direction of each force with arrows.

4. Identify Distances
   - **a.** Measure or estimate the perpendicular distances from each force's line of action to the pivot. Note that if the force is acting vertically downwards then the perpendicular distance will be the horizontal distance which meets the line of action of this force.
   - **b.** Mark these distances clearly on your diagram.
5. Apply the Principle of Moments
   - **a.** Write down the expression for moments about the pivot:

     Moment = Force × Perpendicular distance from pivot
   - **b.** Set up the balance equation where anticlockwise moments equal clockwise moments for equilibrium: $F1 \times d1 = F2 \times d2$
   - **c.** Assign the forces and distances from your diagram to this formula.
6. Explain Balance and Rotation
   - **a.** Using your equation, explain under what conditions the wheelbarrow or seesaw will:
     - **i.** be balanced (in equilibrium)
     - **ii.** rotate or tip over (when moments are unequal)
   - **b.** Discuss how changing forces or distances affect the moment and thus the ease or difficulty of lifting or balancing.

Activity 1.3 Determining the Centre of Gravity of Different Shapes

Objective: Find the centre of gravity (CG) of a regular object by drawing intersecting lines, and of an irregular cardboard shape using the plumb line suspension method.

What you need

1. Regular flat object (e.g., rectangular cardboard or paper)
2. Irregular cardboard shape (e.g. draw a randomly shaped 'blob' and cut it out!)
3. Ruler or straightedge
4. Pencil or marker
5. Thread or thin string with a small weight attached (plumb line)

6. Pin, nail, or strong needle to make small holes and act as a suspension point
7. Clamp stand or support to suspend the irregular shape (optional)

What to do

1. Take the regular flat shape and use a ruler to draw two straight lines connecting opposite corners (the diagonals).
2. Identify and mark the point where the two diagonals intersect; this point is the centre of gravity (CG) of the regular shape.
3. For the irregular cardboard shape, make three small holes spaced well apart near the edges.
4. Suspend the irregular shape from the first hole using a loop of thread so it can swing freely.
5. Hang the weighted plumb line from the same suspension point so the string hangs in front of the shape. When the swinging stops, mark two points along the plumb line on the cardboard surface.
6. Use a ruler to draw a straight line through these two marks: this line represents the path of the gravitational force through the CG.
7. Repeat the suspending and drawing processes for the other two holes, creating three lines in total.
8. Find the point where all three lines intersect inside or near the irregular shape; mark this as the centre of gravity.
9. Reflect on how the position of the centre of gravity affects stability and balance by relating it to real objects — for example, how a low CG increases stability in vehicles or furniture.
10. You can support your activity on finding the centre of gravity with this helpful video that demonstrates the plumb line method using simple cardboard shapes:

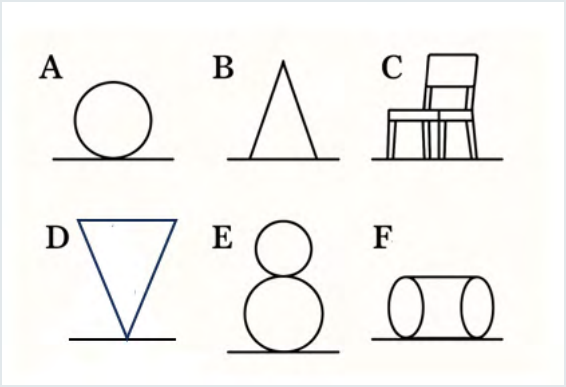
    https://www.youtube.com/watch?v=eXJo9xwhFXw

Activity 1.4 Predicting Types of Equilibrium

Objective: To develop the ability to identify and classify different types of equilibrium—stable, unstable, and neutral—by analysing visual diagrams and reasoning based on the position of an object's centre of gravity and its response to disturbance.

What you need

1. Diagrams of objects in various equilibrium states (check below)
2. Notebook or paper
3. Pen or pencil
4. Sticky tape
5. Scissors



What to do

1. Look carefully at the diagram above showing an object balanced in a certain position.
2. Estimate the centre of gravity. Observe how the object is supported or balanced.
3. For each diagram, decide whether the object is in:
   - **a.** Stable equilibrium: object returns to its original position after a small disturbance.
   - **b.** Unstable equilibrium: object moves away from its original position after a small disturbance.
   - **c.** Neutral equilibrium: object stays in its new position after a small disturbance (neither returns nor moves further away).
4. Write down why you classified the equilibrium type. Use ideas like:
   - **a.** Position of the centre of gravity relative to the base of support

b. Effect of a small push or tilt on the object's position

5. Share your answers with a partner. Compare reasoning and resolve any differences through discussion.
6. Think of real-life examples for each type of equilibrium. Write down one example for each type.
7. Roll a piece of paper into a cone shape and secure it with tape. Cut the base so that it is a circle that sits flat on the table. Use your cone to demonstrate to your neighbour the three different types of equilibrium.

Activity 1.5 Calculating Torque, Moments, and Reactions in Equilibrium

Study the worked examples below carefully before attempting the practical questions that follow.

Worked example 1

Imagine you are steering a car. You apply a force with both hands on the steering wheel. Your left hand pushes the wheel downwards with a force of 25 N, and simultaneously, your right hand pulls the wheel upwards with a force of 25 N. The diameter of the steering wheel is 0.4 m. Find the torque.

Step-by-Step Solution

Step 1 - Identify the Given Values

- Force F = 25 N
- d=0.4 m

Step 2 - Introduce the formula for torque

From torque $\tau = F \times d$

Step 3 - Substitute the given values and calculate

It implies that $\tau = 25 \times 0.4$

$\tau = 10\ Nm$

Worked example 2

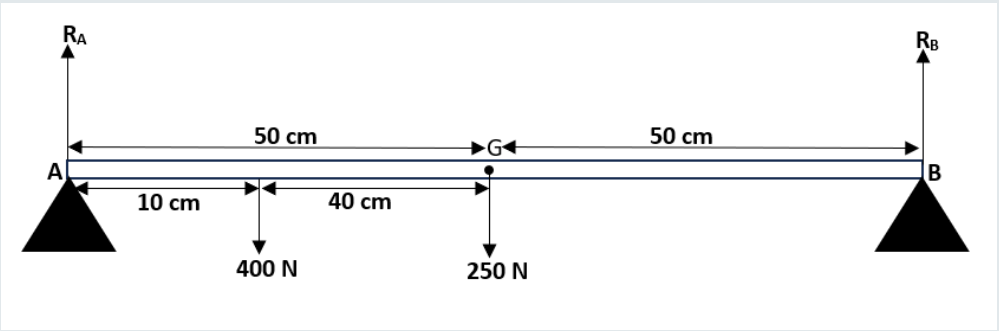
A uniform metre rule AB weighing 250 N is supported by two knife edges at its ends. If a load of 400 N is placed at a point 10 cm from one of the ends. Calculate the reactions given by the knife edges.

Step-by-Step Solution

Weight of metre rule = 250 N

The load = 400 N

Step 1 - Identify forces acting on the metre rule



Step 2 - Apply the equilibrium conditions

Taking moment about G.

The force $\mathbf{R}_A$ will cause the rule to move in a clockwise direction and it is at a distance 50 cm (0.5 m) from G.

Hence clockwise moment = $\mathbf{R}_A \times 0.5$

$$= 0.5\ \mathbf{R}_A$$

The forces $\mathbf{R}_B$ and 400 N will cause the rule to move anticlockwise

Hence anticlockwise moment = $(\mathbf{R}_B \times 0.5) + (400 \times 0.4)$

$$= 0.5\ \mathbf{R}_B + 160$$

At equilibrium, sum of clockwise moment equals sum of anticlockwise moments

That is $0.5\mathbf{R}_A = 0.5\mathbf{R}_B + 160$ ..... (1)

Also from translational equilibrium, sum of upward forces equals sum of downward forces.

That implies that, $\mathbf{R}_A + \mathbf{R}_B = 400 + 250$

$$\mathbf{R}_A + \mathbf{R}_B = 650$$

$$\mathbf{R}_A = 650 - \mathbf{R}_B \text{ ..... (2)}$$

Putting equation (2) into equation (1) gives

$0.5\ (650 - \mathbf{R}_B) = 0.5\mathbf{R}_B + 160$

$325 - 0.5\mathbf{R}_B = 0.5\mathbf{R}_B + 160$

$325 - 160 = 0.5\mathbf{R}_B + 0.5\mathbf{R}_B$

$\mathbf{R}_{B=}165N$

Putting $\mathbf{R}_B = 165$ into equation 2 gives

$\mathbf{R}_A = 650 - 165$

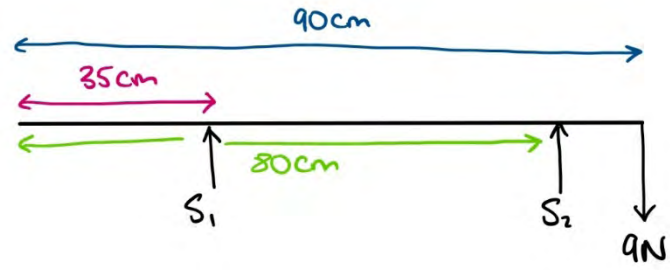
$\mathbf{R}_A = 485$ N

Hence the reactions given by the knife-edges at ends A and B are 485 N and 165 N respectively.

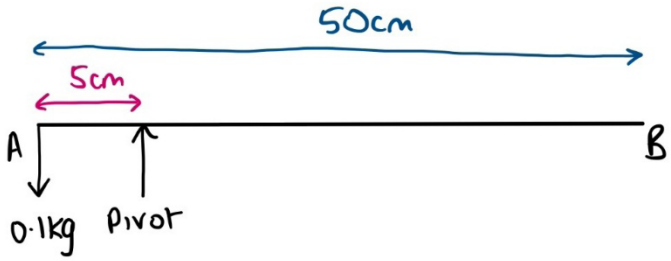
Practice Problems

Now, using the worked examples as a guide, solve the following problems individually or in groups.

1. A uniform ruler of length 90 cm is supported horizontally on two knife-edges, one at 35 cm mark and the other at 80 cm mark. A load of 9 N is hung at the 90 cm mark to keep the ruler in equilibrium. If the sum of the reactions at the knife edges is 52 N, find the
   a. reactions at the knife-edges.
   b. Weight of the ruler.



2. A uniform half-metre rule AB balances horizontally at the 5 cm mark from A where a mass of 0.1 kg is suspended. Calculate the mass of the rule.



Activity 1.6 Application of Moments and Equilibrium to a Common Tool

Objective: To investigate a tool or machine which employs moments and/or equilibrium to achieve a task, and to produce a labelled diagram and explanation available for your class to read or listen to.

What You Need

1. Small tool such as scissors, nutcracker, wrench, model crane
2. Access to the internet for research
3. Paper
4. Pens

Procedure

1. Get yourself into a group of 3-4 learners and together look closely at the tool you have chosen. Discuss how it is used, and how your understanding of moments and equilibrium apply to its function.
2. Use the internet to confirm whether your understanding is correct; search for diagrams of your tool and its relation to moments (e.g. Google 'moments in scissors' and have a look at the diagrams and explanations.
3. Produce a 1-page sheet including a diagram and an explanation of your findings. Make this sheet available for other members of your class to read, whilst you read their research. If instructed by your teacher, present your findings orally.

GRAVITATIONAL FIELDS AND SATELLITE MOTION



Figure 1.12 :*An artificial satellite*

Pick up your pencil and drop it a few centimetres onto the table. Why did it behave like that? Spend a minute considering all that you already know about the force that determines the behaviour of the pencil.

The words "gravitation" and "gravity" stem from the Latin *gravitas*, meaning "weight" or "heaviness." The verb "gravitate" means "to move toward something under the influence of an attractive force." For example: Some metals gravitate toward magnets when brought near them. When you jump, you return to the ground because all objects above Earth's surface gravitate toward it unless held up by an opposing force.

Gravity is the fundamental force that causes objects with mass to attract each other. We call this motion **gravitation**. Whether obvious—like an apple falling from a tree—or subtle—like the Moon orbiting Earth—this attraction controls motion across the universe.

In this discussion, we will explore how gravitation shapes everything, from falling objects to the structure of galaxies.

Gravitational Fields

Every object with mass—whether a planet, a phone, or a person—creates an invisible **gravitational field** around itself. This field is like an invisible force zone that pulls other objects toward it.

1. *The farther you go, the weaker it gets*, but it never completely disappears.
2. *It is a pulling force*—always pointing toward the object's centre (like Earth pulling you down when you jump).
3. *Its strength depends on mass*—bigger objects (like the Sun) have a much stronger pull than smaller ones (like a tennis ball).

Think of it like a giant magnet you cannot see: Earth's gravity keeps you on the ground, while the Moon's gravity pulls on the oceans to create tides. Even distant stars pull on each other slightly!

Gravitational Field Strength

It is defined as the force (F) per unit mass (m) experienced in a gravitational field. This is mathematically stated as $g = \frac{F}{m,}$

Were,

- F is the gravitational force of attraction exerted on a test mass in the field, measured in N

- m is the mass, measured in kg
- g (a vector), is the force per unit mass, measure in N/kg or ms-2, and is directed towards the centre of the body/mass m.

Every object with mass has its own gravitational field, no matter how small. On the surface of the Earth, the magnitude of the gravitational field strength is approximately 9.8 m/s2, though it varies from place to place on Earth. It is *called acceleration of free fall* or, more popularly, ac*celeration due to gravity.*

Newton's Law of Universal Gravitation



Figure 1.13*: The solar system-the planets in their obits around the sun*

For centuries, people have wondered why objects fall to Earth or why planets move across the sky. Ancient Greeks, such as Aristotle, believed that objects "naturally" sought their place—rocks fell because Earth was their natural home, while stars moved in perfect circles. Later, Kepler described *how* planets orbited the Sun (in ellipses, not circles), but no one knew *why* they stayed in motion.

Then came **Isaac Newton** in 1687. Legend says an apple's fall inspired him. Newton had an idea that changed everything: *What if the same force that pulled the apple also kept the Moon in orbit?*

His Law of Universal Gravitation declared,

- Every mass attracts every other mass, from apples to planets.
- The force weakens with distance but never vanishes.

The law is formally stated as

"*Every two masses in the universe attract each other with a force (F) proportional to the product of their masses and inversely proportional to the square of the distance between their centres (r)*".

Consider the diagram below.

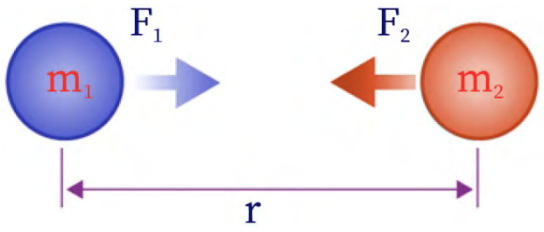


Figure 1.14 *:Two masses m_1 and m_2, separated by r from their centres exert attractive forces F_1 and F_2, respectively on each other.*

This is stated mathematically as $F \propto \frac{Gm_1m_2}{r^2}$

$F = \frac{Gm_1m_2}{r^2}$,

Where m1 and m2 are the respective masses of the two bodies, r is the distance between the centres of masses of the bodies and G is called the universal gravitational constant, with a numerical value of $G = 6.67 \times 10^{-11}\, Nm^2kg^{-2}$.

Since the masses pull each other with equal but opposite forces, $F_1 = F_2 = F$

What sense does this law make to you? Have a chat with Mother Earth!

"**A Chat with Planet Earth**"

You: *Hey, Earth… can I ask you something?*

Earth: *Of course, little one. What is on your mind?*

You: *They say we are pulling on each other with the same gravitational force. Is that true?*

Earth: *Absolutely. I pull you with a certain force, and you pull me back with exactly the same force.*

You *(laughing): No way. I am just one person — how could I possibly pull you?*

Earth: *It is Newton's Law of Gravitation. The force between two masses depends on both masses and the distance between them. The formula is:* $F = \frac{Gm_1m_2}{r^2}$

You and I are two masses. That means we both pull each other with equal force.

You: *Okay… but I fall when I jump. You do not fly up to meet me. That is not fair!*

Earth *(chuckles): It is fair — just physics. You see, even though the force is equal, our masses are very different.*

You: *How different?*

Earth: *Let us put it this way — you might weigh around 60 kg. I weigh* about 6,0 00,000,000,000,000,000,000,000 kg. *That is,* 6×10^{24} *kg. I am way heavier.*

You: *So… because I am small, the force moves me more?*

Earth: *Exactly! Acceleration depends on mass:* $g = F$–

Same force, but small mass means big acceleration — that is you falling.

Huge mass means tiny *acceleration — that is* me barely moving.

You: *So technically, you do move when I fall?*

Earth: *Technically, yes — I wobble just a little. But not enough for anyone to notice.*

You: *Wow… I never thought of gravity as a two-way thing.*

Earth: *It always is. You pull me, I pull you. That is gravity — always mutual.*

You: *Thanks, Earth. I guess we are more connected than I thought.*

Earth: *Always have been, always will be.*

Relationship Between the Universal Gravitational Constant (G) and the Acceleration of Free fall (g) on the Surface of the Earth

1. Remember $g = F$, and $F = \frac{G m_1 m_2}{r^2}$
2. You are certainly on earth, so let's say your mass is m, and that of the earth is M. This means $m = m_1$ *and* $M = m_2$.
3. If the distance between the central part of your body and the centre of the Earth is R, then the force of attraction between you and the Earth is $F = \frac{GmM}{R^2}$

   $g = \frac{F}{m} = \frac{\left[\frac{Gm}{R^2}\right]}{m} = \frac{GmM}{mR^2}$

   $g = \frac{GM}{R^2}$
4. Since the distance between the central part of you is insignificant, R is virtually the Radius of the Earth. *Challenge: Can you use the values that you know for G, M (the mass of Earth) and R (the radius of Earth) to calculate g at Earth's surface?*

5. As the distance between you and the Earth increases, the force of gravity reduces.
6. This relationship is called an *inverse square law*.

Gravitational Potential

When you hear the word *'potential'*, what comes to mind? A *possibility*, right?

Exactly!

In physics, *gravitational potential* refers to the *possibility* that a body can move within a gravitational field — that is, the potential for the gravitational force to cause movement.

You see, whenever a force moves an object through a distance in the direction of the force, work is done — or in other words, energy is used.

So, *gravitational potential* is simply the potential/possibility for energy to be spent or work to be done when a body is placed in a gravitational field.

It tells us how much energy per kilogram of mass is available to be released (or required) due to gravity at a particular point.

The gravitational potential at a point in a gravitational field is defined as *the work done in bringing a unit test mass from infinity to that point.*

$$Work\ done = force \times distance$$

$$gravitational\ potential\ (V) = work\ done\ per\ unit\ mass = \frac{force \times distance}{m}$$

$$V = \frac{F \times R}{m}$$

$$V = \frac{\left(\frac{GmM}{R^2}\right) \times R}{m}$$

$$V = \left(\frac{GmM}{mR^2}\right) \times R$$

$$V = \frac{GM}{R}$$

Finally, we attach a negative sign to the formula, thus $V = -\frac{GM}{R}$, and this is why:

Gravitational potential energy is less than zero

- When a mass is in a gravitational field, its energy is lower than if it were far away (at infinity).

- Infinity is taken universally as the zero level of potential energy.
- So, bringing a mass closer to a planet means its energy is decreasing, becoming more negative.

Gravity always pulls objects toward lower energy, which is why gravitational potential energy is **negative** near planets, stars, etc.

Gravitational Potential Energy (u)

The gravitational potential (V) we considered above is the work done/energy used per unit mass (1 kg). So, what if we are to consider work done in moving the entire mass?

We would have to multiply V by the entire mass.

$U = Vm$

$U = -\frac{GM}{R}m,$

Orbital Period and Geostationary Satellites

A **satellite** is any object that moves around a heavenly body. It could be **another natural body** (like the moon orbiting Earth) or a **man-made object** (an artificial satellite).

For now, we will focus on **artificial satellites** — the ones built by humans.

Why are satellites launched?

Artificial satellites are designed for **different purposes** like communication, weather forecasting, GPS, or scientific research. The **purpose** of the satellite determines the **height (altitude)** at which it orbits. This **altitude** affects the **speed** at which it must travel to stay in orbit.

Geostationary Satellites

If a satellite orbits at just the right altitude and speed such that it takes 24 hours to complete one revolution — matching Earth's rotation — it becomes a geostationary satellite. This kind of satellite appears to stay fixed over one spot on Earth.

That is why it is called **geo** (Earth) + **stationary** — it looks like it's not moving when viewed from the ground.

Since the motion of a satellite is circular, the centripetal force $F_c = \frac{mv^2}{R}$ is derived from the Earth's gravitational force $F = \frac{GmM}{R^2}$

Hence

$F_c = F$

$\frac{mv^2}{R} = \frac{GmM}{R^2}$

Our target is to derive the revolutionary period of a satellite, so we are looking for T.

From the equation above, $v^2 = \frac{GM}{R}$,

Where v is the velocity of the satellite and

$velocity = \frac{distance}{time}$

The distance here is the circular path taken (orbit), which is $2\pi R$, and time is the period of revolution (T).

So

$v = \frac{2\pi R}{T}$

Putting these into $v^2 = \frac{GM}{R}$,

$$\Rightarrow \left(\frac{2\pi R}{T}\right)^2 = \frac{GM}{R},$$

$$\frac{4\pi^2 R^2}{T^2} = \frac{GM}{R}$$

$$T^2 = \left(\frac{4\pi^2}{GM}\right) \times R^3$$

This is known as **Kepler's Third Law**, which states that "the period squared of a satellite orbiting a given astronomical body is proportional to its orbital radius cubed".

Escape Velocity

Normally, any object you throw upward will eventually fall back to Earth, as long as it remains within Earth's gravitational field. But if you want an object to completely escape Earth's gravity and never return, it must be given a minimum speed. This speed is called the escape velocity. To achieve this, the object must be given enough initial kinetic energy to match the gravitational potential energy pulling it back.

In simple terms

Escape velocity is the minimum speed needed to break free from Earth's gravity without falling back. This holds for all other larger celestial bodies with significant gravity.

Hence $\frac{1}{2}m v^2 = \frac{GM}{R}m$

$$v^2 = \frac{2GM}{R}$$

but

$g = \frac{GM}{R^2}$ *and* $GM = g R^2$

$$v^2 = \frac{2g R^2}{R}$$

$$v^2 = 2gR$$

$$v = \sqrt{2gR}$$

Weightlessness: The Illusion of No Gravity



Figure 1.15: *A vivid demonstration of weightlessness, where being in a constant state of free-fall allows a person to float and liquids to form suspended spheres, completely unconstrained by the sensation of gravity.*

Weightlessness is the feeling of being completely free from gravity's pull, like when astronauts float in space. It happens because they're in a constant free-fall around Earth, not because gravity disappears (at the distance of, for example, the international space station the gravitational field strength is still 89% of g at the surface of the Earth!). You can briefly feel weightless on a roller coaster drop or in a falling elevator!

Activity 1.7 Comparing Coulomb's Law with Newton's Gravitational Law

Objective: Recall Coulomb's law for electric forces, compare it with Newton's gravitational law, identify their similarities and differences (including inverse-square relationships), and express the gravitational law in its general formula form.

What you need

1. Notebook or paper
2. Pen or pencil
3. Calculator (optional)
4. Ruler or straightedge (optional, for neat diagrams or formula layout)

What to do

1. Write down the formula for Coulomb's law describing the force between two electric charges.
2. Write down the formula for Newton's law of universal gravitation describing the force between two masses.
3. Compare the two laws by listing:
   - **a.** Similarities in their structure and relationships.
   - **b.** Differences in the types of forces and properties involved.
4. Express Newton's gravitational law clearly as a general formula, including the meaning of each symbol and constant.
5. In your own words, explain:
   - **a.** the concept of inverse-square law for these forces.
   - **b.** the difference between electric and gravitational forces regarding attraction/ repulsion and nature.
6. Draw simple diagrams of two charges and two masses with the forces acting between them, indicating the direction.

Activity 1.8 The Moon and Man-made Satellites

What you need

1. Pen or pencil
2. Worksheet

What to do

1. Observe the images below



Figure 1.16: *The Moon – Earth's natural satellite*

Artificial Satellites, like



Figure 1.17: *A communication satellite*

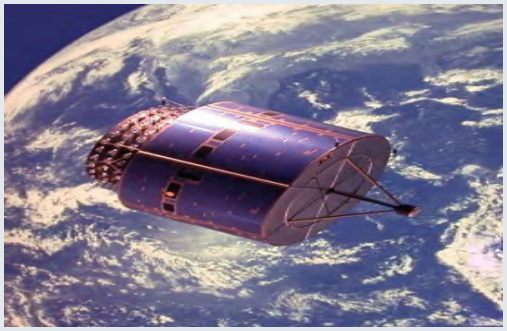


Figure 1.18: *A weather satellite*



Figure 1.19: *A scientific satellite (like the Hubble Telescope)*

2. As you observe, ask yourself the following questions

a. What do these objects look like?

b. What parts or features do you notice?

c. How are they similar? How are they different?

Focus on shape, surface, size, and visible parts like antennas or panels.

3. Fill out the chart below (in your notebook or on the worksheet). Write at least **two similarities** and **two differences** between the Moon and artificial satellites.

Similarities (Both)	Differences	
	Moon	Artificial satellites

Activity 1.9 Exploring Satellites: Our Helpers in Space

Objective: To understand different types of satellites, their orbits, functions, and real-life applications.

Hello Scientists-in-Training!

Today, you and your team will become space researchers!

Your Mission

In pairs or small groups (2–4 students), **choose one type of satellite** from the list below and prepare a short presentation to **teach your classmates** about it.

Satellite Types (Pick one)

1. Communication Satellite
2. Weather Satellite
3. Navigation Satellite
4. Earth Observation Satellite
5. Military Satellite
6. Scientific/Research Satellite

What Your Research Should Include

1. Name and Type of your satellite
2. What it does (Its functions)
3. Orbit type (e.g., geostationary, polar orbit – explain it simply)
4. Where we see or use it in everyday life (e.g., GPS on phones, satellite TV, weather forecasts, Google Maps)

Presentation Options

Pick **ONE** creative way to share your findings

a. A Poster (include diagrams or drawings)

b. A Voice Note (record your team's explanation)

c. A Simple Model (use paper, plastic, or even cardboard to show your satellite and its orbit)

Tips for Success

a. Use books, school internet, or ask your teacher for help.

b. Make sure every group member participates.

c. Keep it simple but clear — teach your friends like a mini teacher!

Materials You Might Need

a. Chart paper / drawing sheets

b. Markers / pens / coloured pencils

c. Glue / tape / scissors

d. Cardboard / paper for models

e. Phone or tablet (for voice notes or research)

Let your creativity shine — and remember, satellites may be far away in space, but their work affects us right here on Earth!

Activity 1.10 Watching a Video on Weightlessness

Objective: Your mission is to investigate the fascinating phenomenon of weightlessness. By watching a short video, you will uncover the real reason astronauts float on the International Space Station (ISS).

What you need

1. A smartphone or tablet with a camera

2. An internet connection

3. A pen or pencil

4. QR code

What to do

Part 1: Before You Watch (Your Prediction)

1. Pair up with a friend or form a group with your colleagues and carry out the following activities.
2. Before you scan the code, answer this question based on what you already know or believe. There are no wrong answers here—this is about your initial hypothesis!

Why do you think astronauts float around on the International Space Station?

Part 2: Scan, Watch, and Discover

Now it's time to investigate! Follow these steps:

3. Open the camera app on your device and point it at the QR code above.
4. Tap the link that appears on your screen to open the video.
5. Watch the video carefully. You may want to watch it more than once to catch all the details. You may observe other videos associated to this one.
6. As you watch, listen for the answers to the questions in the next section.

Part 3

Now that you have observe the video, answer the following questions to complete your mission report.

7. What is the one-word scientific term for the condition of an object that is falling with only gravity acting on it?
8. Based on the video, what is *really* happening to the ISS and the astronauts inside it as they travel around the Earth? Explain in your own words.
9. **Thought Experiment** Imagine you are standing on a bathroom scale in an elevator. Suddenly, the elevator cable snaps, and it begins to free-fall.
   a. What weight would the scale show?
   b. Why would it show this reading?
10. **Challenge Question** An astronaut has a mass of 75 kg. What is her
    a. mass when she is on the ISS?

b. *apparent weight* on the ISS, and is it the same as on Earth? Explain why or why not.

11. If prompted, you can show your answers to your teacher for confirmation.

Activity 1.11 Calculating Gravitational Forces, Fields & Orbital Mechanics

Study the worked examples carefully before attempting the practical questions that follow.

Worked Example 1

Problem:

Two objects, each of mass 5.0 kg, are placed:

Case A: 2.0 metres apart

Case B: 4.0 metres apart

a. Calculate the gravitational force between them in each case.

b. By what factor does the force change when the distance is doubled?

Solution

Introduce the formula

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

Where:

F = gravitational force

G = 6.674×10^{-11} Nm²/kg² (gravitational constant)

m_1, m_2 = masses of objects

r = distance between the centres of mass

a. Case A

$$F_A = G\frac{5 \times 5}{2^2} = G\frac{25}{4}$$

$$F_A = 6.674 \times 10^{-11} \times \frac{25}{4} = 4.171 \times 10^{-10}$$

Case B

$$F_B = G\frac{5 \times 5}{4^2} = G\frac{25}{16}$$

$$F_B = 6.674 \times 10^{-11} \times \frac{25}{16} = 1.043 \times 10^{-10}$$

b. Comparison

$$\frac{F_A}{F_B} = \frac{\left(G\frac{25}{4}\right)}{\left(G\frac{25}{16}\right)}$$

$$\frac{F_A}{F_B} = \frac{25}{4} \times \frac{16}{25}$$

$$\frac{F_A}{F_B} = \frac{16}{4} = 4$$

Doubling the distance reduces the force by a factor of 4.

Worked Example 2

The Moon orbits Earth at an average distance of 3.84×10^8 m, and the mass of Earth is 5.97×10^{24} kg.

a. Calculate the orbital period of the Moon in seconds.

b. Convert the period to days.

Solution

a. **Step 1** - Identify the knowns

r = 3.84×10^8 m

G = $6.674 \times 10\text{-}^{11}$ Nm²/kg²

M = 5.97×10^{24} kg

Step 2 - Introduce the appropriate formula

Given that $T = 2\pi\sqrt{\frac{r^3}{GM}}$

Where

T = orbital period

r = radius of orbit

M = mass of the Earth

G = gravitational constant

Step 3 - Substitute the values and calculate

$$T = 2\pi\sqrt{\frac{r^3}{GM}}$$

$$T = 2\pi\sqrt{\frac{(3.84 \times 10^8)^3}{(6.674 \times 10-^{11}) \times (5.97 \times 10^{24})}}$$

$$T = 2368625.7057\ s$$

$T = 2.37 \times 10^{-6}\ s$

b. To convert this to days, know that

$1\ day = 24\ hour$

$1\ day = 24 \times 60\ minutes = 1440\ minutes$

$1\ day = 1440 \times 60\ seconds = 86400\ seconds$

so if 86400 *seconds make* 1 *day*

$$then\ 2368625.7057\ seconds = \frac{2368625.7057\ s \times 1day}{86400\ s} = 27.4146\ days$$

Worked Example 3

A satellite of mass 800 kg is located:

a. At a distance of 6.4×10^6 m (Earth's surface)

b. At a distance of 1.28×10^7 m (twice Earth's radius).

Calculate the gravitational potential and gravitational potential energy in each case.

Solution

Step 1: Identify the knowns

m = 800 kg

G = 6.674×10^{-11} Nm²/kg²

M = 5.97×10^{24} kg

Step 2: Introduce the appropriate formula

Gravitational potential at a distance r from Earth is given by: $V = -\frac{GM}{r}$

Gravitational potential energy (GPE) of a mass m is: $GPE = mV = -\frac{GMm}{r}$

Where:

V = gravitational potential (J/kg)

G = 6.674×10^{-11} Nm²/kg²

M = mass of Earth (5.97×10^{24} kg)

Mass of satellite

r = distance from Earth's centre in meters

Step 3: Substitute the values and calculate

a. At r = 6.4×10^6 m

$$V = -\frac{GM}{r}$$

$$V = -\frac{6.674 \times 10^{-11} \times 5.97 \times 10^{24}}{6.4 \times 10^6}$$

$$V \approx -6.23 \times 10^7$$

$$GPE = mV$$

$$GPE = 800 \times (-6.23 \times 10^7)$$

$$GPE = -4.98 \times 10^{10} J$$

b. At r = 1.28×10^7 m

$$V = -\frac{GM}{r}$$

$$V = -\frac{GM}{r}$$

$$V = -\frac{6.674 \times 10^{-11} \times 5.97 \times 10^{24}}{1.28 \times 10^7}$$

$$V \approx -3.12 \times 10^7$$

$$GPE = mV$$

$$GPE = 800 \times (-3.12 \times 10^7)$$

$$GPE = -2.50 \times 10^{10} J$$

Conclusion: As distance increases, gravitational potential becomes less negative, and GPE becomes less negative too.

Worked Example 4

What speed is needed for a rocket to leave Earth without returning If the mass and radius of the earth is 5.97×10^{24} kg and 6.4×10^6 m respectively (G = 6.674×10^{-11} Nm²/kg²)

Solution

Step 1 - Identify the knowns

v_e = escape velocity

G = 6.674×10^{-11} Nm²/kg²

M = 5.97×10^{24} kg

r = 6.4×10^6 m (Earth's radius)

Step 2 - Introduce the appropriate formula $v_e = \sqrt{\frac{2GM}{r}}$

Step 3 - Substitute the values and calculate

$$v_e = \sqrt{\left[\frac{2 \times 6.674 \times 10^{-11} \times 5.97 \times 10^{24}}{6.4} \times 10^6\right]}$$

$$v_e = \sqrt{7.98 \times 10^7} \approx 11{,}230\ m/s$$

Conclusion: A rocket must travel at about 11.23km/s to escape Earth's gravity from the surface (ignoring air resistance).

Practice Problems

Now, using the worked example as a guide, solve the following problems individually or in groups.

1. Calculate the acceleration due to gravity at a height of 100km above the surface of Mars, given that the Mass of Mars = 6.42×10^{23} kg, and radius = 3.39×10^6 m.
2. Calculate the gravitational field strength at the surface of the Moon: Mass = 7.35×10^{22} kg and radius = 1.74×10^6 m
3. Find the gravitational force between Earth and Moon whose centres of mass are separated by 3.84×10^8 m.

   Mass of Earth: 5.97×10^{24} kg; Mass of Moon: 7.35×10^{22} kg
4. Jupiter and a moon are 4.2×10^8 m apart. Calculate the mutual force of attraction between them.

   Mass of Jupiter: 1.90×10^{27} kg; Mass of Moon: 8.9×10^{22} kg
5. Find gravity at a 100 km altitude: Earth radius = 6.4×10^6 m and Earth mass = 5.97×10^{24} kg
6. At what altitude is gravity half of 9.8 m/s²?

Activity 1.12 - Recap on Motion, Forces, and Rotational Dynamics

Objective: Work in groups without a teacher to quiz each other and discuss key physics concepts from Years 1 to 3.

What you need

1. Notebook or paper for each participant
2. Pens or pencils
3. Calculator
4. Ruler and protractor (optional)

5. Tables or whiteboard (optional for group notes)

What To do

1. Form small groups of 4-6 learners

   Sit together in a circle or around a table to facilitate easy conversation.

2. Prepare quiz questions
   - **a.** Each member writes 3–5 quiz questions based on the key topics from these main categories:
     - *i. Year 1:* Types of motion, equations of motion, graphs of motion
     - *ii. Year 2:* Vectors, circular motion (centripetal force, speed, period)
     - *iii. Year 3:* Moments and equilibrium, calculating support reactions, Newton's law of gravitation, satellite period formula

3. **Exchange and ask questions**
   - **a.** Take turns asking each other the prepared questions orally.
   - **b.** Each question should be answered aloud by another member, who then explains their reasoning or works through calculations if needed.

4. **Use diagrams and examples**
   - **a.** When relevant, draw simple diagrams to illustrate answers (e.g., velocity-time graph, vector addition, beam with forces, satellite orbit).
   - **b.** Peers can challenge or ask for clarification, fostering deeper discussion.

5. **Peer teaching**
   - **a.** For questions that members find difficult, another member who understands better gives a *short explanation or mini-lesson* in their own words.
   - **b.** Encourage everyone to participate equally in asking, answering, and explaining.

6. **Group summary challenge**
   - **a.** After rounds of quizzing, collaboratively create a **shared summary** of the key points from each topic on a large sheet or whiteboard.
   - **b.** Organise the summary under headings like: Motion, Vectors, Circular Motion, Moments & Equilibrium, Gravitation & Satellites.

7. Reflection and feedback

a. Each member shares one concept they feel more confident about after the quiz and one they want to review further.

b. Optionally, plan a next group session to revisit difficult topics.

Sample Quiz Questions

- What are the three main types of motion?
- Write one equation of motion and explain the terms.
- How do you find the resultant of two vectors acting at a point?
- What force keeps a satellite moving in a circular orbit?
- How do you calculate moments in a beam in equilibrium?
- State Newton's law of universal gravitation and what the symbols mean.
- How do you find the period of a satellite orbiting a planet?

REVIEW QUESTIONS

Review Questions 1.1

1. A non-uniform rod AB of length 5 m has its centre of gravity located 2 m from end A. The rod has a mass of 50 kg. It is supported by a pivot at point P, which is 3 m from end A. A mass M is hung from end B, and the rod is in equilibrium.

- **a.** Determine the mass M.
- **b.** Calculate the force exerted by the pivot on the rod. (Take $g = 10\ m/s^2$)

2. A ladder has a length of 8 m and mass 15 kg rests against a smooth vertical wall at an angle of 60° to the horizontal ground. The coefficient of friction between the ladder and the rough horizontal ground is 0.45.

- **a.** Calculate the minimum horizontal force required at the base of the ladder to prevent it from slipping down.
- **b.** What is the maximum height a 55 kg man can climb up the ladder before it starts to slip? (Assume the ladder's centre of gravity is at its midpoint).

3. You are given a uniform wooden beam and a set of weights. You need to balance this beam horizontally on a single pivot point.

- **a.** Explain, using the concept of moments, why placing a heavy weight closer to the pivot has the same balancing effect as placing a lighter weight further from the pivot.
- **b.** Describe a practical method to experimentally find the centre of gravity of the *uniform* wooden beam using only the pivot and no additional measuring tools (like a ruler or scale). Justify your method using the principle of moments.

Review Questions 1.2

1. **a.** The mass of Mars is 6.42×10^{23} kg, and its radius is 3.39×10^6 m. Calculate the gravitational field strength (g) on the surface of Mars.

- **b.** If an astronaut has a mass of 70 kg, what would be their weight (gravitational force) on the surface of Mars?

2. A space probe of mass 150 kg is at a distance of 2.0×10^7 m from the centre of the Earth. Calculate the;

- **a.** gravitational potential at the probe's location.
- **b.** gravitational potential energy of the space probe at this location.
- **c.** If the probe moves to a new location where the gravitational potential is -1.5×10^7 J/kg, does its GPE increase or decrease? Explain your reasoning.

3. Using the concepts of centripetal force and gravitational force,

- **a.** Deduce the formula for the orbital period (T) of a satellite in a circular orbit around a central body of mass M at an orbital radius R. Show your steps clearly.
- **b.** Calculate the speed of the satellite in its orbit.
- **c.** Calculate the orbital period of this satellite in hours.

4. Calculate the escape velocity from the surface of Jupiter, given that Jupiter's mass is 1.90×10^{27} kg and its radius is 6.99×10^7 m.

5. Describe a common misconception about weightlessness that the "free-fall" explanation clarifies.

SECTION

2 THERMAL EXPANSION AND ITS APPLICATIONS



HEAT ENERGY

INTRODUCTION

This section explores how heat energy causes substances—solids, liquids, and gases—to expand. You will examine the concepts of linear, area, and volume expansion, and how these relate to real-life applications such as bridges, power lines, thermometers, and thermostats. The section provides opportunities to calculate expansion in different materials and to compare the expansivity of various metals. Through experiments and activities, you will gain hands-on experience with devices like bimetallic strips and ball-and-ring apparatuses, deepening your understanding of how thermal expansion affects engineering design and safety. Prior knowledge from Year One on particle theory and thermometers will be linked to this topic.

KEY IDEAS

- **Anomalous Expansion of Water:** behaves uniquely by expanding as it cools from 4°C to 0°C, which is essential for aquatic life survival.
- **Applications of Thermal Expansion:** Thermal expansion affects everyday objects and structures, such as bridges, railway tracks, power lines, thermometers, and thermostats.
- **Coefficient of Expansion:** Materials expand at different rates; linear, area, and volume expansivities quantify these changes for solids, liquids, and gases.
- **Effect on States of Matter:** Solids, liquids, and gases expand differently when heated; gases expand the most, followed by liquids, then solids.
- **Real-Life Design Considerations:** Expansion joints in bridges, sagging of power lines, and gaps in railway tracks are deliberate engineering designs to prevent damage.

THERMAL EXPANSION AND ITS APPLICATIONS

Have you ever noticed the behaviour of these everyday objects when they get hot?



Figure 2.1: *An electric iron*



Figure 2.2: *Electric Kettle*

When you switch on an iron to heat it up, you might hear it "click" and see it turn off by itself once it gets hot enough. It then switches on and off repeatedly while you use it. This on-and-off behaviour is closely connected to how the iron's metal parts behave when heated.

Similarly, have you ever watched an electric kettle boil water? You switch it on, and after a few minutes, it suddenly switches off by itself once the water reaches its boiling point. It seems almost like the kettle "knows" when to stop heating.

But how do both the iron and the kettle know when to stop heating? The answer lies in a process called thermal expansion.

Thermal Expansion

What is thermal expansion?

Thermal expansion is the increase in size of a material when its temperature rises.

Think of it like this: everything is made of tiny, tiny pieces called atoms or molecules. When you heat something, these tiny pieces get more excited and start wiggling and jiggling around faster. As they jiggle more, they push each other a little further apart, making the whole material expand.

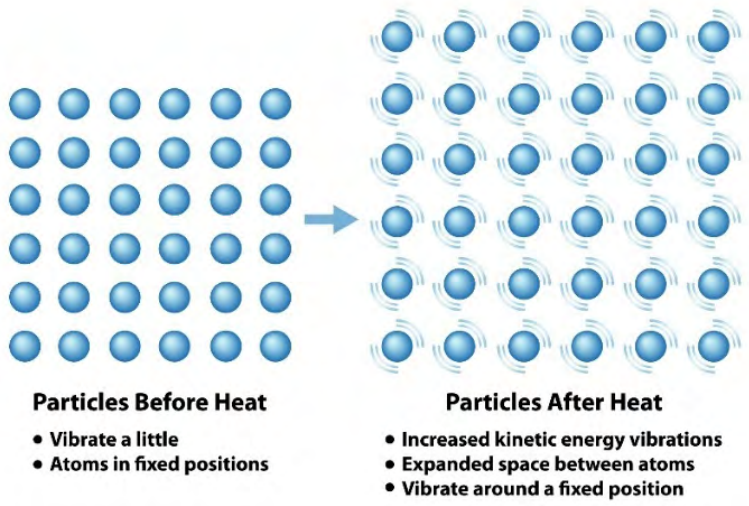


Figure 2.3: *Thermal expansion of solids*

This expansion can happen in different ways:

Length: A long, thin object like a metal rod will get slightly longer.

Area: A flat object like a metal sheet will get slightly bigger in both its length and width, increasing its surface area.

Volume: A 3D object like a block of metal, or even liquids and gases, will take up more space.

In solids, these tiny particles are usually packed tightly, but they still vibrate. When heated, the amplitude of their vibrations becomes larger, pushing them further apart and increasing the overall size of the material. In liquids and gases, particles can move around more freely, so they generally expand even more than solids.

What is happening inside the iron and the kettle?

Inside the iron's flat metal base and the electric kettle's metal base and thermostat, the metal parts heat up as electricity passes through. The tiny atoms inside these metals vibrate faster and push each other slightly apart, causing the metal to expand. This is known as thermal expansion.

In the iron, this expansion is detected by a thermostat that switches the heating element off once the metal reaches a set temperature. When the metal cools and contracts, the thermostat switches it back on, causing the iron to click on and off.

In the electric kettle, a special part called a bimetallic strip (usually made from iron combined with another metal like copper) is used. Because the two metals expand at different rates when heated, the bimetallic strip bends as the kettle heats. When enough steam is produced from boiling water, the strip bends enough to trigger a

switch that turns off the kettle automatically. As it cools, the strip straightens and resets for the next use.

Applications of Expansion

Where Do We See Thermal Expansion in Real Life?

Thermal expansion is not just a scientific concept; it happens all around us!

1. Bridges and Railway Tracks: Have you ever noticed gaps in bridges or railway tracks? These are called expansion joints. On hot days, materials like steel expand. If there were not gaps, the tracks or bridge could buckle and get damaged!



Figure 2.4: *Railway track*

2. Sagging Power Lines: On a hot day, you might see electrical power lines hanging lower between poles. This is because the wires expand with the heat. This sagging is actually a good thing! It prevents the cables from becoming too tight and snapping when they contract in cold weather.



Figure 2.5: *Sagging Power lines*

3. Stuck Jar Lids: If you have trouble opening a jar with a metal lid, try running it under hot water. The metal lid heats up and expands slightly, making it easier to twist off!
4. Thermometers: The mercury or alcohol inside a thermometer expands when it gets warmer, rising up the tube to show you the temperature.
5. Engines and Machines: The metal parts in engines and machines get very hot when they're working. Engineers have to design these parts carefully, leaving tiny gaps (called clearances) so that they can expand without getting stuck or wearing out too quickly.
6. Hot Water Heaters: A hot water heater has a special expansion tank. This tank gives the water, which expands as it gets hot, a place to go, preventing damage to the heater.
7. Thermal Fatigue: Imagine something that gets hot and cold over and over again, like parts in an airplane engine. This constant expanding and contracting can eventually make the material weak and cause it to break. This is called thermal fatigue

Bimetallic Strips

As mentioned earlier, a bimetallic strip is a special type of material made by bonding together two different metals, such as brass and steel. These metals are chosen because they expand at different rates when heated. When the strip is heated, one metal expands more than the other, causing the strip to bend. This bending occurs because the two metals try to lengthen by different amounts, but are stuck together, forcing the strip to curve. This unique behaviour makes bimetallic strips very useful in devices like thermostats and electric kettles, where the bending action can be used to turn switches on or off based on temperature changes.



Figure 2.6 :*Bimetallic strip showing two sides made up of different metals*

Here is how it works

1. Both metals start at the same length.
2. When heated, one metal expands more than the other because it has a higher "coefficient of linear expansion" (meaning it expands more for the same temperature change).
3. Since they are stuck together, the strip has to bend, with the metal that expanded more on the outside of the curve.
4. When it cools down, the bending reverses.

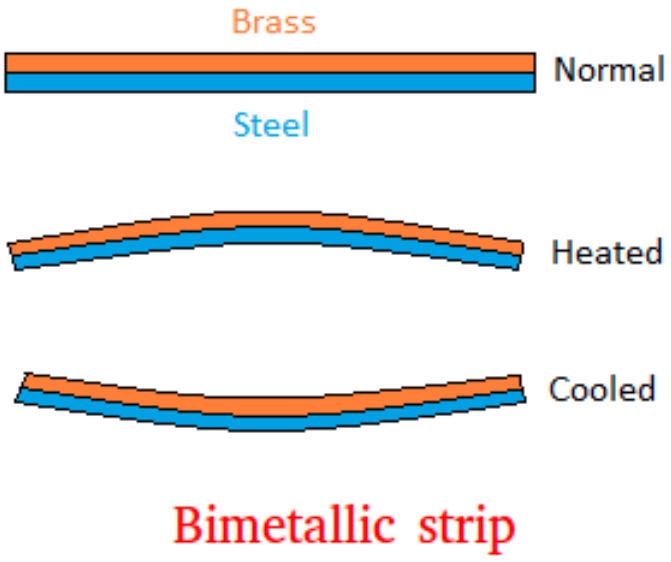


Figure 2.7: *Bimetallic strip when heated and cooled*



Figure 2.8: *Bimetallic strip being heated*

Cool Applications of Bimetallic Strips

1. **Thermostats**: Help regulate temperature by turning heating or cooling devices on and off. They are found in household appliances like irons (to maintain soleplate temperature), ovens, refrigerators, air conditioners, and electric heaters.
2. **Fire Alarms**: Early fire alarms used bimetallic strips as a simple temperature sensor. When a fire caused the surrounding air to heat up, the strip would bend. This bending would complete an electrical circuit, triggering an alarm bell to ring.
3. **Automotive Parts**: Bimetallic strips are also used in automotive parts, such as the thermal switches that control engine fans. The strip bends when the engine gets hot, completing a circuit that turns on the cooling fan. Once the engine cools down, the strip returns to its original position, turning off the fan.
4. **Circuit Breakers**: Bimetallic strips can act as thermal circuit breakers. When excessive current flows through the strip, it heats up and bends, breaking the circuit and preventing damage from overheating. This protects electrical circuits from overloads and short circuits in various applications.
5. **Thermometers**: Some thermometers use spiral bimetallic strips that uncoil or coil up with temperature changes, moving a pointer to show the reading.

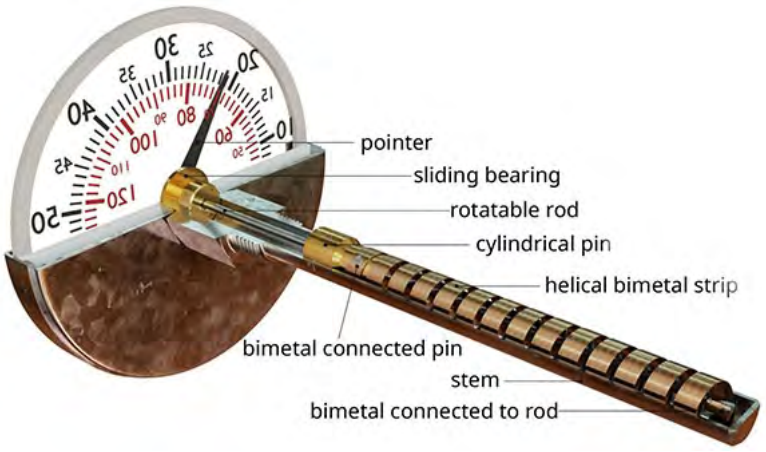


Figure 2.9: *Bimetallic thermometer*

How a bimetallic strip thermometer works

- A **bimetallic strip**, made of two different metals, is coiled into a helix. One metal has a higher coefficient of thermal expansion than the other.
- When the temperature changes, the two metals in the strip expand or contract at different rates.

- This unequal expansion causes the coiled strip to either tighten or unwind.
- One end of the coil is fixed, while the other end is attached to a pointer.
- As the coil winds or unwinds, it moves the pointer along a calibrated scale, which indicates the temperature.

Measuring Expansion: Linear, Area, and Volume

Scientists and engineers have ways to measure exactly how much things expand.

Linear Expansion

This is about how much the **length** of an object change. It is usually looked at for long, thin things like rods or wires.

Linear expansion refers to the change in length of an object due to temperature change.

A term called *linear expansivity or coefficient of linear expansion* is used to describe how much a material expands in length for every degree its temperature changes.

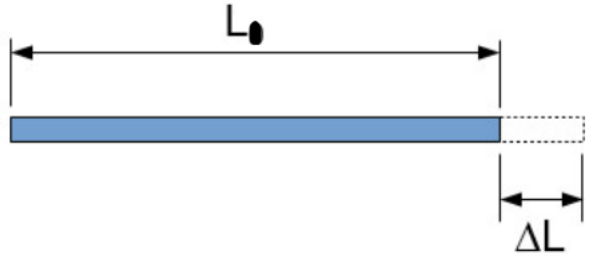


Figure 2.10: *Linear expansion, showing how the original length (L_1) of a surface increases by ΔL when it is heated and expands.*

Linear Expansivity (α): is the fractional increase in length per unit temperature change.

$$\alpha = \frac{\Delta l}{l_1 \times \Delta\theta}$$

Where,

Δl= change in length

l_1 = initial length

$\Delta\theta$ = temperature difference

You can also find the new length (l_2) after heating:

$$\Delta l = l_2 - l_1$$

$$\alpha = \frac{l_2 - l_1}{l_1 \times \Delta\theta}$$

$$l_2 - l_1 = \alpha l_1 \Delta\theta$$

$$l_2 - l_1 = l_1 + \alpha l_1 \Delta\theta$$

$$l_2 = l_1(1 + \alpha \Delta\theta)$$

Area Expansion

This applies to flat, two-dimensional objects like metal sheets. When heated, both the length and width expand, making the overall surface area bigger.

Area expansion refers to the change in area of an object due to temperature change.

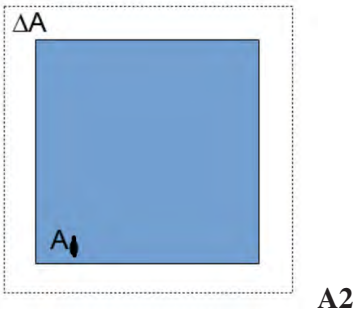


Figure 2.11: *Area expansion (also called superficial expansion), showing how the original area (A_1) of a surface increases by ΔA when it is heated and expands. The blue square is the original area, and the dashed outline shows the expanded area.*

Area (Superficial) Expansivity (β) tells us the fractional increase in surface area per unit temperature change. The formula for area expansivity is

$$\beta = \frac{\Delta A}{A_1 \times \Delta\theta}$$

Where,

ΔA= change in area

A_1 = initial length

$\Delta\theta$ = temperature difference

The new area (A_2) can be found

$$\Delta A = A_2 - A_1$$

$$\beta = \frac{A_2 - A_1}{A_1 \times \Delta\theta}$$

$$A_2 - A_1 = \beta A_1 \Delta\theta$$
$$A_2 = A_1 + \beta A_1 \Delta\theta$$
$$A_2 = A_1(1 + \beta\Delta\theta)$$

It's interesting to note that for most materials, the area expansivity is approximately twice the linear expansivity ($\beta = 2\alpha$).

Proof

Let θ represents $\Delta\theta$

$A_2 = A_1(1+ \beta\theta)$ …… (1)

Original area of sheet, $A_1 = l_1 \times b_1$

Where l_1 = original length, b_1 = original breadth

Final area after rise in temperature, $A_2 = l_2 \times b_2$

But from linear expansivity,

$l_2 = l_1(1+ \alpha\theta)$, $b_2 = b_1(1 + \alpha\theta)$

$A_2 = l_2 \times b_2 = l_1(1+ \alpha\theta) \times b_1(1+ \alpha\theta)$

$A_2 = l_1 b_1 (1+ \alpha\theta)^2$

$A_2 = l_1 b_1 [1 + 2\alpha\theta + (\alpha\theta)^2]$

$\alpha^2 \approx 0$ (since α is small)

$A_2 = l_1 b_1 [1 + 2\alpha\theta]$…….(2)

Comparing (1) and (2)

$\beta = 2\alpha$

Volume Expansion

This is about how much the **volume** (the amount of space an object takes up) changes. This applies to solids, liquids, and gases.

Volume expansion refers to the change in volume of an object due to temperature change.

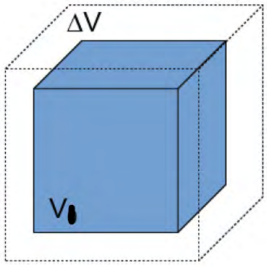


Figure 2.12: *Volumetric expansion, showing how the volume of a substance (initial volume V_1) increases by ΔV when its temperature changes. The larger (dotted outline) cube shows the expanded volume after heating*

Volume (Cubical) Expansivity (γ): describes the fractional increase in volume per unit temperature change. The formula for volume expansivity is

$$\gamma = \frac{\Delta V}{V_1 \times \Delta\theta}$$

Where

ΔV= change in volume

V_1 = initial volume

$\Delta\theta$ = temperature difference

The new volume (V_2) is calculated as

$$\Delta V = V_2 - V_1$$

$$\gamma = \frac{V_2 - V_1}{V_1 \times \Delta\theta}$$

$$V_2 - V_1 = \gamma V_1 \Delta\theta$$

$$V_2 = V_1 + \gamma V_1 \Delta\theta$$

$$V_2 = V_1(1+ \gamma \Delta\theta)$$

For most solids, the volume expansivity is approximately three times the linear expansivity ($\gamma = 3\alpha$)

Proof

Let θ represents $\Delta\theta$

$V_2 = V_1(1+ \gamma\theta)$ ..... (1)

Original volume of sheet, $V_1 = l_1 \times b_1 \times h_1$

Where l_1 = original length, b_1= original breadth, h_1 = original height

Final volume after rise in temperature, $V_2 = l_2 \times b_2 \times h_2$

But from linear expansivity,

$l_2 = l_1(1+ \alpha\theta)$, $b_2 = b_1(1+ \alpha\theta)$, $h_2 = h_1(1+ \alpha\theta)$,

$$V_2 = l_2 \times b_2 \times h_2 = l_1(1+ \alpha\theta) \times b_1(1+ \alpha\theta) \times h_1(1+ \alpha\theta)$$

$$V_2 = l_1 b_1 h_1 (1+ \alpha\theta)^3$$

$$V_2 = l_1 b_1 h_1 (1+ 3\alpha\theta + 3\alpha^2\theta^2 + \alpha^3\theta^3$$

But $\alpha^2 \approx \alpha^3 \approx 0$ (since α is small)

$V_2 = l_1 b_1 h_1 (1+ 3\alpha\theta)$..... (2)

Comparing (1) and (2)

$\gamma = 3\alpha$

Different Metals, Different Expansion Rates

Not all metals expand the same amount when heated! The **coefficient of linear expansion (α)** is different for different metals. This difference is due to their unique atomic structures and how their atoms are bonded together.

Here is a general idea of how common metals expand (from less expansion to more expansion)

Table 2.1: Some metals and their coefficient of linear expansion

Metal	Coefficient of Linear Expansion α $10^{-6}\,K^{-1}$)
Steel	11–13
Cast Iron	~10
Brass	19–21
Copper	16.5–17.5
Aluminium	22–24
Zinc	30
Lead	29–31

Metals with Low Expansion

These metals are ideal for applications where maintaining a stable size is critical, even with temperature fluctuations.

Steel and Cast Iron (10 – 13 × $10^{-6}\,K^{-1}$)

These are strong and do not expand much, making them perfect for building things that need to stay a specific size. In construction, they are used in the framework of tall buildings, bridges, and railway tracks. The low expansion rate helps these massive structures remain stable and prevents them from buckling or cracking. In cooking, cast iron pots and pans maintain their shape and size even when heated to high temperatures, ensuring they cook food evenly and last for many years.

Metals with Medium Expansion

Engineers must account for the expansion of these metals when designing products, often by including small gaps or using flexible joints.

Brass and Copper ($\alpha \approx 17 - 21 \times 10^{-6}\ K^{-1}$)

These metals expand more than steel but are excellent conductors of heat and electricity. In bimetallic strips, because brass expands more than steel, the two metals are bonded together to create bimetallic strips. These are used in thermostats to automatically turn heating and cooling systems on and off by bending with temperature changes. In plumbing, copper pipes are widely used for carrying hot water. They expand when the water is hot, which is why plumbers often use flexible connectors or leave small gaps to allow for this movement without causing leaks.

Metals with High Expansion

These metals are often chosen for applications where a large expansion is a desired or manageable effect.

1. **Aluminium and Zinc ($\alpha \approx 22 - 30 \times 10^{-6}\ K^{-1}$)**

   These metals have relatively high expansion rates. In Window Frames, Aluminium is a popular choice for window frames. Its high expansion rate means that when it gets hot, it expands more than the glass. Engineers use flexible seals and clever design to prevent the glass from breaking. In Galvanisation, Zinc is used to coat steel (a process called galvanisation) to prevent rust. The difference in expansion rates between the zinc coating and the steel is a factor that engineers must consider to ensure the coating remains intact.

2. **Lead ($\alpha \approx 29 - 31 \times 10^{-6}\ K^{-1}$)**

   Lead has one of the highest coefficients of thermal expansion among common metals. In Sealing, historically, lead was used in plumbing joints because it is soft and flexible. Its high expansion rate helped create a tight seal when heated, but it has largely been replaced due to health concerns.

Anomalous Expansion of Water

Have you ever placed a full bottle of water in the freezer and found it burst open? If not – have a go! This is a common occurrence many people experience but might not fully understand. The reason behind this surprising event is water's unique and unusual behaviour as it cools down — something known as the anomalous expansion of water.

Unlike most substances that shrink continuously as they get colder, water behaves differently below 4°C. When cooled from room temperature down to 4°C, water shrinks as expected. However, below this temperature, instead of getting denser,

it actually begins to expand. This expansion continues as it freezes into ice at 0°C, which is why ice floats on liquid water rather than sinking.

So, when you put a fully filled bottle of water in the freezer, the water expands as it freezes and needs more volume than the bottle can contain. Since the bottle is sealed and rigid, the expanding ice pushes against its walls until it bursts. This simple everyday example highlights a vital and fascinating property of water that is quite different from most other materials.

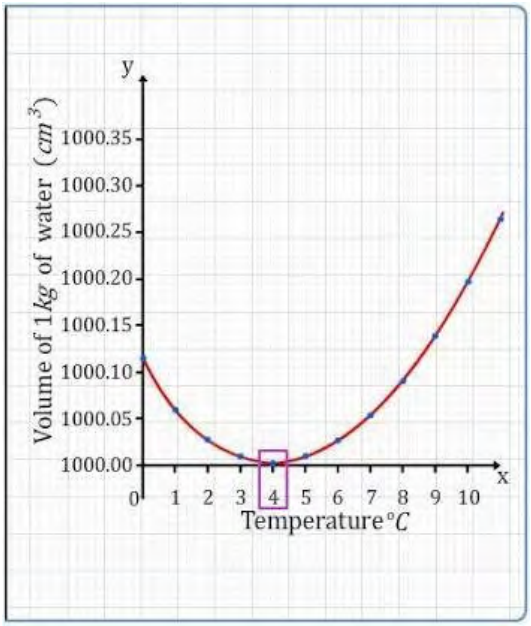


Figure 2.13: *This image represents how the volume of 1 kg of water changes with temperature near 0–10 °C, showing that water reaches its minimum volume (maximum density) at around 4 °C.*

The scientific reason for this anomaly (abnormal behaviour) lies in the molecular structure of water. Water molecules are polar and tend to form hydrogen bonds with each other. At temperatures above 4°C, water molecules move more freely and can pack closer together. But below 4°C, those hydrogen bonds arrange molecules into a more open, hexagonal lattice structure. This lattice requires more space, making the water less dense as it cools further and eventually freezes into solid ice.

This unusual property of water has profound implications for life and nature. For instance:

1. Because ice is less dense and floats, lakes, rivers, and ponds freeze from the surface downward, creating an insulating layer of ice on top of the water. This insulation prevents the water below from freezing solid, enabling fish and other aquatic organisms to survive harsh winter conditions.

2. If water behaved like most other substances and contracted upon freezing, ice would sink, causing entire bodies of water to freeze from the bottom up. This would be devastating for aquatic ecosystems and disrupt countless natural processes.



Figure 2.14: *Large iceberg floating in the ocean*

Activity 2.1 Exploring Thermal Expansion in Solids, Liquids, and Gases

Objective: Observe through videos how heat causes expansion and contraction in solids, liquids, and gases, identify real-life examples of thermal expansion, and understand the different ways each state of matter responds when heated.

What you need

1. A device with internet access (computer, tablet, or smartphone)
2. Access to these videos on YouTube
   a. Thermal Expansion and Contraction of Solids, Liquids and Gases — observe **the full video**

   b. Thermal Expansion | Some Applications Of Thermal Expansion In Everyday Life | Evergreen Publications — observe **the first 1 minute**

c. Additional video: Thermal Expansion Explained — Observe



3. Notebook or digital notes app for recording your observations and reflections
4. Pen or keyboard

What to do

1. Watch or listen to the **first video** completely. Observe how solids, liquids, and gases expand and contract when heated.
2. Take notes on examples and explanations given, including key ideas about particle movement and thermal energy causing expansion.
3. Watch or listen to the first minute of the **second video**. Note everyday examples given for thermal expansion.
4. Watch or listen to the **third video** completely.
5. Fill in the table below with information from the videos and your own understanding

State of Matter	How it Expands When Heated	Examples	Tick which of them expand the most when heated
Solid			
Liquid			
Gas			

6. Think, reflect, and discuss in pairs using the following questions
   a. Why do we provide expansion gaps in railways and bridges?
   b. How can knowledge of thermal expansion be useful in daily life?

Activity 2.2 Research & Create a Report or Poster about Bimetallic Strips

Objective: To understand what a bimetallic strip is, how it works, and where it's used, then present your findings clearly with diagrams.

What you need

1. Device with internet access (computer, tablet, or smartphone)

2. Access to reliable online resources (articles, videos, websites) for research
3. Notebook or digital document for notetaking
4. Paper, pens, markers, or digital tools for creating your report or poster
5. Drawing materials or software to create diagrams (hand-drawn or digital)

What to do

1. **Open Your Research Tool**

   Use your internet-connected device to begin your research. You can use search engines (like Google, Bing, DuckDuckGo) or educational websites.

2. **Follow the Headings**

   Conduct your research focusing on answering the questions under these specific headings. As you find information, write down key points, definitions, and facts in your notebook under each heading. Try to use your own words rather than copying word-for-word from the search results!

   a. **What is a bimetallic strip?**
      i. Search terms: "What is a bimetallic strip?", "bimetallic strip definition".
      ii. Look for information explaining what it's made of and its basic structure.

   b. **How does it work?**
      i. Search terms: "How does a bimetallic strip work?", "bimetallic strip principle", "thermal expansion bimetallic strip".
      ii. Look for explanations about how the two different metals react to heat and cold, and why it causes the strip to bend. Try to understand the concept of different rates of expansion.

   c. **Where is it used?**
      i. Search terms: "Applications of bimetallic strip", "devices using bimetallic strip", "bimetallic strip in thermostats". Find examples of everyday devices or industrial applications that use bimetallic strips.
      ii. Think about anything that controls temperature

3. **Gather Diagrams**

   As you research, look for clear diagrams of a bimetallic strip. Save images if you're working digitally or be prepared to sketch them accurately if creating a physical report.

4. Decide if you want to create a concise Brief Report or an Informative Poster.

   a. **If creating a Brief Report**

      i. On a fresh page or in a new digital document, title it: "Bimetallic Strip: An In-Depth Look."

      ii. Organise your findings under clear headings: "What is a bimetallic strip?", "How does it work?", and "Where is it used?".

      iii. Write your answers in your own words, making them clear and easy to understand.

      iv. Draw or insert at least two diagrams: one showing a bimetallic strip (labelled with the two metals) and another showing how it bends when heated. Label your diagrams!

   b. **If creating an Informative Poster**

      i. Grab your large paper/poster board or open your digital design tool.

      ii. Create an engaging title, like "Bimetallic Strip: Unveiling Its Secrets!"

      iii. Arrange your information clearly using the same headings: "What is a bimetallic strip?", "How does it work?", and "Where is it used?". Use bullet points, short paragraphs, or concise phrases.

      iv. Draw at least two large, clear, and well-labelled diagrams. Show what a bimetallic strip looks like, and crucially, how it bends when heated (and perhaps when cooled). Use colours to make your diagrams stand out!

      v. Make your poster visually appealing with neat handwriting/fonts and a good layout.

Activity 2.3 Experiment with a Bimetallic Strip or Ball-and-Ring Apparatus

Objective: Perform an experiment to observe how heating affects a bimetallic strip or a ball-and-ring apparatus.

What you need

1. **Option 1: Bimetallic Strip Experiment**
   - **a.** Bimetallic strip
   - **b.** Clamp or stand to hold the strip
   - **c.** Heat source (e.g., spirit burner, candle, or hot water)
   - **d.** Thermometer – infrared/forehead (optional)
   - **e.** Ruler (optional to measure bending)
2. **Option 2: Ball-and-Ring Apparatus**
   - **a.** Ball and ring set (metal ball that just fits through a metal ring at room temperature)
   - **b.** Heat source to heat the ball
   - **c.** Icy water to cool the ring
   - **d.** Tongs or protective gloves for handling hot metal
3. Notebook or paper to record observations
4. (Optional) Access to a video demonstrating these experiments if you do not have the materials

Caution

This experiment should be done in a small group of 3-4 people and under the guidance of a teacher. Be careful when handling heat sources and hot materials to avoid burns and accidents.

What to do

Bimetallic Strip Experiment

1. Place the bimetallic strip securely in a clamp or hold one end firmly so it can bend freely. Observe if the strip is straight at room temperature.
2. Heat one end of the strip gently with the flame or hot water, taking care not to burn yourself.
3. Watch carefully what happens to the free end of the strip as it heats. Note which direction it bends (up or down).

4. If possible (with the aid of an infrared/forehead thermometer), note the temperature after each increase or at specific time intervals and observe changes.
5. After heating, remove the heat source and let the strip cool down. Observe if and how the strip returns to its original shape.
6. Record all observations clearly, describing how the strip bends during heating and cooling.

Ball-and-Ring Apparatus

1. Check that at room temperature, the metal ball passes through the ring.
2. Heat the metal ball using a flame or hot water until it's warm (carefully handle it with tongs or gloves).
3. Try to pass the heated ball through the ring.
4. Observe if the ball fits or not and record your observations.
5. Let the ball cool down and check again if it fits through the ring.
6. Once fully cooled, repeat the experiment but this time leave the ball at room temperature and submerge the ring into icy water. Leave it for 2-3 minutes to cool and then lift it out and see if the ball still fits through it.
7. Describe what happened and why in your notes.

If You Do Not Have the Materials

If you do not have these items or cannot do the experiment, you can observe demonstration videos online. Search for terms like "bimetallic strip heating experiment" or "ball and ring thermal expansion" to find clear videos. Observe carefully and write down what is happening in the videos.

Activity 2.4 Material Expansivity Challenge

Objective: To understand how different metals expand at different rates and to discuss why this property is crucial when choosing materials for construction and engineering projects.

What you need

1. Your notebook or a digital document for recording your answers.
2. Pen or pencil.

3. Access to the internet (optional, if you want to verify or find more examples)

What to do

1. Examine the Table: Look carefully at the table below, which shows the coefficient of linear expansion (α) for several common metals. This coefficient tells you the factor by which a material expands *per degree Celsius* for each unit of its original length.

Metal	Coefficient of Linear Expansion (α) (per °C)
Steel	1.2×10^{-5}
Aluminium	2.3×10^{-5}
Copper	1.7×10^{-5}
Brass	1.9×10^{-5}
Iron	1.2×10^{-5}

2. Rank the Metals: In your notebook, list the metals from the table in order from lowest expansivity (expands the least) to highest expansivity (expands the most).
3. Now let's connect your ranking to real-world design choices. Answer these questions in your notebook
   - **a.** Bridges and Railway Tracks (Long Structures): Why is steel (or iron) often chosen for massive structures like railway tracks and long bridges, even though it still expands? What problem would arise if a metal with a very high expansivity was used for a long bridge without proper allowances for expansion?
   - **b.** Cooking Utensils (Pots and Pans): When choosing metals for the base of high-quality cooking pots and pans, engineers consider thermal expansion. Would you want a metal with very high expansivity or lower expansivity for the base of a good cooking pot? Explain your reasoning.
   - **c.** Bimetallic Strips (Smart Devices): You might recall that bimetallic strips rely on two different metals bending when heated. Looking at the table, which two metals from the list would be the best choices to create a bimetallic strip that would show the most significant bend for a given temperature change? Explain why you chose those specific two metals.

d. General Construction Advice (Accra's Climate): Imagine you are an engineer advising a company building a large metal-framed building in Accra, Ghana, where temperatures can vary significantly between hot days and cooler nights. What general advice would you give them about considering thermal expansion when selecting and installing different metal components? Why is this understanding so critical for safe and durable construction?

Activity 2.5 Calculating Thermal Expansions

Study the worked examples carefully before attempting the sample questions that follow.

Worked Example 1

A steel railway track is 10 metres long at 20 °C. If the temperature rises to 45 °C on a sunny day, what will be its new length? (The coefficient of linear expansion for steel is 1.2×10^{-5} °C^{-1})

Step 1 - Identify the Given Values

Original length (l_1) = 10 m

Initial temperature (T_i) = 20 °C

Final temperature (T_f) = 45 °C

Coefficient of linear expansion (α)= 1.2×10^{-5}

Step 2 - Introduce the formula for new length

$$l_2 = l_1(1+ \alpha \Delta \theta)$$

Step 3 - Substitute the given values and calculate

$$l_2 = 10\ (1 + 1.2 \times 10^{-5} \times (45 - 20))$$

$$l_2 = 10.003\ m$$

Worked Example 2

A rectangular aluminium roof sheet has an area of 5 m^2 at 25 °C. If the temperature of the sheet rises to 65 ∘°C under the strong sun, what will be its new area? (The coefficient of linear expansion for aluminium=2.3×10^{-5} °C^{-1}

Step 1 - Identify the Given Values

Original area (A_0) = 5 m^2

Initial temperature (T_i) = 25 °C

Final temperature (T_f) = 65 °C

Coefficient of linear expansion for aluminium (α)

Step 2 - Calculate the Coefficient of Area Expansion

$\beta = 2\alpha$

$\beta = 2 \times 2.3 \times 10^{-5}\ °C^{-1}$

$\beta = 4.6 \times 10^{-5}\ °C^{-1}$

Step 3 - Introduce the formula for new length

$A_2 = A_1(1+\beta\Delta\theta)$

Step 4 - Substitute the given values and calculate

$A_2 = 5(1 + (4.6 \times 10^{-5} \times (65 - 25))$

$A_2 = 5.0092\ m^2$

Worked Example 3

A car's steel fuel tank is filled with 50 litres of petrol at 22 °C. If the temperature of the petrol rises to 38 °C during the day, how much petrol will overflow from the tank? (Assume the tank itself does not expand significantly. The coefficient of volume expansion for petrol is $9.5 \times 10^{-4}\ °C^{-1}$)

Step-by-Step Solution

Step 1 - Identify the Given Values

Original volume of petrol (V_0) = 50 L

Initial temperature (T_i) = 22 °C

Final temperature (T_f) = 38 °C

Coefficient of volume expansion for petrol $\gamma = 9.5 \times 10^{-4}\ °C^{-1}$

Step 2 - Introduce the formula for new length

$V_2 = V_1(1+\gamma\theta)$

Step 3 - Make the change in volume the subject

$V_2 - V_1 = V_1 \gamma\theta$

Step 4 - Substitute the given values and calculate

$V_2 - V_1 = 50 \times 9.5 \times 10^{-4} \times (38 - 22))$

$V_2 - V_1 = 0.76\ L$

Practice Problems

Now, using the worked example as a guide, solve the following problems individually or in groups.

1. An overhead copper power cable is 500 metres long on a cool Harmattan morning at 15 ∘C. If the temperature in the afternoon rises to 35 °C, by how much does the cable's length increase? (*linear expansitivity of copper* = 1.7×10^{-5} $°C^{-1}$)
2. A square glass window pane (made of ordinary glass) has sides of 1.5 metres at 20 ∘C. What will its area be if the temperature drops to 0∘C on a cold night? (Note: expansion can also be contraction!) (*linear expansitivity of copper of glass* = 3.3×10^{-6} $°C^{-1}$)

Activity 2.6 Revision on Thermometric Substances, Thermometers & Expansivities

Objective: Refresh your understanding of thermometric substances and their characteristics, features and uses of different types of thermometers, and the concepts of linear, area, and volume expansivities including how to calculate them.

What you need

1. Notebook or paper and pen/pencil

2. Calculator (optional)

3. Access to previously learned notes or resources for reference (if needed)

What to do

1. Write brief explanations for these topics

- **a.** What is a thermometric substance?
- **b.** Characteristics of common thermometric substances.

c. Features and uses of different types of thermometers (e.g., mercury, alcohol, gas thermometers).

2 Write what you remember about

a. Linear expansivity

b. Area expansivity

c. Volume expansivity

3. Using data or examples from your notes or studies, calculate at least one of each kind of expansivity (linear, area, volume) for metals or other materials you know.

4. Answer these questions in your own words

a. Why would you choose one thermometric substance over another in making a thermometer?

b. How are linear, area, and volume expansions related?

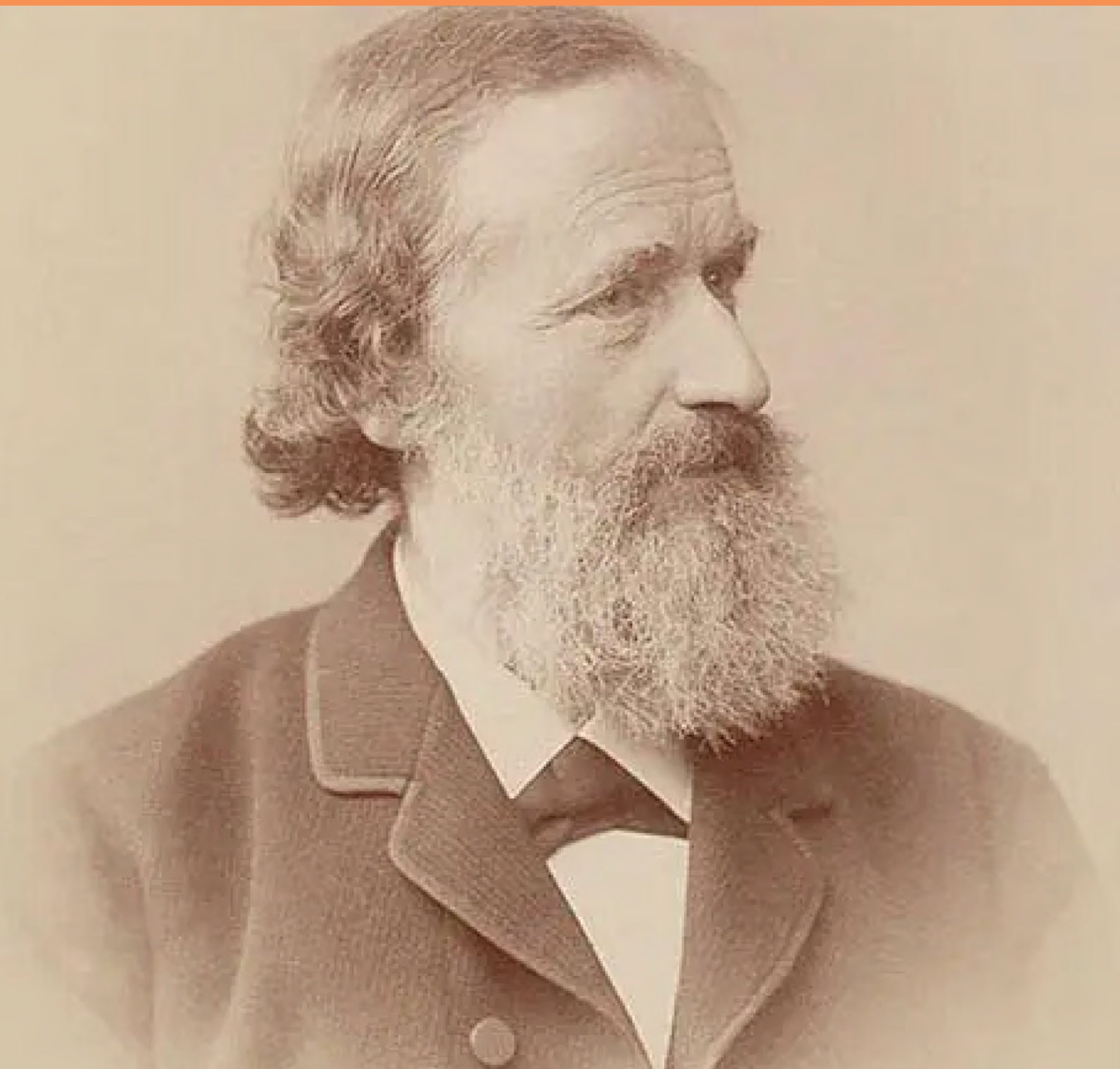
c. Why is understanding expansivity important in real-world applications like engineering or construction?

REVIEW QUESTIONS

1. A farmer stores petrol in a sealed steel tank during the Harmattan season when temperatures are around 15 °C. Explain what precautions should be taken when the temperature rises to 40 °C, considering the expansion of both the tank and the petrol (you may wish to research these coefficients of expansion).
2. Two cooking pots are made of different metals: aluminium and stainless steel. Both are used in the same kitchen environment. Compare and justify which pot will be more durable against thermal fatigue when used repeatedly for cooking and cooling.
3. A bimetallic thermostat uses brass and steel strips bonded together. Explain why these metals are chosen and predict what would happen if two metals with very similar expansion rates were used instead.
4. A steel railway track is 30 m long at 15 °C. The maximum temperature in the region can rise to 45 °C.
   a. Calculate the increase in length of the track. (Coefficient of linear expansion for steel, $\alpha = 1.2 \times 10^{-5}\ °C^{-1}$)
   b. Suggest why engineers allow expansion gaps between rails and calculate the minimum gap required if two consecutive rails are joined end to end.

SECTION

3 ELECTRIC CIRCUITS, RESISTANCE, AND KIRCHHOFF'S LAWS



DIRECT CURRENT

INTRODUCTION

This section introduces you to the foundational concepts of direct current (DC) circuits. It begins with an exploration of key electrical terms—current, voltage (potential difference), resistance, and electromotive force (EMF)—and their interrelationships using Ohm's Law. You will be guided through the identification and behaviour of ohmic and non-ohmic conductors, and how to construct and analyse circuits using resistors in series and parallel. The section further examines the structure and function of fixed and variable resistors, including potentiometers and rheostats, and their applications. It culminates in an in-depth study of Kirchhoff's Current and Voltage Laws and how these are used to determine unknown quantities in complex networks. You will also explore how galvanometers are adapted into ammeters and voltmeters. Prior knowledge from earlier years on charge, electric fields, and magnetic effects of currents is linked to deeper understanding.

KEY IDEAS

- **Circuit Analysis Using Kirchhoff's Laws**: Application of Kirchhoff's Current and Voltage Laws to determine currents and potential differences in complex electrical networks.
- **Direct Current (DC) Circuit Fundamentals**: Exploration of current, voltage, EMF, resistance, and their relationships using Ohm's Law.
- **Galvanometers and Their Adaptations**: Understanding how galvanometers are converted into ammeters and voltmeters using shunt and multiplier resistors.
- **Ohmic and Non-Ohmic Conductors**: Identification of materials that obey Ohm's Law versus those whose resistance varies with voltage or temperature.
- **Resistor Types and Applications**: Description of fixed and variable resistors, their classification, and their practical uses in controlling current and voltage.
- **Resistors in Series and Parallel**: Analysis of how different resistor arrangements affect total resistance, current distribution, and voltage drops in circuits.

ELECTRIC CIRCUITS AND OHM'S LAW

Understanding Electricity: The Basics

Welcome to the exciting world of electricity! You encounter electricity every day – it powers our homes, phones, and countless devices that make modern life possible. But what exactly is it, and how does it work? At its core, electricity is all about the movement of tiny particles called **electrons**. Imagine them like incredibly small, energetic dancers moving through a wire. When these electrons have a net movement, we have an electric current.

Electric Circuits

An electric circuit is a complete path that electric charges move through. An example is the wiring/connections in your room that makes it possible for your light and fan to work. For the charges to flow continuously, the path must be closed, meaning there are no breaks in it. A **simple circuit** is the most basic setup that allows electricity to flow. It consists of three important components:

1. **A Power Source (e.g., Battery)**: This provides the Electromotive Force (EMF) or the "push" (voltage) to get the electrons moving.
2. **Conductors (e.g., Wires)**: These are materials that allow electrons to flow easily, providing the path.
3. **A Load (e.g., Light Bulb, Resistor)**: This is the device that uses the electrical energy and offers resistance to the flow.

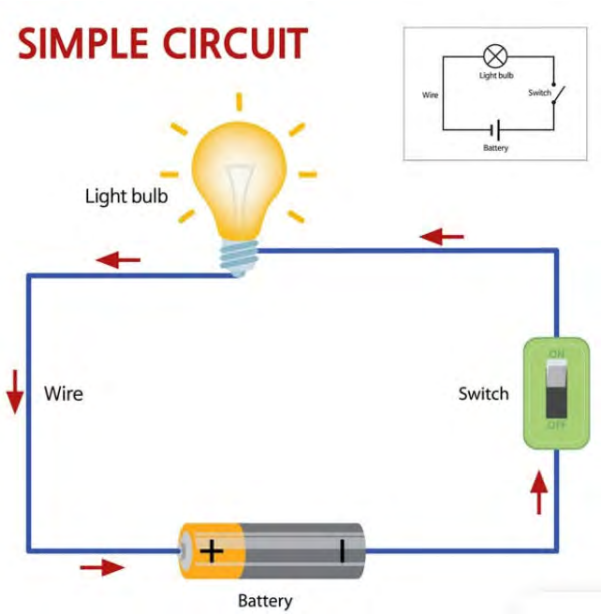


Figure 3.1: *Simple Circuit*

Key Terminologies of Circuitry

To understand how electricity works in our devices, we need to learn some important terms related to **circuits**.

1. **Current (I)**

   Electric current is the time rate of flow of electric charge past a point. *Think of it as how many electrons are passing a certain spot in a wire every second.*

   $I = \frac{q}{t}$

   Where q is electric charge in Coulombs (C), t is time in seconds (s).

   Current is also measured in Amperes (A)

2. **Potential difference**

   It is defined as the work done to move a unit charge between two points in a circuit. *Commonly known as voltage, is the electrical "push" that makes electrons move from one point to another, just like water pressure that drives water through pipes.*

   $V = \frac{W}{q}$

   Where W is the work done in Joules (J), q is the charge in Coulombs (C) and V is the potential difference in Volts (V).

   Potential difference is what makes current flow through circuit elements such as resistors or bulbs, causing energy to be used up or transformed. Its unit is volt (V).

3. **Electromotive Force (EMF)**

   It is the total energy supplied by a source (like a battery or generator) per unit of charge to drive the charge around a complete circuit. It's the *cause* of the potential difference that drives the current. While closely related to voltage, EMF specifically refers to the energy provided *by the source* before any energy is lost within the source itself.

   EMF is the maximum potential difference the source can provide when no current flows (open circuit). It corresponds to the source's capability to convert other forms of energy (chemical, mechanical) into electrical energy.

   When current flows in a circuit, the voltage or potential difference measured across the terminals of the source (called the **terminal voltage or terminal potential difference)** is usually less than its EMF. This is due to internal resistance of the source (energy lost inside the source).

Hence,

$E = V + Ir$

where

E = EMF,

V= terminal potential difference,

I= current,

r= internal resistance of the source.

Ir is known as the 'lost voltage'

If there is no current (I=0), then V=E

Difference Between Electromotive Force and Potential Difference

Electromotive Force (EMF)	Potential Difference (p.d.)
Energy supplied per unit charge by the power source	Energy transferred per unit charge between two points
Across terminals of the power source when no current flows	Across any two points/ components in the circuit
Includes energy lost inside the source	Excludes internal energy losses, shows energy used by components
Generally constant for a given source	Varies depending on load and circuit conditions
Related to energy provided by sources (battery, generator)	Related to energy used by components (e.g., bulbs, resistors)
Drives the current by supplying energy	Causes energy to be transformed within the circuit

4. Resistance (R)

Electrical resistance is the opposition to the flow of electric current. *Imagine it as something that tries to slow down those flowing electrons.* Its unit is ohms (Ω).

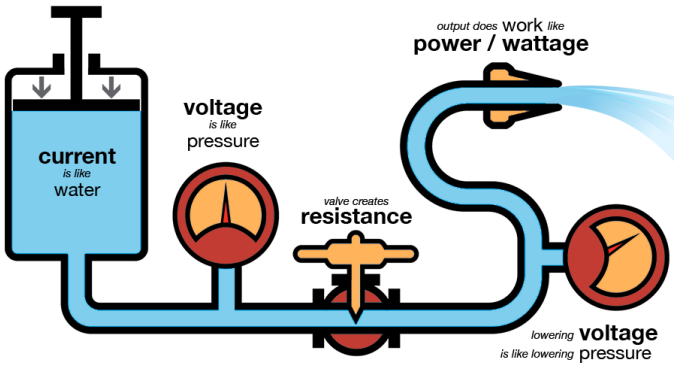


Figure 3.2: *Water Flow Analogy for understanding key terminologies of circuitry*

We can easily understand the concepts of electricity by imagining a system of water flowing through pipes. In this simple analogy, the tiny **electrons** that make up electric **current** are like the **water molecules**, and the **wires** they travel through are the **pipes**. The **Electromotive Force (EMF)** from a power source, such as a battery, acts as the **water pump** that initiates the flow. This initial push creates the electrical **pressure**, or **voltage**, that drives the current. The opposition to this flow is called **resistance**, which is analogous to a **valve** that restricts the water's path and causes a drop in pressure (voltage) across it. Finally, the useful **work** performed by the system, like a water jet spraying from a nozzle, represents electrical **power**, or **wattage**, which is the energy delivered by the electrical current.

Ohm's Law

Now that we understand what voltage, current, and resistance are, let us talk about **Ohm's Law**. This is a fundamental rule in electricity that tells us exactly how these three things are related to each other. It's named after German physicist Georg Simon Ohm, who published his findings in 1827. This law is crucial for understanding how electrical components interact and for designing and analysing virtually any electronic circuit.

Ohm's Law states that the current passing through a metallic conductor or wire is directly proportional to the potential difference across its ends provided the temperature and other physical conditions remain constant.

This fundamental relationship can be expressed by the following mathematical formula:

$$V \propto I$$

$$V = IR$$

Where:

V = Voltage (measured in Volts, V)

I = Current (measured in Amperes, A)

R = Resistance (measured in Ohms, Ω)

Understanding the Proportionalities

1. **Direct Proportionality between Voltage and Current (for fixed Resistance)**
   a. If you increase the voltage across a bulb, the current flowing through it will increase proportionally, assuming the resistance remains constant.
   b. *Example*: If a 10 Ohm bulb has 5 Volts across it, it draws 0.5 Amps. If the voltage is doubled to 10 Volts (and resistance stays 10 Ohms), the current also doubles to 1 Amp.
2. **Inverse Proportionality between Current and Resistance (for fixed Voltage)**
   a. If you increase the resistance in a circuit while keeping the voltage constant, the current flowing through the circuit will decrease. Conversely, if you decrease the resistance, the current will increase. Where there is less resistance, more electrons move.
   b. *Example*: With a constant 12 Volt battery, a 6 Ohm resistor will draw 2 Amps. If you replace it with a 12 Ohm resistor, the current will halve to 1 Amp.

It is important to note that Ohm's Law applies directly to **ohmic materials** (like most metals and resistors), where resistance remains constant regardless of the applied voltage. However, for **non-ohmic materials** (like diodes or transistors), the resistance can change with voltage or current, and Ohm's Law is still used, but the resistance value is considered dynamic.

Ohmic Conductors

An **ohmic conductor** is a material or component that strictly obeys Ohm's Law. This means that its electrical resistance (R) remains constant over a wide range of applied voltages and corresponding currents, provided that physical conditions like temperature do not change significantly.

Characteristics

1. **Linear V-I Characteristic**

   When a graph of voltage (V) versus current (I) is plotted for an ohmic conductor, it results in a straight line passing through the origin. The slope of this V-I graph is constant and represents the resistance (R) of the conductor ($R = \frac{\Delta V}{\Delta I} = slope$). Note that conventionally these axes are drawn the other way around, meaning that the gradient of the graph actually represents the inverse of the resistance.

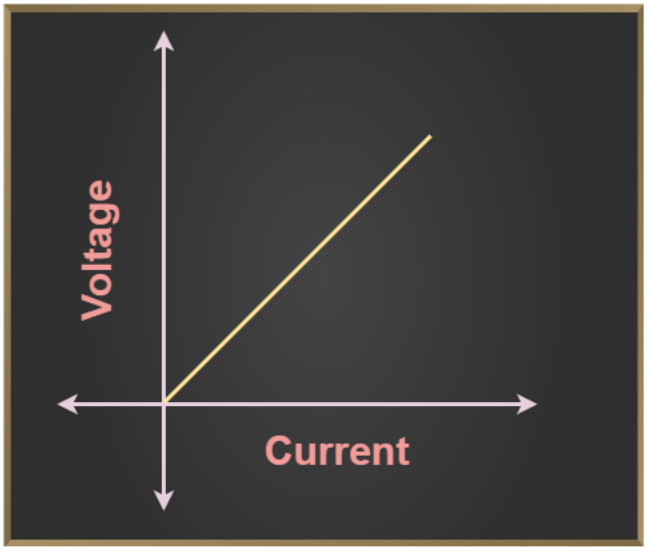


Figure 3.3: *A graph illustrating Ohm's law*

2. **Constant Resistance**

   The resistance value of an ohmic conductor does not change with variations in the applied voltage or the current flowing through it.

3. **Temperature Dependence (Implicit)**

   While ohmic conductors maintain constant resistance under *constant* physical conditions, their resistance can still change if the temperature changes. For most metals, resistance increases with increasing temperature. However, within a limited operating temperature range, they are considered ohmic.

Examples of Ohmic Conductors

1. Most metallic conductors: Copper wires, aluminium wires, silver, gold.
2. Fixed Resistors: Standard carbon-composition resistors or wire-wound resistors, designed to have a specific, constant resistance value.
3. Heating elements (at constant temperature): The resistance of the filament in a toaster or kettle can be considered ohmic *if its temperature is kept constant*.

However, in typical operation, as they heat up, their resistance changes, making them behave non-ohmically over a wide range of operation. For introductory purposes, they are often used as simple ohmic examples within a narrow temperature range.

Non-Ohmic Conductors

A **non-ohmic conductor** is a material or component that does *not* obey Ohm's Law. For these materials, the electrical resistance changes with variations in the applied voltage, the current flowing through them, or other external factors like temperature or light intensity.

Characteristics

1. **Non-linear V-I Characteristic**

   When a graph of voltage (V) versus current (I) is plotted for a non-ohmic conductor, it results in a curve, not a straight line. This indicates that the ratio V/I (which is effectively the resistance) is not constant and changes depending on the operating point.

2. **Variable Resistance**

   The "resistance" of a non-ohmic conductor is not a fixed value but rather a dynamic quantity that varies with the operating conditions. This varying resistance is sometimes referred to as dynamic or differential resistance.

3. **Sensitivity to External Factors**

   Many non-ohmic devices are specifically designed to have their resistance change based on external stimuli (like temperature, light, pressure or applied voltage), which makes them useful for various electronic applications.

Examples of Non-Ohmic Conductors

1. **Semiconductor Devices**
   a. Diodes: These devices allow current to flow easily in one direction (forward bias) after a certain "threshold" voltage is reached, and barely at all in the opposite direction (reverse bias). Their V-I graph is highly non-linear.
   b. Transistors: Fundamental components for amplification and switching, their resistance is controlled by an input signal, leading to highly non-linear behaviour.

2. **Incandescent Light Bulb Filaments**

   As current flows through the tungsten filament, it heats up significantly. The resistance of tungsten increases dramatically with temperature, so as the voltage increases, the filament gets hotter, its resistance increases, and the current does not increase proportionally (it increases less rapidly than predicted by Ohm's Law with a fixed resistance). This makes them non-ohmic over their full operating range.

3. **Thermistors**

   These are resistors whose resistance changes significantly with temperature. They are used as temperature sensors.

4. **Varistors (Voltage-Dependent Resistors, VDRs)**

   Their resistance changes with the applied voltage, typically decreasing as voltage increases. They are used for surge protection.

5. **Gas Discharge Lamps**

   (E.g., neon lamps, fluorescent lamps) require a high voltage to ionise the gas, after which their resistance drops sharply, leading to a non-linear V-I characteristic.

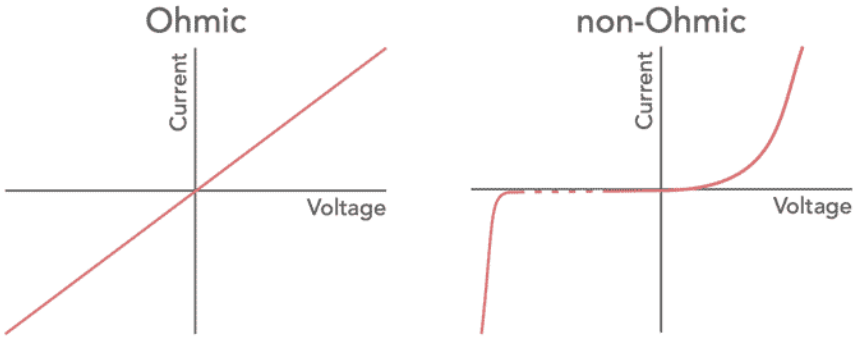


Figure 3.4: *Current-voltage characteristics of Ohmic conductor (left) and an example of a non-ohmic (right) conductor. The component characteristics shown in this particular example (left) are for a diode.*

Electrical Symbols for Circuit Diagrams

Circuit diagrams are like blueprints for electrical and electronic circuits. Instead of using words or pictures, they use a universal set of standardised symbols to represent different components and their connections. Learning these symbols is essential for anyone who wants to understand, design, or troubleshoot electrical circuits. Think of electrical symbols as the "alphabet" or "vocabulary" of circuit diagrams. Just like you need to know letters to read a book, you need to know these symbols to "read" a circuit diagram.

Below are some of the most fundamental and frequently encountered electrical symbols you'll see in circuit diagrams. Have a go at drawing a circuit diagram for a battery powered torch. Compare your drawing with your neighbour.

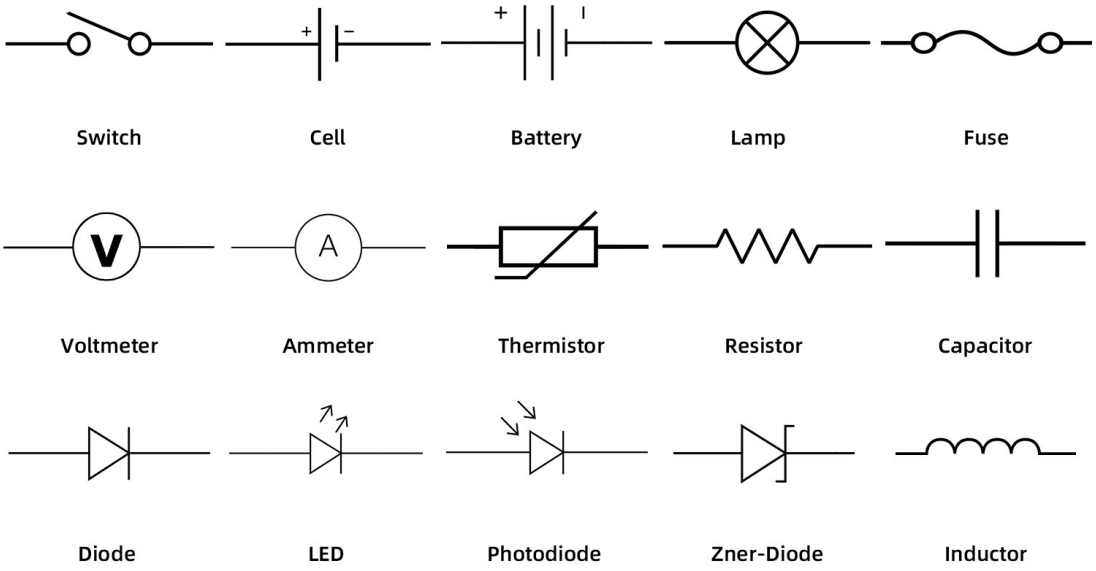


Figure 3.5: *Common electrical circuit symbols and their components*

Activity 3.1 Researching and Connecting Key Electrical Terms

Objective: To enhance understanding of key electrical terms by engaging in collaborative research, peer teaching, and visual mapping.

What you need

1. Access to internet for online research
2. Notebook or digital document for notes
3. Pen or pencil
4. Large paper for drawing a concept map, or a computer/digital whiteboard app

What to do

1. Choose one or more friends to work with. Form a small group (ideally 2–4 learners).
2. As a group, list these electrical terms:
   a. Current
   b. Resistance
   c. Potential Difference (Voltage)

   d. Electromotive Force (EMF)
   e. Power
   f. Energy

3. Divide the terms so each person researches at least one term.
4. For your assigned term, research and find out:
   a. What does it mean? (Definition)
   b. What is its scientific symbol?
   c. What is its standard unit (and symbol)?
   d. Where is it used? Give a real example in an electrical circuit or daily device.
5. Together, organise your notes clearly. Get ready to explain your term(s) to others briefly and clearly. Practice if you want.
6. Each group presents their findings to one other group. Listen carefully to other groups and take notes.
7. After all presentations, join with everyone to create a concept map showing how the terms connect.
   a. Write each term on a large sheet or digital board.
   b. Draw arrows to link related terms.
   c. Add short notes or formulas on the arrows to explain the relationships (e.g., "Power = Voltage × Current").
   d. Include examples to make connections clearer.

Activity 3.2 Match Electrical Terms with their Symbols, Units & Definitions

Objective: Test your understanding of voltage, current, resistance, and power by matching each term with its correct definition, symbol, unit, and exploring how they are related.

What you need

1. Pen or pencil
2. Notebook or blank paper
3. (Optional) Cut out printed tables as cards for matching or use sticky notes

What to do

1. Review the Four Tables Below

Table 3.1: Electrical Terms
1. Voltage
2. Current
3. Resistance
4. Power

Table 3.2: Symbols
A. I
B. R
C. P
D. V

Table 3.3: Units
a. Watt (W)
b. Ampere (A)
c. Volt (V)
d. Ohm (Ω)

Table 3.4: Definitions and Relationships
i. The flow of electric charge through a circuit; affected by voltage and resistance.
ii. The potential energy difference per unit charge between two points in a circuit.
iii. The property that opposes or limits the flow of electric current in a circuit.
iv. The rate at which electrical energy is converted into other forms like heat or light.
v. Increasing resistance decreases current if voltage stays constant.
vi. Equals voltage multiplied by current (= V × I).

2. Create a 4-column table in your notebook with these headers:

| Term | Symbol | Unit | Definition/Relationship |

3. Fill in your answers by matching the items from Tables 1-4. Use the numbered, lettered, and letter/roman-numeral codes to help keep track.

4. Under your completed table, write short sentences describing how these terms relate, for example: Increasing resistance (iii) causes current (i) to decrease if voltage stays constant (v).

5. Use your matching table to quiz yourself or a friend. Try to explain in your own words how the electrical terms connect and what happens in a circuit if one changes.

Activity 3.3 Using the PhET Circuit Construction Kit to Explore Voltage, Resistance, and Current

Objective: Use the PhET Circuit Construction Kit (DC) simulation to build circuits where you manipulate voltage and resistance independently and together. Observe and explain how current changes using the formula $I = \frac{V}{R}$.

What you need

1. Access to the simulation here: PhET Circuit Construction Kit: DC



2. Notebook or digital document for recording your data and observations
3. Pen or keyboard

What to do

1. Go to the PhET simulation link above. Click "Intro" or "Start" to open the workspace where you can build circuits.
2. **Set Up Your First Circuit: Constant Resistance, Varying Voltage**
   - **a.** Drag a battery onto the workspace and set a starting voltage (e.g., 3 V).
   - **b.** Place a resistor with a fixed resistance value (e.g., 10 Ω).
   - **c.** Connect a wire to complete a simple circuit including an ammeter to measure current.
   - **d.** Record the current reading (you can choose any point on the wire/components to measure the current).
   - **e.** Gradually increase voltage (e.g., 3 V, 5 V, 7 V, 9 V) by clicking the battery and adjusting the voltage slider.
   - **f.** For each voltage, record the current displayed by the noncontact ammeter.
   - **g.** Note how current changes with voltage when resistance is constant.

3. **Set Up Your Second Circuit: Constant Voltage, Varying Resistance**
   - **a.** Fix the battery voltage (e.g., 9 V).
   - **b.** Change the resistor's resistance to different values (e.g., 5 Ω, 10 Ω, 20 Ω, 40 Ω) by clicking on the resistor and adjusting it.
   - **c.** Record the current for each resistance value.
   - **d.** Observe how current changes as resistance increases with voltage constant.
4. **Set Up Your Third Circuit: Vary Both Voltage and Resistance**
   - **a.** Try different combinations by changing voltage and resistance together.
   - **b.** For example, increase voltage and decrease resistance, or vice versa.
   - **c.** Record current readings for at least 4 different voltage-resistance pairs.
   - **d.** Look for patterns in how current changes with both variables changing.
5. Create a table in your notebook with columns: Voltage (V), Resistance (Ω), Current (A), and your observations.
6. **Analyse Your Results**

   Using the formula, explain
   - **a.** How does current change when you increase voltage but keep resistance the same?
   - **b.** How does current change when you increase resistance but keep voltage the same?
   - **c.** What happens to current when you change both voltage and resistance?
7. Write a short paragraph describing how voltage and resistance affect current in a circuit based on your observations from the simulation.

Activity 3.4 Testing Electronic Components and Plotting V–I Graphs to Identify Ohmic and Non-Ohmic Behaviour

Objective: Use a circuit to measure the voltage across and the current through different components (such as resistors, bulbs, and diodes). Plot voltage-current

(V–I) graphs to determine which components obey Ohm's Law (ohmic) and which do not (non-ohmic) and explain the differences in their behaviour.

What you need

1. Power supply (variable voltage)
2. Resistors of different values
3. Filament bulbs
4. Diodes
5. Connecting wires and switch
6. Ammeter (to measure current)
7. Voltmeter (to measure voltage)
8. Rheostat or variable resistor (to change circuit voltage or current)
9. Breadboard or circuit board (optional)
10. Graph paper or software for plotting graphs
11. Notebook and pen for recording data

What to do

1. Connect the power supply, ammeter, variable resistor/rheostat and the component to be tested (resistor, bulb, or diode) in series as shown in the typical circuit diagram for V–I characteristics. Ensure that a voltmeter is connected in parallel across the component.
2. **Measure Voltage and Current**
   - **a.** Close the switch and start with the power supply at a low voltage.
   - **b.** Record the voltage across the component from the voltmeter and the current through it from the ammeter.
   - **c.** Gradually increase the voltage in small steps (e.g., 0.5 V increments), recording multiple pairs of voltage and current readings (aim for 5–6 readings).
   - **d.** Take multiple readings at each step and average the current to improve accuracy.
   - **e.** For diodes, keep the supply voltage very small and increase by 0.1V at a time if possible. Also, reverse the polarity of the power supply to observe the behaviour in reverse bias.

3. **Repeat for Each Component**
   - **a.** Replace the resistor with the filament bulb and repeat the measurements.
   - **b.** Then test the diode similarly (with care to record forward and reverse bias behaviour).
4. **Plot V–I Graphs**
   - **a.** For each component, plot a graph of voltage (V) on the x-axis and current (I) on the y-axis using your recorded data.
   - **b.** Draw smooth curves or straight lines depending on the shape of your data.
5. **Analyse Your Graphs**
   - **a.** Identify which graph is a straight line passing through the origin – this indicates ohmic behaviour (component obeys Ohm's Law with constant resistance).
   - **b.** Identify which graphs are curved or non-linear – these indicate **non-ohmic behaviour**, where resistance varies with voltage or current.
6. **Safety Reminder**
   - **a.** Work carefully with electrical equipment.
   - **b.** Do not exceed voltage ratings of components to avoid damage.
   - **c.** Switch off power supply when changing components or wiring.

Summary Table for Recording (one per component)

Voltage (V)	Current (A) Repeat 1	Current (A) Repeat 2	Current (A) Repeat 3	Current (A) Average
(Add rows as needed)				

Activity 3.5 - Choosing Efficient Lighting for a Solar-Powered Community Library

Objective: Solve a real-world problem by comparing different bulbs to find lighting that uses the 12V solar battery efficiently. Calculate current for each bulb using Ohm's Law, test bulb brightness in a circuit (physical or simulated), and justify your choice using both calculations and observations.

What you need

1. Calculator
2. Notebook or paper for recording data and calculations
3. Pen or pencil
4. Access to a circuit simulation tool (e.g., PhET Circuit Construction Kit) **or** physical components:
   - **a.** 12V power supply (or 12V battery/simulation)
   - **b.** Several bulbs or LEDs with known voltage and resistance ratings
   - **c.** Connecting wires and switch
   - **d.** Ammeter and voltmeter (for physical circuit) or built-in meters in simulation

What to do

1. **Understand the Problem**

   Imagine your community library runs on a 12V solar battery. The lighting should provide enough brightness but also preserve battery life by not drawing excessive current.

2. **Collect Bulb Data**

   For each bulb, note the following (from product specs or simulation settings):
   - **a.** Rated voltage (should be near 12V)
   - **b.** Resistance (if given) or power rating (Watts)

3. **Calculate Current Using Ohm's Law**

   For each bulb, calculate the current drawn when connected to the 12V battery. Use the formula: $I = \frac{V}{R}$ where V=12V and R is bulb resistance.

4. **Set Up the Circuit or Simulation**
   - **a.** Using a physical circuit or a circuit simulator, build a simple circuit with the 12V source and one bulb.
   - **b.** Connect the bulb and measure the current flowing through it (or observe the simulated current).
   - **c.** Observe the brightness of the bulb.

5. **Test All Bulbs**
   - **a.** Repeat the circuit or simulation setup for each bulb.

b. For each, record:

i. The measured/calculated current

ii. Your observation about bulb brightness

6. Compare Results

a. Make a table listing bulbs, their calculated currents, observed brightness, and your notes.

b. Consider which bulbs draw less current but still provide adequate brightness.

7. Choose the Best Bulb

a. Based on your calculations and observations, decide which bulb best balances brightness and battery life.

b. Write a short explanation justifying your choice using numbers (current values) and your brightness observations.

c. Answer the question: What affects the brightness of a bulb in a circuit?

Example Table to Fill

Bulb Type/ Model	Resistance (Ω)	Calculated/ Measured Current (A)	Observed Brightness	Notes/ Recommendation
Bulb A				
Bulb B				
Bulb C				

Activity 3.6 Applying Ohm's Law to Calculate Current and Resistance

Study the worked example below carefully before attempting the example questions that follow.

Worked Example 1

An electric heater is connected to a 240 V power supply. If the heating element has a resistance of 20 Ω, how much current flows through the heater?

Solution

Step 1 - Identify the knowns and unknowns

Voltage (V) = 240 V

Resistance (R) = 20 Ω

Current (I) =? (unknown)

Step 2 - Introduce the appropriate formula

$I = \frac{V}{R}$

Step 3 - Substitute the values and calculate

$I = \frac{240}{20}$

$I = 12\ A$

Practice Problems

Now, using the worked example as a guide, solve the following problems individually or in groups.

1. An electric fan is operating on a 220 V supply. If the motor has a resistance of 110 Ω, how much current does the fan draw?
2. A smartphone charger outputs 5 V and provides a current of 2 A to your phone. What is the equivalent resistance of your phone's charging circuit at that moment?

RESISTORS, VARIABLE RESISTORS, AND THEIR APPLICATIONS IN CIRCUITS

Resistors

What is a Resistor?

In any electrical circuit, all components, including the wires, offer some resistance to the flow of electrons. This inherent resistance is often undesirable, as it can lead to energy loss. However, there are many cases where we need a specific, controlled amount of resistance in a circuit to limit the current. This is where a resistor comes in.

A resistor is a dedicated component engineered to provide a precise amount of resistance, ensuring that the current is reduced to a desired level for a particular part of the circuit.

In simpler terms, it is a passive two-terminal electrical component device that **opposes the flow of electric current**.

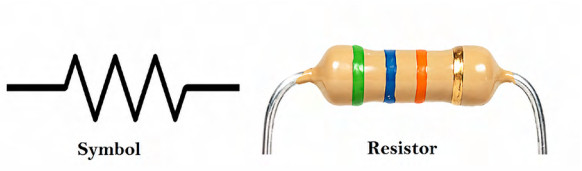


Figure 3.6: *A resistor (right) and its circuit symbol (left)*

Why Do We Use Resistors?

Resistors cannot be ignored in electronics and are used for a variety of crucial functions:

1. Current Limiting: One of the most common uses is to protect sensitive components (like LEDs or integrated circuits) from excessive current that could otherwise damage them. By adding a resistor in series, you can control the current flowing through that part of the circuit.
2. Voltage Division: Resistors can be arranged to create specific voltage levels from a higher supply voltage. This is achieved by placing two or more resistors in series, where the voltage drops across each resistor are proportional to their resistance values.
3. Biasing Components: In circuits with transistors or other active components, resistors are used to set the correct operating conditions (bias points) for optimal performance.
4. Pull-up/Pull-down Resistors: In digital circuits, these resistors are used to ensure that a digital input has a defined state (either high or low) when no other signal is applied, preventing "floating" inputs that can lead to unpredictable behaviour.
5. Signal Conditioning: Resistors are used in filters, timing circuits, and other signal processing applications to shape or modify electrical signals.

Types of Resistors

Resistors come in many forms, each suited for different applications based on their construction, precision, and power handling capabilities:

Resistors are mainly classified into two broad types: **linear resistors** and **non-linear resistors**.

Linear Resistors

These resistors have a resistance value that largely remains constant or changes predictably with applied voltage and temperature. They generate a voltage drop proportional to the current passing through them. Linear resistors are further divided into:

1. Fixed Resistors: These have a set resistance value that does not change.
2. Variable Resistors: These resistors allow their resistance value to be adjusted.
    i. Potentiometers: These are three-terminal devices that function as adjustable voltage dividers. They are commonly used for volume control in audio equipment, brightness control for lights, or as input sensors for microcontrollers where a variable voltage is needed.
    ii. Rheostats: Typically, two-terminal devices (or potentiometers used with only two terminals), rheostats are primarily used to control current in a circuit. They are often found in higher power applications.

Non-Linear Resistors

Their resistance varies non-linearly with voltage, temperature, or other factors. Key types include:

1. Thermistors: Their resistance changes significantly with temperature. They are widely used as temperature sensors (NTC thermistors decrease resistance with increasing temperature, PTC thermistors increase).
2. Photoresistors (LDRs - Light Dependent Resistors): Their resistance decreases as the intensity of light falling on them increases. They are used in light-sensing applications, like automatic streetlights or light meters.
3. Varistors (Voltage Dependent Resistors - VDRs): Their resistance changes with the applied voltage, typically decreasing sharply at a certain voltage. They are primarily used for surge protection, diverting excess voltage away from sensitive components.

Resistor Colour Code

The **resistor colour code** is a system that uses coloured bands painted on the resistor body to indicate its resistance value, tolerance, and sometimes reliability or temperature coefficient. This system allows you to quickly determine resistor specifications without reading numerical labels.

Here is how it works

1. Each colour represents a specific digit, multiplier, or tolerance value based on an international standard (IEC 60062).
2. The colour bands are read from one end, typically starting closest to a band that is spaced farther apart or a tolerance band.
3. Commonly, resistors have 4 or 5 colour bands:
    a. In a **4-band resistor**, the first two bands represent the significant digits, the third band is the multiplier (power of ten), and the fourth band indicates tolerance (how much the actual resistance may vary).
    b. In a **5-band resistor**, the first three bands are significant digits, the fourth is the multiplier, and the fifth is the tolerance, allowing more precise values.

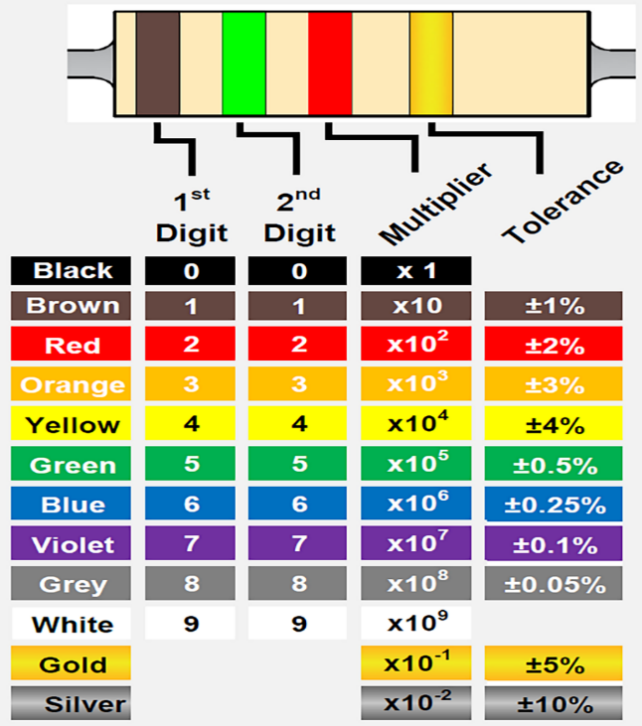


Figure 3.8: *Resistor colour code chart*

To Read a Resistor Colour Code

1. Identify the tolerance band (gold, silver, or none), usually spaced apart or at one end.
2. Read bands from the opposite end towards the tolerance band.
3. Convert the first two or three bands into digits.
4. Apply the multiplier from the next band.
5. Note the tolerance from the last band.

Resistors in series and parallel

In electrical circuits, how resistors are connected drastically affects the total resistance and how current flows through the circuit. Two fundamental ways to connect resistors are in series and in parallel, each influencing voltage, current, and resistance differently.

Resistors in Series

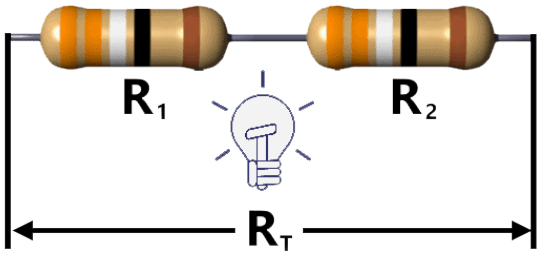


Figure 3.9: *Two resistors in series*

When resistors are connected end-to-end, one after the other, they form a **series circuit**. This simply means the electrons making up the current will enter the resistors one after the other (serially), from first to the last. In this arrangement, the electric current has only one path to follow. Because of this, the same current flows through each resistor without changing. This is an important point: current is constant through resistors connected in series. However, the voltage across each resistor in the series varies depending on its resistance. The total voltage supplied by the power source is divided among the resistors. The voltage drop across each resistor can be different, depending on how much each resistor resists the current.

To find the total resistance of resistors in series, simply add their resistance values:

$$R_{total} = R_1 + R_2 + R_3 + \ldots R_n$$

This means that the total resistance increases as more resistors are added in series

Proof

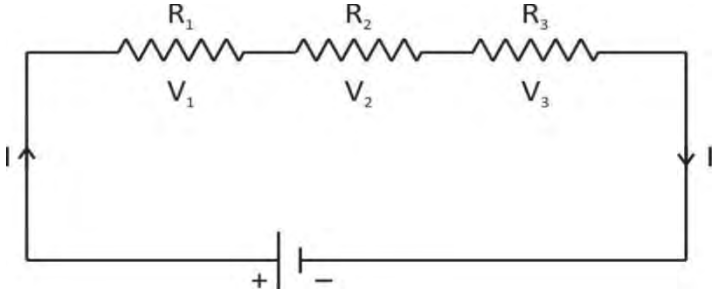


Figure 3.10: *Circuit diagram of three resistors connected in series*

Let us consider three resistors, R_1, R_2 and R_3, in series with a voltage source V. Current I flows through both.

From Ohm's law,

$$V = IR_{total}$$

Voltage across each resistor

Voltage across R_1 $\quad V_1 = IR_1$

Voltage across R_2 $\quad V_2 = IR_2$

Voltage across R_3 $\quad V_3 = IR_3$

Total voltage supply $\quad V = V_1 + V_2 + V_3$

By substitution

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

$$IR_{total} = I(R_1 + R_2 + R_3)$$

Divide both sides by I

$$R_{total} = R_1 + R_2 + R_3$$

This can be extended to any number of resistors in series:

$$R_{total} = R_1 + R_2 + R_3 + \ldots R_n$$

The total resistance of a series connection is greater than the single greatest resistance in the connection.

Resistors in Parallel

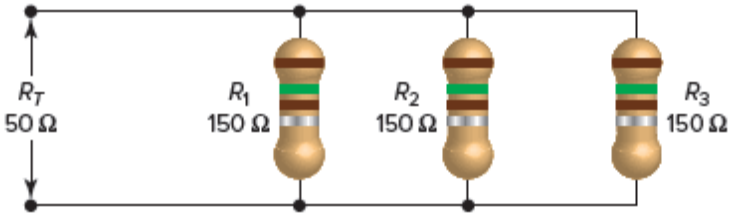


Figure 3.11: *Three resistors in parallel*

Resistors are connected in **parallel** when they are connected across the same two points, giving the current multiple paths to flow. Again, this simply means the current will divide and enter the resistors at the same time (parallel or concurrent entry).

Unlike series circuits, the voltage across each resistor in parallel is the same, and equal to the total voltage supplied by the source.

Because the current can split and flow through each resistor separately, the total current flowing into the parallel network is the sum of currents through each resistor.

The key characteristic of resistors in parallel is that the total or equivalent resistance is always less than the smallest individual resistor in the group. This happens because adding more paths allows more current to flow, reducing overall resistance.

The formula for total resistance in a parallel circuit is

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}$$

Proof

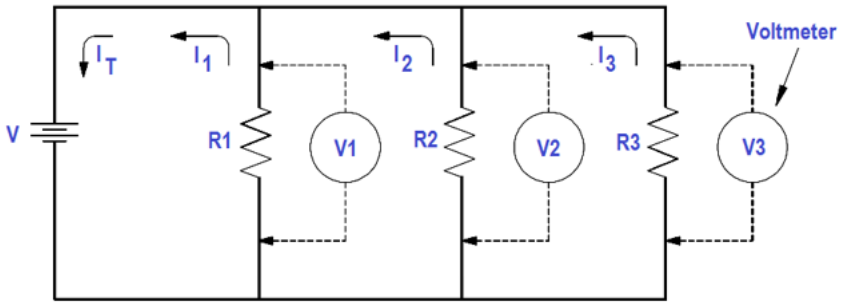


Figure 3.12: *Circuit diagram of three resistors connected in parallel*

Consider three resistors, R_1, R_2 and R_3, in parallel across a voltage source V. The voltage across each resistor is the same (V) because their ends are directly connected.

By Ohm's law, the current through each resistor is:

$$I_1 = \frac{V}{R_1}$$

$$I_2 = \frac{V}{R_2}$$

$$I_3 = \frac{V}{R_3}$$

Also, total current

$$I_{total} = \frac{V}{R_{total}}$$

The total current I_{total} supplied from the source is the sum of currents through each resistor by

$$I_{total} = I_1 + I_2 + I_3$$

Substitute:

$$\frac{V}{R_{total}} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

$$\frac{V}{R_{total}} = V\left(\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right)$$

Divide both sides by V

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

This formula also generalises to n resistors in parallel:

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \ldots + \frac{1}{R_n}$$

Many practical circuits are not just simple series or parallel but are a combination of both. In these cases, you can simplify complex circuits step-by-step.

First, identify groups of resistors that are clearly in parallel or series. Calculate their equivalent resistances individually, then replace those groups with their equivalent resistor in the circuit. Repeat this process until you find the total resistance between two points.

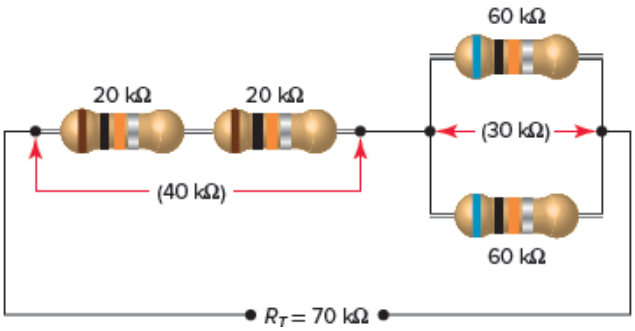


Figure 3.13: *Series-parallel connections of resistors*

Looking at the circuit above; how would you expect the supply voltage to be shared between each of the resistors in the circuit? How would the current through each resistor compare?

Resistivity

Resistivity is an **intrinsic property of a material** that quantifies how strongly that material opposes the flow of electric current. It is a fundamental characteristic of the material itself, regardless of its shape or size.

Resistivity depends only on the **type of material** (e.g., copper, silver, wood, glass) and its **temperature**. The unit of resistivity is the **Ohmmeter (Ω·m)**

The resistance R of a uniform conductor depends on its resistivity ρ, its length l, and the cross-sectional area A, described by the formula:

$$R = \frac{\rho l}{A}$$

where

R = resistance (ohms, Ω)

ρ = resistivity of the material (Ω·m)

l = length of the resistor (m)

A = cross-sectional area (m^2)

This formula tells us

1. Resistance **increases** with greater length (l) because electrons encounter more obstacles as they travel farther.
2. Resistance **decreases** with a larger cross-sectional area (A) because a thicker conductor allows more paths for electrons to flow.
3. Different materials have different resistivity values ρ, affecting their resistance even if they have the same size and shape.

Variable Resistors

In many electronic circuits, we need to be able to adjust the resistance to control the current or voltage. Think of a volume knob on a radio, a dimmer switch for a light, or a speed control for a fan. These devices all rely on a **variable resistor**.

A variable resistor is an electrical component whose resistance can be changed manually. The two most common types of variable resistors are the **rheostat** and the **potentiometer**. While they share a similar internal construction, they are used for very different purposes in a circuit.

The Rheostat: Controlling Current

A rheostat is a two-terminal variable resistor used to control the **current** in a circuit. It works by varying the total resistance of the circuit. By changing the

resistance, it changes the total current flowing through the circuit, according to Ohm's Law (I=V/R).



Figure 3.14: *Rheostat*

The Structure

A rheostat typically consists of a resistive wire wound around an insulating core. A sliding contact, or "wiper," moves along the wire. The two terminals are:

1. One end of the resistive element.
2. The sliding contact.

When you move the wiper, you change the length of the resistive wire that the current must travel through. A longer path means more resistance, and a shorter path means less resistance.

Common Applications

1. Dimmer Switches: For lights, a rheostat controls the amount of current flowing to the bulb, changing its brightness.
2. Motor Speed Control: Rheostats can be used to control the speed of a DC motor by varying the current flowing through it.
3. Some Heaters: By changing the resistance of a heating element, a rheostat can control the amount of heat produced.

The Potentiometer: Controlling Voltage

A potentiometer (often called a "pot") is a three-terminal variable resistor used to control the **voltage** in a circuit. It acts as a **voltage divider**, providing an output voltage that is a fraction of the input voltage.



Figure 3.15: *A typical single turn Potentiometer*

The Structure

A potentiometer has three terminals:

1. Terminal A: One end of the resistive element.
2. Terminal B: The other end of the resistive element.
3. Terminal C (Wiper): A sliding contact that moves along the resistive element.

When an input voltage is applied across the two ends (A and B), the wiper (C) can be moved to "tap" off a fraction of that voltage. The output voltage is measured between one end terminal (e.g., B) and the wiper (C).

The Voltage Division Principle

The total resistance between terminals A and B is constant (R_{total}). The resistance between the wiper C and terminal B (R_{out}) varies as the wiper moves. The output voltage (V_{out}) is a fraction of the input voltage (V_{in}) given by the formula:

$$V_{out} = V_{in} \frac{R_{out}}{R_{total}}$$

By moving the wiper, you change R_{out}, which in turn changes V_{out}.

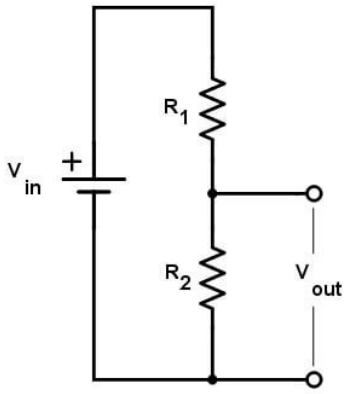


Figure 3.16: *Voltage divider circuit using two resistors*

$$V_{out} = V_{in} \frac{R_2}{R_1 + R_2}$$

Common Applications

1. Volume Control: The volume knob on an audio system is a potentiometer. It adjusts the voltage signal sent to the amplifier, which controls the output volume.
2. Sensor Input: Potentiometers can be used as simple position sensors. For example, a joystick or a rotary sensor can be a potentiometer, where the position of the wiper sends a different voltage signal to a microcontroller.
3. Dimmer Switches: While a rheostat can be used, many modern dimmers use a potentiometer to control the voltage supplied to a more complex power control circuit.

While many potentiometers are small, rotary components used for volume controls and everyday electronics, the **sliding wire potentiometer** is a specialised, high-precision instrument. It is a fundamental tool in physics laboratories and electrical engineering for accurate measurement of electromotive force (EMF) and voltage without drawing any current from the circuit under test. This type of potentiometer is not used for continuously variable output in everyday devices, but rather as a precise measuring instrument based on the principle of **null deflection**.

The sliding wire potentiometer operates on the principle that the potential drop across a uniform resistance wire is directly proportional to its length, provided a constant current flow through it. The core idea is to find a "balance point" where the voltage drop across a section of the wire is exactly equal to an unknown EMF. At this point, no current flows through the measuring circuit, which means the potentiometer measures the true, open-circuit EMF of the source. This is a significant advantage over a voltmeter, which always draws some current and therefore measures a slightly lower terminal voltage.



Figure 3.17: *Sliding wire potentiometer*

The Structure

A sliding wire potentiometer typically consists of:

1. A long, uniform resistance wire: This is the "sliding wire" itself. It is often made of a material like manganin or constantan, which has a high resistivity and a very low temperature coefficient to ensure the resistance is uniform and stable.

2. A driving or "driver" cell: A battery that provides a constant current through the entire length of the sliding wire. A rheostat is usually connected in series with this cell to adjust and standardise the current.
3. A jockey (sliding contact): A metal contact that can be moved along the length of the wire to tap off a specific voltage drop.
4. A standard cell: A cell with a precisely known EMF (e.g., a Weston cell) used to "standardise" or calibrate the potentiometer before making a measurement.
5. A galvanometer: A sensitive current-detecting device used to indicate when no current is flowing in the measuring circuit (the null point).

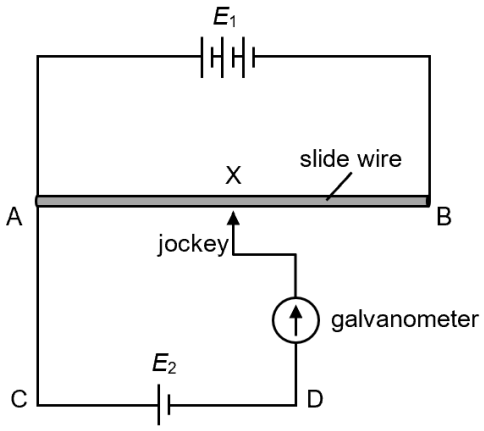


Figure 3.18 *Potentiometer circuit*

How it Works (The Null Method)

The potentiometer uses a **null method** to accurately measure the EMF of an unknown cell (E2) without drawing any current from it. A driving cell (E_1) sets up a constant potential drop (voltage) across the entire length of a uniform resistance wire A to B (let's call this length L_1). The cell to be measured (E_2) is connected in a separate circuit with a galvanometer and a sliding contact called a jockey. The jockey is moved along the wire until the galvanometer shows **zero deflection**. This is the **null point**. At this null point, the voltage drop across the length of the wire from A to the jockey X (let's call this length L_2) is **exactly equal** to the EMF of the unknown cell (E_2). Since no current flows from the unknown cell at this point, the measurement is of its true, open-circuit EMF, which is the most accurate possible.

$$E \propto L$$

$$\frac{E_1}{L_1} = \frac{E_2}{L_2}$$

$$E_2 = \frac{L_2}{L_1} \times L_1$$

Activity 3.7 Determining and Verifying Resistor Values Using Colour Codes and a Multimeter

Objective: To develop practical skills in identifying and verifying resistor values by applying knowledge of the resistor colour code and using a digital multimeter.

What you need

1. A variety of resistors (at least 4–6, each with different bands of colours)
2. Resistor colour code chart (printed or digital)
3. Digital multimeter (set to measure resistance)
4. Pen and notebook or worksheet for recording values
5. Calculator (optional)

What To do

1. Identify a friend or friends to form a small learner group.
2. Observe the example below

   Suppose you have a resistor with the colour bands: **Red, Violet, Yellow, Gold**



Figure 3.19: *Resistor with colours red, violet, yellow, gold*

   a. Use the colour code chart
      i. Red = 2 (first digit)
      ii. Violet = 7 (second digit)
      iii. Yellow = ×10,000 (multiplier)
      iv. Gold = ±5% (tolerance)

   b. Calculate the value

   Value = (2 7) × 10,000 = 270,000Ω or 270kΩ

   Tolerance = ±5%

   So, this resistor's value is **270kΩ ±5%**

3. Take a set of resistors from your kit or group's supply. Assign each group member one or more resistors.
4. Use the colour code chart to decode the bands on each resistor. Write down
   - **a.** The colours
   - **b.** Each digit and the multiplier value
   - **c.** The calculated resistance value and tolerance
5. Use a table to organise your findings

Resistor Number	Colours	Calculated Value (Ω)	Tolerance
1	Red, Violet, Yellow, Gold	270,000	±5%
2	...	...	...
3	...	...	...

6. **Measure with a Multimeter**
   - **a.** Set the multimeter to the resistance (Ω) setting.
   - **b.** Hold the resistor leads and measure the resistance.
   - **c.** Record the measured value in your table.

Resistor Number	Calculated Value (Ω)	Measured Value (Ω)	Difference
1	270,000	268,500	-1,500
2	...	...	...

7. **Compare and Discuss**
   - **a.** Compare each calculated value (from colour codes) with the measured value. Does it fall within the tolerance indicated on the colour bands?
   - **b.** Write down any differences or discrepancies.
   - **c.** Discuss possible reasons for differences (e.g., tolerance limits, accuracy of multimeter or resistor, small manufacturing variations).
8. **Group Discussion**
   - **a.** As a group, share your findings and explanations.
   - **b.** Reflect on why resistors have tolerances and the importance of accurately knowing resistance in circuits.

Activity 3.8 Identifying Appliances That Use Resistors and Understanding Their Role

Objective: To enhance understanding of the practical applications of resistors by exploring their roles in everyday electrical appliances.

What you need

1. Notebook or digital device for writing
2. Internet access for research
3. Pen or keyboard

What to do

1. Make a list of common electrical appliances you know or find that use resistors. Examples include heaters, toasters, electric stoves, chargers, LED lights, and fan speed controllers.
2. Think about and write down: *Why do you think these appliances need resistors?* Consider what resistors do in electrical circuits, such as controlling current, dividing voltage, or converting electricity to heat.
3. Pick one appliance from your list that interests you most.
4. Use reliable online resources to find out
   a. How resistors are used in this device.
   b. Why the resistors are important for the device's operation or for protecting other components.
   c. Any specific types of resistors used in the appliance (e.g., variable resistors, heating elements, ballast resistors).
5. Summarise what you learned in your notebook or digital document. Explain the role of resistors clearly and briefly in your chosen appliance, using your own words.
6. If possible, share your findings with a friend or group. Discuss how resistors help make appliances work safely and efficiently.

Activity 3.9 Building and Investigating Series and Parallel Resistor Circuits

Objective: Build resistor circuits in series and parallel using a breadboard, bulbs, resistors, and batteries. Observe bulb brightness, measure current,

voltage, and equivalent resistance using a multimeter, and compare your measurements with calculated values.

What you need

1. Breadboard
2. Resistors (e.g., 3 resistors of known values, such as 1 kΩ each)
3. Bulb (with holder)
4. Batteries or a DC power supply (e.g., 5V)
5. Connecting wires
6. Multimeter (to measure voltage, current, and resistance)
7. Switch (optional)
8. Calculator
9. Notebook and pen for recording data

What to do

1. **Set Up the Series Circuit**
   - **a.** Connect three resistors in series on the breadboard.
   - **b.** Connect the bulb, also in series with the resistors, to observe brightness.
   - **c.** Connect the series circuit to the battery or power supply.
   - **d.** Connect the multimeter as follows
     - **i.** Use the ammeter mode and place it in series to measure the current flowing through the circuit.
     - **ii.** Use the voltmeter mode and connect it in parallel across the entire resistor chain or individual resistors to measure voltage drops.
2. **Record Measurements for Series Circuit**
   - **a.** Measure the current through the circuit and write it down.
   - **b.** Measure the voltage across each resistor and across the entire series combination, noting each reading.
   - **c.** Measure the resistance of each resistor individually using the ohmmeter function.
   - **d.** Calculate the total resistance using the formula:

     $R_{total} = R_1 + R_2 + R_3$

e. Use Ohm's Law (V=IR) with your measured current and voltage to calculate the total resistance and compare with the sum of individual resistors and measured total resistance.

3. Set Up the Parallel Circuit

a. Rearrange the three resistors so they are connected in parallel on the breadboard.

b. Connect the bulb adjacent to these; in series with the parallel resistor combination.

c. Connect this parallel circuit to the battery or power supply.

d. Measure current using the multimeter placed in series with the power supply.

e. Measure voltage across each parallel resistor (should be the same).

f. Measure the equivalent resistance using the formula

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

g. Use your measurements of current and voltage to calculate total resistance via Ohm's Law and compare with your formula result and direct resistance measurement via the multimeter.

4. Observe and Record

a. Note differences in bulb brightness between series and parallel setups.

b. Record all measurements in your notebook with clear labels.

5. Compare and Explain

a. Compare measured voltage, current, and resistance values with calculated values for both circuits.

b. Explain any differences and relate how series and parallel configurations affect current flow, voltage distribution, total resistance, and bulb brightness.

Activity 3.10 How Changing Resistance Affects Current Using a Variable Resistor

Objective: Understand how adjusting resistance in a circuit changes current flow by observing how it affects the brightness of a bulb or the sound of a buzzer. Relate your observations to Ohm's Law and discuss real-world uses of variable resistors.

What you need

1. Power source (e.g., battery or DC power supply)
2. Bulb (with holder) or buzzer
3. Variable resistor (potentiometer or rheostat)
4. Connecting wires
5. Switch (optional)
6. Notebook and pen

What to do

1. Connect the power source, variable resistor, and bulb or buzzer in series using the wires. If you have a switch, include it to control the circuit easily.
2. Close the switch (or complete the circuit) so current can flow.
3. Slowly turn the knob of the variable resistor, or slide the contact, to increase and decrease the resistance.
4. Observe how the bulb's brightness or buzzer's sound changes as you adjust the knob.
5. Note what happens to the brightness or sound as resistance increases or decreases. Write down your observations clearly in your notebook.
6. Remember the formula

   $I = \frac{V}{R}$

   Discuss in your notes how increasing resistance lowers current (dimmer bulb or quieter buzzer) and decreasing resistance raises current (brighter bulb or louder buzzer).
7. Write about some examples where variable resistors are used, like volume controls on radios, light dimmers, or motor speed controls.
8. Explain how changing resistance in these devices adjusts their output or performance.

Activity 3.11 How Wire Length, Thickness, and Material Affect Resistance

Objective: Explore how different physical properties of wires—length, thickness, and material—affect their electrical resistance by measuring with a multimeter and analysing the results.

What you need

1. Wires of different lengths (e.g., 10 cm, 20 cm, 30 cm)
2. Wires of different thicknesses/gauges (e.g., thin and thick wires)
3. Wires made of different materials if available (e.g., copper, nichrome)
4. Crocodile clips or alligator clips
5. Digital multimeter (for measuring resistance)
6. Ruler or tape measure
7. Notebook and pen

What to do

1. Gather various wire samples that differ in length, thickness, and material. Label each wire to keep track of which wire you are testing.
2. Use a ruler or tape measure to record the exact length of each wire. Note the thickness or gauge of each wire if known.
3. **Measure Resistance**
   - **a.** Set the multimeter to resistance mode.
   - **b.** Attach the multimeter probes to each end of a single wire and record the resistance reading.
   - **c.** Repeat for every wire sample, measuring one wire at a time.
4. Record your data. Use the table below to record measurements and observations for each wire separately.

Wire ID	Material	Length (cm)	Thickness/ Gauge	Measured Resistance (Ω)	Observations/ Notes
1					
2					
3					
4					

5. **Analyse Your Results**
   - **a.** Look for how resistance changes with wire length.
   - **b.** Compare resistance readings between wires of different thicknesses but equal lengths.

c. Compare resistance between wires made from different materials with similar sizes.

6. Draw Conclusions

a. Explain how the length, thickness, and material of the wire influence its resistance.

b. Relate your findings to the formula

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

where R is resistance, L is length, A is cross-sectional area (thickness), and ρ is resistivity (material).

Activity 3.12 Resistance in Electrical Circuits: Series, and Parallel

Study the worked example below carefully before attempting the sample questions that follow.

Worked Example 1

A string of 10 identical Christmas lights is connected in series. Each light bulb has a resistance of 15 Ω. What is the total resistance of the string of lights?

Solution

Step 1: Identify the individual resistance

Each light bulb (R1, R2, ..., R10) has a resistance of 15 Ω.

Step 2: Introduce the series resistance formula

$R_{total}=R_1+R_2+...+R_{10}$

Step 3: Substitute and calculate the total resistance

R_{total}= 15 Ω + 15 Ω+ 15 Ω+ 15 Ω+ 15 Ω+ 15 Ω+ 15 Ω+ 15 Ω+ 15 Ω+ 15 Ω

R_{total}= 150 Ω

Worked Example 2

In a kitchen, a toaster of resistance 24 Ω and a coffee maker of resistance 18 Ω are plugged into the same parallel circuit. What is the total resistance of these two appliances when they are both operating.

Solution

Step 1: Identify the individual resistance

$R_{toaster}=24\ \Omega$

$R_{coffee\ maker}=18\ \Omega$

Step 2: Introduce the parallel resistance formula

$$\frac{1}{R}=\frac{1}{R_{toaster}}+\frac{1}{R_{coffee\ maker}}$$

Step 3: Substitute and calculate the total resistance

$$\frac{1}{R}=\frac{1}{24}+\frac{1}{18}$$

$$\frac{1}{R}=\frac{7}{72}$$

$$R=\frac{72}{7}$$

$$R=10.29\ \Omega$$

Worked Example 3

A house is wired with copper wire having a resistivity of $1.68\times10^{-8}\ \Omega\cdot m$. If a particular circuit requires a 15-metre length of wire with a circular cross-sectional radius of 1.0 mm, what is the resistance of this wire?

Solution

Step 1: Identify the given values

$\rho=1.68\times10^{-8}\ \Omega m$

$l=15\ m$

Radius (r) $= 1.0\ mm = 1.0\times10^{-3}\ m$

Step 2 - Calculate the cross-sectional area

$$A=\pi r^2$$

$$A=\pi(1.0\times10^{-3}m)^2$$

$$A=3.14\times10^{-6}m^2$$

Step 2 - Introduce the resistance formula

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

Step 3 - Substitute and calculate the total resistance

$$R = \frac{1.68 \times 10^{-8} \times 15}{3.14 \times 10^{-6}}$$

$$R = 8.025 \times 10^{-2}\ \Omega$$

Practice Problems

Now, using the worked examples as a guide, solve the following problems individually or in groups.

1. A car's taillight system has two bulbs.

   Scenario A: If the bulbs are wired in series, and each bulb has a resistance of 6 Ω, what is the total resistance?

   Scenario B: If the bulbs are wired in parallel, and each bulb has a resistance of 6 Ω, what is the total resistance?

   Which car's lights would you expect to shine with a greater brightness, and why?

2. You are designing a heating element for a small portable heater using Nichrome wire, which has a resistivity of 1.1×10−6 Ωm. You need the heating element to have a resistance of 50 Ω. If you use Nichrome wire with a diameter of 0.5 mm, what length of wire will you need?

KIRCHHOFF'S LAWS AND GALVANOMETERS IN ELECTRICAL NETWORKS

Kirchhoff's Laws

Imagine you are trying to figure out the traffic flow at a busy intersection. You know cars are coming in from three different streets and leaving on a fourth. You cannot just guess how many cars are going to each street, can you? You need a rule! The rule is simple: the number of cars entering the intersection must equal the number of cars leaving. This is the basic idea behind Kirchhoff's Laws, but for electric current and voltage in a circuit.

Ohm's Law is a powerful tool, but it only works for simple, single-loop circuits or for individual components. What about complex circuits with multiple loops and junctions (points where wires split)? That's where Kirchhoff's Laws come in. They provide a set of rules to analyse these more complicated circuits.

Kirchhoff's First Law- The Current Law (KCL)

The principle

Kirchhoff's Current Law, or KCL, is based on the **principle of conservation of charge**. Just like cars at an intersection, electric charge cannot be created or destroyed. It must flow somewhere.

Kirchhoff's first law states that at any junction of an electrical network, the sum of all currents entering the junction is equal to the sum of all currents leaving it.

OR

It states that the algebraic sum of the electric currents at any junction or node of an electrical network is zero.

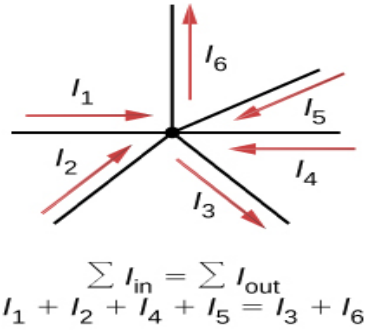


Figure 3.20: *An illustration of Kirchhoff's Current Law at a circuit junction*

Practical Example

Let's say a circuit junction has three wires. We know the current in the first wire is 5A flowing in, and the current in the second wire is 2A flowing out. What is the current in the third wire?

Using KCL: $I_{in}=I_{out}$

$$5A = 2A+I_{third}$$

$$I_{third}= 5A-2A = 3A$$

So, the current in the third wire is 3A, and it must be flowing out of the junction.

Kirchhoff's Second Law - The Voltage Law (KVL)

The principle

Kirchhoff's Voltage Law, or KVL, is based on the **principle of conservation of energy**. Think of a rollercoaster. It starts at a high point, goes down, and then gets lifted back up to the starting point. The net change in its height (potential energy)

after one complete loop is zero. Similarly, in an electrical circuit, the total change in potential (voltage) around any closed loop must be zero. The voltage supplied by the sources (batteries) is consumed by the components (resistors, etc.) in the loop.

Kirchhoff's second law states that in any closed loop or circuit of an electrical network, the algebraic sum of the e.m.fs is equal to the algebraic sum of the p.ds around the same loop.

OR

It states that the algebraic sum of the p.ds around any closed loop or circuit in an electrical network is zero.

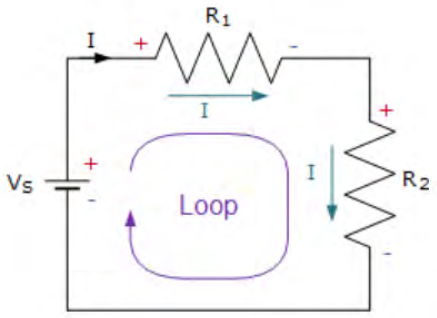


Figure 3.21: *simple series circuit to demonstrate Kirchhoff's Voltage Law (KVL) for a single loop.*

$$V_s + \left(-IR_1 \right) + \left(-IR_2 \right) = 0$$

$$V_s = IR_1 + IR_2$$

Important Sign Convention

To use KVL correctly, we need a sign convention. This is a rule you must follow consistently.

1. **For a voltage source (battery):** If you trace the loop from the negative terminal to the positive terminal, the voltage is considered positive (+V). If you trace from positive to negative, it's negative (-V).
2. **For a resistor:** If you trace the loop in the same direction as the assumed current flow, the voltage drop across the resistor (V=IR) is negative (-IR). If you trace against the current flow, it's positive (+IR).

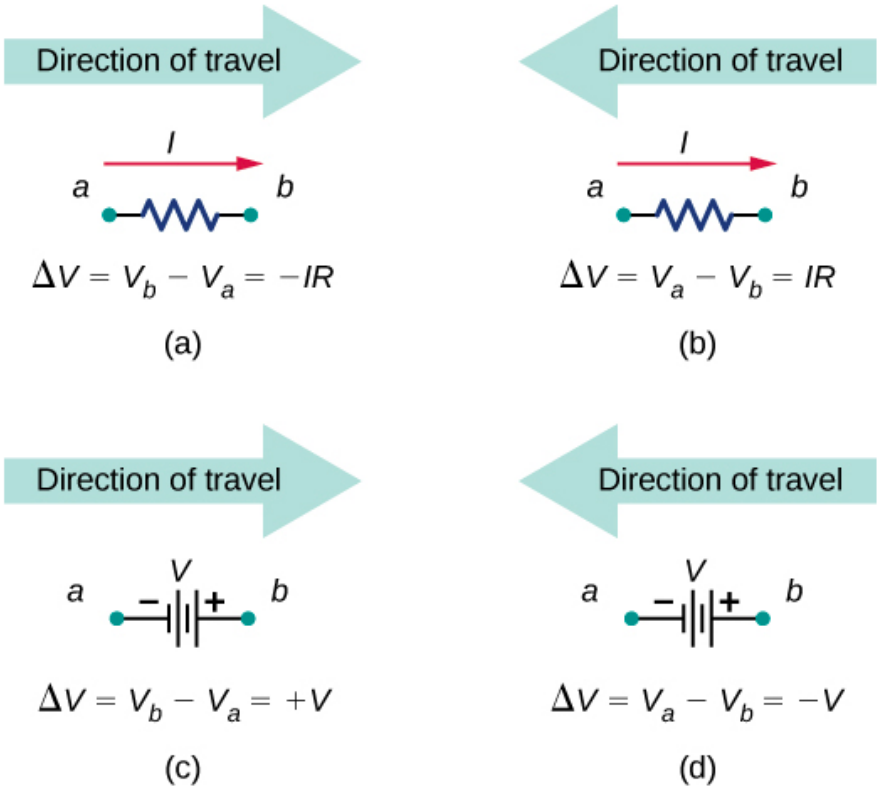


Figure 3.22: *Each of these resistors and voltage sources is traversed from a to b. (a) When moving across a resistor in the same direction as the current flow, subtract the potential drop. (b) When moving across a resistor in the opposite direction as the current flow, add the potential drop. (c) When moving across a voltage source from the negative terminal to the positive terminal, add the potential drop. (d) When moving across a voltage source from the positive terminal to the negative terminal, subtract the potential drop.*

Summary and How to Apply Kirchhoff's Laws

Steps to Solve a Complex Circuit

1. Label Currents: Assign a unique current variable (I1,I2,I3,...) to each branch of the circuit. Arbitrarily choose a direction for each current. Do not worry if you guess wrong; the final answer will just be negative, indicating the current flows in the opposite direction.
2. Apply KCL: Write a KCL equation for each junction in the circuit. You do not need to do this for every single junction; once you've used a certain number, the rest will be redundant.
3. Apply KVL: Identify the independent loops in the circuit. Write a KVL equation for each loop, carefully following the sign convention. You will need as many independent KVL equations as there are unknown currents.
4. Solve the System of Equations: You will now have a system of linear equations (from your KCL and KVL steps). Use substitution, elimination, or matrix methods to solve for the unknown currents.

Understanding Kirchhoff's Laws is not just an academic exercise—it is the fundamental principle that governs almost every electrical device and system you interact with daily. The concepts of KCL and KVL are so deeply embedded in modern technology that you benefit from them constantly, even if you do not realise it.

An example of how Kirchhoff's Laws are essential to our everyday lives include **household wiring and electrical safety**. Your home's electrical system is a complex network of wires, outlets, and appliances. It is a classic example of a multi-loop circuit.

1. **Kirchhoff's Current Law (KCL) in action**

   Every outlet in your home is a "junction" where current can split off. KCL ensures that the current entering your home from the power grid equals the sum of all the currents being used by your lights, TV, refrigerator, and other appliances. This balance is crucial. If a fault causes more current to flow out than what is being used, a safety device like a circuit breaker or fuse will trip, preventing an overload that could cause a fire.

2. **Kirchhoff's Voltage Law (KVL) in action**

   KVL explains why all your appliances receive the same voltage (e.g., 220V or 120V). The voltage from the power company is distributed across a closed loop that includes all the parallel branches in your home's wiring. KVL guarantees that the total voltage supplied by the source is fully consumed by the appliances in each loop. This ensures consistent power and prevents appliances from receiving an unsafe voltage.

Have a discussion with the person next to you about other real-world applications of KCL and KVL and why it is important to analyse the design of these.

Galvanometer and its Adaptations

What is a Galvanometer?

A galvanometer is a sensitive instrument used to detect and measure very small electric currents. It works on the principle that a current-carrying coil placed in a magnetic field experiences a torque, causing it to rotate. The amount of rotation is proportional to the current flowing through the coil. A pointer attached to the coil moves across a calibrated scale, indicating the current. However, a standard galvanometer has some limitations:

1. It is very sensitive and can only measure tiny currents (typically in the microampere range). A large current would damage the coil.

2. It has an internal resistance, which would affect the total resistance and therefore the current in the circuit that it is placed in.
3. It measures current, but we often need to measure voltage as well.

Because of these limitations, a galvanometer is almost never used on its own for practical measurements. Instead, it is the core component of two more versatile and widely-used instruments: the **ammeter** and the **voltmeter**.

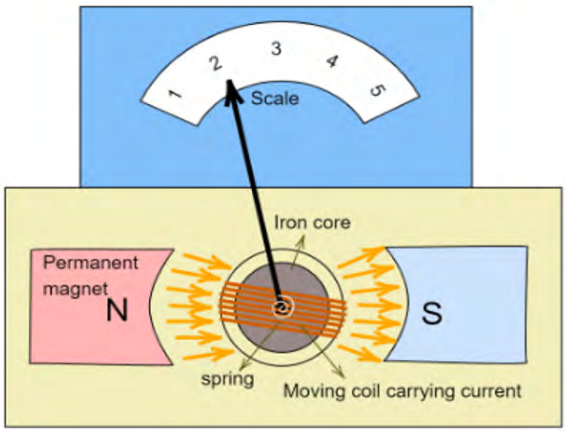


Figure 3.23: *Front view of a moving coil Galvanometer*

The Ammeter: Measuring Current

An ammeter is a device used to measure the current flowing through a component or a branch of a circuit. To measure current, the ammeter must be connected **in series** with the component so that all the current you want to measure flows directly through it.

Why a Galvanometer Alone Will Not Work

A standard galvanometer has a certain internal resistance (R_g). If we place it in a circuit, its resistance will add to the total resistance, thereby changing the very current we are trying to measure (according to Ohm's Law, $I = \frac{V}{R_{total}}$). A good ammeter should ideally have **zero resistance,** so it does not affect the circuit. Furthermore, a galvanometer's coil cannot handle large currents.

The Adaptation: Adding a Shunt Resistor

To adapt a galvanometer into a practical ammeter, we connect a very small resistance, called a **shunt resistor (R_s)**, in **parallel** with the galvanometer.

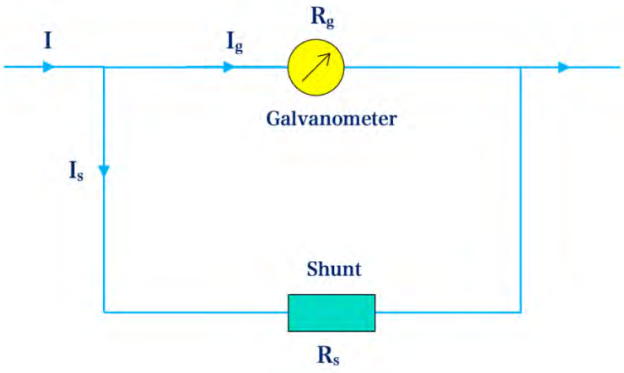


Figure 3.24: *A galvanometer is converted into an ammeter by connecting a low-resistance shunt resistor in parallel with it. The shunt allows most of the current to bypass the sensitive galvanometer coil.*

How it Works

The shunt resistor is designed to have a very low resistance. Because it's in parallel with the galvanometer, most of the total current (I) will choose the path of least resistance and flow through the shunt resistor (I_s). Only a very small, safe amount of current (Ig) flows through the sensitive galvanometer coil. Since the shunt and galvanometer are in parallel, the voltage across both is the same. We can use this principle to calculate the required shunt resistance for a specific range:

$$V_s = V_g$$

$$I_s R_s = I_g R_g$$

Since $I = I_g + I_s$, we have $I_s = I - I_g$

$$\left(I - I_g\right) R_s = I_g R_g$$

$$R_s = \frac{I_g R_g}{I - I_g}$$

This equation allows us to select a shunt resistor that extends the galvanometer's measurement range to a desired maximum current (I) without damaging the galvanometer. The scale of the galvanometer is then re-calibrated to indicate the total current (I).

The Voltmeter: Measuring Voltage

A voltmeter is a device used to measure the potential difference (voltage) between two points in a circuit. To measure voltage, the voltmeter must be connected **in parallel** across the component you want to measure.

Why a Galvanometer Alone Will Not Work

If we simply place a galvanometer in parallel with a component, the galvanometer's low resistance would provide a new, low-resistance path for the current. This would significantly change the current distribution in the circuit and alter the very voltage we are trying to measure. A good voltmeter should ideally have **infinite resistance** so that it draws no current and does not affect the circuit.

The Adaptation: Adding a Multiplier Resistor

To adapt a galvanometer into a practical voltmeter, we connect a very large resistance, called a **multiplier resistor (Rm)**, in **series** with the galvanometer.

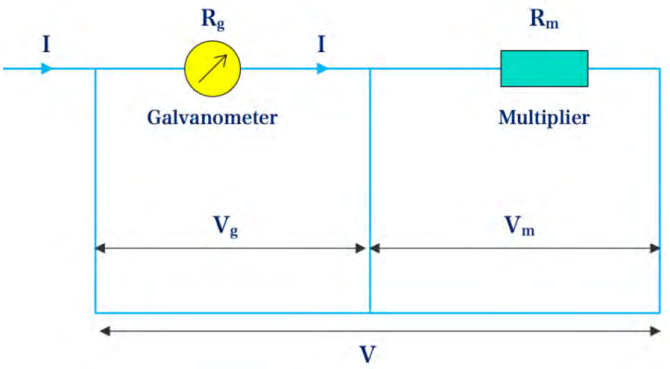


Figure 3.25: *A galvanometer is converted into a voltmeter by connecting a high-resistance multiplier resistor in series with it. The multiplier resistor ensures that the voltmeter draws a very small current and does not affect the circuit's voltage.*

How it Works

The multiplier resistor is designed to have a very high resistance. Since it is in series with the galvanometer, the total resistance of the voltmeter is very high ($R_{total}=R_g+R_m$). According to Ohm's Law ($I=V/R$), this high resistance ensures that only a tiny, negligible amount of current flows through the voltmeter.

The voltage being measured (V) is the sum of the voltage drops across the galvanometer and the multiplier resistor. We can use this to calculate the required multiplier resistance for a specific range:

$$V = V_m + V_g$$

$$V = I_g R_m + I_g R_g$$

$$V = I_g \left(R_m + R_g\right)$$

$$R_m = \frac{V}{I_g} - R_g$$

This equation allows us to select a multiplier resistor that extends the galvanometer's measurement range to a desired maximum voltage (V). The scale of the galvanometer is then re-calibrated to indicate this new, higher voltage range.

Activity 3.13 A Two-Loop Resistor Circuit to Verify Kirchhoff's Laws

Objective: Build a two-loop circuit with resistors and batteries, use multimeter to measure currents at junctions and voltages around loops, verify Kirchhoff's Current Law (KCL) and Kirchhoff's Voltage Law (KVL), compare measurements with theoretical calculations, and discuss any discrepancies.

What you need

1. Breadboard or circuit board
2. Resistors (e.g., three resistors with known values, e.g., 10 Ω, 15 Ω, 20 Ω)
3. Batteries or DC power supply (e.g., two batteries of known voltage, or one battery and a voltage divider)
4. Connecting wires
5. Digital multimeter (at least one, ideally two for current and voltage measurements)
6. Switch (optional)
7. Calculator
8. Notebook and pen for recording data

What to do

1. **Build the Circuit**
   - **a.** Arrange the resistors and batteries to form a two-loop circuit with a junction where current splits.
   - **b.** Example
     - **i.** Battery connected to resistor R1 (10 Ω) leading to junction A.
     - **ii.** From junction A, one branch contains resistor R2 (15 Ω), the other branch resistor R3 (20 Ω).
     - **iii.** Both branches rejoin at junction B, then back to battery.
   - **c.** This forms two loops sharing resistor R1 and nodes A and B.

2. Identify Measurement Points

- **a.** Identify junction points (e.g., A and B) where current splits or combines.
- **b.** Identify loops (Loop 1: battery – R_1 – R_2 – back to battery; Loop 2: battery – R_1 – R_3 – back to battery).

3. Measure Currents to Verify KCL (Current Law)

- **a.** Set the multimeter in ammeter mode.
- **b.** Measure the current entering junction A by placing the meter in series before R1.
- **c.** Measure the current leaving junction A by placing the meter in each branch after the junction (through R_2 and through R_3).
- **d.** Record the currents.
- **e.** According to KCL, current entering junction = sum of currents leaving junction.

4. Measure Voltages to Verify KVL (Voltage Law)

- **a.** Set the multimeter in voltmeter mode.
- **b.** For Loop 1 (battery – R_1 – R_2): Measure voltage across each resistor (use voltmeter in parallel with each resistor).
- **c.** Measure voltage of battery terminals.
- **d.** Add voltage drops across resistors and verify if total equals battery voltage (around closed loop voltage sum zero).
- **e.** Repeat similarly for Loop 2 (battery – R_1 – R_3).

5. Calculate Expected Values

- **a.** Use Ohm's Law V= IR and series/parallel rules to calculate theoretical currents and voltages.
- **b.** For the junction, calculate how current splits based on resistor values in parallel branches.
- **c.** Calculate voltage drops around each loop.

6. Compare and Discuss

- **a.** Compare your measured currents and voltages to the calculated theoretical values.
- **b.** Discuss any differences, considering
  - **i.** Measurement errors
  - **ii.** Internal resistance of batteries or wires

iii. Accuracy of resistors (tolerance)

iv. Contact resistance in breadboard connections

Activity 3.14 Exploring Kirchhoff's Laws Using an Online Circuit Simulator

Objective: To deepen understanding of Kirchhoff's Current Law (KCL) and Kirchhoff's Voltage Law (KVL) by constructing and analysing circuits using an online simulator.

What you need

1. Access to Online circuit simulator (PhET Circuit Construction Kit: DC)

   https://phet.colorado.edu/sims/html/circuit-construction-kit-dc-virtual-lab/latest/circuit-construction-kit-dc-virtual-lab_en.html



2. Notebook or digital document for recording results
3. Calculator (optional)
4. Pen or keyboard

What to do

1. Go to the PhET Circuit Construction Kit (DC) online simulator or similar. Select "Lab" or "Intro" mode to access the workspace.
2. **Build a Circuit with Multiple Loops and Junctions**
   - **a.** Use batteries (voltage sources), resistors, and wires to create a circuit that has at least two loops and at least one junction where current can split.
   - **b.** For example, make a circuit where two branches come off a common node and reconnect, creating two closed loops. In each of the loops, ensure that there is at least one resistor or other component.
3. **Add Measuring Tools**
   - **a.** Place ammeters in each branch to measure current.
   - **b.** Add voltmeters to measure voltage across resistors and batteries.

4. Set and Adjust Circuit Values

a. Assign different resistance values to each resistor and set the battery voltage(s).

b. After taking a set of readings, change some resistor values and/or battery voltage and repeat your measurements.

5. Record Measurements

a. For each configuration, record

- The current in every branch (especially at junctions)
- The voltage across each resistor and battery

b. Organise your data in a table, for example:

Branch or Loop	Resistance (Ω)	Voltage (V)	Current (A)
Branch 1			
Branch 2			
Loop 1			
...			

6. At every junction, add the current entering and compare to the sum leaving. They should be equal if KCL holds.

9. For each closed loop, sum all the voltage gains (batteries) and drops (resistors) around the loop. The total should be zero (account for direction/sign).

10. Vary Circuit Settings

a. Change one or more resistor values and observe how KCL and KVL still apply under new conditions.

b. Repeat measurements and checks for at least two different setups.

11. In your notebook, think about, discuss with a friend and write down:

a. How did the simulator make it easier or harder to measure and verify KCL and KVL?

b. How might results be different in a real circuit (e.g., due to wiring resistance, contact issues, or human error)?

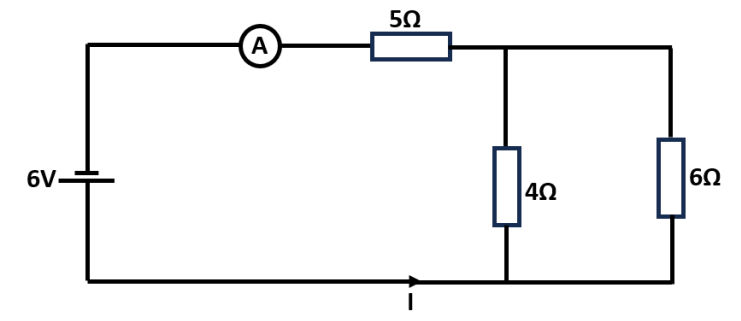
c. What are the practical strengths and weaknesses of simulations versus hands-on circuits?

Activity 3.15 Calculating Currents and Potential Differences

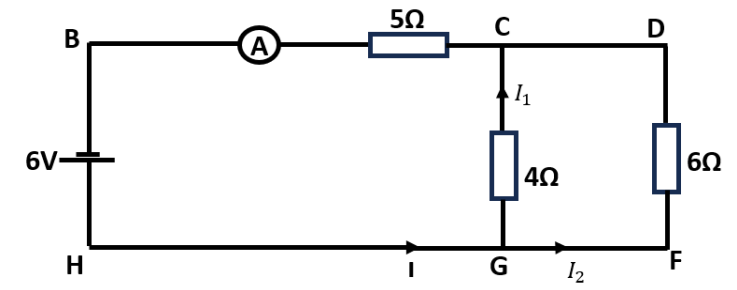
Study the worked example below carefully before attempting the example questions that follow.

Worked Example 1

In the circuit diagram below, calculate the current I if the internal resistance of the cell is negligible



Solution



Let I be the current entering the junction G, I_1 be the current leaving the junction G into GC and I_2 the current leaving the junction G into GF.

By Kirchoff's first law,

$I = I_1 + I_2$ ..... (1)

Taking the closed loop BCGHB in anticlockwise direction and applying Kirchoff's second law,

$6 = 5I + 4I_1$

$I_1 = \frac{6 - 5I}{4}$..... (2)

Taking the closed loop CDFGC in the clockwise direction and applying Kirchoff's second law,

$0 = 4I_1 - 6I_2$

$I_2 = \frac{4I_1}{6}$ ..... (3)

Putting equations 2 and 3 into 1 give

$$I = \frac{6 - 5I}{4} + \frac{4I_1}{6}$$

Substituting equation 3

$$I = \frac{6 - 5I}{4} + \frac{4(6 - 5I)}{24}$$

Multiplying through by 24 gives

$24I = 36 - 30I + 24 - 20I$

$24I = 60 - 50I$

$24I + 50I = 60$

$74I = 60$

$$I = \frac{60}{74}$$

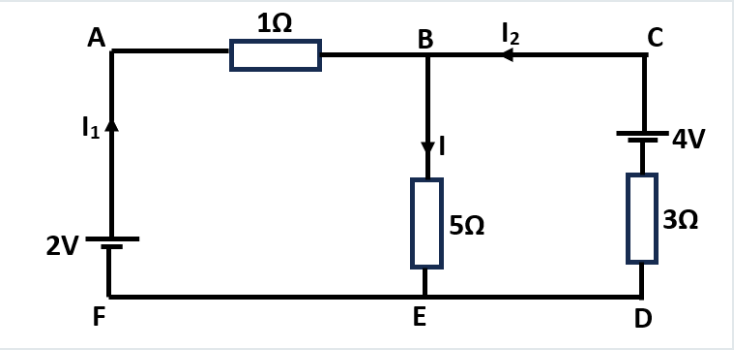
I = 0.8108A. Hence the current is given as 0.81A

Worked Example 2

Study the electrical circuit below carefully.

a. Calculate current flowing through the 5Ω resistor.

b. Find the potential difference across BE.



Solution

a. Applying Kirchhoff's first law at the junction B,

$I_1 + I_2 = I$ …….. (1)

Taking the closed loop ABEFA in a clockwise direction and applying Kirchhoff's second law,

$2 = 1 \times I_1 + I \times 5$

$2 = I_1 + 5I$

$I_1 = 2 - 5I$ ..... (2)

Taking the closed loop BCDEB in the anticlockwise direction and applying Kirchoff's second law,

$4 = 3I_2 + 5I$

$I_2 = \frac{4 - 5I}{6}$ ..... (3)

Putting equations 2 and 3 into equation 1 gives

$2 - 5I + (4 - 5I)/3 = I$

$6 - 15I + 4 - 5I = 3I$

$10 = 3I + 20I$

$10 = 23I$

$I = 10/23$

$I = 0.435$ A

b. The p.d across BE is given as VBE

$V_{BE} = 5I$

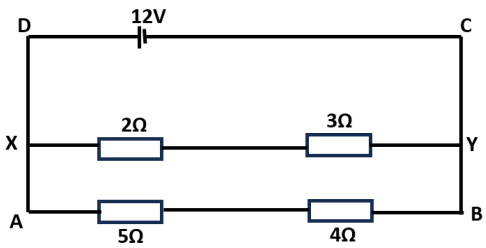
$V_{BE} = 5 \times 0.434782$

$V_{BE} = 2.174V$

Practice Problems

Now, using the worked example as a guide, solve the following problems individually or in groups. Before answering the questions, you should identify all junctions and loops in the circuit.

1.

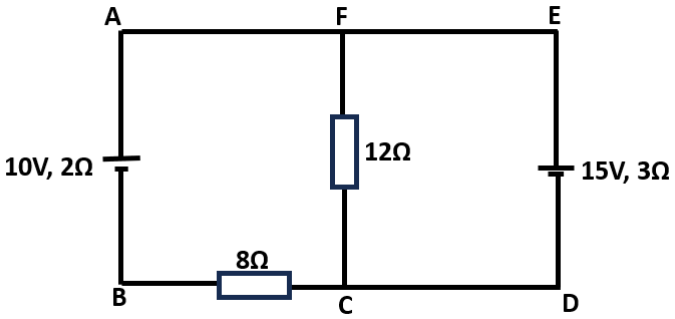


i. Calculate the current that enters the junction X.

ii. Find the p.d across the 3Ω resistor.

iii. Calculate the p.d across AB.

2. The diagram below shows an electrical network. Calculate the potential difference across the 12Ω resistor.



Activity 3.16 Converting a Galvanometer into an Ammeter and a Voltmeter

Objective: Learn how to convert a galvanometer into an ammeter by connecting a low-resistance shunt resistor in parallel and into a voltmeter by connecting a high-resistance multiplier resistor in series. Build both configurations and test them in simple circuits to observe and understand their function.

What you need

1. Galvanometer (moving coil type)
2. Shunt resistors (very low resistance values, e.g., fractions of an ohm)
3. High-resistance multipliers (resistors with large resistance values, e.g., kilo-ohms to mega-ohms)
4. DC power supply or batteries (low voltage, e.g., 3–12 V)
5. Known resistors (for building simple test circuits)
6. Connecting wires
7. Switch or key (optional)
8. Multimeter (optional, for verification)
9. Breadboard or circuit board (optional)
10. Notebook and pen to record observations

What to do

Part 1: Converting Galvanometer to an Ammeter (Using Shunt Resistor)

1. **Understand the Idea**

   The galvanometer can only safely measure very small currents directly. To measure larger currents, you connect a low-value resistor (shunt resistor) in parallel with it. The shunt bypasses most of the current, protecting the galvanometer while allowing the total current to be measured.

2. **Connect the Shunt Resistor**
   - **a.** Connect the shunt resistor in parallel with the galvanometer terminals.
   - **b.** Ensure good electrical contacts and secure the connections.

3. **Complete the Ammeter Circuit**
   - **a.** Connect this combination in series with a battery, a known resistor (load), and a switch to form a simple circuit.
   - **b.** The galvanometer with shunt now acts as an ammeter.

4. **Test and Observe**
   - **a.** Close the switch to allow current flow.
   - **b.** Observe the deflection of the galvanometer needle; it corresponds to the total current flowing through the circuit.
   - **c.** Record the deflection for different circuit currents by varying the load resistor or power supply.

5. Measure the actual current with a digital multimeter connected in series to compare with galvanometer readings.

Part 2: Converting Galvanometer to a Voltmeter (Using Multiplier Resistor)

6. **Understand the Idea**

   The galvanometer measures current, so to measure voltage, you connect a high-value resistor in series with it. This limits the current flowing through the galvanometer so it can measure voltage without damage.

7. **Connect the Multiplier Resistor**
   - **a.** Connect a high-value resistor in series with the galvanometer.
   - **b.** Secure all connections.

8. Complete the Voltmeter Circuit

a. Connect this series combination across a voltage source or circuit element whose voltage you want to measure.

9. Test and Observe

a. Connect the voltmeter across a power supply or resistor, noting the galvanometer deflection as the voltage changes.

b. Record the deflections corresponding to known voltages (you can use a digital voltmeter for reference).

Part 3: Comparing and Discussing

10. Record Observations

a. Note how the galvanometer deflection changes with current in the ammeter setup and voltage in the voltmeter setup.

b. Discuss how the shunt resistor allows higher current measurement by bypassing excess current, while the multiplier limits current to allow voltage measurement.

11. Analyse and Reflect

In your own words, describe and explain how galvanometers are adapted to act as ammeters and voltmeters. Write your answer down.

Summary Table for Recording

Configuration	Resistor Type	Resistor Value (Ω)	Circuit Description	Galvanometer Deflection	Observations
Ammeter (Shunt)	Shunt resistor (low)		Series with battery + load		
Voltmeter (Series)	Multiplier resistor (high)		Connected across voltage source		

Activity 3.17 Calculating Shunt and Series Resistance for Converting a Galvanometer into an Ammeter or Voltmeter

Study the worked example below carefully before attempting the example questions that follow.

Worked Example 1

A galvanometer has a resistance 25 Ω and gives full-scale deflection at 5 mA. How can it be converted into an ammeter that reads up to 2 A?

Solution

Step 1: Identify known values

Galvanometer resistance, $R_g = 25\ \Omega$

Full-scale current, I_g=5 mA = 0.005 A

Desired full-scale ammeter current, I=2 A

Step 2: Use the formula for shunt resistance Rs

$$R_s = \frac{I_g R_g}{I - I_g}$$

Step 3: Substitute values into the formula

$$R_s = 0\frac{.005 \times 25}{2 - 0.005}$$

Step 4: Perform the calculation and write the final answer

$R_s = 0.0627\ \Omega$

To convert the galvanometer to a 2 A ammeter, connect a shunt resistance of approximately **0.0627 ohms** in parallel.

Worked Example 2

A galvanometer has a resistance of 50 Ω and requires a current of 1 mA for full-scale deflection. What resistance must be connected in series to convert it to a voltmeter that can read up to 10 V?

Solution

Step 1: Identify known values

Galvanometer resistance, R_g=50 Ω

Full-scale current, I_g=1 mA=0.001 A

Desired voltage range, V=10 V

Step 2: Use the formula for multiplier resistance Rm

$$R_m = \frac{V}{I_g} - R_g$$

Step 3: Substitute values and calculate

$$R_m = \frac{10}{0.001} - 50$$

$$R_m = 9950\ \Omega$$

Practice problem

Now, using the worked example as a guide, solve the following problems individually or in groups.

1. A galvanometer has resistance 20 Ω and current of 2 mA. Find the value of the resistance enable it to convert it to read up to 1 A.
2. A galvanometer has 40 Ω, and current of 1.5 mA. Find the series resistance to make it read up to 15 V.

Activity 3.18 Recap for Electricity and Circuits

Objective: Review key concepts from Years 1 to 3 focused on electricity and circuits.

What you need

1. Notebook or paper
2. Pen or pencil
3. Coloured pencils or markers (optional, for drawing diagrams)

What to do

1. Write short answers to the following questions
   - **a.** What is electric charge, and what are its types?
   - **b.** Explain charge conservation and how charges distribute on conductors.
   - **c.** Describe mobile charge carriers and their role in conducting electricity.
   - **d.** Define electric field strength and potential difference in your own words.

e. How does a magnetic field form around a current-carrying conductor?

f. State Ohm's Law and explain what makes a conductor ohmic or non-ohmic.

g. Describe the roles of resistors in circuits and the difference between fixed and variable resistors.

h. What happens to current and voltage in series and parallel resistor arrangements?

i. State Kirchhoff's Current Law and Voltage Law with simple explanations.

j. How can a galvanometer be converted into an ammeter or a voltmeter? Explain why these modifications are necessary.

2. Draw and label the following diagrams from memory

a. A simple gold leaf electroscope showing charge influence.

b. Electric field lines between two charged plates.

c. A circuit with resistors arranged in series and parallel.

d. A two-loop circuit showing junctions and loops for Kirchhoff's laws.

e. The symbols for resistor, battery, switch, ammeter, voltmeter, and galvanometer.

3. Create a concept map linking these terms

Charge, Electric field, Potential difference, Current, Resistance, Ohm's Law, Resistor types, Series circuit, Parallel circuit, Kirchhoff's Laws, Galvanometer, Ammeter, Voltmeter.

Show relationships with arrows and brief notes.

4. True or False Statements

Write "True" or "False" and briefly justify your choice for each

a. The resistance of a wire decreases as its length increases.

b. A voltmeter is connected in parallel to measure voltage.

c. Kirchhoff's Current Law applies to any junction in a circuit.

d. Increasing resistance always increases current in a circuit.

e. In a series circuit, the current is the same through all components.

5. In your own words, summarise how Ohm's Law and Kirchhoff's Laws help analyse electrical circuits. Include why resistors are important and how different resistor arrangements affect current and voltage.

6. In a pair, one person should act as a galvanometer designer and the other as a technician converting it for field use. The galvanometer designer should explain the basic working principle of a galvanometer to the technician. The technician should explain to the galvanometer designer how and why they will make certain adaptations to produce an ammeter and a voltmeter, and what would happen if the wrong resistor was used.

7. Self-Quiz or Group Discussion

- **a.** Quiz yourself or with peers by asking and answering the above questions.
- **b.** Explain answers aloud.
- **c.** Discuss common misunderstandings and clarify them together.

REVIEW QUESTIONS

Review Question 3.1

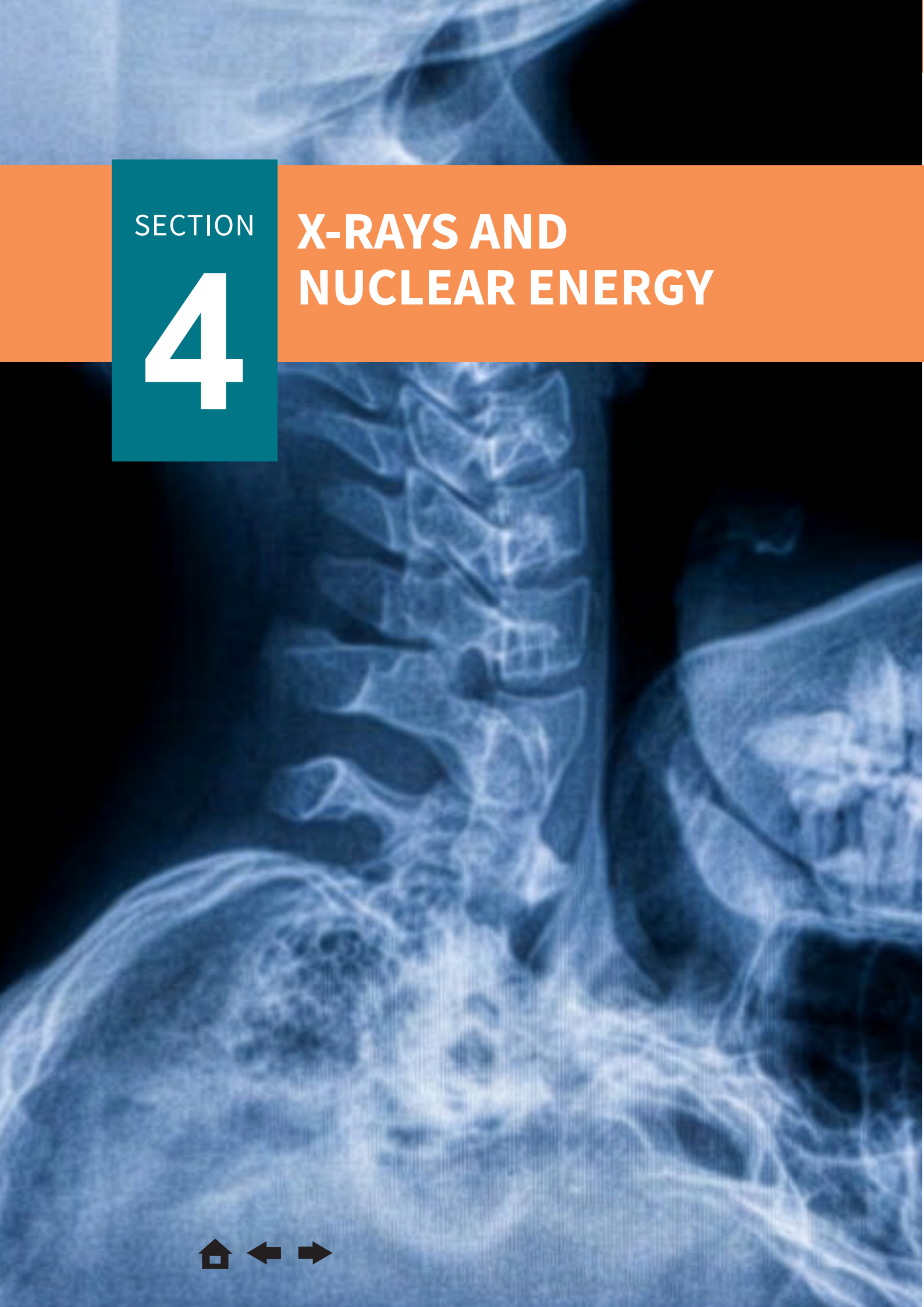
1. A student notices that when they plug in a kettle (2000W, 240V) at home, the lights dim temporarily. The home has 5 light bulbs of 60W each, and the household wiring has an internal resistance of 0.4Ω.
   - **a.** Using Ohm's law and circuit principles, analyse why this phenomenon occurs.
   - **b.** Evaluate the potential risks this might indicate about the home's electrical system.
   - **c.** Design and justify three different solutions to prevent this problem, considering cost, safety, and effectiveness.

Review Question 3.2

1. A learner needs to create a 15Ω resistance using only 10Ω and 30Ω resistors. Design two different circuit arrangements and justify which is more practical.
2. Compare the suitability of a potentiometer versus rheostat for controlling the speed of a 5A motor, considering their structural limitations.

Review Question3.3

1. Evaluate the advantages and limitations of galvanometer-based meters versus digital multimeter, then propose which type would be better for a rural school's physics laboratory with limited resources.



SECTION

4

X-RAYS AND NUCLEAR ENERGY

ATOMIC AND NUCLEAR PHYSICS

INTRODUCTION

This section explores the fascinating world of X-rays and nuclear energy, highlighting both theoretical and practical aspects. You will examine how X-rays are produced, their types (hard and soft), and their applications in medicine, industry, and security. The section also covers calculations involving energy, frequency, and wavelength of X-rays. Additionally, it introduces the principles of nuclear reactions, distinguishing between fission and fusion, and showing how nuclear energy is harnessed using reactors. Real-world implications, safety precautions, and biological effects of radiation are emphasised to connect concepts with everyday relevance.

KEY IDEAS

- X-rays are used in medical imaging (e.g., CT scans, mammography), industrial inspection (e.g., weld testing), and security scanning (e.g., airport luggage checks).
- X-rays are generated in an X-ray tube when fast-moving electrons strike a metal target, producing radiation with high energy, no mass or charge, and deep penetration power.
- X-rays are classified into hard and soft types based on energy and wavelength; this classification determines their penetrating ability and appropriate applications.
- Nuclear energy is released when mass is converted to energy in fission or fusion reactions, described by Einstein's equation $E=mc^2$.
- Fission splits heavy nuclei (e.g., Uranium-235), while fusion joins light nuclei (e.g., Hydrogen isotopes), both processes influenced by nuclear binding energy and mass defect.
- Nuclear reactors control fission using fuel rods, moderators, and control rods to produce electricity, with strong safety protocols to manage radiation hazards and waste.

X-RAYS: NATURE, PRODUCTION, PROPERTIES, AND APPLICATIONS

X-Rays

Have you ever been to a hospital or a clinic where you needed to get an x-ray? Maybe for a broken bone or a dental check-up? If so, you might have seen the x-ray machine or the room where the x-rays are taken.

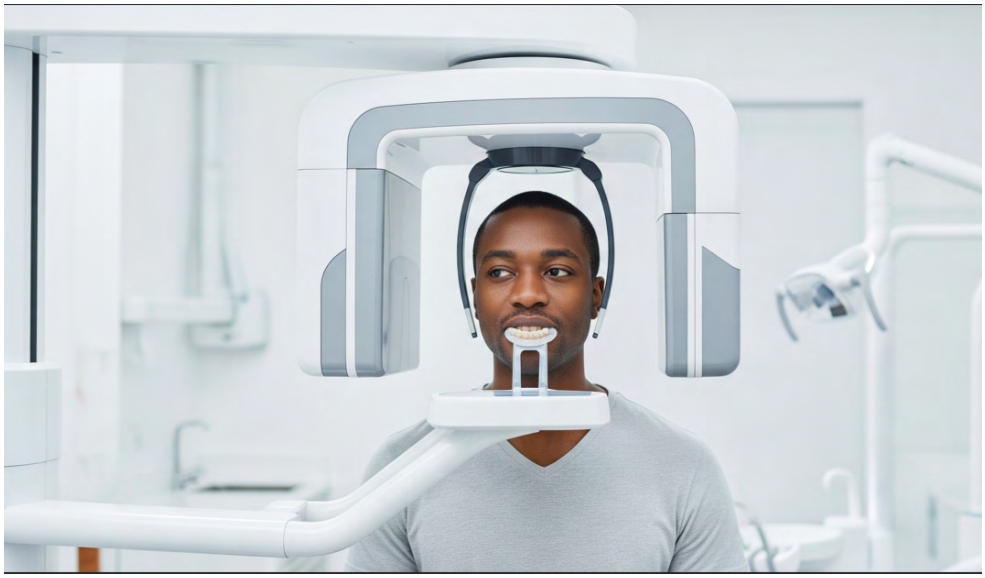


Figure 4.1: *A modern panoramic X-ray machine captures a detailed dental scan of a man*

X-rays are a type of electromagnetic wave; a special kind of non-visible light that doctors use to see inside your body without having to do surgery. They can help show broken bones, cavities, or other problems inside you.

You might wonder: how do these x-rays get made? Well, inside that x-ray machine is a device that shoots out very high-energy rays called x-rays. These rays come from speeding up tiny particles called electrons and stopping them suddenly inside what's called an x-ray tube. So, by thinking about your experience visiting an x-ray unit, you're already connected to the fascinating world of how these powerful rays are produced and used to help doctors look inside the body safely and quickly.

Nature and Production of X-rays

X-rays are a form of **electromagnetic radiation**. The spectrum of electromagnetic waves in order of increasing energy are radio waves, microwaves, infrared, visible light, ultraviolet light, x-rays and gamma waves. The key difference between all

of these types of wave lies in their **wavelength** and **energy**. X-rays have very short wavelengths (generally ranging from 0.01 to 10 nanometres) with very high frequency and energy. This high energy is what allows them to penetrate materials including human body that visible light cannot.

Properties of X-rays

X-rays possess unique properties that make them incredibly useful

1. High Penetrating Power: This is their most well-known property. Due to their short wavelength and high energy, x-rays can pass through many materials that absorb or reflect visible light. The degree of penetration depends on the material's density and atomic number. Denser materials with higher atomic numbers (like bone) absorb more X-rays, while less dense materials (like soft tissue) absorb less.
2. Ionising Radiation: X-rays have enough energy to remove electrons from atoms, a process called ionisation. This property is both useful (in medical imaging and treatment) and potentially harmful (requiring protective measures).
3. Travel in Straight Lines: Like all electromagnetic radiation, X-rays travel in straight lines unless they interact with matter. This property is crucial for creating clear images.
4. Invisible to the Human Eye: We cannot see X-rays directly. Special detectors or photographic films are needed to visualise them.
5. No Electric Charge or Mass: X-rays are photons, fundamental particles of light, and therefore have no charge or rest mass. This means they are not affected by electric or magnetic fields.
6. Produce Fluorescence: When X-rays strike certain materials (like those containing phosphor), they can cause these materials to emit visible light, a phenomenon called fluorescence. This property is utilised in intensifying screens in radiography.
7. Affect Photographic Film: X-rays can expose photographic film, leading to a visible image after processing. This was the original method of X-ray imaging.

Production of X-rays

How are these powerful rays generated? The production of x-rays relies on the principle of accelerating high-energy electrons and then suddenly stopping them. This process commonly occurs within a specialised device called an **x-ray tube**.

The X-ray Tube

An X-ray tube is essentially a vacuum tube containing two main electrodes:

1. Cathode (Negative Electrode): This is typically a heated filament (like in an old light bulb). When heated, the filament undergoes thermionic emission, releasing a cloud of electrons.
2. Anode (Positive Electrode): This is a metal target, often made of tungsten or molybdenum, which has a high atomic number and high melting point.

Steps in X-ray Production

1. **Electron Emission**

   The filament in the cathode is heated, causing electrons to "boil off" its surface.

2. **Acceleration**

   A high voltage (potential difference) is applied between the cathode and the anode. This voltage creates a strong electric field that accelerates the emitted electrons towards the positively charged anode with tremendous speed.

3. **Collision and X-ray Generation**

   When these high-speed electrons strike the anode target, their kinetic energy is rapidly converted into other forms of energy. A small fraction (less than 1%) of this energy is converted into x-rays, while the vast majority is converted into heat (which is why x-ray tubes require cooling systems).
   There are two primary mechanisms for x-ray production when electrons hit the target:

   a. **Bremsstrahlung (Braking Radiation)**

      This is the most common mechanism. As the high-speed electrons approach the positively charged nuclei in the anode material, they are suddenly decelerated or "braked" by the electric field of the nuclei. This deceleration causes the electrons to lose energy, which is emitted as x-ray photons with a range of energies.

   b. **Characteristic X-rays**

      If an incident electron has enough energy, it can knock out an inner-shell electron from an atom in the anode material. When an outer-shell electron drops down to fill the vacant inner-shell, it releases a photon with a specific, discrete energy. These are called characteristic x-rays because their energies are characteristic of the target material's atomic structure.

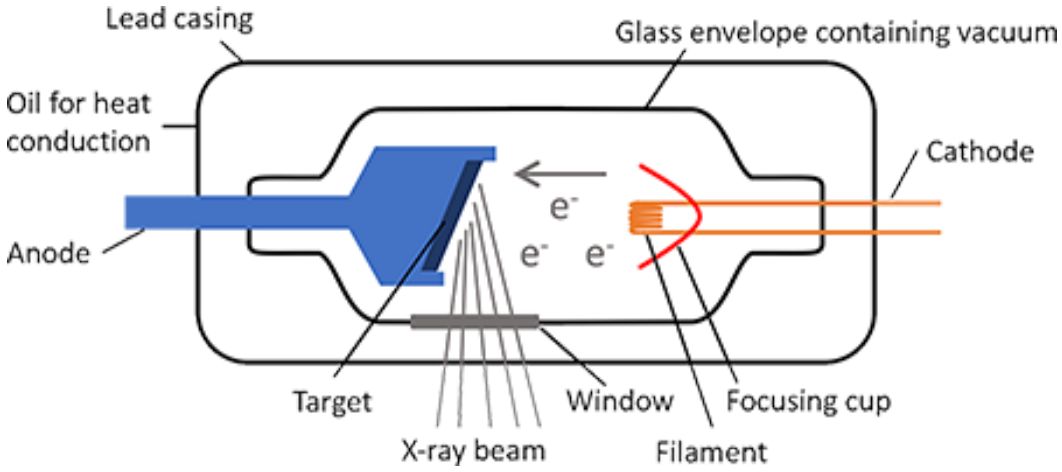


Figure 4.2: *Diagram of the x – ray tube*

Functions of the parts of the X – ray tube

1. Filament (Cathode): Heats up to emit electrons by thermionic emission.
2. Focusing Cup: Concentrates the electron beam toward the anode.
3. Anode (Target): Usually tungsten, chosen for its high melting point and atomic number, converts electron kinetic energy into x-rays.
4. Glass Envelope: Maintains vacuum to allow free electron movement.
5. Cooling System: Often a rotating anode or cooling fins to dissipate heat generated.
6. High Voltage Supply: Accelerates electrons from cathode to anode

The x-rays exit the tube through a thin window and are directed toward the object or patient for imaging or analysis.

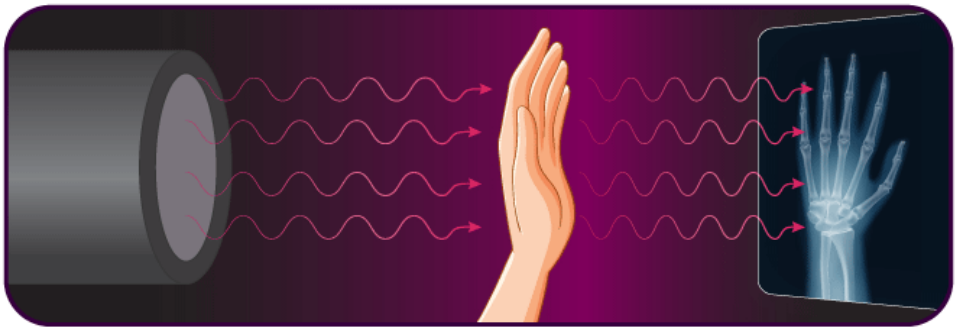


Figure 4.3: *Diagram showing how x-rays work*

When we consider different types of x-rays, we can categorise them in a couple of ways:

1. Based on their energy/wavelength (soft vs. hard x-rays): This refers to the characteristics of the X-ray photons themselves.

2. Based on their application/imaging technique: This refers to how x-rays are used in practical settings, especially in medicine.

Let us expand on the "types" as defined by their energy/wavelength.

Types of X-rays: Based on Energy and Wavelength

X-rays are part of a continuous spectrum of electromagnetic radiation. While all X-rays possess the fundamental properties discussed (penetrating power, ionising ability, no mass/charge), their specific energy and wavelength determine how they interact with matter and, therefore, their suitability for different applications. This leads to the classification of x-rays into two main types: **soft x-rays** and **hard x-rays**.

This distinction is crucial because it dictates the penetrating power and the type of information x-rays can reveal.

Soft X-rays

Energy: Lower energy, typically less than 10 keV (kiloelectron volts).

Wavelength: Longer wavelength, generally ranging from about 0.1 to 10 nanometres.

Penetrating Power: Less penetrating. They are easily absorbed by air and thin materials.

Interaction with Matter: Due to their lower energy, they interact more readily with the outer electrons of atoms and are absorbed quickly by denser materials.

Uses of the soft x–rays

1. Surface Imaging: Useful for imaging surfaces or very thin objects because they do not penetrate deeply.
2. Mammography: A common medical application where lower energy x-rays are preferred to visualise soft breast tissue and detect subtle changes, minimising the dose to deeper structures.
3. X-ray Microscopy: Used in scientific research to image very small objects at high resolution, often in specialised vacuum environments because they are absorbed by air.
4. Spectroscopy: Used in materials science to study the chemical composition and electronic structure of surfaces.

Hard X-rays

Energy: Higher energy, typically greater than 10 keV.

Wavelength: Shorter wavelength, generally below 0.1 nanometres.

Penetrating Power: More penetrating. They can pass through denser and thicker materials, including bones and metals, with less absorption.

Interaction with Matter: Their higher energy allows them to pass through many atoms without significant interaction, only being significantly absorbed or scattered by very dense or thick materials.

Uses of the hard x–rays

1. General Radiography: Standard medical x-rays for visualising bones, diagnosing fractures, and examining internal organs like the lungs (e.g., chest x-rays).



Figure 4.4: *An X-ray Image of the chest*

2. Computed Tomography (CT scans): Used to create detailed cross-sectional images of the body, requiring X-rays that can penetrate complex structures.
3. Industrial Inspection (Non-destructive Testing): Detecting flaws, cracks, or internal defects in metal components, welds, or other dense industrial materials without damaging the object.
4. Security Scanning: Used in airports and other security checkpoints to scan luggage, cargo, and sometimes people for hidden objects or threats.
5. Radiation Therapy (Radiotherapy): High-energy hard x-rays are precisely directed at cancerous tumours to destroy malignant cells.

6. X-ray Crystallography: Used in science to determine the atomic and molecular structure of crystalline materials, as their short wavelengths are comparable to atomic spacing.

Energy of X-rays

X-rays are a form of **electromagnetic radiation**, meaning they are composed of discrete packets of energy called **photons**. The energy of these individual photons is what defines the "energy of the x-ray."

Fundamental Relationship (Planck's Equation)

In a previous topic, you learnt that the energy of an x-ray photon is directly related to its **frequency** (f) and inversely related to its **wavelength** (λ). This relationship is described by Planck's equation:

$$E = hf$$

And since for all electromagnetic waves, the speed of light (c) is equal to frequency times wavelength (c=fλ), we can also write the equation as:

$$E = \frac{hc}{\lambda}$$

Where:

E is the photon energy (typically measured in Joules (J) or, more commonly for x-rays, in electron volts (eV) or kiloelectron volts (keV)).

h is Planck's constant (6.626×10^{-34} Js or 4.136×10^{-15} eVs).

f is the frequency of the X-ray (in Hertz, H_z).

c is the speed of light in a vacuum (3.00×10^{8} m/s).

λ is the wavelength of the X-ray (in metres, m).

Hazards of x-rays

1. Radiation burns (skin erythema, hair loss).
2. Genetic effects on reproductive cells.
3. DNA damage leading to mutations or cancer.
4. Acute radiation sickness (at high doses).
5. Effects on developing foetus.



Figure 4.5: *Diagram showing effect of X-rays radiation on human body*

Safe Measures of Using X-Rays

1. Shielding: Lead aprons, thyroid collars, and barriers protect patients and staff.
2. Distance: Operators keep a safe distance or stay behind protective screens.
3. Time: Minimise exposure duration.
4. Controlled Areas: X-ray rooms are clearly marked and access limited during use.
5. Monitoring: Personnel wear dosimeters to track exposure.
6. Proper Training: Only qualified personnel operate x-ray equipment.
7. Equipment Maintenance: Regular checks ensure safety features work correctly.

Further Detail on the Applications of X-rays

The diverse properties of x-rays have led to their widespread application in numerous fields:

1. **Medical Applications**
    a. Diagnostic Imaging: This is the most common application.
        i. Radiography (X-ray Imaging): Used to visualise bones, teeth, and certain internal organs. For example, diagnosing fractures, pneumonia, or dental cavities.



Figure 4.6: *Image of full-mouth dental X-ray*

ii. Fluoroscopy: Provides real-time x-ray images, allowing doctors to observe the movement of organs (e.g., in angiography to visualise blood vessels).

iii. Computed Tomography (CT) Scans: Uses multiple x-ray images taken from different angles to create detailed cross-sectional images of the body, providing more comprehensive information than traditional x-rays.

iv. Mammography: Specialised x-ray imaging for breast cancer screening.

b. Radiation Therapy (Radiotherapy): High-energy x-rays are used to destroy cancerous cells while minimising damage to surrounding healthy tissue.

2. **Industrial Application**

a. Non-Destructive Testing (NDT)

X-rays are used to inspect materials and products for flaws, cracks, or defects without damaging them.

i. Weld Inspection: Checking the integrity of welded joints in pipelines, aircraft, and other structures.

ii. Casting Inspection: Identifying voids or inclusions in metal castings.

iii. Security Screening: Used in airports to scan luggage for hidden objects.

b. Material Analysis

i. X-ray Diffraction (XRD): Used to determine the atomic and molecular structure of crystalline materials.

ii. X-ray Fluorescence (XRF): Used to identify the elemental composition of materials.

3. **Security Applications**
   a. Airport Security: As mentioned, x-ray scanners are a staple in baggage screening.
   b. Mail and Package Screening: Used to inspect suspicious packages for dangerous contents.
   c. Border Control: Used to scan vehicles and cargo for contraband.
4. **Scientific Research**
   a. Astronomy: X-ray telescopes are used to study high-energy phenomena in space, such as black holes, neutron stars, and galaxy clusters.
   b. Materials Science: Researching new materials and understanding their properties at an atomic level.
   c. Art and Archaeology: Used to examine the internal structure of artifacts, authenticate artworks, and reveal hidden details in paintings.

Activity 4.1 X-rays; Importance, Biological Effects & Safety Precautions

Objective: To build foundational understanding of X-rays by engaging in a collaborative discussion that connects personal experiences to scientific concepts.

What you need

1. Notebook or paper for each group member
2. Pen or pencil
3. Optional: Device with internet access for quick research
4. Whiteboard or large paper for group notes (if available)

What to do

1. **Form small groups of 3-4 people**

   Sit together comfortably, ideally facing one another, to facilitate a conversation.
2. Begin by asking each group member:
   a. *Have you ever heard of an x-ray before?*
   b. *Have you or someone you know ever taken an x-ray?*

3. Take turns sharing your experiences or stories related to x-rays, such as medical x-rays, dental x-rays, or other encounters. Discuss how these experiences made you feel or what you remember about the process.

4. **Discuss what x-rays are and why they are important**
   - **a.** Together, define x-rays in your own words.
   - **b.** Talk about why x-rays are useful in fields like medicine, security, and industry.
   - **c.** List specific examples of x-ray uses that group members know.
   - **d.** Write a brief group summary of your ideas.

5. **Discuss the Biological Effects of Excessive X-ray Exposure**
   - **a.** Discuss what you have heard can happen to the human body if exposed to too much x-ray radiation.
   - **b.** Note effects on sensitive parts of the body such as eyes and reproductive organs.
   - **c.** Write down agreed-upon key points.

6. Brainstorm protective measures against harmful x-ray exposure. Discuss why shielding and reducing exposure time are important safeguards. Write a short paragraph explaining these safety practices.

7. Combine your notes into one clear summary covering:
   - **a.** What x-rays are and their purpose
   - **b.** Biological effects of radiation exposure
   - **c.** Important safety precautions, especially shielding and exposure time

8. Prepare to share this summary verbally with another group or display it if possible.

Activity 4.2 Observing and Presenting X-ray Production in an X-ray Tube

Objective: In groups, observe an x-ray tube operation through an interactive simulation or educational video.

What you need

1. Device with internet access (computer, tablet, or smartphone)
2. Access to the link below:

Educational Video on X-ray Production

https://www.youtube.com/watch?v=0vUQgKNpy2Y

3. Notebook or paper and pens/pencils
4. Chart paper or poster board / computer with presentation software (PowerPoint, Google Slides)
5. Coloured markers, pencils, or drawing tools
6. Presentation/display area (wall or digital projector)

What to do

1. Form Your Group: Work with 3 to 5 classmates.
2. Open the video link above.
3. Watch or interact as a group, pausing frequently to discuss important parts:
   - **a.** How are electrons are emitted at the cathode?
   - **b.** How does the accelerating voltage speed up electrons toward the anode?
   - **c.** What occurs at the anode to produce x-rays?

   Make sure everyone understands each component's role.
4. Use devices to search online for another video or animation that explains x-ray production in an x-ray tube. Watch it together and compare with your initial resource. Add any new insights or clarifications to your notes.
5. **Take Notes and Sketch**
   - **a.** Write down each step of the x-ray production process in your own words.
   - **b.** Draw a labelled diagram of the x-ray tube showing cathode, anode, electron path, and X-ray emission.
6. **Create a Poster or Slide Presentation**: Include in your presentation:
   - **a.** A clear, labelled diagram.
   - **b.** A step-by-step explanation of the production process.

c. Key properties of x-rays (e.g., penetrating power, invisibility, effect on photographic film).

d. Real-life applications such as medical imaging, security screening, and material testing.

e. Safety precautions which should be carried out when exposure to x-rays is likely, including the importance of shielding an minimising exposure time.

Make your work visually appealing and easy to understand with colours, arrows, and bullet points.

7. Display and Share

a. Put your poster up on a wall or present your slides to other groups or classmates.

b. Explain the x-ray production process clearly and answer any questions.

c. View and discuss other groups' presentations to learn more.

Activity 4.3 Researching and Presenting Sector-Specific Applications of X-rays

Objective: To develop an understanding of the diverse, real-world applications of X-rays across various sectors (medicine, security, and industry) by engaging in collaborative research.

What you need

1. Device with internet access (computer, tablet, or smartphone) for research
2. Notebook or paper and pens/pencils for note-taking
3. Poster materials (chart paper, markers, coloured pencils) or computer with presentation software (PowerPoint, Google Slides)
4. Presentation area (classroom wall, screen, or shared online space)

What to do

1. Join 3–5 classmates to form a group.
2. Decide which sector your group will focus on
   a. Medicine
   b. Security

c. Industry

3. Search online or use textbooks to find specific ways x-rays are used in your sector.

4. Identify which type of x-rays (hard or soft) are involved in each application.

a. *Hard x-rays* are high-energy, deeply penetrating (often used in medicine and industrial inspection).

b. *Soft x-rays* are lower-energy, less penetrating (used in some medical imaging, surface studies, or research).

5. Take notes on

a. How x-rays help in your sector (e.g., diagnosis, security screening, quality control).

b. Examples of applications and how they work.

c. The benefits and importance of these x-ray applications.

6. Create a poster or slide presentation including

a. A title with your sector's name.

b. Clear explanations of at least 3 specific x-ray applications in your sector.

c. Identification of the type(s) of x-rays used (hard or soft).

d. Illustrations, labelled diagrams, or images showing x-ray equipment or processes.

e. Bullet points highlighting key properties and benefits of the x-rays in this context.

7. Present and Share

a. Present your poster or slides to other groups or classmates.

b. Explain the applications clearly, emphasising how x-rays contribute to the sector.

c. Answer any questions the audience might have about your findings.

8. Learn from Others

a. View presentations from other groups focusing on different sectors.

b. Discuss similarities and differences in how x-rays are applied and the types used.

Activity 4.4 Comparing Hard and Soft X-rays

Objective: To develop a clear conceptual understanding of the differences between hard and soft x-rays by comparing their physical properties and relating these differences to real-world applications.

What you need

1. Table of x-ray properties (see example below)
2. Worksheet with matching tasks (check below)
3. Pens or pencils
4. Notebook or paper for notes and discussion
5. Calculator (optional)

What to do

1. Form Small Groups (3–5 learners): Work together to read and understand the table of x-ray properties.
2. Review the key properties of hard and soft X-rays, including their energy ranges, penetration abilities, wavelengths, and typical characteristics.
3. As a group, discuss how hard and soft x-rays differ in
   a. Energy levels (photon energy in keV)
   b. Ability to penetrate materials (hard x-rays penetrate deeper)
   c. Use cases suggested by their penetration and energy
4. Read the list of x-ray applications below
5. Match each application to the appropriate X-ray type (hard or soft) based on the properties in the table.
6. Justify each match with a brief explanation referencing energy and penetration.
7. Write a short group summary stating the main differences between hard and soft x-rays and why these differences matter for their uses.
8. Be ready to present your matched pairs and reasoning if asked in a group sharing session.

Example Properties Table

Property	Hard X-rays	Soft X-rays
Energy Range (photon energy)	Above ~5–10 keV	Below ~5 keV
Wavelength	Short (0.01–0.2 nm)	Longer (>0.2 nm)
Penetration Ability	High (penetrate thick materials)	Low (absorbed easily by air or tissue)
Typical Uses	Medical radiography, airport security, industrial inspection, crystallography	Surface studies, dental imaging, material science research
Interaction with Matter	Primarily via Compton scattering and photoelectric effect	Mainly photoelectric absorption

Worksheet Sample Questions (Matching Exercises)

1. Match the x-ray type used for airport luggage scanning.
2. Which x-ray type is used in studying thin surface layers of materials?
3. Identify the x-ray type that can penetrate bones and tissue for medical imaging.
4. Which x-rays are less penetrating and often absorbed by air?
5. Match the application of x-rays used in crystallography.

Activity 4.5 Calculating Energy of an X-ray photon

Study the worked example below carefully before attempting the sample questions that follow.

Worked Example 1

A medical x-ray machine is designed to produce x-ray photons with a frequency of 2.5×10^{15} Hz for general radiography. Calculate the energy of a single x-ray photon from this machine in Joules. ($h = 6.6 \times 10^{-34}\ Js$)

Step by step Solution

Step 1 - Identify known values

$h = 6.6 \times 10^{-34}\ Js$

$f = 2.5 \times 10^{15} Hz$

Step 2 - Introduce the formula for energy of a photon

$E = hf$

Step 3 - Substitute known values and calculate

$E = 6.6 \times 10^{-34} \times 2.5 \times 10^{15}$

$E = 16.5 \times 10^{-19} J$

Worked Example 2

A security scanner at Kotoka International Airport (Accra, Ghana) uses x-ray photons with an energy of 95 keV to inspect checked luggage. Calculate the wavelength of these x-ray photons in metres. ($h = 6.6 \times 10^{-34}$ Js, c= 3.00×10^{8} m/s, 1 eV=1.6×10^{-19} J)

Step by step Solution

Step 1 - Identify known values

E = energy = 95 keV= $95 \times 10^{3} \times 1.6 \times 10^{-19}$ J=1.52×10^{-14} J

h = Planck's constant = 6.6×10^{-34} J s

c = speed of light = 3.00×10^{8} m/s

Step 2 - Introduce the formula for energy of a photon in terms of wavelength

$E = h\frac{c}{\lambda}$

Step 3 - Rearrange the formula to solve for λ

$\lambda = h\frac{c}{E}$

Step 4 - Substitute known values and calculate

$\lambda = 6.6 \times 10^{-34} \frac{3.00 \times 10^{8}}{1.5219 \times 10^{-14}}$

$\lambda = 1.30 \times 10^{-11}$ m.

Practice Problem

Now, using the worked example as a guide, solve the following problem.

An x-ray machine at Tamale Teaching Hospital uses photons with an energy of 120 keV for diagnostic imaging. Calculate the wavelength of these x-ray photons in metres. ($h = 6.6 \times 10^{-34}$ *Js*, c= 3.00×10^{8} m/s, 1 eV=1.602×10^{-19} J)

NUCLEAR REACTIONS AND ENERGY GENERATION

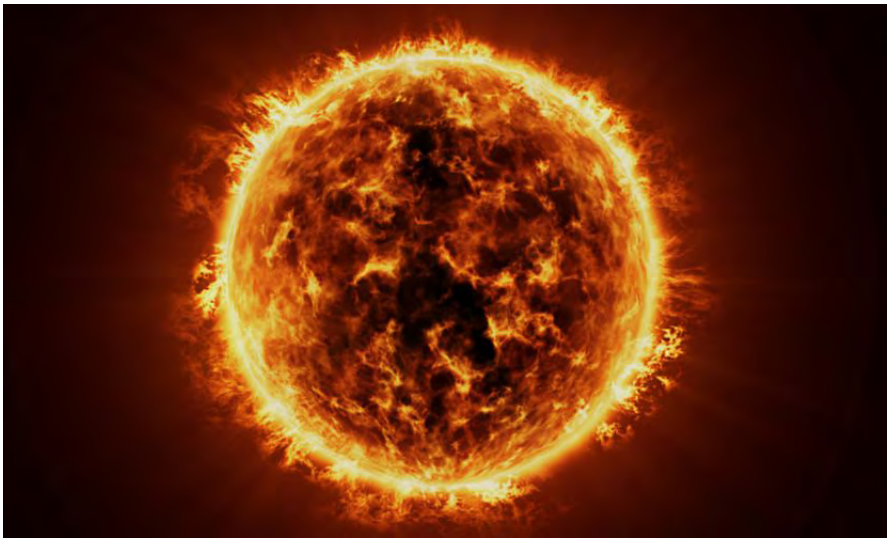


Figure 4.7: *The Sun*

Have you ever wondered what powers the Sun, making it shine so brightly and provide energy to our entire solar system? Or thought about how electricity can be generated from tiny particles inside atoms? At the heart of these incredible phenomena are powerful nuclear reactions that change the very cores—or nuclei—of atoms, releasing immense amounts of energy.

You may be familiar with how Ghana produces electricity from natural resources such as hydropower from rivers, thermal plants burning fuel, solar energy from the sun, and biomass from plants and organic material. These are important and renewable ways to create electricity.

But did you know that electricity can also be produced from inside atoms themselves? This happens through nuclear power, which uses nuclear reactions to release energy stored in the nucleus of atoms. For example, nuclear power plants use a process called nuclear fission, where heavy atoms like uranium are split into

smaller parts. This splitting releases huge amounts of heat energy, which is then used to boil water, create steam, and spin turbines that generate electricity.

This method of producing electricity is incredibly efficient because a very small amount of nuclear fuel can generate a large amount of energy, helping to meet the needs of homes, schools, and industries. Nuclear power is an important part of the global energy mix and is used alongside other sources to provide reliable electricity.

In this section, we will explore how nuclear reactions work, how energy is released from atoms, and how humans harness this powerful energy safely to meet our electricity needs—both here on Earth and in the stars above.

Energy from the Atom - $E = mc^2$

Nuclear Reactions: Changes within the Core

When we talk about "nuclear reactions," we mean changes happening deep inside the **nucleus** of an atom. Unlike chemical reactions (where atoms just rearrange), nuclear reactions actually change the types of atoms themselves! These changes can release or absorb huge amounts of energy.

Einstein's Energy Equation: $E=mc^2$

The energy released in nuclear reactions comes from something truly amazing: a tiny bit of **mass can be converted directly into energy!** This idea was discovered by Albert Einstein and is captured in his world-famous equation:

$E=mc^2$

Where:

E = Energy (in Joules, J)

m = Mass (in kilograms, kg)

c = Speed of light (a very large number: approximately 3×10^8 m/s)

Because the speed of light (c) is so large, squaring it (c^2) makes it an even bigger number. This means even a tiny bit of mass can turn into an enormous amount of energy!

Mass Defect and Energy Release (The Q-value)

In nuclear reactions, we often find that the total mass of the atoms *after* the reaction (the products) is slightly less than the total mass of the atoms *before* the reaction (the reactants). This "missing" mass is called the mass defect. It's

not truly missing; it has been converted into energy! This energy released (or absorbed) in a nuclear reaction is called the Q-value.

Calculating the Q-value

$Q = (\text{total mass of reactants} - \text{total mass of products}) \times c^2$

$Q = (\Delta m)\, c^2$

Where Δm is the mass defect.

- If the products have less mass than the reactants (Δm is positive), energy is released (this is an exothermic reaction).
- If the products have more mass than the reactants (Δm is negative), energy must be supplied for the reaction to happen (this is an endothermic reaction).

Units in Nuclear Physics

In nuclear reactions, masses are often measured in **atomic mass units (amu)**, and energy in **megaelectron volts (MeV)**.

A useful conversion factor: $1\ amu = 931.5\ MeV/c^2$

This means if you calculate your mass defect in amu, you can multiply it directly by 931.5 MeV to get the energy released.

Fission vs. Fusion - Two Ways to Release Nuclear Energy

Two main types of nuclear reactions release energy: fission and fusion.

Nuclear Fission: Splitting Heavy Atoms

What is it?

Nuclear fission is the process where a heavy, unstable atomic nucleus splits into two or more smaller nuclei. When this happens, it releases a significant amount of energy, along with some free neutrons.

How it Works

Fission is usually started by firing a neutron at a large, unstable nucleus (like Uranium-235). The neutron is absorbed by the nucleus, making it incredibly unstable. The nucleus then splits apart, releasing energy and more neutrons.

Chain Reaction

The exciting part is that the neutrons released from one fission can then go on to be absorbed by other nearby nuclei, causing *them* to split. This creates a chain reaction – a self-sustaining process!

- Critical Mass: There's a minimum amount of fissile material (e.g. Uranium-235) needed to keep this chain reaction going. This is called the critical mass.
- Control: In nuclear power plants, we use control rods (made of materials like cadmium or boron) to absorb these extra neutrons and keep the chain reaction at a safe, controlled rate.

Where is it used?

1. Nuclear Power Plants: They use controlled fission to generate electricity.
2. Atomic Weapons: These use uncontrolled fission to create massive explosions.

Nuclear Fusion: Combining Light Atoms

What is it?

Nuclear fusion is the process where two or more light atomic nuclei combine to form a heavier nucleus. This process also releases a huge amount of energy, often even more per unit of mass than fission!

How it Works

Fusion requires extreme conditions: incredibly high temperatures (millions of degrees Celsius) and immense pressures. These conditions are needed to overcome the natural repulsion between the positively charged nuclei, allowing them to get close enough to "fuse."

Where does it happen?

- The Cores of Stars: This is how our Sun and all other stars generate their enormous energy! They constantly fuse hydrogen into helium.
- Experimental Fusion Reactors: Scientists are working hard to try and create controlled fusion on Earth, as it promises a clean, virtually limitless energy source.

Examples of Fusion

1. Deuterium (a hydrogen isotope with one proton and one neutron) fuses with Tritium (a hydrogen isotope with one proton and two neutrons) to form Helium, a neutron, and a lot of energy:

   $^{2}H+^{3}H\rightarrow^{4}He+n+energy$

2. Deuterium-Deuterium (D-D) Fusion

   $^{2}H+^{2}H\rightarrow^{3}He+n+Energy$

3. Proton-Proton Chain (Simplified Overall Reaction, as it's a multi-step process):

   $4\times^{1}H\rightarrow^{4}He+2e^{+}+2\nu_{e}+Energy$

Fission vs. Fusion

Aspect	Nuclear Fission	Nuclear Fusion
Process	Splitting a heavy nucleus into smaller ones	Combining light nuclei into a heavier nucleus
Natural Occurrence	Does not occur naturally (requires initiation)	Occurs naturally in stars (e.g., Sun)
Energy Released	High, but less per unit mass than fusion	Very high (3-4 times more than fission per unit mass)
Energy Requirement	Requires neutron bombardment	Requires extremely high temperature and pressure
Byproducts	Produces long-lived radioactive waste	Minimal radioactive waste (mostly stable helium)
Applications	Nuclear reactors (power), atomic bombs	Stars (natural), experimental fusion reactors (future power)
Safety Concerns	Radioactive waste disposal, meltdown risk	Technical challenges in containment, extreme conditions

Nuclear Power Generation - The Nuclear Reactor



Figure 4.8: *A nuclear reactor assembly*



Figure 4.9: *Nuclear reactor cooling towers*

A **nuclear reactor** is a complex machine designed to control nuclear chain reactions to generate electricity.

How a Nuclear Reactor Works (Simplified)

1. Fuel: Enriched uranium fuel rods (usually Uranium-235) are placed inside the reactor core.
2. Fission: Neutrons are absorbed by the uranium nuclei, causing them to fission and release heat energy. More neutrons are also released.
3. Moderator: A substance like water or graphite surrounds the fuel rods. It slows down the fast neutrons released from fission. These slower neutrons (called "thermal neutrons") are much better at causing more uranium atoms to split, keeping the chain reaction going efficiently.

4. Control Rods: Rods made of materials that absorb neutrons (like cadmium or boron) can be moved in or out of the core.
   a. Insert rods: Slows down the reaction by absorbing more neutrons.
   b. Withdraw rods: Speeds up the reaction by absorbing fewer neutrons.
   c. These rods control the rate of the chain reaction, preventing it from getting out of control (like in a bomb).
5. Coolant: A fluid (often water) circulates through the reactor core. It absorbs the tremendous heat generated by the fission reactions, preventing the reactor from overheating.
6. Heat Exchange & Steam Generation: The hot coolant then transfers its heat to a separate water loop in a steam generator. This boils water to produce high-pressure steam.
7. Turbine and Generator: The high-pressure steam is directed at a turbine, causing it to spin rapidly. The spinning turbine is connected to an electric generator, which converts this mechanical energy into electrical energy that can be sent to our homes.
8. Containment Structure: The entire reactor system is housed within a massive, strong containment structure (often made of thick concrete and steel). This acts as a final barrier to prevent any radioactive materials from escaping in case of an accident.

Diagrams of a Nuclear Reactor System

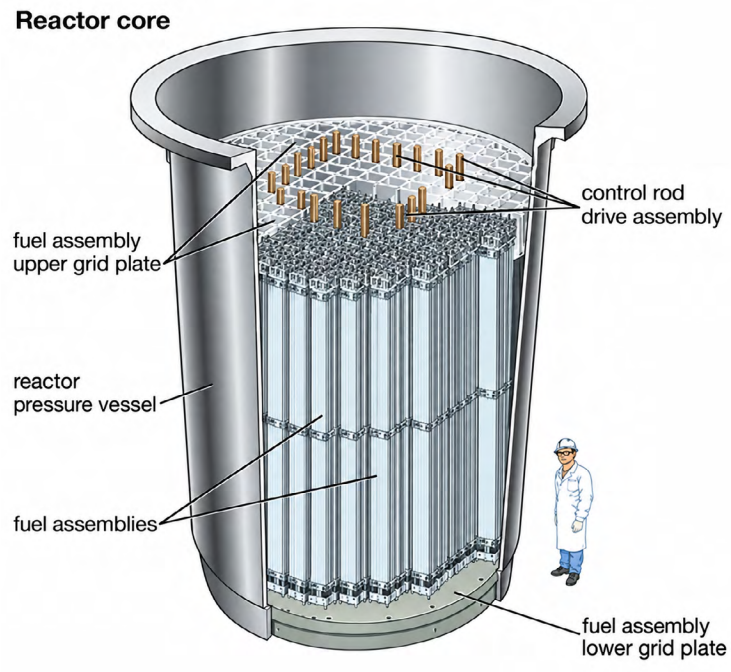


Figure 4.10: *A nuclear reactor core*

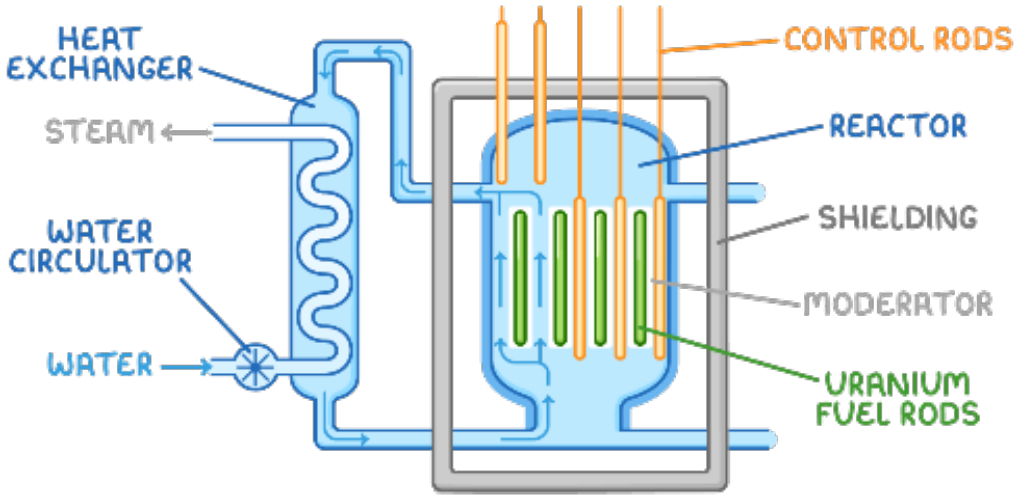


Figure 4.11: *A Nuclear reactor*

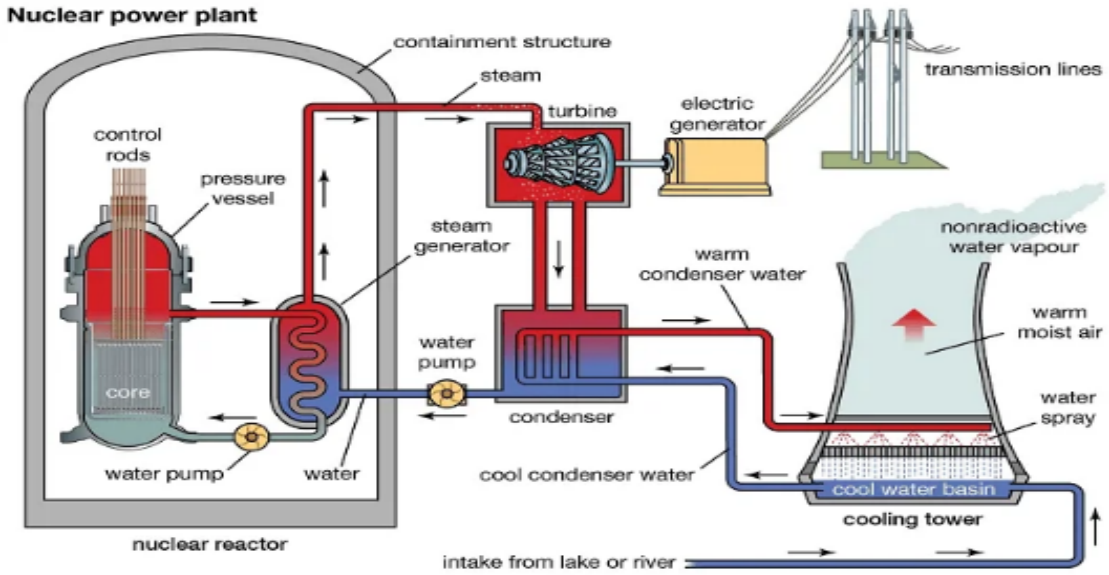


Figure 4.12: *A Nuclear power plant*

Hazards and Safety

Nuclear power is powerful, but it comes with risks:

1. Radiation Damage: Ionising radiation can harm living cells, causing DNA damage, mutations, cancer, and radiation sickness.
2. Radioactive Waste: Spent nuclear fuel and other materials become radioactive waste, which remains hazardous for thousands of years.
   a. Low-level waste: Stored in sealed containers in shallow landfills.
   b. High-level waste: Vitrified (turned into glass) and stored deep underground in secure geological repositories.

3. Accident Risk: Although rare, accidents like Chernobyl or Fukushima can release large amounts of radioactive material into the environment.



Figure 4.11: *Chernobyl nuclear disaster of 1986*

Safety Precautions

To manage these risks, strict precautions are taken:

1. Shielding: Using thick barriers of lead, concrete, or water to block radiation.
2. Distance: Keeping a safe distance from radiation sources.
3. Time: Minimising the duration of exposure.
4. Protective Clothing: Workers wear specialised protective gear designed to shield them from hazards.
5. Monitoring: Using devices like dosimeters to track radiation exposure.
6. Strict Regulations: Following international and national guidelines for operation and waste disposal.

Nuclear Stability

Nuclei with higher binding energy per nucleon (abbreviated to BE/A) are more stable because it requires more energy to break them apart. Iron-56 is the most stable nucleus.

Implications for Fission and Fusion

Fusion

Very light nuclei (like hydrogen isotopes) have relatively low BE/A. When they fuse to form heavier, more stable nuclei (moving *up* the BE/A curve towards iron), they release energy because the resulting nucleus has a higher binding energy per nucleon.

Fission

Very heavy nuclei (like uranium or plutonium) have lower BE/A compared to medium-sized nuclei. When they split into smaller, more stable nuclei (moving *up* the BE/A curve towards iron), they release energy because the fission products have a higher binding energy per nucleon than the original heavy nucleus.

Both fission and fusion are processes where the total binding energy of the system *increases*, leading to the release of energy as the nuclei move towards a state of greater stability.

In summary

You have learned that nuclear reactions convert a tiny bit of mass into a huge amount of energy, described by $E=mc^2$. This "missing" mass is called the mass defect, and it's directly related to the binding energy that holds the nucleus together. The more binding energy per nucleon (protons and neutrons) a nucleus has, the more stable it is!

Key Concepts to Remember

- Nucleons: Protons and neutrons, the particles that make up the nucleus.
- Atomic Number (Z): Number of protons.
- Mass Number (A): Total number of nucleons (protons + neutrons).
- Number of Neutrons (N): A - Z

Some formulae

1. Mass Defect (Δm)

   $\Delta m = [Z \times (mass\ of\ a\ proton) + N \times (mass\ of\ a\ neutron)] - (actual\ mass\ of\ the\ nucleus)$

2. Binding Energy (BE)

   $BE = \Delta m \times c^2$

   Or, using the conversion factor for amu to MeV:

   $BE = \Delta m\ (in\ amu) \times 931.5\ MeV/amu$

3. Binding Energy Per Nucleon (BE/A)

$$BE/A = \frac{Binding\ Energy}{Mass\ Number\ (A)}$$

Activity 4.6 Observing, Reflecting, and Discussing the Chernobyl Disaster

Objective: To understand what caused the Chernobyl nuclear disaster, what happened afterward, and what safety lessons were learned.

What you need

1. Access to the following videos
   a. The Chernobyl Disaster: How It Happened (Radio Free Europe/Radio Liberty) **(about 13 minutes)**

   b. Chernobyl Disaster 1986: What Really Happened? (On Demand News) **(about 4 minutes)**

2. Notebook or paper and pens/pencils for notes and group reflections
3. Quiet space for group viewing and discussion

What to do

1. **Form small groups**

   Gather where everyone can see and observe the videos clearly, and you have space for discussion.

2. **Watch or listen to the First Documentary**
   a. Play "The Chernobyl Disaster: How It Happened" video.
   b. Take notes on key points about what caused the disaster and its immediate effects.
   c. Pause at important moments as needed to discuss.

3. Watch the Second Documentary

a. Watch "Chernobyl Disaster 1986: What Really Happened?"

b. Note additional details, especially about the aftermath, health consequences, and long-term impacts on people and the environment.

c. Discuss any new information or perspectives this video provides.

4. Group Reflection and Discussion

Use the following guided questions to facilitate your reflection and discussion:

a. Causes

i. What were the main technical and human factors that caused the accident?

ii. How did the reactor design and safety protocol failures contribute?

b. Consequences

i. What were the immediate impacts on workers and nearby residents?

ii. What long-term effects on health, environment, and society are described?

iii. How large was the evacuation zone and how many people were relocated?

c. Safety Lessons

i. What safety measures and protocols were introduced or improved after the disaster?

ii. Why is radiation dangerous, and what precautions are important to protect people?

iii. What can nuclear power plants do to avoid accidents like Chernobyl in the future?

5. Write a Group Summary

a. Summarise your group's understanding of

i. The causes of the disaster

ii. Its major consequences

iii. The key safety lessons learned related to radiation hazards and nuclear power safety

b. Prepare to share this summary verbally or in writing with other groups or the class.

Activity 4.7 Comparing Fission and Fusion with Side-by-Side Animations

Objective: To help understand the differences between nuclear fission and nuclear fusion by watching animations, comparing what happens in each process, and creating a poster or model to show the steps

What you need

1. Devices with internet access to watch the following video animations or access diagrams:
   a. **Fission Animation**: Nuclear fission Atomic energy Animated



   b. **Fusion Animation**: Nuclear fusion - animated 3d program



2. Notebook or worksheet for notes and comparison table
3. Pens or pencils
4. Large paper or poster board (optional, for group summaries)
5. Markers, coloured pencils, large paper/poster board OR modelling clay, cardboard, foam, small balls/beads (for 3D models)
6. Scissors, glue, tape

What to do

1. Form Teams: Gather and set up your devices so everyone can see the videos or diagrams.
2. Observe both video animations or review diagrams showing nuclear fission and nuclear fusion processes side by side.
3. Focus on the sequence in each process: What initiates the process, what happens to the nuclei, and what is formed? Pause as needed to take notes or clarify points during viewing.

4. Work together to fill out a FOUR-ROW comparison chart in your notebook or on poster paper:

Comparison Point	Fission (What do you observe?)	Fusion (What do you observe?)
Source Nuclei		
Products		
Conditions Required		
Energy Output		

5. **Discuss as a Group**: Talk through each point in your chart:
   - **a.** Why do the source nuclei differ?
   - **b.** Which process needs higher temperatures and why?
   - **c.** Why is more energy released in fusion? Where in nature do we find each process?
   - **d.** Which of the two processes is considered safer as an electricity generation method? Why?

6. **Create a Poster or 3D Model**
   - **a.** Choose either **fission or fusion as your focus.**
   - **b.** Design a poster (with drawings and labels) OR build a 3D model using craft materials. Your model/poster MUST show:
     - **i.** Inputs: The starting materials/nuclei
     - **ii.** Process: What happens (splitting or joining)
     - **iii.** Outputs: Products formed (new nuclei, neutrons, etc.)
     - **iv.** Energy Released: **Visualise with arrows, explosion symbols, or labelled light/heat**
   - **c.** Use colour, labels, and creative touches!

7. Prepare a short explanation answering
   - **a.** Which process happens in stars?
   - **b.** Which process is used in nuclear reactors on Earth?
   - **c.** Point to your model or poster to describe the steps.

Activity 4.8 Exploring Nuclear Reactor Components

Objective: To help understand the main parts of a nuclear reactor and what each part does by using a diagram and matching activity.

What you need

1. Pen or pencil
2. Notebook or paper for notes
3. Labelled diagram of a nuclear reactor showing the key parts (shown below)

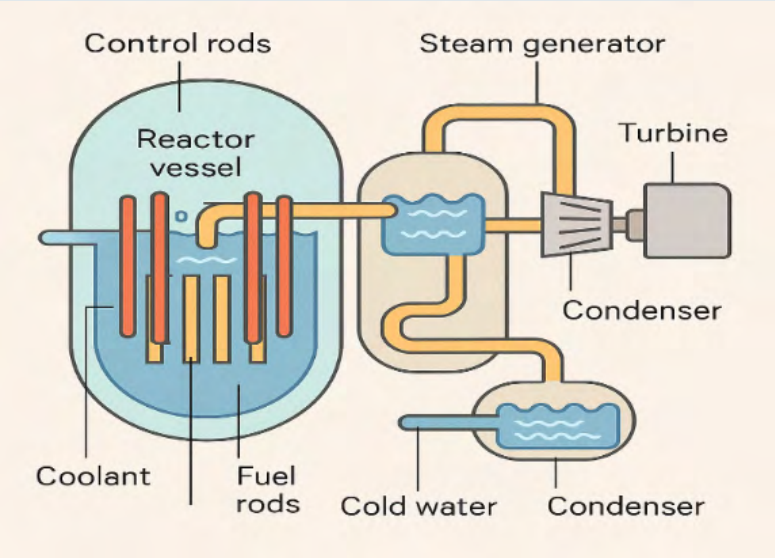


Figure 4.11: *Diagram of a nuclear reactor*

What to do

1. Find a partner to work with for this activity.
2. Review the diagram above and discuss.

   Take turns explaining each part's role to your partner, using the diagram for reference.
3. Look at the **Parts Table** and the **Functions Table below.** Match each **part (from Table 1)** to the correct function **(from Table 2).**
4. Write Your Matches in Your Notebook.

   For example, write: Number of the part → [Letter of the matching function] (1 → D)
5. Compare your matches with your partner and talk through any differences or questions.

Table 1: Nuclear Reactor Parts

Part Number	Part Name
1	Fuel Rods
2	Moderator
3	Control Rods
4	Coolant

Table 2: Nuclear Reactor Functions

Function	Function Description
A	Contains the uranium fuel where nuclear fission occurs.
B	Absorbs excess neutrons to control or stop the reaction.
C	Slows down fast neutrons to make the chain reaction more efficient.
D	Removes heat from the reactor core and carries it away.

Activity 4.9 Calculating mass defect and binding energy

Study the worked example below carefully before attempting the example questions that follow

Worked example 1

Carbon-12 (^{12}C) is a very common and stable isotope, used as the reference for the atomic mass unit.

a. How many protons and neutrons are in a Carbon-12 nucleus?

b. Calculate the

- **i.** expected total mass of its individual nucleons.
- **ii.** mass defect (Δm) for Carbon-12 in amu.
- **iii.** binding energy of the Carbon-12 nucleus in MeV.
- **iv.** binding energy per nucleon for Carbon-12 in MeV/nucleon.

(Atomic Number = 6, mass number = 12, actual atomic mass = 12.000000 amu, mass of proton =1.007276 amu, mass of neutron =1.008665 amu, 1 amu=931.5 MeV/amu)

Solution

a. Number of protons (Z) = 6

Number of neutrons (N) = Mass Number (A) - Atomic Number (Z)

= 12−6=6

So, Carbon-12 has 6 protons and 6 neutrons.

b. *Expected total mass of individual nucleons* = $(Z \times mp) + (N \times mn)$

i. *Expected mass* = $(6 \times 1.007276\ amu) + (6 \times 1.008665\ amu)$

Expected mass = $6.043656\ amu + 6.051990\ amu$

Expected mass = $12.095646\ amu$

ii. *Mass defect* (Δm) = *Expected mass* − *Actual atomic mass*

$\Delta m = 12.095646\ amu - 12.000000\ amu$

$\Delta m = 0.095646\ amu$

iii. *Binding Energy* (*BE*) *in MeV* = $\Delta m \times 931.5\ MeV/amu$

$BE = 0.095646\ amu \times 931.5\ MeV/amu$

$BE \approx 89.07\ MeV$

iv. $Binding\ Energy\ per\ Nucleon\ (BE/A) in\ MeV/nucleon = \frac{BE}{Mass\ Number\ (A)}$

$\frac{BE}{A} = \frac{89.07 MeV}{12\ nucleons}$

$BE/A \approx 7.42\ MeV/nucleon$

Worked example 2

Oxygen-16 (^{16}O) is the most abundant isotope of oxygen and plays a crucial role in life.

a. How many protons and neutrons are in an Oxygen-16 nucleus?

b. Calculate the

i. expected total mass of its individual nucleons.

ii. mass defect (Δm) for Oxygen-16 in amu.

iii. binding energy of the Oxygen-16 nucleus in MeV.

iv. binding energy per nucleon for Oxygen-16 in MeV/nucleon.

(Atomic Number = 8, mass number = 16, actual atomic mass = 15.994915 amu, mass of proton = 1.007276 amu, mass of neutron = 1.008665 amu, 1 amu = 931.5 MeV/amu)

Solution

a. Protons (Z) and Neutrons (N)

Number of protons $(Z) = 8$

Number of neutrons $(N) =$ *Mass Number* $(A) -$ *Atomic Number* (Z)

Number of neutrons $(N) = 16 - 8 = 8$

So, Oxygen $- 16$ *has* 8 *protons and* 8 *neutrons.*

b. Expected total mass of individual nucleons = (Z×mp)+(N×mn)

i. *Expected mass* $= (8 \times 1.007276\ amu) + (8 \times 1.008665\ amu)$

Expected mass $= 8.058208\ amu + 8.069320\ amu$

Expected mass $= 16.127528\ amu$

ii. *Mass defect* $(\Delta m) =$ *Expected mass* $-$ *Actual atomic mass*

$\Delta m = 16.127528\ amu - 15.994915\ amu$

$\Delta m = 0.132613\ amu$

iii. *Binding Energy* (BE) *in MeV* $= \Delta m \times 931.5\ MeV/amu$

$BE = 0.132613\ amu \times 931.5\ MeV/amu$

$BE \approx 123.51\ MeV$

iv. $\text{Binding Energy per Nucleon } (BE/A) \text{ in MeV/nucleon} = \dfrac{BE}{\text{Mass Number } (A)}$

$BE/A = \dfrac{123.51\ MeV}{16\ nucleons}$

$BE/A \approx 7.72\ MeV/nucleon$

Practice Problems

Now, using the worked example as a guide, solve the following problems individually or in groups.

1. Lead-208 (208Pb) is the heaviest known stable isotope and represents a very high point of stability among heavy nuclei.

   a. How many protons and neutrons are in a Lead-208 nucleus?

   b. Calculate the

      i. expected total mass of its individual nucleons.

      ii. mass defect for Lead-208 in amu.

      iii. binding energy of the Lead-208 nucleus in MeV.

iv. binding energy per nucleon for Lead-208 in MeV/nucleon.

(Atomic Number = 82, mass number = 208, actual atomic mass = 207.976652 amu, mass of proton =1.007276 amu, mass of neutron =1.008665 amu, 1 amu=931.5 MeV/amu)

c. Based on the BE/A values for Carbon-12, Oxygen-16, and Lead-208 (and recalling Iron-56 from your earlier problem), describe the general trend of binding energy per nucleon as the mass number increases, and explain what this trend means for nuclear stability and the possibility of fission or fusion.

Activity 4.10 Role-Play on Radiation Dangers and Waste Handling

Objective: To understand the dangers of radiation and how to safely handle radioactive waste by acting out different roles—like a nuclear worker, doctor, or environmental officer

What you need

1. Paper or notebook for notes and the worksheet
2. Pens or pencils
3. Optional: simple props like hats, badges, scarves to help with role playing
4. Reference books or internet devices for research
5. Large sheet of paper (optional) to summarise your findings

What to do

1. Form small groups of 3-6 people and assign roles within your group (Nuclear Worker(s), Doctor(s), Environmental Officer(s))
2. Research your role: Each person finds out about their role
   a. Nuclear Worker: How to recognise radiation hazards, importance of careful waste handling, what protective equipment is used.
   b. Doctor: What health risks radiation can cause and how to help people exposed to radiation.
   c. Environmental Officer: How radiation affects the environment and how to properly store and monitor radioactive waste.
3. Plan a Short Role-Play (3–5 minutes): Create a small scene where each role explains:
   a. What radiation dangers are present

b. What warning signs to look for (like the yellow trefoil symbol)

c. How to handle waste safely

d. What protective equipment to wear and why? Practice your dialogue so everyone knows their part.

4. Perform Your Role-Play

Act out your scene with your group. Be clear and loud enough so everyone listening can understand the dangers and safety steps.

5. Complete the Worksheet

On your worksheet or notebook

a. Draw or list 3 different radiation warning signs you learned about.

b. Draw or name 3 to 4 types of protective equipment (e.g., lead apron, gloves, dosimeter badge).

c. For each, write a short note about what it is and why it is important.

6. Share and Compare

If you can, show your worksheet and role-play with another group. Ask questions and learn new points from their work.

Activity 4.11 Revision of Atomic and Nuclear Physics Areas

Objective: To help review and understand key areas in atomic and nuclear physics by working in groups to explain, discuss, and summarise each topic.

What you need

1. Paper or notebooks for writing notes and summaries

2. Coloured pens, markers, or pencils

3. Large sheet(s) of paper, poster board, or digital device (optional) to make a summary poster

4. Textbooks, notes, or internet-enabled devices for research and reference

5. Calculators for calculations

6. Writing tools (pens, pencils, erasers)

What to do

1. Form a small group: Sit with your group and organise your materials.

2. Assign each member one or two topics from the list below to focus on

   a. Atomic models & energy of a photon
   b. Radioactivity & nucleus structure
   c. Balancing nuclear reactions
   d. Photoelectric effect & wave-particle duality
   e. X-rays & nuclear reactions
   f. Einstein's mass-energy relation and its application to nuclear reactors

3. Use your notes, learning material, books, or the internet to
   a. Write simple explanations or definitions
   b. Write important formulas (e.g., photon energy formula: $E = hf$)
   c. Draw diagrams if you can (like atomic models or nuclear reactions)
   d. Give examples or solve small problems if possible

4. Take turns explaining your topic to others in the group. Ask and answer questions about unclear points. Help each other understand key ideas.

5. Together, make a poster or chart that includes
   a. Clear bullet points for each topic
   b. Diagrams or formulas next to each summary
   c. Use colours or headings to divide sections clearly

6. Make and take a quiz
   a. Together, write 3 to 5 quiz questions based on all the topics.
   b. Take turns asking these questions and answering them as a group.
   c. Discuss answers and clarify any misunderstandings.

7. Reflect on your learning
   a. Talk about which topics were easiest or hardest.
   b. Discuss what helped you understand better.
   c. Think about what else you might like to explore more.

REVIEW QUESTIONS REVIEW QUESTIONS

Review Questions 4.1

1. A medical diagnostic centre in Accra is considering purchasing a new x-ray unit. They are evaluating two potential units based on the properties of the x-rays they produce:

Unit A: Produces x-rays with a wavelength of 0.05×10^{-9} metres.

Unit B: Produces x-rays with a frequency of 2.0×10^{18} Hz.

- **a.** Calculate the energy (in keV) of a single x-ray photon produced by **Unit A**.
- **b.** Calculate the energy (in keV) of a single x-ray photon produced by **Unit B**.
- **c.** Based on your calculations and the document's information on "soft x-rays" and "hard x-rays," recommend which unit (A or B) would be more suitable for detailed bone imaging in fracture diagnosis, and justify your recommendation by explaining how the energy of the x-rays relates to their penetrating power in the human body.

2. An x-ray machine used in a dental clinic produces photons with a wavelength of 0.025 nm.

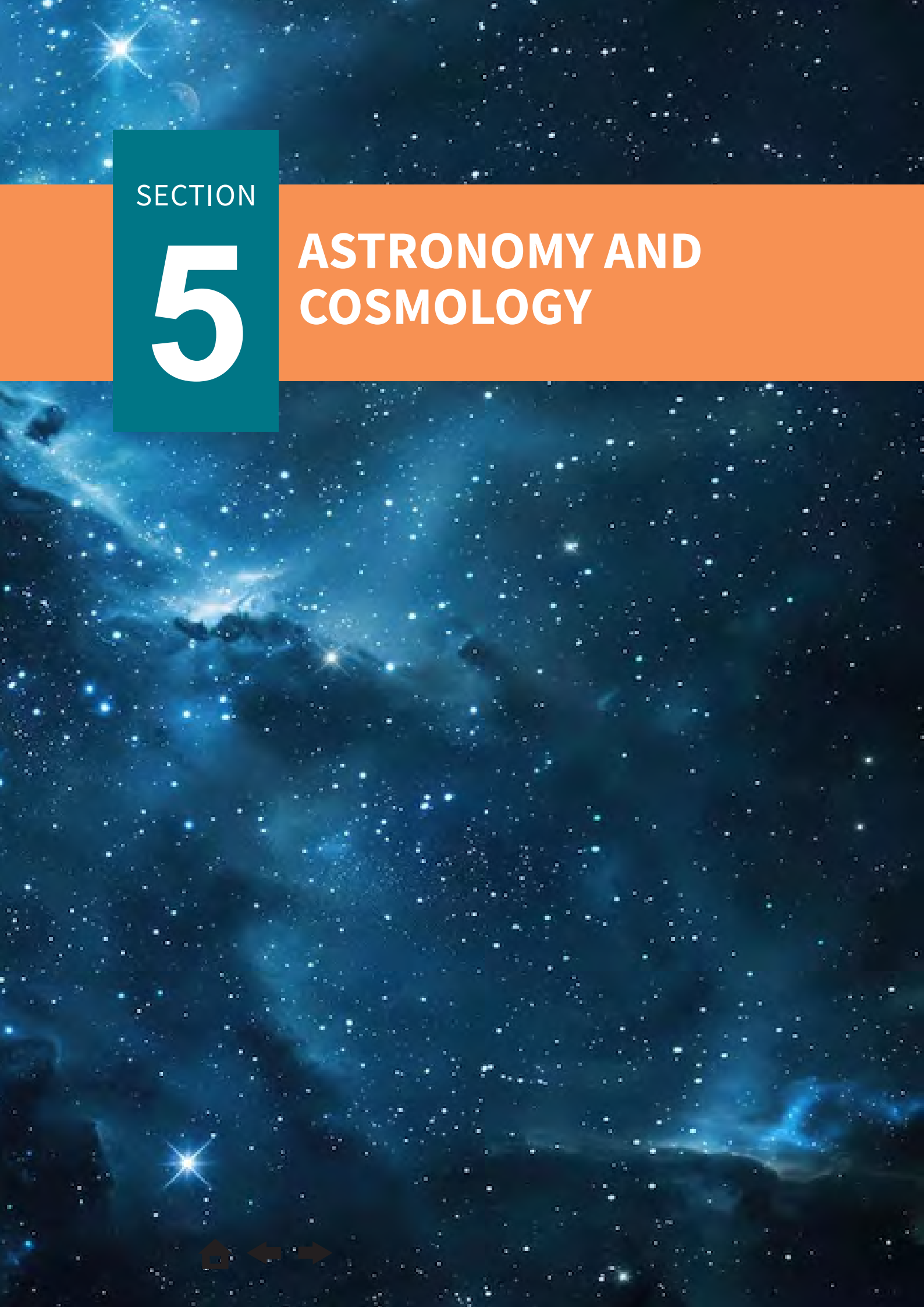
- **a.** Calculate the energy of a single photon in Joules.
- **b.** Calculate the frequency of these x-ray photons.
- **c.** If the accelerating voltage in the x-ray tube determines the maximum photon energy, what minimum accelerating voltage (in kilovolts) would be required to produce these x-rays?

3. In an x-ray tube, electrons are accelerated towards a tungsten target. The electrons impact the target, and x-rays are produced.

- **a.** Explain the two primary mechanisms by which x-rays are produced when accelerated electrons strike a target.
- **b.** If the x-ray tube operates with an accelerating voltage of 80 kV, what is the shortest wavelength (cutoff wavelength) of the x-rays produced?

Review Questions 4.2

Investigate why many African countries are hesitant to adopt nuclear power despite energy shortages, then create a balanced argument for whether Ghana should invest in nuclear technology or focus on renewable alternatives.



SECTION

5

ASTRONOMY AND COSMOLOGY

BASIC PHYSICS

INTRODUCTION

This section explores the structure, origin, and components of the universe through both scientific and cultural views. You will investigate foundational concepts such as the Big Bang theory, the formation and evolution of stars and galaxies, and the role of dark matter and dark energy. The section also highlights how indigenous cultures interpret celestial phenomena, emphasising astronomy's relevance to daily life, agriculture, and traditions. You will discover different galaxy types, celestial bodies like comets and meteors, and Ghana's growing involvement in space science through initiatives like the Ghana Radio Astronomy Observatory.

KEY IDEAS

- **Astronomical Structures**: The universe has a layered structure from particles to stars, galaxies, and superclusters, shaped by gravity and dark matter.
- **Big Bang and Evidence**: The origin of the universe is best explained by the Big Bang theory, supported by redshift, cosmic microwave background, and elemental abundances.
- **Cultural Astronomy**: Indigenous beliefs and practices use celestial bodies for timekeeping, agriculture, and rituals, offering valuable non-scientific perspectives.
- **Formation of Stars and Planets** : Stars and planetary systems form in nebulae through gravitational collapse and accretion processes.
- **Galaxies and Phenomena**: Galaxies vary in shape and size, and the universe includes dynamic objects like comets, asteroids, meteors, and black holes.
- **Space Science Applications**: Astronomy advances technology, communication, and development, with institutions like Ghana's GRAO contributing to global research.

THE UNIVERSE: ORIGIN, STRUCTURE AND CULTURAL PERSPECTIVES

Have you ever looked up at the night sky from your town such as Accra, Ho, Keta, Koforidua, Tamale, etc and wondered how it all began? What are those tiny points of light made of, and how did they get there? For thousands of years, humans across the globe have asked these very questions. In this module, we will embark on an incredible journey to explore the Universe – from its mysterious birth to its colossal structures, and how diverse cultures, including those from our own African continent, have sought to understand its deepest secrets.

The Origin of the Universe - The Big Bang Theory

Cosmology

Cosmology is the scientific study of the Universe's origin, evolution, and large-scale structure. It is about piecing together the story of everything, from the smallest particles to the grandest galaxies.

The Dominant Theory

The Big Bang Theory is the leading scientific model for the origin of our Universe. It proposes that the Universe began about **13.8 billion years ago** from an extremely hot, dense point (a **singularity**), and has been expanding and cooling ever since. It is not an explosion in space, but rather an expansion *of* space itself, carrying galaxies along with it.

Key Evidence Supporting the Big Bang Theory

Scientists do not just "believe" in the Big Bang; they have gathered strong observational evidence:

The Expanding Universe (Hubble's Law & Redshift)

1. In the 1920s, astronomer Edwin Hubble observed that galaxies are moving away from Earth, and the farther away a galaxy is, the faster it is receding. This phenomenon is called **redshift** (like the Doppler effect for light – light from receding objects is stretched towards the red end of the spectrum).
2. This observation strongly suggests that the Universe is expanding, just as the Big Bang theory predicts. Imagine dots on an inflating balloon – as the balloon expands, the dots move farther apart from each other. This analogy is helpful because it helps us to understand that there is no 'centre' of

expansion; no matter which dot you focus on, all the other dots are moving away from it (and the greater the distance between dots, the greater the speed at which they are moving apart).

Cosmic Microwave Background (CMB) Radiation

1. This is perhaps the strongest evidence! The Big Bang theory predicted that the early Universe was extremely hot and dense, like a fiery fog. As it expanded and cooled, this "fog" should have cleared, leaving behind a faint glow or "afterglow" of radiation spread uniformly across the entire sky.
2. In 1964, Arno Penzias and Robert Wilson accidentally discovered this faint radiation, which we now call the **Cosmic Microwave Background (CMB)**. It is a uniform "hum" of microwaves coming from every direction. These microwaves were once waves of a much higher energy and shorter wavelength but have stretched with expanding space. They provide a snapshot of the Universe when it was only about 380,000 years old. It's the "echo" of the Big Bang.

Abundance of Light Elements

1. The Big Bang theory predicts that during the first few minutes after the Big Bang (a process called **nucleosynthesis**), the extreme temperatures and pressures would have fused the initial fundamental particles into specific proportions of light elements: mainly **hydrogen** (about 75%), **helium** (about 25%), and trace amounts of **lithium**.
2. Astronomical observations of the actual proportions of these elements in the oldest parts of the Universe match these predictions almost perfectly. This is strong confirmation of the early Big Bang processes.

Large-Scale Structure of the Universe

1. Simulations based on the Big Bang model, incorporating gravity and dark matter (which we will discuss later), predict that matter should have clumped together over billions of years to form the "cosmic web" – giant filaments of galaxies separated by vast empty "voids."
2. Observations of the distribution of galaxies and galaxy clusters on the largest scales perfectly match these theoretical predictions, further supporting the Big Bang.

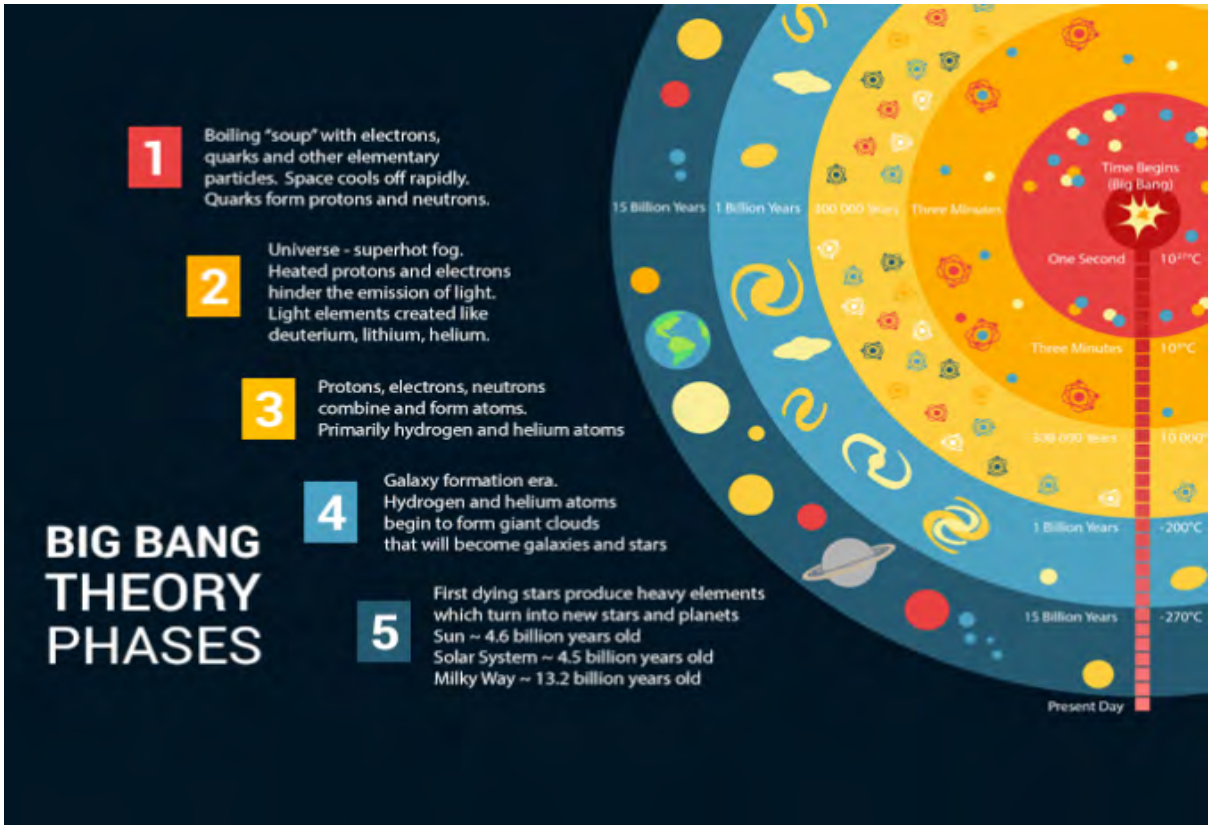


Figure 5.1: *A diagram showing the Big Bang theory*

The Early Universe

We consider the history of the Universe, spanning 13.8 billion years, as a few key periods

1. 10-43 seconds (Planck Epoch): The Universe is unimaginably hot and dense, all four fundamental forces (gravity, electromagnetism, strong nuclear, weak nuclear) are unified. Our current physics breaks down here.
2. 10-36 to 10-32 seconds (Inflationary Epoch): The Universe undergoes an incredibly rapid, exponential expansion. This smooths out irregularities and sets the stage for the large-scale structure we see today.
3. 10-12 seconds to 3 minutes (Quark, Lepton, Nucleosynthesis Epochs): Fundamental particles (quarks, leptons) form, then combine to form protons and neutrons. As it cools, these protons and neutrons fuse to form the first atomic nuclei: hydrogen and helium.
4. 380,000 years (Recombination/Decoupling): The Universe cools enough for electrons to combine with nuclei, forming the first neutral atoms. This allows photons (light) to travel freely for the first time, creating the Cosmic Microwave Background (CMB) we observe today. The Universe becomes transparent.

5. 200 million years (Dark Ages End, First Stars and Galaxies): Gravity begins to pull together the slightly denser regions of matter. The first stars ignite, ending the "Dark Ages" and reionising the universe. These stars clump together to form the first galaxies.
6. Today (13.8 billion years): The universe continues to expand, stars are born and die, galaxies merge, and complex structures evolve.

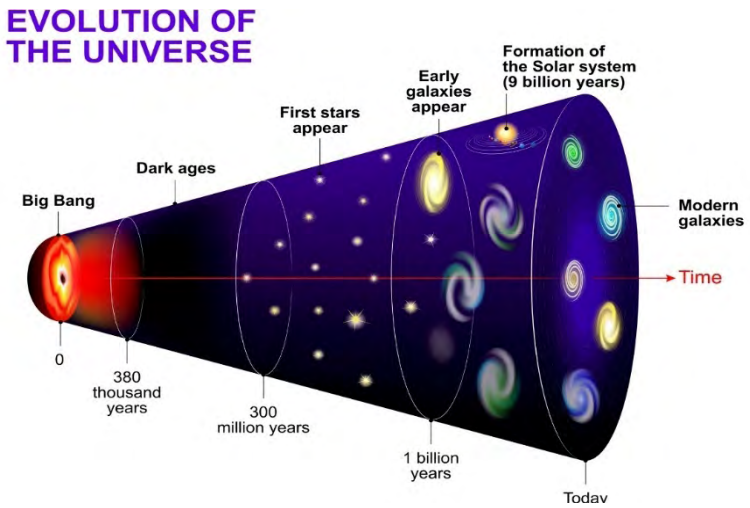


Figure 5.2: *A diagram showing the evolution of the universe*

The Structure of the Universe - From Particles to Cosmos

The Universe is not just a random collection of objects; it has a beautiful and organised hierarchical structure, held together by the fundamental force of **gravity**.

The Cosmic Hierarchy (from Small to Large)

1. Subatomic Particles: The most basic building blocks – quarks (which make up protons and neutrons) and leptons (fundamental particles which cannot be broken down, like electrons).
2. Atoms: Protons, neutrons, and electrons combine to form atoms, primarily hydrogen and helium (from the Big Bang), and heavier elements forged inside stars.
3. Stars: Giant balls of hot, glowing plasma and gas, primarily hydrogen and helium, held together by their own gravity. They generate light and heat through nuclear fusion. Stars have life cycles: they are born in nebulae, burn for millions or billions of years, and then die, sometimes explosively as supernovae, scattering heavier elements into space. Our Sun is a star.
4. Planets and Planetary Systems: Celestial bodies that orbit stars. Our solar system includes Earth and seven other planets orbiting the Sun.

5. Galaxies: Enormous collections of billions to trillions of stars, gas, dust, and dark matter, all bound together by gravity. Galaxies come in different shapes:
   a. Spiral Galaxies: Like our own Milky Way, with a central bulge and spiral arms.
   b. Elliptical Galaxies: Oval or spherical in shape, often older with less gas and dust.
   c. Irregular Galaxies: Without a defined regular shape.
6. Galaxy Clusters and Superclusters: Galaxies are not evenly distributed. They clump together into galaxy clusters (tens to thousands of galaxies), which in turn form even larger structures called superclusters (collections of many clusters, spanning hundreds of millions of light-years).
7. The Cosmic Web: On the very largest scales, superclusters are arranged in a vast, filamentary network known as the cosmic web, with huge empty spaces called voids between the filaments.

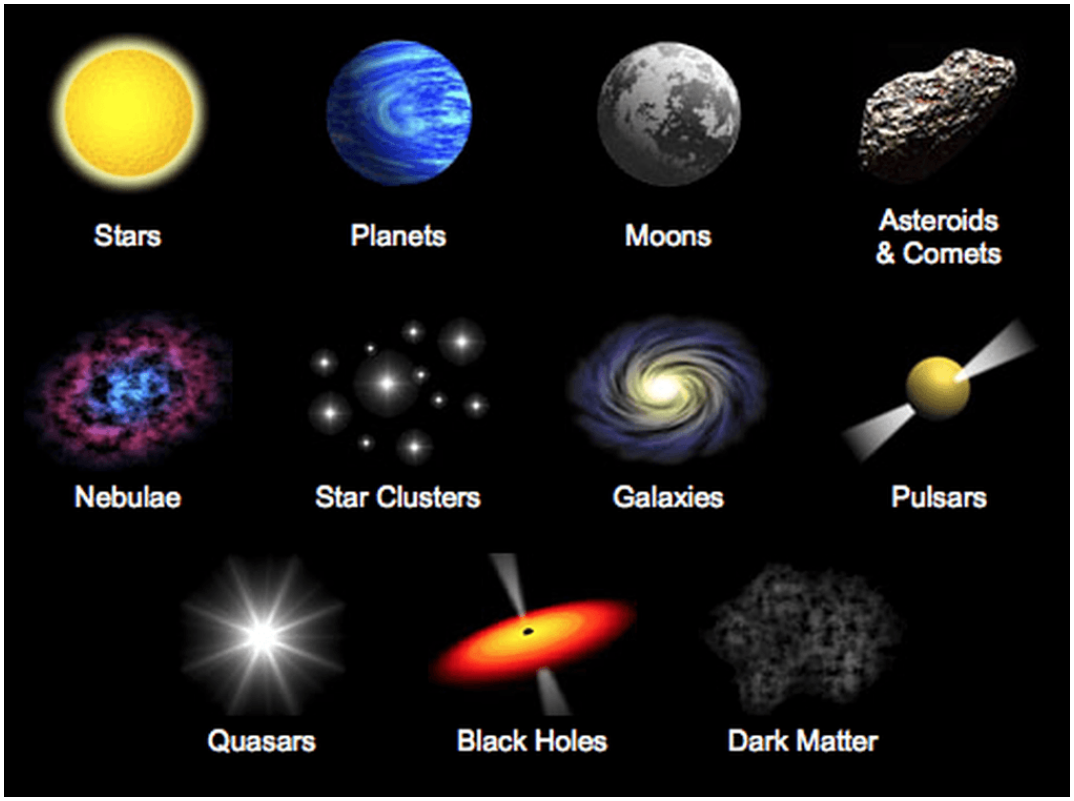


Figure 5.3: *A grid of twelve illustrated astronomical objects*

The Mysterious Composition of the Universe: Ordinary, Dark, and Dark Energy

What is the Universe actually made of? It turns out, the matter we can see and interact with is only a tiny fraction!

Ordinary (Baryonic) Matter (5%)

1. This is the "stuff" we are familiar with – protons, neutrons, electrons, and the atoms they form.
2. It includes everything from stars, planets, and galaxies to gas and dust clouds. We can detect this matter directly (by light, radio waves, etc.).

Dark Matter (27%)

1. This is a mysterious substance that does not emit, absorb, or reflect light, making it invisible to telescopes.
2. We infer its existence through its gravitational effects. For example, galaxies rotate much faster than they should if they only contained visible matter; extra gravity from dark matter explains this. Galaxy clusters also show evidence of more mass than their visible components.
3. Its exact nature is one of the biggest unsolved mysteries in cosmology. It's likely made of a type of particle we have not discovered yet.

Dark Energy (68%)

1. This is an even more mysterious form of energy that is thought to be responsible for the accelerated expansion of the Universe.
2. Observations show that the expansion of the Universe is not slowing down due to gravity but is actually speeding up! Dark energy acts like an anti-gravitational force, pushing space apart.
3. Its nature is also unknown, but it's the dominant component of the Universe's energy density.

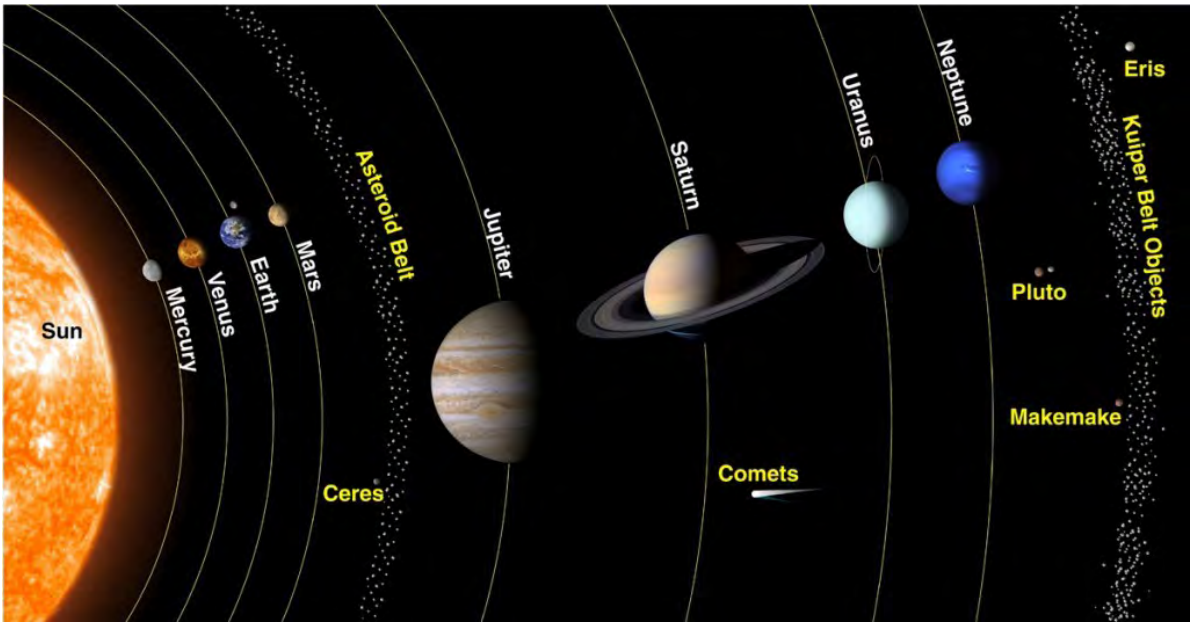


Figure 5.4: *A diagram showing the planets of the solar system*

The Lifecycle of a Star

All stars, including our Sun, are born in giant clouds of gas and dust called nebulae. Here is how it happens.

1. Gravity pulls gas and dust together, forming a dense ball called a protostar.
2. As it collapses, the temperature and pressure at the centre increase.
3. When the centre becomes hot enough, nuclear fusion begins—hydrogen atoms combine to form helium, releasing energy.
4. The star begins to shine. This is the birth of a main-sequence star.

Around the newly formed star, the leftover gas and dust form a rotating disc. Over time, this material sticks together to form:

a. Planets
b. Moons
c. Asteroids and comets

This process is called accretion. **Accretion** is the process by which small particles of dust and gas in space come together to form larger objects like planets.

It begins in a protoplanetary disk, a flat, rotating ring of material that surrounds a young star. This disk is made up of tiny grains of rock, ice, and gas. At first, these grains stick together through weak forces like static electricity, forming pebbles and small rocks. As these rocks grow, their gravity increases, pulling in more material around them. Over time, they become planetesimals—large, solid objects

that can be tens or hundreds of kilometres across. When planetesimals collide and stick together, they form even larger bodies called protoplanets.

Eventually, these grow into the planets we know today. Accretion is a slow process, taking millions of years, but it explains how planets form naturally from the leftover material after a star is born. You can think of it like raindrops in a cloud combining to make larger drops – gravity acts like a glue that pulls more and more material together. Earth, along with the other planets in our solar system, formed this way about 4.6 billion years ago.

Cultural perspective

Before modern science, people used observation and tradition to understand the sky. In many cultures, including those in Ghana and across Africa, the stars, the Moon, and the Sun were carefully studied to guide farming, fishing, festivals, and religious ceremonies.

For example:

- Farmers looked at star patterns to decide when to plant or harvest.
- The phases of the Moon were used to plan market days, funerals, or rituals.
- Many communities passed down folktales and songs that describe how stars appeared or what they meant.

This knowledge is passed on orally and remains important in many areas today. It may not use the same language as science, but it reflects careful observation and deep understanding.

Science and culture are not enemies—they are two ways of understanding the same world. Scientific astronomy explains how stars and planets form and how the universe behaves. Cultural astronomy reflects how people interpret what they see in the sky and how they connect it to life.

Activity 5.1 Exploring the Universe – Visible and Invisible Components

Objective: To develop a foundational understanding of the universe by exploring its visible and invisible components through group discussion, observation, and creative mapping.

What you need

1. Notebook or paper for each group member
2. Pen or pencil

3. Optional: Internet-enabled device for quick research (if available)
4. Large paper or whiteboard (optional, for group notes or drawing a concept map)

What To do

1. Form small groups (3-5 people) and sit together in a way that allows easy sharing of ideas
2. Start by sharing your thoughts on what the word *universe* means to you. Write a simple group definition for the universe based on your discussion.
3. Together, make a list of things or objects in the universe that you can see or observe directly. Write down your list.
4. Discuss what might exist but cannot be seen directly with the naked eye or even normal telescopes. Write down these invisible or hidden components.
5. Share why some parts of the universe are visible and others are invisible.
6. Discuss how science helps us learn about invisible components (e.g., through microscopes, telescopes, detectors). Think about the scale of the universe, from the very small (particles inside atoms) to the very large (galaxies and beyond).
7. On a large sheet of paper or whiteboard, draw a concept map with the word "Universe" at the centre. Branch out to "Visible Components" and "Invisible Components" with examples under each. Use arrows, colours, or drawings to make connections and visualise your ideas.
8. Present your lists, concept map, or summary to another group or to the whole class. Listen to other groups' ideas and add any new insights to your notes.

Activity 5.2 Creating a Tactile or Visual Timeline of the Universe

Objective: To research and present the major stages in the universe's formation in the correct sequence by creating a tactile or visual timeline that clearly shows when key events happened and why they are important.

What you need

1. Long sheet of paper, cardboard strip, string, or masking tape (to lay out the timeline)
2. Index cards or sticky notes (for labelling events)

3. Coloured markers, pens, or pencils
4. Scissors, glue/tape
5. Optional: Modelling clay, buttons, beads, or small objects (for tactile timeline)
6. Books, internet or textbooks for research
7. Ruler (to keep spacing neat)

What to do

1. **Form small groups of 3-5 people**. Sit together with your materials on a table or the floor.
2. As a group, use textbooks, online resources, or classroom posters to find the main stages in the universe's early history. Examples of stages you might include:
   a. The Big Bang
   b. Formation of basic particles (protons, neutrons, electrons)
   c. Formation of hydrogen and helium atoms
   d. First light (cosmic microwave background)
   e. Formation of the first stars
   f. Formation of galaxies
3. Stretch out your long paper, cardboard, string, or tape on a flat surface — this is the base of your timeline. Decide one end will be the "Beginning" (Big Bang) and the other the "Recent Past" (galaxy formation).
4. **Create and Place Event Markers**
   a. For each key event, write a short description and the approximate time after the Big Bang it occurred (e.g., "380,000 years: First atoms form").
   b. Use index cards/sticky notes, or create event models (clay particles, beads for atoms, star sticker for first stars, etc.)
   c. Place or attach these events to the correct order on your timeline. Try to space them in proportion (e.g., use more space for longer intervals).
   5. As you build, discuss what happened at each stage. On your timeline, add short notes or keywords to highlight why each event is important.

6. Walk through your finished timeline as a group, explaining the sequence and significance of each stage.
7. Visit other groups' timelines and compare approaches.
8. Tape your timeline to a wall, display it on a table, or keep it rolled for sharing in class or with family/friends.

Activity 5.3 Building 3D or Textured Models of Galaxies and Solar Systems

Objective: To visualise some of the systems and groups of astronomical bodies found in our universe.

What you need

1. Modelling clay or playdough (various colours)
2. Cardboard, paper plates, or thick paper (for bases)
3. Scissors, glue, and tape
4. String, yarn, pipe cleaners (for orbits or connecting parts)
5. Aluminium foil, bottle caps, beads, buttons, and small balls (for planets, stars, etc.)
6. Markers or coloured pencils
7. Toothpicks or wooden skewers (optional, for support)
8. Paint (optional, for added detail)
9. Old magazine cutouts, cotton balls, glitter, or sequins (for texture and decoration)
10. Ruler (for measuring distances between objects)
11. Notebook or paper for sketching your design plan

What to do

1. **Form small Groups**

   Gather your materials and workspace. Decide if your group will build a model of a specific solar system, a type of galaxy (spiral, elliptical, irregular), or both.

2. Use textbooks, the internet, or pictures to look at examples of galaxies or solar systems. Note key features: galaxy shapes, arrangement of stars,

spiral arms or central bulges, layout of planets around the sun, asteroid belts, etc.

3. **Plan Your Model**
   - **a.** Draw a sketch of what your finished model will look like.
   - **b.** Decide which materials you will use for different parts (e.g., clay for planets, string for orbits, beads for stars).
4. **Build the Base**
   - **a.** Use cardboard, paper plates, or thick paper to create a sturdy base.
   - **b.** For a galaxy, sketch spiral arms or overall shape as a guide.
   - **c.** For a solar system, mark spots for the sun, planets, and orbits.
5. **Create the Parts**
   - **a.** Galaxy: Shape spiral arms with clay or string, add stars (beads, buttons, foil balls) along the arms, make a bright core.
   - **b.** Solar System: Make planets of varying sizes from clay or foil, use a large ball or sphere for the sun, and show orbits with yarn or pipe cleaners.
6. **Assemble the Model**
   - **a.** Attach all components securely with glue or tape.
   - **b.** Arrange the galaxies' features or solar system's planets in correct order or position.
   - **c.** Add texture—cotton for nebulae, glitter for star clusters, coloured markers for detail.
7. **Label and Explain**
   - **a.** Label key parts using small paper tags or directly on the base (e.g., Sun, Earth, Spiral Arm, Galactic Centre).
   - **b.** Write a short group note or card explaining the features you chose and any creative touches.
8. **Display and Share**
   - **a.** Present your model to the rest of the class or your group.
   - **b.** Walk others through the main features and why you designed it that way.
   - **c.** View and discuss the models made by other groups.

Activity 5.4 Local Stories, Proverbs, or Beliefs About the Stars or Moon

Objective: To explore and understand local stories, proverbs, or beliefs about the stars and moon, and compare them with scientific explanations.

What you need

1. Notebook or paper and pens/pencils for note-taking
2. Device with internet access (optional, for researching additional stories or scientific facts)
3. Poster paper, chart paper, or digital presentation tools (PowerPoint, Google Slides)
4. Coloured markers, pencils, or other art supplies for creative presentation
5. Space to display posters or to share presentations

What to do

1. Form small groups of 3-5 people.
2. **Collect Local Stories and Beliefs**
   - **a.** Research or talk to family members, teachers, friends, or community elders to find stories, proverbs, or beliefs about the stars or moon in your local culture.
   - **b.** Write down or record these stories clearly.
3. **Share Within the Group**
   - **a.** Each member shares the stories or beliefs they collected.
   - **b.** Discuss the meanings and cultural significance of these stories.
   - **c.** Choose the most interesting or meaningful stories to present.
4. **Research Scientific Concepts**
   - **a.** Together, find simple scientific explanations related to your stories:
     - **i.** What are stars and how do they shine?
     - **ii.** What is the moon really like? Why does it change shape (phases)?
     - **iii.** Why do we see marks or shapes on the moon?
     - **iv.** How do science and astronomy explain eclipses, moons, and star patterns?
     - **v.** How do science and astronomy explain the seasons, solstices and equinoxes in countries further from the equator.

b. Use books, the internet, or other sources to gather the scientific facts.

5. **Create a Creative Presentation**
   - **a.** Prepare a poster or digital presentation that includes:
     - **i.** The local stories or proverbs with short summaries or quotes.
     - **ii.** Artistic elements like drawings, symbols, or decorations inspired by the stories.
     - **iii.** Scientific explanations that relate to or contrast with the stories. Use simple diagrams if helpful (e.g., moon phases, star formation).
     - **iv.** A comparison section highlighting how the cultural stories and scientific facts relate or differ.
6. **Display and Present**
   - **a.** Present your group's work to other groups or classmates.
   - **b.** Explain both the cultural stories and the scientific ideas clearly.
   - **c.** Invite questions or comments from others to encourage discussion.

Activity 5.5 Creating a Flowchart on the Formation of Stars and Planets

Objective: To understand how stars and planets are formed by working together to create a step-by-step flowchart with simple drawings or tactile models.

What you need

1. Large sheets of paper, cardboard, or poster board (for the flowchart)
2. Markers, coloured pencils, or crayons
3. Scissors and glue or tape
4. Sticky notes or small index cards (for stages/steps)
5. Modelling clay, yarn, cotton balls, beads, or small objects (for tactile/model elements)
6. Ruler (for neat layout)
7. Books or internet access for quick research (optional)

What to do

1. **Form small groups of 2-4 people**

   Gather your materials and sit together where everyone can help and share ideas.

2. **Research the Main Stages**

   a. As a group, look up or recall the sequence of events in the formation of stars and planets.

   b. Typical key steps include:

   i. Nebula (cloud of gas and dust) forms

   ii. Parts of the nebula condense due to gravity

   iii. Protostar forms in the densest region

   iv. Nuclear fusion starts—star is "born"

   v. Leftover material creates a rotating disc

   vi. Dust and gas clump together—planetesimals form

   vii. Planetesimals collide and grow—planets form around the new star

   c. Extension: Continue your flowchart by researching the stages beyond the stable / main sequence phase of a star like our Sun. How will it eventually 'die'?

3. **Design the Flowchart Structure**

   a. Decide together whether your flowchart will be vertical (down the page) or horizontal (across the page) or even shaped like a spiral or timeline.

   b. Draw boxes/arrows for each main step. Number the steps and leave space in each box for both text and a drawing or tactile model.

4. **Add Drawings or Tactile Representations**

   For each stage

   a. Make a small drawing showing what is happening.

   b. OR create a tactile model (e.g., use cotton balls for a nebula, clay for planets, beads for stars, yarn for spinning discs).

   c. Attach your drawings or 3D/tactile elements to each box/step in the flowchart.

5. Write a brief, clear sentence or two in each box describing what happens at that stage
6. **Review and Present**
   a. Walk through your flowchart as a group, explaining each step to make sure everyone understands.
   b. Display your finished flowchart on the wall or show it to other groups or friends.
   c. Allow others to touch and move the tactile parts to explore how stars and planets form.

EXPLORING GALAXIES AND CELESTIAL PHENOMENA: SCIENTIFIC AND CULTURAL PERSPECTIVES

Galaxies

A collection of gas, dust, and millions or billions of stars (and their solar systems) is called a galaxy. A galaxy is held together by gravity. Our galaxy, the Milky Way, also has a supermassive black hole in the middle. When you look up at stars in the night sky, you're seeing other stars in the Milky Way.

Components of a Galaxy

1. Stars: The most prominent feature, ranging from tiny red dwarfs to colossal blue giants.
2. Gas and Dust: Called the "interstellar medium," this material fills the space between stars and is the raw material for new star formation.
3. Dark Matter: An invisible substance that makes up most of a galaxy's mass, inferred by its gravitational effects on visible matter.
4. Stellar Remnants: The "dead" cores of stars, like white dwarfs, neutron stars, and black holes.
5. Central Supermassive Black Hole: Most large galaxies, including our own, are believed to harbour a supermassive black hole at their very centre.

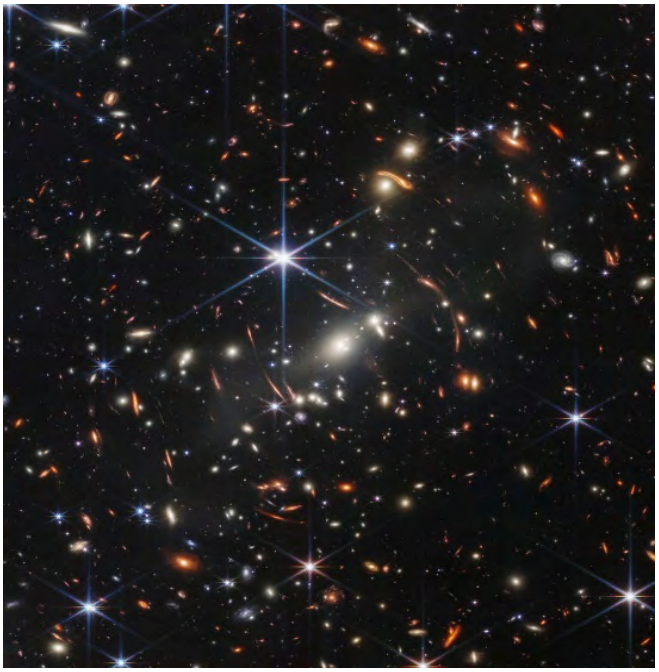


Figure 5.5: *A diagram showing collection of galaxies*

Types of Galaxies

Galaxies come in a variety of shapes and sizes:

1. **Spiral Galaxies**
   a. Appearance: Characterised by a flat, rotating disk with a central bulge and prominent spiral arms that wind outwards. These arms are regions of active star formation, making them appear brighter and bluer.
   b. Examples: Our Milky Way Galaxy is a barred (the arms initially appear straight before curving back on themselves) spiral galaxy, as is the famous Andromeda Galaxy.
   c. Star Content: Contain a mix of young, hot stars (in the arms) and older stars (in the bulge and halo).
2. **Elliptical Galaxies**
   a. Appearance: Range from nearly spherical to highly elongated (cigar-shaped). They have no distinct spiral arms and appear smooth and featureless.
   b. Star Content: Mostly composed of older, redder stars, with very little gas and dust, indicating that star formation has largely ceased.
   c. Size: Can range from tiny dwarf ellipticals to the largest galaxies in the Universe.

3. **Irregular Galaxies**
   a. Appearance: Do not have a regular, defined shape. They are often chaotic in appearance.
   b. Star Content: Contain abundant gas and dust, and are often sites of intense star formation, giving them a bluish hue.
   c. Origin: Many irregular galaxies are thought to be the result of gravitational interactions or collisions between other galaxies.
   d. Examples: The Magellanic Clouds (small companion galaxies to the Milky Way) are irregulars.

Our Home Galaxy (The Milky Way)

When you look up at the night sky from Accra and see that hazy band of light stretching across it, you are looking towards the centre of our own galaxy, the Milky Way, edge-on.

It is a **barred spiral galaxy**, estimated to contain between 200 and 400 billion stars. Our Solar System, including Earth, is located in one of its spiral arms (the Orion Arm), about two-thirds of the way out from the centre. At the very centre of the Milky Way lies a supermassive black hole called **Sagittarius**.



Figure 5.6: *A Diagram of some types of galaxies*

Astronomers study galaxies by observing the light they emit across different wavelengths. At the Ghana Radio Astronomy Observatory (GRAO), for example, scientists use radio waves to investigate galaxies and other distant objects that are not visible with regular telescopes. Radio astronomy makes it possible to study space even during the day or through clouds and dust that block visible light.

Beyond stars and galaxies, the universe contains other fascinating objects known as **celestial objects.** These include comets, asteroids, meteoroids, meteors, meteorites, and exoplanets. These objects vary in size, material, movement, and visibility.

A comet is a body made mostly of ice and dust. It travels in a long orbit around the Sun. As a comet approaches the Sun, the heat causes its icy surface to release gas and dust, forming a bright glowing tail that points away from the Sun (it does not 'trail behind' the comet, which is a common misconception). The tail and the fuzzy head of the comet can sometimes be seen in the sky without a telescope.

An asteroid is a rocky object that orbits the Sun, mostly found between the orbits of Mars and Jupiter in a region known as the asteroid belt. Some asteroids occasionally come close to Earth. They are irregular in shape and vary in size from small rocks to large bodies hundreds of kilometres wide.

A meteoroid is a smaller rock or metal fragment travelling through space. When a meteoroid enters Earth's atmosphere and burns up, it creates a bright streak of light known as a meteor, or what is commonly called a shooting star. If a part of the meteoroid survives the journey and lands on Earth, it is called a meteorite.

Exoplanets are planets that orbit stars outside our solar system. Thousands of them have been discovered using powerful telescopes and by analysing the behaviour of the stars around which they orbit. Some of these planets may have conditions suitable for life, which makes them a major focus of current astronomical research.

Stars: The Cosmic Furnaces

Stars are born in dense clouds of gas and dust (nebulae) through the force of gravity. Once a star forms, it spends most of its life on the **main sequence**, fusing hydrogen into helium in its core, releasing immense amounts of energy as light and heat (like our Sun). The **life cycle of a star** depends on its mass:

1. Sun-like Stars: End their lives as red giants, then shed their outer layers to form a planetary nebula, leaving behind a dense, hot core called a white dwarf.
2. Massive Stars: End their lives much more dramatically, expanding into red super giants, and then collapsing in a spectacular explosion called a supernova. The remnant can be an incredibly dense neutron star or, if the star was massive enough, a black hole.

Nebulae: Stellar Nurseries and Remnants

Nebulae are vast clouds of gas (mostly hydrogen and helium) and dust in space.

1. Star-forming Nebulae: Some nebulae are "stellar nurseries" where new stars are born (e.g., the Orion Nebula).
2. Planetary Nebulae: These are the beautiful, expanding shells of gas shed by dying Sun-like stars.
3. Supernova Remnants: The expanding clouds of gas and dust left behind after a supernova explosion (e.g., the Crab Nebula).

Black Holes: Gravity's Ultimate Pull

A **black hole** is a region of spacetime where gravity is so strong that nothing, not even light, can escape. The boundary beyond which nothing can escape is called the **event horizon**. **Stellar-mass black holes** form from the collapse of very massive stars at the end of their lives. **Intermediate-mass black holes** are formed when clusters of stars or small galaxies collapse together under the force of gravity. **Supermassive black holes** (millions to billions of times the Sun's mass) are at the centres of most large galaxies and cause by the strong gravitational field and high density of matter in that area.

Supernovae: Cosmic Explosions

A **supernova** is a powerful and luminous stellar explosion. It is the catastrophic death of a massive star, or the sudden reignition of a white dwarf in a binary system.

Significance: Supernovae are crucial for life in the Universe because they are the primary factories for creating and dispersing most of the heavy elements (like carbon, oxygen, iron, gold, and uranium) into space. These elements then become the building blocks for new stars, planets, and even life itself. Without supernovae, there would be no elements heavier than iron.

Quasars and Active Galactic Nuclei (AGN)

Some galaxies have extremely bright centres, known as **Active Galactic Nuclei (AGN)**. The most luminous type of AGN is a **quasar**. These phenomena are powered by supermassive black holes at the galaxy's centre that are actively accreting (sucking in) vast amounts of gas and dust. As the matter spirals into the black hole, it heats up to extreme temperatures, emitting tremendous amounts of

radiation across the electromagnetic spectrum, making the core brighter than the entire rest of the galaxy.

Each of the celestial objects described above play a role in helping scientists understand the origin and structure of the solar system, the formation of planets, and the likelihood of life elsewhere in the universe. By comparing them, you can begin to develop a deeper understanding of how dynamic and diverse space truly is.

Cultural Perspective

As science provides tools for explaining how celestial phenomena work, many cultures including those in Ghana have their own interpretations of what these events mean. Cultural astronomy refers to the way communities use the sky for storytelling, ritual, timekeeping, and guidance. This includes beliefs, symbols, myths, and ceremonies associated with celestial bodies and events. Eid-ul Fitr and Easter Sunday are dependent on the sighting of the crescent moon.

For example, in some communities, the appearance of a bright comet may be seen as a sign of change or warning. A shooting star might be interpreted as a message from ancestors, a soul transitioning, or an omen. Full moons often mark the time for communal gatherings, spiritual activities, or farming rituals. Constellations are identified in local terms and used to predict seasonal changes or navigation patterns.

These beliefs are usually passed on through oral traditions—stories, proverbs, songs, dances, and rituals—and form part of indigenous knowledge systems. Although they differ from scientific explanations, they are based on real observation and are used to organise social, agricultural, and spiritual life. This knowledge is important and should be respected as part of the broader human understanding of the cosmos.

Comparing cultural beliefs with scientific models allows learners to appreciate both ways of knowing. For example, a scientific explanation might describe a meteor as a rock burning up in Earth's atmosphere, while a cultural belief might interpret it as a star falling, sent by a spirit or a deity. Both views carry meaning, one from physical observation and the other from social or spiritual symbolism.

By exploring both scientific and cultural understandings, we gain critical thinking skills and cultural awareness. So, we must not reject one view in favour of another but to understand how different perspectives serve different purposes.

Space exploration is not only about satisfying curiosity about what lies beyond our world; it plays a crucial role in advancing technology, improving life on Earth, and preparing for the future. As you begin to understand galaxies, stars, and celestial phenomena, it is important to see how this knowledge connects to real-world benefits.

Real-world Benefits of Space Exploration and Studying Celestial Phenomena

Many of the tools and services we rely on today, such as mobile phones, satellite television, weather forecasts, and GPS navigation, are all made possible through technologies developed for space science. Even areas like agriculture and health benefit from space research. Satellites monitor soil moisture, track changes in forest cover, and observe ocean currents. In medicine, materials and techniques used in space exploration have inspired innovations in surgery and drug delivery systems.

In Ghana, space science and technology are emerging as important contributors to national development. The Ghana Space Science and Technology Institute (GSSTI) leads efforts to build capacity in astronomy, satellite technology, and atmospheric science. In Kuntunse, the Ghana Radio Astronomy Observatory (GRAO) is already part of global space research, using radio waves to study black holes, galaxies, and pulsars. Ghana is also contributing to the African Very Long Baseline Interferometry Network, which links radio telescopes across Africa into a continent-wide observatory.



Figure 5.7: *Image of Ghana radio astronomy observation*

Activity 5.6 Comparing Galaxy Types with Astronomy Benefits for Ghana

Objective: To learn about the three main types of galaxies by researching their features, creating visual or 3D models, and comparing their differences and similarities.

What you need

1. Devices with internet access (for research) and/or textbooks
2. Large sheets of paper, poster board, or cardboard for diagrams
3. Drawing materials (coloured pencils, markers, crayons) with scissors, glue and tape
4. Modelling clay, playdough, yarn, beads, or other crafting materials (for tactile models)
5. Notebook or paper and pens/pencils for notetaking and writing explanations
6. Optional: Presentation space (wall, table, or digital slideshow tools)

What to do

1. Form small groups of 3 to 5 people. Work together and decide how to divide the tasks.
2. Research the three types of galaxies: Find information on each galaxy type:
   a. Spiral Galaxies
   b. Elliptical Galaxies
   c. Irregular Galaxies
3. Use diagrams or pictures from your sources to understand their shapes and features.
4. Create Visual or Tactile Diagrams
   a. Using drawing or craft materials, create a diagram or 3D model for each galaxy type.
   b. Clearly label parts like spiral arms, central bulge, or explain the "irregular" nature.
   c. Use colour, shapes, and textures to help distinguish features (e.g., blue for young stars in spirals, smooth round shapes for ellipticals).

5. Talk about the differences and similarities between the three galaxy types focusing on:
   - **a.** Shape and structure
   - **b.** Star populations (age and amount)
   - **c.** Presence of gas and dust
   - **d.** Star formation activity
6. Note these comparisons in your notebook and discuss why space exploration matters.
7. Based on your class discussions and research, list ways Ghana benefits from astronomy.
8. Arrange your galaxy diagrams/models and comparison notes clearly on a poster or slide show. Include a section explaining the importance of space exploration and Ghana's benefits from astronomy. Use visuals and concise bullet points for clarity.
9. Present your work to another group or the class.
10. Explain the galaxy types, their features, why space exploration is important, and Ghana's gains from astronomy. Answer questions and engage in discussions to deepen understanding

Activity 5.7 Discussing Differences Between Comets, Asteroids & Meteors

Objective: To understand the differences between comets, asteroids, meteors, and meteorites by researching and discussing their features.

What you need

1. Devices with internet access (or printed materials) containing information on comets, asteroids, meteors, and meteorites
2. Images or diagrams illustrating these space objects
3. Notebook or paper and pens/pencils for notetaking
4. Large paper or poster board (optional) for creating a group summary or mind map
5. Coloured markers or pencils for illustrations and notes

What to do

1. Form small groups of 3 to 5 people. Sit together so everyone can see the materials and participate in discussion.
2. Use the internet or printed resources to find information about
   a. Asteroids: Rocky objects orbiting the Sun, mostly found in the asteroid belt between Mars and Jupiter, generally larger than meteoroids.
   b. Comets: Icy bodies orbiting the Sun, composed of ice, dust, and rocky material; when near the Sun, they develop glowing comas and tails.
   c. Meteoroids: Small fragments of asteroids or comets in space, pebble-sized or smaller.
   d. Meteors: Meteoroids entering Earth's atmosphere, burning up and creating bright streaks of light called "shooting stars."
   e. Meteorites: Meteoroids that survive passing through the atmosphere and land on Earth's surface.
3. Discuss how these objects differ in composition, size, location, origin, and observable effects. Take notes summarising these differences.
4. Ensure that you include a comparison of how the path of a comet differs from the path of a planet. Research and then sketch a diagram to help to visualise the similarities and differences.
5. Each group member shares any local or cultural stories, proverbs, or beliefs heard about shooting stars, comets, or other bright celestial objects.
6. Discuss the meaning and significance of these stories in your culture. Write down the cultural ideas shared.
7. Compare the cultural beliefs with the scientific facts you researched. Discuss questions like:
   a. How do stories explain phenomena before science understood them?
   b. Why can the opposing explanations of phenomena by science and from different cultures cause friction between different groups of people? Who may these groups be?
   c. Why might people create these cultural stories?

8. Use large paper or poster board to organise your notes. Divide into sections such as:
   a. Scientific definitions and differences between space objects
   b. Cultural beliefs and stories
   c. Scientific explanations of those stories
9. Decorate with drawings or diagrams to visualise your ideas.
10. Present your discussion summary or mind map to other groups or classmates. Explain both the scientific facts and cultural stories clearly.
11. Listen to other groups' stories and scientific findings to broaden understand

Activity 5.8 Mapping Ghana's Benefits from Space Science

Objective: To explore and show how space science helps Ghana in different ways—like communication, weather forecasting, farming, and education—by creating an infographic.

What you need

1. Poster paper, chart paper, or cardboard (for the infographic base)
2. Markers, coloured pencils, or crayons
3. Scissors, glue, and tape
4. Old magazines, newspapers, or printouts (for cutting images)
5. Computer/tablet (optional, for research or digital design)
6. Sticky notes or index cards (for organising ideas)
7. Photos, small craft items (optional: for decorations)
8. Notebook or paper for taking notes

What to do

1. Form small groups of 3 to 5 people.

   Sit together and organise your materials.
2. Research Ghana's space science benefits: Use books, the internet, or classroom resources to find out:
   a. How satellites improve communication (TV, internet, phone networks).

b. How space technology helps with weather forecasting, climate monitoring, or disaster alerts.

c. How farmers use satellite images for agriculture (predicting rain, tracking crops).

d. How space science encourages STEM (Science, Technology, Engineering, Mathematics) education and inspires students to study science.

e. Any national organisations (e.g., Ghana Space Science and Technology Institute) and their roles.

f. Use local news stories or posters for extra ideas.

3. Brainstorm and organise your data

a. Write down each benefit on a sticky note or index card.

b. Group similar ideas together (e.g., all communication uses; all weather/earth observation uses).

c. Decide what visuals, symbols, or images to use for each field (e.g., a satellite for communication, a cloud and sun for weather, a graduation cap for STEM).

4. Design the infographic layout

a. Choose a creative format: a map of Ghana with icons, a web connecting different benefits, or columns for each field.

b. Arrange your points so viewers can easily see which fields are helped by space science.

c. Draw or paste images, icons, and arrows linking space science to its benefits.

5. Add explanations and decorations

a. Next to each picture or icon, write a short, clear explanation (1–2 sentences) saying how Ghana benefits in that area.

b. Use bold colours, headings, and neat handwriting for impact and clarity.

c. Decorate with borders, symbols, or any creative craftwork you like.

6. Review, present and share

a. Walk through your infographic as a group to check that all benefits are clearly shown and explained.

b. Present your infographic to the class or another group, explaining what you learned and why these benefits matter for Ghana.

c. Answer questions and listen to other groups' ideas.

Activity 5.9 Scientific & Cultural Explanations of a Celestial Phenomenon

Objective: To explore and compare how science and culture explain the same sky event like a lunar eclipse or a shooting star and to creatively present both views

What you need

1. Devices with internet access or printed materials for research (books, articles, videos)
2. Notebook or paper and pens/pencils for notes and scripts
3. Large paper, poster board, or digital presentation tools (Google Slides, PowerPoint)
4. Art supplies (markers, coloured pencils, scissors, glue, tape)
5. Optional: Costumes or props for role-play
6. Space for presentations or a display area for posters and narratives

What to do

1. Form small groups of 3 to 5 people. Sit together and choose one celestial phenomenon your team will explore (examples: lunar eclipse, shooting star, the Milky Way, comets).
2. Research Both Perspectives
   - **a.** Collect scientific explanations about the phenomenon: how and why it happens according to astronomy (e.g., causes, physical details).
   - **b.** Gather cultural beliefs, stories, myths, or proverbs from different cultures related to the same phenomenon. These might come from local, indigenous, or historical traditions.
   - **c.** Take notes on key points from both sides.
3. Plan a Creative Presentation

   Choose one of the following methods to share your comparison:

   - **a.** Role-Play: Assign team members roles, e.g., a scientist explaining the phenomenon and a storyteller or elder sharing the cultural tale.

Act out a dialogue or short scene where both views are presented and discussed.

b. Storytelling: Narrate the cultural story with dramatic flair, then follow with the scientific explanation, highlighting differences and similarities. Use visuals or props as support.

c. Dual-Narrative Display: Create a poster or digital slide with two columns or sections—one for the scientific view, one for the cultural story. Use drawings, symbols, and brief texts to showcase both perspectives side by side.

4. Prepare Supporting Materials

a. Write scripts or bullet points for your presentation.

b. Create visuals: drawings, charts, or simple props that represent key ideas or symbols.

c. Practice your roles or narration so everyone is confident.

5. Present Your Work

a. Share your role-play, storytelling, or display with other teams or the class.

b. Emphasise the value in both scientific and cultural viewpoints and how they help people understand the sky and its mysteries differently but meaningfully.

c. Be open to questions or discussions afterward.

6. Reflect as a Team

a. After presenting, discuss what you learned from combining science and culture.

b. Consider how cultural stories connect people to the cosmos in ways science does not, and how science explains the "how" behind the phenomena.

REVIEW QUESTIONS

1. Describe the main difference between an asteroid, a comet, and a meteoroid.
2. How does the observed abundance of light elements (Hydrogen, Helium, Lithium) support the Big Bang theory?

SECTION

6

ALTERNATING CURRENT



ALTERNATING CURRENT THEORY

INTRODUCTION

This section introduces you to the fundamental concepts and applications of alternating current (AC), building on earlier knowledge of wave motion from Year 2. It explores how AC differs from direct current (DC) in behaviour and characteristics. You will study various AC waveforms, analyse sinusoidal signals using mathematical relationships, and investigate the roles of resistors, capacitors, and inductors in series AC circuits. The section also introduces the concepts of reactance, impedance, power factor, and the power triangle, helping learners to understand real-world applications such as energy transmission and power factor correction in industrial settings. Through hands-on activities, you will measure, interpret, and calculate AC parameters and appreciate their significance in electrical systems.

KEY IDEAS

- **Capacitive reactance** decreases with increasing frequency, allowing more current to flow through a capacitor in AC circuits.
- **Current leads voltage by 90°** in a purely capacitive circuit, due to the capacitor's opposition to voltage change.
- **Inductive reactance** increases with increasing frequency, reducing the current flow through an inductor in AC circuits.
- **In a purely resistive circuit**, voltage and current are in phase, meaning they reach their peak values at the same time.
- **Resonance** occurs in an RLC circuit when inductive and capacitive reactances are equal, resulting in minimum impedance and maximum current.
- **The power factor** is the cosine of the phase angle between voltage and current, indicating how efficiently power is used in an AC circuit.

FUNDAMENTALS OF ALTERNATING CURRENT (AC)

Welcome, Electrical Engineers-In-Training!

Think about how electricity powers your home, charges your phone, and lights up your school. Most of the electricity you use every day has an Alternating Current (AC)… but what exactly is AC, and how is it different from the Direct Current (DC) you might get from a battery?

Here, we will explore the fascinating world of AC, learning about its unique characteristics, different forms, and how we describe it mathematically. Get ready to understand the power that moves our modern world!

Alternating Current (AC)

You have already learned about Direct Current (DC). Remember how a battery pushes electrons in one continuous direction, like water flowing steadily through a pipe?

Alternating Current (AC) is different! Imagine the water in that pipe sloshing/oscillating back and forth, continuously reversing its direction. That's AC! The direction of the flow of electric charge (electrons) periodically reverses.

Why AC?

AC is incredibly important because it's much more efficient to transmit over long distances than DC (from power plants to your home) and can be easily converted to different voltage levels using transformers.

Key Characteristics of AC

1. **Periodic Variation**

   The voltage and current in an AC circuit are not constant. Their strength (magnitude) and direction continuously change, repeating the same pattern over and over again at regular intervals. This regular, repeating pattern is what we call "periodic variation."

   Period (T) is the time it takes for one complete cycle of the AC waveform to occur. It is the shortest time after which the waveform exactly repeats itself. It's measured in seconds (s).

2. **Amplitude (Peak Value)**

   This is the maximum value that the voltage or current reaches during a cycle. It represents the "highest point" or the "strongest" instantaneous value the wave attains. We denote peak voltage as V_o and peak current as I_o.

3. **Instantaneous Value**

   In an AC circuit, the voltage and current are constantly changing. The value of the voltage or current at any specific moment in time (t) is called its instantaneous value.

   a. For a sinusoidal AC, the value typically starts from zero, increases to a maximum (peak), then decreases back to zero. After passing zero, it reverses direction, increases to a maximum (peak) in the opposite direction, and then returns to zero, completing one cycle.

   b. Instantaneous voltage is denoted as V(t) in volts (V), and instantaneous current as I(t) in amperes (A).

4. **Waveform**

   This is the shape of the graph you get when you plot voltage or current against time. It visually represents how the electrical quantity varies over time. The most common and efficient waveform for power distribution is the sinusoidal (sine) wave.

5. **Time-varying Direction (and Analogy)**

   Unlike Direct Current (DC), where the flow is in one consistent direction, the direction of the current flow in AC constantly reverses.

   Analogy for easy understanding

   Imagine the two pins of your phone charger (ignoring the earth pin if it has three). One is called the live pin, and the other is called the neutral pin. At one instant, current flow *into* the live pin and *out of* the neutral pin. A fraction of a second later, this reverses: current flows *out of* the live pin and *into* the neutral pin. This back-and-forth flow happens repeatedly as long as the phone is plugged into power.

6. **Frequency (f)**

   Building on the idea of the current constantly reversing direction (as explained in points 1 and 5), Frequency (f) tells us how many complete cycles of the AC waveform happen every second. It's measured in Hertz (Hz).

   a. In Ghana, the frequency of mains electricity is 50 Hz. This means the current completes 50 full back-and-forth cycles every single second.

b. Since each complete cycle involves the current changing its direction twice (from positive to negative flow, and back again from negative to positive flow), a 50 Hz supply means the current actually reverses its direction 100 times every second.

Relationship between Frequency and Period

Frequency and period are inversely related: $f = \frac{1}{T}$. If the frequency is high, the period is short (many cycles per second). If the frequency is low, the period is long (fewer cycles per second). This is the same inverse relationship you've seen in other types of wave propagation.

Types of AC Waveforms

The waveform is the visual representation of how AC voltage or current changes over time. While the sine wave is 'king' for power, other shapes exist and are used in different electronic applications.

1. **Sinusoidal Waveform (Sine Wave)**
   a. Shape: Smooth, continuous, and symmetrical oscillation. It looks like a mathematical sine curve.
   b. Where it's used: This is the standard waveform for electricity supplied to your homes and businesses by power plants. It's efficient for long-distance transmission.

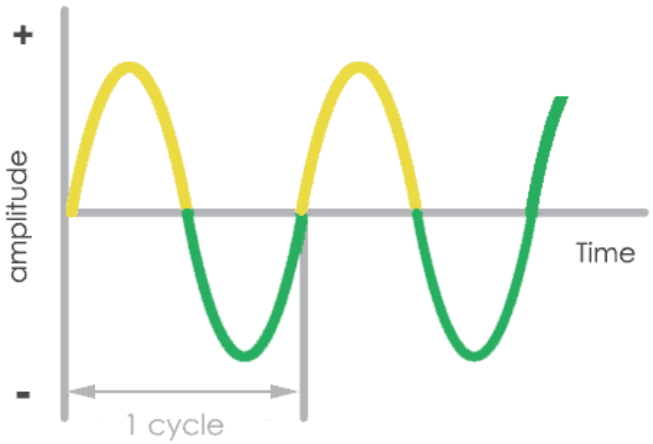


Figure 6.1: *Sine wave*

2. **Square Waveform**
   a. Shape: Abruptly switches between two constant voltage (or current) levels, staying at each level for a period before switching again. It looks like a series of squares.

b. Where it is used: Very common in digital electronics (e.g., computers, microcontrollers) where signals are either "on" (high voltage) or "off" (low voltage). Also used in some power inverters to create an AC signal from DC.

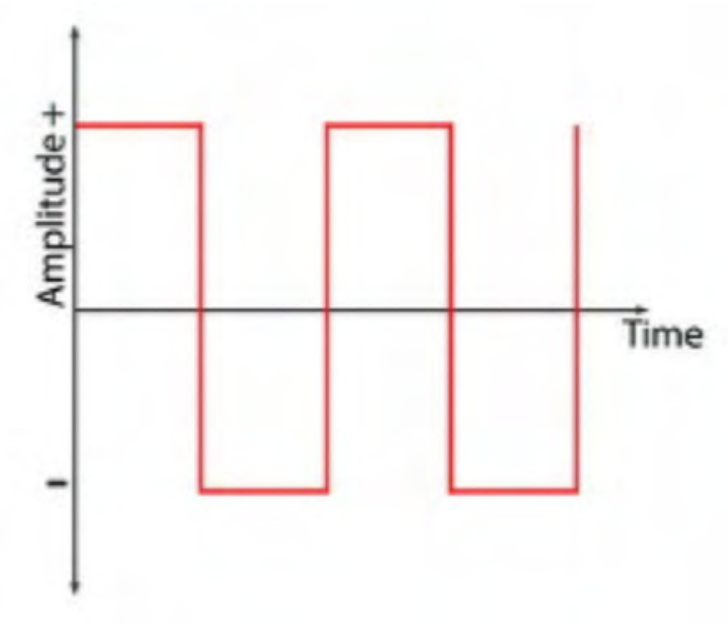


Figure 6.2: *Square wave*

3. Triangular Waveform

a. Shape: Changes linearly with time, rising at a constant rate and then falling at a constant rate. Looks like a series of triangles.

b. Where it's used: Found in some electronic circuits like sweep generators and in music synthesisers for creating certain sounds.

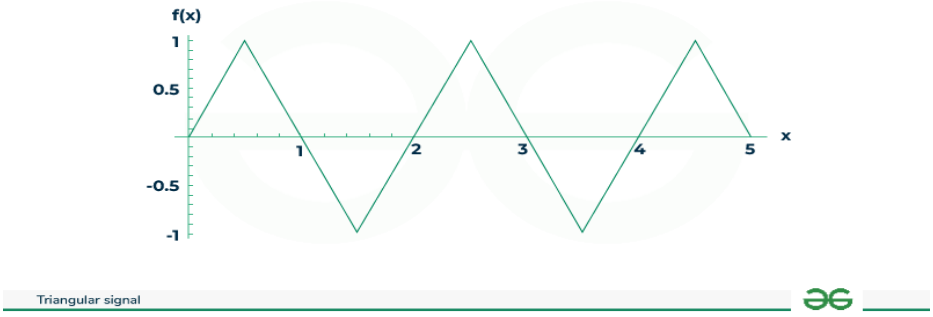


Figure 6.3: *Triangular wave*

4. Sawtooth Waveform

a. Shape: Rises linearly with time and then drops abruptly back to its starting level. Looks like the teeth of a saw.

b. Where it's used: Commonly used in old television sets and oscilloscopes for scanning electron beams across the screen (sweep circuits), and also in some audio applications.

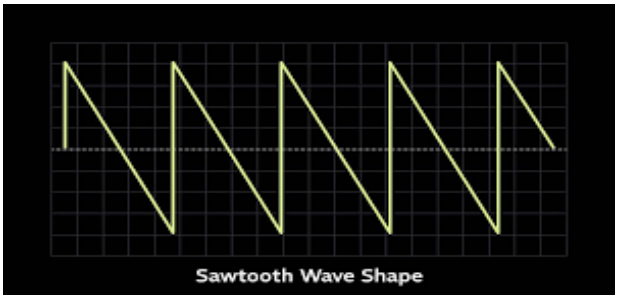


Figure 6.4: *Sawtooth waveform*

Mathematical Relationships of AC Voltage and Current

Since AC voltage and current vary continuously, we use mathematical equations to describe their instantaneous values at any given time. For sinusoidal AC (the most common type), these are sine functions:

Instantaneous Voltage: $V(t) = V_o \sin\omega t$

Instantaneous Current:: $I(t) = I_o \sin\omega t$

Where:

V(t) = Instantaneous voltage at time t

I(t) = Instantaneous current at time t

V_o = Peak (maximum) voltage (Amplitude)

I_o = Peak (maximum) current (Amplitude)

$\omega = 2\pi f$ = angular frequency (radians per second)

t = time (seconds)

These equations describe a smooth wave oscillating between $+V_o$ and $-V_o$ (or $+I_o$ and $-I_o$) over time.

Root Mean Square (RMS) Values

When you hear about the voltage of a household outlet (like "240 V" in Ghana), that's not the peak voltage. It's the Root Mean Square (RMS) value!

The RMS value of AC voltage or current is a measure of its effective value. It's the equivalent DC voltage or current that would deliver the *same amount of power* to a load. Because an AC voltage is constantly changing, its average value over a full cycle is zero (it goes positive and negative). RMS gives us a way to describe its "power equivalent."

Formulae for RMS Values:

$$RMS\ Voltage\ (V_{rms}) = \frac{V_o}{\sqrt{2}}$$

$$RMS\ current\ (I_{rms}) = \frac{I_o}{\sqrt{2}}$$

RMS values are used for most practical applications

1. Specifying voltage ratings for household outlets.
2. Current ratings for circuit breakers and wires.
3. Calculating power in AC circuits (Power =VrmsIrms).

Multimeter

When you use a multimeter to measure AC voltage or current, it typically displays the RMS value.

Activity 6.1 Comparing Alternating Current (AC) and Direct Current (DC)

Objective: To help learners visually observe, compare, and understand the key differences between Alternating Current (AC) and Direct Current (DC) in terms of current direction, voltage behaviour, waveform shape, and typical uses.

What you need

1. Paper or notebook
2. Pen or pencil
3. Printed or digital copy of the voltage vs. time diagram showing AC and DC waveforms (like the provided image below)

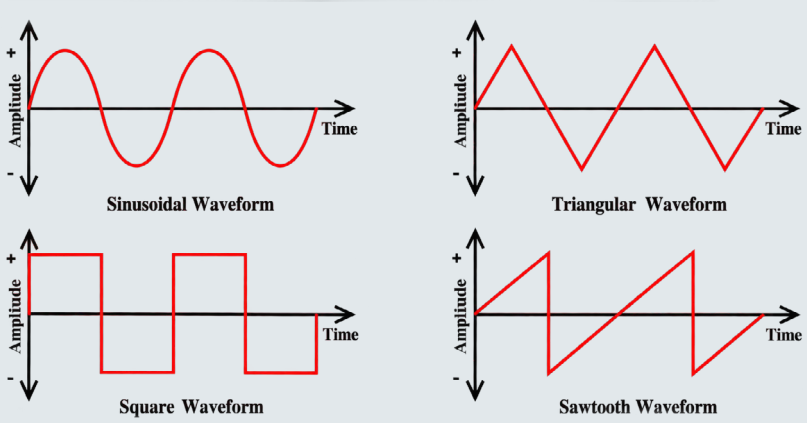


Figure 6.5a *Different types of AC signal*
What is Alternating Current or AC Current ElectroDuino

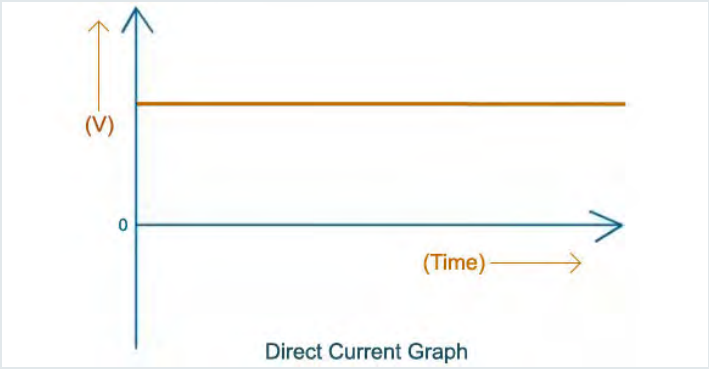


Fig 6.5b: DC signal

What is DC current ? Who Was inventor of dc current ?

What to do

1. Carefully look at the voltage versus time graphs: Different types of Alternating Current (AC) and one for Direct Current (DC).
2. For each graph, note down characteristics such as:
   - **a.** Direction of current flow (does it change direction or stay the same?)
   - **b.** How voltage changes over time (does it vary or stay constant?)
   - **c.** Shape of the waveform (e.g., sinusoidal, flat)
3. Use textbooks or the internet to find common examples where AC and DC are used (e.g., household power, batteries).
4. On your paper, draw a table with these columns
   - **a.** Sinusoidal Alternating Current (AC)
   - **b.** Square Alternating Current (AC)
   - **c.** Triangular Alternating Current (AC)
   - **d.** Sawtooth Alternating Current (AC)
   - **e.** Direct Current (DC)
5. Fill in the table based on your observations and research with entries such as:
   - **a.** Direction of flow
   - **b.** Voltage consistency
   - **c.** Typical applications
6. Check that your comparison captures the main differences between AC and DC clearly.

Activity 6.2 Deriving the Relationship Between Peak and RMS Values

Objective: To understand and derive the mathematical relationship between peak value and RMS (root mean square) value for sinusoidal waveforms, and to apply this knowledge to calculate and compare electrical quantities in AC circuits.

What you need

1. Internet-enabled device or textbooks for research
2. Paper or notebooks
3. Pens or pencils
4. Calculator (optional)

What to do

1. Partner up and gather your materials.
2. Use your textbooks, online resources, or videos to find out:
   - **a.** What is the definition of peak value?
   - **b.** What is the RMS value and why it is important?
   - **c.** How are peak (I_0 or V_0) and RMS (Irms or Vrms) values related?
3. Look up how to derive the relationship between peak and RMS values for a sinusoidal waveform and follow the steps
4. Summarise the derivation and write down the final formula for RMS in terms of peak value.
5. Practice Conversions Using Simple Values
   - **a.** Given I_0=10 A, calculate Irms.
   - **b.** Given Irms =7 A, calculate I_0.

   Repeat with other values to practice.
6. Take turns explaining the derivation and conversion to your partner to reinforce understanding.

Activity 6.3 Observing AC Waveform Using Oscilloscope and Multimeter

Objective: To observe and understand the characteristics of an AC waveform using an oscilloscope and multimeter, identify its peak and RMS values, and compare measured and calculated RMS values for a sinusoidal signal.

What you need

1. Oscilloscope with appropriate probes
2. Digital multimeter set to AC mode
3. AC power source or function generator set to sinusoidal output
4. Connecting wires and test leads
5. Calculator
6. Paper and pen for recording observations

What to do

1. Connect the AC power source output to the circuit where both the oscilloscope and multimeter can measure the same signal.
   - **a.** Connect one oscilloscope probe across the output to measure voltage or current waveform.
   - **b.** Connect the multimeter test leads in parallel to measure the voltage or in series for current, ensuring it is set to AC measurement mode.
2. Observe the Waveform on the Oscilloscope
   - **a.** Turn on the oscilloscope and adjust settings (time/div, volts/div) so you can clearly see at least one full cycle of the AC waveform.
   - **b.** Notice the waveform's peak amplitude (maximum positive or negative value) on the screen.
   - **c.** Observe features such as the waveform's time period (time for one complete cycle), frequency (= 1 / time period), and zero-crossings (points where the waveform crosses the time-axis).
3. Note the value displayed by the multimeter. This value represents the RMS (root mean square) voltage or current of the AC source.
4. Calculate Theoretical RMS Value
   - **a.** Use the peak value from the oscilloscope to calculate the theoretical RMS value by applying:

     $$RMS\ value = \frac{Peak\ value}{\sqrt{2}}$$

   - **b.** Show your calculation on paper.
5. Compare and Analyse
   - **a.** Compare the RMS value displayed by the multimeter with the value you calculated theoretically.

b. Reflect on any differences and reasons why they might occur (e.g., instrument accuracy, waveform distortion).

6. Record Your Observations

a. Write down measured frequency, period, peak value, RMS reading, and your calculated RMS value.

b. Make notes on the waveform shape and key features you observed

Activity 6.4 Calculating Peak, RMS & Instantaneous Values in AC Signals

Study the worked example below carefully before attempting the example questions that follow.

Worked Example 1

A sinusoidal AC voltage source has a frequency of 50 Hz and a peak voltage of 340 V.

a. What is the period (T) of this AC voltage?

b. What is the instantaneous voltage at t=0.005 s?

c. Calculate the RMS voltage of this source.

Solution

a. Period (T)

We know that $f = \frac{1}{T}$

$so\ T = \frac{1}{f}.$

Given f=50 Hz

$T = \frac{1}{50} = 0.02\ s$

The period of the AC voltage is 0.02 s

b. Instantaneous voltage at t=0.005 s

First, we need to find the angular frequency (omega).

$\omega = 2\pi f = 2\pi \times 50 = 100\pi$

$V(t) = 340 sin(100\pi)(0.005)$

$V(t) = 340\ V$

c. RMS voltage

$$RMS\ Voltage\ (V_{rms}) = \frac{V_o}{\sqrt{2}}$$

$$RMS\ Voltage\ (V_{rms}) = \frac{340}{\sqrt{2}} = 240\ V$$

The RMS voltage of this source is approximately 240.42 V.

Worked Example 2

An AC voltage is described by the equation: V(t)=325sin(100πt)

a. What is the peak voltage?

b. Determine the frequency of the AC voltage.

c. What is the rms voltage?

Solution

a. Peak voltage, 325 V

b. $\omega = 100\pi = 2\pi f, f = \frac{100\pi}{2\pi} = 50\ Hz.$

c. $V_{rms} = \frac{V_0}{\sqrt{2}} = \frac{325}{\sqrt{2}} = 229.81\ V$

Practice problems

Now, using the worked examples as guide, solve the following problems individually or in groups.

1. An AC voltage has a frequency of 60 Hz and a peak voltage of 325 V.
   - **a.** Find the period.
   - **b.** Calculate the RMS voltage.
2. An alternating current is given by the expression: $I(t) = 8sin(314t)$. Calculate the frequency of the current.
   - **a.** What is the peak current?
   - **b.** Determine the rms current.
   - **c.** How much time does it take for the current to reach its first peak after t=0?

AC CIRCUITS WITH RESISTORS, INDUCTORS AND CAPACITORS IN SERIES

Welcome back, future electrical innovator! You have already built a solid foundation in understanding the fundamental characteristics of alternating current and voltage. We've explored how AC differs from the steady flow of DC, delved into the various types of AC waveforms that power our world, and even mastered the mathematical relationships that define these constantly changing currents and voltages.

Here, we're taking that knowledge a step further. Having understood the *nature* of AC, we're now ready to see how common electronic components such as resistors, inductors, and capacitors interact with these dynamic waves when connected in series. Get ready to uncover how the combination of these simple components affects the operation of AC circuits. Let us now seek further understanding!

The Dynamic Trio: Resistors, Inductors and Capacitors in AC Circuits

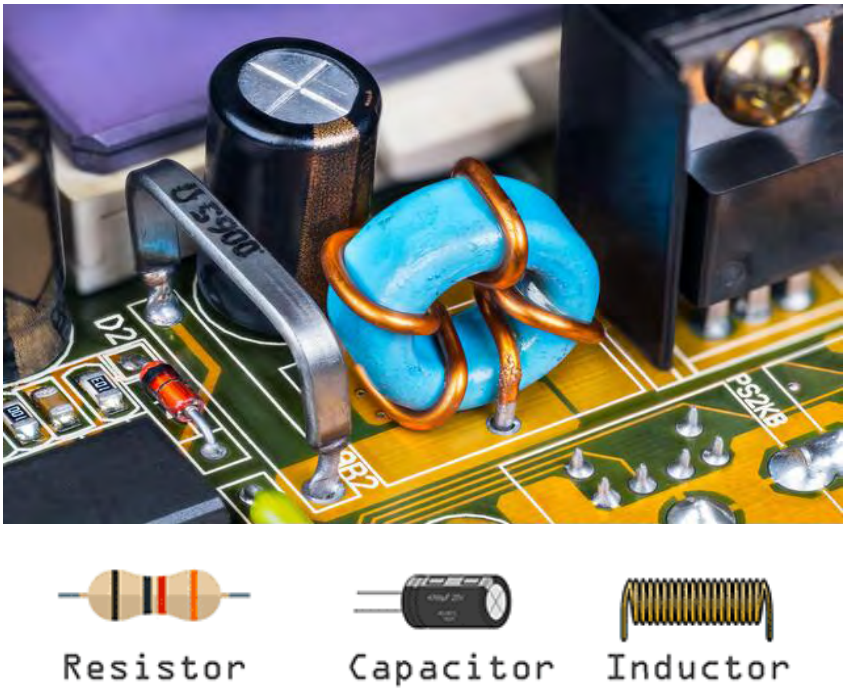
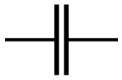


Figure 6.6: *The blue ring is a toroidal inductor, which stores energy in a magnetic field. Next to it is a capacitor, used to store electrical energy and smooth out voltage in circuits.*

Imagine these three components as characters with distinct personalities in an AC circuit. Let us get to know them!

Component	Symbol	Unit	Description
Resistor 	**R** 	**Ω (Ohm)**	**The Current Opposer:** Just like in DC circuits as you learnt in year 2, a resistor opposes the flow of current. It converts electrical energy into heat. In AC, the voltage and current are *always in phase*, meaning they rise and fall together in magnitude. Think of it like two friends climbing and descending hills and valleys together at the same time.
Capacitor 	**C** 	**F (Farad)**	**The Charge Storer:** A capacitor stores electrical energy in an electric field. We learnt this in year 2; that as current flows through the capacitor, it stores charges which can be released later. · In AC, it *opposes changes in voltage. Whether the voltage is increasing or decreasing, it opposes it, seeking to let the voltage remain at a constant value.* · Because of this, the current, which is free to change, always increases or decreases well ahead of the voltage; we say the current *leads* the voltage by 90°. · So, like the two friends, when the current is at the peak of the hill, the voltage is halfway up, climbing the hill behind. · This property of opposing the change in voltage is called **capacitive reactance, X_C** *and decreases* as frequency increases.

Component	Symbol	Unit	Description
Inductor 	**L** 	**H (henry)**	**The Current Change** Resister**:** An inductor (often a coil of wire) stores electrical energy in a magnetic field. Its fundamental job is to oppose any change in the current flowing through it. Here's how it acts in an AC circuit: · **When the AC current is increasing**: As the current tries to get stronger, the inductor fights back. It creates its own induced voltage (sometimes called "back-EMF") that pushes against the incoming current, trying to keep it from increasing. It's like a strong water current pushing against a door trying to open it wider, and the inductor pushing back to slow that opening down. · **When the AC current is decreasing**: If the current tries to get weaker or stop, the inductor again fights back. Its magnetic field starts to collapse, and this collapse generates an induced voltage that tries to maintain the current flow. It's like the inductor giving the current a push from behind to keep it going. · In both situations, this "pushing back" or "pushing forward" by the induced voltage represents **energy being stored in, or released from, the coil's magnetic field**. This is why an inductor can even make current flow briefly in a circuit even after the main AC source has been disconnected – it's releasing its stored energy.

Component	Symbol	Unit	Description
			· Since the coil opposes only the current from increasing or decreasing, it means the voltage is free to increase and decrease ahead of the current and is said to lead the current by 90°. · Still, think of the two friends; while voltage is at the peak of the hill, current is halfway through its uphill journey behind. · The opposition to the change in the current is called inductive reactance and increases as frequency increases.

So, in summary we can say that

1. For a resistor, the current and voltage are in phase, and the phase difference is 0°.
2. For a capacitor, the current and the voltage are 90° out of phase, with the current leading, the phase difference being 90°.
3. For an inductor, the current and the voltage are 90° out of phase, with the voltage leading, the phase difference being 90°.

Why are these phase differences so important?

They are the key to understanding how these components interact in AC circuits, especially when combined!

Let us look at each of the three components individually when they are in an AC circuit.

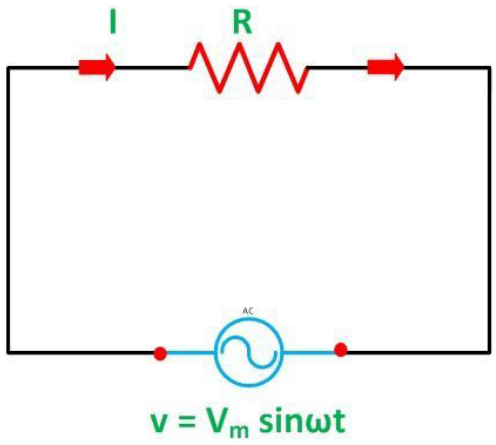


Figure 6.7: *A purely resistive circuit contains only one or more resistors*

Purely Resistive Circuit

What is it? A circuit with **only** resistors.

Behaviour in AC

Simple! The voltage and current are perfectly synchronised.

Mathematically

Ohm's Law still rules! V=IR holds for;

Instantaneous voltage; $\boldsymbol{V(t) = I(t)\, R}$

Peak voltage; $\boldsymbol{V_o = I_o\, R}$

RMS voltage; $\boldsymbol{V_{rms} = I_{rms}\, R}$

Also,

Instantaneous Current: $I(t) = I_o \sin\omega t$

Instantaneous Voltage: $V(t) = V_o \sin\omega t$

Notice how V and I have the same sin(ωt) part – they are in phase!

Instantaneous Power: $P(t) = I(t) \times V(t) = I_o \sin\omega t \times V_o \sin\omega t = I_0 V_0 sin^2 \omega t$

Average Power: $P = I_{rms} V_{rms} = \frac{I_o}{\sqrt{2}} \times \frac{V_o}{\sqrt{2}} = \frac{I_o V_o}{2}$

All the power is converted into heat, useful work!

Visualising the Action

Phasor Diagram

It's a "Vector" (like an arrow): Each AC voltage or current is drawn as an arrow, called a "phasor."

Length of the arrow: Represents the *strength* or *maximum value* (amplitude) of the voltage or current. A longer arrow means a higher voltage or current.

Angle of the arrow: Shows its *phase* or *timing* relative to other voltages/currents in the circuit. Remember how current can lead or lag voltage? This angle visually represents that. We usually imagine these arrows rotating counter-clockwise, like the hands of a clock in reverse.

The Reference

Usually, we pick one quantity (like the current in a series circuit, since it's the same everywhere) and draw its phasor horizontally, pointing to the right. This is our "reference point." All other phasors are then drawn at an angle relative to this reference.

1. If a voltage/current leads the reference, its arrow will be drawn counter-clockwise (ahead) of the reference arrow. (Think of Capacitors, where current leads voltage.)
2. If a voltage/current lags the reference, its arrow will be drawn clockwise (behind) the reference arrow. (Think of Inductors, where current lags voltage, or voltage leads current, which is the same thing).

As we consider the phasor diagrams of these components individually, we will learn how their phasors are drawn.

If they are in phase (like voltage and current across a resistor), their arrows point in the same direction, as show below

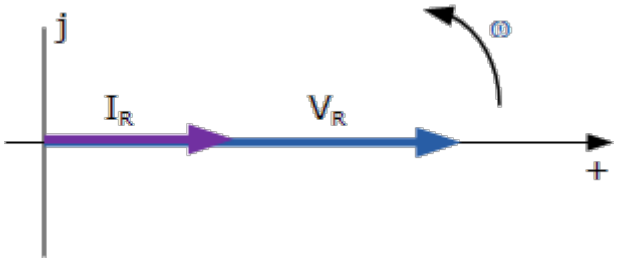


Figure 6.8: *Phasor diagram for resistive voltage and current in phase*

Since the voltage and current are in phase, their phasors align with each other on the reference axis.

Note that their magnitudes are different, though; however, they both achieve maximum magnitude at the same time, and that's what 'in phase' means.

Waveform Diagram

If you plot the voltage and current over time, their sinusoidal waves will *overlap perfectly* as depicted below.

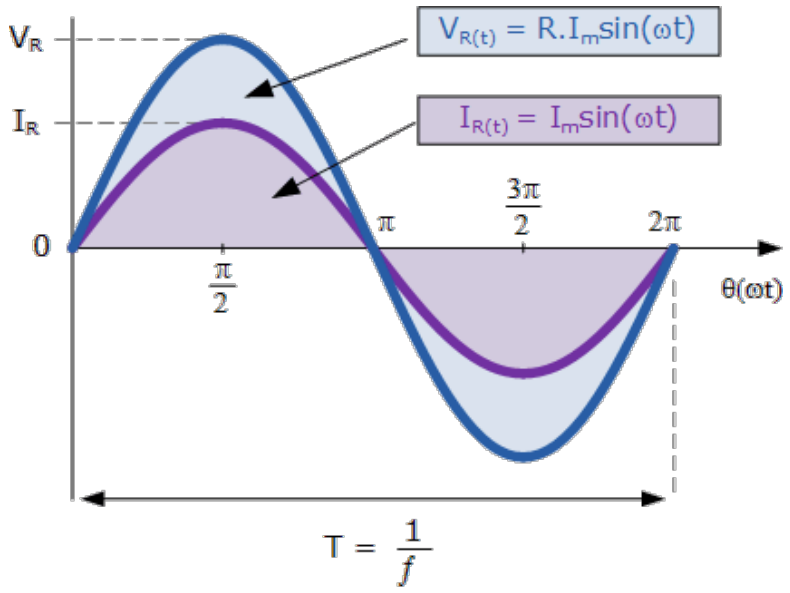


Figure 6.9: *Waveforms of the resistive voltage and current in phase.*

Purely Inductive Circuit

What is it? A circuit with **only** an inductor.

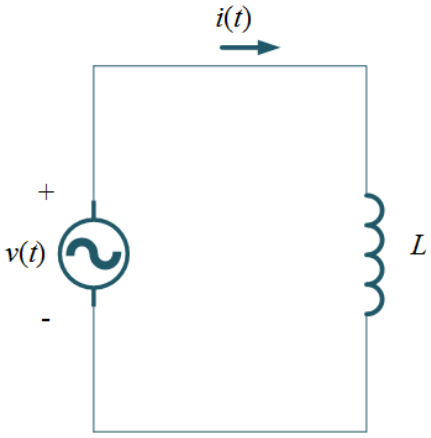


Figure 6.10: *A purely inductive circuit contains only one or more inductors/coils*

Behaviour in AC

This is where things get interesting! The inductor resists changes in current. This resistance to change causes the current to lag the voltage by 90°.

Mathematically,

Inductive Reactance (X_L): This is the inductor's opposition to AC flow. It's also measured in ohms (Ω), just like resistance, but it's not the same!

$X_L = \frac{V_o}{I_o}$ but $V_o = \omega L I_o$ (deriving this is beyond the scope of this book)

$X_L = \frac{\omega L I_o}{I_o} = \omega \mathrm{L}$

Also $\omega = 2\pi f$

$X_L = 2\pi f L$

Where

ω is the angular frequency (radians/second)

f is the frequency (Hz)

L is the inductance (Henry, H)

You will learn how to derive some of the equations if you pursue Electrical Engineering at the university.

Voltage-Current Relationship

$V_L = IX_L$ (Similar to Ohm's Law, but using reactance)

1. Instantaneous Voltage: Voltage $V(t) = V_o \sin\omega t$
2. Instantaneous Current: Current $(t) = I_o \sin\left(\omega t - \frac{\pi}{2}\right) = I_o \cos\omega t$, The current is "behind" the voltage by 90° or $\frac{\pi}{2}$ *radians*.)
3. Instantaneous power: $P(t) = I(t) \times V(t) = I_o \cos\omega t \times V_o \sin\omega t = \frac{I_o V_o}{2} \sin 2\omega t$
4. Average Power: Pav = 0

Surprise! A pure inductor does not consume average power. It stores energy during one half-cycle and returns it to the source during the next.

Visualising the Action

Phasor Diagram

Since in an inductor the voltage leads, the voltage phasor points upwards (or leads), and the current phasor points to the right on the reference axis (or lags by 90°).

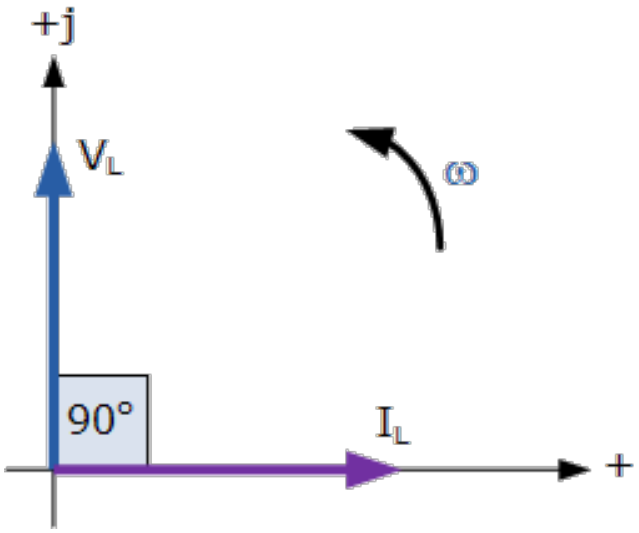


Figure 6.11: *Phasor diagram of inductive voltage leading current by 90°*

Waveform Diagram

The voltage wave reaches its peak *before* the current wave. The instantaneous power oscillates symmetrically above and below zero, visually confirming that no net power is consumed.

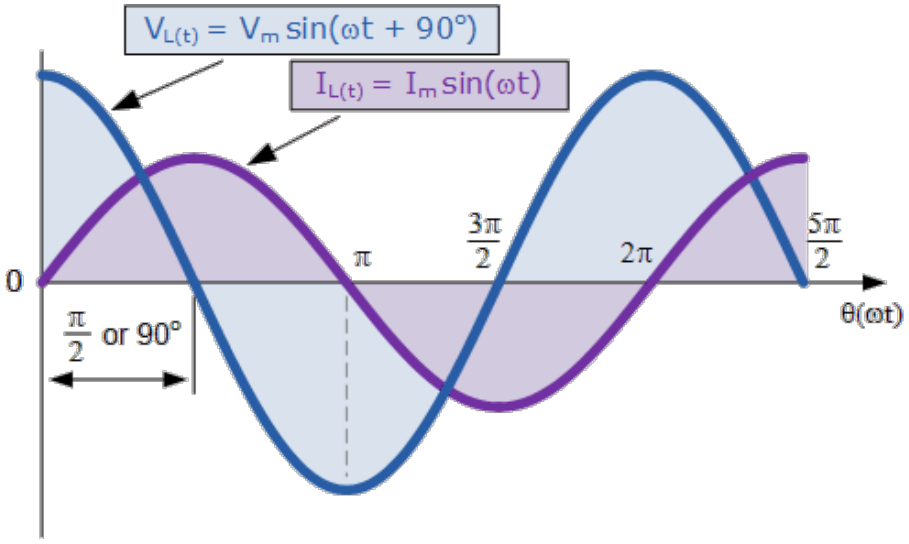


Figure 6.12: *Waveforms of inductive voltage and current 90° out of phase.*

Purely Capacitive Circuit

What is it? A circuit with only a capacitor.

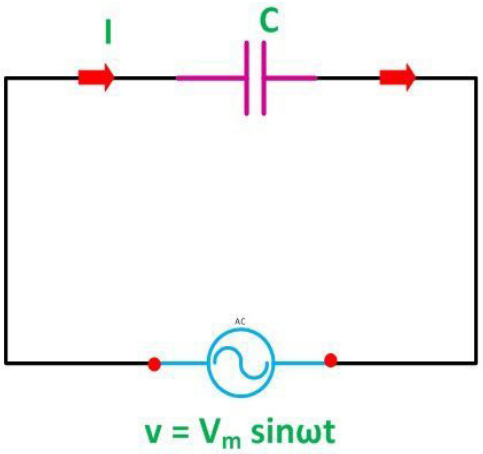


Figure 6.13: *Purely capacitive circuit*

Behaviour in AC

The capacitor resists changes in voltage. This leads to the current leading the voltage by 90°.

Mathematically,

Capacitive Reactance (X_C): This is the capacitor's opposition to AC flow. Also measured in Ohms (Ω).

But $I_O = \omega C V_o$ (deriving this beyond the scope of this book)

$$X_c = \frac{V_o}{\omega C V_o} = \frac{1}{\omega C}$$

Also $\omega = 2\pi f$

$$X_c = \frac{1}{2\pi f C}$$

Where

ω is the angular frequency (radians/second)

f is the frequency (Hz)

C is the capacitance (Farad, F)

Key Takeaway

The faster the AC (higher frequency), the *less* the capacitor opposes current flow!

1. Voltage-Current Relationship: $V_C = IX_C$
2. Instantaneous Voltage: Voltage $V(t) = V_o \sin\omega t$
3. Instantaneous Current: Current $I(t) = I_o \sin\left(\omega t - \frac{\pi}{2}\right) = I_o \cos\omega t$

4. The current is "ahead" of the voltage!
5. Average Power: $P_{av} = 0$

Like inductors, pure capacitors also do not consume average power. They store and release energy.

Visualising the Action

Phasor Diagram

Since the current leads the voltage, the current phasor points upwards (or leads), and the voltage phasor points to the right on the reference axis (or lags by 90°).

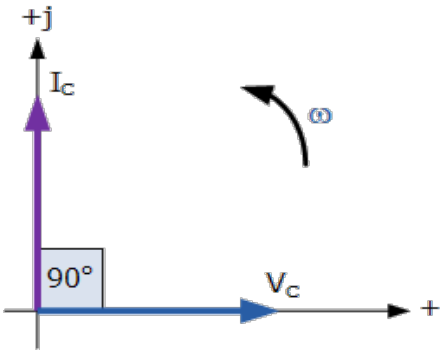


Figure 6.14: *Capacitive current leads capacitive voltage by 90°*

Waveform Diagram

The current wave reaches its peak *before* the voltage wave. The instantaneous power also oscillates symmetrically about zero.

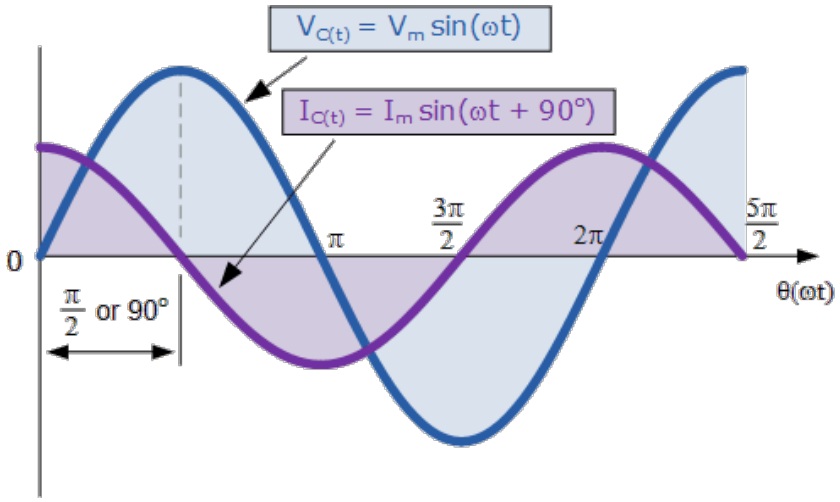


Figure 6.15: *Waveforms of capacitive current leading voltage*

Reactance verses Impedance: The Total Opposition

Now that we understand how the individual components oppose AC, let's look at the bigger picture when they are combined.

Reactance (X)

It is the opposition to AC current due to *energy storage elements* (inductors and capacitors). It's all about how these components *react* to changes in current or voltage by storing energy. Unit**:** Ohms (Ω)

Net Reactance (X)

When you have both inductors and capacitors, their reactance partially cancels each other out because their actions are opposite. $X_{net} = X_L - X_C$

1. If $X_L > X_C$: The circuit is primarily **inductive**. The current will lag the voltage.
2. If $X_C > X_L$: The circuit is primarily **capacitive**. The current will lead the voltage.
3. If $X_L = X_C$: This is a special condition called **resonance**, where the net reactance is zero.

We will explore this exciting concept later!

Impedance (Z)

It is the *total* opposition to the flow of alternating current in an AC circuit. It combines the effects of both resistance (which dissipates energy) and reactance (which stores and releases energy). Unit**:** Ohms (Ω)

Think of it as the AC version of total/equivalent resistance!

Impedance in Series R-L-C Circuits

When resistors, inductors, and capacitors are connected in series, the total opposition (impedance) is found by considering their phase relationships. We cannot just add them up directly like in DC circuits! Their sum is found by using vector addition as follows;

$$Z = \sqrt{\left(R^2 + \left(+\left(X_L - X_C\right)\right)^2\right)}$$

$$Z = \sqrt{R^2 + X^2}$$

This can be represented in other ways such as the following

$Z = R + jX$ (Rectangular form, where j is the imaginary unit)

$Z = |Z|\angle\theta$ (Polar form)

In complex notation, R is said to be the real component, while X is called the imaginary component, signified by the presence of j. (*In some university courses you will learn in engineering maths about complex numbers)*

Where

Z is the impedance (Ω)

R is the resistance (Ω)

X is the net reactance (Ω)

Graphical Representation (Impedance Triangle)

Just like voltages, we can represent impedance using a right-angled triangle.

The horizontal side is **Resistance (R)**.

The vertical side is **Net Reactance (X)**.

The hypotenuse is **Impedance (Z)**.

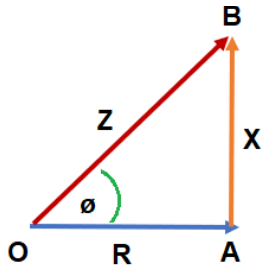


Figure 6.16: *Impedance triangle*

Phase Angle (θ)

The phase angle of impedance tells us the overall phase difference between the total voltage and total current in the circuit.

A positive θ means the circuit is inductive (current lags voltage).

A negative θ means the circuit is capacitive (current leads voltage).

A θ of 0° means the circuit is purely resistive or at resonance (current and voltage are in phase).

Series Connected AC Circuits: R-C, R-L and R-L-C

When components are in series, the *current (I)* flowing through each element is the same, but the *voltages* across them will have different magnitudes and phases.

Let's consider the individual series combinations of resistor, capacitor and inductor in pairs.

Series R-C Circuits (Resistor and Capacitor)

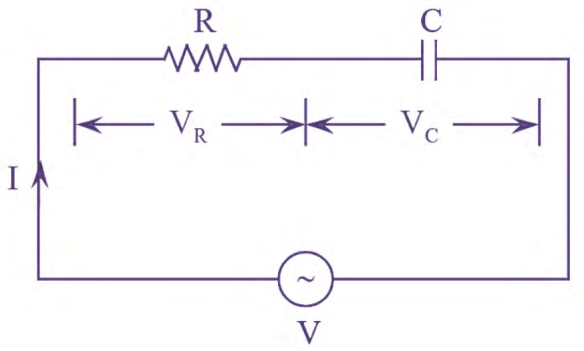


Figure 6.16: *A circuit containing a resistor (R) and a capacitor (C) in series.*

1. Current (I): Same through R and C.
2. Voltage across Resistor (VR): In phase with current.
3. Voltage across Capacitor (VC): Lags current by 90°.
4. Total Voltage (V): The phasor sums of VR and VC given as

$$V^2 = V_R^2 + V_C^2$$
$$V^2 = (IR)^2 + \left(IX_c\right)^2$$
$$\mathrm{V2} = I^2R^2 + I^2X_C^2$$
$$V^2 = I^2\left(R^2 + X_C^2\right)$$
$$V = I\sqrt{(R^2 + X_C^2)}$$

Impedance (Z) is given as

$$\mathrm{Z} = \mathrm{V/I} = \sqrt{(\mathrm{R2} + X_C^2)}$$

$$Z = \sqrt{(R^2 + X_C^2)}$$

Phase Angle (θ) is given as

$$\tan\phi = \frac{V_C}{V_R} = I\frac{X_C}{IR} = \frac{X_C}{R}$$

$$\phi = tan^{-1}\left(\frac{X_C}{R}\right)$$

(This will be negative because it's capacitive, current leads voltage)

Note

- ϕ is the phase angle between the overall current and overall voltage of the circuit.
- θ is the phase angle between the current and voltage in each individual component.

Series R-L Circuit (Resistor and Inductor)

1. Current (I): Same through R and L.
2. Voltage across Resistor (VR): In phase with current.
3. Voltage across Inductor (VL): Leads current by 90°.
4. Total Voltage (V): The phasor sums of VR and VL; $V = \sqrt{\left(V_R^2 + V_L^2\right)}$
5. Impedance (Z): $Z = \sqrt{(R^2 + X_L^2)}$
6. Phase Angle (θ): $\theta = \tan^{-1}\left(\frac{X_L}{R}\right)$

(Positive because it's inductive, current lags voltage)

Series R-L-C Circuit (Resistor, Inductor, and Capacitor)

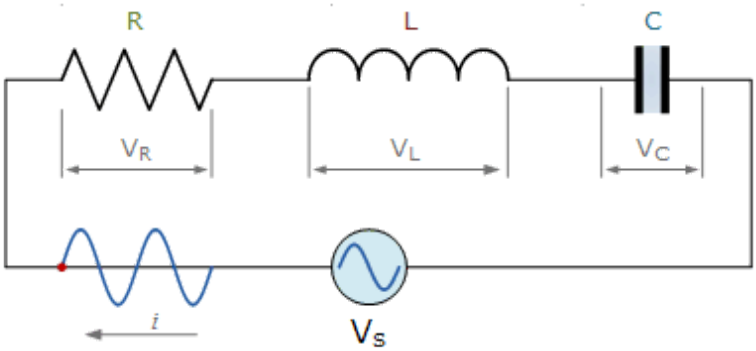


Figure 6.17: *A Resistor (R), inductor (L) and capacitor (C) in series.*

This is the most general and exciting case!

1. Current (I): Same through all elements.
2. Voltages
   a. V_R: In phase with current.
   b. V_L: Leads current by 90°.
   c. V_C: Lags current by 90°.
3. Net Reactive Voltage: Since VL and VC are both 90° ahead and behind the current, respectively, they are 180° apart/out of phase. So they directly oppose each other. The net reactive voltage is VL−VC.
4. Total Voltage (V): The phasor sum of VR and the net reactive voltage. $V = \sqrt{V_R^2 + \left(V_L^2 - V_C^2\right)}$

   Impedance (Z): As derived earlier, $Z = \sqrt{\left(R^2 + (X_L - X_C)^2\right)}$

5. Phase Angle (θ): $\theta = \tan^{-1}\left(\frac{(X_L - X_C)}{R}\right)$

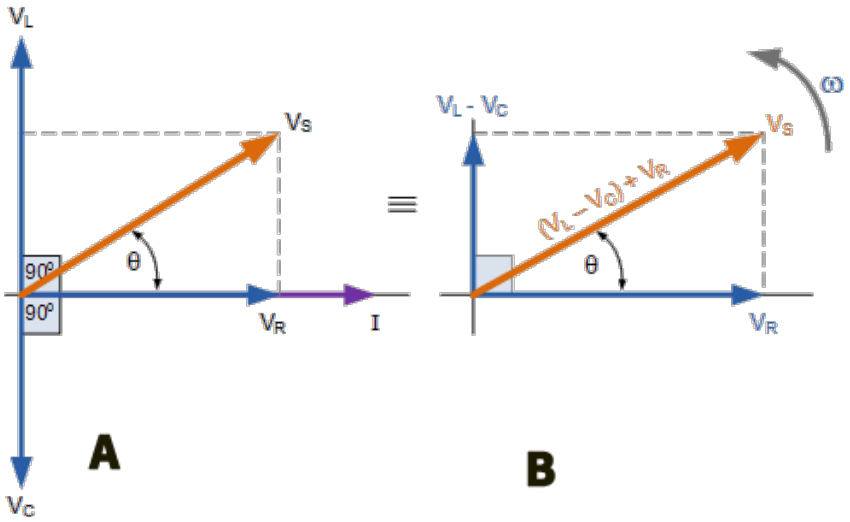


Figure 6.18 – *A: Phasors of inductive (V_L) and capacitive (V_C) voltages 180° apart and 90° out of phase with the resistive voltage (V_R). B: Effective reactive voltage leading V_R by 90°– B.*

The Magic of Resonance

A truly special condition occurs in an R-L-C series circuit when: Inductive Reactance (X_L) = Capacitive Reactance (X_C)

At resonance

1. $X_L - X_C = 0$, so the net reactance is zero.
2. The impedance $Z = \sqrt{(R^2 + (0)^2)} = R$. This means the impedance is at its *minimum* value, equal to the resistance!
3. The current in the circuit will be at its *maximum* for a given voltage (since I=V/Z, and Z is minimum).
4. The phase angle θ=0°, meaning the circuit behaves like a purely resistive circuit, with voltage and current in phase.

Resonance Frequency (f_0)

This is the specific frequency at which resonance occurs.

Inductive reactance = Capacitive reactance

i.e. $X_C = X_L$ and $f = f_o$

$$\frac{1}{2\pi f_o C} = 2\pi f_0 L$$

$$4\pi 2 f_0^2 LC = 1$$

$$f_0^2 = \frac{1}{4\pi^2 LC}$$

$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

Resonance is a fundamental concept used in radio tuning, filters, and many other electronic applications! However, you do not need to know the details of this.

The Power Triangle And Power Factor: Efficiency In Ac Circuits

In AC circuits, power is not as simple as P=VI. Due to the phase differences, we talk about three types of power.

1. **Active Power (P)/Real Power/True Power**
   a. What it is: The actual power that is *consumed* by the circuit and converted into useful work (like heat in a resistor, light from a bulb, or mechanical energy in a motor).
   b. Where it's dissipated: Only by resistive components.
   c. Unit: Watts (W)
   d. Formula: $P=V_{RMS}\, I_{RMS} \cos\theta$
2. **Reactive Power (Q)**
   a. What it is: The power that is exchanged between the source and the reactive components (inductors and capacitors). It's stored in their magnetic and electric fields during one part of the cycle and then returned to the source in the next. It *does not do useful work*.
   b. Why it's needed: Essential for the operation of inductive and capacitive devices.
   c. Unit: Volt-Ampere Reactive (VAR)
   d. Formulae
      i. $Q_L = V_L I = I2X_L$ (Inductive reactive power, conventionally positive)
      ii. $Q_C = V_C I = I^2 X_C$ (Capacitive reactive power, conventionally negative)
      iii. $Q = V_{RMS}\, I_{RMS} \sin\theta$ (Net reactive power)
3. **Apparent Power (S)**
   a. What it is: The total power supplied by the source, comprising both active and reactive power. It's the product of the total voltage and total current, without considering phase.

b. Unit: Volt-Amperes (VA)

c. Formula: $S=V_{RMS}I_{RMS}$

The Power Triangle

This is a powerful visual tool! It's a right-angled triangle where:

1. The **horizontal side** represents **Active Power (P)**.
2. The **vertical side** represents **Reactive Power (Q)**.
3. The **hypotenuse** represents **Apparent Power (S)**.
4. The angle between P and S is the **phase angle (θ)** we discussed earlier!

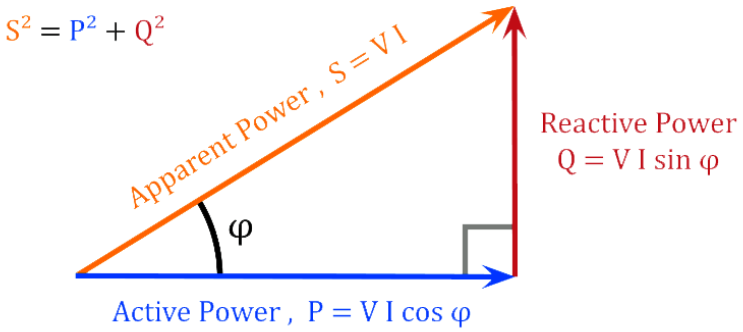


Figure 6.19: *The power triangle follows Pythagoras' theorem to conveniently represent power in an AC circuit.*

From the Pythagorean theorem: $S^2= P^2 + Q^2$

Power Factor (PF)

a. What it is: The Power Factor tells us how efficiently electrical power is being converted into useful work. It's the ratio of active power to apparent power.

b. Formula: $PF = \frac{P}{s} = cos\theta$.

This is why the phase angle θ is so important!

c. Range: The power factor is a dimensionless number between 0 and 1.

Interpreting the Power Factor

1. **PF = 1 (Unity Power Factor)**

   The ideal scenario! This happens in purely resistive circuits or at resonance in RLC circuits. Voltage and current are perfectly in phase, so *all* the apparent power is active power. This is the most efficient use of power.

2. **PF < 1 (Lagging Power Factor)**

   Occurs predominantly in inductive circuits (like motors, transformers, fluorescent lights). The current lags the voltage. A lower lagging PF means a larger portion of the apparent power is reactive, not useful.

3. **PF < 1 (Leading Power Factor)**

   Occurs in predominantly capacitive circuits. The current leads the voltage. Less common for typical loads, but capacitors are often used to *correct* lagging power factors.

4. **PF = 0**

   Occurs in purely inductive or purely capacitive circuits. No active power is consumed; all power is reactive.

Why is a High-Power Factor Important?

A low power factor (meaning a large phase difference between voltage and current) is bad news for electricity generation and distribution!

1. Increased Current: To deliver the same amount of useful (active) power, a low PF circuit draws *more* total current ($I = \frac{S}{V}$).
2. Higher Losses: More current means more energy lost as heat (I2R losses) in transmission lines and equipment.
3. Larger Equipment: Utilities need to install larger, more expensive wires, transformers, and generators to handle the extra current.
4. Higher Bills: Industrial consumers are often charged penalties for maintaining a low power factor because it costs the utility more to deliver the power.

Power Factor Correction

To combat low power factors (especially from inductive loads like motors), capacitors are often connected in parallel with the load. These capacitors provide leading reactive power that cancels out the lagging reactive power, bringing the power factor closer to unity and improving overall system efficiency!

You have now taken a significant step into understanding the complex yet incredibly important world of AC circuits! These concepts are the bedrock for advanced electrical engineering and play a vital role in the technology that powers our modern world. Keep exploring!

Activity 6.5 Voltage and Current vs. Time Graphs for Pure Circuit Elements

Objective: To help learners sketch and understand how voltage and current waveforms behave in pure resistor, capacitor, and inductor circuits, with a focus on identifying and explaining the phase relationships and their physical meanings.

What you need

1. Paper or notebook
2. Pen or pencil
3. Ruler (optional, for neater graphs)

What to do

1. Make three sets of axes labelled "Voltage/Current" (vertical) and "Time" (horizontal), one set for each: pure resistor, pure capacitor, and pure inductor.
2. Sketch the Waveforms and Mark Phase Relationships
   - **a.** Resistor (R): Sketch two sine waves—one for voltage and one for current. Show them perfectly overlapping (in phase): their peaks, troughs, and zero-crossings are at the same times.

     Annotate: "Voltage and current are in phase. Peaks and zero-crossings happen together."
   - **b.** Capacitor (C): Draw voltage as a sine wave. Sketch the current sine wave so that it reaches its peak a quarter cycle (90°) before the voltage does (current LEADS voltage).
     - **i.** Mark and label the time difference: "Current leads voltage by 90° (¼ cycle)."
     - **ii.** Annotate: "At each zero-voltage crossing, current is at a peak. Physically, the fastest charging/discharging happens when voltage passes zero (fully changing)."
   - **c.** Inductor (L): Draw voltage as a sine wave. Sketch the current sine wave so that it reaches its peak a quarter cycle (90°) after the voltage does (current LAGS voltage).
     - **i.** Mark and label the time difference: "Current lags voltage by 90° (¼ cycle)."

ii. Annotate: "When voltage crosses zero, current is at a peak. The inductor resists changes, so peak current comes after peak voltage."

3. On all your graphs, use arrows or markers to indicate where peaks/troughs and zero-crossings occur for both the voltage and the current waveforms.
4. Next to each graph or underneath, write a short explanation of what the phase relationship means for energy flow in that element:
   a. In resistors, energy is dissipated as heat instantly.
   b. In capacitors, energy is stored and released in the electric field, with current showing the fastest flow as voltage changes most rapidly.
   c. In inductors, energy is stored and released in the magnetic field, with current building up or decreasing with a delay due to inductance.

Activity 6.6 - Deriving Frequency Dependence of Current in Capacitor and Inductor Circuits

Objective: To derive and understand how the current in capacitor and inductor circuits depends on the frequency of an AC supply, by calculating and analysing the frequency dependence of capacitive and inductive reactance using given data and standard formulas.

What you need

1. Paper or notebook
2. Pen or pencil
3. Calculator
4. Provided exemplar data set (see below)

Example of dataset:

At a known AC frequency f=50 Hz:

Capacitor circuit: Current I_C=0.5 A when voltage V=10 V, capacitance C=100 µF

Inductor circuit: Current I_L=0.2 A when voltage V=10 V, inductance L=0.05 H.

What to do

1. Write down the values of voltage, current, frequency, capacitance, and inductance provided for the two circuits.

2. Calculate Capacitive Reactance Xc. Use the formula: $X_c = \frac{V}{I_c}$ to calculate XC from the given voltage and capacitor current.
3. **Recall Capacitive Reactance Formula**. Research or remember that

   $X_c = \frac{1}{2\pi fC}$

   Notice the inverse relationship between X_C and frequency f.
4. Using the calculated XC, verify it matches the formula and conclude that the capacitive reactance decreases as frequency increases, causing current to increase.
5. Calculate Inductive Reactance XL using similar steps:

   $X_L = V\frac{}{I_L}$

   Compute X_L using the voltage and inductor current data.
6. Recall Inductive Reactance Formula: $X_L = 2\pi fL$

   Note the direct relationship between X_L and frequency f.
7. Compare the calculated XL with the formula and understand that inductive reactance increases with frequency, causing current to decrease.
8. Summarise Your Result. Write down the two standard expressions clearly:

   $I_c = V\frac{}{X_c} = V \times 2\pi fC$

   $I_L = \frac{V}{X_L} = \frac{V}{2\pi fL}$

   Emphasising the inverse frequency dependence for capacitors and direct frequency dependence for inductors.

Activity 6.7 Constructing the Power Triangle and Calculating Power Factor Linked to Phasor Diagrams

Objective: To help learners construct and interpret the power triangle, calculate power factor, and relate it to phasor diagrams, in order to understand how true power, reactive power, and apparent power are connected and how the phase difference between current and voltage affects power usage in AC circuits.

What you need

1. Paper or notebook
2. Pen or pencil

3. Calculator
4. Provided values for apparent power (S), true power (P), and reactive power (Q)
5. Reference materials or images of power triangles and phasor diagrams (optional)

Provided Values

Apparent Power, S=5000 VA

True Power, P=4000 W

Reactive Power, Q=3000 VAR

What to do

1. Understand the Components. Recall that
   - **a.** S (apparent power) is the hypotenuse of the power triangle
   - **b.** P (true or real power) is the adjacent side (horizontal)
   - **c.** Q (reactive power) is the opposite side (vertical)
2. Draw the power triangle
   - **a.** On graph paper, draw a right-angled triangle.
   - **b.** Label the hypotenuse as S=5000 VA.
   - **c.** Label the adjacent side as P=4000 W.
   - **d.** Label the opposite side as Q=3000 VAR.
3. Calculate the angle θ between P and S using:

   $cos\theta = \frac{P}{S}$
4. Calculate the Power Factor (PF) using:

   $PF = \frac{P}{s} = cos\theta$
5. Link to the Phasor Diagram
   - **a.** Understand that in the phasor diagram, the vector for voltage is usually the reference (horizontal axis).
   - **b.** The current vector lags or leads voltage by angle θ depending on whether the load is inductive or capacitive.
   - **c.** The reactive power Q is associated with this phase difference.
   - **d.** Sketch simple phasor vectors for voltage and current showing this angle θ.

6. Resolve Components of the Power Triangle. Using Pythagoras theorem, verify

   $S^2 = P^2 + Q^2$.

   Calculate the left-hand side and right-hand side values and compare.

7. Summarise your findings
   - **a.** Explain how the power triangle represents the relationship among P,Q,S, and power factor.
   - **b.** Explain how power factor relates to the phase difference shown in phasor diagrams.

Activity 6.8 Building and Measuring R-C, R-L and R-L-C Series Circuits with AC Power

Objective: To build and measure R-C, R-L, and R-L-C series circuits using AC power, and to observe and analyse how resistors, capacitors, and inductors affect current, voltage, and phase relationships, in order to understand the behaviour of AC circuits with different components.

What you need

1. Resistors (various values)
2. Capacitors (known capacitance)
3. Inductors (known inductance)
4. AC power source or function generator with adjustable frequency
5. Digital multimeter (set for AC voltage and current)
6. Oscilloscope with probes
7. Connecting wires and breadboard or circuit board
8. Paper and pen for recording observations

What to do

1. Work together in small groups to complete the activity.
2. Build the circuits
   - **a.** Construct an R-C series circuit using a resistor and capacitor in series connected to the AC power source.
   - **b.** Build an R-L series circuit with resistor and inductor in series.

c. Build an R-L-C series circuit by combining resistor, inductor, and capacitor in series.

3. Set Up measurement instruments
   a. Connect the multimeter to measure current in the circuit (series connection).
   b. Connect multimeter or oscilloscope probes across each component to measure voltage.
   c. Use the oscilloscope to observe voltage and current waveforms.
4. Take measurements
   a. Record the voltage across each component and the total current using the multimeter.
   b. On the oscilloscope, observe and note the waveforms of voltage and current. Pay attention to their phase relationships.
5. Analyse phase relationships
   a. Observe if current and voltage are in phase or out of phase for each component.
   b. Explore how adding capacitors or inductors shifts the phase between current and voltage.
6. Discuss effects of components
   a. In your group, discuss how the resistor, capacitor, and inductor each affect current magnitude and phase in the circuit.
   b. Consider how the combination of all three components influences the overall circuit behaviour.
7. Write down your measured values, waveform observations, and group conclusions about the components' impact on current and phase.

Activity 6.9 - Exploring R-C & R-L Series Circuits Using PhET Virtual Lab

Objective: To explore and compare how capacitors and inductors behave in AC circuits by building R-C and R-L series circuits using the PhET virtual lab, and to observe the effects on voltage and current, leading to a better understanding of the roles of these components in alternating current systems.

What you need

1. Computer or tablet with internet access

2. Access to the PhET Circuit Construction Kit: AC virtual lab

   (Link: https://phet.colorado.edu/en/simulation/circuit-construction-kit-ac-virtual-lab)



3. Paper or notebook
4. Pen or pencil

What to do

1. Open the PhET Circuit Construction Kit: AC

   Go to the link and launch the virtual lab in your browser.

2. Build an R-C Series Circuit
   - **a.** Select a resistor and capacitor from the component options.
   - **b.** Connect them in series to the AC voltage source by dragging wires accordingly.
   - **c.** Make sure the circuit is complete with the power source.
3. Measure Voltages Across Components
   - **a.** Use the built-in voltmeter tool in the simulation to measure the voltage across the resistor.
   - **b.** Repeat for the capacitor.
   - **c.** Record these voltage values in your notebook.
4. Use the ammeter tool to measure and record the current flowing through the entire circuit.
5. Build an R-L Series Circuit
   - **a.** Replace the capacitor with an inductor, keeping the resistor and AC source connected in series.
   - **b.** Repeat the voltage measurement across the resistor and inductor, recording your results.
   - **c.** Measure and record the total current again.
6. Observe and Compare
   - **a.** Notice how voltage is divided differently in the R-C and R-L circuits.
   - **b.** Observe any changes in current magnitude.

c. Reflect on how capacitors and inductors influence the circuit compared to resistors.

7. Summarise how the presence of capacitors and inductors affects voltage and current in AC circuits based on your measurements.

Activity 6.10 Calculating Current, Power and Reactance in AC Circuits

Study the worked example below carefully before attempting the example questions that follow.

Worked Example 1

An AC voltage of 120 V (rms) at 60 Hz is applied across a purely resistive load of 15 Ω. Find:

a. The current in the circuit.

b. The power consumed.

Solution

a. Current, $I = \frac{V}{R} = \frac{120}{15} = 8\ A$

b. Power consumed, $P = V \times I = 120 \times 8 = 960\ W$

Worked Example 2

An AC source of 100 V (rms) at 50 Hz is connected to a capacitor of capacitance 100 μF.

Find the current in the circuit.

Solution

Capacitive reactance: $X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi \times 50 \times 100 \times 10^{-6}} \approx 31.8\ \Omega$

Current: $I = \frac{V}{X_C} = \frac{100}{31.8} \approx 3.14\ A$

Worked Example 3

An inductor of 0.2H is connected to a 240V (rms), 60Hz AC source.

Find the current in the circuit.

Solution

Inductive reactance: $X_L = 2\pi fL = 2\pi \times 60 \times 0.2 = 75.4\ \Omega$

Current: $I = \frac{V}{X_L} = \frac{240}{75.4} \approx 3.18\ A$

Worked Example 4

In a series R-L-C circuit, R = 10Ω, L = 0.1 H, and C = 100μF, connected to a 120V (rms), 50Hz source. Find the current in the circuit.

Solution

Step 1: find the net reactance

$X_L = 2\pi fL = 2\pi \times 50 \times 0.1 = 31.4\ \Omega$

$X_C = \frac{1}{2\pi fC} = \frac{1}{2\pi \times 50 \times 100 \times 10^{-6}} = 31.8\ \Omega$

Net reactance, $X = X_L - X_C = 31.4 - 31.8 = -0.4\ \Omega$

Impedance, $Z = \sqrt{R^2 + X^2}$

$$Z = \sqrt{10^2 + (-0.4)^2} \approx 10.01\ \Omega$$

Step 2: use ohm's law to find the current

Current, $I = \frac{V}{Z} = \frac{120}{10.01} \approx 11.99\ A$

Worked Example 5

A device draws 10 A at 230 V with a power factor of 0.8 lagging.

Calculate:

a. Real power

b. Reactive power

c. Apparent power

Solution

a. $S = V \times I = 230 \times 10 = 2300\ VA$

b. $P = S \times cos(\theta) = 2300 \times 0.8 = 1840\ W$

c. $Q = \sqrt{(S^2 - P^2)} = \sqrt{(2300^2 - 1840^2)} \approx 1380\ VAR$

Worked Example 6

A load has a real power consumption of 1500 W and draws 2000 VA of apparent power.

Find the power factor and state whether it is lagging or leading if the load is inductive.

Solution

Power factor $= \frac{P}{S} = \frac{1500}{2000} = 0.75$Since the load is inductive, the power factor is lagging

Practice Problems

1. An electric heater rated at 230 V (rms) draws a current of 10 A from an AC supply.
   a. Calculate the resistance of the heater. [
   b. Find the power consumed by the heater.
2. A 60 Hz AC voltage of 120 V (rms) is applied across a 50 μF capacitor.
   a. Calculate the capacitive reactance.
   b. Find the current in the circuit.
3. A coil of inductance 0.1 H is connected to a 100 V (rms), 50 Hz AC supply.
   a. Calculate the inductive reactance.
   b. Determine the current through the coil.
4. A series RLC circuit contains a resistor (R = 40 Ω), an inductor (L = 0.2 H), and a capacitor (C = 60 μF). It is powered by a 120 V (rms), 50 Hz AC source.
   a. Calculate the inductive and capacitive reactance.
   b. Determine the net reactance and the total impedance.
   c. Calculate the current in the circuit.
5. A device draws a current of 15 A at 220 V (rms) with a power factor of 0.75 lagging.
   a. Calculate the real power, apparent power, and reactive power.
   b. Determine the required reactive power compensation to raise the power factor to 0.95.
   c. Suggest a component that could be added to achieve this.

Activity 6.11 Case Study Improving Poor Power Factor

Objective: To understand the impact of poor power factor in industrial systems and explore how installing capacitor banks can correct it, improve energy efficiency, and reduce electricity costs.

What you need

1. Case study description (provided below)
2. Paper or notebook
3. Pen or pencil
4. Calculator (optional)
5. Access to research materials (textbooks, internet) for background on power factor and capacitors

What to do

1. You are presented with an industrial plant experiencing poor power factor (e.g., around 0.68). This has resulted in high reactive power demand, increased current flow, energy loss, and extra charges on the electricity bill.
2. Research why poor power factor causes
   - **a.** Inefficient energy use
   - **b.** Higher demand from the power supplier
   - **c.** Increased energy losses and higher electricity costs
3. Research Capacitor Use in Power Factor Correction. Learn how capacitors supply reactive power locally, reducing the total current drawn from the utility and improving the power factor.
4. Based on your research, suggest installing appropriately sized capacitor banks at the plant. Explain how these capacitors will:
   - **a.** Supply reactive power
   - **b.** Reduce the load on the utility
   - **c.** Improve the plant's power factor to a more efficient level (e.g., above 0.95)
   - **d.** Result in reduced energy losses and electricity bills
5. Using your understanding or sample calculations, explain how improving power factor reduces electricity demand charges and lowers monthly costs. Consider the payback period due to savings on energy bills.
6. Write a short report or presentation summarising:
   - **a.** The problem of poor power factor in the plant
   - **b.** How capacitors correct the power factor
   - **c.** The benefits in terms of efficiency and cost savings

d. Any other factors to consider (e.g., maintenance, monitoring)

Activity 6.12 Phasor Diagrams for R, R-L and R-C series circuits

1. **R Series Circuit (Pure Resistor)**

   Steps

   a. Draw a horizontal line to the right — this is the voltage phasor (V).

   b. Draw the current phasor (I) in phase with voltage — it lies on the same line as voltage.

2. **R-L Series Circuit (Resistor + Inductor)**

   Steps

   a. Draw the current phasor (I) horizontally to the right — this is your reference.

   b. Draw the voltage across the resistor (V_R) in phase with current — on the same horizontal line.

   c. Draw the voltage across the inductor (V_L) straight up — it leads the current by 90°.

   d. Draw the total voltage (V) as the vector sum of VRV_R and VLV_L — use the tip-to-tail method to complete the right triangle.

3. R-C Series Circuit (Resistor + Capacitor)

   Steps

   a. Draw the current phasor (I) horizontally to the right — this is your reference.

   b. Draw the voltage across the resistor (V_R) in phase with current — on the same horizontal line.

   c. Draw the voltage across the capacitor (V_C) straight down — it lags the current by 90°.

   d. Draw the total voltage (V) as the vector sum of VRV_R and VCV_C — complete the triangle.

4. Now, use Pythagoras's Theorem to calculate the impedance for each of these circuits. Also, use trigonometry to find the phase angle (angle of impedance).

REVIEW QUESTIONS

Review Question 6.1

1. A sinusoidal alternating current has a peak value of 5 A. Calculate:
   - **a.** The RMS value of the current.
   - **b.** The peak-to-peak current.
2. An AC voltage is represented by the equation: $V(t) = 240sin(100\pi t)$. Determine the
   - **a.** Peak voltage.
   - **b.** RMS voltage.
   - **c.** Frequency of the AC source.
3. A resistor of resistance 20 Ω is connected to an AC source with an RMS voltage of 120 V. Calculate:
   - **a.** The RMS current through the resistor.
   - **b.** The peak current.
   - **c.** The average power dissipated in the resistor.
4. An oscilloscope displays a periodic voltage waveform that repeats every 4 milliseconds. The peak voltage is 15 V. Calculate:
   - **a.** The frequency of the waveform.
   - **b.** The RMS value of the voltage.

Review Question 6.2

1. An AC voltage of 125 V (rms) at 50 Hz is applied across a purely resistive load of 25 Ω.

   Find
   - **a.** The current in the circuit.
   - **b.** The power consumed.
2. A 60 Hz AC source of 84 V (rms) is connected to a capacitor of capacitance 100 μF. Find the current in the circuit.

3. An inductor of 0.3H is connected to a 230V (rms), 50Hz AC source.

Find the current in the circuit.

4. In a series RLC circuit, R = 20 Ω, L = 0.05 H, and C = 150 μF, connected to a 100 V (rms), 60 Hz source. Find the current in the circuit.

5. An industrial sewing machine draws 10 A at 150 V with a power factor of 0.8 lagging.

Calculate the

a. Real power

b. Reactive power

c. Apparent power

6. A load has a real power consumption of 1800 W and draws 3000 VA of apparent power.

Find the power factor and state whether it is lagging or leading if the load is inductive.

7. A series RLC circuit in a radio set has R=30 Ω, L=0.2 H, and a variable capacitor C.

If the circuit is driven by a 100 V (rms) source at 60 Hz, determine the value of C that causes resonance, and compute the current in the circuit at resonance.

8. An AC motor rated at 5 kW operates with a lagging power factor of 0.7 and draws 8.5 kVA

a. Calculate the reactive power.

b. Determine how much reactive power must be cancelled (using a capacitor) to improve the power factor to 0.9.

c. What will be the new apparent power after correction?

9. A factory in Kasoa operates with several inductive machines and has a total real power consumption of 200 kW and an average power factor of 0.65 lagging. The management wants to improve the power factor to 0.95 to reduce losses and avoid penalties.

a. Calculate the existing reactive power demand.

b. Calculate the required reactive power compensation.

c. Determine the capacitance (in μF) of a bank of capacitors connected in parallel to the supply (at 50 Hz) that would provide the required compensation.

d. Discuss how this power factor improvement affects the total current drawn and energy costs over time.

SECTION

7 BEHAVIOUR OF LIGHT IN LENSES AND LASER SYSTEMS



LIGHT WAVE

INTRODUCTION

This section explores the behaviour of light in lenses and laser systems, focusing on how lenses refract light to form images and how lasers generate coherent beams. It begins with the classification, features, and applications of convex and concave lenses, alongside methods for determining image characteristics using ray diagrams, lens formulas, and magnification calculations. The section also covers the principles behind laser production, including pumping, population inversion, and stimulated emission, as well as the properties, configurations, and applications of lasers in various fields. Safety considerations for laser use are addressed, ensuring awareness of both beam and non-beam hazards. These concepts build on earlier topics such as spherical mirrors and refraction, establishing a strong foundation for understanding optical instruments and photonic technologies.

KEY IDEAS

- **Applications of convex and concave lenses,** including magnifying glasses, cameras, telescopes, microscopes, projectors, eyeglasses, solar concentrators, peepholes, flashlights, beam expanders, and dental mirrors.
- **Determination of image distance and magnification** using the lens formula and magnification equations, applying real-is-positive and new Cartesian sign conventions.
- **Features of lenses** such as centre of curvature, radius of curvature, optical centre, aperture, focal length, principal focus, and principal axis.
- **Hazards associated with lasers**, including beam hazards (eye damage, skin burns, fire) and non-beam hazards (electrical, chemical, mechanical, and collateral radiation).
- **Principles of laser production**, including pumping, population inversion, spontaneous emission, stimulated emission, and light amplification in an optical resonator.
- **Properties of lasers—**monochromaticity, coherence, and directionality—as well as types of lasers and their applications in medicine, manufacturing, communication, research, consumer products, defence, and entertainment.

LENSES

Have you ever noticed how a straw in a glass of water looks bent, or how objects look bigger when you see them through a drop of water? That is because light changes direction when it passes from one material to another — a phenomenon called **refraction**, as you learnt in previous years.

Lenses, like those in eyeglasses, cameras, microscopes, telescopes, and magnifying glasses, work using this same idea. They are clear, curved pieces of glass or plastic that bend light so it either comes together at a point (focuses) or spreads out. By bending light in just the right way, lenses can make things look bigger, bring faraway objects closer, sharpen blurry vision, and even capture images.

This simple bending of light is what makes so many tools possible — from the tiny lens in a smartphone camera that takes selfies, to the big lens in a telescope that lets us see the Moon's craters, to the lenses in eyeglasses that help people see clearly every day.

Types of lenses

Lenses are broadly grouped into two main types based on their shape and how they affect light. The two main types of lenses are convex lens and concave lens.

Convex lens (converging lens)

Shape

Thicker in the middle and thinner at the edges (like a magnifying glass).



Figure 7.1: *A biconvex lens*

Effect on Light

They cause parallel light rays to converge to a single point called the *focal point*.

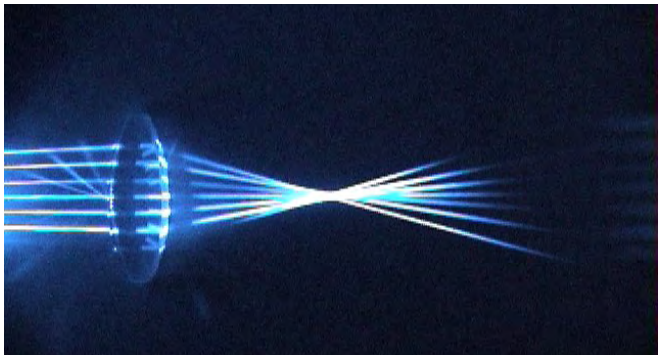


Figure 7.2: *A convex converging a parallel beam of light at the focus*

Image Formation

Can form both real and virtual images, depending on the object's distance from the lens. A real image is formed where light rays actually converge, while a virtual image is formed where the light rays *appear* to originate from.

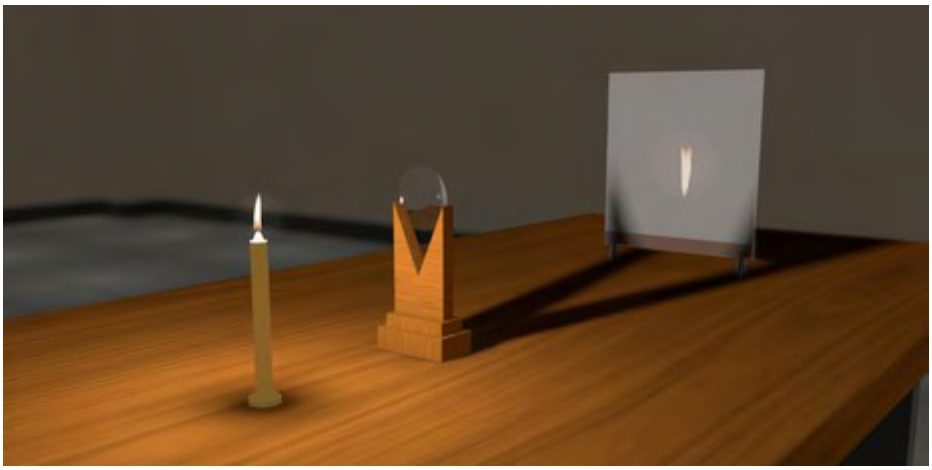


Figure 7.3: *A convex lens forms a real inverted image of a burning candle on a screen*



Figure 7.4: *A Convex also forms virtual images, upright and magnified. So it is used as a magnifying glass for reading.*

Types

Biconvex (curved outwards on both sides), Plano-convex (flat on one side, convex on the other), Concavo-convex (one convex, one concave, but thicker in the centre).

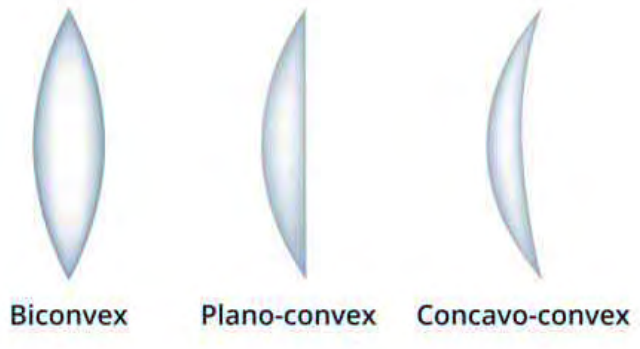


Figure 7.5: *Diagram showing types of convex lenses*

Concave lens (Diverging lens)

Shape

Thinner in the middle and thicker at the edges (like a peephole).



Figure 7.6: *A real image of a concave lens*

Effect on Light

They cause parallel light rays to diverge or spread out. When traced backward, these diverging rays appear to originate from a virtual focal point on the same side of the lens as the object.

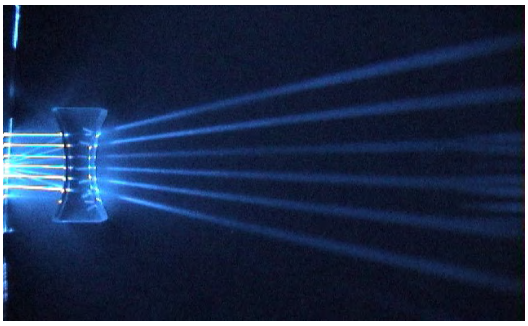


Figure 7.7: *A concave lens diverging a parallel beam of light*

Image Formation

Always form virtual, upright, and diminished (smaller) images.



Figure 7.8: *How a concave lens makes a large scene appear smaller*

Types

Biconcave (curved inwards on both sides), Plano-concave (flat on one side, concave on the other), Convexo-concave (one concave, one convex, but thinner in the centre).

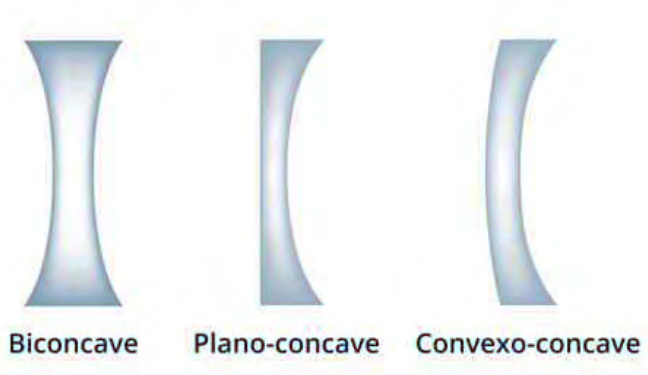


Figure 7.9: *Diagram showing types of concave lenses*

Features of Lenses

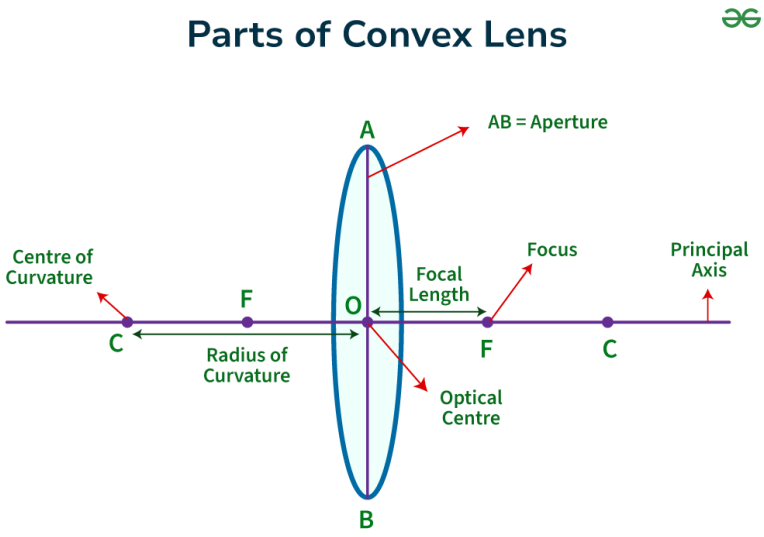


Figure 7.10: *A diagram showing the features of a lens*

1. Centre of curvature (C or 2F): The centre of the sphere from which the lens surface is a part.
2. Radius of curvature (R): The distance between the centre of the lens and the centre of curvature. It is equal to double the focal length.
3. Optical centre: A point on the principal axis where any ray of light passing through the centre has not deviated. It is denoted by "O".
4. Aperture: The diameter of the lens through which light can pass.
5. Focal length(f): The distance from the centre of the lens to the principal focus. In the case of convex lens, it is positive and negative in the case of concave lens.
6. Principal focus
    a. For a converging lens, this is the point on the principal axis where parallel rays of light converge after passing through the lens. There are two principal foci, one on each side of the lens, equidistant from the optical centre. It is a real focus.
    b. For a diverging lens, this is the point on the principal axis from which parallel rays of light appear to diverge after passing through the lens. It is a virtual focus.
7. Principal axis: An imaginary straight line passing through the centre of the lens and perpendicular to its surfaces.

Power of a Lens

The lens has the ability to converge or diverge light rays passing through. The measure of the ability of a lens to converge or diverge light rays passing through it is the power of the lens. It is the reciprocal of the focal length in metres of the lens, typically measured in dioptre. A higher power lens has a shorter focal length and bends light rays more strongly. It is mathematically expressed as

$$P = \frac{1}{f}$$

Where P is the power of the lens in dioptre (D)

And f is the focal length in metre (m)

Parallel Rays Through Convex and Concave Lenses

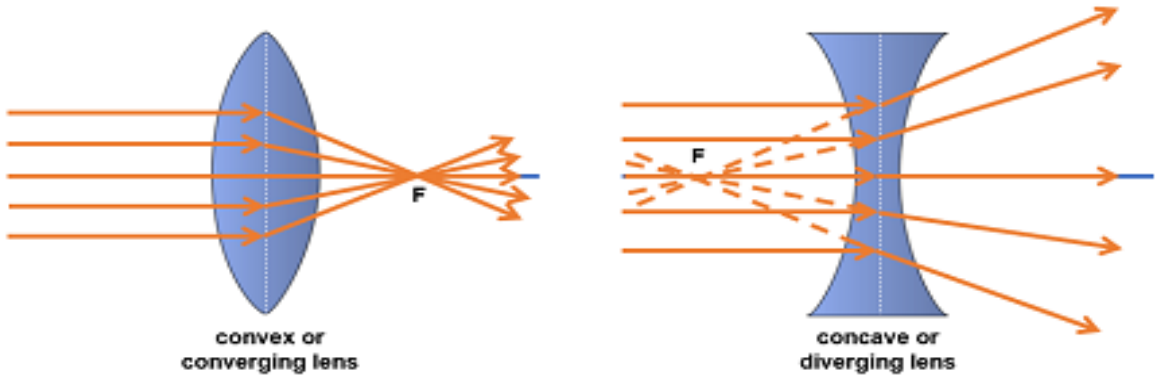


Figure 7.11: *A diagram showing parallel rays refracted by convex lens and concave lens.*

Images Formed by Lenses (Ray Tracing)

Ray tracing is a graphical method used to determine the characteristics or nature (position, type, size and orientation) of an image formed by a lens. It involves drawing at least two principal rays from the top of an object and observing where they intersect after passing through the lens. Where the two refracted rays meet is the where the image is formed.

Rules of tracing a ray through a lens

To trace an image formed by a lens, there are some rules to follow and these rules are highlighted below:

1. A ray parallel to the principal axis passes through (converging) or appears to diverge from (diverging) the principal focus (F) after refraction.
2. A ray passing through the optical centre (O) is undeviated.

3. A ray passing through (converging) or directed towards (diverging) the principal focus (F) emerges parallel to the principal axis after refraction.

Images Formed By Convex Lens

The nature of the images formed by the convex lens depends on the position of the object.

Case 1: Object placed at infinity

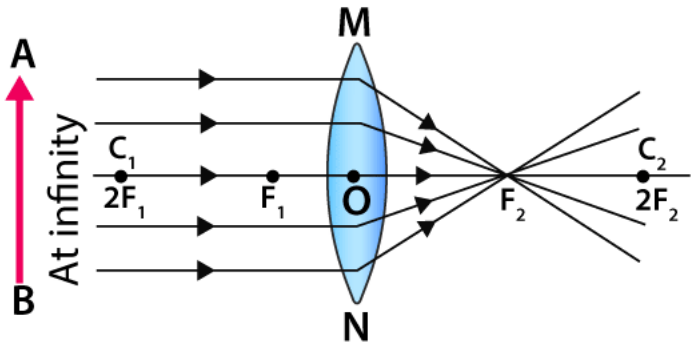


Figure 7.12: *Ray diagram showing the formation of image by a convex lens for an object at infinity*

Nature of image

1. Smaller than object
2. Inverted
3. Real
4. Formed at F

Case 2: Object placed beyond 2F

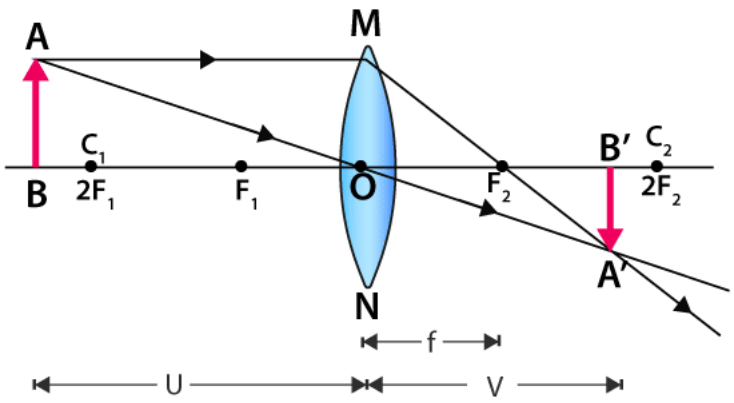


Figure 7.13: *Ray diagram showing the formation of image by a convex lens for an object beyond 2F*

Nature of image

1. Inverted
2. Formed between F and 2F
3. Real
4. Smaller than object

Case 3: Object placed at 2F

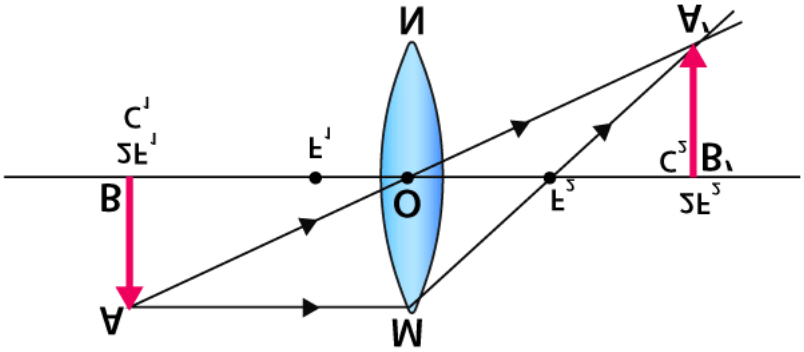


Figure 7.14: *Ray diagram showing the formation of image by a convex lens for an object at 2F*

Nature of image

1. Same size as the object
2. Inverted
3. Real
4. Formed at 2F

Case 4: Object placed between F and 2F

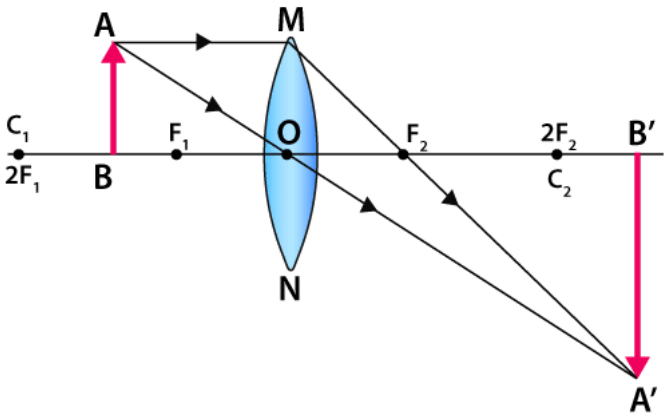


Figure 7.15: *Ray diagram showing the formation of image by a convex lens for an object between F and 2F*

Nature of image

1. Magnified
2. Formed beyond 2F
3. Real
4. Inverted

Case 5: Object placed at F

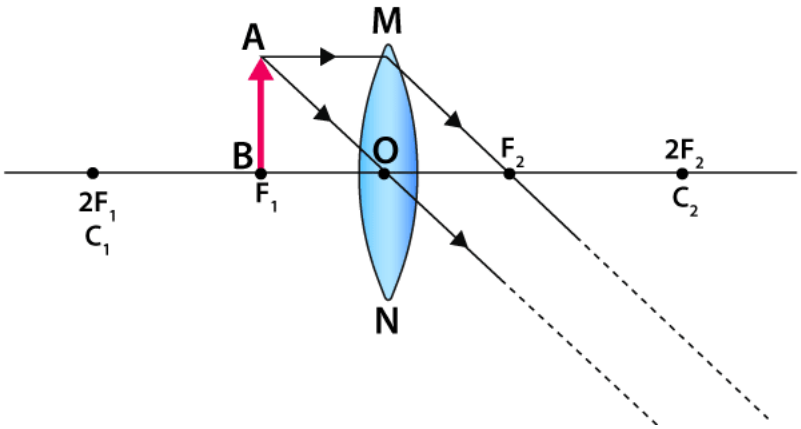


Figure 7.16: *Ray diagram showing the formation of image by a convex lens for an object at F*

Nature of image: Formed at infinity

Case 6: Object placed between F and O

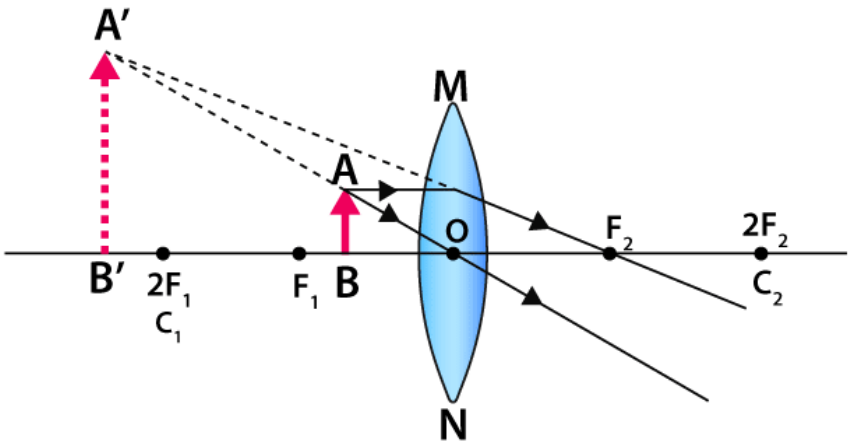


Figure 7.17: *Ray diagram showing the formation of image by a convex lens for an object between F and optical centre*

Nature of image

1. Virtual
2. Erect or Upright
3. Magnified
4. Formed at the same side of the lens as the object

Summary of image formation of convex lens

Object location	Image location	Image type and orientation	Image size
Infinity	At F	Real and inverted	Diminished
Beyond 2F	Between 2F and F	Real and inverted	Diminished
Between 2F and F	Beyond 2F	Real and inverted	Enlarged
At F	At infinity	Real and inverted	Infinitely large
At 2F	At 2F	Real and inverted	Same size
Between F and O	On the same side as the object	Virtual and erect	Enlarged

Images Formed by a Concave Lens

The image formed by a concave lens is always virtual, upright, diminished that is smaller than the object and formed at the side of the lens as the object irrespective of the position of the object.

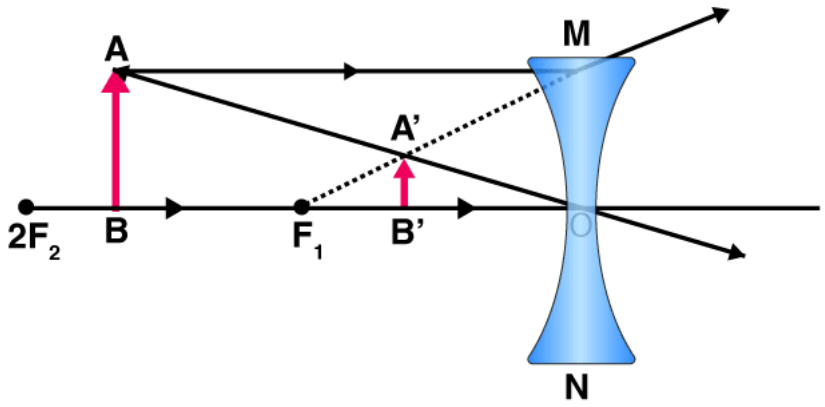


Figure 7.18: *Image formed by concave lens*

Determination of Image Distance and Magnification Using Lens Formula

While ray tracing provides a visual understanding, the lens formula and magnification formula offer precise mathematical calculations for image characteristics.

The **lens formula** is a fundamental equation in optics that relates the object distance (u), image distance (v), and the focal length (f) of a thin lens. It is applicable to

both convex (converging) and concave (diverging) lenses and helps predict where an image will form and its size relative to the object.

$$\frac{1}{f} = \frac{1}{\mathrm{u}} + \frac{1}{\mathrm{v}}$$

Where,

f = focal length of the lens (positive for convex, negative for concave)

v = image distance from the lens

u = object distance from the lens

Magnification (*m*) is a measure of how much larger or smaller the image formed by a lens is compared to the actual object. It describes the ratio of the image height to the object height. Its formula is expressed as

$$m = \frac{h_i}{h_o} = \frac{v}{u}$$

Where

m = magnification

h_i = height of the image

h_o = height of the object

v = image distance from the lens

u = object distance from the lens

To use the lens formula correctly, one of the following sign conventions must be applied consistently throughout the calculation. The "Real-is-Positive" convention (RPC)and the "New Cartesian convention" (NCC).

The real-is-positive convention defines distances to the right of the pole (or optical centre) as positive and to the left as negative, while the New Cartesian rule assigns positive signs to distances measured in the direction of the incident light and negative signs for distances measured against it.

Real-is-Positive Convention

1. Distances of real objects and images are positive, while those of virtual objects and images are negative.
2. Convex lens has a real principal focus and thus a positive focal length, while concave lens has a virtual principal focus and a negative focal length.

New Cartesian Convention

1. All distances are measured from the lens's optical centre.

2. Distances measured in the same direction as the incident light are positive.
3. Distances measured against the direction of the incident light are negative.

Applications of Convex and Concave Lenses

Applications of Convex Lenses (Converging Lenses)

Convex lenses are thicker in the middle and converge parallel light rays to a focal point. This property makes them incredibly useful for magnifying, focusing, and correcting farsightedness.

Here are some key applications

1. Magnifying Glass: This is one of the most common and direct applications. When an object is placed within the focal length of a convex lens, it produces a magnified, upright, and virtual image, making small objects appear larger.
2. Cameras: The primary lens in a camera is a convex lens (often a complex system of multiple convex and concave elements). It focuses light from the scene onto the camera's sensor or film, forming a real, inverted, and diminished image. By adjusting the distance between the lens and the sensor, the camera can focus on objects at different distances.
3. Telescopes
    a. Refracting Telescopes: These use a large objective convex lens to gather light from distant objects and form a real, inverted image. A smaller convex eyepiece then magnifies this image.
    b. Binoculars: Essentially two refracting telescopes mounted side-by-side, allowing for stereoscopic vision.
4. Microscopes: Compound microscopes use two main convex lenses:
    a. Objective Lens: A short focal length convex lens that produces a magnified, real, and inverted image of the specimen.
    b. Eyepiece Lens: Another convex lens that further magnifies the image from the objective, creating a large, virtual, and upright final image for the observer.
5. Projectors (Movie Projectors, Slide Projectors, Overhead Projectors): Convex lenses are crucial for projecting images onto a screen. They take a small, illuminated transparency or digital image and enlarge it by projecting a real, inverted image onto a distant surface.
6. Eyeglasses for Farsightedness (Hyperopia): Farsightedness occurs when the eye's lens focuses light behind the retina. A convex lens helps to converge

the light rays *before* they enter the eye, ensuring they focus correctly on the retina, allowing for clear vision, especially up close.

7. Solar Concentrators/Solar Furnaces: Large convex lenses (or parabolic mirrors, which act similarly) are used to concentrate sunlight onto a small area, generating extremely high temperatures for research, material processing, or generating electricity.

Applications of Concave Lenses (Diverging Lenses)

Concave lenses are thinner in the middle and cause parallel light rays to diverge. This property makes them ideal for spreading light, reducing magnification, and correcting near-sightedness.

Here are some key applications

1. Eyeglasses for Near-sightedness (Myopia): Near-sightedness occurs when the eye's lens focuses light in front of the retina. A concave lens diverges the light rays *before* they enter the eye, effectively moving the focal point backward onto the retina, allowing for clear distant vision.
2. Peepholes in Doors: A wide-angle peephole often uses a strong concave lens. This allows for a wider field of view, making distant objects appear smaller and fitting more of the scene into the viewer's sight.
3. Flashlights (for Wide Beam): While convex lenses focus light, concave lenses can be used in flashlights (or in conjunction with other lenses) to create a wider, more dispersed beam of light, illuminating a larger area.
4. Some Telescopes (Galilean Telescope): While less common than refracting telescopes, the Galilean telescope uses a convex objective lens and a concave eyepiece. This configuration produces an upright, virtual image, but with a smaller field of view than other telescope types.
5. Cameras (as part of Compound Lens Systems): While the main camera lens is typically convex, concave lens elements are frequently incorporated into complex camera lens designs (e.g. zoom lenses, wide-angle lenses) to correct various optical aberrations (like chromatic aberration and spherical aberration) and achieve specific focal lengths or fields of view. They help to flatten the field, reduce distortion, and improve overall image quality.
6. Beam Expanders: In laser systems, a combination of lenses, often including concave lenses, is used to expand the diameter of a laser beam. This is useful for applications where a wider, less intense beam is required, or for reducing divergence over long distances.

7. Dental Mirrors: Some dental mirrors are slightly concave to provide a slightly magnified view of the teeth, though flat mirrors are also common.

Activity 7.1 Researching Key Optical Terms Using the Internet or Books

Objective: To research, understand, and clearly define key optical terms related to lenses, using reliable sources, and present them in your own words with examples and diagrams for easier learning and revision.

What you need

1. Internet-enabled device (computer, tablet, or smartphone) OR access to reference books
2. Paper or notebook
3. Pen or pencil

What to do

1. Use the internet or your textbooks to research the meanings of the following terms related to lenses and optics:
   - **a.** Convex lens
   - **b.** Concave lens
   - **c.** Pole
   - **d.** Principal focus
   - **e.** Principal axis
   - **f.** Focal length
   - **g.** Optical centre
2. For each term, write down:
   - **a.** A clear definition or description of the term.
   - **b.** Important characteristics or features
   - **c.** Any examples or typical uses mentioned in your sources for a and b.
3. Use simple diagrams from your research, if possible, to help visualise these terms.
4. After gathering definitions, summarise your findings by writing short explanations in your own words for each term.
5. Create a glossary or flashcards for these terms to review later.

Activity 7.2 Key Features & Measuring of Focal Length of a Convex Lens

Objective: To identify the key features of convex and concave lenses, compare how they refract light, and accurately measure the focal length of a convex lens by observing and recording image formation from a distant object.

What you need

1. One converging (convex) lens
2. One diverging (concave) lens
3. White screen or plain white paper/surface
4. Ray box with adjustable slit or candle flame (for light source)
5. Ruler or meter stick
6. Distant object to observe (e.g., window, tree outside a window)
7. Stand or clamp to hold lenses steady (optional)
8. Paper and pen or notebook to record observations

What to do

1. Classify the lenses by observing refraction
   - **a.** Hold the convex lens and direct the ray box's light or candle flame light through it onto the white screen.
   - **b.** Observe how the light rays refract: do they converge to a point or diverge?
   - **c.** Repeat this with the concave lens and note the difference in how light behaves.
   - **d.** Based on your observations, verify the lenses as *convex (converging)* or *concave (diverging)*.
2. Identify lens features using light rays
   - **a.** Look closely at the convex lens and identify the optical centre (the middle point of the lens).
   - **b.** Notice the principal axis.
   - **c.** Using the ray box or candle, send light rays parallel to the principal axis through the lens and see where they converge (for convex) or appear to diverge from (for concave).
   - **d.** Mark or note this point on the white screen—this is the *principal focus*.

3. Perform the Practical Activity to Find Focal Length of the Convex Lens
   - **a.** Place the convex lens securely between you and a distant object such as a tree or window far away.
   - **b.** Position the white screen on the other side of the lens.
   - **c.** Move the screen slowly back and forth to find the position where a sharp, clear image of the distant object appears on the screen.
   - **d.** Once the sharpest image is formed, measure the distance between the lens and the white screen carefully using a ruler or meter stick.
   - **e.** Record this distance—it represents the *focal length* of the convex lens.
4. Summarise and Reflect
   - **a.** Write down your observations of how the convex and concave lenses refract light differently.
   - **b.** State the locations of the optical centre, principal axis, principal focus, and the measured focal length for the convex lens.
   - **c.** Explain why the focal length is important and how it relates to lens behaviour in forming images.

Activity 7.3 Exploring Image Formation with Lenses Using the PhET

Objective: To explore how convex and concave lenses form images by using an interactive simulation, varying object distance, and applying the lens formula to understand the relationship between object position, image characteristics, and ray diagram behaviour.

What you need

1. Access to the PhET Geometric Optics simulation:

   https://phet.colorado.edu/en/simulation/geometric-optics

2. Paper or notebook
3. Pen or pencil

What to do

1. Open the simulation: Navigate to the PhET Geometric Optics simulation link and launch the "Lenses" interactive module.
2. Choose between a converging (convex) lens and a diverging (concave) lens to investigate.
3. Manipulate object distance
   - **a.** Use the slider or drag the object (arrow) along the principal axis to change the object distance (distance from the lens to the object).
   - **b.** Observe the changes in the image formed on the screen or virtual background as you move the object closer to or further from the lens.
4. For each object distance position, record:
   - **a.** Image location (distance from the lens)
   - **b.** Image size (height relative to the object)
   - **c.** Image nature (real or virtual, upright or inverted)
5. Using your recorded object distance (u), image distance (v), and focal length (f) of the lens, verify the lens formula:

   $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$
6. Interpret ray diagrams
   - **a.** Use the simulation's option to display principal rays passing through the lens.
   - **b.** Observe how the rays intersect at the image position and relate this to your recorded image characteristics.
7. Switch between convex and concave lenses and repeat the process, noting how image location, size, and nature change.
8. Summarise your observations
   - **a.** Describe how changing the object distance influences the image's position, size, and type for each lens.
   - **b.** Explain how these observations reinforce your understanding of the lens formula and ray diagrams.

Activity 7.4 Observing Image Formation with Lenses Using Ray Boxes

Objective: To investigate and compare how convex and concave lenses form images by observing, sketching, and analysing ray diagrams for different object positions, and to understand how lens type and object distance affect image size, orientation, location, and nature.

What you need

1. Ray box with adjustable slit or candle flame as a light source
2. Convex (converging) lens
3. Concave (diverging) lens
4. White screen or plain white paper/surface for projecting or observing images
5. Ruler or meter stick
6. Lens stand or clamp (optional, for stability)
7. Paper or notebook for sketches and notes
8. Pencil or pen

What to do

1. Place the ray box or candle so it emits a narrow beam of light rays. Position the white screen behind where images will appear. Secure the lens on a stand or hold it steadily between the light source and the screen.
2. For each object position below, observe the image formed on the screen or white surface and then
   - **a.** Beyond 2F (twice the focal length): Place the ray box so the object is beyond 2F. Observe and sketch the image, noting its position, size, orientation, and whether it is real or virtual.
   - **b.** At 2F: Move the object to twice the focal length distance. Observe and sketch the image again with notes.
   - **c.** Between F and 2F: Place the object between the focal length (F) and twice the focal length (2F). Observe and sketch the image characteristics.
   - **d.** At F: Place the object exactly at the focal length. Observe what happens to the image—note if it forms or not.
   - **e.** Between Lens and F: Place the object closer than the focal length. Observe, sketch, and record image details, noting particularly if the image appears on the same side as the object (virtual).

3. For each object position, draw a ray diagram showing:

- **a.** The object location relative to F and 2F
- **b.** Three principal rays:
  - **i.** Ray parallel to principal axis refracted through focal point
  - **ii.** Ray through optical centre passes straight
  - **iii.** Ray through focal point refracted parallel to principal axis
- **c.** Image location, size (relative to object), orientation, and type (real or virtual).

4. Replace the convex lens with the concave lens.

- **a.** Position the object at various distances (exact positions like F and 2F are less critical because concave lenses always form virtual images).
- **b.** Observe how the light rays diverge after passing the lens and use the white screen or your eye to note image appearance (usually virtual, upright, and smaller).
- **c.** Sketch ray diagrams for the concave lens using these principal rays:
  - **i.** Ray parallel to principal axis refracted as if from principal focus on the object's side
  - **ii.** Ray through optical centre goes straight without deviation
  - **iii.** Ray directed toward principal focus refracted parallel to principal axis
- **d.** Record image size, orientation, nature (virtual), and relative position.

5. For both lenses, write down for each object position:

- **a.** Image size (larger, smaller, same size)
- **b.** Orientation (upright or inverted)
- **c.** Nature (real or virtual)
- **d.** Image location (same side or opposite side of lens)

6. Summarise how image formation differs between convex and concave lenses and how changing object position affects the image in the case of convex lenses.

Activity 7.5 Calculating Lens Power, Image Position, and Magnification

Study the worked examples below carefully before attempting the example questions that follow.

Worked Example 1

A lens has a focal length of 25 cm, determine the power of the lens.

Solution

f = 25cm

f = 0.25m

From $P = \frac{1}{f}$

$P = \frac{1}{0.25}$ m

P = 4D; Hence the power of the lens is 4 dioptres.

Worked Example 2

An object 4 cm tall is placed 30 cm in front of a convex lens with a focal length of 10 cm. Determine the position, type and size of the image.

Solution

Using real-is-positive convection

Object height (h_o) = 4 cm

Object distance (u) = 30 cm (always positive for real objects)

Focal length of convex lens (f) = 10 cm (positive for a convex lens)

$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$

$\frac{1}{10} = \frac{1}{30} + \frac{1}{v}$

$\frac{1}{v} = \frac{1}{10} - \frac{1}{30}$

$\frac{1}{v} = \frac{1}{15}$

Hence the object is formed at a position 15cm from the lens and it is a real image since the value is positive.

To determine the size of the image formed, we need to find the image height.

$m = \frac{h_i}{h_o} = \frac{v}{u}$

$m = \frac{h_i}{4} = \frac{15}{30}$

$h_i = 0.5 \times 4$

$h_i = 2\ cm$

Hence the image size is 2 cm which is smaller than the object.

Worked Example 3

An object is placed 25cm in front of a concave lens of focal length 15cm. Determine the position and the type of the image formed.

Solution

Using real-is-positive convention

Object distance u = 25cm

Focal length f = -15cm (concave lenses are given negative focal lengths)

Image distance v =?

From the lens formula,

$\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$

$\frac{1}{v} = \frac{1}{f} - \frac{1}{u}$

$\frac{1}{v} = \frac{1}{-15} - \frac{1}{25}$

$\frac{1}{v} = \frac{8}{-75}$

$v = -9.375cm$

Hence the image is formed at a distance 9.375cm from the lens and it is a virtual image.

Practice problems

Now, using the worked example as a guide, solve the following problem individually or in groups.

1. An object is placed 30 cm from a converging (convex) lens. A real image is formed that is 2 times the size of the object.

   a. **Determine the position of the image.**

   b. **Calculate the focal length of the lens.**

   c. **What is the power of the lens?**

Activity 7.6 Research Task About Applications of Lenses

Research Task Guidance: How Lenses Are Used in Different Systems

1. Understand the Task

- **a.** You are researching how lenses are used in different systems.
- **b.** Focus on four areas: the human eye, cameras, microscopes, and telescopes.
- **c.** Think about how lenses help each system to see, focus, or magnify.

2. Organise Your Research

Divide your research into four parts

A. The Human Eye

- **i.** What does the lens in the eye do?
- **ii.** How does it help us see clearly?
- **iii.** What happens if it doesn't work properly?

B. Cameras

- **i.** What kind of lens does a camera use?
- **ii.** How does the lens help form an image?
- **iii.** What changes when the lens is adjusted?

C. Microscopes

- **i.** What are microscopes used for?
- **ii.** How do lenses help magnify small things?
- **iii.** What happens when you change the lenses?

D. Telescopes

- **i.** What are telescopes used for?
- **ii.** How do lenses help us see faraway things?
- **iii.** Are there different types of telescopes?

3. Do Your Research

- **a.** Use books, websites, videos, or ask your teacher for resources.
- **b.** Write down the most important points.
- **c.** Try to understand how lenses work in each case.

4. You could create

- **a.** A short report

b. A slideshow
c. A poster
d. A fact sheet

5. Make sure to
a. include pictures or diagrams
b. use clear labels and short explanations
c. keep it neat and easy to understand

LASER LIGHT

Lasers

Lasers are part of our daily lives — they scan items at supermarkets, perform precise eye surgeries, cut materials in factories, and send information through fibre optic cables.

Unlike ordinary light from a bulb or the sun, laser light is highly focused, travels in a single direction, and has waves that are all in step (coherent).

The word **LASER** is an acronym for L*ight* A*mplification by* S*timulated* E*mission of* R*adiation*, which describes how the light is produced. This principle was first proposed by Albert Einstein in 1917, and in 1960 Theodore Maiman built the first working laser. Since then, lasers have revolutionised medicine, manufacturing, communication, and scientific research.

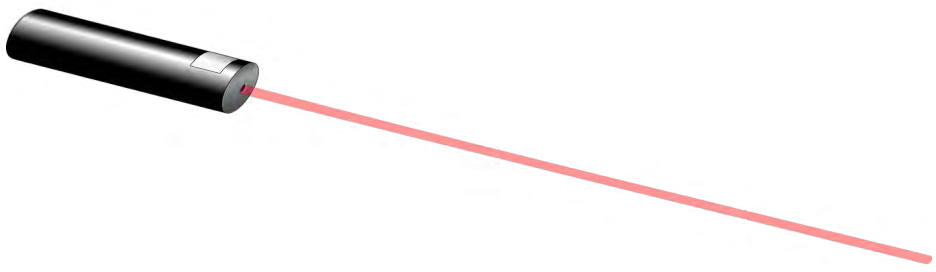


Figure 7.19: *A diagram showing a red laser light*

Properties of Lasers

Laser light is defined by three primary characteristics that distinguish it from ordinary light:

1. **Monochromaticity**

   Laser light consists of a single, highly precise wavelength (or colour). This is in stark contrast to white light, which is a blend of many different wavelengths across the visible spectrum. The specific wavelength of a laser is determined by the "gain medium" used to produce the light.

2. **Coherence**

   This refers to the synchronisation of the light waves. All the photons in a laser beam are in phase, meaning their crests and troughs align perfectly. This spatial and temporal coherence allows the beam to remain focused over long distances and gives it its high intensity.

3. **Directionality (Collimation)**

   A laser beam is highly directional and does not diverge significantly. It travels in a very narrow, concentrated beam with minimal spread. This is because the light is generated in a resonant cavity where only photons traveling in a specific direction are amplified, unlike a flashlight which scatters light in all directions.

Laser Production

The production of a laser beam is a sophisticated process that relies on the principles of quantum mechanics. It involves three key components working in concert: a gain medium, an energy source, and an optical resonator. The mechanism can be broken down into a series of steps:

1. **Pumping (Excitation)**

   The process begins with an energy source, also known as a **pump**, which provides energy to the **gain medium**. The gain medium is the core material (solid, liquid, or gas) where laser action occurs. In its natural state, most of the atoms in the gain medium are in a low-energy level "ground state." The pump, which can be an electrical current, a flashlamp or another laser, "excites" these atoms by transferring energy to them. This causes their electrons to jump to a higher-energy level "excited state."

2. **Population Inversion**

   For a laser to work, a critical condition called **population inversion** must be achieved. In a normal material, more atoms are in the ground state than in an excited state. Pumping must be powerful enough to create an unnatural, non-equilibrium condition where there are more atoms in a higher-energy

state than in a lower-energy state. This "inversion" is necessary because it ensures that stimulated emission will dominate over absorption.

3. **Spontaneous and Stimulated Emission**

Once population inversion is established, two types of emission can occur

a. **Spontaneous Emission**

Some of the excited atoms will naturally and randomly decay back to a lower energy state. When they do, they release a photon of light. These photons are emitted in random directions and with random phases, much like light from a conventional bulb.

b. **Stimulated Emission**

This is the heart of the laser mechanism, a concept first proposed by Albert Einstein. If a spontaneously emitted photon strikes another excited atom, it "stimulates" that atom to release its energy as a new photon. This new photon is an exact copy of the one that stimulated it—it has the same wavelength, phase, direction, and polarisation. This process creates a cascade effect, where one photon leads to two, two to four, and so on. This chain reaction is the source of the high intensity and coherence of laser light.

4. **Light Amplification (Resonation)**

The gain medium is placed inside an **optical resonator**, which consists of two mirrors facing each other. One mirror is fully reflective, and the other is partially reflective. The photons produced by stimulated emission travel back and forth between these mirrors, passing through the gain medium multiple times. With each pass, the photons stimulate more emissions, and the light is amplified. The mirrors ensure that only the photons traveling in a specific, narrow path are amplified, which is what gives the laser beam its directionality.

5. **Laser Beam Emission**

Finally, as the light builds up in the resonator, it becomes so intense that a portion of it passes through the partially reflective mirror. This escaping light is the laser beam. The properties of this beam are a direct result of the resonant amplification: it is monochromatic (single wavelength), coherent (waves are in phase), and highly directional (collimated).

Features of Laser Configuration

A typical laser system includes three essential components

1. **Active Medium (Gain Medium)**

   As discussed, this is the core material that amplifies light. Its choice dictates the laser's wavelength and power characteristics. Examples include ruby crystals (solid), helium-neon gas mixtures (gas), organic dyes (liquid), or semiconductor junctions (diode lasers). See below for more detail.

2. **Energy Source (Pump)**

   Provides the energy to excite the active medium's atoms. This can be electrical discharge (for gas lasers), flash lamps (for solid-state lasers), or even other lasers (for dye lasers or some solid-state lasers).

3. **Optical Resonator (Cavity)**

   Formed by two highly reflective mirrors. Their precise alignment and distance determine the specific wavelengths that are amplified and resonate within the cavity. The length of the cavity also dictates the separation between different modes (allowed wavelengths) of the laser.

Types of Lasers

Lasers are classified based on the type of gain medium they use

1. Gas Lasers: Use a gas or a mixture of gases as the gain medium, such as helium-neon (HeNe), carbon dioxide (CO2), or argon.
2. Solid-State Lasers: Use a solid material, like a crystal or glass, doped with rare-earth elements. The first-ever laser was a ruby solid-state laser.
3. Fiber Lasers: A specialised type of solid-state laser where the gain medium is an optical fibre. They are known for their high power, efficiency, and compact design.
4. Semiconductor Lasers (Laser Diodes): These are the most common type of laser, found in everyday devices like barcode scanners, laser pointers, and optical drives (CD/DVD/Blu-ray players). They are small and energy-efficient.
5. Liquid Lasers (Dye Lasers): Use organic dyes in a liquid solution as the gain medium. Their main advantage is that their wavelength can be "tuned" to produce a wider range of colour.

Applications of Lasers

The unique properties of laser light have made it indispensable in countless fields

1. Medicine: From non-invasive eye surgery (LASIK) and cosmetic procedures (tattoo and hair removal) to precision surgical cutting and cancer treatments.
2. Manufacturing: High-power lasers are used for precision cutting, welding, drilling, and engraving of various materials in industries like automotive, aerospace, and electronics.
3. Technology & Communication: Laser diodes are the backbone of fibre-optic communication, transmitting vast amounts of data at the speed of light. They are also integral to barcode scanners, printers, and data storage devices.
4. Scientific Research: Lasers are used in spectroscopy to analyse the composition of materials, in interferometry to measure distances with extreme accuracy, and in fields like quantum physics and fusion research.
5. Consumer Products: Laser pointers, Blu-ray players, and some high-end projectors all rely on laser technology.
6. Military & Defence: Lasers are used for range-finding, target designation, and in directed-energy weapons.



Figure 7.20: *A high-energy laser military weapon*

7. **Entertainment:** Laser light shows for concerts and events.



Figure 7.21: *Laser lighting for entertainment*

Hazards Associated with Laser

Lasers, particularly high-power ones, present a variety of dangers that can be categorised into two main types: beam hazards and non-beam hazards. The potential for harm depends on factors such as the laser's power, wavelength and the duration of exposure.

Beam Hazards

Beam hazards are the risks directly related to the laser beam itself and are the most commonly recognised dangers.

1. **Eye Damage**
   The eye is the most vulnerable organ to laser radiation. The cornea and lens can focus a laser beam to an extremely small, high-intensity spot on the retina. This can cause thermal damage, photomechanical damage (due to shockwaves from rapid heating), or photochemical damage, all of which can lead to permanent vision loss.
   a. Retinal Burns: Visible and near-infrared light (400 nm to 1400 nm) can pass through the cornea and lens and be focused onto the retina. Even a relatively low-power laser can cause a severe burn on the retina in a fraction of a second, faster than the natural blink reflex.
   b. Corneal Damage: Ultraviolet (UV) light (below 400 nm) and far-infrared light (above 1400 nm) are absorbed by the cornea and lens, leading to conditions like photokeratitis ("welders' flash" or "snow blindness"), cataracts, or severe burns.

2. **Skin Damage**

   High-power lasers can cause thermal burns to the skin. UV lasers can also cause photochemical damage, leading to effects similar to sunburn, accelerated skin aging, and an increased risk of skin cancer from chronic exposure.

3. **Fire Hazard**

   High-power lasers, especially Class 4 lasers, can easily ignite flammable materials in their path. This includes paper, plastics, fabrics, and even certain laser barriers, posing a significant fire risk in a lab or industrial setting.

Non-Beam Hazards

These are dangers associated with the operation of a laser system but are not caused by the laser beam itself.

1. **Electrical Hazards**

   Lasers often require high-voltage power supplies, capacitors, and complex electrical systems. Contact with these components can result in severe electrical shock, burns, or even electrocution.

2. **Chemical Hazards**

   Many lasers use hazardous materials. This includes:

   a. Laser Gases: Gases like those in excimer lasers are often toxic, corrosive, or flammable.

   b. Laser Dyes: Used in dye lasers, these are often carcinogenic or toxic.

   c. Airborne Contaminants: During laser cutting, welding, or ablation, the laser can vaporise materials, releasing toxic fumes, gases, or airborne particles that are a health hazard if inhaled.

3. **Mechanical Hazards**

   High-power lasers can be used to cut materials, which can create flying debris or shards that pose a mechanical hazard. Additionally, high-pressure components like arc lamps in some laser systems can be an explosion risk.

4. **Collateral Radiation**

   Some lasers, particularly those with high-voltage power supplies, can generate non-beam radiation like X-rays, UV radiation, or electromagnetic interference (EMI).

Precautions for Laser Safety

1. Never look directly into a laser beam or its specular (mirror-like) reflection. This is the most common cause of serious laser-related injury.
2. Know the laser's classification. The class determines the necessary safety precautions.
3. Follow alignment procedures with extreme caution. Alignment is often the most dangerous part of laser operation, as beams are exposed. Use the lowest possible power during alignment and wear appropriate eye protection.
4. Appoint a Laser Safety Officer (LSO). A qualified LSO should be responsible for overseeing the safety program, conducting hazard assessments, and ensuring all controls are in place.
5. Have an emergency plan. Know what to do in case of an accident or unexpected exposure, including who to contact and where to seek medical attention
6. Laser Safety Eyewear: This is the most crucial form of PPE. Eyewear must be specifically rated for the laser's wavelength and optical density (OD). It should fit properly and be free of damage. It is essential to use the correct eyewear for the specific laser being operated, as a single pair of glasses may not protect against all wavelengths.
7. Protective Clothing: When working with high-power lasers, protective clothing like lab coats, gloves, and face shields may be necessary to prevent skin burns.
8. Fire-Resistant Materials: Flammable materials should be removed from the laser's path. Fire-resistant drapes or curtains may be needed, especially with Class 4 lasers.

Activity 7.7 Discussing Key Terms Related to Laser Production

Objective: To develop a clear understanding of the fundamental terms and concepts involved in laser production, enabling you to explain these ideas in your own words and illustrate them with diagrams for better comprehension and communication.

What you need

1. Internet-enabled device or reference textbooks
2. Paper or notebook
3. Pen or pencil

4. Whiteboard and markers (for the class discussion and illustrations)

What to do

1. Using the internet or reference books, research and write down clear definitions for the following laser production terms in your notebook:
   - **a.** Pumping
   - **b.** Population inversion
   - **c.** Active medium
   - **d.** Metastable state
   - **e.** Stimulated emission
2. Write concise explanations in your own words for each term along with any relevant details you find.
3. Get ready to share one or more of your definitions with the group.
4. Volunteers from among yourselves to:
   - **a.** define each term aloud for the class
   - **b.** draw energy level diagrams on the board to illustrate the concept (e.g., showing energy levels and transitions involved in stimulated emission or population inversion)

Activity 7.8 Exploring Everyday Laser Applications Using Video

Objective: To identify and understand various real-world applications of lasers, link each application to the specific properties of lasers that make it possible, and recognise the advantages these properties provide in practical use.

What you need

1. Access to the video -The video link: https://www.youtube.com/watch?v=ywMQYiEXWrg
2. Paper or notebook
3. Pen or pencil

What to do

1. Open the video above and watch or listen to it carefully. Observe the different laser applications shown, such as laser surgery, CD/DVD reading, barcode scanning, and fibre-optic communications.
2. While watching or listening, write down each specific application of lasers mentioned. For each application, think about what unique property of lasers is being used (e.g., monochromatic light, coherence, high intensity, directionality).
3. After watching, review your notes and discuss the applications and their corresponding laser properties with a colleague
4. Create a table with the following columns:
   a. Application (e.g., Laser surgery, barcode scanning)
   b. Laser Property Used (e.g., focus, monochromaticity, coherence)
   c. Advantage in Application (e.g., precise cutting, accurate reading, high-speed data transmission)
5. Fill in the table based on your observations and discussion.

Activity 7.9 Understanding Laser Operation Using Video

Objective: To understand and explain the process of laser generation by identifying the key components, principles, and steps involved in producing a coherent, intense, and directional laser beam.

What you need

1. Access to the video "How Does a Laser Work? (3D Animation)" at this link: https://www.youtube.com/watch?v=RQUFOA_8LZg
2. Paper or notebook
3. Pen or pencil

What to do

1. Open the video and watch it fully to learn how a laser works, focusing on how the straight, powerful laser beam is generated.

2. While watching, write notes about
   - **a.** The energy source (pump) that starts the process by exciting electrons.
   - **b.** The active (gain) medium where electrons get excited and photons are produced.
   - **c.** The optical cavity with two mirrors (one fully reflective and one partially reflective) that bounce photons back and forth, amplifying them.
   - **d.** How stimulated emission causes photons to multiply and form a coherent beam.
   - **e.** Why the laser beam is directional and focused (photons bouncing perpendicularly between mirrors).
3. Define and explain in your notes
   - **a.** Pumping (energy supply to excite electrons)
   - **b.** Population inversion (more electrons in excited state than ground state)
   - **c.** Stimulated emission (the release of more photons triggered by photons)
   - **d.** Optical cavity (the system of mirrors amplifying light)
4. Write a short summary describing
   - **a.** How energy from the pump creates excited electrons.
   - **b.** How these electrons emit photons when returning to the ground state.
   - **c.** How photons cause stimulated emission, amplifying light inside the cavity.
   - **d.** How the mirrors form a coherent, intense laser beam that exits the cavity.
5. Share your summaries with classmates, explaining the role of each laser component and how the process produces a powerful beam of coherent light.

Activity 7.10 Laser Types, Safety, Hazards and Applications

Objective: To research and understand laser safety classifications, hazards, and applications, and to communicate this knowledge effectively by creating

an informative poster or infographic that promotes safe laser use in different contexts.

What you need

1. Internet access or access to reference books on laser safety and applications
2. Paper or notebook
3. Pen or pencil
4. Materials for poster/infographic creation (poster board, coloured markers/pencils, or digital design software)

What to do

1. Find 2 to 4 other people with whom to form a small group.
2. Research the different types of laser (gas, solid-state, semi-conductor, dye) and consider the differences in their structure and operation. Is one type of laser preferable to another for any reason, including safety reasons?
3. Research Laser Safety Classes and Hazards
   - **a.** Online sources or science textbooks to investigate the laser safety classifications (Class 1, 2, 3, 4).
   - **b.** Find out what each class means in terms of potential hazard—such as risks of eye injury, skin burns, or fire.
   - **c.** List examples of hazards (e.g., eye damage from direct or reflected beams, skin burns, ignition of flammable materials).
4. Look into what procedures are standard in labs and workplaces for laser safety. Focus on areas like
   - **a.** Use of warning signs and labels
   - **b.** Wearing protective goggles/glasses
   - **c.** Controlling access to areas with powerful lasers
   - **d.** Avoiding reflective jewellery or watches in laser labs
   - **e.** Never pointing lasers at eyes or at reflective surfaces
   - **f.** Emergency procedures for laser accidents
5. Research at least one real-world use of lasers in each of these fields
   - **a.** Medicine (e.g., eye surgery, tissue cutting)
   - **b.** Industry (e.g., welding, cutting, barcode scanning)
   - **c.** Communication (e.g., fibre-optic transmission)
   - **d.** Science/Labs (e.g., spectroscopy, holography, alignment)

6. Summarise your research by designing an informative poster or infographic. Your display should include
   - **a.** Main laser safety classes, labelled with simple explanations and symbols/colours for quick recognition
   - **b.** Common hazards and how to avoid them
   - **c.** Essential safety procedures and personal protective equipment (PPE)
   - **d.** Good practices for safely handling and operating lasers
   - **e.** One or more applications of lasers with how safety is managed in those contexts (for example, why surgeons wear special goggles in laser surgery)

   Use visuals, icons, and simple language to make your poster easy to understand at a glance.
7. Present your poster to another group in your class, explaining your main safety messages and which information you found most surprising or important. Look at other learners' posters/infographics for extra ideas.

Activity 7.11 Exploring Laser Reflection and Beam Properties

Objective: To investigate how laser beams reflect from different types of surfaces, and to understand how surface texture affects the brightness, spread, and clarity of the reflected beam, linking these observations to the directional and coherent properties of laser light.

What you need

1. Class 1 or Class 2 laser pointers (with beam powers safe for supervised classroom use)
2. Small plane mirrors or reflective surfaces
3. Various other surfaces with different textures and finishes (e.g., white paper, black matte paper, glossy magazine cover)
4. Paper or notebook
5. Pen or pencil

What to do

1. Safety Check and Setup
   - **a.** Before starting, ensure that you understand laser safety - never point the laser beam at anyone's eyes, and avoid reflecting the beam toward others.
   - **b.** Keep the laser pointer beam at or below eye level, and do not look directly into the beam or its reflections.
   - **c.** Only operate the laser pointers under direct supervision.
2. Explore reflection on mirrors
   - **a.** Shine the laser pointer beam onto a flat mirror at an angle. Observe where the reflected beam goes.
   - **b.** Move the laser pointer and mirror to observe how the angle of incidence equals the angle of reflection.
   - **c.** Note the brightness/intensity and tightness (spread) of the reflected beam.
3. Investigate reflection on different surfaces
   - **a.** Shine the laser pointer on different surfaces like white paper, black matte paper, and a glossy magazine.
   - **b.** Observe and record how the intensity and spread of the reflected beam changes.
   - **c.** Notice that smooth, shiny surfaces reflect the beam more directly with minimal spread, while rough, matte surfaces diffuse the beam, causing it to spread out and appear less intense.
4. For each surface, write down
   - **a.** How bright the reflected beam appears
   - **b.** How much the beam spreads or remains narrow after reflection
   - **c.** Whether the reflection appears sharp and well-defined or diffused and scattered
5. Link Observations to Laser Properties
   - **a.** Consider that lasers emit light which is highly directional and coherent, resulting in a narrow, intense beam.
   - **b.** Reflect on how the directionality causes sharp reflections on smooth surfaces (mirror-like) and how surface roughness causes scattering, reducing intensity and increasing beam spread.

Activity 7.12 Review Optics Concepts with Quiz and Concept Mapping

Objective: To review and strengthen understanding of key optics concepts—including spherical mirrors, refraction, lenses, and lasers—by answering quiz questions collaboratively, creating a concept map to show connections between topics, and reflecting on areas of confidence and those needing further study.

What you need

1. Paper and pencil or pen
2. Coloured pens or markers (if available)
3. Quiz questions on spherical mirrors, refraction, lenses, and lasers (see below)
4. Large paper or poster paper for concept map (optional)

What to do

1. Form a small group of 3 to 5 people.
2. Work on the quiz questions together
   - **a.** Take turns reading the quiz questions (sample below) about spherical mirrors, refraction, lenses, and lasers.
   - **b.** Discuss each question as a group and agree on the best answer.
   - **c.** Help each other understand the concepts, explain your reasoning, and ask questions if anything is unclear.
3. Make a Concept Map
   - **a.** After finishing the quiz, create a concept map on paper that connects the main ideas from all four topics.
   - **b.** Use keywords like "reflection," "refraction," "image formation," "focal length," and "laser beam."
   - **c.** Draw arrows showing how these ideas relate (for example, how lenses use refraction to form images, or how lasers demonstrate light travel).
   - **d.** Add simple sketches or diagrams to illustrate important points.
4. Present your group's work
   - **a.** Share your concept map with other groups if possible.
   - **b.** Explain the connections you made and anything new you learned from the quiz discussion.

5. Think about what you learned

a. Individually, write a short note on what you found easiest and hardest in the activity.

b. Write down any concepts you want to study more.

Sample Quiz Questions for Optics Review

Spherical Mirrors

1. What type of image (real or virtual) is formed by a concave mirror when the object is beyond the focal point?
2. How does the image change when an object moves closer to the focal point in a concave mirror?
3. What is the difference in image formation between convex and concave mirrors?

Refraction

4. What happens to light when it moves from air into water?
5. State Snell's Law and explain how it relates angle of incidence and refraction.
6. How do you calculate the refractive index of a material given the angle of incidence and angle of refraction?

Lenses

7. Describe how a convex lens forms an image when an object is placed beyond the focal length.
8. What kind of image is formed by a concave lens, and is it real or virtual?
9. How does the focal length of a lens affect the size of the image?

Lasers

10. What is a key property of laser light that differentiates it from ordinary light?
11. How can lasers help demonstrate the behaviour of light in optics experiments?
12. Why are lasers used in precise measuring instruments and communication technologies?

REVIEW QUESTIONS

Review Questions 7.1

1. A student performs an experiment with a lens. They place an object 15 cm in front of the lens and observe that a magnified, upright image is formed 60 cm from the lens on the *same side* as the object.

- **a.** Identify the type of lens used (convex or concave) and explain your reasoning.
- **b.** Calculate the focal length of this lens.
- **c.** Determine the magnification of the image.
- **d.** If the object's height is 4 cm, what is the height of the image?

2. A real object is placed 20 cm from a converging (convex) lens. A real image is formed that is 3 times the size of the object.

- **a.** Determine the position of the image.
- **b.** Calculate the focal length of the lens.
- **c.** What is the power of the lens?

3. An object is placed 35 cm in front of a lens. A real image is formed 70 cm away on the other side of the lens.

- **a.** Determine the magnification of the image.
- **b.** Calculate the focal length of the lens.
- **c.** What is the power of the lens?
- **d.** Identify the type of lens used.

Review Questions 7.2

1. A scientist is using an external energy source to excite the atoms of a material, creating a state where there are more atoms in a high-energy state than in a low-energy state. This is followed by a chain reaction where a single photon causes an excited atom to release an identical photon, which in turn causes another to do the same.

- **a.** What is the name of the critical condition where more atoms are in a high-energy state?

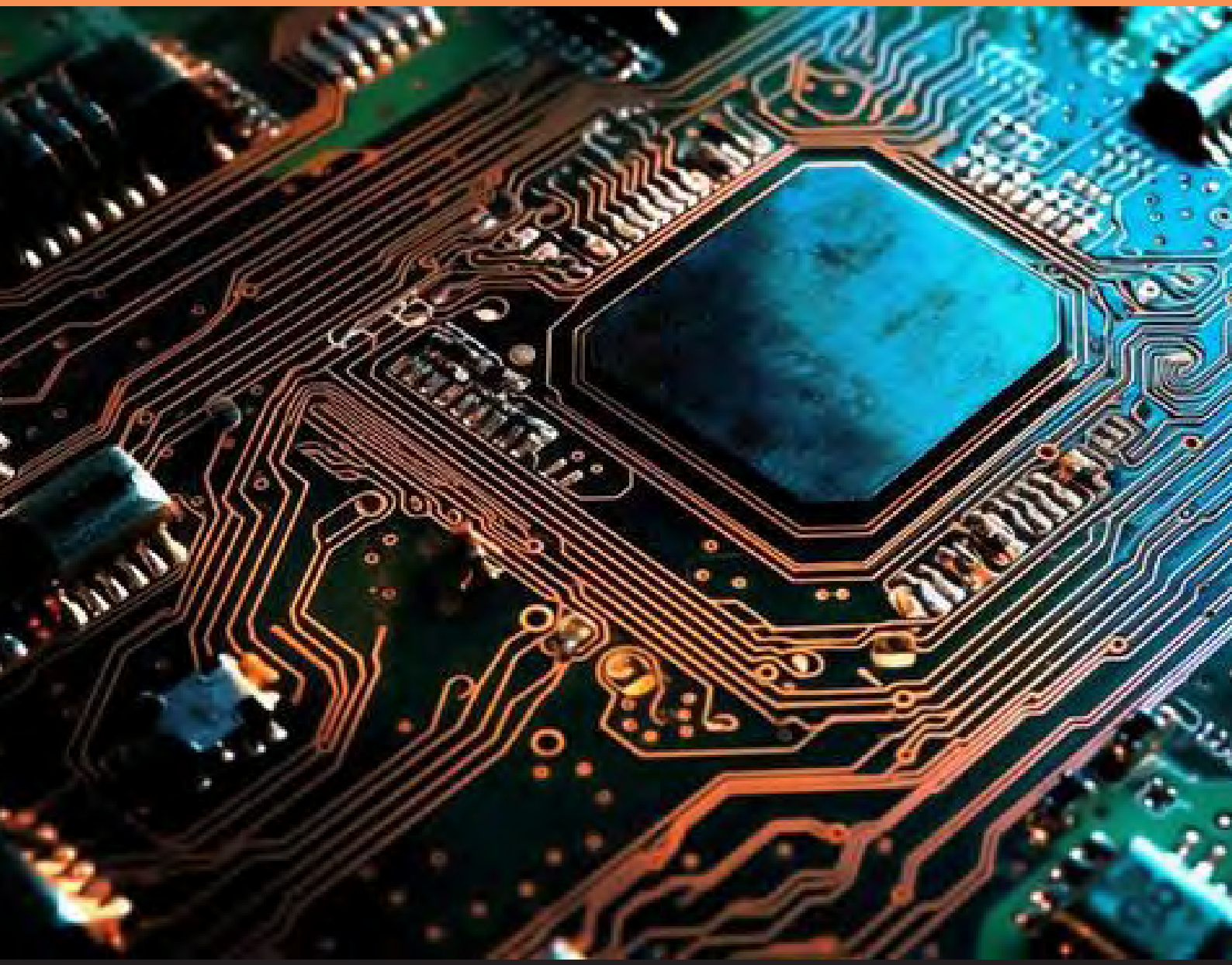
b. What is the name of the physical process where a photon triggers the release of an identical photon?

c. Explain why both of these processes are essential for producing a highly concentrated and coherent laser beam.

SECTION

8

PRINCIPLES AND APPLICATIONS OF ELECTROMAGNETIC INDUCTION



ELECTROMAGNETIC INDUCTION

INTRODUCTION

This section explores the principles and practical applications of electromagnetic induction, covering how changing magnetic fields produce electric currents and how this phenomenon underpins many modern technologies. It examines Faraday's and Lenz's laws, factors affecting induced electromotive force (EMF), and the use of Fleming's Right-Hand Rule to determine current direction.

You will study inductance, its mathematical expression, and the behaviour of inductors in AC and DC circuits, as well as the concept of energy storage in inductors. The section also explains the structure, operation, and efficiency of transformers, the nature and applications of eddy currents, and the role of mutual inductance in energy transfer. Linked to earlier topics on magnetic fields and current-carrying conductors, these concepts provide the foundation for understanding electricity generation, power transmission, and numerous devices used in daily life.

KEY IDEAS

- Changing magnetic fields can produce electricity through the process of electromagnetic induction.
- Direction of induced current always opposes the cause of its production, ensuring energy conservation.
- Electrical energy can be transferred without direct contact using the principle of mutual induction.
- Inductors store energy in magnetic fields and resist sudden changes in current flow.
- Reducing unwanted energy losses in devices like transformers involves minimising eddy currents and other inefficiencies.
- Voltage can be increased or decreased efficiently using transformers for power transmission and device operation.

ELECTROMAGNETIC INDUCTION AND ITS LAWS



Figure 8.1: *Ceiling fan*



Figure 8.2: *Electric doorbell*

Have you ever wondered what happens inside an electric fan when you switch it on? What causes its blades to begin spinning, filling the room with a breeze? Or how pressing the button on an electric doorbell produces a clear ringing sound, alerting everyone at home or school, all without the need for batteries? These everyday devices work because of a natural process called electromagnetic induction.

Electromagnetic induction is a fundamental principle in physics where a changing magnetic field creates an electric current in a conductor. This principle is present all around us and is the key to how many common electrical machines work. To better understand this, it is helpful to look closely at two devices frequently found in homes and schools, the electric fan and the electric doorbell.

When the electric fan is turned on, electricity flows through coils of wire within its motor. This electric current generates a magnetic field around the coils. Inside the motor, this magnetic field interacts with permanent magnets or other coils, resulting in forces that cause the motor's rotor to spin. The spinning rotor then makes the fan blades rotate, producing airflow. In this way, electrical energy is transformed into mechanical motion by the interplay of electric currents and magnetic fields.

Similarly, the electric doorbell provides a simple yet powerful example of electromagnetic induction in action. When the doorbell button is pressed, it completes an electric circuit, allowing current to flow through a coil of wire. This current creates a magnetic field around the coil, which pulls a small metal striker toward a bell, causing it to ring. Releasing the button breaks the circuit, the magnetic field disappears, and the striker returns to its original position. This converts electrical energy into mechanical motion and sound using magnetic forces.

At the core of both devices is the concept that changing electric currents produce changing magnetic fields, which in turn causes movement. This is the essence of electromagnetic induction — an invisible but powerful effect that transforms electricity into motion and sound in our everyday lives.

The phenomenon plays a critical role in modern electrical engineering and forms the basis of the operation of numerous devices, such as electric generators, transformers, induction motors, and induction cooktops.

The discovery of electromagnetic induction is credited to two prominent scientists—**Michael Faraday** in 1831 and **Joseph Henry** in 1832—who independently observed the effect. However, it was Faraday's comprehensive and systematic experimentation that led to the formulation of what is now known as **Faraday's Law of Electromagnetic Induction**, which quantitatively describes how the induced EMF is proportional to the rate of change of magnetic flux.

At the heart of electromagnetic induction is the principle that relative motion between a magnetic field and a conductor can generate an electric current.

One example of this is when you move a magnet towards a coil, and an EMF will be produced in the coil. In the same way, when you begin to move the magnet away, an EMF will be produced too.

Look at the diagrams below:

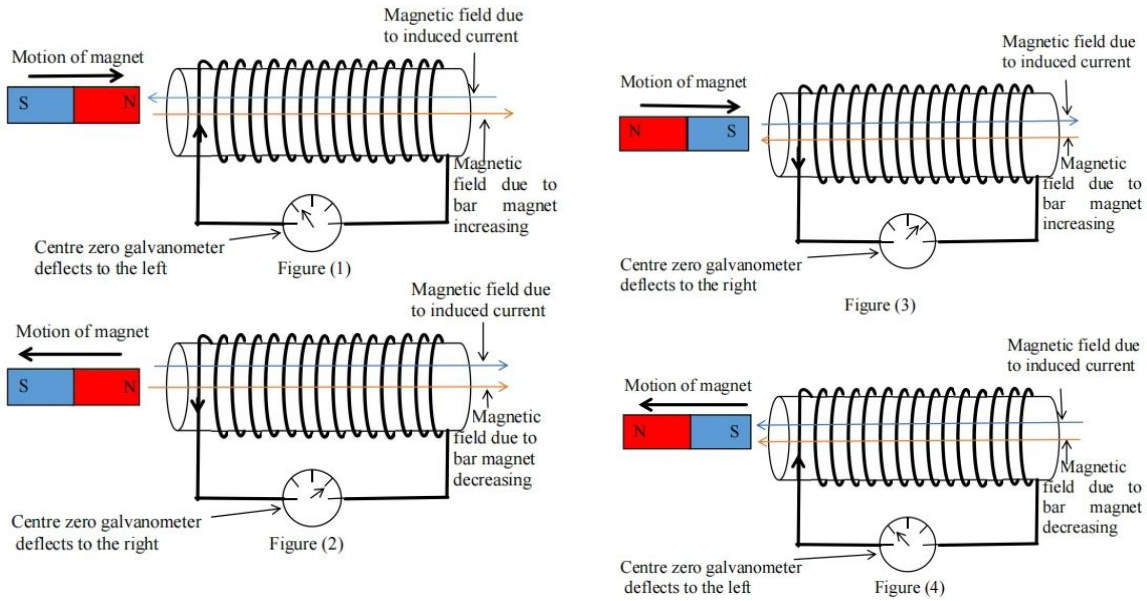


Figure 8.3: *Induced Current in a Coil due to Relative Motion of a Bar Magnet and a coil (Lenz's Law Demonstration)*

In the top left diagram, when the north pole approaches the coil, the coil experiences an increasing magnetic field. The induced electromotive force EMF in the coil

generates a current whose direction is shown by the deflection of the sensitive galvanometer.

In the bottom left diagram, as the north pole of the magnet moves away from the coil, the coil experiences a decreasing magnetic field. This change in field strength induces an EMF in the coil again, whose direction is shown by the deflection of the galvanometer, this time in a reversed direction.

In the top right diagram when the south pole of the magnet approaches the coil, it experiences an increasing magnetic field. Again, the galvanometer deflects to show that, and EMF is induced in the coil and current is flowing in the shown direction. Note that this time the direction same as when the north pole was withdrawn.

In the bottom right diagram, when the south pole is withdrawn from the coil, the coil again sees a weakening field and responds by generating an EMF and current, detected by the galvanometer. A practical demonstration of this will show you that the deflection of the galvanometer (EMF and hence current) increases when

1. the magnet is moved faster
2. a more powerful magnet is used
3. more turns in the coil
4. the cross-sectional area of the coil is larger.

Laws of Electromagnetic Induction

Faraday's Law of Electromagnetic Induction

Basically, this law details what we have explained the preceding notes. It states that, 'whenever there is a change in the magnetic flux linking a circuit, an EMF is induced, and its magnitude is directly proportional to the time rate of charge of magnetic flux linking the circuit.

Faraday goes ahead to give a mathematical expression of his law as follows:

$$E \propto \frac{d\varnothing}{dt} \Longrightarrow E = -N\frac{d\varnothing}{dt}$$

Where

E is the induced EMF in volts (V).

N is the number of turns in the coil.

dΦ is the change in magnetic flux (Wb).

dt is the time interval over which the change occurs (s).

the negative sign shows that the induced emf opposes the change causing it. (This is explained in the 2nd law, soon to be considered)

Clearly, the formula proves that the magnitude of the emf depends on the number of turns of the coil (N), and the time rate of change in the magnitude of the flux/ field.

Magnetic Flux (Φ)

Magnetic flux is a measure of the total number of magnetic field lines passing through a given area. It quantifies how much magnetic field "flows" through a surface.

Mathematically, it is expressed as;

$\Phi = BA\cos\theta$,

Where

B is the magnetic field strength (magnetic flux density) in Teslas (T).

A is the area through which the magnetic field lines pass, in square meters (m^2).

θ is the angle between the magnetic field lines and the normal to the area.

The unit of magnetic flux is the Weber (Wb).

Flux linking a coil

For a coil with **N** turns, the total flux linking it is

$\Psi = N\Phi\Psi$ is called the **flux linkage**.

$\Psi = N\Phi = NBA\cos\theta$

From the above equation, it means flux linkage is maximum when the flux lines are perpendicular to the area.

Note: θ is measured from the normal to the area. So, flux lines parallel to the normal are also normal to the area and make an angle of 0°.

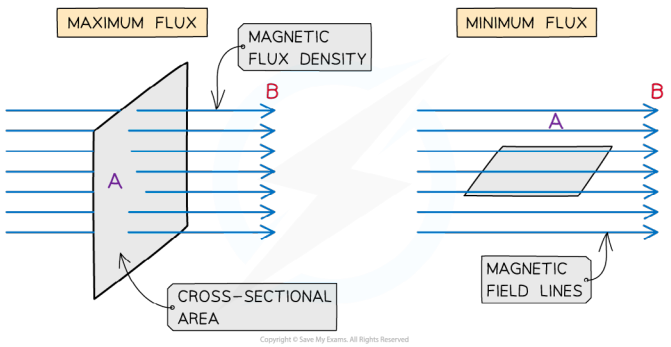


Figure 8.4: *Field lines perpendicular to the area A-maximum flux linkage (left) and field lines parallel to area A-minimum flux linkage (right)*

Lenz's Law

Lenz's Law states that:

"The direction of an induced current is always such that it opposes the change that caused it."

In other words, when a changing magnetic field creates a current in a wire (through electromagnetic induction), that current produces its own magnetic field, which tries to *resist* the original change. For example, if you push a magnet into a coil of wire, the coil will produce a current that creates a magnetic field pushing back against the magnet. Refer to ***figure 8.4***, you see that the galvanometer deflects in a direction opposite to the motion of the magnet.

So why opposition? This in obedience to the law of energy conservation.

Law of Conservation of Energy

This law says that:

"Energy cannot be created or destroyed, only changed from one form to another."

This means the total amount of energy in a closed system stays the same, though it may change forms—for example, from mechanical energy to electrical energy, or from electrical energy to heat.

How The Two Laws Are Related

Lenz's Law is actually a consequence of the Law of Conservation of Energy.

Here is how:

1. When a conductor is moved relative to a magnetic field a current is produced. However, due to the motor effect, a current-carrying conductor in a magnetic field experiences a force.
2. If the force produced in this scenario acted in the same direction as the input force moving the conductor through the field, the object would accelerate as the total force became greater and greater. You'd get acceleration *without* doing any work—basically free energy, which would **violate the Law of Conservation of Energy**.
3. But because Lenz's Law makes the induced current create a force that **opposes** the change, you must do work (like pushing harder against the magnetic resistance), and that work is what gets converted into electrical energy.
4. So, Lenz's Law protects the conservation of energy—it ensures you cannot get more energy out than what you put in.

Analogy!

Pushing a table across a rough floor? It pushes back because of friction, so you have to keep pushing to move it. You never get more motion than the effort you put in.

That is how Lenz's Law works! When a magnetic field changes and causes a current, the current creates a magnetic field that pushes back. This makes sure you do not get free energy, just like friction stops you from sliding a table forever with one small push.

Factors That Determine The Magnitude Of The Induced EMF

1. **Rate of Change of Magnetic Flux** $\left(\frac{d\Phi}{dt}\right)$

   This is the most critical factor. The faster the magnetic flux linking the conductor changes, the larger the induced EMF. This change can occur due to:

   a. Speed of Relative Motion: Moving the conductor faster through the magnetic field or moving the magnet faster relative to the coil.

   b. Rate of Change of Magnetic Field Strength (B): If the magnetic field itself is changing in strength over time (e.g., using an electromagnet whose current is varied).

   c. Rate of Change of Area (A): If the area of the coil exposed to the magnetic field is changing (e.g., a loop expanding or contracting in a magnetic field).

   d. Rate of Change of Orientation (θ): If the angle between the magnetic field and the normal to the coil's area is changing (e.g., rotating a coil in a magnetic field, as in a generator).

2. **Strength of the Magnetic Field (B)**

   A stronger magnetic field will result in a greater induced EMF for the same rate of change of area, relative motion or change of orientation.

3. **Number of Turns in the Coil (N)**

   For a coil, the induced EMF is directly proportional to the number of turns. More turns mean more conductors cutting through the magnetic field lines, leading to a larger total induced EMF.

4. **Length of the Conductor (L) (for a straight conductor moving in a field)**
   For a straight conductor moving perpendicular to a magnetic field, the induced EMF is given by $E = BLv$, where L is the length of the conductor in the field and v is its velocity. A longer conductor will experience a larger induced EMF.

Fleming's Right-Hand Rule

Fleming's Right-Hand Rule is a mnemonic used to determine the direction of the induced current (or induced EMF) when a conductor moves in a magnetic field. It is particularly useful for generators.

It states that if the first two fingers and the thumb of the right hand are held at right angles to each other with the **F**orefinger in the direction of the **F**ield and the thu**M**b in the direction of **M**otion, then the se**C**ond finger points in the direction of the induced **C**urrent.

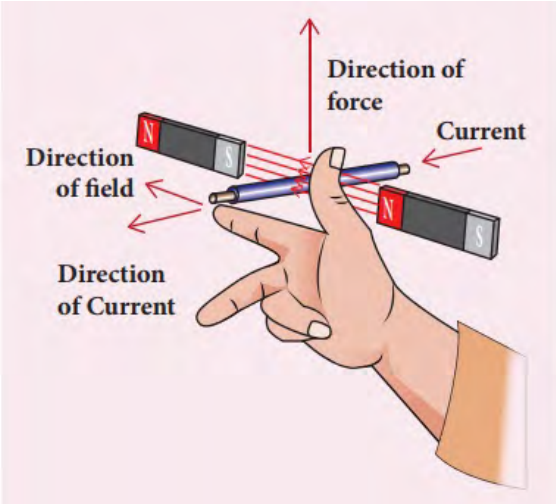


Figure 8.5: *Fleming's Right-hand Rule*

Activity 8.1 Observing Electromagnetic Induction Using a Simulation

Objective: To investigate and understand electromagnetic induction by using a simulation to observe how moving a magnet or coil causes an electric current, and to relate these observations to Faraday's Law and Lenz's Law.

What you need

1. Access to an online simulation (such as PhET Faraday's Law: https://phet.colorado.edu/en/simulation/faradays-law

2. Paper or notebook
3. Pencil or pen

What to do

1. Open the simulation
   - **a.** Open the simulation link above
   - **b.** Familiarise yourself with the tools - you should see a virtual coil and a bar magnet or an option to move a coil in a magnetic field.
2. Explore induced current by moving a magnet
   - **a.** Move the bar magnet towards the coil and observe the simulation. Watch for the light bulb lighting up, the needle of a voltmeter, or a display of electrons flowing—these all indicate an induced current.
   - **b.** Move the magnet away from the coil and observe whether the current flows in the opposite direction.
   - **c.** Hold the magnet stationary inside the coil and notice whether any current is induced.
   - **d.** Switch the magnet's poles (reverse the magnet) and repeat to see if the direction of current changes.
3. Explore induced current by moving the coil
   - **a.** Try keeping the magnet stationary and instead move the coil towards or away from the magnet's pole.
   - **b.** Observe and record if a current is induced in the coil.
4. Write down your observations for each scenario:
   - **a.** When does the current/voltage register a value? When does it stay at zero?
   - **b.** How does the direction of movement affect the direction (sign) of current?
   - **c.** Is there any induced current if nothing is moving?

5. Identify the Principle
   - **a.** From your observations, identify the basic principle
     - **i.** A current is induced only when there is relative motion between the magnet and the coil, causing a change in magnetic field through the coil. This is called electromagnetic induction.
     - **ii.** The direction of induced current changes if you reverse the motion or the magnetic pole facing the coil.
     - **iii.** The faster the movement, the greater the current or brightness.
6. Sketch and Label the Setup
   - **a.** Draw the main setup: a coil of wire connected to a bulb or voltmeter, and a bar magnet near the coil.
   - **b.** Label:
     - **i.** Bar magnet (show North and South poles)
     - **ii.** Direction of motion of the magnet (with an arrow)
     - **iii.** Coil or solenoid
     - **iv.** Bulb or voltmeter
     - **v.** Indicate (with arrows) the direction of induced current for each movement.
7. Describe the Direction of Current
   - **a.** Describe what happens when the magnet is moved towards or away from the coil, and how the direction of current reverses.
   - **b.** Note: The induced current always flows in a direction such that it opposes the change in magnetic field (Lenz's Law).

Activity 8.2 Learning Fleming's Right Hand Rule

Objective: To learn and apply Fleming's Right Hand Rule using the "FBI" mnemonic and hand gestures, in order to determine the direction of induced current in a conductor moving through a magnetic field.

What you need

1. Your own right hand
2. Paper or notebook
3. Pen or pencil

What to do

1. Understand the Components of the Mnemonic "FBI". Remember that
   - **a.** *F* stands for Force (also called motion or direction of movement of the conductor)
   - **b.** *B* stands for Magnetic Field (direction of magnetic field lines)
   - **c.** *I* stands for Current (direction of induced current)
2. Hold your right hand so that your thumb, first finger (index), and second finger (middle) are all perpendicular to each other, roughly like an "L" shape with the middle finger sticking out at right angles
   - **a.** Thumb = F (Force or motion)
   - **b.** First finger (index) = B (Magnetic field)
   - **c.** Second (middle) finger = I (Current)
3. Practice Using the "FBI" Rule
   - **a.** Imagine a scenario where a conductor is moving in a magnetic field and you want to find the direction of current.
   - **b.** Align your first finger (B) to point in the direction of the magnetic field (from North to South).
   - **c.** Point your thumb (F) in the direction of the force or motion of the conductor (the direction the conductor is moving).
   - **d.** Your middle finger (I) will then point in the direction of the induced current.
4. Try Different Examples
   - **a.** Practice visualising or drawing simple situations with varying directions of magnetic fields and conductor motion.
   - **b.** Use your hand to predict the current direction.
   - **c.** Check your answers against diagrams or experiment results, if available.
5. Draw and Label Diagrams
   - **a.** Sketch your right hand showing the thumb, first finger, and middle finger perpendicular.
   - **b.** Label each finger as F, B, and I respectively.
   - **c.** Draw an example of a conductor moving in a magnetic field and use your hand to determine the current direction, labelling each vector on your sketch.

6. Explain the Rule in Your Own Words

Activity 8.3 Exploring Electromagnetic Induction

Objective: To investigate how moving a bar magnet through a coil induces an electric current, and to understand how the speed and direction of the magnet's motion affect the size and direction of the induced current, demonstrating the principle of electromagnetic induction.

What you need

1. Bar magnet
2. Coil of insulated copper wire (several hundred turns preferred)
3. Galvanometer or sensitive ammeter
4. Connecting wires with clips
5. Paper or notebook
6. Pen or pencil

What to do

1. Set Up the Circuit
   - **a.** Connect the coil of wire to the galvanometer using the connecting wires. Make sure the connections are secure.
   - **b.** Place the coil on a flat surface where you can easily move the magnet in and out of it.
2. Observe Galvanometer Deflection with Slow Magnet Movement
   - **a.** Slowly insert the bar magnet into the coil. Watch the needle of the galvanometer carefully.
   - **b.** Note the direction and size of the needle deflection in your notebook.
   - **c.** Slowly pull the magnet out of the coil and record the deflection direction and magnitude again.
3. Repeat with Faster Magnet Movement
   - **a.** Repeat step 2, but this time move the magnet faster (both inserting and withdrawing).
   - **b.** Observe and record how the speed of the magnet affects the deflection magnitude on the galvanometer.

4. Investigate Effect of Reversing Magnet Polarity
   a. Repeat the slow and fast movements, but with the opposite pole (flip the magnet end that goes into the coil facing the coil first).
   b. Observe and record any changes in the galvanometer deflection direction and magnitude compared to the previous results.
5. Draw and Label the Setup
   a. Sketch the coil connected to the galvanometer and a bar magnet moving in and out.
   b. Add arrows to show the magnet motion and note galvanometer needle direction.
6. From your observations, answer these questions in your notebook:
   a. How does moving the magnet faster affect the galvanometer deflection and thus the induced emf?
   b. How does reversing the magnet direction affect the direction of the induced current?
   c. Why do you think mechanical movement of the magnet induces a current in the coil?
   d. What relationship between motion and induced emf can you describe based on your observations?

Activity 8.4 Real-Life Devices That Use Electromagnetic Induction

Objective: To research and explain how real-life devices use electromagnetic induction, demonstrating an understanding of the role of changing magnetic fields, induced currents, and Faraday's law in their operation, and to effectively communicate this knowledge through a clear and visual presentation.

What you need

1. Access to internet or reference books
2. Paper or notebook for notetaking
3. Pen or pencil
4. Materials for presentation (poster paper and markers, or computer with presentation software)

What to do

1. Get together with 2 to 4 classmates to work as a team. Each group picks one device that works based on electromagnetic induction. Some examples you can choose from
   - **a.** Electric generator
   - **b.** Transformer
   - **c.** Inductive wireless charger
   - **d.** Electric motor
   - **e.** Magnetic stripe reader
   - **f.** Induction cooktop
   - **g.** Electric bell
2. Using the internet or books, find out
   - **a.** How the device works with electromagnetic induction.
   - **b.** Which parts create or change a magnetic field.
   - **c.** Where and how current is induced in the device.
   - **d.** How Faraday's law applies (changing magnetic flux induces EMF/current).
3. Write down key points to explain about your device
   - **a.** What is the changing magnetic field?
   - **b.** How does the device produce or use induced current?
   - **c.** What happens when the device operates?
4. Get ready to share your findings with the class by
   - **a.** Creating drawings or diagrams of the device showing coils, magnets, or magnetic fields.
   - **b.** Explaining the role of electromagnetic induction clearly and simply.
   - **c.** Showing how Faraday's law explains the device's function.
5. Present your group's findings.
   - **a.** What it is and what it does.
   - **b.** How electromagnetic induction happens inside it.
   - **c.** How the changing magnetic field causes an induced current that powers or controls the device.
   - **d.** Use your visuals to help others understand.

Activity 8.5 Calculating Induced EMF & Applying Faraday's & Lenz's Laws

Study the worked examples below carefully before attempting the example questions that follow.

Worked Example 1

A coil with 200 turns is placed in a magnetic field. If the magnetic flux through the coil changes by 0.08 Wb in 0.4 seconds, calculate the average induced EMF.

Solution

$$EMF = N\frac{\Delta\Phi}{\Delta t} = 200 \times \frac{0.08}{0.4} = 40 \text{ V}$$

Worked Example 2

A square loop of wire is pulled with a constant velocity out of a uniform magnetic field of strength 0.5 T. The loop is 0.3 m long, and it takes 0.2 seconds to completely leave the field. Determine:

a. The magnitude of the induced EMF

b. The direction of the current if viewed from above

Solution

a. $EMF = \frac{\Delta\Phi}{\Delta t} = \frac{0.5 \times 0.3 \times 0.3}{0.2} = 0.225 \text{ V}$

b. The magnetic field is into the page; as the loop leaves the field, flux decreases, so by Lenz's Law, the induced current tries to maintain it, creating a field into the page. So, the current flows clockwise when viewed from above.

Worked Example 3

A circular coil of radius 0.05 m and 150 turns is placed in a uniform magnetic field perpendicular to its plane. The magnetic field increases uniformly from 0.2 T to 0.8 T in 0.1 seconds. Calculate the magnitude of the average EMF induced in the coil.

Solution

Since the field is perpendicular to the circular plane of the coil, θ is 0°

Area of the coil is πr^2

$\Phi = B \cdot A\cos\theta$

$\Phi = B \cdot \pi r^2 \cos 0 = B \cdot \pi(0.05)^2$

Note that

- the field increased uniformly across the area
- ΔB is the change per unit area

So, for the entire area, $\Delta\Phi = \Delta B \times A = (0.8 - 0.2) \times \pi \times (0.05)^2$

$\Delta\Phi = 0.6 \times \pi \times 0.0025 = 0.004712\ Wb$

$EMF = N\,\Delta\frac{\Phi}{\Delta t} = 150 \times \frac{0.004712}{0.1} = 7.07\ V$

Practice Problems

Now, using the worked examples as a guide, solve the following problems individually or in groups.

1. The magnetic flux through a coil change from 0.05 Wb to 0.01 Wb in 0.2 seconds. What is the average EMF induced in the coil if it has 1 turn?
2. A 150-turn coil is exposed to a changing magnetic field. The magnetic flux through the coil increases by 0.002 Wb in 0.05 seconds. Calculate the induced EMF.
3. A circular coil with 50 turns and area 0.01 m2 lies in a perpendicular magnetic field. The magnetic field decreases uniformly from 0.4 T to 0.1 T in 0.3 seconds.
   a. Calculate the induced EMF.
   b. State the direction of the induced current according to Lenz's Law.
4. A straight metal rod of length 0.25 m moves at 5 m/s perpendicular to a magnetic field of 0.6T
   a. What is the induced EMF across the ends of the rod?
   b. If this rod forms part of a closed loop with resistance 2 Ω, calculate the induced current.

PRINCIPLES AND APPLICATIONS OF INDUCTANCE AND ELECTROMAGNETIC INDUCTION

Have you ever used a radio, a ceiling fan, or even noticed how certain devices hum or behave differently when you switch them on? These devices use a small but powerful component called an inductor to help control and manage electricity.

Think about the ceiling fan. Inside its motor, coils of wire act like tiny inductors. When electric current passes through these coils, a magnetic field builds up. This magnetic field interacts with other parts of the motor to make the fan blades spin steadily. The inductor inside the motor helps control how the current changes, making sure the fan runs smoothly and does not jerk or stop suddenly.

The Inductor

In our lesson on resistors, capacitors, and inductors in AC circuits, we learned that inductors store electrical energy in the form of a magnetic field. In this section, we are focusing specifically on the inductor to explore in more detail how it stores that energy.

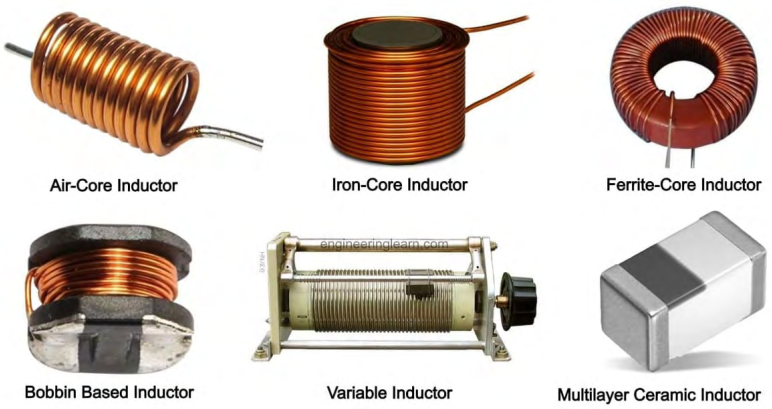


Figure 8.6: *Types of inductors*

Obviously, from the images above, a typical inductor is made up of a conductor wound on a core (coil), and the two ends of the conductor form its terminals. Let us look at the structure in detail.

Structure of an Inductor

1. **The Coil**

   The Wire That Does the Work

   The coil is the heart of the inductor. It's usually just a long wire (like copper) wrapped in a tight spiral or helix. The way this coil is made directly affects its **inductance** (its ability to oppose changes in current).

   a. More Turns, More Inductance: Imagine wrapping a wire around a pencil. If you wrap it many times, the magnetic field from each loop adds up, making a much stronger total magnetic field. More magnetic field means more opposition to change, so more inductance.

   b. Larger Diameter, More Inductance: A wider coil also creates a stronger magnetic field. Think of a bigger loop – it can capture more magnetic field inside it.

   c. Tighter Spacing, More Inductance: When the turns of wire are closer together, their magnetic fields interact more effectively, making the total magnetic field stronger and increasing the inductance.

2. **The Core: The Centre of the Action**

   The core is the material placed inside the coil. It is like the "stuffing" that can dramatically change how the inductor behaves.

   a. Air-Core Inductors: These are just coils with nothing but air inside. They have lower inductance and are great for high-frequency circuits (like in radios) because they do not cause extra energy losses.

   b. Ferromagnetic Core Inductors: These coils have a special magnetic material inside them, like iron or ferrite. These materials are like a superhighway for magnetic field lines. They concentrate the magnetic field, making it much, much stronger. This allows these inductors to have a much higher inductance than air-core inductors. They are used in circuits that need to store a lot of energy in their magnetic field.

3. The **terminals** are simply the two ends of the coil wire, which provide points of electrical connection to a circuit.

Inductors Symbols

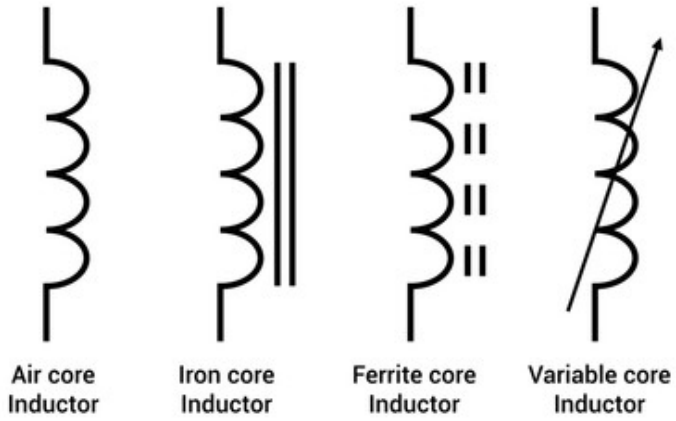


Figure 8.7: *Circuit symbols representing different types of inductors.*

Behaviour of the Inductor in AC and DC Circuits

1. **In a DC circuit**

   Imagine an inductor as a character who absolutely hates change. It will fight to keep the current exactly as it is. Let us see what happens when you introduce it to a steady DC circuit.

   a. **The Moment You Flip the Switch (Switch On)**

      i. The Problem: You just connected the battery! The current wants to jump from zero to its maximum value instantly.

      ii. The Inductor's Reaction: "Oh no you do not!" The inductor immediately fights this change. It creates a powerful "back-voltage" that pushes against the battery, trying to stop the current from flowing.

      iii. The Result: The current cannot jump up instantly. It has to slowly and gradually increase, fighting against the inductor's opposition until it reaches its full strength.

   b. **After a Long Time (Steady State)**

      i. The Problem: The current has reached its full, constant value. It's no longer changing.

      ii. The Inductor's Reaction: "Ah, perfect. No change, no problem!" Because the current is no longer changing, the inductor has no reason to fight. It stops creating any back-voltage.

iii. The Result: The inductor just acts like a normal piece of wire. The current flows through it freely, with almost no opposition. We say the inductor acts like a "short circuit" (a perfect connection).

c. **The Moment You Flip the Switch Off (Switch Off)**

i. The Problem: You just disconnected the battery! The current wants to drop back to zero instantly.

ii. The Inductor's Reaction: "Oh no you do not!" The inductor fights to keep the current flowing. It creates a back-voltage in the opposite direction, trying to keep the current from dying out.

iii. The Result: The inductor's desperate attempt to keep the current going can create a very large, temporary voltage spike. This spike can be so powerful that it creates a spark or even damages other parts of the circuit if they're not protected.

2. **The Inductor's Story in an AC Circuit**

An AC circuit is the inductor's natural enemy! Since AC current is constantly changing, the inductor is always on high alert, fighting to keep the current steady.

a. **A Constant Fight**

i. The Problem: AC current is a restless back-and-forth flow, always changing its strength and direction.

ii. The Inductor's Reaction: "I'll never get any rest!" The inductor is forced to work continuously. It always generates a "back-voltage" to oppose the current's endless changes. This is a nonstop battle.

b. **The Level of Opposition (Inductive Reactance)**

i. What it is: The inductor's opposition to AC current is called inductive reactance (X_L).

ii. How it changes: The faster the AC current changes (that is, the higher the frequency), the harder the inductor has to fight. This means its reactance (X_L) gets bigger as the frequency goes up.

c. **The Leading Partner (Phase Shift)**

i. The Problem: The inductor's fight against the current causes a delay. It cannot stop the current, but it can slow it down.

ii. The Result: The voltage across the inductor reaches its peak a full quarter-cycle before the current flowing through it reaches its peak. We say the voltage leads the current by 90°.

Analogy

Imagine two friends hiking up a wavy path. Voltage is the friend who reaches the top of a hill, while the current is still halfway between the valley and the peak, a quarter-cycle behind.

d. **The Energy Banker**

i. The Problem: Where does the energy go?

ii. The Inductor's Reaction: The inductor is not a burner of energy like a resistor. It's a banker.

iii. The Result: During one part of the AC cycle, it stores energy in its magnetic field. Then, in the next part of the cycle, it releases that energy back into the circuit. It is constantly borrowing and lending energy, not using it up.

Inductance (L) and its Mathematical Expression

What is Inductance (L)?

Imagine an inductor has a personality. Its inductance (L) is a measure of its stubbornness—its natural ability to oppose any change in current.

The higher the inductance, the more "stubborn" the inductor is. It will put up a greater fight against the current, trying to speed up, slow down, or reverse direction. The unit for this stubbornness is the henry (H), named after physicist Joseph Henry.

What the Formula Tells Us

Inductance is defined by a simple relationship that shows how well the inductor creates a magnetic field: $L = \frac{N\Phi}{I}$

Where:

L is inductance (H).

N is the number of turns in the coil.

Φ is the magnetic flux (Wb).

I is the current (A).

Do not worry about the math!

This formula simply tells us:

"*Inductance is a measure of how much magnetic flux (the total magnetic field linking the coil) is created for every unit of current flowing through the coil.*"

Therefore, an inductor with high inductance is extremely efficient, as it can create a strong magnetic field with minimal current.

The solenoid

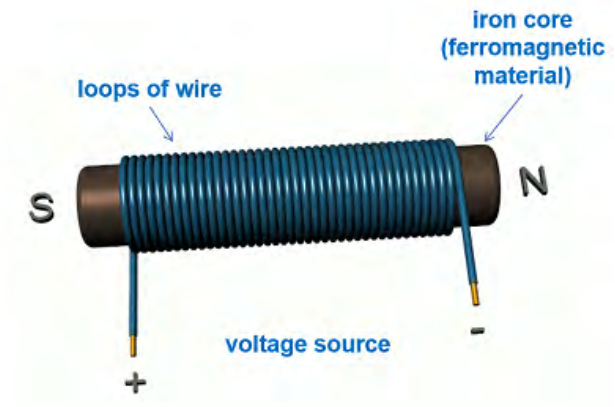


Figure 8.8: *A solenoid with an Iron core and magnetic poles*

In simple terms, a solenoid is a coil of wire that acts as an electromagnet.

It is a length of wire (often insulated copper) wound tightly into a helical or spiral shape, much like a spring. When an electric current is passed through the coiled wire, it generates a magnetic field. The helical shape of the coil causes the magnetic fields from each loop of wire to combine and create a single, strong, and relatively uniform magnetic field inside the coil. Just like a bar of permanent magnet, this magnetic field has a north and a south pole. The direction of the magnetic poles can be determined by the direction of the current flow using the right-hand rule.

The Purpose

While a solenoid is fundamentally an electromagnet, its key purpose in many engineering applications is to convert electrical energy into mechanical motion.

How this works is by

1. Placing a movable metal core (often called a plunger or armature) inside the coil.
2. When you turn on the current, the magnetic field is created.

3. This magnetic field attracts the movable metal core, pulling it into the centre of the coil.
4. This "push" or "pull" motion can be used to perform mechanical work.

Mathematical Expression for a Solenoid (Ideal Inductor)

For a long solenoid (a common model for an inductor), its inductance can be calculated based on its physical dimensions and the properties of its core material:

$$L = \mu \frac{N^2 A}{I}$$

Where:

L is inductance (H).

μ is the magnetic permeability of the core material (H/m). $\mu = \mu_o \mu_r$, where μ_r is the relative permeability of the core (dimensionless) and μ_o is the permeability of free space ($4\pi \times 10^{-7}$ H/m).

N is the number of turns in the coil.

A is the cross-sectional area of the coil (m^2).

l is the length of the coil (m).

Factors Affecting Inductance

This formula clearly shows that inductance increases with:

1. More turns (N).
2. Larger cross-sectional area (A).
3. Shorter length (l).
4. Higher permeability of the core material (μ).

Self-Inductance and Mutual Inductance

Self-Inductance

A Coil's "Self-Defence"

Self-inductance is a coil's natural ability to create a voltage within itself to fight against a change in the current flowing through it. It is a consequence of Lenz's law.

How it works

1. If the current flowing in the coil is not constant (in an AC circuit), creates a changing magnetic field around the coil.

2. This changing magnetic field then does something amazing: it induces a voltage in the coil itself to oppose the original change in current.
3. This self-induced voltage is often called a "back-EMF" because it always acts in a way that opposes the change in current that created it.
    i. If the current is increasing, the back-EMF pushes against it, trying to stop the increase.
    ii. If the current is decreasing, the back-EMF pushes to keep it flowing, trying to stop the decrease.
    iii. The strength of this back-EMF depends on how quickly the current is changing and the coil's inductance (L). The formula for it is: $\varepsilon_L = -L\, d\frac{I}{dt}$, where $\frac{dI}{dt}$ is the time rate of change of current. The minus sign is a reminder that the EMF opposes the change in current.

This property is a superpower for inductors, allowing them to be used in electronic circuits as chokes (which block AC signals while letting DC through), filters, and devices that can store energy.

Mutual Inductance (M)

The Neighbour's Influence

Think of two coils as two neighbours living next to each other.

Coil 1 (The Driver): Has a current flowing through it.

Coil 2 (The Neighbour): Is just sitting there, not connected to any power source.

The Action

When the current in Coil 1 changes (gets stronger or weaker), it creates a magnetic field that also changes. This changing magnetic field does not stay confined to Coil 1; it spreads out and reaches over to Coil 2.

The Reaction

When Coil 2 feels this "influence" from the changing magnetic field, it reacts! According to the laws of induction, this changing magnetic field passing through Coil 2 creates a voltage (an EMF) in Coil 2, even though it has no battery connected to it.

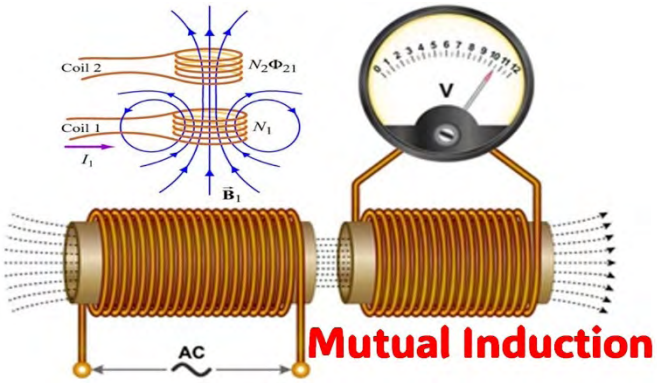


Figure 8.9: *mutual induction between two adjacent coils*

This ability of one coil to induce an EMF in a neighbouring coil is called mutual inductance (M). It is the working principle of the transformer; more on this later!

The mutual inductance 'M' between two coils (coil 1 and coil 2) is defined as:

$$M = \frac{N_2 \varnothing_{12}}{I_1}$$

Where

N_2 is the number of turns in coil 2.

$\varnothing_{12}$ is the magnetic flux from coil 1 that links with coil 2.

I_1 is the current in coil 1.

The induced EMF (ε_2) in coil 2 due to a changing current in coil 1 is

$$\varepsilon_2 = -M\frac{dI_1}{dt}$$

Mutual Inductance and "Coupling"

Mutual inductance (M) is a measure of how well two neighbouring coils magnetically "influence" each other. It describes the strength of the connection between them.

The strength of this influence depends on three main things:

1. How close they are: The closer the coils are, the more the magnetic field from one coil reaches the other.
2. The number of turns: More turns on both coils means a stronger magnetic field and a bigger target for the field to link with.
3. The core material: Placing a magnetic material (like iron) inside the coils is like building a superhighway for the magnetic field lines, making the connection much stronger.

The Coefficient of Coupling (k): The "Coupling Score"

The coefficient of coupling (k) is a simple score that tells us exactly how good the magnetic connection is. It's a number that ranges from 0 to 1.

1. k =1: This means the connection is perfect. Every single magnetic field line from one coil links with the other. This is called perfect coupling and is the goal for devices like transformers.
2. k = 0: This means there is no connection at all. The coils are too far apart or oriented in a way that their magnetic fields do not reach each other.
3. k between 0 and 1: This indicates a partial connection, which is typical in most real-world applications, especially wireless ones.

$$k = \frac{M}{\sqrt{L_1 L_2}}$$

Where L_1 and L_2 are the self-inductances of the individual coils

The formula simply compares the actual mutual inductance (M) to the maximum possible mutual inductance.

Why It is So Important

Mutual inductance is a fundamental principle that allows us to transfer electrical energy from one circuit to another without a direct physical connection. It's the secret behind:

1. Transformers: Changing the voltage in your phone charger or a power grid.
2. Wireless Chargers: Sending power from the charging pad to your phone.
3. Induction Cooktops: Heating a pot by inducing a current directly in its base.



Figure 8.10: *Induction cooktop*



Figure 8.11: *Domestic step-up/ step-down transformer*



Figure 8.12: *Power transformer*



Figure 8.13: *Wireless charger*

Energy Stored in an Inductor

Unlike a resistor, which burns up energy as heat, an inductor is like an electrical spring or a rechargeable battery for magnetic fields. It does not lose energy; it stores it. When current flows through the inductor's coil, it creates a magnetic field. The energy needed to build this magnetic field is not lost—it is stored within the magnetic field itself. This stored energy can be given back to the circuit whenever the current decreases.

The Formula for Stored Energy is

$$E = \frac{1}{2}LI^2$$

Where:

E is the energy stored (in J).

L is the inductance (in H).

I is the current flowing through the inductor (in A).

The amount of energy (E) an inductor can store depends on its inductance (L) and how much current (I) is flowing through it.

Key takeaway from the formula

The energy stored is proportional to the square of the current. This means if you double the current, you store four times as much energy!

Applications of Electromagnetic Induction

Generators(alternators) and Dynamos

Think of a generator as a device that does the opposite of a motor: instead of using electricity to create motion, it uses motion to create electricity.

The entire process is based on the key physics principle of electromagnetic induction.

When a wire or coil moves through a magnetic field, it "cuts" the magnetic field lines. This action forces the electrons in the wire to move, which creates an electric current.

Faraday's Law tells us that the faster you move the wire or the stronger the magnet, the more electricity you'll produce.

Fleming's Right-Hand Rule helps us figure out the direction the current will flow in the wire.

The Generator's Main Parts

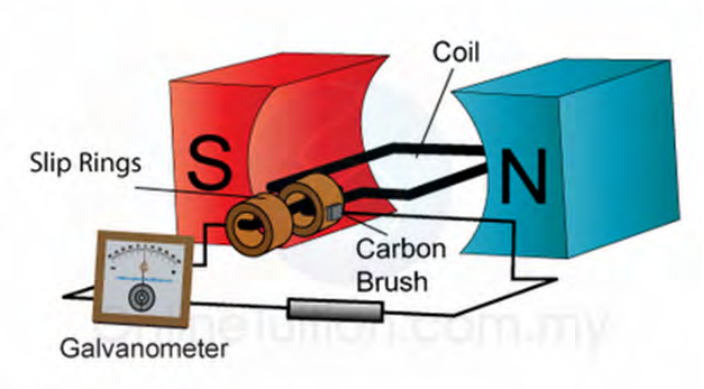


Figure 8.14: *An AC generator in its basic form*

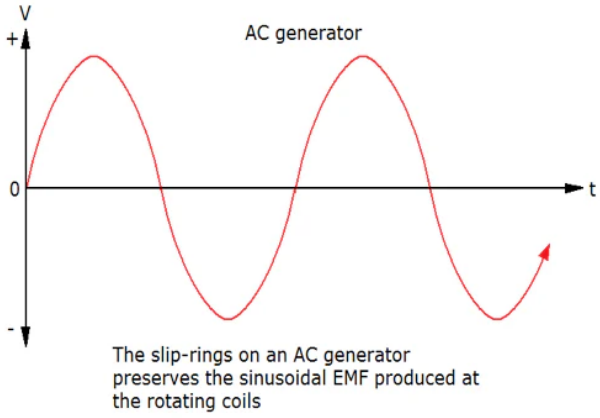


Figure 8.15: *Sinusoidal EMF Output from an AC Generator*

A basic generator is a simple machine with three main parts:

1. The Spinning Coil (Armature): This is a coil of wire that is made to spin inside a magnetic field. It is the "conductor" where the electricity is created.

2. The Stationary Magnet (Stator): This provides the magnetic field that the coil spins through. It's often made of powerful permanent magnets or electromagnets.
3. The Brushes: These are stationary blocks (usually made of carbon) that rub against the spinning coil's connections. Their job is to collect the electricity that is being produced and deliver it to an external circuit, like a light bulb.

How an AC Generator Works

An AC generator (or alternator) produces alternating current (AC)—which is current that constantly reverses its direction—using a simple and clever mechanical trick.

The Key Component

Slip Rings

Instead of a single contact point, the AC generator uses two separate metal rings called slip rings. The ends of the spinning coil are each connected to one of these rings.

The Process

1. As the coil spins in the magnetic field, the current flowing in it naturally changes direction every half-rotation. This is because the coil is cutting the magnetic field lines first one way, and then the other.
2. Two stationary brushes (usually carbon blocks) continuously rub against these two separate slip rings as they spin.
3. As the coil spins, the current flowing into one slip ring will reverse and flow out of the other. The brushes simply pick up this reversing current from the rings and transfer it directly to the outside circuit.

This simple setup ensures that the output is a current that is constantly alternating its direction, giving us alternating current (AC).

So, in short, you provide mechanical energy (spinning motion) to the coil, and the generator converts it into electrical energy (current) that you can use.

How a DC Generator (Dynamo) Works

A DC generator, or dynamo, produces direct current (DC)—a current that always flows in the same direction. It achieves this with a clever mechanical trick.

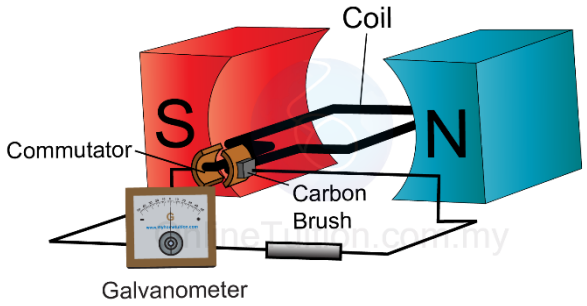


Figure 8.16: *A DC generator*

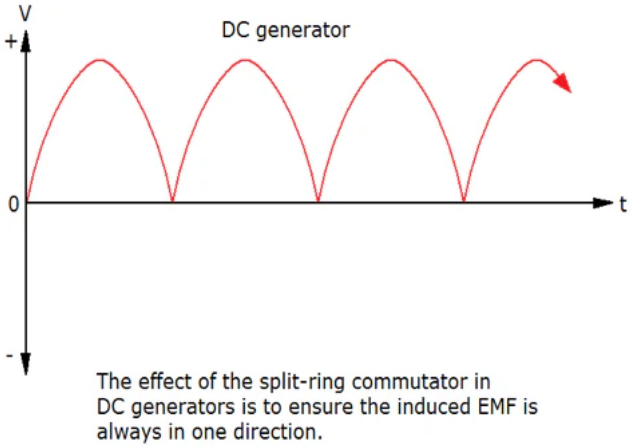


Figure 8.17: *D.C. output waveform*

The Key Component

The Split-Ring Commutator

Instead of two separate slip rings, a DC generator uses a single metal ring that is split in half, called a commutator. Each end of the spinning coil is connected to one of the two halves.

The Process

1. Alternating Current Inside: As the coil spins in the magnetic field, the current flowing inside the coil is actually alternating (just like in an AC generator).
2. As the coil rotates, the stationary brushes rub against the two halves of the split ring. The commutator is precisely aligned so that the connection to the brushes flips at the exact moment the current in the coil is about to reverse.

3. This flipping action acts like a mechanical switch, ensuring that the current flowing out of the brushes and into the circuit is always pushed in the same direction.

This process gives us a pulsating DC output—a current that rises and falls in strength but never reverses direction.

Activity 8.6 Internal Structure and Function of an Inductor

Objective: To understand the internal structure and working principle of an inductor by observing its components, identifying its core type, and representing this knowledge through a clear, labelled diagram.

What you need

1. Access to the video: https://www.youtube.com/shorts/4QkMt8ar7JA

2. Paper or notebook and pen or pencil

What to do

1. Watch the Video Carefully. Open the link above and watch a video to learn about the basic parts inside an inductor and how it works. Focus on identifying the main components.
2. Pay attention to how the coil is wound tightly around the core and how the core material differs (air core or iron core).
3. In your notebook, create a clear, labelled diagram showing:
   - **a.** The wire coil winding
   - **b.** The core inside the coil (indicate if air or iron core)
   - **c.** The external terminals or wires connecting the coil in a circuit

Activity 8.7 How Changing Inductance Relates to the Number of Coil Turns

Objective: To investigate how the number of turns in a coil affects its inductance, using a simulation to observe changes and deduce the relationship between coil turns and inductance.

What you need

1. Access to PhET's Faraday's Electromagnetic Lab simulation:

   Circuit Construction Kit: AC - Virtual Lab - RLC Circuit | AC Circuits | Kirchoff's Law - PhET Interactive Simulations

2. Paper or notebook and pen or pencil

What to do

1. Go to the PhET simulation using the link above.
2. In the simulation, find the part where you can interact with a coil or electromagnet to observe inductance-related behaviour. Use the controls provided to increase or decrease the inductance by changing the coil properties (usually by adjusting the number of coil turns).
3. Pay attention to how the coil visually changes as you adjust inductance—specifically focusing on the number of turns in the coil.
4. For each change in inductance you make, note:
   a. The inductance level shown (check the 'values' box to see this) or whether inductance is increased or decreased.
   b. How the number of coil turns changes when you adjust inductance.
   c. Any visible changes in the coil size or shape.
5. Based on your observations, write down a conclusion about the relationship between the inductance and the number of coil turns. Consider:
   a. Does increasing inductance correspond to more coil turns?
   b. Does decreasing inductance correspond to fewer coil turns?
   c. Why do more coil turns affect inductance?

Activity 8.8 Observing Bicycle Dynamo Operation Using Videos

Objective: To understand how a bicycle dynamo converts mechanical energy from pedalling into electrical energy through electromagnetic induction, and to relate its operation to Faraday's law.

What you need

1. Access to the following videos:
   - **a.** "57 Principle of Generator or Dynamo" (https://www.youtube.com/watch?v=U0fMXsl-yVM)
   - **b.** "Funktion Fahrrad Dynamo - 3D Animation ohne Erklärung" (https://www.youtube.com/watch?v=qoVhqK4Hbrs)
   - **c.** "How a Dynamo Works" (https://www.youtube.com/watch?v=sigHlBZlmZU)
2. Paper or notebook and pen or pencil

What to do

1. View the videos that demonstrate how a bicycle dynamo converts mechanical rotation into electrical energy. Pay close attention to the parts shown: the coil of wire, the magnet, and how the rotation of the bicycle wheel spins the magnet inside the coil.
2. Notice that as the bicycle pedal turns the wheel, the magnet inside the dynamo moves, creating a changing magnetic field inside the coil.
3. Observe how this changing magnetic field induces an electric current in the coil, lighting the bicycle's headlight or powering devices.

4. Write down in your notebook how mechanical rotational energy (from pedalling) results in electrical energy through electromagnetic induction.
5. Note the relationship between the movement of the magnet and the induced current in the coil.
6. Relate Your observations to Faraday's law. Record that Faraday's law states that a changing magnetic flux through a coil induces an electromotive force (EMF) in the coil.
7. Describe how the rotation of the magnet causes continuous changes in magnetic flux, producing the induced emf that powers the bicycle light.
8. Draw a simple diagram showing the bicycle wheel connected to the dynamo. Label the rotating magnet, fixed coil, direction of rotation, and where the electrical current is induced. Use arrows to indicate movement and current flow.
9. Summarising how mechanical energy is converted to electrical energy inside the bicycle dynamo and how faster pedalling increases the induced emf.

Activity 8.9 Inductor Behaviour in an AC Circuit

What you need

1. Access to an interactive AC circuit simulation with inductors (for example, PhET's "Circuit Construction Kit: AC" at https://phet.colorado.edu/en/simulations/circuit-construction-kit-ac)



2. Paper or notebook
3. Pen or pencil

What to do

1. Go to the simulation link and launch the AC circuit simulation that includes components like an AC voltage source, resistor, and inductor.

2. Use the simulation tools to set up a simple series AC circuit with an AC power supply connected to an inductor. If there is a pre-made example circuit with an inductor and AC source, open it.
3. Start the simulation and observe the graphs or visual indicators showing voltage across the inductor and the current flowing through the circuit. Notice the shape and timing of the voltage and current signals.
4. Watch carefully and note how the current waveform lags behind the voltage waveform in time.
5. In your notebook, sketch the two sinusoidal waves (voltage and current) showing the voltage ahead of current by some phase angle. Label the voltage and current curves and indicate the phase lag.
6. If the simulation allows, vary the frequency of the AC source or the inductance value. Observe how this affects the phase difference between voltage and current and the amplitude of current.
7. Write down what you see about how the current lags the voltage in an inductive circuit. Note how changing frequency or inductance changes this lag.

Activity 8.10 Observing Mutual Inductance Between Two Coils

Objective: To investigate how an inductor behaves in an AC circuit, focusing on the phase relationship where current lags voltage, and to observe how changes in frequency or inductance affect this behaviour.

What you need

1. Access to a mutual inductance or transformer simulation

   PhET Faraday's Electromagnetic Lab

2. Paper or notebook
3. Pen or pencil

What to do

1. Go to PhET's Faraday's Electromagnetic Lab simulation, which contains interactive models of coils and transformers.
2. Navigate to the Transformer Tab or Setup. Find and select the transformer or two-coil setup, where two coils (primary and secondary) are placed near each other.
3. Turn on the current or connect the primary coil to a AC source inside the simulation.
4. Observe what happens in the secondary coil: does current flow or does the light bulb connected glow?
5. Vary the current in the primary coil by changing the power source settings (e.g., turning the current on/off, increasing or decreasing the current).
6. Watch how the induced current or voltage in the secondary coil changes as you change the primary coil's current.
7. Write down what you see happening in the secondary coil when
   - **a.** The current in the primary coil is switched on and off.
   - **b.** The primary coil's current is increased or decreased.
   - **c.** Notice how changes in magnetic flux from the primary coil induce an emf in the secondary coil.
8. Think about and note that
   - **a.** When current in the primary coil changes, it creates a changing magnetic field.
   - **b.** This changing magnetic field induces an EMF and current in the secondary coil (mutual inductance).
   - **c.** This is the principle behind transformers, which transfer electrical energy by induction between coils.
9. Sketch two coils side by side, labelling the primary coil (connected to the power source) and the secondary coil (connected to a measuring device or light bulb). Indicate with arrows the direction of current and show how changing current in the first coil induces current in the second.

Activity 8.11 Calculating Self-Induction, Mutual Induction & Induced EMF

Study the worked examples carefully before attempting the sample questions that follow.

Worked Example 1

A coil has a self-inductance of 0.5 H. The current flowing through the coil changes from 3A to 7A in a time interval of 0.25 seconds. Calculate the magnitude of the self-induced electromotive force (EMF) in the coil.

Solution

Given

Self-inductance (L) = 0.5 H

Change in current (dI) = 7 A - 3 A = 4 A

Change in time (dt) = 0.25 s

First, we calculate the rate of change of current ($\frac{dI}{dt}$):

$\frac{dI}{dt} = \frac{4}{.25} = 16\ A/s$

Next, we use the formula for self-induced EMF, taking the magnitude:

$E = \frac{LdI}{dt}$

$E = (0.5\ H)(16\ A/s)$

$E = 8\ V$

Worked Example 2

Two coils are placed close to each other, and their mutual inductance is measured to be 0.12 H. The current in the first coil is changed at a constant rate of 25 A/s. What is the magnitude of the EMF induced in the second coil?

Solution

Given

Mutual inductance (M) = 0.12 H

rate of change of current in the first coil $\left(\frac{dI_1}{dt}\right) = 25$ A/s

We use the formula for the EMF induced in the second coil, taking the magnitude:

$E_2 = \frac{MdI_1}{dt}$

$E_2 = (0.12\ H)(25\ A/s)$

$E_2 = 3\ V$

Worked Example 3

An inductor in an electronic circuit is designed to store 0.8 J of energy when a steady current of 4A flows through it.

a. Calculate the self-inductance (L) of the inductor.

b. If the current is then reduced to zero in a very short time of 0.05 s, what is the average back-EMF induced in the inductor during this time?

Solution

a. Given

Energy stored (E) = 0.8 J and current (I) = 4 A

We use the energy storage formula and rearrange it to solve for L

$E = \frac{1}{2}LI^2$

$L = \frac{2E}{I^2}$

$L = \frac{2(0.8)}{(4)^2}$

$L = \frac{1.6}{16}$

$L = 0.1\ H$

b. Given

Self-inductance (L) = 0.1 H (from part a)

Change in current (ΔI) = 0A - 4A = -4A and change in time (Δt) = 0.05 s We first calculate the rate of change of current: $\frac{dI}{dtI} = \frac{-4}{0.05} = -80\ A/s$

Then we use the formula for induced EMF.

We are looking for the magnitude:

$E = \left|-\frac{LdI}{dt}\right|$

$E = |-(0.1\ H)(-80)|$

$E = 8\ V$

Worked Example 4

Two coils have self-inductances of L_1=0.25 H and L_2=0.64 H. The coefficient of coupling (k) between them is 0.8. a. Calculate the mutual inductance (M) between the two coils. b. If the current in the first coil (L_1) is changed at a rate of 10 A/s, what is the magnitude of the EMF induced in the second coil (L_2)?

Solution

a. Given

$L_1 = 0.25$ H, $L_2 = 0.64$ H and $k = 0.8$

We use the formula for the coefficient of coupling and rearrange it to solve for M

$$k = \frac{M}{\sqrt{L_1 L_2}}$$

$$0.8 = \frac{M}{\sqrt{(0.25)(0.64)}}$$

$$M = 0.8 \times 0.4\ H$$

$$M = 0.32\ H$$

b. Given

Mutual inductance (M) = 0.32 H (from part a)

Rate of change of current in the first coil (dtdI1) = 10 A/s

We use the formula for the EMF induced in the second coil, taking the magnitude:

$$E_2 = M\frac{dI_1}{dt}$$

$$E_2 = (0.32)(10) = 3.2\ \text{V}$$

Practice Problems

Now, using the worked example as a guide, solve the following problems individually or in groups.

1. A coil has 500 turns and a magnetic flux of 2 mWb links each turn when a current of 4 A flows through it. Find the self-inductance of the coil.
2. Two coils are placed close to each other. A current of 3A in the first coil produces a magnetic flux of 0.4 mWb in the second coil having 200 turns. Calculate the mutual inductance.

3. A current in a coil increases uniformly from 0 to 6A in 0.03 s, and the coil has a self-inductance of 0.4 H. Calculate:
   a. The average back EMF
   b. The energy stored in the coil at the end
4. Two coils have mutual inductance of 0.5 H. If the current in the first coil changes from 0 to 5A in 0.01 s, calculate:
   a. The induced EMF in the second coil
   b. The energy transferred to the second coil if it has 100 turns and each turn experiences 0.002 Wb of flux

Activity 8.12 Presentation on the Concept of Self-Inductance

Objective: To understand the concept of self-inductance, how a coil generates an opposing emf when its own current changes, and to explore its practical applications by researching real-life devices that rely on this property.

What you need

1. Access to the Internet or access to reference books
2. Paper or notebooks for notetaking
3. Pen or pencil
4. Presentation materials such as poster paper and markers, or a computer with presentation software (PowerPoint, Google Slides)
5. Access to videos or articles explaining self-inductance and inductors

What to do

1. Organise yourselves into small groups of 3 to 5 classmates. Investigate and learn about self-inductance, focusing on:
   a. The meaning of self-inductance: how a changing current in a coil induces an electromotive force (emf) in the same coil, opposing the change in current.
   b. The physical principle behind self-inductance (magnetic flux linkage with the coil itself).
   c. Examples of devices that demonstrate self-inductance
   d. How inductors function in circuits to resist sudden changes in current.

2. Choose one or more real-life devices where inductors play an important role. Examples include
   - **a.** Radio tuning circuits
   - **b.** Transformers (power supplies, chargers)
   - **c.** Electric motors
   - **d.** Inductive sensors
   - **e.** Switching power supplies or filters
3. Research how inductors operate in your chosen device(s) and how self-inductance contributes to its function. Write down key points covering
   - **a.** The definition and explanation of self-inductance
   - **b.** How changing current in a coil creates a self-induced emf opposing the current change
   - **c.** The role of inductors in your chosen device(s) with specific examples
   - **d.** Diagrams or sketches illustrating self-inductance and device operation
4. Prepare posters or digital slides including
   - **a.** a clear explanation of self-inductance
   - **b.** diagrams showing a coil with changing current inducing emf in itself
   - **c.** pictures or diagrams of the chosen devices highlighting the inductor's role
   - **d.** summaries linking theory to practical application
5. Share your findings with the class, or with another group, by explaining
   - **a.** what self-inductance is and how it occurs in a coil
   - **b.** how the phenomenon is used in your chosen real-life device(s)
   - **c.** why the property of self-inductance is important for the device's function

ELECTROMAGNETIC INDUCTION-EDDY CURRENTS AND TRANSFORMER OPERATION

Eddy currents

Have you ever tried moving a magnet quickly near a metal object, like a cooking pot or a metal sheet, and felt a gentle resistance? Or noticed that some metals seem to "slow down" when near a moving magnet? This happens because of something called eddy currents — tiny swirl-like electric currents that form inside metals whenever the magnetic field around them changes.

How They Form

It all starts with a changing magnetic field. This can happen in two ways:

1. A Magnet is Moving: If you wave a magnet back and forth near the copper sheet, the changing magnetic field "tells" the electrons in the metal to start moving in circles.
2. The Metal is Moving: If you move the copper sheet through a steady magnetic field, the same thing happens. The metal "sees" a changing magnetic field as it moves, and this also makes the electrons swirl around.

These swirling circles of electricity are called eddy currents because they look a bit like little whirlpools or eddies in a river.



Figure 8.18: *Swirling-river-eddy – Eddy currents take this form*

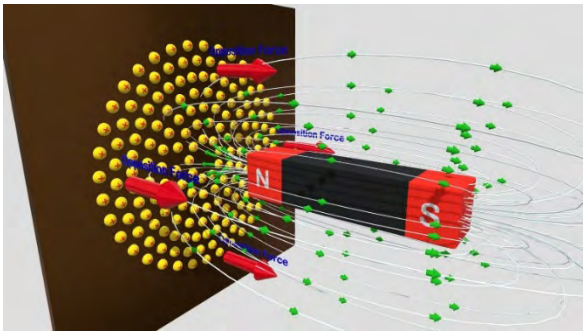


Figure 8.19: *A 3D model of a bar magnet inducing concentric eddy currents in a metal sheet.*

Why They Matter (Lenz's Law)

Eddy currents are not just random; they have a purpose. According to Lenz's Law, these swirling currents create their *own* magnetic field. This new magnetic field always pushes against the original magnetic field that created it. Again, this is a consequence of Lenz's law. Think of it like this:

1. You push a magnet towards a copper sheet.
2. Eddy currents form in the sheet.
3. These currents create a new magnetic field that pushes back against your magnet, trying to stop it from getting closer.

This pushing-back force is what makes them useful in some cases (like braking systems) and a problem in others (like in transformers, where they cause energy loss).

The Downside of Eddy Currents

While they can be useful, eddy currents also have some serious disadvantages, especially in electrical machines.

1. Energy Waste (Heat): Imagine those swirling eddy currents as tiny electric heaters inside the metal. As they flow, the metal resists their movement, which generates heat. This is a waste of energy. In devices like motors and transformers, this heat means less of the electricity is being used to do the actual work, making the device less efficient. This is known as I^2R losses (remember Power = I2R).
2. Unwanted "Braking"/damping: Remember how eddy currents create a magnetic field that pushes back? This push-back acts like a brake. If you have a motor that needs to spin freely, this braking force can slow it down and make it work harder, wasting more energy.

3. Overheating: If the eddy currents get too strong, all that heat can cause the components to get dangerously hot. This can damage the device and shorten its lifespan.

How to Reduce Eddy Currents

Engineers and scientists have found clever ways to minimise eddy currents to make devices more efficient and prevent them from overheating. The most common method is *lamination*.

1. Problem: Solid Blocks of metal. Imagine the core of a transformer or motor is a solid block of metal. Eddy currents would have a huge, continuous path to swirl around, creating a lot of heat.
2. Solution: Using Thin Sheets. Instead, they use many very thin, flat sheets of metal, stacked together. Each sheet is coated with a thin layer of insulation (like a non-conductive varnish).
3. How it Works: This insulation breaks up the large path. Now, the eddy currents can only swirl in tiny loops within each individual thin sheet. These smaller loops have much higher electrical resistance, which drastically reduces the strength of the currents and, therefore, the amount of heat generated. This is the main reason why the cores of transformers and large electric motors are not solid blocks of metal.

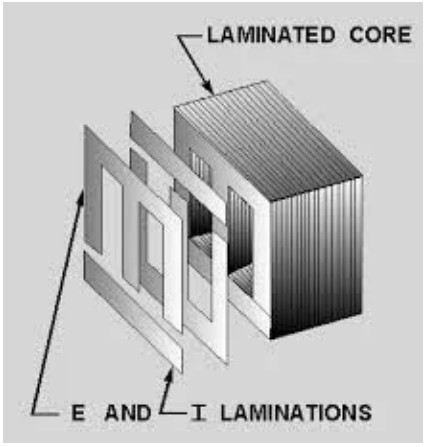


Figure 8.20: *A laminated transformer core*



Figure 8.21: *Laminated motor core*

Other Ways to Reduce Eddy Currents

Besides using laminated cores, engineers use a couple of other strategies:

1. Using "Less Conductive" Materials: If you have two different kinds of metal and one lets electricity flow through it very easily (low resistance), and the other resists the flow of electricity more (high resistance). If you build a device core out of a material with higher resistance, the eddy currents will be weaker. Think of it like trying to swim in thick syrup versus water—it's harder to move. So, even though these materials need to be good at carrying magnetism, using ones with higher electrical resistance helps to cut down on the currents and the heat they produce.
2. Slowing Down the Changing Flux: Remember, eddy currents are created by a *changing* magnetic field. The faster the magnetic field changes, the stronger the eddy currents are. If you can slow down how often the magnetic field changes (for example, by using a lower frequency in an AC circuit), you'll reduce the strength of the eddy currents. This is not always possible because a lot of electronics need to operate at specific frequencies, but when it is, it is a very effective way to minimise the problem.

Where Eddy Currents are Useful

While we often try to get rid of eddy currents, their heat and braking effects can be very useful. Here are a few examples

1. **Induction Furnaces - Super-Fast Metal Melters**

   Imagine you need to melt a huge chunk of metal. An induction furnace does this by using eddy currents.



Figure 8.22: *An induction furnace. The light is a hot metal*

How it Works

a. A powerful, rapidly changing magnetic field is created by an electrical coil. When you place a metal object inside this field, the strong magnetic changes create very high eddy currents within the metal.

b. These currents flow through the metal, and the resistance causes it to get incredibly hot—so hot, in fact, that it melts!

c. The Result: This method is very clean because there's no direct flame, and it's super-fast and easy to control.

2. **Damping in Analogue Meters: Keeping Needles Steady**

Have you ever seen an old-school voltmeter or ammeter? The needle does not just swing wildly; it moves to the right spot and stops smoothly. This is thanks to eddy currents.



Figure 8.23: *An analogue voltmeter*

How it Works

a. The needle is attached to a small coil of wire that moves inside a magnetic field. When the coil moves, eddy currents are induced in a metal frame around it.

b. According to Lenz's Law, these eddy currents create their own magnetic field that **pushes against the motion** of the coil. This "braking" force quickly stops the needle from wobbling back and forth, allowing you to get a steady and accurate reading right away.

3. **Old-School Speedometers: Measuring Car Speed with Magnets**
Before digital displays came into being, analogue speedometers in cars used to function based on eddy currents.



Figure 8.24: *A analogue car speedometer*

How it Works

a. As the car's tyres spin, a cable turns a small magnet inside the speedometer. Next to the magnet is a metal cup attached to the speedometer needle.

b. As the magnet spins, it creates a changing magnetic field that induces eddy currents in the metal cup. These currents, in turn, create a magnetic force that tries to drag the cup along with the spinning magnet. The faster the car goes, the faster the magnet spins, and the stronger this dragging force becomes.

c. The Result: This force is strong enough to turn the cup and the attached needle against a small spring. The needle's position then shows you how fast you're driving.

Do any of these applications sound surprising to you? It is amazing how a seemingly "bad" thing can be used for so much good!

Transformers: (The Voltage Changers)



Figure 8.25: *An electrical transformer*

Have you ever wondered how electricity from power stations travels long distances to reach your home safely and efficiently? Or how the electricity that powers your lights, TV, or phone charger is suited perfectly for these devices without damaging them?

The answer lies in a device called a transformer, which helps change the voltage of electricity to the right level for different uses.

A transformer is a simple but super-important electrical device. Its main job is to change the voltage of an alternating current (AC) electricity supply. It can either increase the voltage (step-up) or decrease it (step-down). You'll find them everywhere, from the power lines that bring electricity to your home to the tiny chargers for your phone.

What's Inside a Transformer?

1. **The Core**

   This is the heart of the transformer, usually made of a special kind of iron. Its job is to act like a highway for magnetism, making sure the magnetic field created by one coil gets to the other coil as efficiently as possible, like a water pipe confines and carries water to places. The core is normally laminated for the obvious reason of reducing the effects of eddy currents. Refer to notes on eddy currents.

2. **The Windings (Coils)**
   These are just coils of wire. A transformer has two of them.
   a. **Primary Winding (Np)**
      This is the coil where the electricity comes in. You connect your AC power source to this side (for example, the generator in a power plant).
   b. **Secondary Winding (Ns)**
      This is the coil where the electricity goes out to power a device. The voltage here is what you want to control.

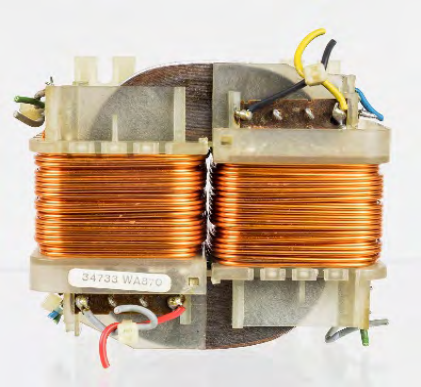


Figure 8.26: *A small single-phase transformer with windings exposed (left).*



Figure 8.27: *A 3-phase power transformer showing windings (middle)*

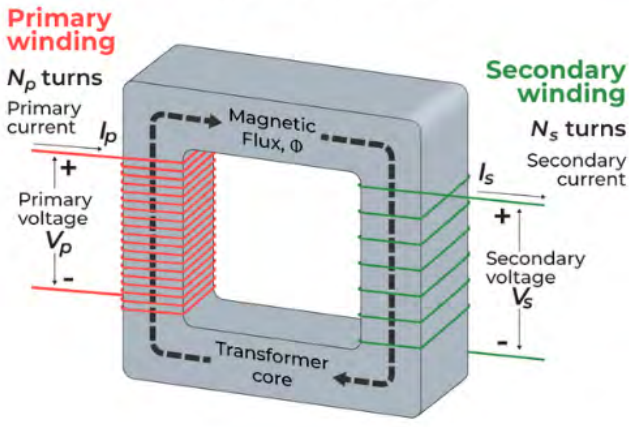


Figure 8.28: *A diagram of a power transformer*

Other Important Components

Insulation

Just like in any electrical device, there's a lot of insulation in the design to make sure that the wires do not touch each other or the core, which would cause a short circuit.



Figure 8.29: *Insulated transformer windings*



a



b

Figure 8.30: *Transformer winding insulation system (a) and a portable transformer for electronics (b)*

Tank and Cooling

For very large transformers (like the ones you see in your neighbourhood), all the parts are put into a tank filled with special insulating oil. This oil helps to cool the transformer down, and the tank often has radiators on the outside to help get rid of the heat.



Figure 8.31: *Power transformers with oil tanks for cooling*

Where We Find Transformers

Transformers are crucial for our electrical grid and many of the electronic gadgets we use every day.

Getting Power to Our Homes

1. Stepping Up the Voltage: Power stations use step-up transformers to boost the voltage for long-distance travel. This is a smart way to send electricity because higher voltage means lower current, and that means less energy is wasted as heat along the power lines.
2. Stepping Down the Voltage: Closer to where we live and work, step-down transformers take that high voltage and bring it down to a safe, usable level for our homes and businesses.

Inside Our Electronics

1. Powering Circuits: From the wall outlet, Electricity frequently passes through a transformer first. The transformer then lowers the high AC voltage to a more manageable level before other components turn it into the DC power our devices need.

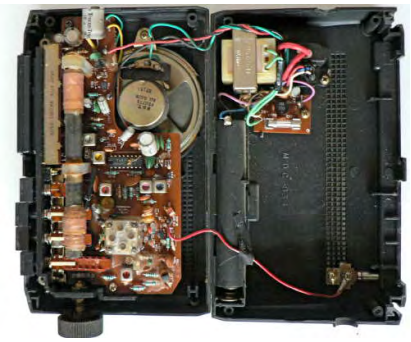


Figure 8.32: *A transformer in an old radio set*

2. Making Speakers Sound Great: In an audio system, a transformer can match the amplifier to the speaker, making sure the speaker gets the most power possible for a better sound.
3. Keeping Us Safe: They can also separate two parts of a circuit, a safety feature known as electrical isolation.

Other Important Uses

1. Welding: If you have seen a welder at work, you have seen a transformer in action. They are essential for delivering the intense, low-voltage current needed for welding.

2. Medical Use: In hospitals, transformers help regulate voltage and provide isolation for sensitive medical equipment.

The Operation of a Transformer Explained

A transformer operates on the principle of **mutual induction**, which is the ability of one coil to induce a voltage in a nearby coil without a direct connection.

1. When you connect an alternating current (AC) power source to the primary coil, a changing electric current begins to flow.
2. This changing current generates a constantly changing magnetic field around the primary coil.
3. A soft iron core efficiently channels this magnetic field from the primary coil to the secondary coil.
4. As the changing magnetic field passes through the secondary coil, it induces a new voltage. This is due to *Faraday's Law of Electromagnetic Induction.*
5. If a device (or "load") is connected to the secondary coil, the newly induced voltage will cause a current to flow, powering the device.
6. The amount of voltage produced in the secondary coil depends entirely on the ratio of the number of turns of wire in each coil. More turns on the secondary coil result in a higher voltage, and fewer turns result in a lower voltage.

   This is expressed mathematically as follows: $\frac{V_s}{V_p} = \frac{N_s}{N_p}$

   a. Step-up Transformer: If $N_s > N_p$, then $V_s > V_p$ (voltage is increased).

   b. Step-down Transformer: If $N_s < N_p$, then $V_s < V_p$ (voltage is decreased).

The Relationship Between Current and Turns

For an ideal (perfect) transformer, we assume there is no power loss, meaning the power entering the transformer is equal to the power leaving it. This is expressed by the formula:

$$P_{in} = P_{out}$$

As power is the product of voltage and current (P=VI), we can also write:

$$V_p I_p = V_s I_s$$

This relationship shows that voltage and current are inversely proportional to one another. Consequently, if a transformer steps up the voltage, it must step down the current by the same proportion to keep the total power constant.

The exact relationship between current and the number of turns in the coils is:

$$\frac{I_s}{I_p} = \frac{V_p}{V_s} = \frac{N_p}{N_s}$$

Why Transformers Are Not Perfect

You have probably heard that no machine is 100% efficient, and the transformer is a great example. Even though they are incredibly good at what they do, a little bit of energy is always lost along the way. We can define a transformer's efficiency (η) by comparing the power it puts out to the power it takes in:

$$\eta = \frac{Power\ Out}{Power\ In} \times 100\%$$

The losses that prevent a transformer from being perfectly efficient are:

1. **Copper Losses (or Heat in the Wires)**

   The Issue

   Think of the wires in the transformer's coils. They have a small amount of resistance. When electricity flows through them, this resistance causes the wires to heat up, just like an electric iron. That heat is wasted energy that cannot be used. This is also known as I^2R loss.

   The Fix

   We build transformers with thick, high-quality copper wires. The thicker the wire, the lower its resistance, which means less heat is generated and less energy is wasted.

2. **Eddy Current Losses (or Heat in the Core)**

   The Issue

   The changing magnetic field in the core does not just affect the coils; it also creates tiny, swirling electric currents within the core itself. These eddy currents also generate heat, which is a waste of energy.

   The Fix

   Instead of using one solid block of metal for the core, we make it out of many thin, insulated sheets of metal (called laminations). This clever design forces the eddy currents to travel in tiny, inefficient loops, making them much weaker and reducing the heat they produce.

3. **Hysteresis Losses (or The Magnetic "Drag")**

The Issue

Every time the AC current changes direction, the magnetic field in the core also has to change. It takes a little bit of energy to do this, like how a motor uses energy to change direction. This "magnetic friction" generates a small amount of heat.

The Fix

We use special materials like silicon steel for the core. These materials are "soft" magnetically, meaning they can be magnetised and demagnetised very easily, so very little energy is lost in the process.

4. **Flux Leakage (or the "Lost" Magnetic Field)**

The Issue

The goal is for all the magnetic field from the primary coil to go directly to the secondary coil. But in reality, some of the magnetic field "leaks" out into the surrounding air and is wasted.

The Fix

Engineers design transformers by winding the coils very tightly and close together, often one on top of the other. This ensures that almost all the magnetic field is captured by the secondary coil.

5. **Humming Losses**

The Issue

The core's laminations can vibrate slightly as the magnetic field changes, creating a humming sound. That sound is a tiny amount of wasted energy.

The Fix

We use a tight physical design and clamping to make sure the core is stable and does not vibrate.

By minimising all of these small losses, modern transformers are able to achieve impressive efficiencies, often exceeding 99% in large power stations!

Activity 8.13 Exploring Eddy Currents and Electromagnetic Braking

Objective: To observe how eddy currents are generated when a conductor moves through a magnetic field, understand how they create electromagnetic braking by opposing motion (Lenz's Law), and see how changing the conductor's structure (solid vs. slitted) affects the strength of these currents.

What you need

1. Access to the video: Faraday's Law Demo: Eddy Pendulum



2. Paper or notebook and pen or pencil

What to do

1. Open and watch or listen to the video "Faraday's Law Demo: Eddy Pendulum."
2. Observe how a sheet of aluminium attached to a pendulum swing through the magnetic field created by horseshoe magnets. Notice the difference in motion when the pendulum passes through the magnetic field region.
3. Observe the Effects of Eddy Currents: Notice how the solid aluminium plate causes the pendulum to slow down significantly more than the slitted aluminium plate. Pay attention to the rate at which the pendulum's motion slows down in each case.
4. Write down answers to these questions in your notebook:
   - **a.** What happens to the speed of the pendulum as it swings through the magnetic field?
   - **b.** How do the solid and slitted aluminium plates differ in their effect on the pendulum's motion?
   - **c.** What might cause the difference in behaviour?
5. Form small groups of 3 to 5 people.
6. Share your observations and thoughts about the pendulum's motion and the damping effect caused by the magnetic field.
7. In your group, discuss and formulate explanations addressing:
   - **a.** How moving the conductor (aluminium plate) through a magnetic field produces eddy currents
   - **b.** Why these eddy currents act to oppose the pendulum's motion (Lenz's Law)
   - **c.** How the presence of slits in the aluminium reduces eddy currents and thus reduces braking

8. As a group, write a brief explanation summarising your shared understanding of
   a. How eddy currents are generated by changing magnetic flux
   b. Why they oppose motion and cause energy loss (electromagnetic braking)
   c. The role of aluminium structure (solid vs. slitted) in controlling eddy currents

Activity 8.14 Observing Eddy Currents by Dropping a Magnet Through a Copper or Aluminium Tube

What you need

1. A strong bar magnet or cylindrical magnet
2. A hollow copper or aluminium tube (vertical, with smooth inner surface)
3. Stopwatch or timer (optional)
4. Paper or notebook
5. Pen or pencil

What to do

1. Hold the copper or aluminium tube vertically, ensuring it is stable and free to allow objects to fall through it unhindered.
2. Release a non-magnetic object to fall freely through the tube (e.g. a coin, a small pencil eraser, etc). Observe the speed of the fall.
3. Release the magnet from the top of the tube, letting it fall freely through the tube to the bottom. Observe how it moves.
4. Observe the speed of fall. Notice that the magnet falls slower through the tube than it would if dropped in open air.
5. Take a moment individually to consider why the magnet falls slower through the tube compared to free fall.
6. Discuss your ideas with a partner. Try to explain what could be causing the slowing effect.
7. Explain the phenomenon using Electromagnetic Induction and Lenz's Law

8. Write down what you observed during the demonstration and summarise your group's explanation relating to electromagnetic induction and Lenz's law.

Activity 8.15 Factors Affecting Transformer Efficiency

Objective: To investigate factors that affect transformer efficiency—such as eddy current loss, copper loss, hysteresis loss, and flux leakage—understand the physics behind each type of loss and explore practical methods (including experiments) to illustrate these effects and ways to minimise them in transformer design.

What you need

1. Access to online resources, videos, or articles about transformers and their efficiency factors
2. Paper or notebooks for notetaking and diagram drawing
3. Pen or pencil
4. If possible, materials for simple experiments (optional, see below)

What to do

1. Organise yourselves into small groups of 3 to 5 learners and research the main factors that affect transformer efficiency. Focus on
   a. Eddy current loss
   b. Copper loss
   c. Hysteresis loss
   d. Flux leakage

   Use reliable websites, online articles, or videos to gather information. Take notes explaining each loss type and why it affects efficiency.
2. Research simple, safe experiments or demonstrations that show these losses or concepts practically.
3. Note down the materials needed and procedures for these demonstrations.
4. Create a summary explaining
   a. The key factors reducing transformer efficiency
   b. How each factor causes energy loss

   c. Suggestions of simple experiments or demonstrations that illustrate these effects. Include diagrams or sketches to support explanations.

5. Present your research findings and demonstration ideas to the class or to one other group. Discuss
   a. Which losses are largest or most important and why
   b. How transformers are designed to reduce these losses (e.g., laminated cores to reduce eddy currents, using high-conductivity copper wire)
   c. Practical implications of efficiency on energy use and equipment design

Activity 8.16 Exploring the Structure of Ghana's Power System

Objective: To understand the structure of Ghana's power system by identifying how electricity is generated, transmitted, and distributed, and to illustrate this process through diagrams and descriptions that show the roles of GRIDCo, ECG, and key power stations in delivering electricity to consumers.

What you need

1. Access to the internet
2. Access to materials from Ghana Grid Company (GRIDCo) and Electricity Company of Ghana (ECG), such as
   a. GRIDCo website or resources (transmission maps, system overview)
   b. ECG website or infographics (distribution network details)
   c. Online videos explaining Ghana's power system (YouTube or educational sites)
3. Paper or notebook
4. Pen or pencil and drawing tools

What to do

1. Research the Power System Structure
   a. Use the internet to find maps, videos, and infographics from GRIDCo and ECG that show how electricity is generated, transmitted, and distributed in Ghana.
   b. Key power stations to focus on include hydroelectric plants like the Akosombo Dam and Bui Dam, as well as thermal plants such as Aboadze.

   c. Study the transmission network managed by GRIDCo, which includes high voltage lines (e.g., 161 kV, 225 kV) transporting electricity from power stations to substations across the country.
   d. Note the distribution network managed primarily by ECG in southern Ghana, delivering electricity from substations to homes and industries.

2. Identify Main Components and Flow and list
   a. Power generation sources (hydro, thermal, renewable)
   b. Transmission system (GRIDCo's role, transmission lines, substations)
   c. Distribution system (ECG's and others' roles, low voltage networks)
   d. End users (homes, industries)

3. On paper, draw a schematic diagram or flow chart showing the path of electricity
   a. Start from power stations (Akosombo Dam, Bui Dam, thermal plants)
   b. Show electricity flowing into the transmission network (GRIDCo's infrastructure, major transmission lines)
   c. Continue to the distribution network handled by ECG (and others, if desired)
   d. End with electricity reaching homes and industries

4. Label all parts clearly, using arrows to show direction of electricity flow.

5. Include Key Details in Your Diagram or Notes
   a. Indicate voltage levels where possible (e.g., 330 kV or 161 kV transmission lines)
   b. Mark important substations or bulk supply points
   c. Show differences between generation types (hydro, thermal) with symbols or colours
   d. Note how electricity is stepped down through transformers for safe usage in homes and businesses.

6. Write a Short Description
   a. Summarise how electricity moves from power stations, through transmission lines, then distribution networks, to consumers.

b. Mention the roles of GRIDCo and ECG in managing transmission and distribution respectively.

Activity 8.17 Transformer Voltages, Currents, Power & Efficiency

Study the worked examples carefully before attempting the sample questions that follow.

Worked Example 1

A step-up transformer has 200 turns in the primary coil and 2,000 turns in the secondary coil. If the input voltage is 120 V, calculate the output voltage.

Solution

Using the transformer formula:

$$\frac{V_s}{Vp} = \frac{N_s}{N_p} \rightarrow V_s = V_p \times \left(\frac{N_s}{N_p}\right)$$

$$V_s = 120 \times \left(\frac{2000}{200}\right) = 120 \times 10 = 1200V$$

Worked Example 2

A transformer has 500 turns on the primary and 100 turns on the secondary. If the primary current is 2 A, calculate the secondary current (assuming 100% efficiency).

Solution

$$\frac{I_s}{I_p} = \frac{N_p}{N_s} \rightarrow I_s = I_p \times \left(\frac{N_p}{N_s}\right)$$

$$I_s = 2 \times \left(\frac{500}{100}\right) = 2 \times 5 = 10\,A$$

Worked Example 3

A transformer supplies 4 A at 240 V to a load. If the primary current is 1.1 A at 920 V, calculate the efficiency of the transformer.

Solution

$$Output\ Power = V_s \times I_s = 240 \times 4 = 960$$

$$WInput\ Power = V_p \times I_p = 920 \times 1.1 = 1012\ W$$

$$Efficiency = \left(\frac{output\ Power}{Input\ power}\right) \times 100 = \left(\frac{960}{1012}\right) \times 100 \approx 94.86\%$$

Worked Example 4

A step-down transformer with an efficiency of 90% has 2,000 turns in the primary and 200 turns in the secondary. It is used to power a 24 W lamp from a 240 V AC supply. Calculate:

a. The secondary voltage

b. The current in the secondary coil

c. The current drawn from the mains

Solution

a. $V_s = V_p \times \left(\frac{N_s}{N_p}\right) = 240 \times \left(\frac{200}{2000}\right) = 240 \times 0.1 = 24\ V$

b. $I_s = \frac{P}{V_s} = \frac{24}{24} = 1.0\ A$

c. $Input\ Power\ (Ip) = Output\ Power/\eta = \frac{24}{0.9} = 26.67\ W$

$I_p = \frac{Input\ Power}{V_p} = \frac{26.67}{240} \approx 0.111\ A$

Practice problems

Now, using the worked example as a guide, solve the following problems individually or in groups.

1. A transformer has 400 turns on the primary coil and 100 turns on the secondary coil. If the primary voltage is 240 V, what is the secondary voltage?
2. A step-up transformer has a primary voltage of 120 V and increases the voltage to 480 V. If the primary coil has 300 turns, how many turns are on the secondary coil?
3. A transformer has 500 turns on the primary and 100 turns on the secondary. If the input current is 2 A, calculate the output current (assuming 100% efficiency).
4. A transformer is rated 100% efficient. If the input power is 240 W and the output voltage is 60 V, what is the output current?
5. A transformer has a primary voltage of 220 V and a secondary voltage of 11 V. If the primary current is 0.5 A, what is the secondary current (100% efficiency)?

6. A transformer has 1000 turns on the primary and 200 turns on the secondary. It supplies 5 A at 24 V to a load. Find the primary voltage and current assuming 90% efficiency.
7. A transformer with 96% efficiency has a primary voltage of 240 V and a current of 1.5 A. Calculate the secondary voltage if the current is 3 A.
8. A transformer steps down 220 V to 11 V and supplies 6 A to a device. If efficiency is 92%, find the current drawn from the mains.
9. A 95% efficient transformer has a 500-turn primary and 100-turn secondary. If it supplies 2 A at 10 V, find the input current and voltage.
10. A transformer has a turns ratio of 10:1. If the load requires 5 A at 12 V, and the transformer is 93% efficient, find the current in the primary.

Activity 8.18 Revision on Magnetism and Electromagnetic Concepts

Objective: To review and connect key concepts of magnetism and electromagnetism—such as magnetic materials, magnetic fields, electromagnetic induction, inductors, eddy currents, and transformers.

What you need

1. Paper or notebooks for notes
2. Pens or pencils
3. Access to reference materials (textbooks, online articles) if needed
4. Whiteboard or large paper (optional, for group summaries)

What to do

1. Form small groups of 6 learners.
2. Each member should take one of the following areas to quickly read and revise on and prepare to discuss:
   a. Magnetic and non-magnetic materials; magnetic field; magnetisation and demagnetisation
   b. Magnetic field around a current-carrying conductor
   c. Electromagnetic induction
   d. Inductors
   e. Eddy currents
   f. Transformers; labelling the parts and explaining how it works.

3. Individually or with a partner, use your notes or trusted resources to briefly summarise your assigned topic, focusing on key ideas:
   - **a.** What defines magnetic vs. non-magnetic materials and how magnetisation occurs or is removed
   - **b.** How electric current in a wire produces a magnetic field and its shape/direction
   - **c.** What electromagnetic induction means and examples of how changing magnetic fields induce voltage/current
   - **d.** What an inductor is, how it stores energy in a magnetic field, and its role in circuits
   - **e.** The formation of eddy currents in conductors placed in changing magnetic fields, their effects and uses
   - **f.** How transformers use electromagnetic induction to change AC voltage levels and the role of coils and the iron core
4. Come together and each member explains their topic in simple terms for everyone to understand. Use sketches or diagrams to illustrate concepts (for example, field lines around a wire or transformer coil).
5. Discuss connections between topics, such as how inductors and transformers both rely on electromagnetic induction or how eddy currents affect transformer operation.
6. As a group, create a summary list or mind map of the main ideas covering all topics. This could include:
   - **a.** Magnetic vs non-magnetic materials and magnetisation processes
   - **b.** Shape and orientation of magnetic fields around current-carrying conductors
   - **c.** Faraday's law of electromagnetic induction and its applications
   - **d.** Inductance and energy storage in inductors
   - **e.** Eddy currents causing energy loss and their practical uses (e.g., brakes, heating)
   - **f.** Transformer design, function, working principles, voltage step-up/down, and importance of core lamination to reduce eddy currents.

REVIEW QUESTIONS

Review questions 8.1

1. A magnetic flux through a single-turn loop increases from 0.02 Wb to 0.06 Wb in 0.1 seconds. Calculate the average induced EMF.
2. A coil with 200 turns is placed in a region with a magnetic field that is perpendicular to its plane. The magnetic field decreases from 0.5 T to 0.1 T in 0.2 s. The area of the coil is 0.01 m².
   a. Calculate the magnitude of the induced EMF.
   b. Using Lenz's Law, state whether the induced current will try to increase or decrease the magnetic field through the coil.
3. A metal rod of length 0.5 m is moved perpendicularly through a 0.4 T magnetic field at a constant speed of 6 m/s. The rod slides along rails to form a closed rectangular loop with a resistor of 2 Ω.
   a. Calculate the induced EMF in the rod.
   b. Explain how this situation illustrates Lenz's Law and the Law of Conservation of Energy.

Review Questions 8.2

1. A solenoid 0.5 m long with 800 turns carries a time-varying current that changes from 0 to 3 A in 0.02 s. The cross-sectional area is 2.5×10^{-4} m². Calculate the average emf induced. Using your result, evaluate how the induced emf would change if the core material were replaced with one of higher magnetic permeability
2. A coil with a self-inductance of 0.6 H is connected to a battery. Calculate the energy stored when the current reaches 4 A. If the coil is disconnected and allowed to discharge its energy through a 10 Ω resistor, calculate the average power dissipated if all energy is released in 0.02 s.
3. A conductor 0.4 m long moves at right angles through a uniform magnetic field of 0.25 T at a speed of 20 m/s. Calculate the emf induced. If this conductor is part of a closed circuit with resistance 0.5 Ω, calculate the induced current and the force required to keep it moving at constant speed.

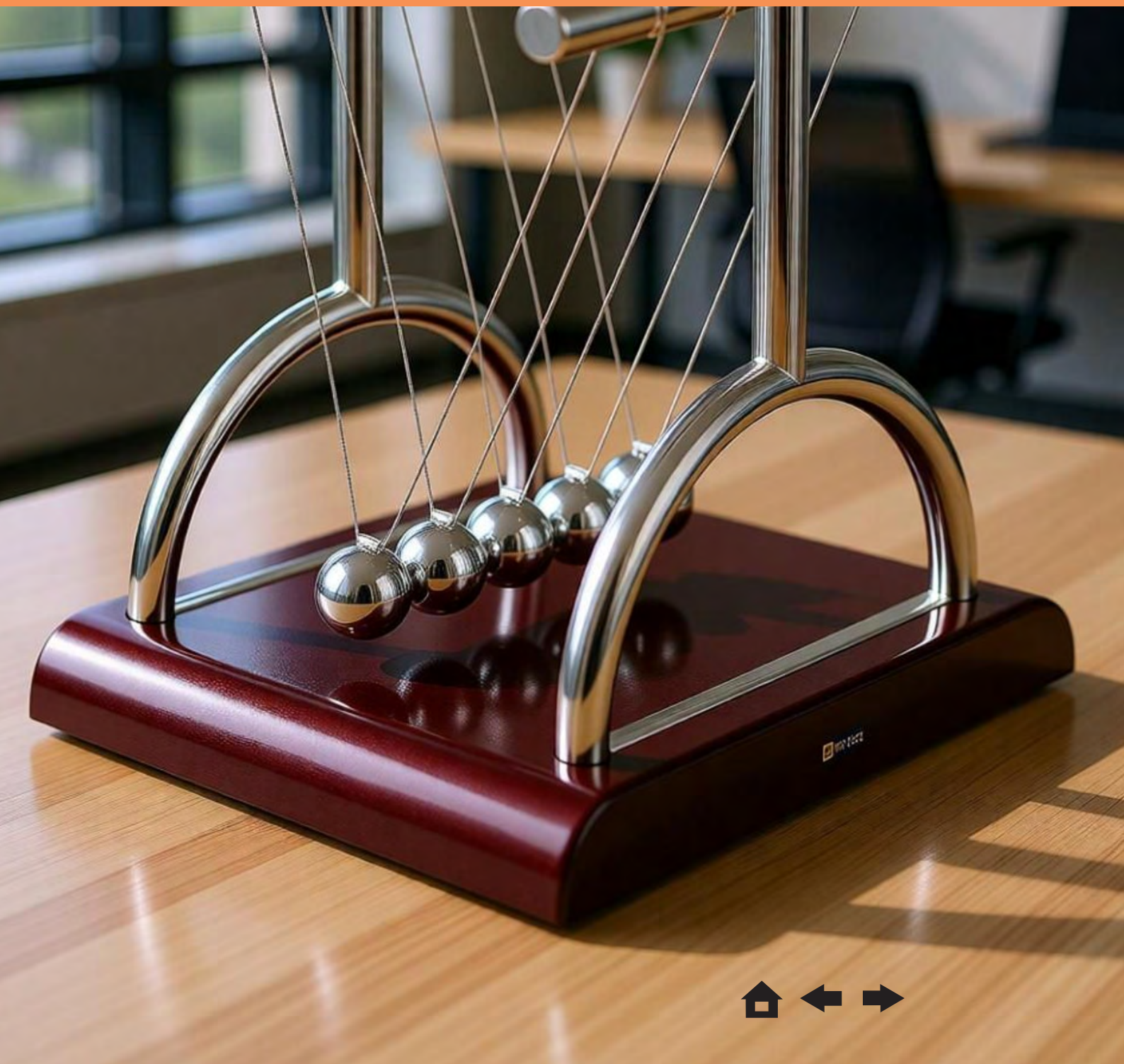
Review Questions 8.3

1. Explain how laminating the iron core of a transformer reduces energy losses due to eddy currents.
2. A transformer uses a solid iron core and gets excessively hot during use. After replacing the core with laminated iron, heating reduces significantly. Explain this in terms of eddy currents.
3. A transformer has 500 turns on the primary coil and 50 turns on the secondary coil. The input current is 0.2 A. Assuming 100% efficiency, calculate the secondary current.
4. In a step-down transformer, the output current is 5 A and output voltage is 12 V. If the transformer is 96% efficient, find the input power and the power lost due to inefficiency.
5. A transformer steps down 240 V to 24 V and delivers 4 A to a load. The efficiency is 90%. Calculate the current drawn from the primary.
6. A transformer designed without laminated cores experiences a 10 W loss due to eddy currents. After introducing lamination, the loss drops to 2 W. Calculate the percentage reduction in eddy current loss.
7. A transformer with 95% efficiency supplies 150 W to a device. Find the power input and total power lost.
8. A transformer has a turns ratio of 20:1. It supplies 6 A at 15 V on the secondary side. Efficiency is 92%. Find the primary current.
9. A transformer operates with a laminated core and has a power loss of 4 W. If it operated with a solid core instead, the loss would increase by 300%. What would the new power loss be?

SECTION

9

SIMPLE HARMONIC MOTION AND COLLISIONS



KINEMATICS AND DYNAMICS

INTRODUCTION

This section explores two fundamental areas of mechanics: **simple harmonic motion (SHM)** and **collisions**. Learners will examine the principles of SHM, including displacement, velocity, acceleration, and energy transformation in oscillatory systems such as pendulums and springs. Practical activities and worked examples highlight how SHM can be used to determine physical quantities, such as acceleration due to gravity. The section also develops an understanding of momentum, impulse, and the laws of motion through the study of collisions. Distinctions between elastic and inelastic collisions are drawn, supported by real-world examples and simulations, to show how momentum and energy behave in different situations. Together, these topics link earlier work on **Newton's laws of motion** (Year 1) and **circular motion** (Year 2), providing a strong foundation for applying mechanics to oscillations and interactions in everyday systems.

KEY IDEAS

- **Acceleration in SHM:** Acceleration is always directed towards the equilibrium position and is proportional to displacement, leading to sinusoidal motion.
- **Collisions:** Momentum is conserved in all collisions, while kinetic energy may or may not be conserved, distinguishing elastic from inelastic collisions.
- **Energy Transformation in SHM:** Mechanical energy remains constant, with continuous interchange between potential and kinetic energy during oscillation.
- **Impulse and Momentum Change:** Impulse equals the change in momentum, providing a basis for Newton's second law of motion.
- **Newton's Third Law Verification:** Conservation of momentum demonstrates that forces between interacting bodies are equal in magnitude and opposite in direction.
- **Simple Harmonic Motion (SHM):** SHM is a periodic oscillation where the restoring force is directly proportional to displacement and opposite in direction.

SIMPLE HARMONIC MOTION: PRINCIPLES, EQUATIONS, AND APPLICATIONS

In previous lessons, you have studied different types of motion such as rectilinear motion, circular motion, and oscillatory motion. A common example of oscillatory motion is seen when playing on a see-saw in the playground. When one side is pushed down, the other rises, and after a while the motion reverses, continuing back and forth around the central balance point. This repeated to-and-fro movement is an example of oscillatory motion.



Figure 9.1: *Two learners enjoying a seesaw ride in their school compound*

Simple Harmonic Motion (SHM)

Among oscillatory motions, there is a special type called **Simple Harmonic Motion (SHM)**. This occurs when the force that brings the object back to its central position (equilibrium) is **always directed towards that position** and is **directly proportional to how far the object has moved from it**. A good example of this is a pendulum bob; when pulled slightly to the side and released, a component of its weight pulls it back to its original position. When it passes this position the direction of this force reverses, once again pulling it back to the centre and causing oscillations back and forth.

In SHM, displacement, velocity, and acceleration are all linked. The displacement decides how strong the restoring force is, the velocity changes continuously as the object swings, and the acceleration always points back to the centre. This makes SHM important for understanding not only playground examples like swings, but also vibrations in musical instruments, clocks, and even some machines.

Simple harmonic motion is defined as the motion of a particle whose acceleration is always directed towards its equilibrium position and is directly proportional to its displacement from that position.

In a simple harmonic motion, the period of oscillation is independent of the amplitude and when displacement of particle is maximum, speed is zero.

Key terms associated with SHM

- Restoring Force: The force that brings the object back to its equilibrium position. For example, for a mass on a spring this force is given by Hooke's Law, $F=-kx$, where k is the spring constant and x is the displacement. The negative sign indicates that the force is always directed opposite to the displacement.
- Period (T): The time it takes for one complete oscillation.
- Frequency (f): The number of oscillations per unit time, $f=1/T$.
- Amplitude (A): The maximum displacement from the equilibrium position.
- Displacement (x): The distance of the oscillating object from its equilibrium position at any instant.
- Angular Frequency/velocity (ω): Related to frequency by $\omega = 2\pi f = 2\pi/T$.

Characteristics of SHM

1. Periodic: The motion repeats itself at regular intervals.
2. Oscillatory: The object moves back and forth about an equilibrium position.
3. Isochronous: The period (T) of oscillation is independent of the amplitude (for small amplitudes).
4. Sinusoidal Variation: Displacement, velocity, and acceleration all vary sinusoidally with time.

Key Conditions for SHM

1. Restoring Force: There must be a restoring force that always acts to bring the object back to its equilibrium position.
2. Proportionality to Displacement: The magnitude of this restoring force must be directly proportional to the magnitude of the displacement from the equilibrium position.
3. Direction: The restoring force must always be directed towards the equilibrium position (opposite to the displacement).

4. Inertia: The oscillating system must possess inertia (mass) so that it can overshoot the equilibrium position.

Mathematical Definition (Differential Equation)

The defining equation for SHM is:

$a = -\omega^2 x$

Where:

a is the acceleration of the oscillating body.

x is the displacement from the equilibrium position.

ω is the angular frequency (constant for a given SHM system), in radians per second (rad/s). The negative sign indicates that acceleration is always opposite to the displacement.

Principles of SHM

The core principle of SHM is the relationship between the restoring force and displacement. This can be understood through Newton's Second Law, $F = ma$. By substituting the restoring force in a spring, we get: $\boldsymbol{-kx = ma}$

Since acceleration is the second derivative of displacement with respect to time ($a = \frac{d^2x}{dt^2}$), the equation of motion for SHM is a second-order linear differential equation:

$$\frac{d^2x}{dt^2} + \frac{k}{m}x = 0$$

The general solution to this equation is: $\mathbf{x = A\sin(\omega t + \phi)}$

Where

x is the displacement from the mean position

A is the amplitude.

ω is the angular frequency, $\omega = k/m$

ϕ is the phase constant, determined by the initial conditions

In simple terms, the solution given above indicates that the position of the oscillating object varies sinusoidally when plotted against time. A graph demonstrating this can be seen below.

Consider a particle executing SHM such that the path taken by the particle is on a straight line, then x is the displacement of particle from the mean position at that instant. The displacement of a particle executing SHM at time t is given by

$x = A\sin(\omega t + \phi)$ ..... (1)

Note that this displacement from the mean position can also be derived by considering the vertical component of the motion of an object moving in a circle as shown in the image below. There are many parallels between SHM and circular motion.

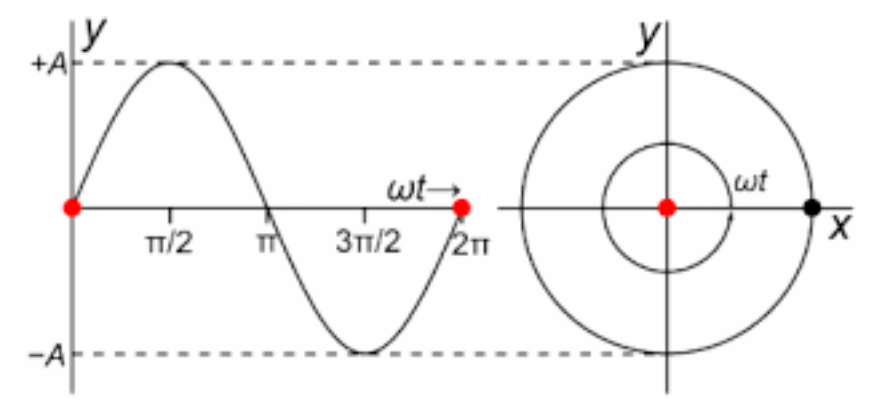


Figure 9.2: *SHM from circular motion*

Before reading on, have a go at using the formula for the position of an object undergoing simple harmonic motion to derive equations for the **velocity** and the **acceleration** of the same object. Remember, velocity is the first derivative of displacement and acceleration is the second! Sketch graphs of your equations when you are finished.

Velocity of Simple Harmonic Motion - Derivation

The velocity v of a simple harmonic motion can be derived by differentiating the displacement x with respect to time t

Thus $v = \frac{dx}{dt}$

Where $x = A\sin(\omega t + \phi)$

$v = \frac{d[A\sin(\omega t + \phi)]}{dt}$

$\mathbf{v = \omega A\cos(\omega t + \phi)}$ ..... (2)

From eqn (1)

$\frac{x}{A} = \sin(\omega t + \phi)$ ..... (3)

From trigonometry, $\sin^2(\omega t + \phi) + \cos^2(\omega t + \phi) = 1$

This implies that, $\cos(\omega t + \phi) = \sqrt{1 - \sin^2(\omega t + \phi)}$ ..... (4)

Putting eqn (3) into eqn (4) gives

$\cos(\omega t + \phi) = \sqrt{1 - \left(\frac{x}{A}\right)^2}$

$\cos(\omega t + \phi) = \sqrt{1 - x\,2\,\_\,A\,2}$

$\cos(\omega t + \phi) = \frac{1}{A}\sqrt{A^2 - x^2}$

putting $\cos(\omega t + \phi) = \frac{1}{A}\sqrt{A^2 - x^2}$ into eqn (2) gives

$\mathbf{v = \omega\sqrt{A^2 - x^2}}$ ..... (5)

Hence equation 2 and 5 represent the velocity of a simple harmonic motion

Putting x = 0 into equations 2 and 5 will each give

v = ωA ..... (6)

This is the maximum velocity of SHM v_{max} which occurs **at the equilibrium position**.

Hence $\mathbf{v_{max} = \omega A}$

The minimum velocity of SHM occurs at the amplitude where x = ±A

Acceleration of Simple Harmonic Motion - Derivation

Acceleration a = dv/dt

But from eqn 2, v = ωAcos(ωt + ϕ)

This implies that, $a = \frac{d[\omega A cos(\omega t + \phi)]}{dt}$

$\boldsymbol{a = -\omega^2 A sin(\omega t + \phi)}$ ..... (7)

Hence the acceleration of SHM "a" is given as shown in the eqn (7) above

When $sin(\omega t + \phi) = \pm 1$

$a = \omega^2 A$

Thus $\boldsymbol{a_{max} = \omega^2 A}$

This is the maximum acceleration of SHM and this **occurs at the amplitude**, thus when x = ±A

The minimum acceleration occurs at the mean position where x = 0

Systems or bodies that can be caused to perform simple harmonic motion

1. A loaded spiral spring
2. A loaded test tube floating in a liquid
3. A cantilever
4. The balance wheel of a clock or watch
5. Simple pendulum
6. Tuning fork

The Simple Pendulum – Deriving an Expression For The Time Period of Oscillations

A simple pendulum consists of a point mass (bob) suspended from a fixed support by a light, inextensible string. When displaced from its equilibrium position (vertical) and released, gravity provides a restoring force that acts to bring the bob back. For small angular displacements (typically less than about 10-15 degrees), the restoring force component (-mg sinθ) is approximately proportional to the angular displacement θ (since sinθ ≈ θ for small angles).

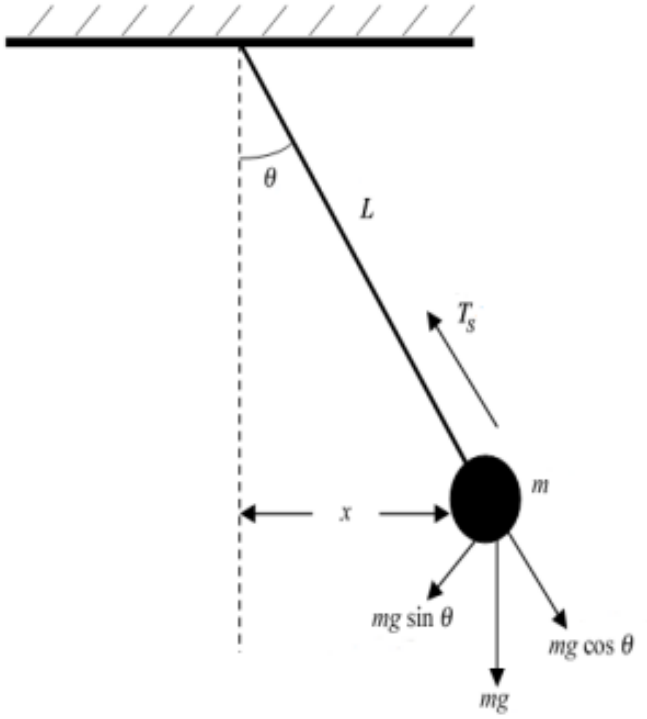


Figure 9.3: *Simple pendulum performing SHM*

From the diagram above the restoring force **F** = - mgsinθ and the displacement **x**

Which is given as $F = - m\ g\ \theta$

But $\theta = \frac{x}{l}$

substituting $\theta = \frac{x}{l}$ into $F = - m\ g\ \theta$ gives

$F = - m\ g\ \frac{x}{l}$

Also, $F = ma$

Hence $ma = - m\ g\ \frac{x}{l}$

This implies that, $a = - g\ \frac{x}{l}$

But the acceleration of SHM is given as $a = -\omega^2 x$

Hence $-\omega^2 x = - g\ \frac{x}{l}$

Thus $\omega^2 =$ [[OMML-EQ-45]]

$\omega = \sqrt{\frac{g}{l}}$ …….. (8)

But $\omega = \frac{2\pi}{T}$

$\frac{2\pi}{T} = \sqrt{\frac{g}{l}}$

Hence $\boldsymbol{T = 2\pi\sqrt{\frac{l}{g}}}$ ……(9)

The Helical Spring – Deriving An Expression For The Time Period Of Oscillations

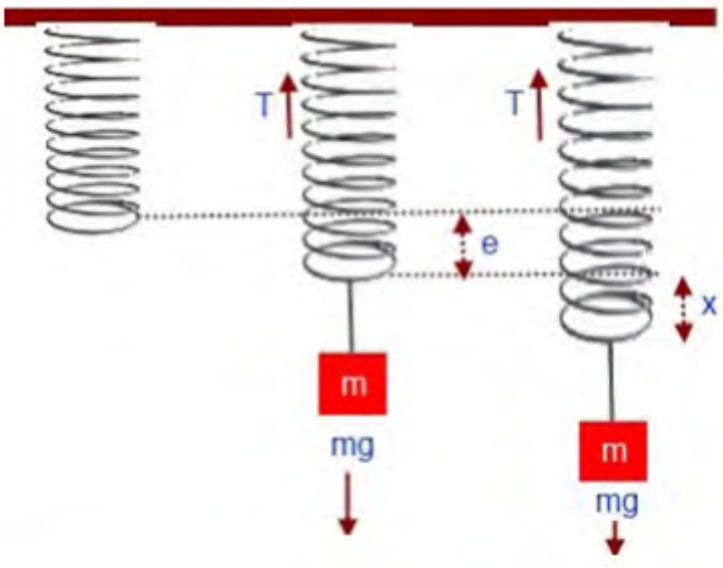


Figure 9.4: *A mass on helical spring performing SHM*

Consider a mass m suspended at rest from a helical spring and let the extension produced be "e" as shown in ***Figure 9.4.*** If the spring constant is k we have:
mg = ke

The mass is then pulled down a small distance x and released. The mass will oscillate due to both the effect of the gravitational attraction (mg) and the varying force in the spring [k (e + x)].

At any point distance x from the midpoint
Restoring force = -[k (e + x) – mg]

But F = ma
Hence ma = $-ke - kx + mg$
But mg = ke
ma = $-ke - kx$+ ke
ma = $-kx$
$a = -\frac{k}{m}x$

Putting a = $-\omega^2 x$ into the equation gives

$\omega^2 = k/m$

$\omega = \sqrt{\frac{k}{m}}$

But $\omega = \frac{2\pi}{T}$

$\frac{2\pi}{T} = \sqrt{\frac{k}{m}}$

$\boldsymbol{T = 2\pi\sqrt{\frac{m}{k}}}$ ..... (10)

From mg = ke

$\frac{m}{k} = \frac{e}{g}$

$\boldsymbol{T = 2\pi\sqrt{\frac{e}{g}}}$ .....(11)

Activity 9.1 Examples of Simple Harmonic Motion (SHM) in Daily Life

Objective: To identify and understand examples of simple harmonic motion (SHM) in daily life by observing real systems, recognising the role of restoring forces, and summarising the common features that define SHM in order to build a clear and practical definition of the concept.

What you need

1. Access to the video: 5 Simple Harmonic Motion Examples In Physics & Daily Life

2. Paper or notebook and pen or pencil

What to do

1. Open the video and watch carefully as it presents five real-life examples of simple harmonic motion.
2. For each example shown, pay attention to how the object moves back and forth around a stable central (equilibrium) position. Notice the smooth, repetitive oscillations and how a restoring force (gravity, tension, elasticity) acts to bring the object back toward equilibrium.
3. In your notebook, write down for each example
   - **a.** The type of object or system
   - **b.** The kind of motion observed
   - **c.** What acts as the restoring force; why is it being pulled back to where it came from?
   - **d.** Whether the motion looks smooth and repeating regularly
4. Based on the video and your notes, list the common characteristics that make these motions examples of simple harmonic motion
5. Using your observations, write your own definition of simple harmonic motion, including its key features. Ensure that you comment on direction and magnitude of the restoring force at different points in the cycle of oscillations.

Activity 9.2 Identifying Examples of Periodic Motion Which are SHM

Objective: To distinguish simple harmonic motion (SHM) from other types of periodic motion by observing different examples, analysing their characteristics, and identifying the key features—such as restoring force, sinusoidal displacement, and linear motion—that define SHM.

What you need

1. Paper or notebook
2. Pen or pencil
3. Access to internet
4. Ruler or protractor (optional for sketching or measurement)

What to do

1. Review a set of given examples showing different types of periodic motion. Examples you might see include:
   - **a.** A mass attached to a spring oscillating back and forth
   - **b.** A simple pendulum swinging at small angles
   - **c.** The vibration of a tuning fork's tines
   - **d.** A bouncing ball moving up and down repeatedly
   - **e.** Riders on a carousel going around in circles
   - **f.** A pendulum swinging with large angles
2. For each example, search online and watch the motion or view pictures/videos, then sketch a graph of displacement versus time showing the motion's pattern (have you best guess at this! Look for sudden changes in direction or velocity and make sure that you make these clear on your graph if they are present).
3. Use these criteria to decide if the motion is SHM:
   - **a.** *Restoring force is directly proportional to the displacement from equilibrium and acts toward the equilibrium position* (linear restoring force following Hooke›s law).
   - **b.** *Displacement as a function of time follows a sinusoidal pattern (like a sine or cosine wave).*
   - **c.** *Motion is along a straight line and smooth, continuous, without sudden changes in direction or speed.*
   - **d.** *Amplitude remains constant over time (in ideal conditions without 'damping', which is a term meaning resistance causing a loss of amplitude).*
4. For each motion that you identify as SHM or not SHM, write a short explanation justifying your reasoning

5. Make two lists: one for motions that are SHM and one for motions that are periodic but not SHM.
6. Write a brief conclusion stating what key factors distinguish SHM from other periodic motions based on your investigation.

Activity 9.3 The Period of a Simple Pendulum for Different Lengths

Objective: To investigate how the period of a simple pendulum depends on its length, and to confirm the relationship $T \propto \sqrt{l}$ by measuring, recording, and analysing experimental data.

What you need

1. A small dense bob (metal ball or small weight) attached to a string
2. A sturdy support stand or place to hang the pendulum so it can swing freely
3. A stopwatch or timer (smartphone timer is fine)
4. A ruler or measuring tape (to measure length of the pendulum)
5. Paper or notebook
6. Pen or pencil
7. Graph paper

Or, in the absence of the appropriate practical material, you could perform this experiment using the PHeT simulation

Pendulum Lab

What to do

1. Attach the bob securely to one end of the string. Tie or fix the other end of the string to a support so the bob can swing freely like a pendulum. Measure the length l of the pendulum from the point of suspension to the centre of the bob. Record this length in your notebook.

2. Perform the Timing for Oscillations
   a. Pull the bob gently to a small angle (less than 15°) and release it to start swinging.
   b. Use the stopwatch to measure the time Ttotal it takes to complete a fixed number of oscillations, for example, 10 full swings (back and forth counts as 1 oscillation).

Note

To improve accuracy, timing multiple oscillations reduces reaction time error.

3. Calculate the period T (time for one oscillation) by dividing the total time by the number of oscillations. Record the period value for that length *l*.
4. Repeat for Different Lengths - e.g., try 20 cm, 40 cm, 60 cm, 80 cm, 100 cm).
   a. For each new length, repeat steps 2 and 3 to measure and calculate the period.
   b. Record all values of length and corresponding period in a table.
5. On graph paper or your notebook, plot a graph of the period T (vertical axis) against the square root of the length l (horizontal axis).
   a. Calculate the square root of each length value before plotting.
   b. Label the axes clearly with units (e.g., T in seconds and l in metres1/2).
6. Analyse the Graph: Observe that the graph should be a straight line, showing a linear relationship between the period T and the square root of the length l.
7. Summarise your findings by describing how the period changed with length

Activity 9.4 Investigating Oscillations of a Mass on a Spring

Objective: To investigate the oscillations of a mass on a spring in order to understand how displacement, velocity, and acceleration vary during simple harmonic motion.

What you need

1. Spring

2. Set of masses (known weights)
3. Stand and clamp to suspend the spring vertically
4. Stopwatch or timer
5. Meter ruler or measuring tape
6. Calculator
7. Paper and pencil for recording data and calculations

What to do

1. Set Up the Apparatus
   - **a.** Attach the spring securely to the stand and clamp so it hangs vertically.
   - **b.** Suspend a known mass from the spring's lower end, allowing it to hang freely.
2. Measure Displacement
   - **a.** Pull the mass down gently to stretch the spring.
   - **b.** Measure the maximum displacement (amplitude) from the rest position using the ruler.
   - **c.** Record this value as the amplitude A.
3. Measure Oscillation Time
   - **a.** Release the mass to start oscillations.
   - **b.** Use the stopwatch to time how long it takes the mass to complete 10 full oscillations.
   - **c.** Repeat this timing two or three times for accuracy and record the results.
   - **d.** Take a moment to consider the accuracy of this experiment; is measuring the time challenging? Why? What effect may this have on your results?
4. Calculate Period T and Angular Frequency ω
   - **a.** Calculate the period T (time for one oscillation) by dividing the total time for 10 oscillations by 10.
   - **b.** Calculate the angular frequency using the formula:

     $\omega = 2\frac{\pi}{T}$

5. Calculate the Spring Constant k

- **a.** Measure the mass m suspended on the spring in kilograms.
- **b.** Using the relationship between the period T, mass m, and spring constant k, calculate the spring constant

$$k = \frac{4\pi^2 m}{T^2}$$

6. Calculate Velocity and Acceleration at Various Points

- **a.** Pick several points during the oscillation (e.g., at certain displacements x from the rest position).
- **b.** Use the displacement and angular frequency to calculate velocity v at each point using:

$$v = \omega\sqrt{A^2 - x^2}$$

- **c.** Calculate acceleration a at each point using:

$$a = -\omega^2 x$$

- **d.** Record the values of x, v, and a in a table.

7. Analyse and Reflect

- **a.** Compare how velocity changes with displacement — it's highest at the equilibrium point and zero at the maximum displacement.
- **b.** Note acceleration is zero at equilibrium and highest (in magnitude) at maximum displacement, and it's directed opposite to the displacement.
- **c.** Sketch graphs of how the displacement, velocity and acceleration are changing with time.
- **d.** Write a few sentences describing what these results show about oscillatory motion.

Activity 9.5 Calculating Motion Parameters in SHM and Pendulums

Study the worked examples carefully before attempting the sample questions that follow.

Worked Example 1

Determine the acceleration due to gravity in a region where a simple pendulum having a length 75.0 cm has a period of 1.7357s

Solution

The length l of a simple pendulum = 0.75m

The period T = 1.7357s

From $T = 2\pi\sqrt{\frac{l}{g}}$

$1.7357 = 2\pi\sqrt{\frac{0.75}{g}}$

$1.7357/2\pi = \sqrt{\frac{0.75}{g}}$

$0.2762^2 = \frac{0.75}{g}$

$g = 0.75/0.076311$

$g = 9.8\ \text{m/s}^2$

Worked Example 2

A particle is executing SHM with an amplitude of A and an angular frequency of ω. At a certain time t, its displacement is x = A/2. Find the magnitude of its velocity and acceleration at this instant, in terms of ω and a.

Solution

We use the general formula for velocity in SHM: $v = \pm\omega\sqrt{A^2 - x^2}$

Substitute the given values: x=A/2.

$v = \pm\omega\sqrt{A^2 - \left(\frac{A}{2}\right)^2}$

$v = +\omega\sqrt{A^2 - \frac{A^2}{2^2}}$

$v = \pm\omega\sqrt{A^2 - \frac{A^2}{4}}$

$v = \pm\omega\sqrt{\frac{3A^2}{4}}$

$v = \pm\frac{\sqrt{3}}{2}\omega A$

The magnitude of the velocity is $\frac{\sqrt{3}}{2}\omega A$

The formula for acceleration in SHM is $a = -\omega^2 x$

Substitute the given value for displacement: x=A/2.

$a = -\omega^2\frac{A}{2}$

$a = -\frac{1}{2}\omega^2 A$

The magnitude of the acceleration is $\frac{1}{2}\omega^2 A$

Practice Problems

1. A load hanged from a vertical spring causes the spring to stretch by 30cm and oscillates when slightly displaced and released, calculate the period of oscillation (g = 10m/s2).

ENERGY TRANSFORMATION IN SIMPLE HARMONIC MOTION

The total mechanical energy in a simple harmonic motion remains constant (if there is no damping). This energy is continuously converted between potential energy and kinetic energy.

Kinetic Energy (KE)

Kinetic energy is the energy possessed by a body due to its motion.

$KE = \frac{1}{2}m v^2$

Substitute $v = A\omega\cos(\omega t + \phi)$ into the kinetic energy equation

$KE = \frac{1}{2}m\left[A\omega\cos(\omega t + \phi)\right]^2$

$KE = \frac{1}{2}m\omega^2 A^2 cos^2(\omega t + \phi)$

From trigonometry, $\sin^2(\omega t + \phi) + \cos^2(\omega t + \phi) = 1$

Also, x = Asin$(\omega t + \phi)$

Therefore $KE = \frac{1}{2}m\omega^2\left(A^2 - x^2\right)$

Maximum Kinetic Energy (KE_{max})

Occurs when velocity is maximum, i.e., at the equilibrium position (x = 0).

$KE_{max} = \frac{1}{2}m\omega^2 A^2$

Minimum Kinetic Energy

Kinetic energy is zero at the extreme positions (x = ±A), where the velocity is momentarily zero.

Potential Energy (PE)

Potential energy in SHM is the energy stored due to the displacement from the equilibrium position (e.g., elastic potential energy in a spring).

$PE = \frac{1}{2}kx^2$ (for a spring-mass system)

The restoring force on the object can be found using Hooke's Law: $F = ma = -kx$

But $a = \omega^2 x$,

so:

$m\omega^2 x = kx$

$k = m\omega^2$Substituting into the PE equation above:

$PE = \frac{m\omega^2 x^2}{2}$

$PE = \frac{m\omega^2 x^2}{2}$

$PE = \frac{m\omega^2 (A\sin(\omega t + \phi))^2}{2}$Therefore,

$PE = \frac{m\omega^2 A^2}{2} sin^2(\omega t + \phi)$

Total Mechanical Energy (E)

The total mechanical energy in an ideal (undamped) SHM system is conserved and is the sum of kinetic and potential energy.

$E = KE + PE$

$E = \frac{1}{2}m\omega^2\left(A^2 - x^2\right) + \frac{m\omega^2 x^2}{2}$

$E = \frac{1}{2}m\omega^2 A^2$

The Energy Transformation Cycle

The energy in an SHM system constantly cycles back and forth between these two forms:

1. At Maximum Displacement (x=±A): The object is momentarily at rest, so its velocity is zero. At this point, all the energy is stored as potential energy and the kinetic energy is zero (K.E=0).

2. Moving Towards Equilibrium (x=0): As the restoring force pulls the object back toward the equilibrium position, its speed increases. The potential energy is converted into kinetic energy.
3. At Equilibrium Position (x=0): The object is moving at its maximum speed ($v=v_{max}$). All the energy is now kinetic energy and the potential energy is zero (P.E=0).
4. Moving Away from Equilibrium ($x=\pm A$): The object moves past the equilibrium position, and the restoring force now acts against its motion, causing it to slow down.

The kinetic energy is converted back into potential energy.

At $x = 0$, $PE = 0$ and the energy is purely kinetic i.e.,

$$E = KE_{max} = \frac{1}{2} m \omega^2 A^2$$

At extreme points or turning points of the SHM, kinetic energy is zero and the energy is purely potential i.e.,

$$E = PE_{max} = \frac{1}{2} m \omega^2 A^2$$

Thus, the total energy remains constant for the system no matter where the particle is.

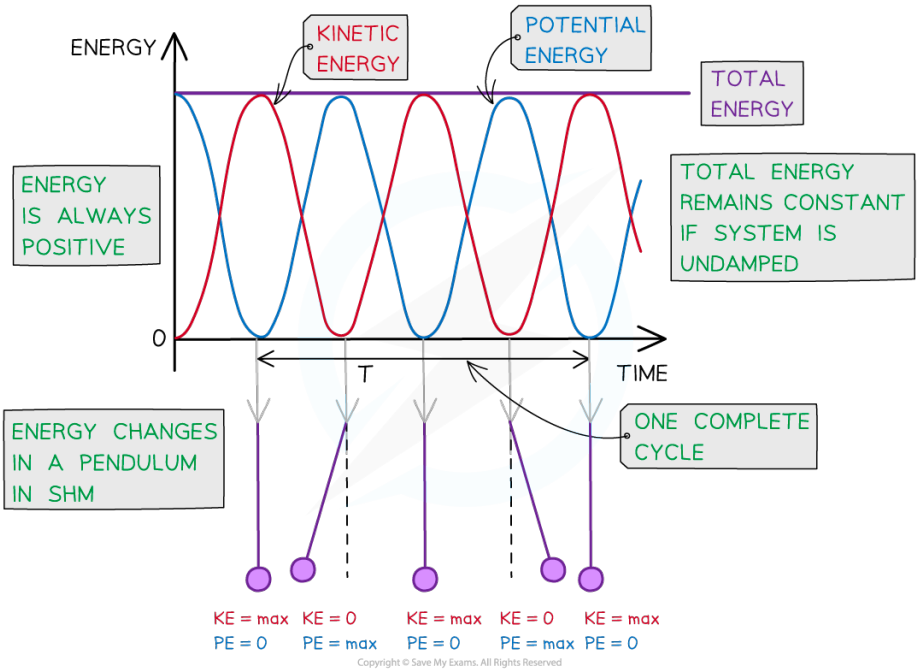


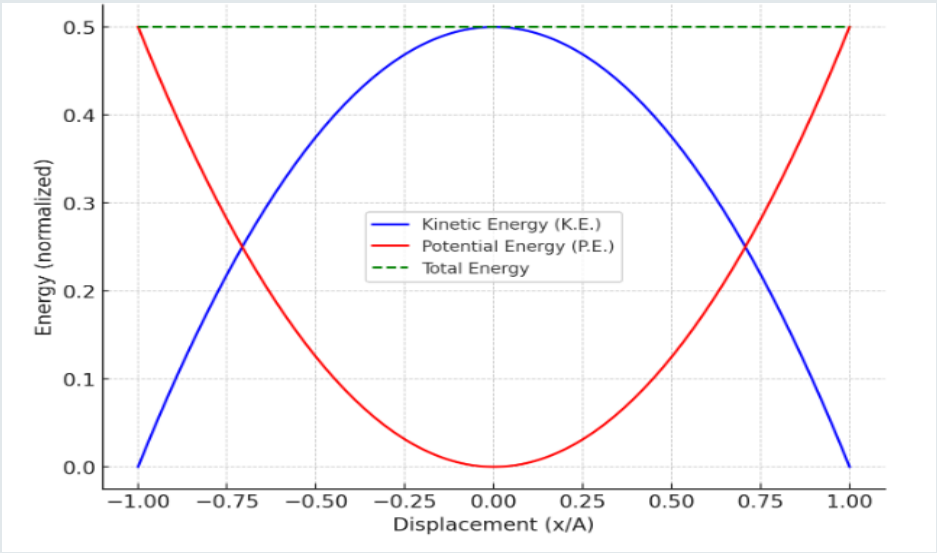
Figure 9.5: *Energy transformation in SHM*

Activity 9.6 Exploring Energy Variation in Simple Harmonic Motion Using Conceptual Energy vs. Displacement Graphs

Objective: To understand how energy changes during simple harmonic motion (SHM) by using energy–displacement graphs to show the transformation between kinetic and potential energy, and to recognise that the total mechanical energy remains constant, demonstrating conservation of energy.

What you need

1. Paper or notebook
2. Pen or pencil
3. Access to internet to see simulation: oPhysics
4. Printed or digital copy of the energy graph diagram (see below)



What to do

1. Open the Simulation and Select ‘Run’. Look at the graphs being generated on the right, which show the position, velocity, acceleration, potential and kinetic energies of the mass on a spring. Take time to look at how these are related; which graphs show maxima at the same time? Why? Which graphs are completely out of phase? Why?
2. Examine the graph that illustrates how kinetic energy, potential energy, and total energy change as the oscillator moves between its extreme positions (-A to +A).

3. Write down answers addressing
   - **a.** How does kinetic energy change as the displacement moves from -A to +A?
   - **b.** How does potential energy vary with displacement in that range?
   - **c.** What does the total energy curve indicate about the overall energy of the system?
4. Consider and note
   - **a.** At the equilibrium position (displacement 0), what do you observe about kinetic and potential energies?
   - **b.** At maximum displacement points (-A and +A), what happens to each form of energy?
   - **c.** Are there points where kinetic energy and potential energy are equal? How many such points are visible?
5. Using the graph shapes, describe in your own words how energy transforms between kinetic and potential forms during oscillation.
6. Reflect on why the total mechanical energy remains constant regardless of displacement and what this implies about energy conservation in the ideal system.
7. Reinforce your learning by drawing a simplified version of the graph, labelling key points such as maximum displacement, equilibrium, and energy equality points.

Activity 9.7 Calculating Total Energy, Potential Energy, and Kinetic Energy

Objective: To calculate and analyse the distribution of total, potential, and kinetic energy during oscillations of a mass on a spring, and to verify the conservation of mechanical energy in simple harmonic motion.

What you need

1. Access to your notes from Activity 9.4.
2. Calculator
3. Paper and pencil for calculations and notes

What to do

1. Review Activity 9.4

- **a.** Write down the mass m (in kilograms) of the object and the spring constant k (in Newtons per metre).
- **b.** Look at your table from Activity 9.4 which contains values of displacement (x) and velocity (v) recorded during oscillation.

2. Calculate Total Energy E

- **a.** Recall that total mechanical energy E in a simple harmonic oscillator is constant and is the sum of potential energy and kinetic energy.
- **b.** Calculate total energy using the maximum displacement A (amplitude) with this formula:

  $E = \frac{1}{2}k\,A^2$
- **c.** Use the known spring constant k and amplitude A from your data.

3. For each displacement x in your table, calculate the potential energy stored in the spring using:

$PE = \frac{1}{2}kx^2$

Write the results in a new column next to your table.

4. Using corresponding velocity v values, calculate kinetic energy at each point with:

$KE = \frac{1}{2}m\,v^2$

Add these values in another column next to P.E.

5. Verify Energy Conservation

- **a.** For each row, add the calculated P.E. and K.E. values. This sum should be close to the total energy E you calculated earlier.
- **b.** Note any small differences and consider reasons (such as experimental error or rounding).

6. Analyse the Energy Changes

- **a.** Observe how potential energy is maximum at maximum displacement and zero at equilibrium.
- **b.** Notice kinetic energy is zero at maximum displacement and maximum at equilibrium.
- **c.** Write a short paragraph explaining these energy changes during oscillations.

Activity 9.8 Calculating Energy in Simple Harmonic Motion

Study the worked examples carefully before attempting the sample questions that follow.

Worked Example 1

A 2 kg mass is attached to a spring with a spring constant of 50 N/m. The system oscillates with an amplitude of 0.3 m. Calculate the total energy of the system and the kinetic energy of the mass when its displacement is 0.1 m.

Solution

The total energy (E_{total}) in SHM is constant and can be calculated using the maximum potential energy, which occurs at the maximum displacement (the amplitude, A).

The formula for total energy is: $E_{total} = \frac{1}{2}kA^2$

Substitute the given values k = 50 N/m, A = 0.3 m

$E_{total} = \frac{1}{2}(50)(0.3)^2$

$E_{total} = 25(0.09)$

$E_{total} = 2.25J$

The total energy of the system is **2.25J**.

To find the kinetic energy (K. E) at a displacement of x=0.1 m, we can use the conservation of energy principle. The total energy is the sum of the kinetic energy and potential energy (P.E).

$E_{total} = K.E + P.E$

$K.E = E_{total} - P.E$

but $P.E = \frac{1}{2}kx^2$

$P.E = \frac{1}{2}(50)(0.1)^2$

$P.E = 0.25J$

$K.E = 2.25 - 0.25 = 2.0\ J$

The kinetic energy of the mass at a displacement of 0.1 m is **2.0 J**.

Practice Problems

1. A block of mass m=0.5 kg is attached to a spring and executes simple harmonic motion (SHM). Its velocity is v=0.2 m/s when its displacement is x=0.1 m. The maximum displacement (amplitude) of the block is A=0.2 m. Calculate the spring constant (k).
2. The bob of a simple pendulum of mass 0.6kg, performs a simple harmonic motion with amplitude 7.0cm and period 2.0s. If the motion of the bob is undamped, calculate the maximum kinetic energy of the bob.

Activity 9.9 Energy Transformations in SHM and Real-Life Systems

Objective: To compare energy transformations between potential and kinetic energy in real-life oscillating systems and relate them to the mass-spring simple harmonic motion (SHM) model, thereby understanding similarities and differences in energy behaviour across systems.

What you need

1. Paper and pencils or pens
2. Reference materials or internet access (for researching examples if needed)
3. Coloured markers for diagrams (optional)
4. Presentation materials (poster paper, whiteboard, or digital presentation tools)

What to do

1. Join with some classmates to work as a team; no more than 5 people in total.
2. Each group picks one of the following oscillating systems:
   - **a.** Child on a swing
   - **b.** Simple pendulum (a mass on a string)
   - **c.** Car suspension system
3. Research and Discuss Energy Transformation
   - **a.** Discuss how energy changes between potential energy (P.E.) and kinetic energy (K.E.) during the oscillation in your chosen system.
   - **b.** Identify when the potential energy is at its maximum (e.g., highest point or maximum displacement) and when the kinetic energy is at its maximum (e.g., lowest or equilibrium point).

c. Make connections to the mass-spring system you studied previously where:

i. P.E. is maximum at maximum displacement (amplitude)

ii. K.E. is maximum at the equilibrium position (midpoint)

4. Create simple diagrams showing the position of the system at maximum P.E. and maximum K.E. Label the points where energy transforms occur during the oscillation cycle.

5. Summarise your group's discussion into a short presentation or poster with diagrams and key points. Explain how the energy transformation in your real-life example is similar to that of a mass-spring SHM system.

6. Share your findings and diagrams with the other groups or the whole class. Listen to and learn how energy transformations occur in the other systems being presented.

MOMENTUM, IMPULSE AND COLLISIONS

In previous lessons, you have seen that moving objects have motion described by speed and velocity. But in order to analyse the behaviour of a moving object, it is often not only the speed that matters—how heavy the object is also makes a difference. For example, it is much easier to stop a rolling football than to stop a moving wheelbarrow. This idea combines both the **mass** of the object and its **velocity**, and together they form a quantity called **momentum**. Momentum therefore helps to explain why heavier or faster objects are harder to stop.



Figure 9.6: *Kicking a football at rest*

Think about kicking a football. When the ball is at rest, it has no momentum. The instant it is kicked, the force from the foot is applied for a short time, making the ball gain speed. This effect of a force acting over time is called **impulse**. The

harder and longer the foot pushes on the ball, the greater the impulse, and the faster the ball moves away. Impulse is the change in momentum of the object.

Linear Momentum

The momentum of a body is the product of mass and velocity which is the measure of the body's motion. It is a vector quantity has the unit of kilogram-metres per second (kgm/s).

Momentum = mass × velocity

$\rho = mv$For an object speeding up or slowing down

Final momentum = mass × final velocity (mv)

Initial momentum = mass × initial velocity (mu)

Change in momentum = final momentum – initial momentum (mv – mu)

Newton's second law of motion (Revision from Year 1)

Newton's second law of motion states that the time rate of change of momentum is directly proportional to the force applied and it takes place in the direction of the force.

Mathematically,

$$F \propto \frac{mv - mu}{t}$$

$$F = k\frac{mv - mu}{t}$$

But k = 1

$$F = \frac{mv - mu}{t}$$

Impulse

Impulse is the effect of a force acting on an object for a period of time. Impulse can be calculated as the product of a force acting on a body and the time during which it acts.

Mathematically,

$$I = Ft$$

From Newton's second law

$$F = \frac{mv - mu}{t}$$

Therefore,

$I = Ft = mv - mu$This is the Impulse-Momentum theorem which states that the impulse acting on an object is equal to the change in its momentum.

Examples of Impulse in Everyday Life

1. Catching a Ball

   A cricketer moving their hands back while catching a ball increases the time of impact. This reduces the force on their hands, making it easier and safer to catch the ball.

2. Airbags in Cars

   Airbags deploy during a collision to increase the time it takes for a passenger to come to a stop. This reduces the force of impact on the passenger, minimising injuries.

3. Jumping onto a Soft Surface

   When someone jumps from a height onto a soft surface like sand, their body sinks into the sand, increasing the time it takes to stop. This reduces the force of impact on their legs and feet, preventing injury.

4. Bending your Knees When Landing

   Similarly, bending your knees when landing from a jump increases the time it takes to stop, reducing the impact force on your legs.

5. Hitting a Baseball or Golf Ball

   A good swing in baseball or golf involves a follow-through, which increases the time the bat or club is in contact with the ball. This imparts a larger impulse, resulting in a faster and farther-travelling ball.

6. Car Crashes

   In a car crash, the forces involved act over a short period, causing a rapid change in momentum. Features like airbags and seatbelts are designed to mitigate the effects of these impulsive forces.

7. Martial Arts

   Martial artists use the concept of impulse to generate powerful strikes. The rapid, forceful movement of their limbs creates a large impulse, transferring a lot of momentum to their target.

Conservation of Momentum

The law of **conservation of momentum** states that for an isolated system (one not acted upon by external forces), the total momentum of the system remains constant. That is the total momentum before collision equals the total momentum after collision. This means that momentum is not created or destroyed but rather transferred between objects within the system.

Isolated (or 'Closed') System

A system where the net external force is zero. While internal forces (forces between objects within the system) can change the momentum of individual objects, they do not change the total momentum of the entire system (i.e. the momentum lost by one object would be gained by the other(s)).

For a system of two interacting objects (e.g., m_1 and m_2):

Total initial momentum = total final momentum

$$p_{initial} = p_{final}$$

$$m_1 u_1 + m_2 u_2 = m_1 v_1 + m_2 v_2$$

Real Life Examples of Conservation of Momentum

1. **Billiards/Pool**

   When a cue ball strikes another ball, the total momentum of the system (both balls) before and after the collision remains the same. The momentum lost by the cue ball is gained by the other ball(s).

2. **Car Accidents**

   In a car collision, the total momentum of the vehicles before the crash is equal to the total momentum after the crash, provided no external forces like braking or skidding are dominant. Accident reconstruction experts use this principle to analyse accidents and determine speeds.

3. **Firing a Gun**

   When a gun is fired, the forward momentum of the bullet is balanced by the backward momentum (recoil) of the gun. The total momentum of the system (gun and bullet) remains zero, as it was before firing.

4. **Rockets**

   Rockets are propelled forward by expelling hot gases backward. The momentum gained by the rocket is equal and opposite to the momentum of the expelled gases, demonstrating conservation of momentum.

5. **Jumping from a Boat**

   Pushing off a dock to get onto a boat causes the boat to move backward in the opposite direction, illustrating the transfer of momentum.

6. **Ice Skaters**

   When ice skaters push off each other, they move in opposite directions with equal and opposite momenta.

7. **Jellyfish and Squid Propulsion**

   Jellyfish and squid use a similar method to propel themselves through water. They expel water from their bodies, gaining momentum in the opposite direction.

Verification of Newton's Third Law from Momentum Change

Newton's third law of motion (Review from Year 1)

Newton's third law of motion states that to every action there is an equal and opposite reaction.

Action* = − *Reaction

Consider two bodies 1 and 2 of masses m_1 and m_2 acting mutually on each other. Let their initial velocities be u_1 and u_2 respectively and let their final velocities be v_1 and v_2 respectively.

From the Impulse-Momentum theorem

For body 1: $I_1 = F_1 t = m_1 v_1 - m_1 u_1$

For body 2: $I_2 = F_2 t = m_2 v_2 - m_2 u_2$

From the principle of conservation of momentum

$$m_1 u_1 + m_2 u_2 = m_1 v_1 + m_2 v_2$$

$$m_1 u_1 - m_1 v_1 = m_2 v_2 - m_2 u_2$$

$$-\left(m_1 v_1 - m_1 u_1\right) = m_2 v_2 - m_2 u_2$$

$$-I_1 = I_2 - F_1 t = F_2 t$$

$$-F_1 = F_2$$

This derivation shows that if momentum is conserved in an isolated system, then the forces between interacting objects must be equal in magnitude and opposite in

direction, which is precisely Newton's Third Law. It underscores the fundamental nature of momentum conservation as a consequence of how forces interact.

Collision

In physics, a collision is any event where two or more objects exert forces on each other for a short period. These interactions can involve direct contact, like a ball hitting a bat, or influence at a distance, such as two charged particles repelling each other. Momentum is always conserved in a collision, meaning the total momentum of the system remains constant. Kinetic energy, however, may or may not be conserved, leading to different types of collisions.

Types of collision

Elastic Collision

An elastic collision is a collision in which both **momentum** and **kinetic energy** are conserved. This means the total kinetic energy of the system *before* the collision is equal to the total kinetic energy *after* the collision.

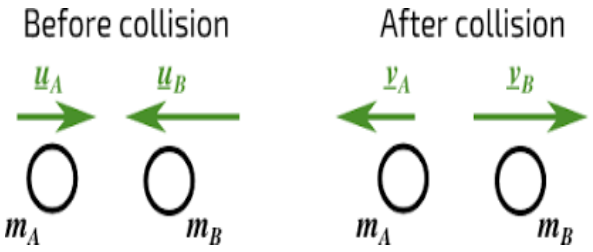


Figure 9.7:*A diagram showing elastic collision*

Characteristics

1. Total momentum is conserved.
2. Total kinetic energy is conserved.
3. No deformation of objects or generation of heat/sound due to the collision itself (in an ideal elastic collision).
4. Objects usually rebound off each other without sticking.

Mathematical conditions

Conservation of momentum

$$m_1 u_1 + m_2 u_2 = m_1 v_1 + m_2 v_2$$

Conservation of kinetic energy

$$\frac{1}{2} m_1 u_1^2 + \frac{1}{2} m_2 u_2^2 = \frac{1}{2} m_1 v_2^2 + \frac{1}{2} m_1 v_2^2$$

Examples

1. Collisions between billiard balls (approximated as elastic, as very little energy is lost).
2. Collisions between subatomic particles (often perfectly elastic).

Inelastic Collision

An inelastic collision is a collision in which **momentum is conserved**, but **kinetic energy is NOT conserved**. Some of the initial kinetic energy is converted into other forms of energy, such as heat, sound, or deformation (e.g., crumpling, breaking).

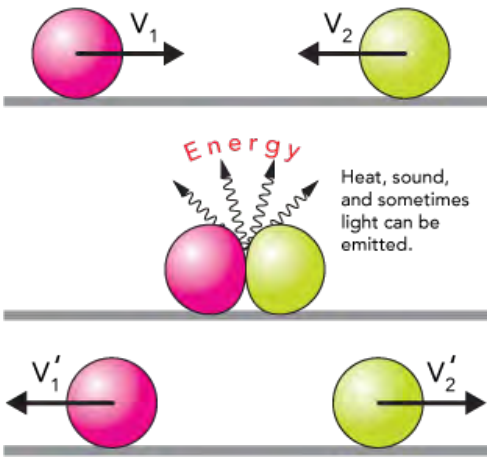


Figure 9.8: *A diagram showing inelastic collision*

Characteristics

1. Total momentum is conserved.
2. Total kinetic energy is NOT conserved (it decreases).
3. Energy is transformed into other forms (heat, sound, deformation).
4. Objects may deform, or stick together, after the collision.

Mathematical Conditions

Conservation of momentum

$$m_1 u_1 + m_2 u_2 = m_1 v_1 + m_2 v_2$$

Examples of Inelastic Collisions (General)

1. Car crashes
2. A clay ball hitting a wall and sticking to it.
3. A dropped ball not bouncing back to its original height (some energy lost to heat and sound on impact).

Perfectly Inelastic Collision

This is a special and extreme case of an inelastic collision where the colliding objects stick together and move as a single combined mass after the collision. This particular type of inelastic collision results in the maximum possible loss of kinetic energy (consistent with momentum conservation).

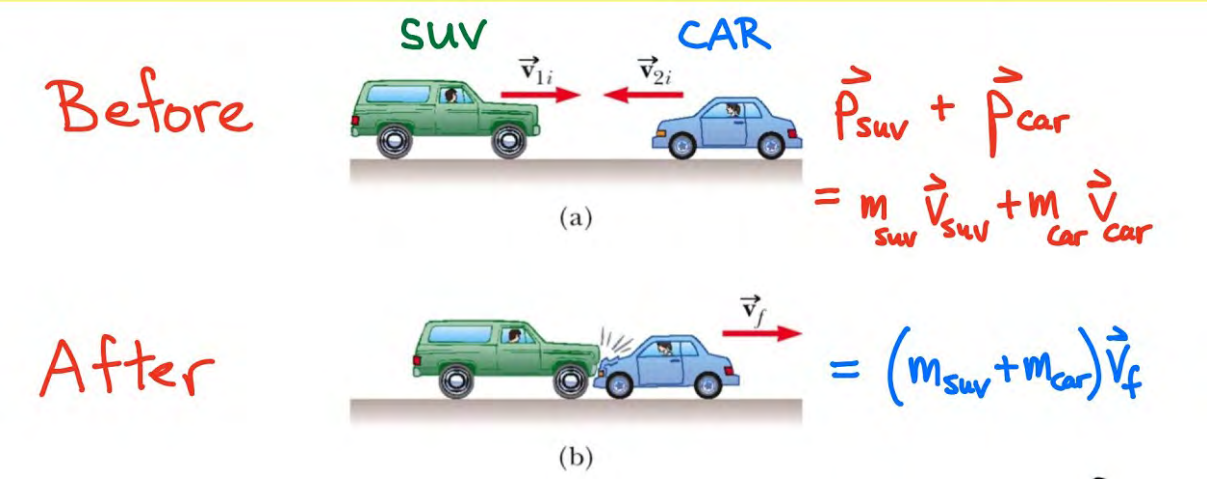


Figure 9.9: *A diagram showing a perfectly inelastic collision*

Example

A bullet embedding itself in a wooden block (ballistic pendulum), two cars colliding and sticking together, a supermarket trolley colliding with another from behind and then moving off together. In this specific case, the objects share a common final velocity.

$$m_1 u_1 + m_2 u_2 = (m_1 + m_2)v$$

Activity 9.10 Verifying Newton's Third Law

Objective: To verify Newton's third law of motion by analysing momentum changes in a two-body elastic collision and demonstrating that the forces exerted by the bodies on each other are equal in magnitude and opposite in direction.

What you need

1. Calculator
2. Paper and pencil for calculations and notes

3. Data below

Mass (kg)	Initial Velocity u (m/s)	Final Velocity v (m/s)
m1 = 0.20	u1 = 6.0	v1 = 0.0
m2 = 0.20	u2 = 0.0	v2 = 6.0

What to do

1. Record the masses m1 and m2, initial velocities $u1$ and $u2$, and final velocities v1 and v2.
2. Compute the initial momentum of each body: $p_{1i} = m_1 u_1$ and $p_{2i} = m_2 u_2$

   Compute the final momentum of each body: $p_{1f} = m_1 v_1$ and $p_{2i} = m_2 v_2$
3. Calculate Momentum Change for Each Body

   $\Delta p_1 = p_{1f} - p_{1i}$

   $\Delta p_2 = p_{2f} - p_{2i}$
4. Compare Momentum Changes
   - **a.** Check if the magnitude of the momentum changes satisfy: |Δp1|=|Δp2|
   - **b.** Verify that the directions of momentum change are opposite (i.e., one gains momentum while the other loses an equal amount).
5. Discuss Newton's Third Law
   - **a.** Explain how this equality and opposition of momentum changes illustrate Newton's third law — for every action there is an equal and opposite reaction.
   - **b.** Discuss how the force during collision on body 1 by body 2 is equal in magnitude and opposite in direction to that on body 2 by body 1.

Activity 9.11 Exploring Elastic and Inelastic Collisions

Objective: To understand the difference between elastic and inelastic collisions by using the PhET Collision Lab simulation to compare how momentum and kinetic energy behave in each case.

What you need

1. Access to the PhET Collision Lab simulation

   https://phet.colorado.edu/en/simulation/collision-lab



2. Paper or notebook and pen or pencil

What to do

1. Go to the PhET Collision Lab link above and select "Explore 1D" to work with one-dimensional collisions.
2. Set Up for Elastic Collisions
   - **a.** Check the boxes for "momentum" and "values" on the right menu to display numerical data.
   - **b.** Set the elasticity slider to 100% (for perfectly elastic collisions).
   - **c.** Set the masses for the two carts (balls) using either the sliders or by typing numbers, and assign initial velocities (e.g., one moving toward the other which is stationary).
3. Run and Record Data for Elastic Collisions
   - **a.** Press "play" to run the collision simulation.
   - **b.** Pause the simulation immediately after the collision.
   - **c.** Record the masses, velocities, momentum, and kinetic energy of each ball before and after the collision in a data table you create in your notebook.
   - **d.** Calculate total momentum and total kinetic energy before and after collision.
   - **e.** Observe and note if momentum and kinetic energy are conserved.
4. Set Up for Inelastic Collisions
   - **a.** Reset the simulation.

b. Move the elasticity slider to 0% (for perfectly inelastic collisions).

c. Repeat the process: set masses and initial velocities, run the simulation, pause after collision, and record data.

5. Run and Record Data for Inelastic Collisions

a. Fill out the data table with masses, velocities, momentum, and kinetic energy before and after collision.

b. Calculate total momentum and total kinetic energy before and after collision.

c. Notice how momentum is conserved but kinetic energy is not, due to energy loss (e.g., heat, deformation).

6. Explore Intermediate Elasticities and Mass Combinations (Optional)

a. Test collisions at intermediate elasticity values (e.g., 50%) or with unequal masses to observe varying behaviour.

b. Record and analyse corresponding data.

7. Summarise Findings Using Tables and Diagrams. Create a comparison table listing:

a. Collision type (Elastic, Inelastic).

b. Whether momentum is conserved.

c. Whether kinetic energy is conserved.

d. Example observations or velocity changes.

Activity 9.12 Calculating Momentum, Impulse, and Velocities

Study the worked examples carefully before attempting the sample questions that follow.

Worked Example 1

Kudzo is going by a slippery snowy hill. He has a mass of 25kg, and he is sliding the hill at a velocity of 6m/s. Kudzo's elder brother has a mass of 40kg. His brother is moving slower with a velocity of 2m/s. Kudzo collides with his brother. Then both of them keep going down the hill as one unit. Calculate the resulting velocity of Kudzo and the impulse on his brother.

Solution

Mass of Kudzo $m_1 = 25kg$

Mass of Kudzo's brother $m_2 = 40kg$

Initial velocity of Kudzo $u_1 = 6m/s$

Initial velocity of Kudzo's brother $u_2 = 2m/s$

Their common final velocity v =?

Since the collision is perfectly inelastic, then $m_1 u_1 + m_2 u_2 = (m_1 + m_2)v$

$25 \times 6 + 40 \times 2 = (25 + 40)v$

$150 + 80 = 65v$

$230 = 65v$

$v = 3.538 m/s$

Hence the resulting velocity of Kudzo is 3.538m/s.

The impulse on the brother $I = m_2 v - m_2 u_2$

$I = 40 \times 3.538 - 40 \times 2$

$I = 141.52 - 80$

$I = 61.52\ kgm/s$

Worked Example 2

A block of mass m_1=2 kg moving with an initial velocity of u_1=+5 m/s collides elastically with a stationary block of mass m_2=3 kg. Find the final velocities of both blocks (note: there are two possible solutions to this question).

Solution

$m_1 = 2kg, u_1 = 5, m_2 = 3kg, u_2 = 0$

Conservation of Momentum

$m_1 u_1 + m_2 u_2 = m_1 v_1 + m_2 v_2$

$(2)(5) + (3)(0) = 2v_1 + 3v_2$

$10 = 2v_1 + 3v_2$ ..... (1)

Conservation of Kinetic Energy

$\frac{1}{2}m_1 u_1^2 + \frac{1}{2}m_2 u_2^2 = \frac{1}{2}m_1 v_1^2 + \frac{1}{2}m_2 v_2^2$

$\frac{1}{2}(2)(5)^2 + \frac{1}{2}(3)(0)^2 = \frac{1}{2}(2)v\ 1\ 2 + \frac{1}{2}(3)v_2^2$

$25 = v_1^2 + 1.5v_2^2$ ..... (2)

From eqn (1)

$v_1 = \frac{10 - 3v_2}{2}$, putting this into eqn (2) and expanding gives

$100 = 100 - 60v_2 + 15v_2^2$

$v_2^2 - 4v_2 = 0$

$v_2(v_2 - 4) = 0$

$v_2 = 0$

$v_2 = 4$

Putting these values into $v_1 = \frac{10 - 3v_2}{2}$ gives

$v_1 = \frac{10 - 3(0)}{2}$

$v_1 = 5m/s$

Or $v_1 = \frac{10 - 3(4)}{2}$

$v_1 = -1m/s$

Hence the possible final velocities of block 1 and block 2 are $v_1 = -1m/s$, 5m/s and $v_2 = 0m/s$, $4m/s$ respectively.

Practice Question

1. A 0.15 kg baseball is moving at 40 m/s when it is hit by a bat. The bat reverses the ball's direction, and the ball leaves the bat with a speed of 50 m/s. The collision lasts for 0.002 seconds. Calculate the impulse delivered to the ball and the average force exerted on it by the bat.
2. A 5 kg block slides at 6 m/s on a frictionless surface and collides with a stationary 3 kg block. After the collision, the 5 kg block continues in the same direction at 2 m/s. What is the final velocity of the 3 kg block?

Activity 9.13 Real-world Examples of Momentum Conserved Collisions

Objective: To investigate real-world examples of collisions in order to explain how momentum is conserved and to distinguish between elastic and inelastic collisions.

What you need

1. Access to internet for online research

2. Access to videos, articles, or other multimedia resources about collisions in the real world
3. Paper or notebook for note-taking
4. Pen or pencil
5. Tools for creating presentations (e.g., PowerPoint, Google Slides, poster paper, or simple drawing tools)
6. Access to video creation or editing apps (optional, for short video clips)

What to do

1. Form small groups of 3-5 people.
2. Each group selects one or more real-life examples of collisions. Some suggested examples include:
   a. Car crashes (inelastic collisions where vehicles deform and stick/slow down)
   b. Billiard or pool ball collisions (elastic collisions where balls bounce off)
   c. Sports collisions like tackles in football or collisions between cricket/basketball balls
   d. Collisions in machinery, such as two gears or parts hitting each other
   e. Everyday events such as a mudball sticking to a wall or a ball bouncing on the ground
3. Use online resources, videos, or articles to gather information on how collisions occur in these examples, noting the type of collision (elastic or inelastic) and how momentum conservation applies.
4. For your chosen example, explain:
   a. The principle of momentum conservation and how it applies to the collision
   b. Whether the collision is elastic (kinetic energy conserved) or inelastic (some kinetic energy lost)
   c. How velocity and mass influence the outcome of the collision
   d. Any energy transformations involved (e.g., sound, heat, deformation)
5. Prepare support materials
   a. Create diagrams illustrating the collision process, showing initial and final velocities, directions, and masses of the objects involved.

b. If possible, find or create short video clips demonstrating similar collisions.

c. Organise your findings into a clear and concise presentation format (slides, posters, or video).

6. Present to the class

a. Each group delivers a short presentation to the whole class or to one other group explaining their example, the momentum conservation principle involved, the collision type, and their supporting visuals or videos.

b. Explain how the laws of physics manifest in the real-world scenario you researched.

Activity 9.14 Videos of Different Types of Collision

What to do

1. Watch the video using the linked (or QR code) to observe example of different types of collision: Types of Collisions explained with animation

2. Write a brief summary of each example, explaining whether the collision is elastic or inelastic *and how you know.*

Activity 9.15 Egg Drop Experiment – Investigating Collision Time and Force

Objective: To demonstrate how increasing the collision time during an impact reduces the force on an object (an egg), using different surface materials.

Materials

1. Raw eggs (at least 5–10)
2. Measuring tape or ruler
3. A step stool or safe elevated drop point (~1 metre height)
4. Surface materials (e.g.)
   a. Concrete or tile (hard surface)
   b. Foam pad or cushion
   c. Bubble wrap
   d. Sand or soil
   e. Towel or thick fabric
5. Notebook or data sheet for observations

Procedure

1. Set Up Surfaces
   a. Place each surface material on the ground, spaced apart if possible.
   b. Ensure each surface area is large enough to catch the falling egg.
2. Measure Drop Height: Use the measuring tape to ensure the drop height is consistent (e.g., 1 metre).
3. Drop the Egg
   a. Carefully hold a raw egg at the set height.
   b. Drop it directly onto the first surface.
   c. Observe whether the egg breaks or remains intact.
4. Repeat
   a. Use a new egg for each surface.
   b. Drop from the same height onto each different material.
   c. Record the result (e.g., broken/not broken, amount of cracking).
5. Analyse Results
   a. Compare which surfaces allowed the egg to survive.
   b. Discuss how softer or more flexible surfaces increase the **collision time**, reducing the **force** experienced by the egg (per the impulse-momentum principle).

Activity 9.16 Skateboard Experiment

Objective: To demonstrate and verify the **conservation of momentum** by observing the motion of two people pushing off each other while standing on skateboards.

Materials

1. 2 skateboards or rolling carts
2. 2 people of known (or measurable) mass
3. Measuring tape or marked floor (to track distance)
4. Stopwatch (optional)
5. Scale (to measure mass, if unknown)
6. Smooth, flat surface (e.g., gym floor)

Procedure

1. Measure Masses. Record the mass of Person A and Person B.
2. Set Up: Both people stand still on their skateboards, facing each other, with hands touching lightly.
3. Push Off
   - **a.** Have the two people push off each other at the same time.
   - **b.** Allow them to roll freely in opposite directions.
4. Measure Velocities
   - **a.** Use a stopwatch and the marked floor to estimate each person's velocity after the push.
   - **b.** Alternatively, use video analysis for more precise velocity measurements.
5. Calculate Momentum
   - **a.** Calculate momentum for each person.
   - **b.** Determine total momentum before (which should be 0, since both were at rest).
   - **c.** Add momenta after the push. The total momentum should still be approximately zero (accounting for direction, one will be negative).
6. Analysis: If momentum is conserved, the final momentum sum should be close to zero (within experimental error).

REVIEW QUESTIONS

1. A particle undergoes SHM with amplitude 10cm and period 2s. Calculate the time taken to move from the equilibrium position to a point 5cm away.
2. A 0.5kg mass is attached to a spring with spring constant k = 200N/m. Find the total energy of the system if the amplitude is 0.3m.
3. A mass on a spring executes SHM. If the kinetic energy is half the total energy, find the displacement from equilibrium.
4. A simple pendulum has a length of 1.5m. calculate the change in period if taken to a place where the acceleration due to gravity decreases by 4%.
5. A block attached to a spring oscillates with angular frequency ω. Calculate the displacement at which the acceleration equals half of its maximum value.
6. The position of a particle is given by the equation $x(t)=0.4\cos(2t-\pi/6)$, where x is in metres and t is in seconds. Determine the time at which the particle first reaches its maximum speed after t=0.
7. A particle of mass m moving with an initial velocity of 10 m/s collides elastically with an identical stationary particle. After the collision, the first particle is deflected by an angle of 30∘ from its original path. Determine the final speeds of both particles and the direction of the second particle.
8. A golf ball with a mass of 46 g is at rest on a tee. A golf club strikes the ball, and the ball leaves the club face with a velocity of 60 m/s. The collision lasts for 0.0005 seconds.
   a. Calculate the impulse delivered to the golf ball.
   b. Calculate the average force exerted on the ball by the club.

SECTION

10 FUNCTIONAL ELECTRONIC CIRCUITS FOR RECTIFICATION, AMPLIFICATION, DETECTION, AND BATTERY CHARGING



APPLICATIONS OF ELECTRONICS

INTRODUCTION

This section will introduce you to the practical applications of electronic circuits used for rectification, amplification, detection, and battery charging. It begins with rectifiers—half-wave and full-wave—and their associated filter circuits, which are essential in converting alternating current (AC) into direct current (DC) for reliable power supplies. The section then explores transistor amplifiers, focusing on the design and operation of NPN and PNP types, highlighting their roles in signal amplification. You are further guided to study darkness detector circuits that employ light-dependent resistors (LDRs) and transistors to automate lighting systems. Finally, the section examines the principles and design of battery chargers, including conventional and solar-based models, to demonstrate how electronic circuits provide efficient charging solutions. The knowledge and skills gained here build on earlier studies of semiconductor devices and simple circuit applications, providing a strong foundation for advanced electronic system design.

KEY IDEAS

- **Amplifiers** use transistors (NPN and PNP) to increase the strength of weak signals without altering their shape.
- **Battery Chargers** convert AC to DC and regulate voltage to safely recharge different types of batteries.
- **Darkness Detectors** use light-dependent resistors (LDRs) and transistors to automatically switch devices on or off depending on light intensity.
- **Filter Circuits** smooth pulsating DC from rectifiers using capacitors or inductors to provide a steadier output.
- **Full-Wave Rectifiers** utilise both halves of an AC cycle to produce more efficient and smoother DC than half-wave rectifiers.
- **Half-Wave Rectifiers** convert only one half of the AC cycle into DC, providing a simple but less efficient power source.

RECTIFIERS AND SMOOTHER/FILTER CIRCUITS

Rectifiers are devices that convert alternating current (AC) to direct current (DC). They are essential in many common everyday devices and applications such as power adapters for electronic devices like smartphones and laptops, in battery chargers for various gadgets, and in larger appliances like refrigerators and washing machines.

Furthermore, rectifiers play a crucial role in power supplies for computers, televisions and other electronic equipment, ensuring a stable and reliable DC power source.

1. **Power Adapters / Battery Charging**

   Rectifiers are a key component in the power adapters that plug into wall outlets. They convert the AC from the outlet into DC, which is then used to charge the batteries of devices like smartphones, laptops, and other portable electronics.

2. **Consumer Electronics and Large Appliances**

   Many devices in your home, including TVs, radios, and audio systems, refrigerators, washing machines and air conditioners rely on rectifiers to convert AC power from the mains to DC for their internal circuits.

3. **Power Supplies for Electronic Devices**

   Computers, servers, and other devices that require a stable DC power source rely on rectifiers within their power supplies to convert AC from the wall socket to the appropriate DC voltage.

4. **Electric Welding**

   Rectifiers, particularly bridge rectifiers, are used in electric welding equipment to provide the steady, polarised DC voltage needed for the welding process.

5. **Renewable Energy**

   Although solar panels and wind turbines generate DC power, rectifiers are used to convert this DC power into AC for use in homes and businesses.

6. **Radio and Audio Systems**

   Rectifiers can be found in radios as detectors, and they are also used in audio amplifiers and other circuits.

7. **Voltage Multipliers**

   Rectifiers are used in voltage multiplier circuits, which are employed in various applications like microwave ovens and other devices requiring high DC voltages.

Types of Rectifiers

There are two main types of rectifiers, and these are half-wave rectifier and full-wave rectifier.

Half-Wave Rectifier

A half-wave rectifier is a circuit that converts alternating current (AC) to direct current (DC) by allowing only one half-cycle of the AC waveform to pass through, while blocking the other.

Watch how the half-wave rectifier works using this link

http://youtube.com/watch?v=HV2NCmopMIw&t=143s

Half-Wave Rectifier Circuit

A half-wave rectifier circuit typically consists of the following components.

1. Diode: Acts as a gate that only allows electrons to flow in one direction, thereby converting AC into pulsating DC.
2. Transformer: Provides voltage transformation to adjust the input voltage to a suitable level for rectification and isolate the circuitry from the power source for safety.
3. Load Resistor: Represents the device that uses the output DC power.

The Half-wave rectifier diagram is given below.

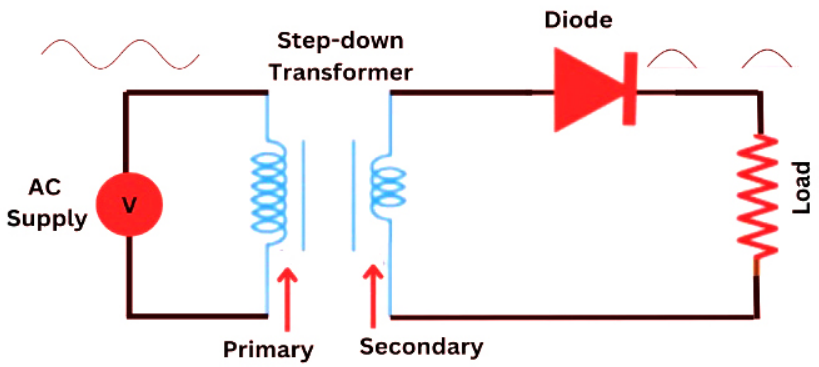


Figure 10.1: *Half-wave rectifier circuit*

The half-wave rectifier receives an Alternating Current as input. The output voltage is measured using the load resistor. As the name suggests, the halfwave rectifier brings out only the positive half-cycle of the input wave. This is achieved due to a p-n junction diode that conducts current only in one direction. As a result, the output pulse only produces output for the positive input cycle.

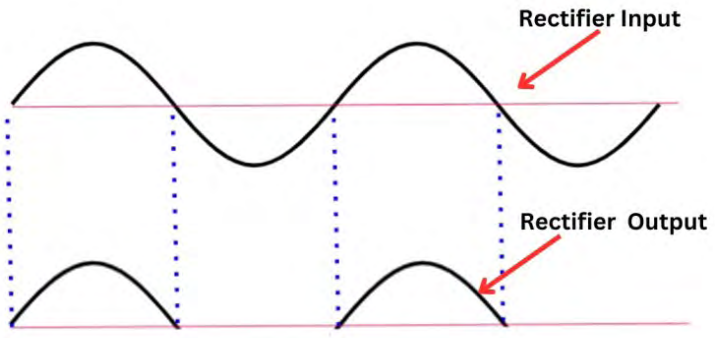


Figure 10.2: *A diagram showing the half-wave rectifier input and output*

Flow of Current During Positive and Negative Half-Cycles

1. **During Positive Half-Cycles**

   When the AC supply goes positive, the diode's anode becomes positive relative to the cathode. If this voltage exceeds the diode's forward voltage (typically around 0.7 V for silicon diodes), the diode conducts, allowing current to flow through the load resistor. The voltage across the load is approximately the input peak voltage minus the diode's forward voltage drop.

2. **During Negative Half-Cycles**

   When the AC supply is negative, the diode's anode is at a lower potential than the cathode. The diode is reverse-biased and blocks current, preventing current from flowing through the load resistor. Thus, the voltage across the load is zero during this half-cycle.

3. **Output Voltage Characteristics**

   The resulting output voltage is a pulsating direct current. It consists of a series of pulses at the frequency of the input AC waveform, separated by periods of zero voltage during the negative half-cycles. This type of waveform has a relatively high ripple factor, which means the DC output is not smooth.

4. **Filtering**

   If smoother DC output is desired, a filter circuit can be added, usually consisting of a capacitor or an inductor. A capacitor placed in parallel with the load helps smooth out the output by charging during the positive half-cycle and discharging when the voltage drops, reducing the ripple.

Applications of Half-Wave Rectifier

1. Power Supply for Low-Power Devices: They provide a DC supply for low-power electronic devices or circuits where ripple filtering is not critical, such as LED lighting circuits.
2. Measuring Instruments: In measuring instruments like voltmeters and ammeters, half-wave rectifiers can convert AC signals to DC signals, simplifying measurement.
3. Basic Battery Chargers: They are sometimes used in basic battery charging circuits, particularly for trickle charging, where a low, unregulated DC voltage can suffice.
4. Temperature Sensing Circuits: Half-wave rectifiers are used in the sensing/control circuitry for specific temperature-sensing circuits or control systems.
5. Signal Conditioning: In some signal processing applications, half-wave rectifiers can condition signals by removing negative cycles.
6. LED lighting: The half-wave rectifier is commonly used in LED lighting circuits to rectify the input AC voltage and provide DC voltage to the LEDs.

Disadvantages of Half-Wave Rectifier

1. Low Efficiency: Half-wave rectifiers only utilise one half-cycle of the input AC signal, effectively discarding the other half. This results in low efficiency, with the rectified output containing significantly less power. Also, when a transformer is used to step down the input voltage, it does so inefficiently because current only flows during half of the AC waveform.
2. Pulsating DC Output: The output of the half-wave rectifier is a pulsating DC voltage, which may cause issues for electronic devices requiring a steady DC voltage.
3. Low Average DC Output: The average DC output voltage is much lower than that of a full-wave rectifier for a given input voltage. This limitation makes the halfwave rectifier less useful in applications that require higher DC voltage.
4. Limited Load Capacity: The high ripple and low DC output make it unsuitable for loads that require stable and clean DC power.

Full-Wave Rectifier

An electronic device that converts the entire input of an alternating current (AC) into a unidirectional direct current (DC). Unlike a half-wave rectifier, which only works on one half of the AC cycle, a full-wave rectifier processes both the positive and negative halves of the AC signal.

This results in a more efficient and consistent DC output.

Types of Full-Wave Rectifiers

Centre-tap ful- wave rectifier

The **centre-tap full-wave rectifier** uses a transformer with a centre tap in its secondary winding. This centre tap creates two equal halves of the input AC signal. The circuit typically involves two diodes: one diode conducts during the positive cycle, and the other during the negative cycle of the AC input.

Characteristics

1. Requires a transformer with a centre tap.
2. Only two diodes are needed for operation.
3. The output voltage is half of the total input voltage since it only uses one-half of the transformer at a time.

Working Of Centre-Tapped Full-Wave Rectifier

The working of a centre-tapped full-wave rectifier involves two main phases during the **positive half cycle** and the **negative half cycle** of the AC input.

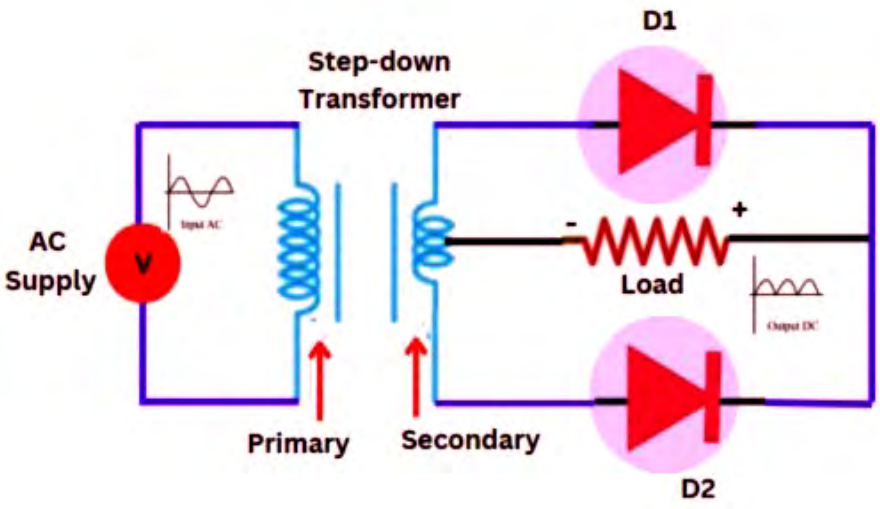


Figure 10.3: *A full-wave rectifier with two diodes*

1. **Positive Half Cycle**
   a. During the positive half of the input AC cycle, the upper half of the transformer secondary winding is positive, and the lower half is negative.
   b. **Diode D1** becomes forward-biased because the anode of **D1** is connected to the positive voltage from the upper half of the transformer. As a result, **D1** conducts current.
   c. **Diode D2** is reverse-biased during this cycle because the anode is connected to the negative voltage of the lower half of the transformer, so **D2** remains off.
   d. The current flows through **D1** and passes through the load resistor in one direction, resulting in a positive output voltage across the load.
2. **Negative Half Cycle**
   a. During the negative half of the AC input cycle, the polarities of the transformer's secondary winding reverse: the lower half becomes positive, and the upper half becomes negative.
   b. **Diode D2** now becomes forward-biased as its anode is connected to the positive voltage from the lower half of the transformer, so **D2** conducts.
   c. **Diode D1**, on the other hand, becomes reverse-biased and does not conduct.
   d. The current now flows through **D2** and again through the load resistor in the same direction, resulting in a positive output voltage across the load.

Output Waveform

As both the positive and negative halves of the AC input are used, the output waveform is continuous but pulsating DC. The voltage across the load resistor does not change direction, and both diodes alternately conduct during each half cycle of the AC input. The result is that the entire AC signal is converted into a unidirectional DC signal.

Bridge Full-Wave Rectifier

The bridge full-wave rectifier consists of four diodes arranged in a bridge configuration. It does not require a centre-tap transformer, making it more commonly used. During the positive half of the AC cycle, two diodes conduct current, and during the negative half, the other two diodes take over. This ensures both halves of the AC waveform is used.

Characteristics

1. No need for a centre-tap transformer.
2. Four diodes are used in the circuit.
3. It allows the full AC voltage to be rectified into DC without halving the voltage.

Working of Full=Wave Bridge Rectifier

The operation of a full-wave bridge rectifier can be broken down into two phases corresponding to the positive half cycle and the negative half cycle of the input AC signal.

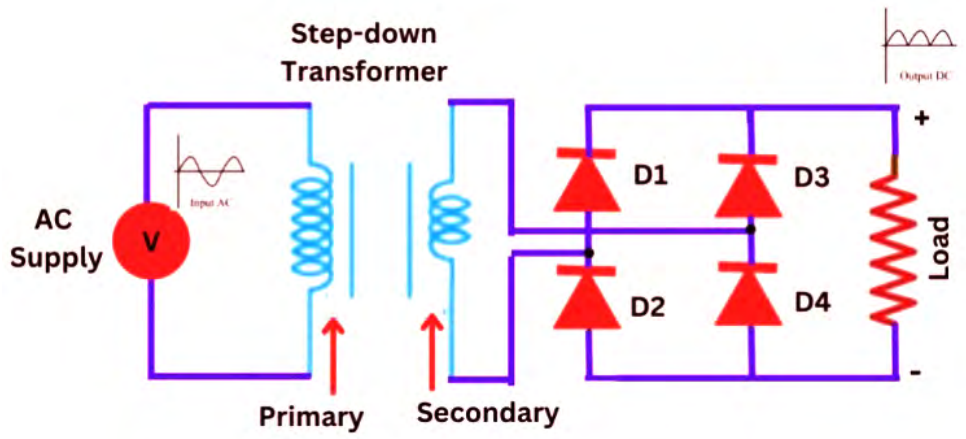


Figure 10.4: *A full-wave rectifier with four diodes*

1. **Positive Half Cycle**
   a. During the positive half of the AC input, the input terminal connected to the **anode of Diode D3** becomes positive, and the terminal connected to the **anode of Diode D**2 becomes negative.
   b. **Diodes D3 and D2** are forward biased, meaning they allow current to pass through them because their anodes are connected to the positive AC voltage and their cathodes are connected to the load.
   c. **Diodes D1 and D4**, on the other hand, are reverse-biased during this cycle, so they block the current from flowing through them.
   d. As the current flows through **D1** and **D2**, it passes through the load resistor in one direction, creating a positive output voltage across the load.

2. **Negative Half Cycle**
   a. During the negative half of the AC input, the polarity of the input voltage reverses. The terminal connected to the anode of **D3** becomes negative, and the terminal connected to the anode of **D1** becomes positive.
   b. Now, **Diodes D1 and D4** become forward-biased, allowing current to pass through them, while Diodes **D2** and D3 become reverse-biased and block the current.
   c. The current flows through **D1** and **D4**, again in the same direction through the load resistor as in the positive half cycle.
   d. This ensures that even during the negative half of the AC cycle, the current flows in a single direction through the load, maintaining a positive output voltage.

Output Waveform

The output from the bridge rectifier is a pulsating DC signal, as both the positive and negative halves of the AC signal are rectified to produce a continuous DC output. The direction of current flow through the load remains the same during both halves of the AC cycle.

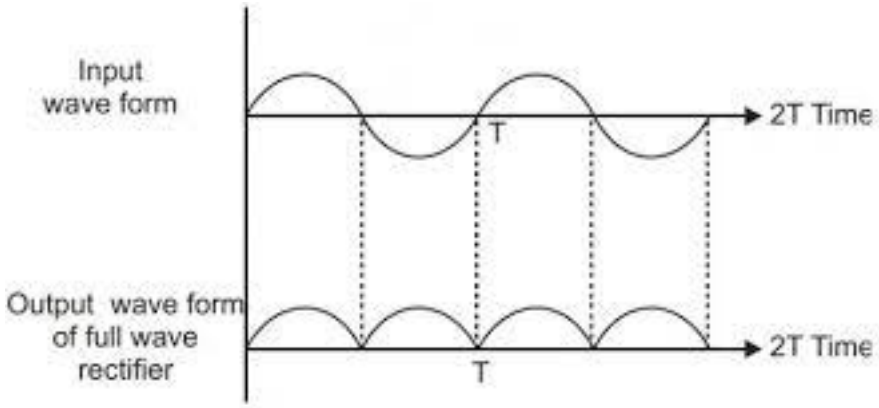


Figure 10.5: *Wave form of input and output of a full-wave rectifier*

Applications of Full-Wave Rectifiers

Full wave rectifiers are frequently used in various electronic devices and systems (E.g. televisions, washing machines) where a stable and continuous DC supply is needed. Here are some of the common applications:

1. Power Supplies for Electronics: Almost all power supplies, especially in home appliances and electronic devices, use full wave rectifiers to convert the mains AC into usable DC.

2. Radio Receivers: Full-wave rectifiers help in demodulating radio signals by converting AC signals into usable DC.
3. Battery Charging: Since batteries require DC for charging, full wave rectifiers are ideal in battery charging circuits for their efficiency and smooth output.
4. DC Motor Drives: Many industrial applications rely on DC motors, and full wave rectifiers are used to provide the required steady DC supply.

Advantages of Full Wave Rectifiers

1. Better Efficiency: Since the full AC signal is converted to DC, full-wave rectifiers are significantly more efficient compared to half wave rectifiers.
2. Reduced Ripple Voltage: The output ripple is lower, meaning less fluctuation in the DC signal, which results in better performance in powering devices.
3. Higher Average Output Voltage: Full-wave rectifiers produce a higher average DC voltage than half-wave rectifiers, making them more effective for a range of applications.
4. Improved Power Utilisation: By utilising both halves of the AC input, the full wave rectifier maximises power conversion efficiency.

Filter Circuit

A filter circuit is an electronic circuit designed to pass or block specific frequencies from an electrical signal, effectively shaping the circuit's frequency response. They are crucial components in many electronic systems, used to isolate desired signals and eliminate unwanted noise or interference.

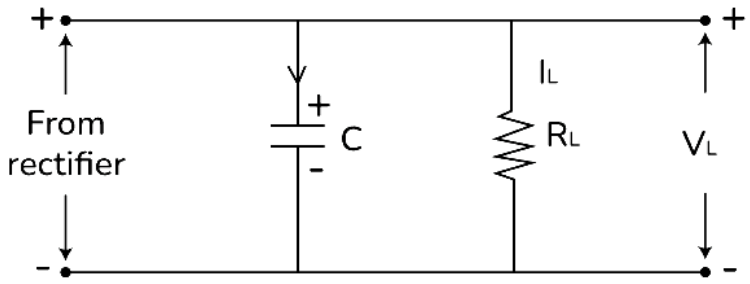


Figure 10.6: *A diagram showing filter circuit*

Importance of Filters

1. In high-performance stereo systems, filter circuits are frequently required because, in order to achieve the highest possible sound quality and power efficiency, specific audio frequency ranges must be increased or suppressed.

2. Noise Reduction: To remove undesired noise or interference from a signal, filters are frequently utilised. This is essential for applications requiring a clean signal, such as audio processing and communication systems.
3. Signal smoothing: Filters are employed in many electrical systems, particularly power supply, to reduce fluctuations in the signal and produce an output that is steadier and more continuous.

Components of a Filter Circuit

The components of a filter circuit are as follows

1. Resistor
2. Capacitor
3. Inductor

Activity 10.1 Simulating and Observing a Half-Wave Rectifier Circuit Using the Falstad Circuit Simulator

Objective: To build and simulate a half-wave rectifier circuit using the Falstad Circuit Simulator in order to observe how a diode converts an AC input into a pulsating DC output and to understand its operation, output characteristics, and limitations.

What you need

1. Access to the Falstad Circuit Simulator: www.falstad.com/circuit



2. Paper and pencil for sketches and notes
3. Access to the video: Introduction to the Falstad Circuit Simulator

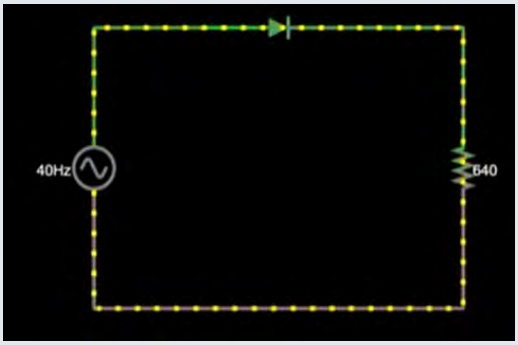


What to do

1. First, watch the video "Introduction to the Falstad Circuit Simulator" using the link provided. This video will help you understand the basic interface,

how to add components, connect wires, and run simulations in the Falstad environment.

2. Open the Falstad Circuit Simulator
3. When the simulator opens, there may be a default circuit loaded. Clear it by selecting all (drag to select) and pressing delete or by using the simulator's menu to start with a blank workspace.
4. Build the Half-Wave Rectifier Circuit
   - **a.** Use the draw menu or keyboard shortcuts to place the following components on the blank canvas:
     - **i.** Sinusoidal AC voltage source (press 'CTRL+V' or find in sources)
     - **ii.** One diode (press 'D' or find in components)
     - **iii.** A resistor
   - **b.** Connect the diode and resistor in series with the AC voltage source so that the diode allows current flow only during the positive half of the AC input.



5. Run the Simulation and Observe Waveforms
   - **a.** Start the simulation by pressing the run button or assuring the simulation is on.
   - **b.** Use the simulator's oscilloscope tool to view and sketch the input waveform at the voltage source terminal.
   - **c.** View and sketch the output waveform across the load resistor.
   - **d.** Notice how only the positive half-cycles appear at the output, illustrating the diode's selective conduction.
6. Understand and write down how the diode allows only the positive half of the AC signal to pass while blocking the negative half.

7. Discuss Inefficiencies and Voltage Gaps
   a. Observe the gaps in the output waveform during negative half cycles.
   b. Discuss why this makes half-wave rectifiers less efficient for producing DC power.
   c. Notice the voltage drop across the diode that reduces output voltage slightly.
8. Summarise Your Findings
   a. Write a brief explanation of how a half-wave rectifier works based on your observation and sketches.
   b. Explain the diode's function and why the output waveform looks like it does in this simulation.

Activity 10.2 Building and Observing a Full-Wave Rectifier with Capacitor Smoothing Using Falstad Circuit Simulator

Objective: To simulate and study the operation of a full-wave rectifier with and without a smoothing capacitor, to understand how diodes convert AC into pulsating DC and how a capacitor reduces ripple to produce a smoother DC output.

What you need

1. Computer, tablet, or smartphone with internet access
2. Access to Falstad Circuit Simulator: www.falstad.com/circuit

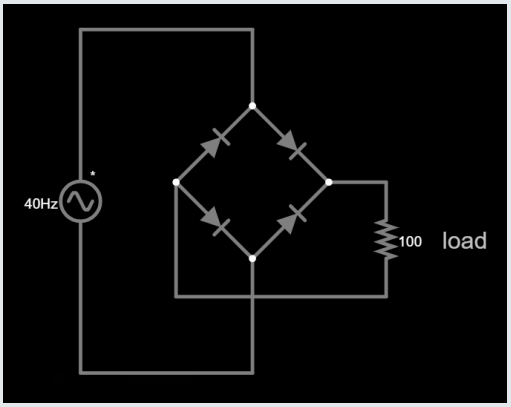


3. Paper and pencil for sketches and notes

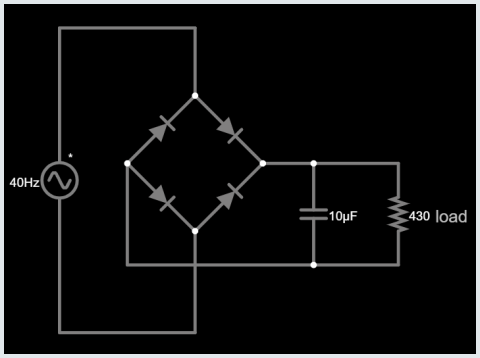
What to do

1. Open the Falstad Circuit Simulator: Open the link above on your web browser
2. Remove any preset components or circuits by selecting all and deleting to start with a blank workspace.

3. Build the Full-Wave Rectifier Circuit
   - **a.** Place an AC Voltage Source: Use the "Draw" menu or press 'v' to add a voltage source.
   - **b.** Add Four Diodes: Use 'd' or the "Draw" menu to place four diodes. Arrange them in a bridge configuration:
     - **i.** Connect two diodes with their anodes connected to the AC source terminals, and their cathodes connecting to the positive output node.
     - **ii.** Connect the other two diodes with their cathodes connected to the AC source terminals, and their anodes connecting to the negative output node (ground).
   - **c.** Place a Load Resistor: Use 'r' or the "Draw" menu to add a resistor connected across the output terminals of the diode bridge.
   - **d.** Connect Ground: Ensure the negative side of the load resistor is grounded to complete the circuit.
   - **e.** Wire all components carefully to avoid loose ends.



4. Run the Simulation and Observe Output Without Capacitor
   - **a.** Start the simulation.
   - **b.** Right-click the load resistor and select "View in Scope" to see the output voltage waveform.
   - **c.** Sketch the waveform, noting the full-wave pulsating DC shape (positive pulses without negative half-cycles).
5. Add a Capacitor Across the Load Resistor
   - **a.** Add a capacitor in parallel with the load resistor across the output terminals. Press 'c' or use the "Draw" menu to place the capacitor.
   - **b.** Begin with a capacitance value such as 10 µF.



6. Run the Simulation and Observe Output with Capacitor
   a. Observe the output waveform again using the scope.
   b. Sketch or note how the waveform appears smoother with fewer dips (reduced ripple).
7. Experiment with Different Capacitor Values
   a. Try increasing capacitance to values like 100 μF or 1000 μF and observe the smoothing effect increasing.
   b. Discuss and note how higher capacitance better reduces voltage ripple but may affect other circuit properties.
8. Think-Pair-Share Discussion
   a. Think individually about how the capacitor acts in the circuit to smooth the output voltage.
   b. Pair up with a peer to explain your ideas and listen to theirs.
   c. Share your discussion points with the class or group.

Activity 10.3 Group Research and Presentation on Real-Life Uses of Rectifiers

Objective: To research and explain real-life applications of rectifiers, highlighting how half-wave and full-wave rectification with filtering are used in electronic devices to provide steady DC power.

What you need

1. Internet-enabled devices (computers, tablets, or smartphones) for research
2. Access to articles, videos, and other resources about rectifiers and their applications
3. Paper or notebook for notes
4. Pen or pencil

5. Tools for preparing presentations (e.g., PowerPoint, Google Slides, poster paper, or drawing materials)

What to do

1. Form small groups
2. Select a Rectifier Application. Each group selects one real-life application of rectifiers to research. Examples include
   a. Phone chargers (full-wave rectifiers)
   b. Radios (AM radios often use half-wave rectifiers for signal demodulation)
   c. Solar power systems (which use rectification to convert AC from inverters back to DC for battery charging)
   d. Battery chargers
   e. Power supply circuits in electronic devices
3. Research Your Application. Investigate how rectifiers are used in your chosen application including:
   a. Whether the device uses half-wave or full-wave rectification
   b. How the rectifier converts AC to DC and why this is necessary for the device's operation
   c. The role of filtering (like capacitors) in smoothing the output DC voltage to make it steady and usable
   d. Any advantages or limitations related to the rectification method used
4. Create a brief presentation explaining
   a. The basic working principle of the rectifier in your application
   b. Why half-wave or full-wave rectification is chosen
   c. The importance of filtering in providing steady DC output
   d. Include diagrams or drawings showing the rectifier circuit or waveform changes before and after rectification
   e. Optionally, include short video clips or animations illustrating the process
5. Share your findings in a clear and engaging way, helping your classmates understand the practical significance of rectifiers and filtering in electronics.

Activity 10.4 Construct a Full Wave Rectifier on a Breadboard

Objective: To build and test a full-wave bridge rectifier circuit using four diodes, which converts AC input into pulsating DC output.

Materials Needed

1. Breadboard
2. 4 diodes (e.g., 1N4007 or 1N4148)
3. AC power source (low voltage, e.g., 6V AC from a transformer or signal generator)
4. Load resistor (e.g., 1kΩ)
5. Capacitor (optional, for smoothing, e.g., 100µF)
6. Wires/jumper leads
7. Multimeter or oscilloscope (to measure output)

Step-by-Step Instructions

1. Insert four diodes on the breadboard to form a bridge (see Fig 10.4 for reference):
   a. D1 and D2: Cathodes (striped end) connected together — this will be +Vout.
   b. D3 and D4: Anodes connected together — this will be Ground or –Vout.
2. Connect AC Input
   a. Connect the first AC wire to the junction of D1 anode and D3 cathode.
   b. Connect the second AC wire to the junction of D2 anode and D4 cathode.
3. Connect the 1kΩ resistor between the +Vout (D1/D2 cathodes) and –Vout/GND (D3/D4 anodes).
4. (Optional) Add Smoothing Capacitor. Place a 100µF electrolytic capacitor in parallel with the load resistor:
   a. Positive leg to +Vout
   b. Negative leg to GND
5. Power the Circuit:
   a. Connect the AC input from a low-voltage AC source.

   b. Make sure the voltage is safe (e.g., 6–12V AC).

6. Test the Output:
   a. Use a multimeter (set to DC volts) to measure across the load resistor.
   b. You should see a DC voltage with or without ripple (depending on whether you added the capacitor).

Activity 10.5 Investigate the Internal Circuitry of an Old Home Appliance

Objective: To safely open and examine an old home appliance to identify and investigate **diodes** and **capacitors** in its internal circuitry.

Materials Needed

1. Old home appliance (e.g., toaster, DVD player, power supply, etc.)
2. Screwdrivers (various sizes)
3. Flashlight or good lighting
4. Safety gloves and eye protection
5. Multimeter (optional, for testing components)
6. Notebook or phone (to take notes/photos)

Safety First

1. Unplug the appliance — make absolutely sure it is disconnected from power.
2. Discharge capacitors before touching any internal parts — large capacitors can retain charge even when unplugged.
3. Avoid microwave ovens or CRT monitors — they contain high-voltage components that can be dangerous even when unplugged.

Procedure

1. Open the Appliance
   a. Use appropriate screwdrivers to remove the casing or housing.
   b. Keep screws in a container so they're not lost.
2. Visually Inspect the Circuit Board
   a. Look for a printed circuit board (PCB) — usually where most components are located.
   b. Identify major components first (transformer, large capacitors, etc.).

3. Identify Diodes
   a. Look for small cylindrical components with a black or glass body and a silver stripe on one end.
   b. The stripe indicates the cathode.
   c. Common markings: 1N4007, 1N4148, etc.
4. Identify Capacitors
   a. Look for
      i. Electrolytic capacitors: cylindrical, usually black, blue, or gold, with one leg marked "–".
      ii. Ceramic capacitors: small disks, usually yellow or orange.
   b. Check voltage and capacitance ratings printed on the component (e.g., 100µF 25V).
5. (Optional) Use a Multimeter
   a. Use diode mode to check if a diode conducts one way.
   b. Use capacitance mode (if available) to measure capacitors.
6. Take Notes or Photos
   a. Document where you found each component.
   b. Sketch or photograph the board for reference.

Wrap-Up

1. Once finished, reassemble the appliance or recycle the parts responsibly.
2. Reflect on how diodes may be used for rectification or protection, and how capacitors may be used for filtering or timing.

Activity 10.6 Design a Low-Cost Rectifier Circuit

Objective: Work collaboratively to design a low-cost rectifier circuit that converts AC voltage to DC using minimal and inexpensive components. You are not required to build the circuit—just plan and present your design.

Task Instructions

1. Form Your Group
   a. Work in teams of 3–5.
   b. Assign roles such as:

i. Circuit Designer (draws the schematic)
ii. Component Researcher (finds affordable parts)
iii. Cost Analyst (calculates total cost)
iv. Presenter (shares the group's design with the class)

2. Design the Circuit
   a. Create a circuit diagram for a full-wave bridge rectifier using 4 diodes.
   b. Add a load resistor to simulate a device being powered.
   c. Optionally include a capacitor to reduce ripple (for smoother DC output).

3. Research Components
   a. Find real-world examples of suitable components (e.g., 1N4001 diodes, 100µF capacitors).
   b. Use online sources or catalogues to list current prices.
   c. Aim to keep the total cost as low as possible (target: under GHC30 if feasible).

4. Draw the Final Design
   a. Sketch a clear and labelled circuit diagram.
   b. Identify component values (e.g., 1N4007 diode, 100µF capacitor, 1kΩ resistor).
   c. Show where the AC input and DC output are connected.

5. Prepare a Short Presentation
   a. Explain how the circuit works (AC to DC conversion).
   b. Describe the role of each component.
   c. Present your estimated total cost and cost-saving choices.
   d. Discuss any trade-offs (e.g., no capacitor = more ripple but lower cost).

Deliverables

1. A labelled circuit diagram
2. A component list with estimated costs
3. A brief explanation of the circuit's function and design choices

AMPLIFIERS

Transistors

A transistor is a semiconductor device that can be used to increase (amplify) or switch electrical signals. It's a fundamental building block of modern electronics, found in everything from computers and smartphones to radios and more. Essentially, a transistor acts like a tiny electronic switch or amplifier, controlling the flow of electrical current in a circuit. Transistors have at least three terminals that is a base, collector, and emitter

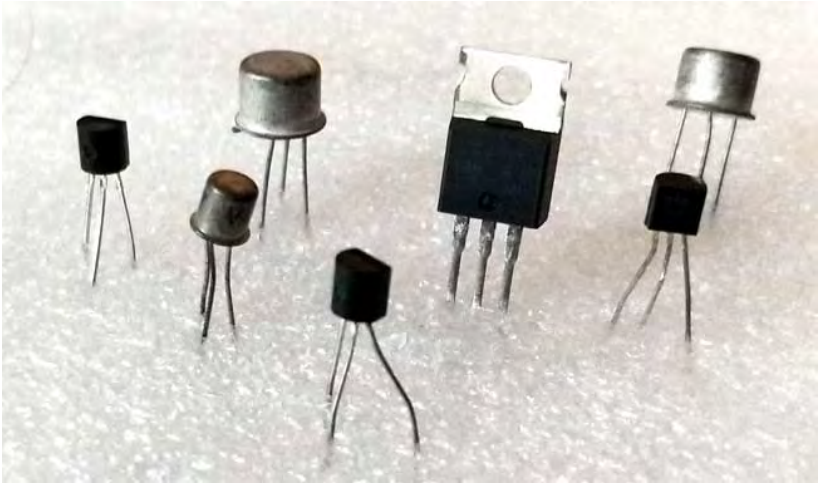


Figure 10.7: *A diagram showing different types of transistors*

In an NPN transistor, current flows from the collector to the emitter when a small current is applied to the base, which must be at a higher voltage than the emitter. This allows the transistor to conduct and amplify signals.

In contrast, a PNP transistor conducts when the base is at a lower voltage than the emitter; current flows from the emitter to the collector when the base is effectively grounded (low voltage). Understanding the direction of current flow and the voltage relationship between terminals is crucial for designing and analysing amplifier circuits.

NPN stands for Negative-Positive-Negative, and PNP stands for Positive-Negative-Positive.

Let us delve into the differences between NPN and PNP transistors.

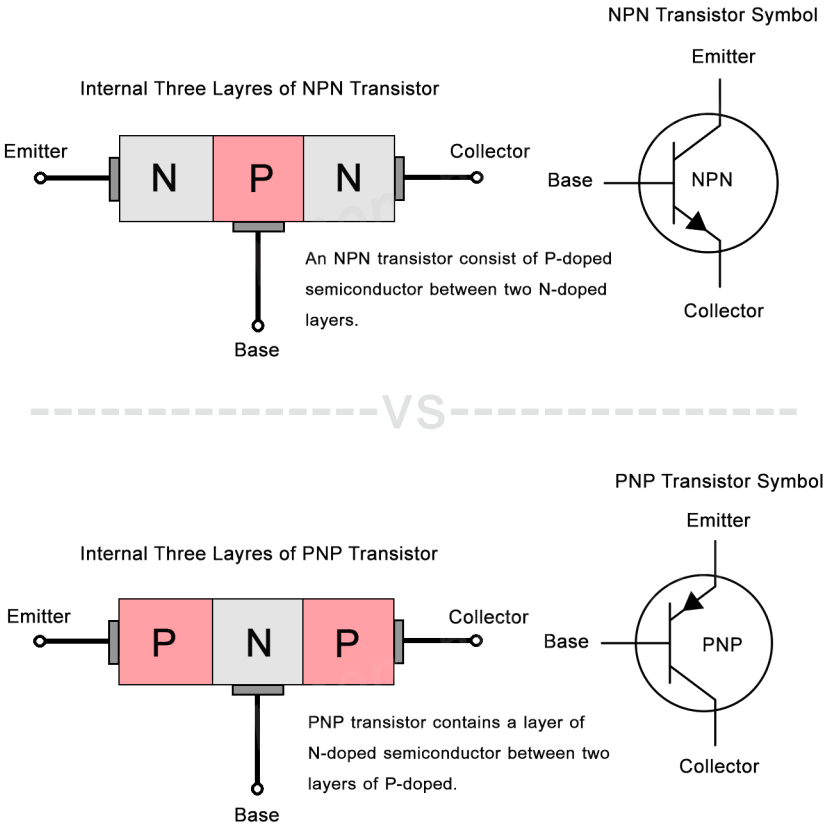


Figure 10.8: *NPN and PNP transistors*

PNP transistors activate with a low signal, whereas NPN transistors activate with a high signal. In PNP transistors, the "P" signifies the polarity of the emitter terminal, and "N" signifies the polarity of the base terminal. In NPN transistors, "N" denotes the negatively charged coating of the material, while "P" denotes the positively charged layer. Applying a positive voltage to the collector terminal induces a current flow from the collector to the emitter in an NPN transistor. Conversely, providing a positive voltage to the emitter terminal in a PNP transistor causes current to flow from the emitter to the collector.

PNP transistors offer the advantage of a lower turn-on voltage, making them well-suited for high-speed applications. On the other hand, NPN transistors boast a higher current-carrying capacity, rendering them ideal for use in low-power applications.

How Transistors Work

A transistor operates as a switch or gate for electronic signals, opening and closing an electronic gate many times per second. It ensures the electronic circuit is on if the current is flowing and switched off if it isn't. Complex switching

circuits that make up all modern networking and telecommunications systems rely on transistors. Circuits also offer high switching speeds, such as hundreds of Gigahertz or more than 100 billion on-and-off cycles per second.

Transistors are combined to form a logic gate, which compares multiple input signals to provide a different output. Computers with logic gates can make simple decisions using Boolean algebra. These techniques are the foundation of modern-day computing and computer programs. Transistors also play an important role in amplifying electronic signals. For example, in radio applications such as FM receivers, where the received electrical signal is weak due to disturbances, amplification provides audible output. Transistors increase signal strength to provide this amplification.



Figure 10.9: *Some home appliances with transistor amplifiers*

Amplifier Design

Transistors are basically used as amplifiers for amplification. The process of raising the amplitude of a weak signal without change in its frequency and shape is known as ‘amplification”. In order to achieve this, the input circuit of the transistor remains forward biased and the output circuit always remains reverse biased to all parts of the signal this is known as ‘transistor biasing’. The base of the transistor receives the weak signal, and the collector circuit produces an output that has been amplified. One crucial prerequisite for amplification is that the signal should only rise in magnitude and not alter in shape. The term “faithful amplification” refers to this rise in signal strength without any modification in form. Below is the circuit diagram of transistor as an amplifier.

The common-emitter configuration is widely used in amplifier circuits because it provides significant voltage gain. For stable operation, proper biasing is essential—typically requiring a base-emitter voltage of around 0.7V for silicon (Si) transistors to turn on the junction and allow controlled current flow. The voltage gain of a common-emitter amplifier is given by the formula:

$$A_v = -\frac{R_C}{R_E}$$

where R_C is the collector resistor and R_E is the emitter resistor. The negative sign indicates a phase inversion between the input and output signals.



Figure 10.10: *Simple audio amplifier circuit of a transistor*

Key Differences Summarised

Feature	NPN Amplifier	PNP Amplifier
Activation	Requires a **positive** base voltage relative to the emitter	Requires a **negative** base voltage relative to the emitter
Current Flow	Collector to Emitter	Emitter to Collector
Active Charge Carriers	Electrons	Holes
Typical Use	Low-side switching, general-purpose amplification	High-side switching, complementary to NPN

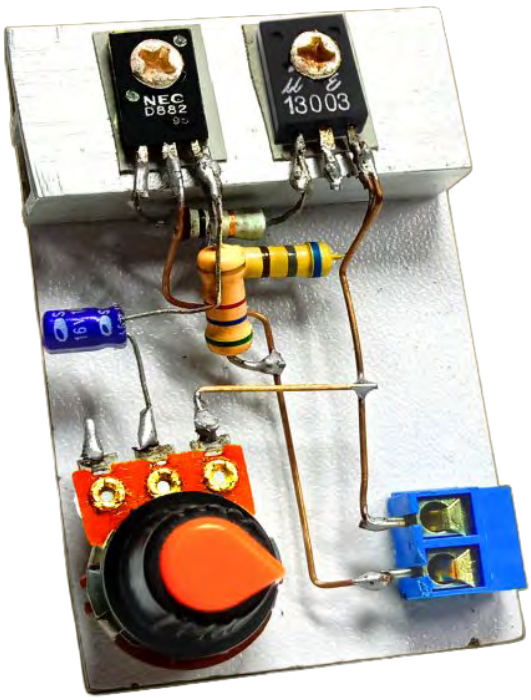


Figure 10.11: *Simple amplifier circuit with volume control*

Activity 10.7 Observing and Comparing PNP and NPN Transistors

Objective: To observe, compare, and understand the structure and operation of NPN and PNP transistors, focusing on current flow, biasing, and the role of charge carriers in their functioning.

What you need

1. Internet-enabled device (computer, tablet, or smartphone), notebook and pen
2. Access to this video

   NPN & PNP Transistors explained - electronics engineering

What to do

1. Form small groups of 3-5 people.
2. Play the selected videos or animations that illustrate the internal structure of NPN and PNP transistors.

3. While watching, pay close attention to how current flows through each transistor type. Note the direction of current flow relative to the emitter, base, and collector. Observe the roles of each terminal.
4. Write down key points about the operation of each type
5. Sketch the transistor symbols with arrows showing current flow directions for both NPN and PNP.
6. Compare
   a. how the biasing voltages for the base-emitter and base-collector junctions differ between NPN and PNP.
   b. the direction of current flow in both transistor types.
   c. the role of majority charge carriers (electrons in NPN, holes in PNP) and how that affects their operation.
7. Discuss practical implications of these differences, such as how the transistor is connected in circuits.

Activity 10.8 Research and Peer Teaching on NPN and PNP Amplifiers

Objective: To observe, compare, and understand the structure and operation of NPN and PNP transistors, focusing on current flow, biasing, and the role of charge carriers in their functioning.

What you need

1. Access to internet for research
2. Access to online resources, videos, and articles about NPN and PNP transistor amplifiers
3. Paper, poster board, or digital presentation tools (e.g., PowerPoint, Google Slides, or poster paper and markers)
4. Pens, pencils, and coloured markers for note-taking and poster making

What to do

1. Create a group of 6 people, then split into two sub-groups
   a. Group 1 will research NPN amplifiers
   b. Group 2 will research PNP amplifiers

2. Each group independently researches the following aspects of their assigned amplifier type
   a. Structure: The physical construction and semiconductor layers in NPN or PNP transistors
   b. Working Principle: How the transistor operates as an amplifier, including current flow and amplification process
   c. Biasing Conditions: The required base-emitter and base-collector biasing for proper operation
   d. Typical Applications: Real-life uses where the amplifier type is preferred (e.g., audio amplifiers, switching circuits, mobile devices)
3. Organise your findings in a clear format that you can present to others
   a. Use diagrams to illustrate transistor structure and current flow
   b. Include biasing voltage polarities and explanation of how biasing activates the transistor
   c. Summarise key points about operation and applications
   d. Use bullet points, flowcharts, or tables as needed for clarity
4. Teach the Other Group
   a. Each group takes turns presenting their poster or presentation to the other group.
   b. Explain your amplifier type's structure, operation, biasing, and applications clearly.
   c. Encourage questions and discussion to reinforce understanding.

Activity 10.9 Building NPN and PNP Transistor Amplifier Circuits

Objective: To construct and simulate NPN and PNP transistor amplifier circuits, observe their amplification behaviour and phase relationships, and compare their practical use in amplifier applications.

What you need

1. Computer, tablet, or smartphone with internet access
2. Access to Falstad Circuit Simulator: www.falstad.com/circuit

3. Paper and pencil for notes and sketches

What to do

1. Open Falstad Circuit Simulator: Open the link above. Clear any default circuit components or start with a blank workspace.
2. Build an NPN Transistor Amplifier
   a. Add an NPN transistor (press 'N' or select from the components menu).
   b. Add a DC voltage source for power supply.
   c. Add resistors for biasing the transistor base and for load at the collector. Common emitter configuration is recommended.
   d. Add a small AC signal source at the base input (use a small AC voltage source).
   e. Complete the circuit with proper ground connections.
   f. Connect an oscilloscope or analogue output to the collector or output node.
3. Run the Simulation and Observe the Output
   a. Start the simulation.
   b. Observe the input AC signal waveform and the output waveform on the scope.
   c. Note the amplitude difference (gain) and observe the phase relationship between input and output (commonly a 180° phase shift in common emitter amplifiers).
   d. Sketch input and output waveforms.
4. Build a PNP Transistor Amplifier
   a. Remove the previous NPN transistor.
   b. Add a PNP transistor (press 'P' or select from components).
   c. Repeat the circuit construction with appropriate biasing, supply polarity, and connections suitable for PNP (reverse voltages as necessary).
   d. Add the same small AC signal at the base input and connect the output to scope or analogue output.
5. Run the Simulation and Observe the Output for PNP
   a. Observe input and amplified output waveforms again.

b. Note gain and compare phase change with the input signal (PNP common emitter amps also typically invert phase like NPN).

6. Compare and Reflect
   a. Write short reflections on which transistor configuration (NPN or PNP) is more commonly used in amplifiers and why. Consider availability, ease of biasing, and typical circuit design preferences.
   b. Include observations about gain, phase change, and ease of simulation.

Activity 10.10 Building a Simple NPN Transistor Amplifier on a Breadboard

Objective: To construct and test a simple NPN transistor amplifier on a breadboard, observe its ability to amplify signals, and relate the working circuit to real-life amplifier applications.

What you need

1. Breadboard
2. NPN transistor
3. Resistors
4. Capacitors
5. Signal source
6. Power supply (9V DC)
7. Connecting jumper wires
8. Multimeter and/or oscilloscope
9. Input device (e.g., small speaker or headphones for audio output, optional)
10. Paper and pencil for notes and sketches

What to do

1. Set up the components on the breadboard
   a. Insert the NPN transistor into separate rows on the breadboard. Identify the transistor pins: Collector (C), Base (B), and Emitter (E) from the datasheet or marking.
   b. Connect the emitter pin of the transistor to the ground (negative) rail on the breadboard.

2. Bias the Transistor Properly

- **a.** Use a voltage divider bias circuit for the base:
  - **i.** Connect two resistors (e.g., 10kΩ and 4.7 kΩ) in series between the positive power supply rail (+9V) and ground.
  - **ii.** Connect the junction between these two resistors to the transistor base.
- **b.** This sets a stable bias voltage to the base to turn the transistor on in its active region.

3. Connect the Collector Load

- **a.** Connect a resistor (e.g., 1 kΩ) between the collector and the positive power supply rail (+9V).
- **b.** This resistor acts as the collector load.

4. Couple the Input Signal

- **a.** Connect the input signal source (e.g., audio device or function generator) to the transistor base via a coupling capacitor (e.g., 0.1 µF).
- **b.** Connect the other side of the input signal source to the ground.
- **c.** If you don't have a function generator, you can use a small audio source such as a phone or audio player with a low signal output.

5. Connect the Output

- **a.** Measure the output signal at the transistor collector by connecting the oscilloscope probe or multimeter across the collector resistor and ground.
- **b.** You can also connect an output device such as a small speaker through a coupling capacitor after the collector resistor (optional).

6. Power Up the Circuit

- **a.** Connect your 9V power supply to the breadboard rails (positive to power rail, negative to ground).
- **b.** Turn on the input signal and observe the electrical signal at the output (collector).

7. Measure Input and Output Signals

- **a.** Use a multimeter or oscilloscope to measure the voltage or waveform at the input (base) and output (collector).
- **b.** Observe how the output signal is an amplified version of the input.

8. Analyse and Record Your Observations
   a. Sketch the input and output waveforms if using an oscilloscope.
   b. Note the increase in amplitude indicating voltage gain.
   c. Discuss the role of the transistor as a current amplifier with voltage gain.
9. Discuss Real-Life Applications
   a. Reflect on where NPN transistor amplifiers are commonly used, such as in audio amplifiers, signal processing, switching circuits, and in mobile devices for amplification of weak signals.
   b. Discuss why NPN transistors are often preferred for these applications — for instance, due to their faster switching times, availability, and efficient current amplification properties.

Activity 10.11 Debate on the Efficiency and Suitability of NPN vs PNP Amplifier Transistors

Objective: To compare the efficiency and suitability of NPN and PNP transistors through debate, evaluate their strengths and limitations, and draw conclusions about their applications in electronic circuits.

What you need

1. Paper and pens for note-taking and preparing arguments
2. Research materials (textbooks, handouts, or internet access for reference)
3. Whiteboard or large paper for summarising debate points (optional)

What to do

1. Form a group of 8 people, then split yourselves into two sub-groups. One group will advocate for NPN transistors as the more efficient or suitable choice for applications like mobile devices or audio systems. The other group will argue for PNP transistors.
2. Each team will research their assigned transistor type to gather points on:
   a. Efficiency and power consumption
   b. Speed and switching capabilities
   c. Suitability for high-frequency or low-frequency applications
   d. Stability and temperature tolerance

e. Common real-world applications (e.g., mobile devices, audio amplifiers)

f. Any known advantages or limitations

3. Debate Format

a. Each team takes turns presenting their main arguments and evidence supporting their transistor type.

b. Teams can ask questions or challenge the opposing side's points respectfully.

c. After initial presentations, teams may give rebuttals or clarifications.

4. Think-Pair-Share Reflection

a. After the debate, individually reflect on the points discussed.

b. Pair up with a classmate from the opposite team and discuss what you found most convincing or surprising about the other's arguments.

c. Share insights and any changed perspectives with the class.

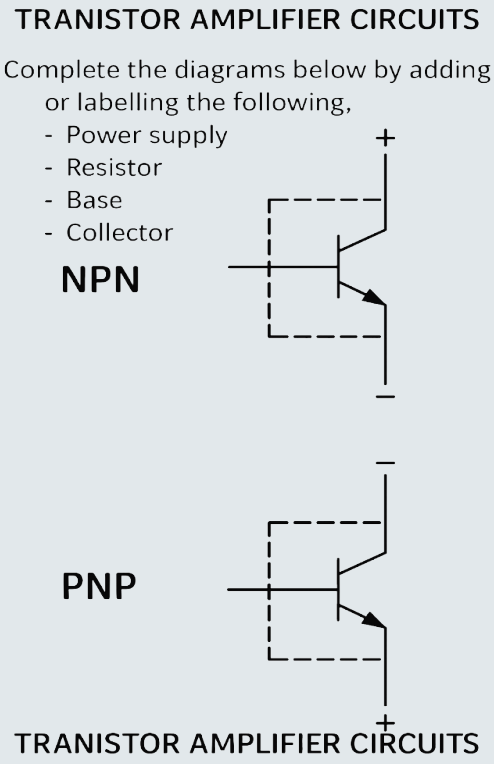
5. Class Summary

a. Gather as a whole class to summarise key points from both sides.

b. Note that both NPN and PNP transistors are valuable for different reasons and often used together in complementary configurations.

6. Write a Brief Conclusion. Each learner writes a short paragraph on which transistor they think is more efficient or suitable for a given application and why, based on the debate.

Activity 10.12 Complete the Circuit Diagram



DARKNESS DETECTOR

Darkness Detector

Darkness detectors are very useful, and you have probably seen them in action without even realising it! They are used in all sorts of situations where something needs to react when the lights go out or when it gets dim.

Here are a few common places you will find them:

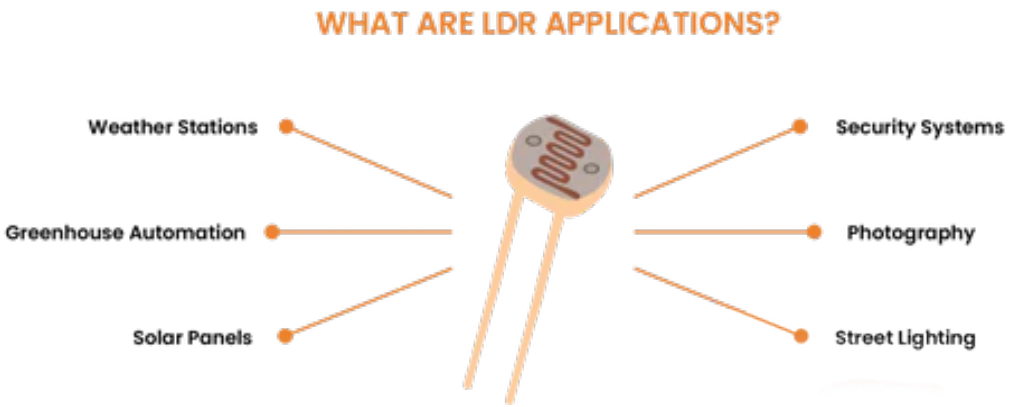


Figure 10.11: *LDR and some applications*

1. Automatic Streetlights: This is probably the most obvious one. Think about how streetlights (e.g. those in your school or neighbourhood) just *know* when to turn on at sunset and off at dawn. That is a darkness detector doing its job, saving energy by only lighting up when needed.



Figure 10.12: *A street light fitted with a photocell to operate automatically*

2. Security Systems: Ever wonder how an alarm system knows if someone is hiding in the shadows? Darkness detectors can be part of motion sensors or light-beam setups. If a light beam is broken or the ambient light drops suddenly, it can trigger an alert.
3. Emergency Lighting: In big buildings, or even at home, if the power goes out, you want emergency lights to come on, right? Darkness detectors help make sure those lights come on automatically, especially if it's nighttime.
4. Gardening and Agriculture: For indoor growing or in greenhouses, plants need specific amounts of light. Darkness detectors can help control *grow lights*, making sure the plants get just the right "sunshine" throughout the day.



Figure 10.13: *Grow lights are used to grow plants in rooms. The brightness of the lights is controlled by darkness detectors.*

5. Photography: If you have ever used an old-school light meter with a camera, you have used a type of darkness detector. They measure how much light is around to help photographers set their cameras for the perfect shot.

How Darkness Detectors Work

So, how do these things actually *work*? At its heart, a darkness detector is an electronic circuit designed to turn something on (like a light or an alarm) when there's no light around. The key player here is something called a Light Dependent Resistor *(*LDR*)*.

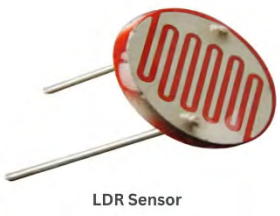


Figure 10.14: *An LDR sensor*

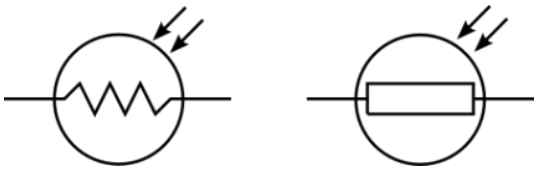


Figure 10.15: *LDR circuit symbol*

An LDR is a special component whose electrical resistance changes based on how much light hits it. Think of it like this:

1. When it's bright, the LDR lets electricity flow through it pretty easily (low resistance). But as it gets darker, the LDR starts to resist that flow of electricity more and more (high resistance).
2. This change in the LDR's resistance then affects the *voltage* at a specific point in the circuit, usually at the *base of a transistor*.
3. This voltage changes acts like a switch, telling the transistor to turn the connected device (your light or alarm) either on or off.

The principle behind the LDR itself is called *photoconductivity*. When light hits the LDR's special material, it absorbs that light energy. This energy gets the electrons in the material all excited, making them jump from one energy level to another (remember your lesson in atomic physics!). When these electrons move, they increase the material's ability to conduct electricity – that's why the conductivity goes up as the light gets more intense. But there's a catch: the light's energy has to be strong enough to "kick" those electrons into action!

LDC circuits

Below is a sample circuit designed to control an incandescent bulb.

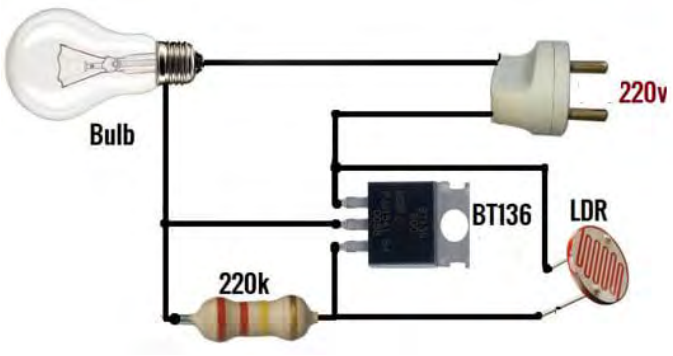


Figure 10.16: *A circuit demonstrating how an LDR controls a lighting system*

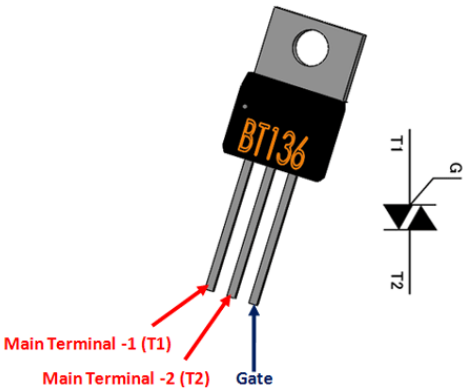


Figure 10.17: *Description of the TRIAC's terminals/pins*

Here is a description of how this circuit works

Key Components

1. LDR (Light Dependent Resistor): The light sensor. Its resistance is low in the light and high in the dark.
2. BT136 (TRIAC): The AC switch. It controls the flow of 220V AC to the light bulb.
3. 220k Resistor: A high-value resistor that, along with the LDR, controls the current flowing into the TRIAC's gate.
4. Light Bulb: The load.
5. 220V AC Power Source: The power supply.

How it Works

1. Gate Triggering

The TRIAC's gate (the control pin) needs a small current to "turn on" and allow a much larger current to flow through the main terminals (the upper and middle pins). The circuit's design provides this current via a path through the LDR and the 220k resistor.

2. During Daylight (Sufficient Light)

a. The LDR's resistance is low.

b. The LDR is connected in parallel with the gate-to-terminal-1 path of the TRIAC.

c. Since the LDR's resistance is low, it essentially acts as a short circuit or a low-resistance path for the gate current.

d. Any potential triggering current that would flow from the main terminal through the 220k resistor is instead shunted away from the TRIAC's gate and through the LDR.

e. The gate current is too low to trigger the BT136 TRIAC.

f. The TRIAC remains in its "off" state, and the light bulb stays off.

3. During Darkness (Insufficient Light)

a. The LDR's resistance increases dramatically.

b. With the high resistance of the LDR, the path for current to flow away from the TRIAC's gate is blocked.

c. Now, as the AC voltage is applied, a small current flows from the main AC line, through the light bulb, through the 220k resistor, and into the gate of the BT136 TRIAC (connected to the 220k resistor).

d. This gate current is now sufficient to trigger the TRIAC into its "on" state.

e. Once the TRIAC is "on," it acts as a closed switch, allowing the full 220V AC current to flow through the bulb, which then lights up.

f. This process repeats for each half-cycle of the AC waveform, keeping the bulb lit as long as it's dark.

Activity 10.13 Building Process of a Darkness Detector Circuit

Objective: To explore how an LDR and transistor can be combined in a circuit to automatically switch on an LED in darkness.

What you need

1. Paper or notebook and pen or pencil
2. Access to the video

   Light Sensor circuit on Breadboard + Darkness Detector | LDR & Transistor Projects - YouTube

What to do

1. Watch the Video Carefully. Use the link provided to watch the step-by-step process of building a darkness detector circuit using an LDR (Light Dependent Resistor), a transistor (such as BC547), and an LED on a breadboard. Pay close attention to how each component is connected and how the circuit works to turn the LED on or off depending on the ambient light level.
2. While watching, note the following:
   - **a.** The LDR changes its resistance based on the amount of light falling on it.
   - **b.** The transistor acts as a switch that activates the LED when the light level is low (darkness detected).
   - **c.** The LED lights up when the transistor is switched on by the voltage created through the voltage divider formed by the LDR and a fixed resistor.
3. After watching the video, draw the circuit diagram on your paper or notebook:
   - **a.** Include and label all components: LDR, transistor (with emitter, base, collector), LED, resistors, battery or power supply, and breadboard connections.
   - **b.** Show how the LDR and resistor form a voltage divider connected to the transistor base.

c. Indicate the LED connected to the transistor's collector and its connection to the power supply.

4. Write a short explanation of how the LDR controls the LED:

a. Describe how the LDR's resistance changes with ambient light—low resistance in high light, and high resistance in darkness.

b. Explain how this change affects the voltage at the transistor base, turning the transistor (and consequently the LED) on or off.

c. Clarify that when it gets dark, the high resistance of the LDR causes enough voltage to turn on the transistor, lighting the LED.

Activity 10.14 Simulating a Darkness Detector Circuit Using Tinkercad

Objective: To use Tinkercad Circuits to build and simulate a darkness detector, observe how light levels control the circuit through an LDR and transistor, and understand how component values affect the operation of the LED.

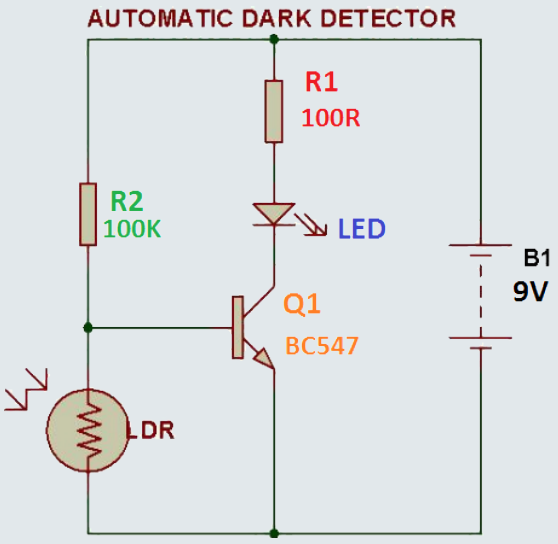
What you need

1. Computer, tablet, or smartphone with internet access

2. Access to Tinkercad Circuits (https://www.tinkercad.com/circuits)

3. Paper and pencil for notes

4. Circuit diagram



What to do

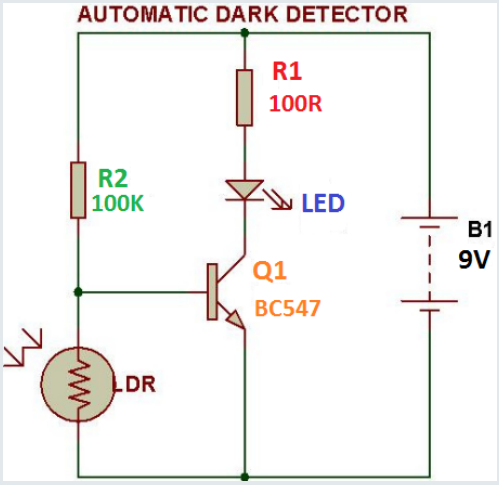
1. Explore Tinkercad Circuits
   - **a.** Search for a brief introduction to Tinkercad, focusing on how to use their circuit simulation tool.
   - **b.** Watch a short tutorial video on placing components, wiring, and running simulations.
2. Study the Provided Circuit Diagram
   - **a.** Examine the darkness detector circuit diagram with an LDR, NPN transistor (BC547), LED, and resistors as shown.
   - **b.** Understand the role of each component.
3. Build the Circuit in Tinkercad
   - **a.** Open Tinkercad Circuits and start a new circuit project.
   - **b.** Place components: LDR, resistor (100 kΩ), NPN transistor (BC547), resistor (100 Ω), LED, and power supply (9V).
   - **c.** Wire the components according to the circuit diagram.
4. Simulate and Test the Circuit
   - **a.** Run the simulation.
   - **b.** Adjust the simulated light level on the LDR to observe how the LED turns on or off.
   - **c.** Note the behaviour of the LED under different lighting conditions.
5. Explain the Operation
   - **a.** Write a brief explanation of how the resistance of the LDR changes with light intensity.
   - **b.** Describe how this change controls the transistor switching and the resulting LED behaviour.
6. Optional Exploration
   - **a.** Modify resistor values or circuit connections to see how circuit behaviour changes.
   - **b.** Record your observations.

Activity 10.15 Building and Testing a Basic Darkness Detector Circuit with LDR, NPN Transistor, and LED

Objective: To design, build, and test a simple darkness detector circuit that uses an LDR and an NPN transistor to automatically switch an LED on in low-light conditions, and to explore how resistor values affect the circuit's sensitivity.

What you need

1. Breadboard
2. Light Dependent Resistor (LDR)
3. NPN Transistor (e.g., BC547)
4. LED (any colour)
5. Resistors: 100 Ω (R1), 100 kΩ (R2) plus additional resistors for testing (10 kΩ, 220 kΩ, etc.)
6. 9V battery and battery clip or power supply
7. Connecting wires
8. Multimeter (optional, to measure resistance and voltages)
9. Ruler or divider to help control light exposure (e.g., paper to partially shade LDR)
10. Circuit diagram



What to do

1. Assemble the Circuit
   a. Use the provided circuit diagram to connect components on the breadboard:

   i. Connect the LDR and resistor R2 (100 kΩ) in series as a voltage divider.
   ii. Connect the junction between LDR and R2 to the base of the transistor Q1 (BC547).
   iii. Connect the collector of the transistor to the positive side of R1 (100 Ω) and LED in series.
   iv. Complete the circuit with the 9V battery correctly connected, making sure the emitter of the transistor is connected to ground.

   b. Double-check your connections against the diagram.

2. Test the Circuit Under Different Light Conditions
   a. Power up the circuit.
   b. Observe the LED behaviour with the LDR exposed to normal room light. The LED should be off or dim.
   c. Shade or cover the LDR gradually to simulate darkness. Notice when the LED turns on as light intensity decreases.
   d. Observe and note how LED brightness changes with different light levels.

3. Explain the Operation
   a. Understand and write down how the resistance of the LDR decreases in light and increases in darkness.
   b. Higher resistance in darkness causes more voltage at the transistor base, turning it on and lighting the LED.
   c. In light, low LDR resistance results in a lower base voltage, keeping the transistor and LED off.

4. Challenge: Modify for Sensitivity
   a. Form small groups and experiment by changing the resistor R2*R2* in the voltage divider.
   b. Try resistors with different values: lower (e.g., 10 kΩ) or higher (e.g., 220 kΩ).
   c. Observe how this changes the light level at which the LED turns on.
   d. Record your observations and discuss which resistor values improve sensitivity to darkness and why.

5. Group Discussion and Summary
   a. Share your findings within your group.

b. Write a brief conclusion on how changing resistor values affects the darkness detector's sensitivity and how you might select resistor values for different use cases.

Activity 10.16 Investigating Real-World Applications of Darkness Detectors and Proposing Local Use Cases

Objective: To investigate real-world applications of darkness detectors, understand their benefits in energy saving, safety, and convenience, and propose practical local use cases where such devices could solve problems or improve daily life.

What you need

1. Access to internet for online research
2. Paper or notebook for note-taking
3. Pen or pencil
4. Optional: presentation tools (posters, PowerPoint, or slides) for sharing findings

What to do

1. Form small groups of 3-5 people.
2. Investigate how darkness detectors, often using Light Dependent Resistors (LDRs), are used in everyday life to detect low light levels and trigger actions. Some common real-world applications to explore include:
   - **a.** Street lighting systems that automatically turn on at night and off during the day
   - **b.** Emergency lights that activate when ambient light falls below a threshold
   - **c.** Solar garden lamps which switch on at dusk and conserve energy by turning off during daylight
   - **d.** Security systems that detect darkness or sudden light changes
   - **e.** Automatic lighting in homes and commercial buildings for energy efficiency
3. Use online articles, videos, and tutorials to learn how these devices work, what components they use (such as LDR sensors and transistors), and the benefits they provide (e.g., convenience, energy saving, safety).

4. Take notes about specific examples, explaining how the darkness detector functions in each context.
5. Identify potential local use cases
    a. Discuss within your group to think about your local environment or community.
    b. Propose practical ways a darkness detector could be used in your area to solve a problem or improve daily life. Examples could be:
        i. Activating street lamps in poorly lit village roads automatically
        ii. Turning on pathway or garden lights in homes to enhance safety at night
        iii. Controlling lights in community centres, parks, or public spaces to save electricity
        iv. Alerting residents in case of power failure or abnormal darkness
    c. Justify why your proposed use case would be beneficial locally (considering safety, convenience, energy savings, or environmental impact).
6. Summarise your research findings, examples of existing real-world applications, and your group's proposed local use case with justification. Support your explanation with diagrams, pictures, or simple sketches if possible.
7. Present your findings and proposal to the class or other groups. Listen to other groups' proposals to understand the variety of use cases and the value of darkness detectors in different contexts.

Activity 10.17 Fix a Broken Circuit

Follow these steps to investigate and repair a simple broken circuit

1. Observe the Circuit: Carefully look at the circuit to spot any obvious problems, such as loose wires, burnt components, or disconnected parts.
2. Test Each Part: Use a multimeter or a simple continuity tester to check whether all components (like bulbs, switches, or wires) are working correctly.
3. Identify and Repair the Fault: Once you've found the broken or faulty part, replace or reconnect it as needed to restore the circuit.

4. Check Your Fix: Switch the circuit on to see if it now works as expected. If not, repeat the steps above until it is working properly.

Remember to always work safely: switch off the power before making any repairs and ask your teacher if you are unsure about anything.

BATTERY CHARGER

You have probably used regular batteries to power some toys or gadgets, like TV remotes. Did you just throw the batteries out when they stopped working? Well, think of rechargeable batteries as the complete opposite of that.

These are the hardworking batteries inside your phone, laptop, or portable speaker. The main difference is right in the name: you can **recharge** them. Instead of being only once, they are designed to be used, drained of power, and then filled back up again, over and over.

In simple terms, a rechargeable battery is a clever box that stores energy chemically. When you are using your device, it's busy converting that stored chemical energy into the electricity that powers your screen and all the fun you enjoy. When that energy runs low, you have to do something called **charging**. This process is like hitting a "rewind" button on the chemical reactions that happen inside, getting it ready to go again.

The best part? These batteries are built to last through hundreds, even thousands, of these use-and-recharge cycles. That's why your devices last so long.

Types of Batteries

Ever wonder why the battery in your car looks so different from the tiny one in your phone? That's because not all rechargeable batteries are the same! Let us consider some common types.

1. **Lead-Acid Batteries** (popularly called "car battery")

   This is the original workhorse, a kind of grandpa of all rechargeable batteries. They are cheap to make and can deliver a lot of power all at once. You'll find them in places where you need a lot of steady power, like in your car or for emergency power backups. They're a bit heavy and bulky, though!

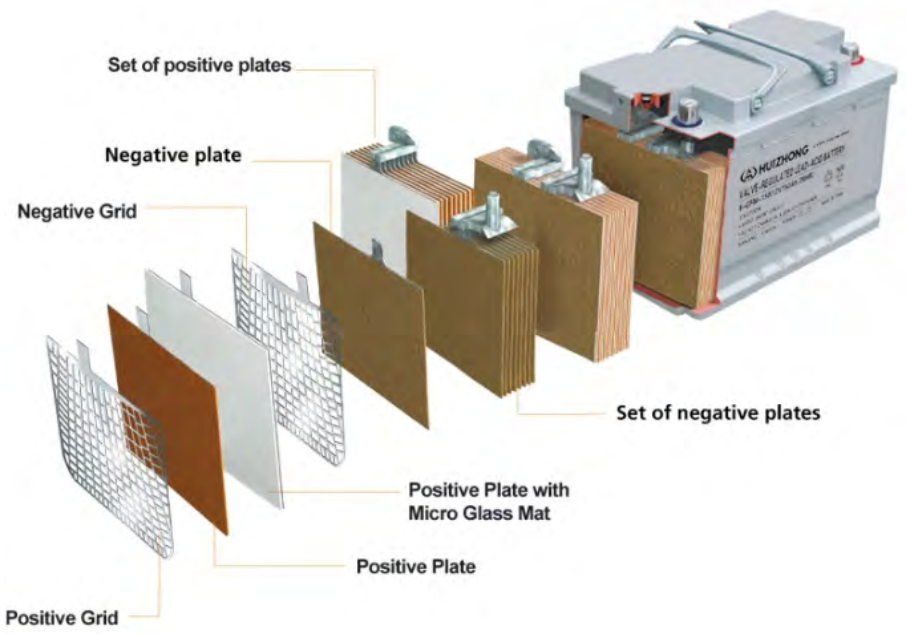


Figure 10.18 *:Parts of a lead acid accumulator*

2. Nickel-Cadmium (Ni-Cd) Batteries

For a long time, these were a popular choice. They were super tough and reliable. The only negative side is that, they contain a toxic material called cadmium, which isn't safe for the environment. Because of this, they have largely been replaced by a better option.



Figure 10.19: *Nickel Cadmium batteries*



Figure 10.20: *Nickel Cadmium cells*

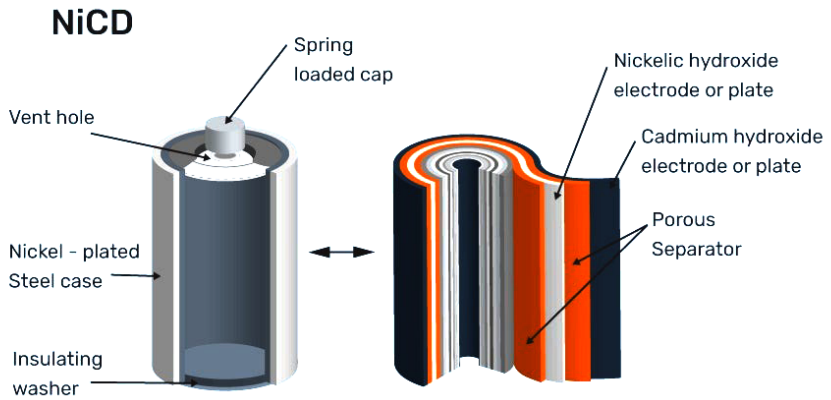


Figure 10.21: *Anatomy of a Nickel Cadmium cell*

3. Nickel-Metal Hydride (Ni-MH) Batteries

Think of these as the improved version of Ni-Cd batteries. They can store more energy in the same amount of space and are much more eco-friendly since they don't use toxic cadmium. You might still find them in some older rechargeable gadgets or powerful battery packs.



Figure 10.22: *A 9 V rechargeable Nickel Metal Hydride battery*

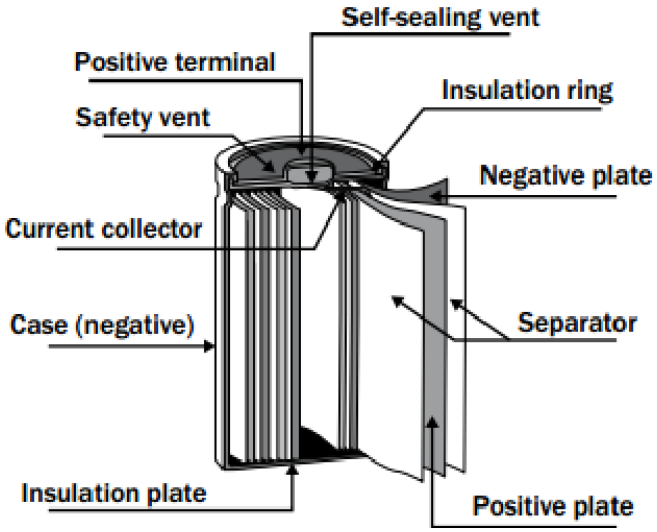


Figure 10.23: *Anatomy of a Nickel Metal Hydride battery*

4. Lithium-Ion (Li-ion) Batteries

This is the superstar of modern electronics! These are the batteries that power your phone, laptop, drone, etc. They are amazing because they can store a ton of energy in a small, lightweight package, last for a very long time, and hold their charge even when you're not using them. There's also a variant called lithium polymer, which is super flexible and thin, perfect for modern gadgets.



Figure 10.24: *Rechargeable Li-Iron coin cell*



Figure 10.25: *Lithium-Ion Battery*

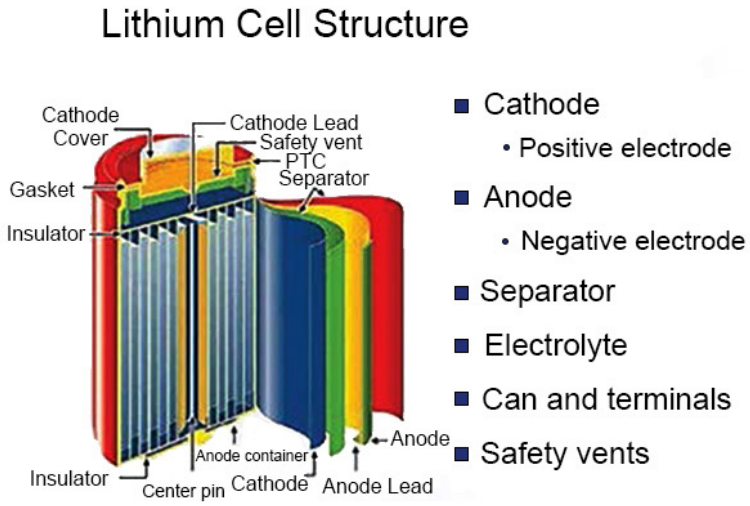


Figure 10.26: *Structure of a Lithium-Ion Battery*

Scientists are even working on new types of batteries, like ones made with sodium or solid materials, to make them even better in the future!

Summary Table

Battery Type	Key Features	Common Applications
Lead-acid	Low cost, high discharge currents, oldest chemistry	Stationary applications (power backups), car batteries
Nickel-cadmium (Ni-Cd)	Moderate energy density, durable, but high toxicity	Power tools, older portable electronics
Nickel-metal hydride (Ni-MH)	Higher energy density than Ni-Cd, lower toxicity	Rechargeable AA/AAA batteries, some older portable devices
Lithium-ion (Li-ion)	Highest energy density, long cycle life, low self-discharge	Smartphones, laptops, drones, and modern portable electronics

Design of a 12 V Battery Charger Circuit

Components

1. Transformer: One 220V/14V Step-Down Transformer
2. Diodes: Four 1N4007 PN Junction Diodes (for the bridge rectifier)
3. Capacitors:
   a. One 1000uF, 25V Electrolytic Capacitor
   b. One 0.01uF Ceramic Capacitor (often labelled "103")
4. Resistor: One 1K, 1W Resistor
5. LED: One Light Emitting Diode (LED)
6. Battery: One 12V DC Rechargeable Battery
7. Connecting materials: Wires for connections, and a breadboard or PCB for assembly.
8. Power Source: A 220V AC input power supply.

Diagram

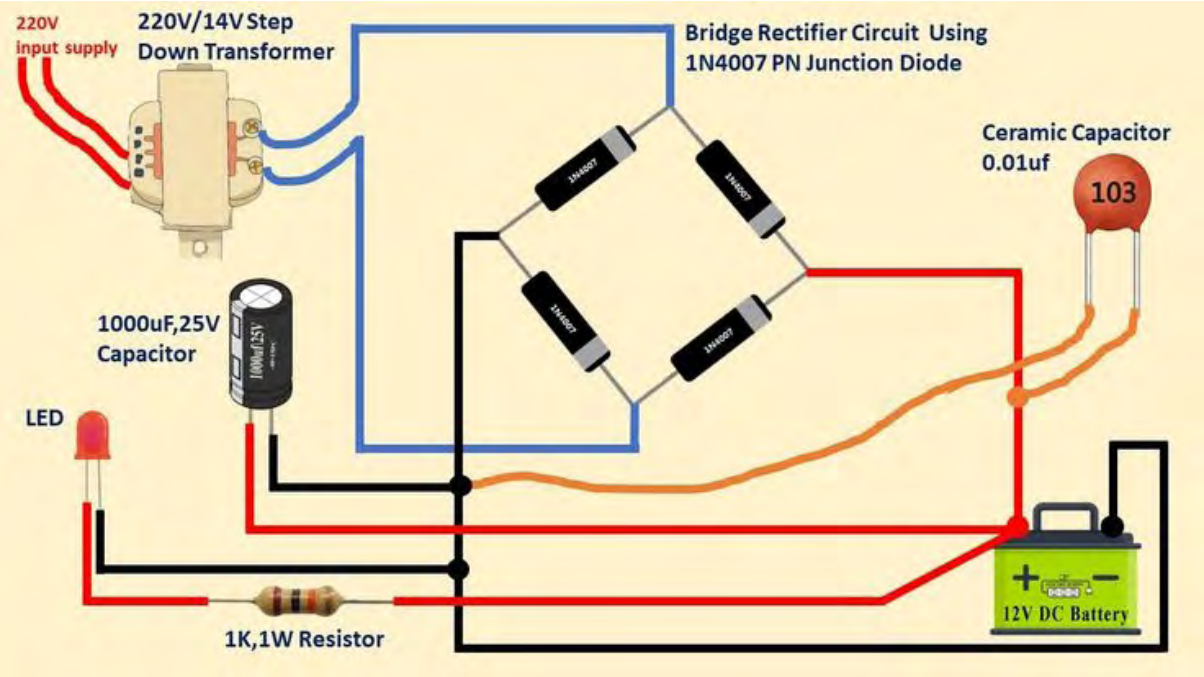


Figure 10.27: *A 12 V Battery charger circuit*

This circuit is a **12V DC power supply and battery charger** that converts a high-voltage AC input into a low-voltage DC output suitable for charging a 12V battery.

How It Works

1. Step-Down Transformation: The circuit begins with a 220V/14V step-down transformer. Its purpose is to take the high 220 V AC voltage from the input supply and safely reduce it to a much lower 14 V AC voltage. This is a crucial first step to prevent damage to the subsequent components.
2. Bridge Rectification: The 14 V AC output from the transformer is then fed into a Bridge Rectifier Circuit, which consists of four 1N4007 PN Junction Diodes. Since diodes only allow current to flow in one direction, this arrangement converts the alternating current (AC) into pulsating direct current (DC). The output voltage is always positive, but it is not yet a smooth, steady voltage.
3. Filtering and Smoothing: The pulsating DC from the rectifier is connected to a large 1000 µF, 25 V Capacitor. This capacitor acts as a filter, smoothing out the pulses of the DC voltage. It charges up during the peaks of the voltage and then discharges slowly in the dips, effectively turning the pulsating DC into a more stable, continuous DC voltage. The smaller 0.01 µF Ceramic Capacitor is also included to filter out high-frequency noise.
4. Charging and Indication: The final, smoothed DC output is connected to a 12 V DC Battery. This voltage is used to charge the battery.
5. A parallel circuit is also included with a 1K Resistor and an LED. The resistor is essential to limit the current flowing to the LED, protecting it from being burned out. The LED serves as a simple indicator light, confirming that the circuit is powered on and providing a DC output.

In summary, the circuit takes 220 V AC from the wall,

1. steps it down,
2. converts it to DC,
3. smooths it out, and
4. uses that power to charge a 12V battery while also providing a visual indication that it is operating.

Activity 10.18 Creating a Block Diagram of a Basic Battery Charger

Objective: To understand the working of a basic battery charger by identifying its main stages and representing them in a block diagram, showing how AC power is converted into regulated DC for charging a battery.

What you need

1. Paper or notebook for drawing and writing
2. Pen or pencil
3. Device with internet access to watch a video

   e.g. Battery Charger 101 - The Basics

What to do

1. Use your device to search and watch a video explaining the working of a basic battery charger. Focus on understanding the main components and how power flows through the charger.
2. While watching, note the key components or circuit stages such as the transformer, rectifier, filter, and voltage regulator.
3. On your paper or notebook, draw a block/flow diagram showing the sequence of these stages. Leave space in each block to label the component and write its function.
4. For each block, write down the name of the component or stage and explain, in your own words, its role in the battery charging process.
5. Look over your diagram and notes. Reflect on how the charger converts the mains AC voltage to safe, constant DC voltage for charging a battery. Think about how each stage contributes to this.

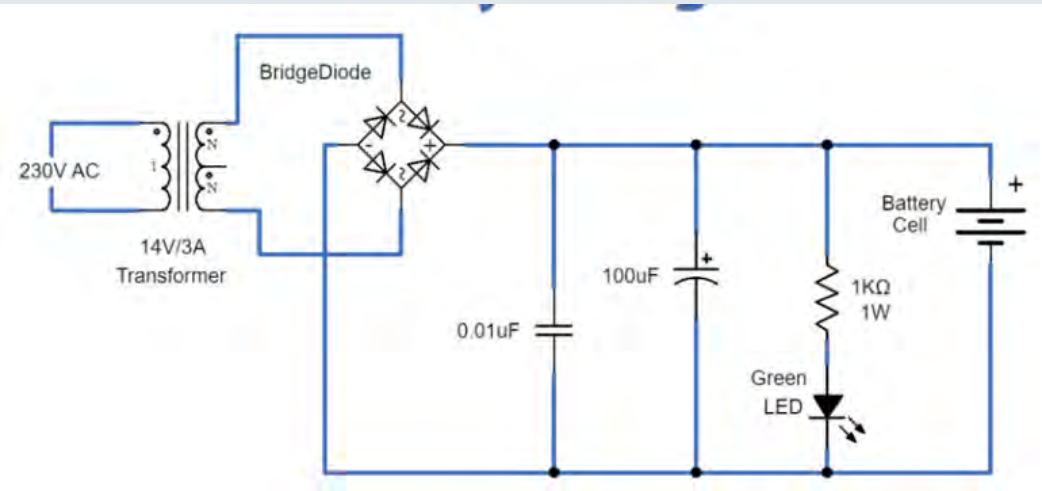
Activity 10.19 Simulating and Exploring a Basic Battery Charger Circuit

Objective: To simulate and study the working of a basic battery charger circuit using Simulation, understand the role of each component, and observe how the circuit charges a battery and indicates charging using an LED.

What you need

1. Access to internet
2. Access to Tinkercad Circuits (https://www.tinkercad.com/circuits)

3. Paper and pencil for notes and sketches
4. The provided circuit diagram (see image below)



What to do

1. Work together with 2-4 other classmates.
2. Look closely at the circuit diagram showing a basic battery charger circuit including:
   - **a.** Transformer (14V/3A)
   - **b.** Bridge diode rectifier
   - **c.** Capacitors (0.01 µF and 100 µF)
   - **d.** Current limiting resistor (1 kΩ)
   - **e.** Green LED indicator
   - **f.** Battery cell

3. Recreate the Circuit in Tinkercad Circuits
   a. Use the components in Tinkercad Circuits to build the circuit exactly as shown in the diagram.
   b. Place and wire the transformer, bridge rectifier, capacitors, resistor, LED, and battery as per the connections in the diagram.
4. Run the Simulation
   a. Start the simulation and observe the voltage output and behaviour of the LED.
   b. Note the charging effect on the battery cell and when the LED lights up as a charge indicator.
5. Explore the Circuit Behaviour
   a. Identify the function of each component by observing the circuit in operation.
   b. Observe the waveform smoothing effect of the capacitors.
   c. Understand the role of the resistor and LED as the current limiter and charge indicator.
6. Record Observations
   a. Write down your observations about how the circuit charges the battery and the conditions under which the LED lights.

Activity 10.20 Designing a Portable Solar Battery Charger Using Circuit Simulation

Objective: To design, simulate, and test a portable solar battery charger using simulation, while understanding the function of each component, testing charging performance, and evaluating the practicality of the design.

What you need

1. Access to internet
2. Access to Tinkercad Circuits (https://www.tinkercad.com/circuits)



3. Paper and pencil for notes and sketches

What to do

1. Work in groups of 3 to 4 learners.
2. Your challenge is to design a portable solar battery charger using Tinkercad Circuits simulation.
3. Research Solar Battery Charger Circuits
   a. Use the internet, books, or videos to research various solar battery charger circuit diagrams.
   b. Pay attention to key components such as solar panels, blocking diodes, voltage regulators, batteries, and charge indicators.
4. Draw a Functional Circuit Diagram
   a. Based on your research, draw your own functional circuit diagram for a portable solar battery charger.
   b. Include all essential components and clearly label them.
   c. Ensure your design is practical and could be assembled or simulated.
5. Use Available Components to Build Your Design
   a. Open Tinkercad Circuits and start a new project.
   b. Use available components like solar cells, diodes, resistors, capacitors, voltage regulators, LEDs, and batteries to create a functional charger circuit.
   c. Focus on connecting the solar panel to the battery through a rectifier or diode to prevent reverse current, regulating voltage for charging, and adding an LED as a charging indicator.
6. Simulate and Test Your Design
   a. Run the simulation to observe the output voltage and behaviour of the LED.
   b. Adjust component values (resistors, regulators) to improve charging stability and indicator performance.
7. Document Your Design and Observations
   a. Draw your final circuit diagram.
   b. Write notes explaining how your charger works and what each component does.
   c. Discuss any challenges or limitations encountered in simulation.

8. Group Presentation and Reflection

a. Present your solar charger design to the class, explaining component choices and charger operation.

b. Reflect on the benefits and trade-offs in your design.

REVIEW QUESTIONS

Review Questions 10.1

1. Explain why a full-wave bridge rectifier is generally preferred over a half-wave rectifier for power supply applications, especially concerning transformer utilisation and filtering.
2. Explain the concept of **biasing** in a transistor amplifier circuit. Why is it essential for achieving **faithful amplification**?
3. Compare and contrast the typical applications and operating characteristics of NPN and PNP transistor amplifiers.

Review questions 10.2

1. Design a simple circuit that performs the *opposite* function of the darkness detector.
   a. Your circuit should be a light detector that automatically turns on a light bulb when it gets bright and turns it off when it gets dark.
   b. Explain the specific changes you would make to the components of a common darkness detector circuit and provide a step-by-step description of how your new circuit would operate in both light and dark conditions.
   c. Use your understanding of the LDR's resistance and the TRIAC's gate to justify your design.

Review Questions 10.3

1. Project Work**: Design of an Automatic Battery Charger with Overcharge Protection.**

   The current circuit is a simple battery charger that provides a constant voltage but has no mechanism to prevent overcharging, which can damage the battery. Your task is to design a modification to this circuit to create a more intelligent battery charger that automatically stops charging when the 12V battery reaches its full charge (approximately 14.4V).

Instructions

a. Research a component or a small sub-circuit that can be used to detect a specific voltage threshold (14.4V in this case). You might consider using a voltage comparator, a Zener diode, or a similar voltage-sensitive switching component.

b. Create a new circuit diagram that integrates your chosen component into the existing battery charger circuit. The new circuit should

- Sense the voltage of the 12V battery.
- Use this information to control the flow of charging current.
- Turn off the charging current when the battery voltage reaches the 14.4V threshold.

c. Write a detailed description of your design, explaining the following.

i. The specific component(s) you added and their function.

ii. How your new circuit senses the battery's voltage.

iii. How the control mechanism works to interrupt the charging path (i.e., where in the circuit the charging is turned off).

iv. the advantages of your modified circuit

ANSWERS TO REVIEW QUESTIONS

SECTION 1

Review Questions 1.1

1. **a.** The mass M is 25 kg.

b. The force exerted by the pivot on the rod is 750 N.

2.

a. The minimum horizontal force required at the base of the ladder to prevent it from slipping down is 0 N. This means it will not slip.

b. The maximum height a 55 kg man can climb up the ladder before it starts to slip is approximately 5.93 m (or 6.85 m along the ladder).

3.

a. A moment is defined as the product of the force (in this case, the weight) and the perpendicular distance from the pivot to the line of action of the force. For a beam to be in rotational equilibrium (balanced), the sum of all clockwise moments about the pivot must equal the sum of all anti-clockwise moments about the pivot. The reason they can have the same balancing effect is that the moment calculation involves a product. If one factor (force/weight) is large, the other factor (distance) can be small to produce the same product. On other hand, if the force is small, the distance must be proportionally larger.

b. Carefully place the Beam on the Pivot. Slowly slide the beam back and forth over the pivot. Continue adjusting until the beam rests perfectly horizontally and shows no tendency to rotate when released. The point on the beam directly above the pivot, where the beam is perfectly balanced, is its centre of gravity.

Review Questions 1.2

1. **a.** 3.73 m/s²

b. 260.99 N]

2. **a.** $-1.9 \times 10\ 7\ J/kg$

b. $-2.9 \times 10\,9\ J/kg$

c. New potential (-1.5×10^7 J/kg) is more negative than original → probe is deeper in the gravity well → GPE decreases.]

3. a. $T = \frac{2\pi R}{v}$

$T = 2\frac{\pi R}{\sqrt{\frac{GM}{R}}} = 2\pi\left(\sqrt{\frac{R^3}{GM}}\right)]$

b. 7715 m/s

c. T = 5458.5 s ≈ 1.52 hours

4. 60234.64 m/s

5. • A common misconception is that astronauts experience weightlessness because they are far from Earth's gravity. In reality, weightlessness occurs because the spacecraft and the astronauts inside are in free-fall, continuously falling towards Earth but also moving forward fast enough that they keep missing it – essentially orbiting the Earth.]

In other words:

• In free-fall (e.g., orbiting the Earth), astronauts and their spacecraft accelerate toward Earth at the same rate, creating the sensation of weightlessness. Gravity is still present (about 90% of surface gravity in low-Earth orbit), but the continuous free-fall motion cancels its apparent effects.

• Key Point: Weightlessness occurs due to free-fall, not the absence of gravity.

SECTION 2

1. Petrol has a much higher coefficient of volume expansion than steel, so it will expand more and could cause the tank to burst or leak. The farmer should avoid filling the tank completely (leave some empty space), use a vented tank, or install an expansion chamber to accommodate the increased volume.

2. Stainless steel will be more durable because it has a lower coefficient of expansion than aluminium. Aluminium expands and contracts more with temperature changes, increasing stress and risk of deformation or cracking over time.

3. Brass has a higher coefficient of expansion than steel, so when heated, the strip bends predictably to operate the thermostat. If two metals with

similar expansion rates were used, the strip would bend very little or not at all, making the thermostat ineffective.

4.

a. 1.08cm

b. 2.16 cm, to prevent buckling or damage due to thermal expansion.

SECTION 3

Review Questions 3.1

1. **a.** The lights dim temporarily because switching on the 2000 W kettle causes a large current to flow. Due to the internal resistance (0.4 Ω) of the household wiring, this current causes a voltage drop across the wires. As a result, the voltage available to the lights is temporarily reduced, leading to dimming.

b. This suggests the home's wiring may be undersized or poorly distributed. The significant voltage drop can lead to:

- Overheating of wires, increasing fire risk.
- Repeated voltage fluctuations that may damage sensitive devices.
- Signs of overloading or poor circuit segmentation.

c. Three solutions:

- Upgrade household wiring to thicker cables with lower resistance to minimise voltage drops.
- Install a dedicated circuit for high-power appliances like the kettle to isolate them from lighting circuits.
- Use voltage stabilisers or uninterruptible power supplies (UPS) for lights or sensitive electronics to maintain consistent voltage.

Review Questions 3.2

1. Arrangement 1: Two 30Ω resistors in parallel = 15Ω

Arrangement 2: Two pairs of (10Ω || 30Ω, connected in parallel) connected in series = 15Ω

More Practical: Arrangement 1

Justification: Uses fewer components (2 vs 4 resistors), simpler circuit, lower cost, higher reliability, and easier to construct.

2. Rheostat is more suitable for controlling a 5A motor due to its structural advantages over a potentiometer. Rheostats are designed with thick resistance wire, heavy-duty contacts, and robust construction that can handle high current applications like 5A motor control, while also providing better heat dissipation through their larger physical size. In contrast, potentiometers have thin resistance tracks, delicate wipers, and compact designs optimised for low-current signal applications (typically milliamps), making them structurally inadequate for 5A current as they would overheat and fail.

Review Questions 3.3

1. Galvanometer-based meters offer significant advantages over digital multimeters for a rural school's physics laboratory with limited resources. While digital meters provide higher accuracy (±0.5-1% vs ±3-5%), multi-functionality, and easy numerical readings, they require batteries, are more expensive, and prone to electronic failures in harsh conditions. Galvanometer-based meters, though less accurate and requiring separate instruments for different measurements, operate without power, are mechanically robust, cost-effective, and provide superior educational value by allowing students to visualise measurement principles through needle deflection. Given the rural setting's challenges with unreliable electricity, limited budget, and educational objectives focused on understanding fundamental physics concepts, galvanometer-based meters are the better choice as they ensure consistent functionality regardless of power availability, have lower total ownership costs, and enhance conceptual learning of electrical measurement principles, making them more practical and pedagogically valuable for the school's specific context.

SECTION 4

1. **a.** 24.82 keV,

b. 8.27 keV.

c. For detailed bone imaging in fracture diagnosis, Unit A (producing hard X-rays) would be more suitable. To obtain a clear image of a fracture within a bone, the X-rays must have sufficient energy to pass through the surrounding soft tissue and then penetrate the bone itself. Hard X-rays, with their higher energy (like the 24.82 keV from Unit A), are capable of this penetration.

2. a. 7.95×10^{-15} J

b. 1.2×10^{19} Hz.

c. 49632 V

3. a. Bremsstrahlung (Braking Radiation): This is the main mechanism for producing a continuous spectrum of X-rays. When high-speed electrons from the cathode pass near the nucleus of an atom in the target material (anode), they are decelerated and deflected by the strong electric field of the nucleus. This deceleration causes the electrons to lose kinetic energy, which is emitted as electromagnetic radiation, specifically X-ray photons. The energy of these photons can vary, leading to a continuous X-ray spectrum, with the maximum energy corresponding to the full kinetic energy of the incident electron.

Characteristic X-ray Production: This mechanism produces discrete, specific X-ray energies (a line spectrum) unique to the target material. When a high-speed incident electron collides with and ejects an inner-shell electron (e.g., from the K or L shell) of an atom in the target, the atom becomes ionised and unstable. An electron from a higher energy shell (e.g., L or M shell) then drops down to fill the vacancy in the lower energy shell. As this electron transitions to a lower energy state, it emits an X-ray photon with an energy exactly equal to the difference in energy between the two shells. This energy is characteristic of the specific target atom.

b. The shortest wavelength of the X-rays produced is approximately 1.55×10−11 m.

Review Questions 4.2

1. Model answer: African countries hesitate to adopt nuclear power due to enormous upfront costs, lack of technical expertise, safety concerns following Chernobyl/Fukushima, political instability affecting long-term

projects, and complex waste disposal challenges that require decades of secure storage. For Ghana specifically, renewable alternatives appear more practical because the country has abundant solar potential, existing hydroelectric infrastructure, lower capital requirements, faster deployment times, and greater energy security through diversified sources rather than dependence on uranium imports. While nuclear power offers reliable baseload electricity and could support industrial development, Ghana's current energy demands can be met more cost-effectively through a combination of solar, wind, and hydroelectric expansion, which also aligns with international climate commitments and reduces technological dependence on foreign expertise. Ghana should prioritise renewable energy development while maintaining nuclear as a long-term option once the country develops sufficient technical capacity and economic stability to safely manage nuclear technology.

SECTION 5

1. Asteroid: A rocky, airless body that orbits the Sun, too small to be called a planet. Most are found in the asteroid belt between Mars and Jupiter.

Comet: An icy, rocky body that orbits the Sun. When it approaches the Sun, the ice sublimates, forming a visible coma (head) and often a tail.

Meteoroid: A small piece of rocky or metallic debris in space. If it enters Earth's atmosphere, it becomes a meteor (a "shooting star"). If it survives passage through the atmosphere and hits the ground, it's called a meteorite.

2. The Big Bang theory, specifically Big Bang Nucleosynthesis (BBN), predicts the precise proportions of the lightest elements formed in the first few minutes after the Big Bang, when the universe was hot and dense enough for nuclear fusion to occur but too cool for elements heavier than lithium to form. The observed cosmic abundances of roughly 75% hydrogen, 25% helium-4, and trace amounts of lithium-7 (by mass) remarkably match these theoretical predictions. Any significant deviation would pose a serious challenge to the Big Bang model.

SECTION 6

Review Questions 6.1

1. **a.** RMS current = 3.54 A
   b. Peak-to-peak current = 10 A
2. **a.** Peak voltage = 240 V
   b. RMS voltage = 169.7 V
   c. Frequency = 50 Hz
3. **a.** RMS current = 6 A
   b. Peak current = 8.49 A
   c. Power = 720 W
4. **a.** Frequency = 250 Hz
   b. RMS voltage = 10.61 V

Review Questions 6.2

1. Current = 5 A, Power = 625 W
2. Current ≈ 2.65 A
3. Current ≈ 2.4 A
4. Current ≈ 4.72 A
5. Real Power = 1200 W, Reactive Power ≈ 900 VAR, Apparent Power = 1500 VA
6. Power Factor = 0.6 (Lagging)
7. At resonance: C ≈ 35.2 μF, Current ≈ 3.33 A
8. **a.** Q ≈ 5.1 kVAR
   b. Q (to be cancelled) ≈ 4.17 kVAR
   c. New apparent power ≈ 5.26 kVA
9. **a.** Existing Q ≈ 175.4 Kvar
   b. Compensation required ≈ 116.7 kVAR
   c. Required capacitance ≈ 23.6 mF
   d. Total current reduces significantly; energy losses and penalties decrease.

SECTION 7

Review Questions 7.1

1. a. The lens used is a convex lens.

Reason

A magnified, upright, and virtual image can only be formed by a convex lens when the object is placed between its focal point (F) and the optical centre.

b. The focal length of the lens is 20cm.

c. The magnification is 4.

d. The height of the image is 16cm.

2. a. The position of the image is 60cm from the lens.

b. The focal length of the lens is 15cm.

c. The power of the lens is 6.667D.

3. a. The magnification is 2.

b. The focal length of the lens is 23.333 cm.

c. The power of the lens is 4.286 D.

d. The type of lens is a convex lens.

Review Questions 7.2

1. a. The critical condition where more atoms are in a high-energy state is called population inversion.

b. The physical process where a photon triggers the release of an identical photon is called stimulated emission.

c. Both processes are essential because they work together to amplify and control the light. Population inversion is the necessary prerequisite; it creates the unusual state where stimulated emission is more likely to occur than absorption. Stimulated emission then acts as the amplification engine, creating a cascade of identical photons that are all in phase (coherent) and travelling in the same direction, which results in the highly concentrated and coherent laser beam.

SECTION 8

Review Questions 8.1

1. $EMF = 0.4\ V$
2. **a.** $EMF = 4\ V$

   b. The current will try to increase the magnetic field (oppose the decrease).
3. **a.** $EMF = 1.2\ V$

   b. The magnetic field induces a current that opposes the motion (Lenz's Law), and the mechanical energy used to move the rod is fully converted to electrical energy (Law of Conservation of Energy).

Review Questions 8.2

1. • EMF: 3.77 V
   • Effect of higher permeability core: Increases magnetic flux, thus increasing emf
2. • Stored energy: 4.8 J
   • $P = 240$ W
3. • Induced emf: 2.0 V
   • $I = 4\ A$
   • $F = 0.4\ N$

Review Questions 8.3

1. Laminating the iron core restricts the paths for eddy currents, increasing electrical resistance and reducing energy lost as heat.
2. Solid cores allow large eddy current loops, generating more heat. Laminated cores break up these loops, reducing eddy currents and heating.
3. $I_2 = \frac{N_1}{N_2} \times I_1 = \left(\frac{500}{0}\right) \times 0.2 = 2.0\ A$
4. $Output\ power = 12 \times 5 = 60\ W$

   $Input\ power = \frac{60}{0.96} \approx 62.5$

   $WPower\ lost = 62.5 - 60 = 2.5\ W$

5. $Output\ power = 24 \times 4 = 96\ W$

$Input\ power = \frac{60}{0.90} \approx 106.67\ W$

$Primary\ current = \frac{106.67}{240} \approx 0.444\ A$

6. $Loss\ reduced = 10 - 2 = 8\ W$

$Percentage\ reduction = \left(\frac{8}{10}\right) \times 100 = 80\%$

7. $Input\ power = \frac{150}{0.95} \approx 157.89\ W$

$Power\ lost = 157.89 - 150 = 7.89\ W$

8. $Output\ power = 15 \times 6 = 90\ W$

$Input\ power = \frac{90}{0.92} \approx 97.83\ W$

$Primary\ voltage = 20 \times 15 = 300\ V$

$Primary\ current = \frac{97.83}{300} \approx 0.326\ A$

9. $Increase = 300\%\ of\ 4 = 12\ W$

$New\ power\ loss = 4 + 12 = 16\ W$

SECTION 9

1. 0.1667s

2. 9.0J

3. $\frac{A}{\sqrt{2}}$

4. 2.06%

5. $\frac{A}{2}$

6. The particle first reaches its maximum speed at t=π/3 seconds.

7. The final speed of the first particle is approximately 8.66 m/s at an angle of 30◦ and the final speed of the second particle is 5 m/s at an angle of 60◦.

8. **a.** The impulse delivered to the golf ball is 2.76 kg m/s.

b. The average force exerted on the ball by the club is 5520 N.

SECTION 10
Review Questions 10.1

1. The reasons why full-wave bridge rectifier is preferred are

- Better Transformer Utilisation: In a full-wave bridge rectifier, current flows through the secondary winding during both the positive and negative half-cycles of the AC input. This allows for more efficient use of the transformer's capacity compared to a half-wave rectifier, which only draws current during one half-cycle.
- Higher Average DC Output: The average DC output voltage of a full-wave rectifier is approximately twice that of a half-wave rectifier for the same transformer peak voltage
- Easier Filtering: The output of a full-wave rectifier has a ripple frequency that is double the input AC frequency. This higher frequency makes the ripple much easier to filter. A smaller capacitance value is needed to achieve the same ripple reduction as in a half-wave rectifier, which has a ripple frequency equal to the input frequency. The smaller capacitance means the circuit can be more compact and cost-effective.

2. Concept of biasing in a transistor amplifier circuit and reason it is essential for achieving faithful amplification

- Biasing is the process of setting the DC operating point (also known as the Q-point) of a transistor. This is done by applying specific DC voltages and currents to the transistor's terminals (base, emitter, and collector) to ensure it stays in the active region of operation.
- It's essential for faithful amplification because without proper biasing, the transistor would not be able to amplify the entire input signal without distortion. For example, if the transistor is not biased correctly, parts of the input signal could push it into the cutoff region (turning it off) or the saturation region (turning it fully on), which would clip the signal and alter its original shape. Correct biasing allows the transistor to linearly respond to the AC input signal, producing an amplified output that is a faithful, scaled-up version of the original.

3. NPN and PNP transistors are complementary in their operation and are often used in different types of circuits due to their polarity.

- Operating Characteristics

  NPN Amplifier: Activated by a positive voltage at the base relative to the emitter. The primary charge carriers are electrons, and current flows from the collector to the emitter. This configuration is often used for low-side switching, where the transistor is placed between the load and ground.

  PNP Amplifier: Activated by a negative voltage at the base relative to the emitter. The primary charge carriers are "holes," and current flows from the emitter to the collector. This configuration is ideal for high-side switching, where the transistor is placed between the positive supply and the load.

- Applications

  NPN amplifiers are more common in general-purpose amplification and logic circuits because they align with a positive supply voltage and a ground reference, which is standard in many electronic systems. They are widely used in audio preamplifiers and sensor circuits.

  PNP amplifiers are often found in complementary circuits, such as push-pull amplifiers, where they are paired with an NPN transistor to amplify both the positive and negative halves of a signal with high efficiency. They are also used in power regulation systems where high-side switching is required.

Review Questions 10.2

1. Goal: Design a light detector (turns on when it's bright, off when it is dark).

   a. Key Idea for Modification: To reverse the functionality, we need to ensure that:

   i. In bright light, the TRIAC gets triggered.

   ii. In darkness, the TRIAC does not get triggered.

   The LDR's property is: Low resistance in light, High resistance in dark

   The TRIAC triggers when its gate current is sufficient.

   Proposed Modification to a Common Darkness Detector Circuit:

The core change is to swap the positions of the LDR and the 220k resistor.

- Original Circuit (Darkness Detector): AC Line -- Bulb -- 220k Resistor -- Junction -- LDR -- Other AC Line (and Gate connected at Junction) (LDR in parallel with Gate, relative to the 220k resistor)
- Modified Circuit (Light Detector): AC Line -- Bulb -- LDR -- Junction -- 220k Resistor -- Other AC Line (and Gate connected at Junction) (220k Resistor in parallel with Gate, relative to the LDR)

  (Alternatively, and perhaps more commonly seen in practice: the LDR in series with the gate, and a fixed resistor shunting the gate to MT1, but swapping is a direct inversion for this specific circuit's current path.) Let's go with the direct swap of the 220k resistor and LDR as it directly inverts the logic based on the existing circuit structure.

b. Step-by-step Description of Operation for the Modified Light Detector:

i. Placement Change: The LDR is now placed where the 220k resistor was, and the 220k resistor is placed where the LDR was. The TRIAC's gate (G) is still connected to the junction between the LDR and the 220k resistor.

ii. During Darkness (Insufficient Light):

- The LDR's resistance is very high.
- Since the LDR is now in series with the current path leading to the junction (and the TRIAC's gate), it's very high resistance will significantly limit the current flowing towards the gate.
- The current flowing to the gate (through the LDR) will be too low to trigger the BT136 TRIAC.
- The TRIAC remains in its "off" state, and the light bulb stays off.

iii. During Daylight (Sufficient Light):

- The LDR's resistance is very low.

- With the LDR's resistance being low, it now allows a relatively significant current to flow through it from the AC line (after the bulb) to the junction.
- At this junction, the current now has a path into the TRIAC's gate.
- Because the LDR's resistance is low, the current reaching the gate is now sufficient to trigger the BT136 TRIAC into its "on" state.
- Once the TRIAC is "on," it acts as a closed switch, completing the circuit for the 220V AC current to flow through the bulb, which then lights up.
- This process repeats for each half-cycle of the AC waveform, keeping the bulb lit as long as there is sufficient light.

c. Justification for Design

By swapping the LDR and the fixed resistor, we effectively invert the voltage (and thus current) division at the gate. In the darkness detector, high LDR resistance in parallel with the gate allows current to flow to the gate. In the light detector, low LDR resistance in series with the gate allows current to flow through to the gate. This direct inversion of the current path to the gate provides the desired inverted functionality.

Review Questions 10.3

1. Project Work: Automatic Battery Charger with Overcharge Protection

Design Concept: To prevent overcharging, the circuit needs to automatically sense when the battery voltage reaches 14.4V and then open the charging path. A simple but effective way to achieve this is by using a Zener diode as a voltage reference and a bipolar junction transistor (BJT) as a switch to control the charging current.

Circuit Modification and Explanation

a. Component Selection

i. Zener Diode: A Zener diode with a breakdown voltage of approximately 13V to 14V. (e.g., a 13.8V Zener).

ii. Transistor: A general-purpose NPN transistor (e.g., 2N2222) to act as a switch.

iii. Resistors: A few current-limiting resistors for the Zener diode and the transistor's base.

b. Circuit Integration (Simplified): The new sub-circuit would be connected in parallel with the battery terminals.

i. A resistor and the Zener diode are placed in series across the battery's terminals.

ii. The transistor's base is connected to the junction between the Zener diode and its resistor.

iii. The transistor is wired to control the charging path (e.g., by being in series with the charging current).

c. Working Principle of Overcharge Protection

i. Battery Voltage Below 14.4V: When the battery voltage is below the Zener diode's breakdown voltage, the Zener diode acts like an open circuit and does not conduct. This means no current flows to the base of the transistor, so the transistor remains in its "off" state. With the transistor off, the charging path remains closed, and the battery continues to charge.

ii. Battery Voltage Reaches 14.4V: As the battery's voltage rises and reaches the Zener diode's breakdown voltage (e.g., 13.8V), the Zener diode starts to conduct. This allows a small current to flow into the base of the transistor, turning it "on" and allowing a much larger current to flow through its collector-emitter terminals.

iii. Interrupting the Charge: The turned-on transistor is used to disrupt the charging path. For instance, it could be wired to act as a low-resistance path that diverts the charging current away from the battery or to control a relay that physically disconnects the battery from the charging circuit. The end result is that the battery is no longer receiving a charging current, preventing it from being overcharged.

Advantages of the Modified Circuit

- Battery Health: The most significant advantage is the prevention of overcharging, which drastically extends the life of the rechargeable battery.
- Safety: It eliminates the risks of electrolyte boiling, gassing, and potential battery damage or explosion that are present with a simple, unsupervised charger.
- Automation: The process is fully automatic, removing the need for manual monitoring of the charging time or voltage.

ANNEX

Section 1

Expected Observations for Activity 1.1

- Force Magnitude: Increasing the force (weight) increases the turning effect (moment).
- Perpendicular Distance: Increasing the perpendicular distance increases the turning effect (moment).
- Direction: Forces on one side of the pivot cause rotation in one direction (e.g., clockwise), while forces on the other side cause rotation in the opposite direction (e.g., anti-clockwise).

Activity 1.5

1. a. Given that: $R_1 + R_2 = 52N$ .....(1)

The ruler is in equilibrium and taking moment about the centre of gravity G. From the principle of moment, sum of clockwise moment = sum of anticlockwise moment.

$10R1 + (45 \times 9) = 35R_2$

$10R1 + 405 = 35R_2$ ..... (2)

From equation 1, $R_1 = 52 - R_2$ and putting it into equation two gives

$10(52 - R_2) = 35R_2$

$520 - 10R_2 = 35R_2$

$520 = 35R_2 - 10R_2$

$520 = 25R_2$

$R2 = 20.8$ N

Putting this value into $R_1 = 52 - R_2$ gives

$R_1 = 52 - 20.8$

$R_1 = 31.2$ N

Hence the reactions at the knife edges are 31.2 N and 20.8 N.

b. Again, since the ruler is in equilibrium, then

$R_1 + R_2 = W + 9$

$52 = W + 9$

$W = 52 - 9$

$W = 43$ N; Hence the weight of the ruler is 43 N.

2. Since the rule is horizontally balanced, it implies that sum of clockwise moment equals sum of anticlockwise moment

$0.2 \times m = 0.05 \times 0.1$

$0.2m = 0.005$

$m = 0.005/0.2$

$m = 0.025$kg; Hence the mass of the rule is 0.025 kg.

Activity 1.11

1. Acceleration due to gravity at a height of 100km above Mars

$$g = \frac{GM}{R^2}$$

$$g = \frac{6.67430 \times 10^{-11} \times 6.42 \times 10^{23}}{(3.39 \times 10^6 + 100 \times 10^3)^2}$$

$$g = 3.52\ m/s^2$$

2. Gravity on the Moon

$$g = \frac{GM}{R^2}$$

$$g = \frac{6.67430 \times 10^{-11} \times 7.35 \times 10^{22}}{(1.74 \times 10^6)^2}$$

$$g = 1.62\ m/s^2$$

3. Gravitational Force between Earth and Moon

$$F = \frac{GM_1M_2}{R^2}$$

$$F = \frac{6.67430 \times 10^{-11} \times 5.97 \times 10^{24} \times 7.35 \times 10^{22}}{(3.84 \times 10^8)^2}$$

$$F = 1.99 \times 10^{20}\ N$$

4. Force between Jupiter and a Moon

$$F = \frac{GM_1M_2}{R^2}$$

$$F = \frac{6.67430 \times 10^{-11} \times 1.9 \times 10^{27} \times 8.9 \times 10^{22}}{(4.2 \times 10^{8})^2}$$

$$F = 6.4 \times 10^{22}\ N$$

5. Gravity at 100 km Altitude

$$g = \frac{GM}{(R+h)^2}$$

$$g = \frac{6.67430 \times 10^{-11} \times 5.97 \times 10^{24}}{(6\,400\,000 + 100\,000)^2}$$

$$g = 9.43\ m/s^2$$

6. Altitude where gravity is half of 9.8 m/s²

Refer to question 5 for the values of G and R

$$\frac{GM}{(R+h)^2} = 4.9$$

$$R + h = \sqrt{\frac{GM}{4.9}}$$

$$h = \sqrt{\frac{GM}{4.9}} - R$$

$$\sqrt{\frac{6.67430 \times 10^{-11} \times 5.7 \times 10^{24}}{4.9}} - 6.4 \times 10^{6}$$

Altitude ≈ 2,640 km

Section 2

Activity 2.5

1. $l\,2 = l\,1(1 + \alpha\,\Delta\,\theta)$

$$l_2 - l_1 = l_1\,\alpha\,\Delta\,\theta$$

$$l_2 - l_1 = 500\ m \times 1.7 \times 10^{-5} \times (35 - 15)$$

$$l_2 - l_1 = 0.17\ m$$

2. $A_1 = 1.5^2 = 2.25\ m^2$

$\beta = 2\alpha$

$\beta = 2 \times 3.3 \times 10^{-6}$

$\beta = 6.6 \times 10^{-6}\ °C^{-1}$

$A_2 = A_1(1+ \beta \Delta \theta)$

$A_2 = 2.25(1+ 6.6 \times 10^{-6}(0 - 20)$

$A_2 = 2.252.249703$ m2

Section 3

Activity 3.6

1. $I = \frac{V}{R}$

$I = \frac{220}{110}$

$I = 2\ A$

2. $R = \frac{V}{I}$

$R = \frac{5}{2}$

$R = 2.5\ A$

Expected results for Activity 3.11

Resistance increases with length, decreases with greater cross-sectional area (thickness), and depends on resistivity (material).

Activity 3.12

1. **a.** Rtotal=R1+R2

Rtotal= 6 Ω + 6 Ω

Rtotal= 12 Ω

b. $\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2}$

$\frac{1}{R_{total}} = \frac{1}{6} + \frac{1}{6}$

$\frac{1}{R_{total}} = \frac{1}{3}$

$R_{total} = 3\ \Omega$

2. $A = \frac{\pi d^2}{4}$

$A = \frac{\pi(0.5 \times 10^{-3} m)^2}{4}$

$A = 1.963 \times 10^{-7} m^2$

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

$L = \frac{RA}{\rho}$

$L = \frac{50 \times 1.963 \times 10^{-7}}{1.1 \times 10^{-6}}$

$L = 8.92\ m$

Activity 3.15

1. Let the current I be the current entering junction X, I_1 leaving the junction into XY and I_2 leaving the junction into AB.

i. $I = I_1 + I_2$ ..... (1)

Taking the closed loop CDXYC in the anticlockwise direction and applying Kirchoff's second law,

$12 = 2I_1 + 3I_1$

$12 = 5I_1$

$I_1 = 12/5$

$I_1 = 2.4A$

Taking the closed loop ABYXA in the clockwise direction,

$0 = 5I_1 - 9I_2$

$9I_2 = 5I_1$

$9I_2 = 5 \times 2.4$

$I_2 = 12/9$

$I_2 = 1.333A$

The current that enters the junction X is given as 2.4 +1.333 = 3.733A

ii. The p.d across the 3Ω resistor is given as $3 \times 2.4 = 7.2V$

iii. The p.d across AB is given as V_{AB}

$V_{AB} = 1.333 \times 5 + 1.333 \times 4$

$V_{AB} = 6.665 + 5.332$

$V_{AB} = 11.997V$

2. Let the currents I, I1 and I2 flow through the branches of the circuit such that I is the current from the 10V cell into the junction F, I2 is the current from the 15V cell into the junction F and I1 the current leaving the junction F into the 12Ω resistor

Applying Kirchoff's first law,

$I_1 = I + I_2$ ..... (1)

Taking the closed loop ABCFA in the clockwise direction and applying Kirchoff's second law,

$10 = 8I + 2I + 12I_1$

$10 = 10_I + 12I_1$

$(10 - 12I_1)/10 = I$ ..... (2)

Also taking the closed loop CDEFC in the anticlockwise direction and applying Kirchoff's second law,

$15 = 3I_2 + 12I_1$

$(15 - 12I_1)/3 = I_2$

$5 - 4I_1 = I2$ ..... (3)

Putting equations 3 and 2 into 1 give

$I_1 = (10 - 12I_1)/10 + 5 - 4I_1$

Multiplying through by 10 gives

$10I_1 = 10 - 12I_1 + 50 - 40I_1$

$10I_1 = 60 - 52I_1$

$10I_1 + 52I_1 = 60$

$62I_1 = 60$

$I_1 = 60/62$

$1_I = 0.96774A$

Since I_1 is the current flowing through the 12Ω resistor, then the potential difference across it is given as VFC

Hence $V_{FC} = 12I_1$

$V_{FC} = 12 \times 0.96774$

$V_{FC} = 11.7288V.$

Activity 3.17

1. $R_s = \frac{I_g R_g}{I - I_g}$

$R_s = \frac{0.002 \times 20}{1 - 0.002}$

$R_s = 0.040\ \Omega$

2. $R_m = \frac{V}{I_g} - R_g$

$R_m = \frac{10}{0.0015} - 40$

$R_m = 9960\ \Omega$

Section 4

Activity 4.4

Worksheet Sample Questions (Matching Exercises)

- Match the x-ray type used for airport luggage scanning.

  Hard x-rays
- Which x-ray type is used in studying thin surface layers of materials?

  Soft x-rays
- Identify the x-ray type that can penetrate bones and tissue for medical imaging.

  Hard x-rays
- Which x-rays are less penetrating and often absorbed by air?

  Soft x-rays

- Match the application of x-rays used in crystallography.

  Hard x-rays

Activity 4.5

$E = 120\ \text{keV} = 120 \times 10^3 \times 1.602 \times 10^{-19}\ \text{J} = 1.9224 \times 10^{-14}\ \text{J}$

$E = h\frac{c}{\lambda}$

$\lambda = h\frac{c}{E}$

$\lambda = 6.6 \times 10^{-34}\ \frac{3.00 \times 10^8}{1.9224 \times 10^{-14}}$

$\lambda = 1.34 \times 10^{-11}\ \text{m}.$

Activity 4.9

1. a. Number of protons (Z) = 82

Number of neutrons (N) = *Mass Number* (A) − *Atomic Number* (Z)

$= 208 - 82 = 126$

So, Lead − 208 *has* 82 *protons and* 126 *neutrons.*

b. *Expected total mass of individual nucleons* $= (Z \times mp) + (N \times mn)$

i. *Expected mass* $= (82 \times 1.007276\ amu) + (126 \times 1.008665\ amu)$

Expected mass $= 82.596632\ amu + 127.091790\ amu$

Expected mass $= 209.688422\ amu$

ii. *Mass defect* (Δm) = *Expected mass* − *Actual atomic mass*

$\Delta m = 209.688422\ amu - 207.976652\ amu$

$\Delta m = 1.711770\ amu$

iii. *Binding Energy* (BE) *in MeV* $= \Delta m \times 931.5\ MeV/amu$

$BE = 1.711770\ amu \times 931.5\ MeV/amu$

$BE \approx 1594.5\ MeV$

iv. *Binding Energy per Nucleon* (BE/A)*in MeV/nucleon*

$= \frac{BE}{\text{Mass Number } (A)}$

$BE/A = \frac{1594.5 MeV}{208\ nucleons}$

$BE/A \approx 7.67\ MeV/nucleon$

c. Discussion

Trend: The binding energy per nucleon generally increases from very light nuclei (like Deuterium, ≈1.12 MeV/nucleon) to a peak around Iron-56 (≈8.79 MeV/nucleon), and then it gradually decreases for very heavy nuclei (like Lead-208, ≈7.67 MeV/nucleon, and Uranium-235, ≈7.6 MeV/nucleon).

Section 6

Activity 6.4

1. f = 60 Hz

$V_o = 325$ V

a. $T = \frac{1}{f} = \frac{1}{60} = 0.017\ s$

b. $RMS\ Voltage\ (V_{rms}) = \frac{V_o}{\sqrt{2}}$

$RMS\ Voltage\ (V_{rms}) = \frac{325}{\sqrt{2}} = 230\ V$

2. $I(t) = 8sin(314t)$

$I(t) = I_0 \sin(\omega t)$

peak current $I_o = 8$ A

$I_{rms} = \frac{I_0}{\sqrt{2}} = \frac{8}{\sqrt{2}} = 5.66\ A$

$I(t) = 8sin(314t)$.

$I(t) = I_0 \sin(\omega t)$.

At the first peak, $\omega t = 314t = \frac{\pi}{2}$,

$t = \frac{\pi}{2\omega} = \frac{\pi}{2 \times 314} = 0.005\ s = 5\ ms$

Activity 6.10

1. **a.** Resistance = 23 Ω

b. Power = 2300 W

2. **a.** [$X_C \approx 53.05\ \Omega$]

b. [Current ≈ 2.26 A]

3. **a.** [$X_L \approx 31.42\ \Omega$]
   b. [Current ≈ 3.18 A]
4. **a.** [$X_L \approx 62.83\ \Omega$, XC ≈ 53.05 Ω]
   b. [Net reactance ≈ 9.78 Ω, Impedance ≈ 41.2 Ω]
   c. [Current ≈ 2.91 A]
5. **a.** [Real Power = 2475 W, Apparent Power = 3300 VA, Reactive Power ≈ 2112 VAR]
   b. [Required compensation ≈ 1472 VAR]
   c. [Suggestion: Add a capacitor in parallel]

Section 7

Activity 7.5

1. Object distance u = 30cm

   Magnification m = 2

   Image distance v =?

   Focal length f =?

   Power of lens P =?

   a. From m = v/u

   2 = v/30

   v = 2 × 30

   v = 60cm

   Hence the image position is 60cm from the lens.

   b. From 1/f = 1/v + 1/u

   1/f = 1/60 + 1/30

   1/f = 1/20

   f = 20cm

   Hence the focal length of the lens is 20cm.

   c. Power of lens P = 1/f

   But f = 0.2m

   Hence P = 1/0.2

   P = 5D.

Section 8

Activity 8.5

1. $EMF = \frac{\Delta\Phi}{\Delta t} = \frac{0.01 - 0.05}{0.2} = -0.2\ V$

2. $EMF = N \cdot \frac{\Delta\Phi}{\Delta t} = 150 \cdot \left(\frac{0.002}{0.05}\right) = 6\ V$

3. **a.** $\Delta B = 0.1 - 0.4 = -0.3\ T$

$\Delta\Phi = A \cdot \Delta B = 0.01 \cdot (-0.3) = -0.003\ Wb$

$EMF = N \cdot \frac{\Delta\Phi}{\Delta t} = 50 \cdot \left(-\frac{0.003}{0.3}\right) = -0.5\ V$

b. Since the field is decreasing, the induced current will flow in a direction to oppose the decrease — i.e., it will reinforce the original magnetic field direction.

4. **a.** $EMF = B \cdot l \cdot v = 0.60 \times 25 \times 5 = 0.75\ V$

b. $I = \frac{EMF}{R} = \frac{0.75}{2} = 0.375\ A$

Activity 8.11

1. $L = \frac{N\phi}{I}$

$= \frac{500 \times 2 \times 10^{-3}}{4} = 0.25\ H$

2. $M = \frac{N\phi}{I}$

$= \frac{200 \times 0.4 \times 10^{-3}}{3} \approx 0.0267\ H$

3. **a.** $emf = -L\left(\frac{dI}{dt}\right) = -0.4 \times \left(\frac{6}{0.03}\right) = -80\ V\ (magnitude = 80\ V)$

b. Energy = ½LI² = ½ × 0.4 × 6² = 7.2 J

4. **a.** $emf = M\left(\frac{dI}{dt}\right) = 0.5 \times \left(\frac{5}{0.01}\right) = 250\ V$

b. $Energy = N\phi I = 100 \times 0.002 \times 5 = 1\ J$

Activity 8.17

1. $V_2 = \left(\frac{N_2}{N_1}\right) \times V_1 = \left(\frac{100}{400}\right) \times 240 = 60\ V$

2. $N_2 = \left(\frac{V_2}{V_1}\right) \times N_1 = \left(\frac{480}{120}\right) \times 300 = 1200 \; turns$

3. $\mathrm{I}_2 = \frac{N_1}{N_2} \times I_1 = \left(\frac{500}{100}\right) \times 2 = 10 \; A$

4. $P = VI \rightarrow I = \frac{P}{V} = \frac{240}{60} = 4 \; A$

5. $P_1 = P_2 \rightarrow V_1 I_1 = V_2 I_2$

$\rightarrow I_2 = \frac{V_1 I_1}{V_2} = \frac{220 \times 0.5}{11} = 10 \; A$

6. $Output \; power = 24 \times 5 = 120 \; W$

$Input \; power = \frac{120}{0.9} = 133.33 \; W$

$V_1 = \frac{N_1}{N_2} \times V_2 = \left(\frac{1000}{200}\right) \times 24 = 120 \; V$

$I_1 = \frac{P_{in}}{V_{out}} = \frac{133.33}{120} \approx 1.11 \; A$

7. $Input \; power = 240 \times 1.5 = 360 \; W$

$Output \; power = 0.96 \times 360 = 345.6 \; W$

$V_2 = \frac{P_{out}}{I_2} = \frac{345.6}{3} = 115.2 \; V$

8. $Output \; power = 11 \times 6 = 66 \; W$

$Input \; power = \frac{66}{0.92} \approx 71.74 \; W$

$I_1 = \frac{P_{in}}{V_1} = \frac{71.74}{220} \approx 0.33 \; A$

9. *Simplified Solution* : $Output \; power = 10 \times 2 = 20 \; W$

$Input \; power = \frac{20}{0.95} \approx 21.05 \; W$

$V_1 = \left(\frac{N_1}{N_2}\right) \times V_2 = \left(\frac{500}{100}\right) \times 10 = 50 \; V$

$I_1 = 2\frac{1.05}{50} \approx 0.42 \; A$

10. *Simplified Solution* : $Output \; power = 12 \times 5 = 60 \; W$

$Input \; power = \frac{60}{0.93} \approx 64.52 \; W$

$I_1 = \frac{P_{in}}{V_1}, \; V_1 = 10 \times 12 = 120 \; V$

$I_1 = \frac{64.52}{120} \approx 0.54 \; A$

Section 9

Activity 9.5

1. $T = 2\pi\sqrt{\frac{e}{g}}$

$E = 0.3m$ and $g = 10m/s2$

$T = 2\pi\sqrt{\frac{0.3}{10}}$

$T = 2\pi\sqrt{0.03}$

$T = 2\pi(0.1732)$

$T = 1.088s$

Hence the period of oscillation is 1.088s.

Activity 9.8

1. From the conservation of mechanical energy E,

$E = KE + PE$

Which is expanded as $\frac{1}{2}kA^2 = \frac{1}{2}kx^2 + \frac{1}{2}mv^2$

Multiplying through by 2 and grouping like terms gives

$kA^2 - kx^2 = mv^2$

$k(A^2 - x^2) = mv^2$

$k(0.2^2 - 0.1^2) = 0.5 \times 0.2^2$

$k(0.04 - 0.01) = 0.02$

$0.03k = 0.02$

$k = 0.667N/m$

Hence the spring constant is 0.667N/m

2. The maximum kinetic energy, $K.Emax = \frac{1}{2}m\omega^2A^2$

But $\omega = \frac{2\pi}{T}$

$\omega = \frac{2\pi}{2}$

$\omega = 3.1416rad/s$

$hence$, $K.Emax = \frac{1}{2}(0.6)(3.1416)^2(0.07)^2$

$K.Emax = 0.01451J$

Activity 9.11

1. Mass of baseball mb = 0.15kg

Initial velocity of baseball u = 40m/s

Final velocity of baseball v = -50m/s

But impulse $I = -mv - mu$

$I = -0.15 \times 50 - 0.15 \times 40$

$I = -7.5 - 6$

$I = -13.5Ns$

Also, impulse $I = Ft$

$-13.5 = 0.002F$

$F = -6750N$

2. Let $m_1 = 5kg$, $u_1 = 6m/s$, $v_1 = 2m/s$, $m_2 = 3kg$, $u_1 = 0$ and $v_2 = ?$

From $m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$

$(5 \times 6) + (3 \times 0) = (5 \times 2) + (3v_2)$

$30 + 0 = 10 + 3v_2$

$30 - 10 = 3v_2$

$20 = 3v_2$

$v_2 = 6.667m/s$

Hence the find velocity of the 3kg block is 6.667m/s.

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GLOSSARY

Acceleration: Rate of change of velocity; in SHM, directed opposite to displacement.

Acceleration due to gravity (g): Rate at which objects accelerate towards Earth ($\approx 9.8\ m/s^2$).

Accretion: The process by which small particles of dust and gas in space come together to form larger objects like planets, moons, asteroids, and comets.

Alternating Current (AC): Electric current that periodically reverses direction in a circuit.

Ammeter – An instrument used to measure electric current in a circuit; connected in series with low resistance.

Amplification – The process of increasing the strength of a weak electrical signal.

Amplitude – Maximum displacement from the equilibrium position during oscillation.

Amplitude: Maximum value of current or voltage in a waveform.

Anode: Positive electrode in an x-ray tube where electrons strike to produce x-rays.

Anomalous Expansion of Water – Unusual property of water where it expands as it cools from 4°C to 0°C.

Aperture – Diameter of the lens through which light can pass.

Area Expansion – Increase in the surface area of a material when its temperature rises.

Battery Charger – A device or circuit used to restore electrical energy in rechargeable batteries.

Bimetallic Strip – A strip made of two metals with different expansion rates, which bends when heated.

Binding Energy: Energy holding protons and neutrons together in the nucleus.

Black Hole: A region of spacetime where gravity is so strong that nothing, not even light, can escape.

Bremsstrahlung: Radiation produced when electrons are decelerated near atomic nuclei.

Capacitive Reactance: Opposition to AC by a capacitor; decreases with frequency.

Capacitor – An electronic component that stores and releases electrical energy, often used for filtering.

Centre of gravity: Point where the weight of a body appears to act.

Circuit – A closed loop through which electric current can flow, including components like power sources, conductors, and loads.

Coefficient of Expansion – A constant that measures how much a material expands per unit temperature change.

Coherence – Consistent phase relationship between light waves in a beam.

Collector – The terminal of a transistor through which the main current flows.

Collimation – Property of laser light to travel in a narrow, parallel beam.

Collision – Interaction where two or more bodies exert forces on each other briefly.

Concave Lens – Lens thinner in the middle that diverges light rays.

Contraction – The decrease in size of a material when its temperature decreases.

Control Rods: Devices in a reactor that absorb neutrons to regulate the fission process.

Convex Lens – Lens thicker in the middle that converges light rays.

Couple: Pair of equal and opposite forces not acting along the same line, causing rotation.

Current (I) – The time rate at which electric charge flows through a conductor; measured in amperes (A).

Cycle: One complete back-and-forth of AC waveform.

Darkness Detector – A circuit that automatically activates a device when ambient light is low.

Diode – A semiconductor device that allows current to flow in only one direction.

Eddy currents – Loops of induced current in conductors caused by changing magnetic fields.

Elastic Collision – A collision conserving both momentum and kinetic energy.

Electromagnetic induction – Production of EMF when a conductor experiences a changing magnetic field.

Electromotive Force (EMF) – The total energy supplied per unit charge by a power source; measured in volts (V).

EMF (Electromotive Force) – Voltage generated by a source or through electromagnetic induction.

Emitter – The terminal of a transistor through which current leaves the device.

Equilibrium: A state where net force and net moment on a body are zero.

Escape velocity: Minimum speed needed to leave a planet's gravitational field without return.

Expansion Joint – A gap left in structures like bridges to allow safe expansion during heat changes.

Filter Circuit – A circuit designed to smooth or remove fluctuations in voltage or current.

Fission: Splitting of a heavy nucleus into smaller nuclei, releasing energy.

Fleming's Right-Hand Rule – Rule to find induced current direction in a moving conductor.

Focal Length – Distance from the optical centre to the principal focus.

Frequency – Number of oscillations completed per unit time.

Frequency: Number of cycles per second; measured in hertz (Hz).

Full-Wave Rectifier – A rectifier that converts both halves of an AC cycle into DC.

Fusion: Combining of light nuclei to form a heavier nucleus, releasing energy.

Gain Medium – Material in which laser light amplification occurs.

Galvanometer – A sensitive device used to detect and measure small electric currents.

Gravitational field: Region around a mass where another mass experiences a force.

Gravitational potential energy (GPE): Energy due to an object's position in a gravitational field.

Gravitational potential: Work done in bringing a unit mass from infinity to a point in a field.

Half-Wave Rectifier – A rectifier that converts only one half of an AC cycle into DC.

Hard x-rays: High-energy x-rays with greater penetration power.

Impedance (Z): Total opposition to AC; combines resistance and reactance.

Impulse – Product of force and time; equal to change in momentum.

Inductance – Property of a coil to oppose current change via induced EMF.

Inductive Reactance: Opposition to AC by an inductor; increases with frequency.

Inductor – Coil that stores energy in a magnetic field and resists current change.

Inelastic Collision – A collision conserving momentum but not kinetic energy.

Instantaneous Value: Current or voltage at a specific time.

Ionising Radiation: Radiation that removes electrons from atoms, creating ions.

Kinetic Energy – Energy a body possesses due to motion.

Kirchhoff's Current Law (KCL) – States that the total current entering a junction equals the total current leaving it.

Kirchhoff's Voltage Law (KVL) – States that the sum of all voltages around any closed-circuit loop is zero.

Lenz's Law – Induced current opposes the change in magnetic flux that caused it.

Lever arm (moment arm): Perpendicular distance from pivot to force's line of action.

Light Dependent Resistor (LDR) – A resistor whose resistance changes with the amount of light falling on it.

Linear Expansion – The increase in length of a solid when heated.

Linear Expansivity (α) – Fractional increase in length per degree change in temperature.

Magnetic flux – Measure of magnetic field lines passing through a surface.

Mass Defect: Difference between the total mass of individual nucleons and the actual nuclear mass.

Moderator: Material in a reactor that slows down neutrons to sustain fission.

Moment: Turning effect of a force about a point or axis.

Momentum – Product of mass and velocity; a vector quantity.

Monochromaticity – Property of light having a single wavelength.

Multimeter – A measuring device that combines functions of an ammeter, voltmeter, and ohmmeter.

Mutual inductance – Induction of EMF in one coil due to changing current in another.

Neutral equilibrium: Disturbance causes the object to settle in a new position without restoring force.

Newton's Law of Gravitation: Every mass attracts another with a force proportional to the product of masses and inversely proportional to the square of the distance.

NPN Transistor – A transistor type where current flows from collector to emitter when a small base current is applied.

Nuclear Fusion: The process where light atomic nuclei (like hydrogen) combine to form heavier nuclei (like helium), releasing immense amounts of energy. This is how stars generate light and heat.

Nuclear Reactor: A system that controls nuclear fission to generate electricity.

Ohm's Law – A law that relates voltage (V), current (I), and resistance (R) by the formula $V = IR$.

Ohmic Conductor – A conductor that obeys Ohm's Law with constant resistance regardless of applied voltage.

Optical Centre – Point on a lens where light passes without deviation.

Parallel Circuit – A circuit in which components are connected across the same two points, providing multiple current paths.

Peak Value: Maximum positive or negative value of a waveform.

Period – Time taken for one complete oscillation.

Period (T): Time taken to complete one full AC cycle.

Phasor: Rotating vector representing AC quantity with magnitude and phase.

Photon: A quantum (packet) of electromagnetic energy.

Planetary Nebula: The beautiful, expanding shell of gas shed by a dying Sun-like star.

Planets: Celestial bodies that orbit stars.

PNP Transistor – A transistor type where current flows from emitter to collector when the base is at a lower potential.

Population Inversion – Condition where more atoms are in an excited state than the ground state.

Potential Difference (Voltage) – The energy transferred per unit charge between two points; drives current in a circuit.

Potential Energy – Energy stored due to position or configuration in a system.

Power Factor: Ratio of real power to apparent power; indicates efficiency.

Principal Axis – Imaginary line passing through the optical centre and curvature centres.

Principal Focus – Point where parallel rays converge or appear to diverge after refraction.

Protoplanetary Disk: A flat, rotating ring of material (dust, ice, gas) that surrounds a young star, from which planets form.

Protostar: A dense ball of gas and dust formed from a collapsing nebula, which will eventually become a star once nuclear fusion begins in its core.

Reactance (X): Opposition to AC from inductors or capacitors.

Rectifier – A device or circuit that converts alternating current (AC) to direct current (DC).

Refraction – Bending of light when it passes between different media.

Resistance (R) – The opposition to current flow in a material or component; measured in ohms (Ω).

Resistor – A component that introduces resistance into a circuit to control current flow.

Resonance: Condition where inductive and capacitive reactances are equal; impedance is minimum.

Restoring Force – Force that pulls a body back toward equilibrium in SHM.

Root Mean Square (RMS): Effective value of varying AC voltage or current.

Rotational equilibrium: A state where total clockwise moments equal total anticlockwise moments.

Self-inductance – Induction of EMF in a coil by its own changing current.

Simple Harmonic Motion (SHM) – Oscillatory motion with restoring force proportional to displacement.

Soft x-rays: Low-energy x-rays with limited penetration ability.

Stable equilibrium: After slight disturbance, body returns to original position.

Stimulated Emission – Process where an incoming photon triggers emission of an identical photon.

Superficial (Area) Expansivity (β) – Fractional increase in surface area per degree change in temperature

Supernova: A powerful and luminous stellar explosion, marking the catastrophic death of a massive star or the sudden reignition of a white dwarf

Thermal Expansion – The increase in size of a material when its temperature rises.

Thermal Fatigue – Weakening of a material caused by repeated heating and cooling cycles.

Thermal Stress – Stress produced in a material due to restricted expansion or contraction.

Thermionic Emission: Release of electrons from a heated metal surface.

Thermostat – A device that uses thermal expansion (often a bimetallic strip) to control temperature.

Torque: Rotational effect caused by a couple; product of force and distance between forces.

Transformer – Device that changes AC voltage using electromagnetic induction.

Transistor – A semiconductor device used for switching or amplifying electrical signals.

Variable Resistor – A resistor whose resistance can be adjusted, such as a potentiometer or rheostat.

Velocity – Rate of change of displacement; maximum at equilibrium in SHM.

Voids: Vast, empty spaces between the filaments of the cosmic web, containing very few galaxies.

Volume Expansion – The increase in the volume of a material when heated.

Volume Expansivity (γ) – Fractional increase in volume per degree change in temperature.

X-ray Tube: A device that generates x-rays by accelerating electrons toward a metal target.

This book is intended to be used for the Year Three Physics Senior High School (SHS) Curriculum. It contains information and activities to support teachers to deliver the curriculum in the classroom as well as additional exercises to support learners' selfstudy and revision. Learners can use the review questions to assess their understanding and explore concepts and additional content in their own time using the extended reading list provided.

All materials can be accessed electronically from the Ministry of Education's Curriculum Microsite.

[Scan the QR Code to visit the website]

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