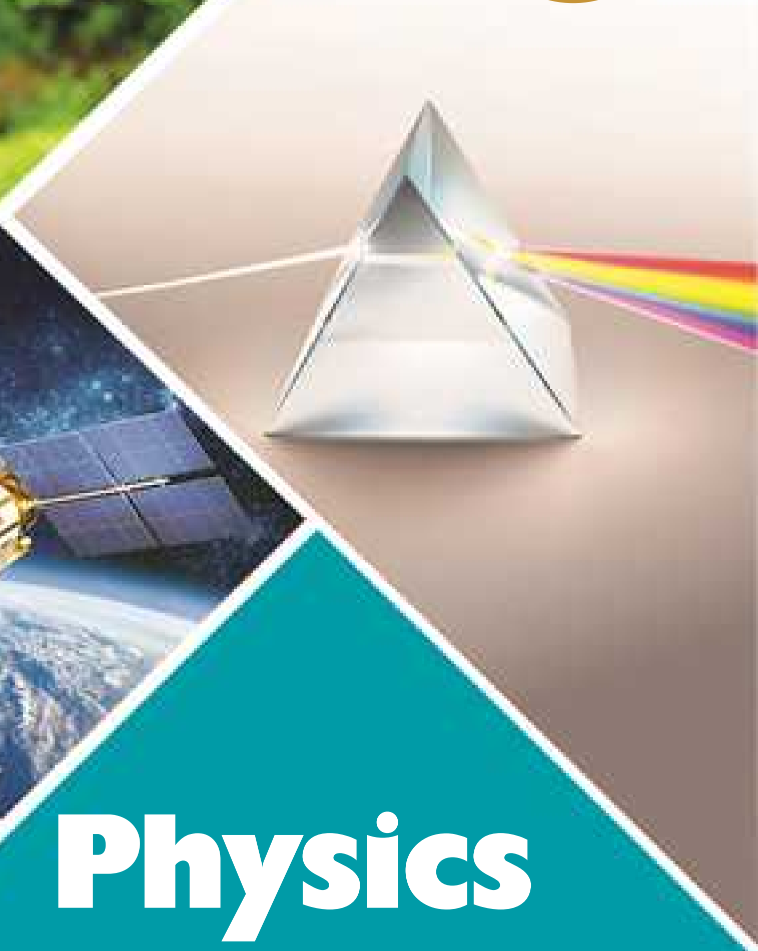

Physics

Second Secondary

Term 2

2025 - 2026

Physics

Second Secondary - Term 2 **2025 - 2026**

Prepared by

Prof. Dr. Mohamed Sameh Said.

Prof. Karima Abdel Aleem Sayed Ahmed

Prof. Dr. Mostafa Kamal Mohamed Youssef,

Dr. Mostafa Mohamed El-Sayed Mohamed

Revision Committee

Mr. Yousry Fouad Sawiris

Mr. Said Mohamed Ali

Mr. Mohamed Sayed Mohamed

Mr. Abdalla Moustafa Mohamed

Mr. Magdy Fathy

Mr. Ayman Shawky El-Sayed

Mr. Ahmed Riyad Abu El-Saud

Participated in Revision and Development

GPS للطبع والنشر والتوزيع Educational Content Management at the Company

Science Consultant Advisor

Dr. Aziza Ragab Khalifa

General Supervision

Dr. Akram Hassan Mohamed

Assistant Minister for Educational Curricula Affairs

And Supervisor of the Central Administration for Curriculum Development

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Introduction

This book represents a pillar of the developed physics curriculum for the second year of secondary school. The book content, alongside its activities and exercises, contributes to the achievement of the objectives of curriculum development in response to the challenges of the twenty-first century, an era marked by a rapid revolution in information and communication technology.

The curriculum aims to achieve the following goals:

- Clarifying the relationship between science and technology in the field of physics and its impact on development.

- Focusing on students' practice of aware and effective behavior regarding the use of technological outputs.

- Acquiring students scientific thinking approach that enables them to pursue self-learning combined with enjoyment and excitement.

- Fostering students' reliance on exploration to obtain information and gain more experience.

- Providing opportunities for students to practice citizenship tasks through self-directed learning, and teamwork that promotes negotiation, persuasion, accepting others' opinions, avoiding fanaticism, and rejecting extremism.

- Building students' life skills by increasing attention to the practical and applied aspects.

- Developing positive environmental attitudes towards the use of environmental resources and maintaining environmental balance locally and globally.

This book contains a set of integrated units that achieve the desired objectives of studying them. These units are:

(1) Work and energy in our daily life.

(2) Waves.

(3) Circular motion.

We ask Almighty God that the benefit of this book be widespread, and we pray to Him that it will be a building block in the sanctuary of our love for our homeland and belonging to it. God is the ultimate goal, and He guides to the straight path.

The Authors

Contents

Unit

One

Work and Energy in Our Daily Life

Chapter One: Work and Energy

Chapter

One

Work and Energy

Expected learning outcomes

By the end of this chapter, you will be able to:

1- *Explain the scientific concept of work.*
2- *Verify that work is a scalar quantity.*
3- *Deduce the units of energy.*
4- *Conclude that potential energy represents stored energy due to work done.*
5- *Identify the mathematical equations for both kinetic energy and potential energy.*
6- *Compare kinetic energy and potential energy.*
7- *Apply changes to an object's potential and kinetic energy when thrown upward as an example of law of conversation of energy.*
8- *Apply the law of conservation of energy to some examples in real life.*

Chapter Terms

- *Work*
- *Energy*
- *Kinetic energy*
- *Potential energy*
- *Law of Conservation of Energy*

Introduction

Energy exists in nature in several different forms such as thermal, chemical, mechanical and other forms of energy.

Figure (1)

This energy can be transformed from one form to another, so what is meant by energy? what is its relation to the work done?

Work

The concept of work in physics differs from its meaning in our daily life. In daily life, work may mean a mental or physical activity in which a person exerts effort to achieve a certain goal.

However in physics, for work to be done on an object, a **force** must act on the object and this object must undergo a **displacement** as a result of this force. If the object does not move, no work is done, no matter how great the force applied to the object.

Thus, from a physical perspective, there are two conditions for work to exist:

1. A certain force acts on the object.
2. The object undergoes a certain displacement along the same direction as the applied force.

Figure (2)

Figure (3) below illustrates an example of work:

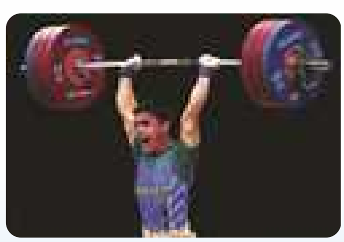


Figure (3)

The weightlifter does work to lift the weights from the ground

The work (W) done by a force (F) on an object to move it through a displacement (d) along the line of action of the force is calculated by the scalar product using the equation:

$$W = F.d \qquad (1)$$

Since both force and displacement are vector quantities, their scalar product yields a scalar quantity (work), meaning that work is not a vector quantity. For example, when moving a flat lawn, it does not matter in which direction the lawn mower moves; mowing (5 m) from east to west requires the same work as mowing (5 m) from north to south.

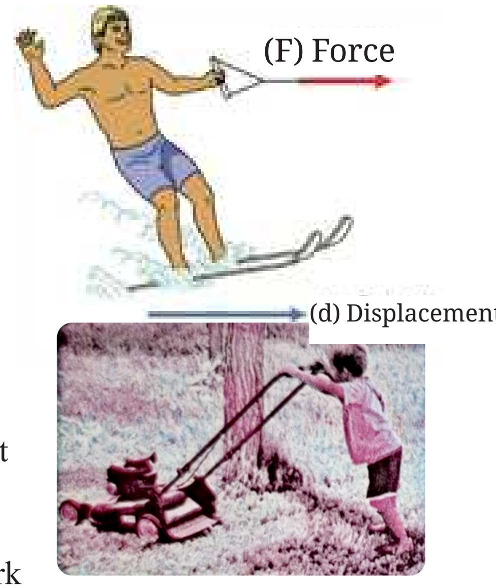


Figure (5)
A child does work

Work is measured in newton-meter (N.m), which is called the joule (J), named after the scientist James Joule. The dimensional formula for work is ML^2T^{-2}

The joule: is the work done by a force of one newton to move an object through a displacement of one meter in the direction of that force.

If a force (F) acts on an object and moves it a displacement (d) such that the direction of the force makes an angle (θ) with the direction of displacement, the force vector is resolved into two perpendicular components. The component of the force acting in the direction of the object's displacement is responsible for the work done, as shown in figures (6a) and (6b), and the work done is given by the equation:

$$W = (F \cos\theta)(d)$$

$$W = Fd \cos\theta \qquad (2)$$

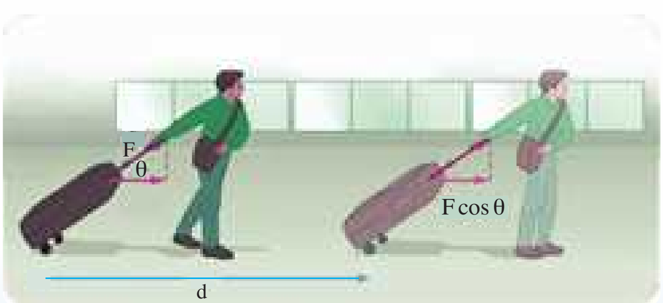


Figure (6a)

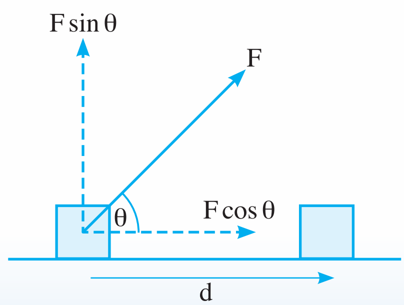
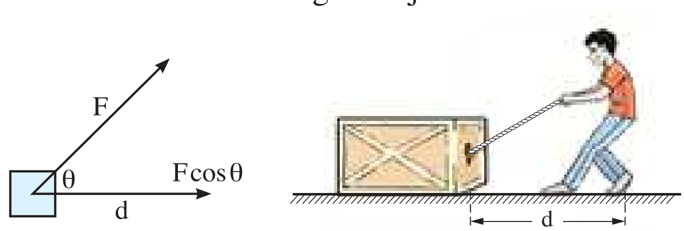
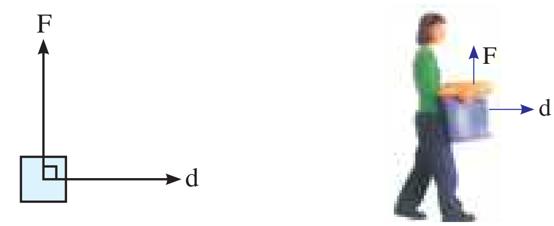
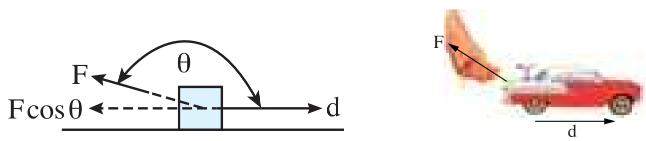


Figure (6b)

From the previous equation, it is clear that work can be positive, negative, or zero, as shown in the following table:

Angle θ	Work	Examples
$0^\circ \leq \theta < 90^\circ$	Positive (The force or one of its components acts in the direction of the object's displacement)	Pulling an object 
$\theta = 90^\circ$	Zero (The force is perpendicular to the direction of the object's displacement)	Horizontal movement of a carried object 
$90^\circ \geq \theta > 180^\circ$	Negative (The force or one of its components acts opposite to the direction of the displacement of the object)	A person tries to pull an object with a force opposite to its direction of displacement 

Example 1

A box with a mass of 20 kg moves under the effect of a tension force of 50 N making an angle of 60° with the direction of displacement as shown in the figure. **Calculate** the work done by the tension force if the box moves a displacement of 4 m

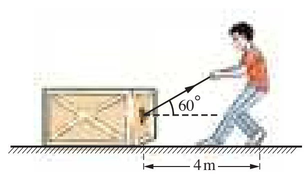


Figure (7)

Solution

$F = 50\ N \quad , \quad d = 4\ m \quad , \quad \theta = 60^\circ$

$W = Fd\cos\theta = (50)(4)(\cos 60^\circ) = 100\ J$

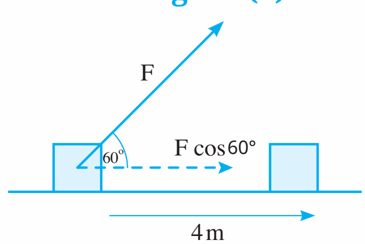


Figure (8)

What if

The angle between the directions of the tension force and the displacement decreases while their magnitudes remain constant, does the work done on the box by the tension force increase or decrease?

Example 2

Calculate the work done on a bucket with a mass of 300 g carried by a girl who moves it for a distance of 10 m in the horizontal direction, **then calculate** the work done by a boy to lift a bucket of the same mass for a distance of 10 cm in the vertical direction ($g = 10\ m/s^2$)

Figure (9)

Solution

* The work done by the girl on the bucket:

Since the force with which the girl carries the bucket is perpendicular to the displacement, the work done equals zero.

* The work done by the boy to lift the bucket:

Calculating the force: $F = mg = \frac{300}{1000} \times 10 = 3\ N$

Calculating work: $W = Fd \cos \theta$

And since the force acting on the bucket and its displacement are in the same direction, the angle (θ) equals zero.

$$W = 3 \times \frac{10}{100} \times \cos 0 = 0.3\ J$$

The work can also be found graphically using the (force-displacement) curve shown in the adjacent figure, where the straight line represents a constant force in magnitude and direction (F) acting on an object causing it a displacement (d) in the same direction as the acting force. Referring to the definition of work, when ($\theta = 0°$) then:

Work = force × displacement = length × width

= the area under the (force-displacement) curve

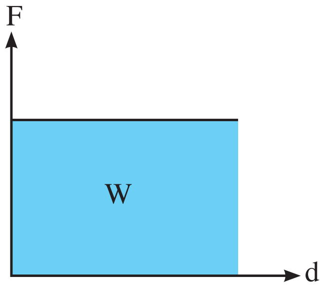


Figure (10)
The work equals the area under the straight line

Scientists who benefited humanity:

James Joule (1818 - 1889 AD) : He was an English scientist who was among the first to realize that work produces heat. In one of his experiments, he found that the temperature of water at the bottom of a waterfall is higher than at the top, proving that some of the energy of falling water is converted into heat.

Figure (11)
James Joule

Energy

If an object can do work, it possesses energy. In simpler terms, the energy of an object is its ability to do work, so energy has the same units as work: the joule (J).

We will discuss in detail below two of the most important forms of energy: kinetic energy and potential energy.

Kinetic energy (KE)

When a force (F) acts on a stationary object of mass (m) and causes a displacement (d) in the same direction, the work (Fd) done on the object is converted into a form of energy known as kinetic energy (KE).

Figure (12)
Examples of kinetic energy

In general, the kinetic energy of an object with speed (v) can be calculated using the equation:

$$KE = \frac{1}{2} mv^2 \qquad (3)$$

From the previous equation, it is clear that kinetic energy is directly proportional to the mass of the object and to the square of its speed.

The unit of measurement for kinetic energy is the joule, and its dimensional formula is ML^2T^{-2}

Example

Find the kinetic energy of a car with a mass of 2000 kg moving at a speed of 72 km/h

Solution

Converting the speed to (m/s):

$$v = \frac{72 \times 1000}{60 \times 60} = 20 \text{ m/s}$$

Calculating kinetic energy:

$$KE = \frac{1}{2} mv^2 = \frac{1}{2} (2000)(20)^2 = 400000 \text{ J} = 4 \times 10^5 \text{ J}$$

Real-life applications

When stopping a car with a mass of (m) moving at a speed of (v) by pressing the brakes, the car is affected by a force (F) and moves a displacement (d) from the moment the brakes are pressed until it stops, and from the equation ($Fd = \frac{1}{2} mv^2$) it is clear that the work done to stop the car is directly proportional to the square of its speed (v^2). So, if a car is moving at a speed of 60 km/h and it is to be stopped by pressing the brake pedal with a certain force, it will slide a distance before stopping that is four times that if it were moving at 30 km/h

Figure (13)

Enrichment information (for reference only)

Figure (14)
Any moving object possesses kinetic energy

∗ Finding the kinetic energy of an object:

Through your study in mathematics (mechanics), assuming you have a car moving from rest in a straight line with a constant acceleration of (a), then:

$$v_f^2 - v_i^2 = 2\,ad$$

Where: v_i is the initial velocity = zero, v_f is the final velocity.

$$\therefore v_f^2 = 2\,ad \quad \Rightarrow \quad d = \frac{v_f^2}{2\,a}$$

By multiplying both sides of the previous equation by (F), which is the force acting on the car during its motion, then:

$$Fd = \frac{1}{2} \frac{F}{a} v_f^2$$

And from Newton's second law:

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

And from the previous two relations:

$$Fd = \frac{1}{2} mv_f^2 \qquad (4)$$

Where the quantity (Fd) in the previous equation represents the work done (the energy required to move the car), and the right side represents ($\frac{1}{2} mv_f^2$) the form of energy to which the work done is converted, which is known as kinetic energy (KE).

Practical experiment to determine the kinetic energy of a moving object

Purpose of the experiment:

Kinetic energy is the energy that an object possesses as a result of its motion, and it is calculated by the equation:

$$KE = \frac{1}{2} mv^2$$

From the previous relation, we conclude that the square of the object's velocity is inversely proportional to its mass, when the kinetic energy is constant, and this is what we will try to prove experimentally.

Materials and tools:

1. A glider of mass m moving on an air track.
2. Elastic thread.
3. Photogate.
4. Digital timer or stopwatch.

Procedure:

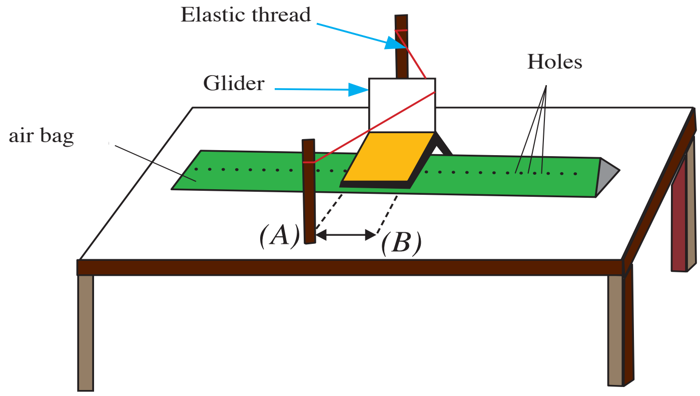


Figure (15)

1. Push the glider from point (A) to point (B) as shown in the diagram, then release it so it returns to its original position.
2. Measure the time taken by the glider during its motion on the air track using the edigital timer connected to the photoelectric cell or the stopwatch.
3. Determine the speed of the glider (v) by dividing the distance it moved by the time (in seconds), then determine the mass of the glider (m) in kilograms.
4. Repeat the steps 2 and 3 several times, changing the mass of the glider (m) and determining the speed at which it moves each time (noting to keep the distance (AB) the glider moves each time fixed).

5. Record the results in the following table:

v^2	$\frac{1}{m}$	Speed v (m/s)	Time t (s)	Glider mass m(kg)
....	....	....	....	....
....	....	....	....	....
....	....	....	....	....
....	....	....	....	....

Using the previous table, draw a graph between the square of the speed (v^2) on the y-axis and the reciprocal of the glider's mass ($\frac{1}{m}$) on the x-axis.

Analysis of results:

Using the graph, answer the following questions:

1. What is the type of relationship between the square of the glider's speed (v^2) and its mass (m)? (Direct or inverse).
2. What does the slope of the straight line you obtained represent?
3. Calculate the kinetic energy of the glider (KE) from the graph.
4. What is the unit of measurement for kinetic energy?

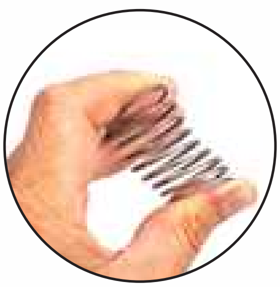
Potential energy (PE)

Objects can store energy inside them as a result of their new positions, and this energy is called potential energy (PE). For example, compressing or stretching a spring causes its parts to store potential energy (called elastic potential energy), and then the spring releases this stored energy as it returns to its equilibrium position.

Another example is when an object is lifted above the surface of the earth, it acquires potential energy (called gravitational potential energy), and this energy is related to the position of objects relative to the surface of Earth (i.e., relative to the gravitational field of Earth).

Why do eroded rocks collapse and fall down?

Why does the stretched rubber string move when the force acting on it is removed?



Why does the compressed spring move when the force acting on it is removed?

Figure (16)

If an object of mass (m) is raised to a height (h) above the ground, this object acquires potential energy (PE) as a result of its new position. Therefore, it can do work if allowed to fall. Thus, the potential energy of the object in its new position determines its ability to do work, i.e., the work done on the object to raise it to a certain point equals its potential energy at that point.

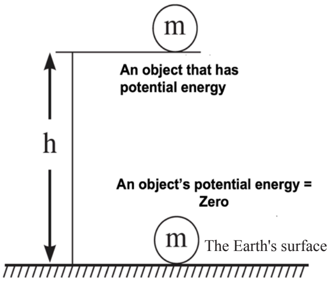


Figure (17)
Lifting an object of mass (m) to a height (h)

$$PE = W = Fh$$

And since the minimum force (F) required to lift the object upwards equals its weight (mg), then:

$$PE = Fh = (mg)\,(h) = mgh \qquad (5)$$

The unit of measurement for potential energy is Joule, and its dimensional formula is ML^2T^{-2}

Real-life applications

To lift a box to place it in a car, work must be done. For example, in Figure (18), we need a force of 450 N to lift the box to a height of 1 m vertically. The same box can be lifted with a smaller force equivalent to 150 N using a smooth inclined plane, but it will require a greater displacement of 3 m.

Figure (18)
Lifting the box vertically upwards requires a force equal to the weight of the box, and the work done is
W = 450 N × 1 m = 450 J

Figure (19)
Using the inclined plane requires a force less than the weight of the box to lift it, but this force must act over a greater displacement.
W = 150 N × 3 m = 450 J

Comparison between kinetic energy and gravitational potential energy of an object:

Aspect of comparison	Kinetic energy	Gravitational potential energy
Definition	It is the energy that an object possesses due to its motion.	It is the energy that an object possesses due to its position.
Mathematical relation	$KE = \frac{1}{2} mv^2$	$PE = mgh$
Factors affecting	It is directly proportional to each of: - The mass of the object (m). - The velocity of the object (v).	It is directly proportional to each of: - The mass of the object (m). - The height above the ground (h). - The acceleration due to gravity (g).
Unit of measurement	Joule	Joule
Dimensional formula	ML^2T^{-2}	ML^2T^{-2}

Physics in the Service of the Environment:

Most energy sources used by humans come from non-renewable energy sources such as coal and petroleum. The use of most non-renewable energy sources produces many substances harmful to the environment and human health. Therefore, there is a global trend towards using clean natural sources to obtain energy and preserve the environment at the same time. For example, wind energy (kinetic energy) and waterfalls (gravitational potential energy) are used to generate electricity and convert it into many forms of energy needed for human practical life.

Figure (20)

Figure (21)

Developing critical thinking

Two girls of equal mass race to climb stairs. The first girl climbed the stairs in 5 seconds, and the second girl climbed the stairs in 15 seconds.

- Is the amount of work done by the two girls to climb the stairs different?
- Would the answer change if the masses of the two girls were different?

Figure (22)

Law of Conservation of Energy

We have previously learned that energy is the ability to do work, and there are many forms of energy. Coal, gasoline, and other types of fuel contain stored chemical energy (a form of potential energy), which can be converted after the fuel burns into mechanical work, as seen in the movement of cars, trains, and others.

Figure (23)
Energy transformations in the car

Likewise, electrical energy in a lamp is converted into thermal and light energy, and the potential energy in a waterfall is converted into kinetic energy. There are many examples of energy being converted from one form to another, and such transformations are subject to the law of conservation of energy, which states that:

> **"Energy is neither created nor destroyed, but it can be transformed from one form to another."**

The law of conservation of mechanical energy

When an object falls under the influence of gravity alone (neglecting air resistance), it is affected by a constant force equal to its weight and directed downward. The motion of this object is called "free fall", and the object moves with a constant acceleration called the acceleration of free fall (g) or the acceleration due to gravity.

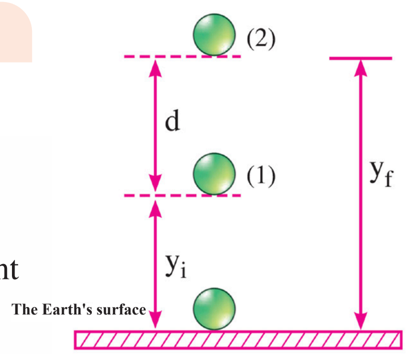


Figure (24)

In the case of throwing an object of mass (m) upwards against the direction of gravity, and its initial velocity is (v_i) at point (1) and its final velocity is (v_f) at point (2) as in figure (24), the potential energy of the object increases as the height increases, while its kinetic energy decreases as its velocity decreases.

Thus: The sum of potential and kinetic energies at point (1) = the sum of potential and kinetic energies at point (2).

This mathematically means: $(PE)_f + (KE)_f = (PE)_i + (KE)_i$

$$mgy_f + \frac{1}{2} mv_f^2 = mgy_i + \frac{1}{2} mv_i^2$$

$$mgy_f - mgy_i = -(\frac{1}{2} mv_f^2 - \frac{1}{2} mv_i^2)$$

$$\Delta PE = -\Delta KE \qquad (6)$$

In other words: the decrease in kinetic energy = the increase in potential energy.

The law of conservation of mechanical energy: When an object moves under the influence of a special type of force such as gravity or elastic force, the sum of the potential and kinetic energies of the object at any point in its path is equal to a constant value.

In general, the sum of the potential and kinetic energies of an object is called mechanical energy.

Mechanical energy = potential energy + kinetic energy = constant value

From the last equation, we conclude that when an object moves under the influence of gravity only, whenever the kinetic energy of the object increases, it is at the expense of potential energy, i.e., the potential energy decreases and vice versa.

Enrichment information (for reference only)

* Proof of the law of conservation of mechanical energy:

When an object is thrown vertically upward, it moves with uniform acceleration (a), so:

$$v_f^2 - v_i^2 = 2\ ad$$

And since the body moves upward against the direction of gravity, it moves with negative acceleration, i.e.:

$$a = -g$$

$$v_f^2 - v_i^2 = 2(-g)\ d$$

$$v_f^2 - v_i^2 = -2\ gd$$

By multiplying by $(\frac{1}{2} m)$, and substituting d with the value $(y_f - y_i)$

$$\frac{1}{2} mv_f^2 - \frac{1}{2} mv_i^2 = -mg\ (y_f - y_i)$$

$$\frac{1}{2} mv_f^2 - \frac{1}{2} mv_i^2 = -mg\ y_f + mg\ y_i$$

$$mg\ y_f + \frac{1}{2} mv_f^2 = mg\ y_i + \frac{1}{2} mv_i^2$$

$$\therefore (PE)_f + (KE)_f = (PE)_i + (KE)_i \qquad (7)$$

Figure (25)
Potential energy increases with height while kinetic energy decreases

Practical experiment to verify the law of conservation of mechanical energy

Purpose of the experiment:

Verifying that the sum of the potential and kinetic energies of an object moving under the influence of gravity at any point in its path is equal to a constant value called mechanical energy.

Materials and tools:

1. Tennis ball.
2. Digital scale.
3. Adhesive tape.
4. Stopwatch.
5. Measuring tape.

Procedure:

1. Determine the mass of the tennis ball using the digital scale in grams, then convert it to kilograms.

   m = ... g = ... kg

2. Stick pieces of adhesive tape on the wall at a height of (2.5 m , 2 m , 1 m)
3. Hold the tennis ball at a height of one meter above the ground (h = 1 m) then let it fall to the ground and determine the time it takes for the ball to reach the ground.
4. Repeat the previous attempt several times.
5. Repeat the steps (3) and (4) for the other heights (2 m , 2.5 m) several times.
6. Record the results you obtained in the following table:

Results:

Height h (m)	Time t (s)			
	The first attempt	Second attempt	Third attempt	Average
1	....	....	....	....
2	....	....	....	....
2.5	....	....	....	....

1. Calculate the potential energy (PE) at different heights using the formula:

   PE = mgh, given that:

   $$g = 9.8 \text{ m/s}^2$$

2. Since that the ball fell from rest, the initial velocity v_i is zero. Therefore, the final velocity v_f of the ball at the moment it hits the ground can be calculated using the following equation:

   $$v_f = gt$$

3. Using the value of v_f, the kinetic energy (KE) of the tennis ball at the moment it hits the ground can be calculated using the relation:

   $$KE = \frac{1}{2} mv^2$$

Record the results in the following table:

Height	1 m	2 m	2.5 m
Potential energy PE	....	....	....
Kinetic energy KE	....	....	....

Analysis of results:

1. By comparing the table results for both (PE, KE), what do you notice?
2. Are the experimental results you obtained consistent with your expectations?
3. If the experimental results differ from your expectations, what are the possible reasons for that? And how can they be adjusted?

Critical thinking

Imagine you have three different paths that a stationary ball on the surface of the earth can take to reach a fixed height. In which path is the work done to lift the ball is the greatest?

- Path a
- Path b
- Path c
- All are equal.

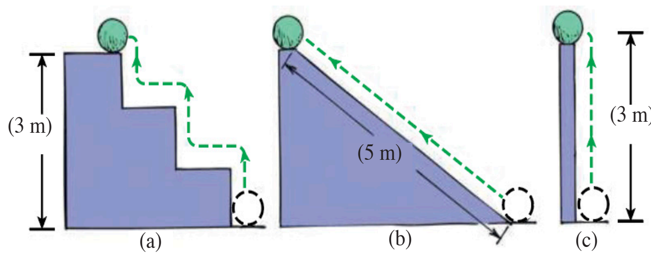


Figure (26)

Example

A stationary object at a height of 30 m above the ground has a potential energy of 1470 J . If the object falls down, neglecting air resistance, **calculate the following:**

(a) The mass of the object.

(b) The kinetic energy and potential energy of the object at a height of 20 m above the ground.

(c) The speed of the object at the moment of impact with the ground ($g = 9.8\ m/s^2$).

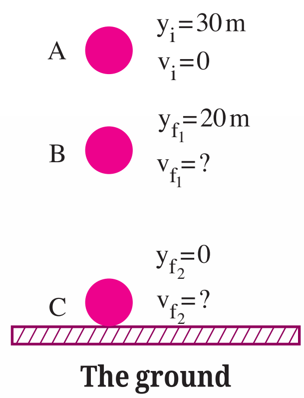


Figure (27)

Solution

(a) At point A:

$$PE = mgh = 1470\ J$$

$$m \times 9.8 \times 30 = 1470\ J$$

$$m = 5\ kg$$

(b) By applying the law of conservation of mechanical energy at points A and B:

$PE_f + KE_f = PE_i + KE_i$

$mg\, y_f + KE_f = PE_i + KE_i$

$(5 \times 9.8 \times 20) + KE_f = 1470 + 0$

$KE_f = 490$ J

∴ The kinetic energy of the object at a height of 20 m is 490 J

The potential energy of the object at a height of 20 m is:

$PE_f = 1470 - 490 = 980$ J

Another method: $PE_f = mgy_f = 5 \times 9.8 \times 20 = 980$ J

(c) To calculate the speed of the object at the moment it hits the ground:
By applying the law of conservation of mechanical energy at points A and C:

$(5 \times 9.8 \times 30) + 0 = 0 + (\frac{1}{2} \times 5 \times v_f^2)$ ∴ $v_f = 24.25$ m/s

What if The object is thrown vertically downward from the same height instead of falling freely from rest, Would any of the calculated values in the example change?

The law of conservation of energy in real life:

When you throw an object upward into the air, you see an example of the law of conservation of energy, or the interconversion between kinetic and potential energy. When we throw a ball upward from of the ground, its potential energy is zero and its kinetic energy is at a maximum. As the ball starts moving upward, its potential energy increases at the expense of its kinetic energy, and thus the transformation from kinetic energy to potential energy continues until it reaches its maximum height. At this point, its kinetic energy becomes zero, while its potential energy is at a maximum. After that, the ball starts to fall back to the ground, and its kinetic energy gradually increases as its potential energy decreases until it reaches of the ground again, and its potential energy becomes zero.

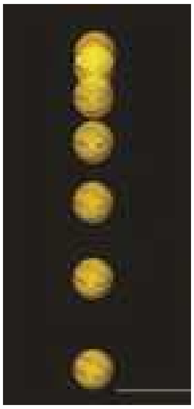


Figure (28)
Exchange The interconversion between potential and kinetic energy in an object thrown upwards

There are many examples of the transformation of kinetic energy into potential energy or vice versa, as shown in the following figures:

Figure (31)

Exchange The interconversion between potential and kinetic energy in a roller coaster

Figure (30)

Exchange The interconversion between potential and kinetic energy when launching an arrow from a bow

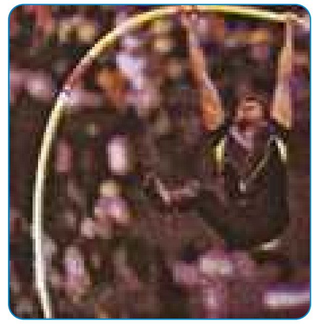


Figure (29)

Exchange The interconversion between potential and kinetic energy in pole vaulting.

Developing critical thinking

Dolphins jumping out of the water:

- What are the mechanical energy transformations that occur from the start of the jump until the dolphin returns to the water?
- Can the impact speed of the dolphin with the water after its jump be calculated if the height reached is known?
- Suggest a simple experiment to simulate the dolphin's jump using a small plastic ball and a deep container filled with water.

Figure (32)

Example

The adjacent figure shows a ball suspended by a string, swinging freely in a defined vertical plane. If the mass of the ball is m and air resistance is neglected, **what** is the maximum speed the ball reaches during its swing?

(Knowing that: $g = 9.8\ m/s^2$).

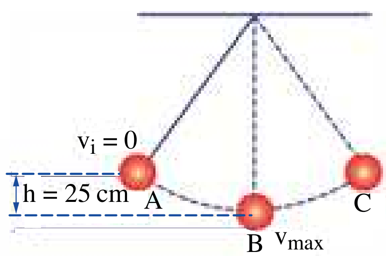


Figure (33)

Solution

The maximum speed the ball reaches during its swing occurs at point B, and by applying the law of conservation of mechanical energy at points A and B:

$$mgh + 0 = 0 + \frac{1}{2} mv_f^2$$

$$m \times 9.8 \times 25 \times 10^{-2} = \frac{1}{2} \times m \times v_f^2$$

$$v_f = 2.2\ m/s$$

Misconceptions

Some believe that the greater the mass of the ball rolling down from the top of a smooth inclined plane, the faster it will reach the end.

In fact, increasing the mass of the ball rolling down from the top of a smooth inclined plane increases its kinetic energy at the bottom of the plane, while its speed at the bottom remains the same as in the first case.

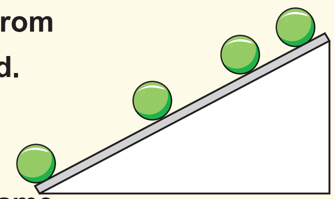


Figure (34)

Summary

First: Key definitions and concepts

- Work: It is the scalar product of the force acting on an object and its displacement. It is a scalar quantity and is measured in Joules (J).
- Joule: The work done by a force of one Newton to move an object a distance of one meter in the direction of the force.
- Energy: It is the ability to do work.
- Kinetic energy: It is the energy that an object possesses due to its motion.
- Potential energy: It is the energy that an object possesses due to its position, and it is stored within it.

Second: Fundamental laws

- Law of conservation of energy: Energy can neither be created nor destroyed, but it can be transformed from one form to another.
- Law of conservation of mechanical energy: The sum of the potential and kinetic energies of an object moving under the influence of gravity at any point in its path is constant.

Third: Fundamental equations

- Work done: $W = Fd \cos \theta$
- Kinetic energy: $KE = \frac{1}{2} mv^2$
- Gravitational potential energy: $PE = mgh$
- Mechanical energy: $E = PE + KE$

Questions and Problems

First: Choose the correct answer

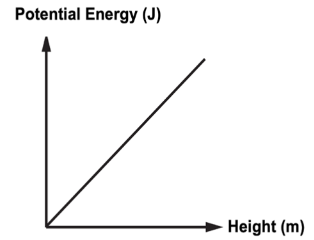
1. A person pushes a cart carrying boxes, and the following forces act on the cart:
   (I) The person's pushing force
   (II) Friction force
   (III) Earth's gravitational force
   (IV) Normal reaction force of the surface of the ground

   Which pair of these forces does not do work on the cart as it moves a displacement (d)?
   ⓐ The forces (I), (II) ⓑ The two forces (III), (IV)
   ⓒ The two forces (I), (IV) ⓓ The two forces (II), (III)

2. An object has a kinetic energy of 4 J, what will its kinetic energy be if its speed is doubled?
   ⓐ 8 J ⓑ 16 J ⓒ 4 J ⓓ 0.8 J

3. A man reached his apartment once by climbing the stairs, and a second time using the elevator. Which of the following statements is correct?
   ⓐ The man's potential energy is greater when climbing the stairs
   ⓑ The man's potential energy is greater when using the elevator
   ⓒ There is no potential energy for the man when using the elevator
   ⓓ The man's potential energy is equal in both cases

4. The slope of the straight line in the adjacent graph represents ....
   ⓐ The mass of the object
   ⓑ The weight of the object
   ⓒ The displacement of the object
   ⓓ The velocity of the object



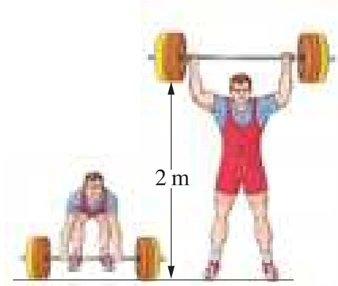
5. An object with a mass of 2 kg is at a height of 5 m above the ground, so its potential energy is .... ($g = 9.8\ m/s^2$)
   ⓐ 98 J ⓑ 10 J ⓒ 2.5 J ⓓ 9.8 J

6. The energy stored in a compressed spring is ....
   ⓐ Kinetic energy ⓑ Potential energy ⓒ Nuclear energy ⓓ Thermal energy

7. If an object is thrown vertically upwards, which of the following physical quantities equals zero at the maximum height it reaches?
   ⓐ Its weight ⓑ Its acceleration
   ⓒ Its potential energy ⓓ Its speed

8. The adjacent figure shows a weightlifter lifting a mass of 100 kg, so the work done by the weightlifter to lift that mass from the ground to a height of 2 m is .... (Knowing that: $g = 10\ m/s^2$)

ⓐ 100 J ⓑ 200 J ⓒ 1000 J ⓓ 2000 J



9. The mechanical energy of an object equals ....

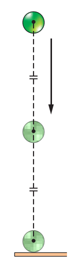
ⓐ The difference between kinetic and potential energy

ⓑ The sum of kinetic and potential energy

ⓒ The ratio between kinetic and potential energy

ⓓ The product of kinetic and potential energy

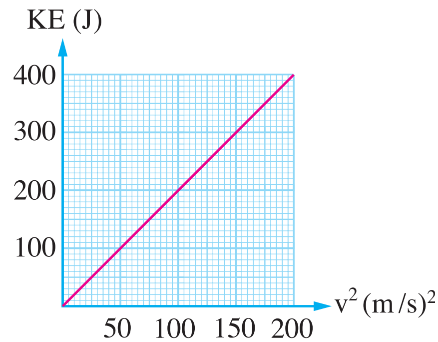
10. In the adjacent figure, a ball with a mass of 12 kg falls freely from rest. If its mechanical energy at the midpoint between its dropping point and the ground is 150 J, then its velocity at the moment it hits the ground is ....



ⓐ 5 m/s ⓑ 25 m/s ⓒ 50 m/s ⓓ 100 m/s

11. The adjacent graph shows the relationship between the kinetic energy (KE) of an object falling from a height of 10 m above the ground and the square of its velocity (v^2) during the fall. Its potential energy at a height of 2 m is ....

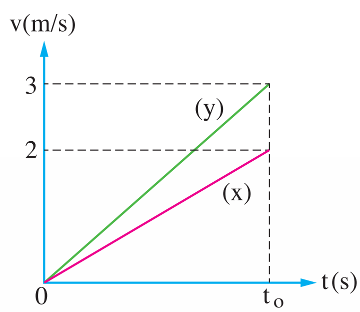
(Knowing that: $g = 10\ m/s^2$)



ⓐ 20 J ⓑ 40 J

ⓒ 60 J ⓓ 80 J

12. Two objects (x) and (y) have the same mass and each moves from rest on a horizontal surface under the effect of a resultant horizontal force of different magnitudes. The adjacent graph represents the relationship between the velocity (v) of each object and time (t). The ratio between the amounts of work done on the two objects $(\frac{W_x}{W_y})$ by the resultant force :



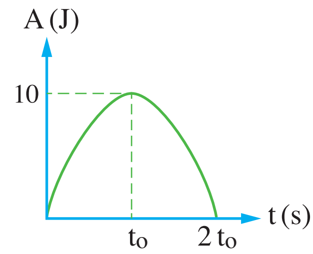
(A) When they cover the same displacement equals ....

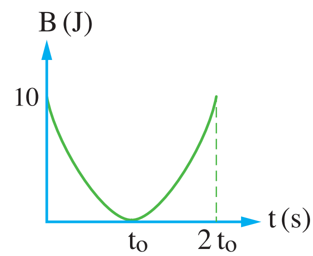
ⓐ $\frac{2}{3}$ ⓑ $\frac{3}{2}$ ⓒ $\frac{4}{9}$ ⓓ $\frac{9}{4}$

(B) During the period from 0 to t_o represented in the graph equals ....

ⓐ $\frac{2}{3}$ ⓑ $\frac{3}{2}$ ⓒ $\frac{4}{9}$ ⓓ $\frac{9}{4}$

13. Each of the adjacent graphs shows the relationship between one of the physical quantities for an object projected vertically upward and time (t) :

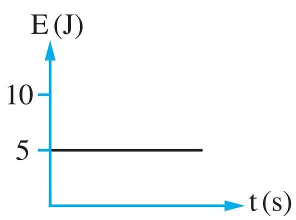




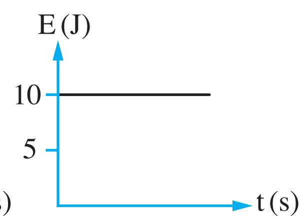
(A) Which of the following options represents the quantity A and the quantity B shown on the vertical axis in the two graphs?

	Quantity (A)	Quantity (B)
ⓐ	Potential energy	Kinetic energy
ⓑ	Kinetic energy	Potential energy
ⓒ	Mechanical energy	Kinetic energy
ⓓ	Mechanical energy	Potential energy

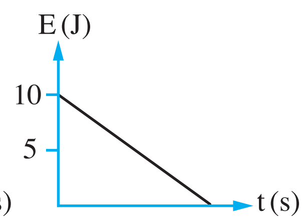
(B) Which of the following graphs represents the relationship between the mechanical energy (E) of the object and time (t)?



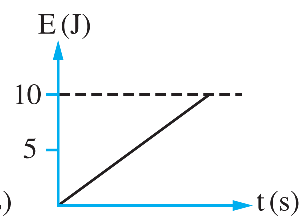
ⓐ



ⓑ

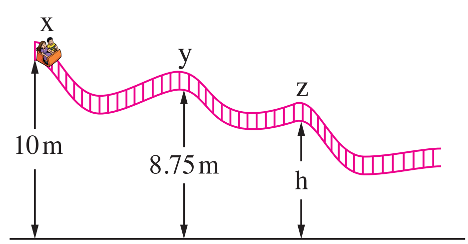


ⓒ



ⓓ

14. In the adjacent figure, an object of mass 1 kg starts sliding from rest on a smooth curve starting from point x : $(g = 10\ m/s^2)$



(A) The speed of the object at point y equals ....

ⓐ 3 m/s ⓑ 5 m/s ⓒ 6 m/s ⓓ 6.5 m/s

(B) If the speed of the object at point z is 7 m/s, then the height of point z above the ground equals ....

ⓐ 8.45 m ⓑ 7.55 m ⓒ 7.25 m ⓓ 6.85 m

15. Two objects A, B have the same mass and were thrown vertically upward from the ground with speeds v, 2 v respectively, so the ratio between the mechanical energy gained by each of them $(\frac{E_A}{E_B})$ is ....

ⓐ $\frac{4}{1}$ ⓑ $\frac{1}{1}$ ⓒ $\frac{1}{2}$ ⓓ $\frac{1}{4}$

Second: Essay Questions

1. Explain the following:
   (A) Work is a scalar quantity.
   (B) The potential energy of water at the top of the waterfall is greater than its potential energy at the bottom of the waterfall.
   (C) When a person carries a bag and walks horizontally on the ground, he does not do any work on the bag.
2. Is kinetic energy a vector or a scalar physical quantity? And why?
3. When you push a fixed wall with a force of 100 N, do you do physical work? And why?
4. In the two illustrated figures, two objects a and b are placed on a smooth horizontal surface. If each is acted upon by forces F and 2 F respectively, and each moves a horizontal displacement of d, on which object is more work done by the resultant force acting on each?

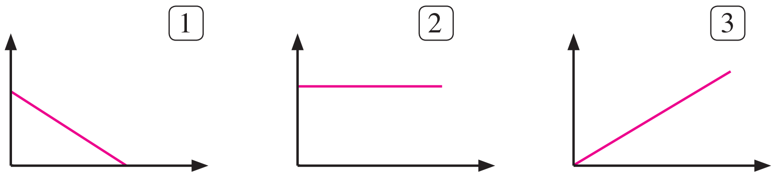
5. An object of mass 4 kg falls freely from a height of 20 m above the ground. Complete the blanks in the following table considering the acceleration due to gravity as $10\ m/s^2$ and neglecting air resistance,

	The displacement of the object in meters from the point of fall	Potential energy in Joules	The speed of the object	Kinetic energy in Joules	The mechanical energy of the object in Joules
a	0	....	....	....	....
b	....	....	5 m/s	....	....
c	....	400 J	....	....	....
d	....	....	....	800 J	....

From the results you have reached, determine the position of the point during the fall at which:
(A) The mechanical energy of the object is equal to its kinetic energy.
(B) The mechanical energy of the object is equal to its potential energy.
(C) The kinetic energy of the object is equal to the potential energy.

6. An object was thrown vertically upwards until it reached its maximum height, and you have

three graphs: 1 , 2 , 3 to express the relationship between some of its physical quantities.



Determine which expresses the relationship between each of the following:

(a) The potential energy of the object (PE) and its height above the ground (h).

(b) The kinetic energy of the object (KE) and its height above the ground (h).

(c) The mechanical energy of the object (E) and its height above the ground (h).

Third: Problems

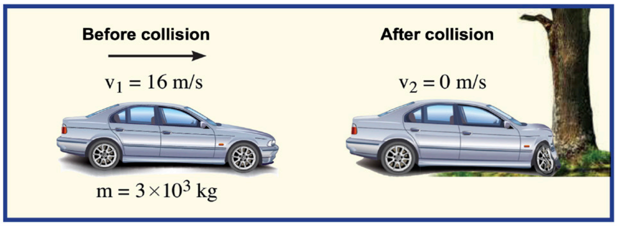
1. Calculate the work done when pushing a cart a horizontal distance of 3.5 m by a force of 20 N in the direction of the cart's movement. (70 J)

2. A force of 100 N acts on an object. Find the work done by this force if the object moves a displacement of 2.5 m in the following cases:
   (a) If the force is in the same direction as the movement of the object.
   (b) If the force is inclined at an angle of 60° to the direction of motion.
   (c) If the force is perpendicular to the direction of the object's movement. (250 J, 125 J, 0 J)

3. A mother pushes her child's cart at a constant speed on a straight horizontal path with a force making an angle of 60° with the horizontal, and if the cart is subjected to a friction force of 20 N, calculate the work done by the mother on the cart to cover a distance of 5 m (100 J)

4. Find the kinetic energy of a car with a mass of 2000 kg moving at a speed of 60 km/h (2.78×10^5 J)

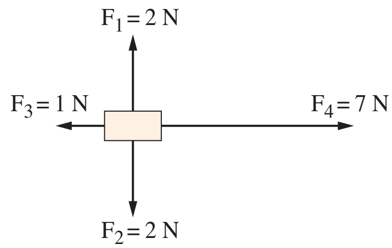
5. A car with a mass of 3×10^3 kg and a speed of 16 m/s collided with a tree, the tree did not move and the car stopped, as shown in the following figure:



   (a) What is the amount of work done on the tree when the front of the car hits the tree?
   (b) What is the change in the kinetic energy of the car?
   (c) Calculate the average force that acted on the front of the car to bend inward a distance of 50 cm

(0 J, 3.84×10^5 J, 7.68×10^5 N)

6. The figure shows a top view of the magnitude and direction of each of four horizontal forces acting on an object placed on a horizontal surface. Calculate the change in the kinetic energy of the object if displaced for 4 m



(24 J)

7. An athlete weighing 700 N climbed a mountain to a height of 200 m above the ground. Find the minimum work the man can do against gravity to reach that height. (1.4×10^5 J)

8. You have two boxes (A) and (B) weighing 40 N and 60 N respectively. Box (A) is placed on the ground, while box (B) is placed at a height of 2 m above the ground. What height should box (A) be raised to so that it has the same potential energy as box (B)? (3 m)

9. Calculate the mass of an object whose potential energy at a point 5 m above the ground is 980 J (knowing that: the acceleration due to gravity is 9.8 m/s^2) (20 kg)

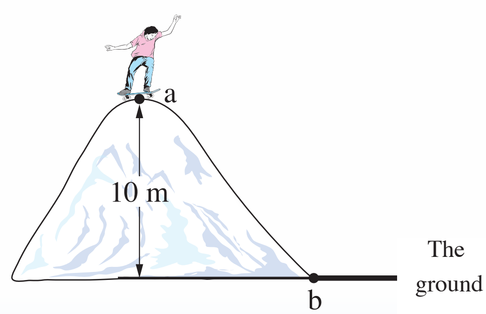
10. Calculate the work done to lift an object of mass 50 kg from the ground to a height of 2.2 m (g = 10 m/s^2)

(1100 J)

11. A ball of mass 0.5 kg was thrown vertically upwards, and its speed was 3 m/s at a height of 4 m. What is the amount of work done to throw the ball if the acceleration due to gravity is 10 m/s^2 (22.25 J)

12. An object of mass 0.2 kg was thrown vertically upwards at a speed of 20 m/s. Neglecting air resistance and considering the acceleration due to gravity as 10 m/s^2, calculate:
   (a) The maximum height reached by the object.
   (b) The speed of the object at a height of 10 m above the ground. (20 m, 14.14 m/s)

13. The adjacent figure shows a skater weighing 500 N. If the skater is stationary at point (a), find each of the following:
(a) The potential energy of the skater at point a
(b) The potential energy of the skater at point b
(c) The mechanical energy of the skater at point b



(5000 J, 0 J, 5000 J)

Unit

TWO

Waves

Chapter

TWO

Wave Motion

Expected learning outcomes

By the end of this chapter, you will be able to:

1- *Explain the meaning of oscillatory motion and some of the physical quantities associated with it, such as: displacement, amplitude of oscillation, complete oscillation, frequency, and periodic time.*

2- *Plot the displacement-time graph of an oscillating object.*

3- *Identify simple harmonic motion and give examples of it.*

4- *Recall the mathematical relationship between frequency and periodic time.*

5- *Explain the conditions necessary for mechanical wave propagation.*

6- *Compare electromagnetic waves and mechanical waves.*

7- *Compare transverse waves and longitudinal waves.*

8- *Define key concepts including:*

9- *Explain the relationship between frequency, wavelength, and the propagation speed of waves.*

10- *Solve problems on the relationship between frequency, wavelength, and wave speed.*

Chapter Terms

- *Wave*
- *Mechanical waves*
- *Electromagnetic waves-*
- *Displacement*
- *Amplitude*
- *Complete oscillation*
- *Periodic time*
- *Frequency*
- *Longitudinal wave*
- *Transverse wave*
- *Wavelength*

Introduction

Some of us find pleasure in watching waves gently move across the surface of water, gently touching a small float of a fishing hook, or lightly hitting a small boat causing it to sway and vibrate. Others enjoy sitting on the shore of a lake or pond, occasionally throwing a small pebble into the water. Each pebble's collision with water surface acts as a source of disturbance that spreads over water surface in the form of regular circles, centered at the point where the pebble falls as in Figure (1). These are called waves. So, what is a wave? And what are its types?

Wave: is a disturbance that propagates and transfers energy.

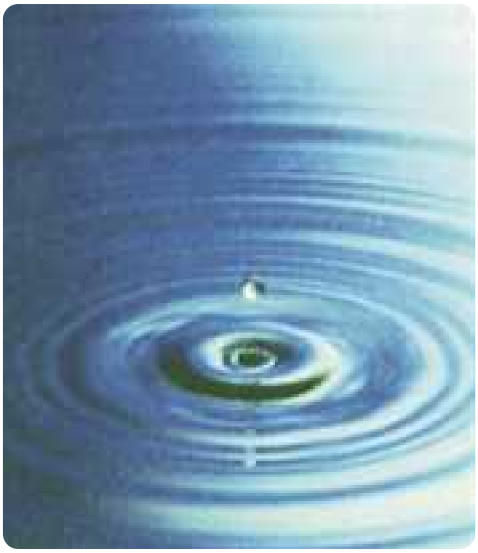


Figure (1)
Propagation of a wave on water surface

Water waves are not the only waves we are familiar with. Every morning, we often hear the announcer's voice saying, for example: "This is Cairo Radio, broadcasting on a medium wave band of 366.7 m". Also, television transmits sound and image, which are converted into waves that travel through the air and are received by the antenna, then these waves are converted into electrical signals in the receiver, where they are turned into sound and image. Similarly, the mobile phone deals with waves that transmit sound from the sender to the receiver, where sound vibrations are converted into electrical signals, then into electromagnetic signals that travel through the air or vacuum, and are received by the mobile phone's antenna at the receiver, then converted into an electrical signal and then into sound.

We see water waves, but the waves used in radio, television, and mobile phones are detected by their effects. Water waves are mechanical waves, as are sound waves and waves propagating in strings during their vibration. However, the waves received by the antennas of radios, televisions, and mobile phones are called electromagnetic waves.

Among these electromagnetic waves are also light waves and X-ray waves which are used in medical radiological diagnosis and other applications. Mechanical waves require a physical medium to propagate, while electromagnetic waves do not require a physical medium as they can propagate in vacuum.

Mechanical waves

Mechanical waves require the presence of:

1. A source of vibration or an oscillator.
2. A type of disturbance that propagates through the medium from the source.
3. The medium that carries the vibration (disturbance).

There are many and varied vibrating sources, including:

1. The vibrating simple pendulum, such as the clock pendulum, Figure (2).
2. The vibrating tuning fork, Figure (3).
3. The vibrating string, Figure (4).
4. A weight suspended in a spring coil during its vibration, known as a mass-spring system, yo-yo, Figure (5).

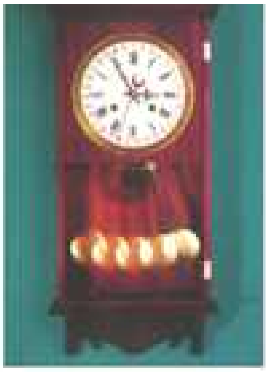


Figure (2)
Clock Pendulum

Figure (3)
The tuning fork

Figure (4)
The vibrating string

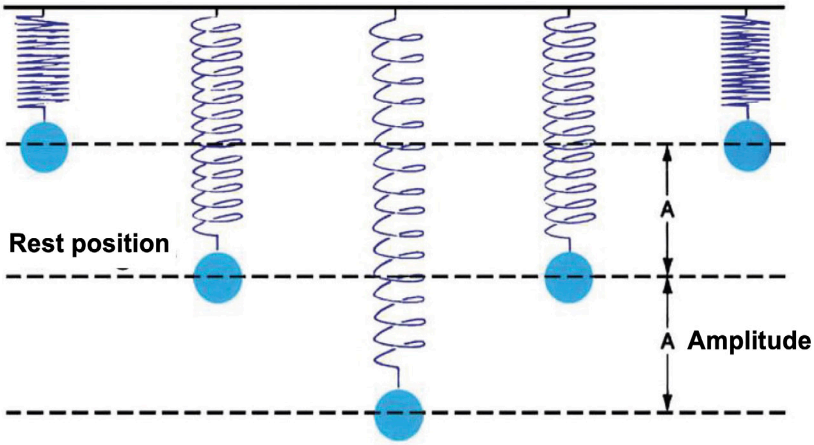


Figure (5)

A weight suspended in a spring coil (the yoyo)

Some essential physical quantities are associated with vibrational motion, such as:

Displacement (d) : is the distance of the vibrating object at any moment from its original rest position or equilibrium. It is a vector quantity, and its unit of measurement is meter.

Amplitude (A) : is the maximum displacement of the vibrating object from its rest position or it is the distance between two points in its path where its speed at one is maximum and at the other is zero. Its unit of measurement is the meter (meter).

Complete Oscillation : is the motion performed by the vibrating object during the time interval between passing through a single point in its path twice consecutively in the same direction, i.e., having the same phase relative to the starting point of this interval.

Frequency (υ) : is the number of oscillations made by the vibrating object in one second, and its unit is the hertz (Hz) which is equivalent to (s^{-1}). Frequency of a vibrating object is calculated using the formula:

$$\upsilon = \frac{N}{t} \qquad (1)$$

Where: (N) is the number of complete oscillations made by the vibrating object, (t) is the time taken for these oscillations.

Period (T) : is the time taken by the vibrating object to make one complete oscillation, or the time it takes to pass through a single point in its path twice consecutively in the same direction. Its unit is second, and the relationship between period and frequency is:

$$\upsilon = \frac{1}{T} \qquad (2)$$

Developing critical thinking

If you displace a swing away from its equilibrium position and then release it:

- What are the energy transformations that occur during one complete cycle?
- Why does the swing stop eventually if you do not push it?

Figure (6)

Simple Harmonic Motion

If we imagine a weight placed on a smooth, horizontal surface and attached at one end of a spring, with the other end attached to a vertical wall, then we pull the weight along the axis of the spring to store potential energy. When the weight is released, it oscillates horizontally about its equilibrium position. If we plot the curve of the center of mass of the object from its equilibrium position relative to time, we obtain a graph known as the sine wave figure, (7). Such motion is known as simple harmonic motion.

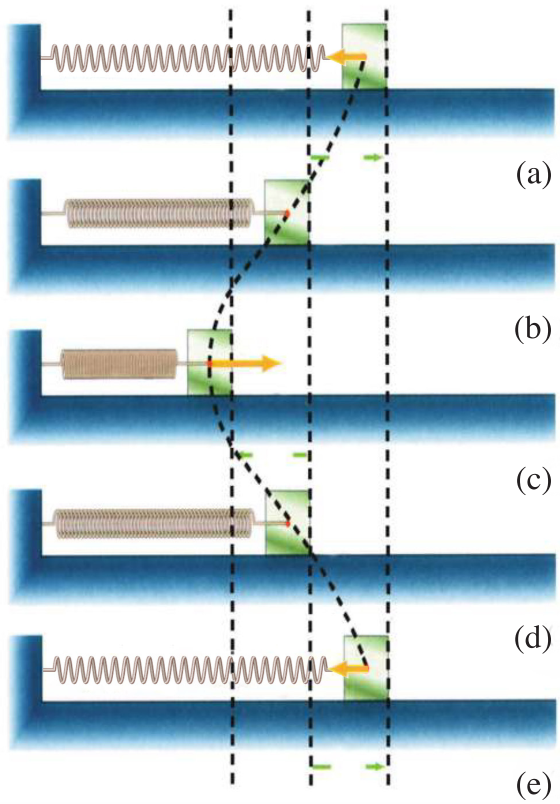


Figure (7)
The sine curve represents simple harmonic motion

A vibrating source that produces simple harmonic motion can generate a mechanical wave that propagates in a medium at speed v, where each part of the medium in turn performs simple harmonic motion around its equilibrium position.

Mechanical waves can be classified into longitudinal waves and transverse waves.

First Longitudinal Waves

- Place a weight (m) on a smooth horizontal surface, attached at one side to a long spring and at the other side to a short spring, with both springs fixed to a wall (Figure 8 A).
- Displace the weight a distance A to the right, so the part of the spring adjacent to the weight is compressed to the right, forming a compression pulse (Figure 8 B).
- Release the weight so it returns to its original equilibrium position under the influence of the force generated in the spring, while the compression pulse moves through the spring to the right from the weight (Figure 8 C).
- The weight passes the original equilibrium position moving to the left, creating a rarefaction in the spring coils to the right (Figure 8 D).

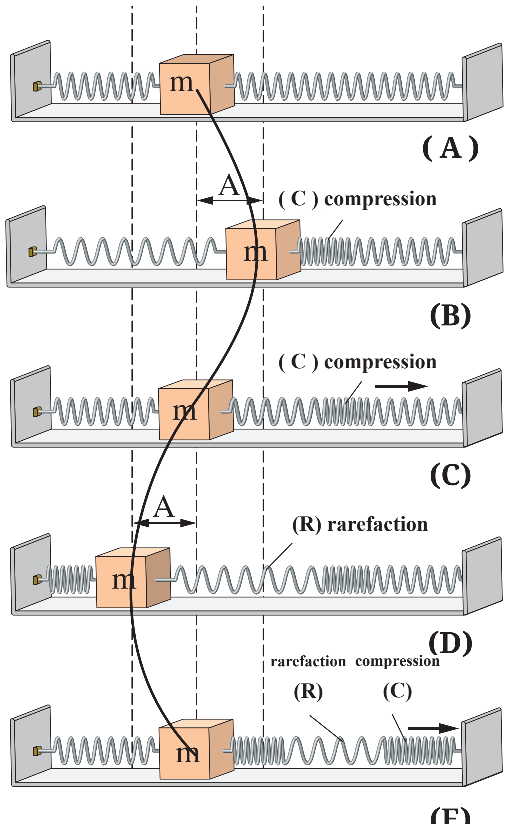


Figure (8)
Longitudinal wave

- The movement of the weight to the right is repeated, and the rarefaction pulse also moves to the right (Figure 8 E).

This series of compressions and rarefactions represents a wave resulting from the oscillation of the medium's particles (represented by this spring) in simple harmonic motion, but the direction of wave propagation is the same as the direction of disturbance transmission. This wave is called a longitudinal wave, as compressions and rarefactions travel along the spring. An example of this is longitudinal sound waves that propagate in air.

Second Transverse waves

If we imagine that mass m is attached to a vertical spring and is also fixed to a horizontal taut rope, with its other end attached to a vertical wall, then when mass m performs simple harmonic motion in the vertical direction, the end of the rope attached to it will also move in the same way. This causes the subsequent parts of the rope to oscillate successively, one after the other. Thus, the motion travels along the rope as a wave in the horizontal direction at speed v, while the parts of the rope move in simple harmonic motion in the vertical direction. This is called a transverse wave, (Figure 9).

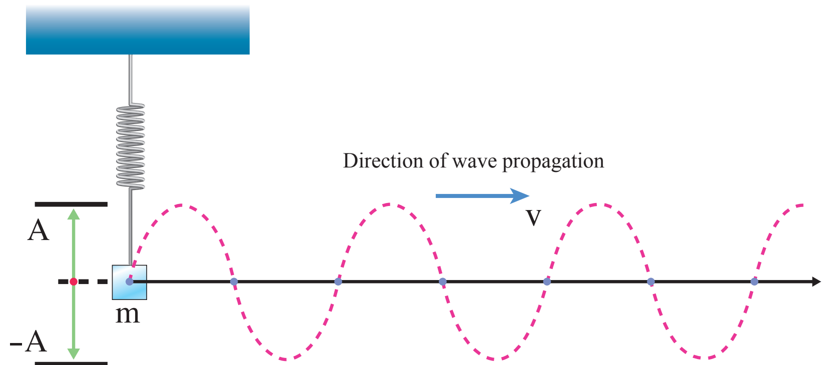


Figure (9)
Transverse wave

You can perform such an experiment yourself using a long taut rope, with one end (the far end) fixed to a vertical wall and the other end held taut in your hand. When you move your hand vertically up and down in the form of a pulse, you will notice a wave in the form of a pulse propagating along the rope. This wave is called a travelling wave, Figure (10).

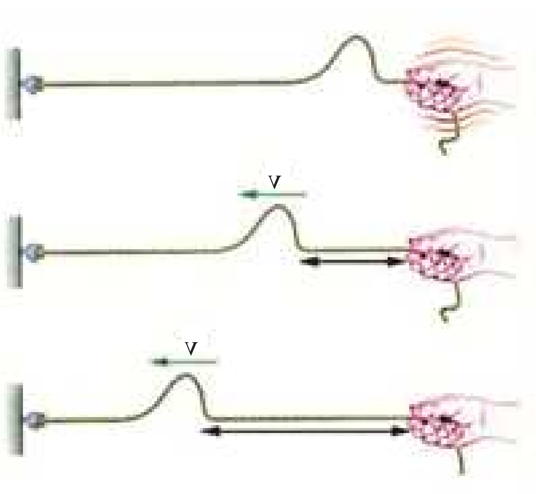


Figure (10)
Travelling pulse

Enrichment information (For reference only)

Waves that travel in a specific direction are referred to as travelling waves, to distinguish them from standing waves that result from the superposition of two identical waves, such as the reflected wave from the fixed end of the rope and the incident wave upon it, as occurs in the strings of musical instruments.

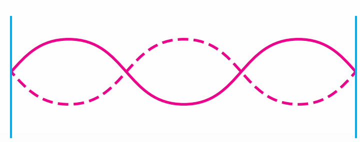


Figure (11)
Standing wave

It is obvious that the work done by the vibrating source on the rope is transferred as potential energy represented by the tension of the rope, and kinetic energy represented by the vibration of the rope. The points representing the maximum displacement in the positive direction are called crests (singular: crest), while the points representing the maximum displacement in the negative direction are called troughs (singular: trough). By observing any part of the rope during its vibration starting from its equilibrium position, we find that each complete oscillation includes one crest and one trough, i.e., the transverse wave consists of successive crests and troughs.

This wave will be continuous (a train of travelling waves) as long as the simple harmonic motion continues, Figure (12).

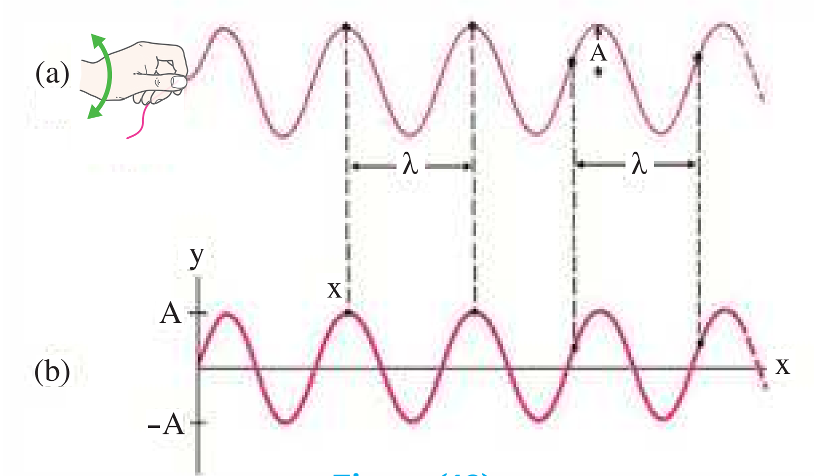


Figure (12)

A Wave train propagating in a taut rope due to simple harmonic motion of one end

And when the taut rope is replaced with a spring coil, a longitudinal wave can be generated, Figure (13) or a transverse wave, Figure (14). As shown, when the source vibrates, the particles of the surrounding medium vibrate in the same way. The vibration is transmitted first from the source to the adjacent or connected particles of the medium, and this continues throughout the medium. Thus, this vibration or disturbance spreads in the medium as a wave motion. As we mentioned before, a wave is nothing but a disturbance that propagates and transfers energy.

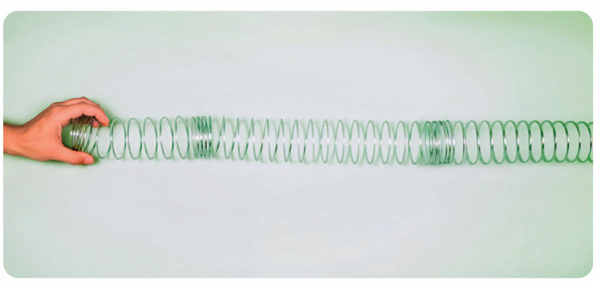


Figure (13)

Longitudinal wave in a spring coil

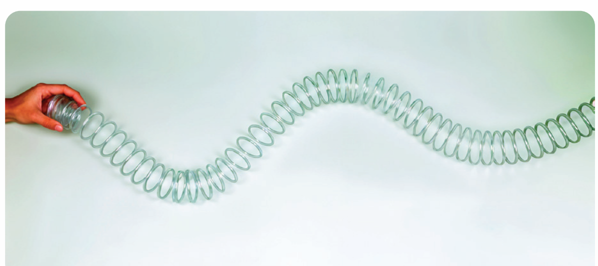


Figure (14)

Transverse wave in a spring coil

Graphical representation of mechanical waves:

The transverse or longitudinal wave is represented by the graphical representation of the relationship between:

1. Displacement of the medium's particles (d) at a certain moment and the distance (x) the wave has traveled Figure (15).
2. Displacement of a particle of the medium (d) and time (t) Figure (16).

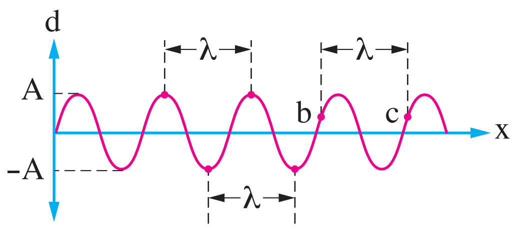


Figure (15)

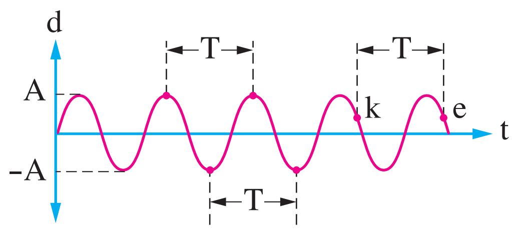


Figure (16)

Creative Thinking Prompt

- Search the Internet for how whales use mechanical waves to communicate with each other in water, and how they benefit from these waves to determine their location relative to objects around them in the depths of the ocean?

Figure(17)

Thus, mechanical waves are classified into two types:

1. **Transverse waves :** are waves in which the particles of the medium vibrate about their equilibrium positions in a direction perpendicular to the direction of wave propagation.
2. **Longitudinal waves :** are waves in which the particles of the medium vibrate about their equilibrium positions along the same line as the direction of wave propagation.

Wavelength and frequency

The distance between any two successive crests or two successive troughs in a transverse wave is expressed as its wavelength, Figure (18), and the distance between the centers of any two successive compressions or two successive rarefactions in a longitudinal wave is also expressed as its wavelength, Figure (19).

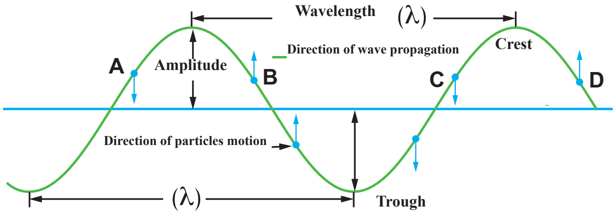


Figure (18)

Wavelength in a transverse wave

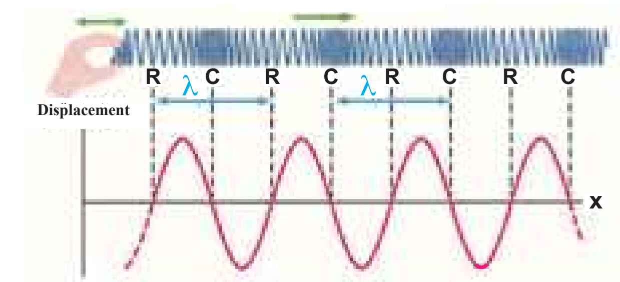


Figure (19)

Wavelength in a longitudinal wave

Accordingly, the wavelength can be represented by either of the two distances (BD) , (AC) as in Figure (18). It is noted that every two successive points (D , B) , (C , A) move at the same time, in the same manner, and in the same direction, having the same phase (i.e., they have the same displacement and direction).

∴ **Wavelength:** is the distance between any two successive points having the same Figure (20)

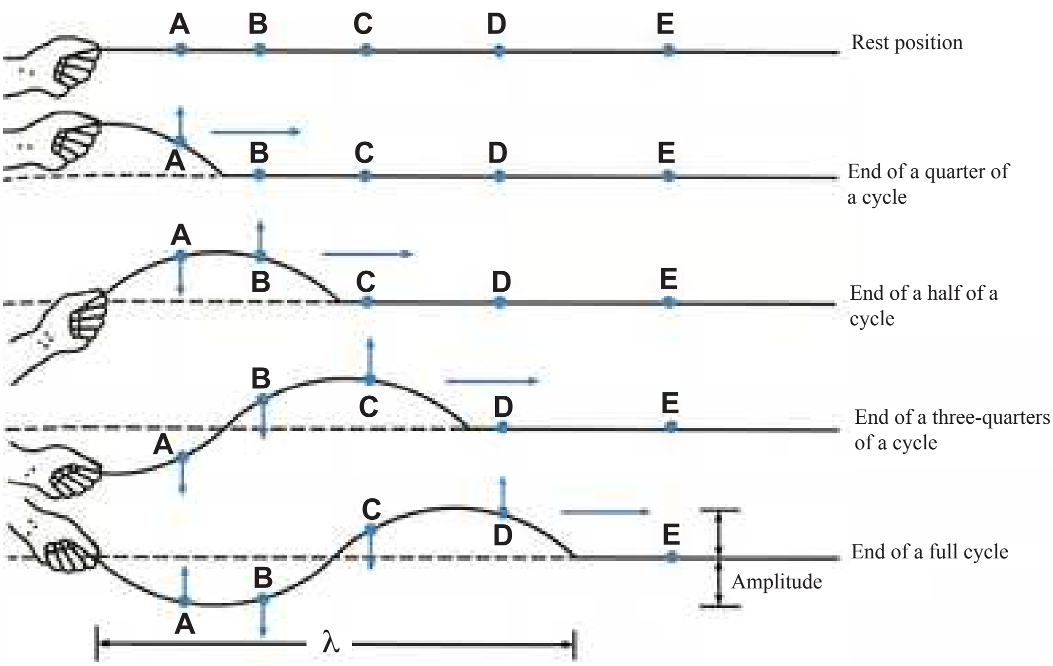


Figure (20)

The wavelength is the distance between two successive points having the same phase

The wavelength is also defined as the distance traveled by the wave during one periodic time, Figure (21)

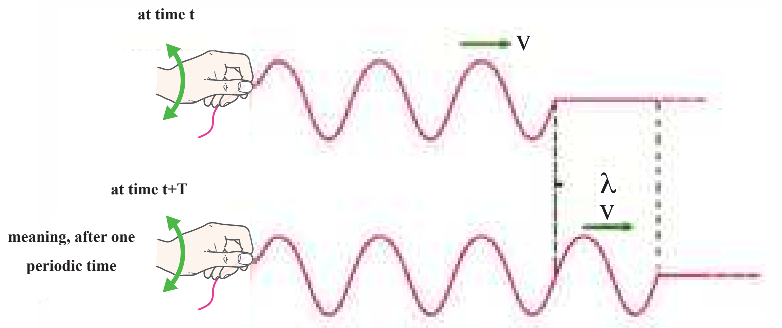


Figure (21)

The wavelength equals the distance traveled by the wave during one periodic time

The number of waves passing a certain point in the path of wave motion in one second is called the frequency.

The relationship between frequency, wavelength, and wave propagation speed

If a wave travels at a speed of v from one place to another separated by a distance equal to the wavelength λ, the wave takes a time equal to the period T

$$v = \frac{\lambda}{T}$$

Since

$$\upsilon = \frac{1}{T} \qquad \text{Or} \qquad T = \frac{1}{\upsilon}$$

So

$$v = \lambda\upsilon \qquad (3)$$

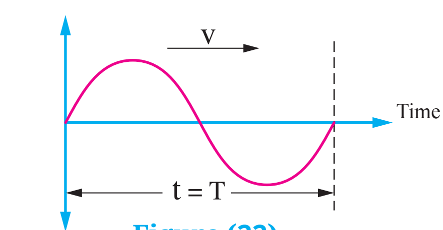


Figure (22)

This is a general relation for the propagation of all types of waves, whether it is a train of waves or a single pulse.

Thus frequency: is the number of vibrations of the source per second, or it is the number of wavelengths that the propagating wave covers in a certain direction in one second.

Example 1

If the wavelength of the sound wave emitted by a stationary train is 0.6 m and its frequency is 550 Hz, **what** is the speed of sound wave propagation in air?

Solution

$v = \lambda\upsilon$, $v = 0.6 \times 550 = 330$ m/s

What if

The frequency of the sound wave emitted by the train was higher, would that change the speed of wave propagation in the air?

Example 2

If the number of water waves passing through a certain point in one second is 12 waves and the wavelength of each wave is 0.1 m **calculate** the speed of wave propagation.

Solution

$v = \lambda \upsilon$, $v = 12 \times 0.1 = 1.2$ m/s

Example 3

Light waves propagate in space at a speed of 3×10^8 m/s. If the wavelength of the light is 5000 Å, **then** what is the frequency of this light? (1 Angstrom (Å) $=10^{-10}$ m)

Solution

$v = c = 3 \times 10^8$ m/s, $\lambda = 5 \times 10^3 \times 10^{-10} = 5 \times 10^{-7}$ m, $c = \lambda \upsilon$

$3 \times 10^8 = 5 \times 10^{-7} \times \upsilon$, $\upsilon = \dfrac{3 \times 10^8}{5 \times 10^{-7}} = 6 \times 10^{14}$ Hz

Misconceptions

Some believe that increasing the vibration speed of a string as a vibrating object leads to an increase in the speed of sound in air.

In fact, increasing the vibration speed of the string as a vibrating object increases the frequency of the sound tone, and does not affect the speed of the tone in the air, as the speed of the wave in a medium depends on the properties of the medium.

Figure (23)

Creative Thinking Prompt

- Why do we sometimes feel the ground shaking beneath our feet when a train passes quickly beside us?
- Does this help explain why many people feel the earthquake even though their areas are far from its epicenter?
- Using the Internet, research how studying mechanical waves contributes to preparing for earthquakes and reducing their negative effects.

Figure(24)
Seismograph

Figure(25)

Summary

First: Key definitions and concepts

- Wave: is a disturbance that moves and transfers energy.
- Displacement: is the distance of the vibrating object at any moment from its original position of rest (or equilibrium).
- Amplitude of vibration (A): is the maximum displacement of the vibrating object from its equilibrium position, or it is the distance between two points in the path of the vibrating object where its speed is maximum at one point and zero at the other.
- Complete vibration: is the motion performed by the vibrating object (such as a simple pendulum) in the time interval between passing by a certain point in its path twice consecutively in one direction.
- Frequency (υ) of a vibrating object: is the number of complete vibrations made by the vibrating object in one second.
- Frequency (υ) of a wave: is the number of waves that pass through a certain point in the path of wave motion in one second.
- Periodic time (T): is the time taken by the vibrating object to make a complete vibration, or it is the time taken by the vibrating object (such as a simple pendulum) to pass a certain point in its path twice consecutively in one direction.
- There are two types of waves:

(1) Electromagnetic waves: are waves that propagate in physical media and in vacuum, such as radio waves and light waves.

(2) Mechanical waves: are waves that propagate only in physical media, such as water waves and sound waves.

- There are two types of mechanical waves:

(1) Transverse waves: are those waves in which the particles of the medium vibrate around their equilibrium positions in a direction perpendicular to the direction of wave propagation, and consist of successive crests and troughs.

(2) Longitudinal waves: are those waves in which the particles of the medium vibrate around their equilibrium positions along the same line as the direction of wave propagation, and consist of successive compressions and rarefactions.

- Wavelength: is the distance between any two consecutive points in the direction of wave propagation that have the same phase (same displacement and same direction)

Second: Fundamental equations

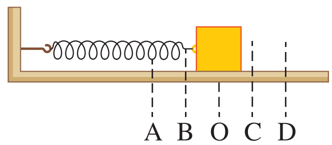
- Frequency: $\upsilon = \frac{N}{t}$
- Periodic time: $T = \frac{t}{N} = \frac{1}{\upsilon}$
- Wave propagation speed: $v = \lambda\upsilon$

Questions and Problems

First: Complete the following statements

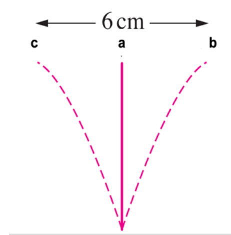
1. Displacement of the vibrating object is ....
2. Amplitude of vibration is ....
3. Complete vibration is ....
4. The periodic time is ....
5. Frequency of the wave is ....

Second: Choose the correct answer



1. The adjacent figure represents an object attached to a spring oscillating between the two points A, D, so the lowest value of the potential energy of the object is at ....

   ⓐ Point A or point D ⓑ Point O
   ⓒ Point B ⓓ Point C



2. In the adjacent figure, a vibrating flexible rod takes a time of 0.01 s to move from point (a) to point (b), then:

   (a) The period of the rod's motion equals ....

   ⓐ 0.02 s ⓑ 0.04 s
   ⓒ 0.06 s ⓓ 0.08 s

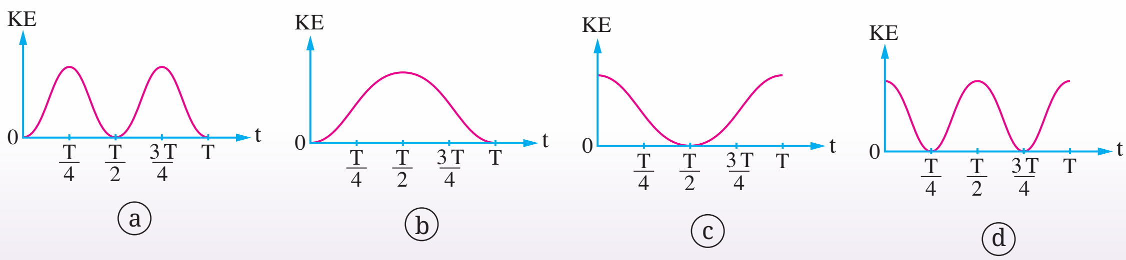
   (b) The amplitude of the rod's end vibration equals ....

   ⓐ 3 cm ⓑ 6 cm ⓒ 9 cm ⓓ 12 cm

   (c) The average speed of the rod's end while moving from point (b) to point (c) equals ....

   ⓐ 600 cm/s ⓑ 300 cm/s ⓒ 150 cm/s ⓓ 75 cm/s

3. A simple pendulum moves in simple harmonic motion, starting its motion from its maximum displacement from its original equilibrium position at t = 0 and completes a full oscillation in a time T. Which of the following graphs represents the relationship between the kinetic energy of the pendulum's bob (KE) and time (t)?



4. Transverse waves are waves that consist of ....

ⓐ Compressions and rarefactions, and the particles of the medium move around their equilibrium positions in a direction perpendicular to the direction of propagation

ⓑ Crests and troughs, and the particles of the medium move around their equilibrium positions along the same line of propagation

ⓒ Crests and troughs, and the particles of the medium move around their equilibrium positions in a direction perpendicular to the direction of propagation

ⓓ Compressions and rarefactions, and the particles of the medium move around their equilibrium positions along the same line of propagation

5. The relationship between the speed of wave propagation (v) in a physical medium and its frequency (υ), and its wavelength (λ) is ....

ⓐ $v = \lambda \times \upsilon$ ⓑ $\frac{\upsilon}{\lambda} = v$

ⓒ $\frac{\lambda}{\upsilon} = v$ ⓓ $v = (\lambda \times \upsilon)^2$

6. If the wavelength of the sound wave emitted by a sound source is 0.5 m and the frequency of the tone is 666 Hz, the speed of sound propagation in air is ....

ⓐ 338 m/s ⓑ 333 m/s

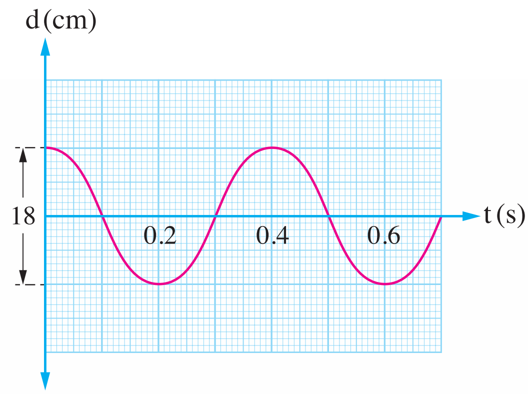
ⓒ 330 m/s ⓓ 346 m/s

7. A tone with a frequency of 225 Hz propagates in air. If you know that the speed of sound in air is 340 m/s, then the wavelength of the tone equals ....

ⓐ 1.33 m ⓑ 0.75 m

ⓒ 2 m ⓓ 1.51 m

8. The adjacent graph represents the relationship between the displacement (d) of a particle in a medium through which a wave propagates and time (t), so:



(a) The amplitude of the wave equals ....

ⓐ 9 cm ⓑ 17.5 cm

ⓒ 18 cm ⓓ 35 cm

(b) The frequency of this wave equals ....

ⓐ 1.7 Hz ⓑ 2.5 Hz

ⓒ 3.3 Hz ⓓ 5 Hz

(c) The periodic time of the wave motion equals ....

ⓐ 0.4 s ⓑ 0.6 s ⓒ 0.7 s ⓓ 0.8 s

9. Light with a wavelength of 6000 Å propagates in space at a speed of 3×10^5 km/s , so its frequency is ....

ⓐ 4×10^{10} Hz
ⓑ 4×10^{14} Hz
ⓒ 5×10^{14} Hz
ⓓ 5×10^{12} Hz

10. Two waves with frequencies of 512 Hz , 256 Hz propagate in a certain medium. The ratio between their wavelengths respectively is ....

ⓐ $\frac{2}{1}$
ⓑ $\frac{1}{2}$
ⓒ $\frac{3}{1}$
ⓓ $\frac{1}{3}$

Third: Essay questions

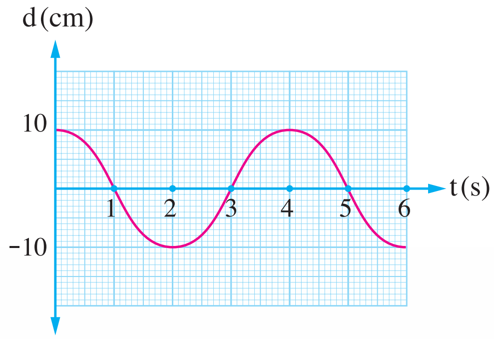
1. Describe the changes in both potential energy and kinetic energy occurring in the swing shown in the adjacent figure during a complete oscillation starting from the equilibrium position.
2. Deduce the relationship between frequency, wavelength, and the propagation speed of waves.
3. Define each of the following:

(a) The wave
(b) The transverse wave
(c) The longitudinal wave
(d) Wavelength

Fourth: Problems

1. The adjacent graph represents the relationship between the displacement (d) of an object moving in simple harmonic motion and time (t). Calculate:

(a) The amplitude of the object's oscillation.
(b) The periodic time of the object's motion.



(10 cm, 4 s)

2. If the distance between the second and seventh crests of a transverse wave is 20 m and the time elapsed between the passage of the first and fifth crests at a fixed point in the wave's path is 0.1 s, calculate:

(a) The wavelength of the wave.
(b) The propagation speed of the wave. (4 m, 160 m/s)

3. A stone was thrown into a lake, forming 50 circular waves on the water surface after 5 seconds from the stone hitting the water, and the radius of the outermost circle was 2 m. Calculate:

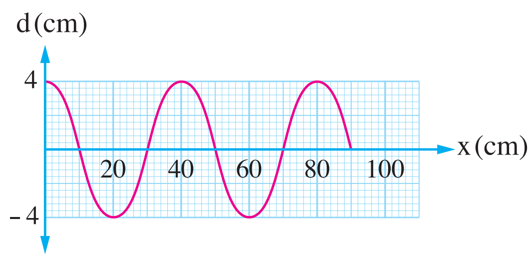
(a) The wavelength of the resulting wave.

(b) The frequency of the wave.

(c) The propagation speed of the wave. (0.04 m, 10 Hz, 0.4 m/s)

4. A wireless transmission station on Earth sends electromagnetic waves toward a satellite at a speed of 3×10^8 m/s, and after 0.03 s the station received the waves reflected from the satellite. Calculate the distance between the transmission station and the satellite. (4.5×10^6 m)

5. The adjacent graph represents the relationship between the displacement (d) of the medium's particles through which a wave travels at a certain moment and the distance (x) the wave travels in the direction of its propagation. If one particle of the medium takes time t to have a displacement of 4 cm from its equilibrium position, what is the distance the wave travels during the time t?



(10 cm)

Chapter

Three

Light

Expected learning outcomes

By the end of this chapter, you will be able to:

1- *Explain the wave nature of light.*

2- *Apply the laws of reflection in light.*

3- *Verify the laws of refraction in light and solves problems using them.*

4- *Identify the relationship between the properties of light in the medium and the absolute refractive index of a medium.*

5- *Apply Snell's law for light.*

6- *Explain the phenomena of interference and diffraction of light.*

7- *Explain the meaning of total reflection and the critical angle.*

8- *Discuss some applications of total reflection.*

9- *Identify the factors affecting the deviation of light in the triangular prism.*

10- *Determine the path of a light ray through a triangular prism and deduces the prism laws practically.*

11- *Identify the conditions for the minimum deviation position in the triangular prism.*

Chapter Terms

- *Electromagnetic Spectrum*
Electromagnetic Spectrum
- *Reflection*
- *Refraction*
- *Snell's law*
- *Interference*
- *Diffraction*
- *Total Reflection*
- *Critical Angle*
- *Optical fibers*
- *Mirage*
- *Dispersion of light*

Introduction

Light is part of a wide range of electromagnetic waves, all of which propagate in vacuum at a constant speed of 3×10^8 m/s. They differ from one another in frequency and wavelength, forming what is called the electromagnetic spectrum, Figure (1).

So what is the electromagnetic spectrum? And what are its properties?

The electromagnetic spectrum includes radio waves, microwaves, infrared waves, visible light waves, ultraviolet waves, X-ray waves, and gamma ray waves.

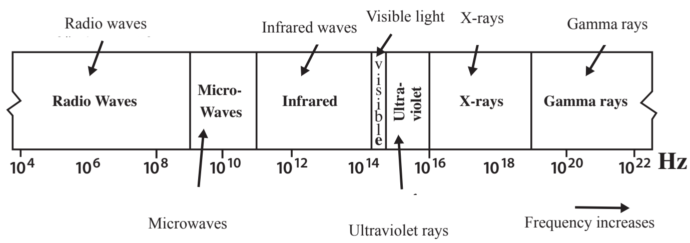


Figure (1)

The electromagnetic spectrum

The electromagnetic wave consists of two fields, one is electric and the other is magnetic, They both oscillate at a frequency υ, are in phase and are perpendicular to each other, and perpendicular to the direction of propagation on the other hand, as shown in Figure (2). Therefore, it is a transverse wave.

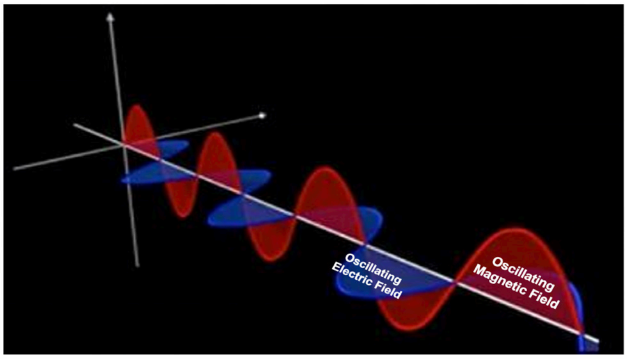


Figure (2)

The electromagnetic wave consists of an electric field and a magnetic field perpendicular to each other and to the direction of wave propagation

Reflection and refraction of light

Light propagates in all directions in straight lines unless it encounters an obstructing medium. If it does, it undergoes reflection, refraction, or absorption in varying proportions depending on the nature of the obstructing medium.

When a light ray falls on the interface between two media with different optical densities, part of the light is reflected and the other part is refracted, neglecting the absorbed portion.

From the opposite figure, we observe the following:

The incident, reflected, and refracted rays, as well as the normal (N) to the interface at the point of incidence, all lie in one plane perpendicular to the interface.

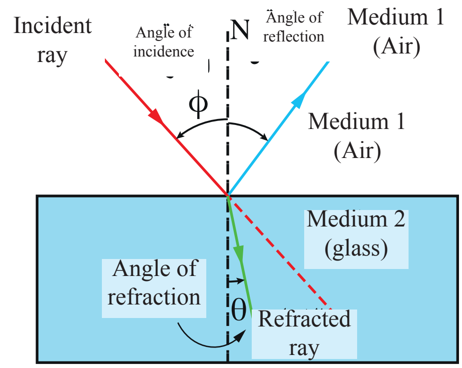


Figure (3)
Reflection and refraction of light

- In case of reflection:

  Angle of incidence = angle of reflection

- In case of refraction:

The ratio of the sine of the angle of incidence in the first medium to the sine of the angle of refraction in the second medium is equal to the ratio of the speed of light in the first medium to the speed of light in the second medium,

That is:
$$\frac{\sin \phi}{\sin \theta} = \frac{v_1}{v_2}$$

And the ratio $\left(\frac{v_1}{v_2}\right)$ is a constant ratio for these two media and is called the relative refractive index from the first medium to the second medium, denoted by $_2n_1$

That is:
$$\frac{\sin \phi}{\sin \theta} = \frac{v_1}{v_2} = {}_1n_2 \qquad (1)$$

Creative Thinking Prompt

- How can the property of electromagnetic wave reflection including light in space, be utilized to support communications and generate electricity on Earth's surface?

Figure (4)
Znamya Space Mirror

Important results

1. The speed of light in a vacuum is one of the universal constants and equals , 3×10^8 m/s. The speed of light in a vacuum is greater than its speed in any material medium. If we denote the speed of light in a vacuum by c and the speed of light in the material medium by v, then the ratio $\frac{c}{v}$ is called the absolute refractive index of this medium and is denoted by n. Its value is always greater than one.

$$\frac{c}{v} = n \quad (2)$$

It has a refractive index n	The material medium
1.000293	Air
1.33300	Water
1.50100	Benzene
1.46100	Carbon tetrachloride
1.36100	Ethyl alcohol
1.52000	Crown glass
1.66000	Flint glass
1.48500	Quartz
2.41900	Diamond

"Refractive indices of some materials"

2. From equation (2) it is clear that:

$$v = \frac{c}{n}$$

That is:

$$\frac{v_1}{v_2} = \frac{n_2}{n_1}$$

And from this,

$$_1n_2 = \frac{n_2}{n_1} \quad (3)$$

And by substituting from (3) into (1)

$$\frac{n_2}{n_1} = \frac{\sin \phi}{\sin \theta}$$

That is:

$$n_1 \sin \phi = n_2 \sin \theta \quad (4)$$

This is known as Snell's Law

That is: the product of the absolute refractive index of the incidence medium and the sine of the angle of incidence equals the product of the absolute refractive index of the refraction medium and the sine of the angle of refraction.

3. Refraction can be used to analyze a light beam into its components of different wavelengths, as the absolute refractive index of a single medium varies according to the wavelength of the spectrum passing through it. Thus, white light disperses into its components (its spectra), which can be observed in the appearance of a rainbow after rainfall.

Explanation of refraction:

If light passes from a medium of lower optical density to a medium of higher optical density, the refracted ray bends toward the normal. This is similar to a cart where one wheel enters a muddy area and slows down, while the other wheel is on a paved road and moves faster, causing the path to bend as in Figure (5). Conversely, when light moves from a region of higher optical density to a region of lower optical density, it refracts away from the normal as in Figure (6).

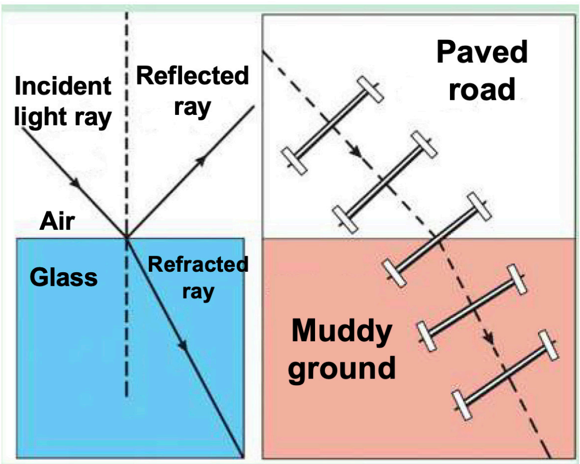


Figure (5)

Refraction from a medium of lower optical density to a medium of higher optical density

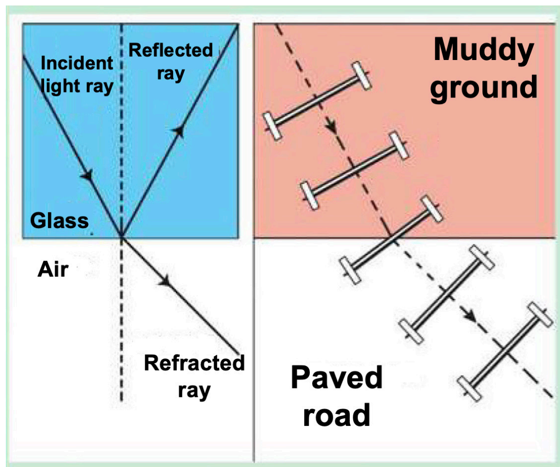


Figure (6)

Refraction from a medium of higher optical density To a medium of lower optical density

Example 1

If a light ray falls from air onto the surface of a glass plate with a refractive index of 1.5 at an angle of incidence of 30°, **calculate** the angle of refraction.

Solution

In general, in all the problems mentioned in this study content, the absolute refractive index of air is considered to be 1

$\because n = \frac{\sin \phi}{\sin \theta}$ $\therefore 1.5 = \frac{\sin 30}{\sin \theta}$

$\therefore \sin \theta = \frac{0.5}{1.5} = 0.333$, $\therefore \theta = 19.5^\circ$

What if The angle of incidence of the ray increased to 60°, What is the effect of that on the refractive index of glass and the angle of refraction of the ray?

Example 2

If the absolute refractive index of water is $\frac{4}{3}$ and the absolute refractive index of glass is $\frac{3}{2}$ **then find:**

(a) The relative refractive index from water to glass.

(b) The relative refractive index from glass to water.

Solution

(a) The relative refractive index from water to glass:

$${}_1n_2 = \frac{n_2}{n_1} = \frac{3}{2} \times \frac{3}{4} = \frac{9}{8}$$

(b) The relative refractive index from glass to water:

$${}_2n_1 = \frac{n_1}{n_2} = \frac{4}{3} \times \frac{2}{3} = \frac{8}{9}$$

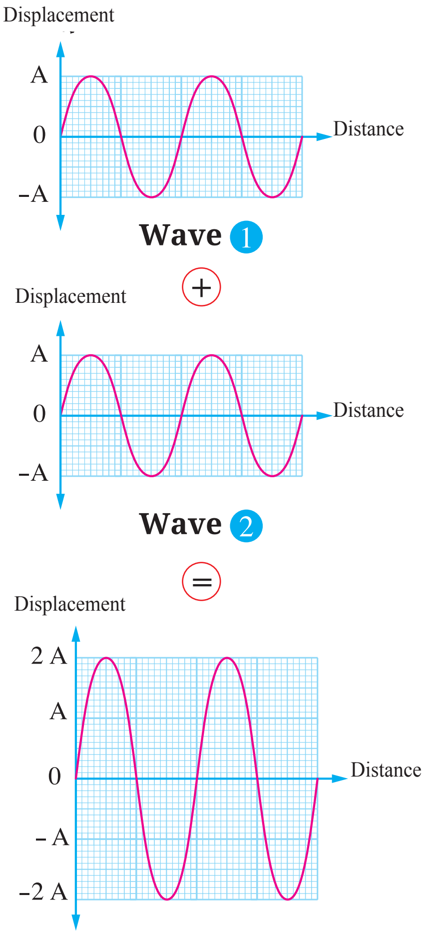
And from this example we see that: ${}_1n_2 = \frac{1}{{}_2n_1}$, and this is an important result.

Light interference

Waves are characterized by their ability to interfere. For example, when two waves of the same frequency and amplitude meet and propagate in the same direction, such as two waves emitted from two coherent sources (sources that emit identical waves with the same phase), they superimpose **and this results in:**

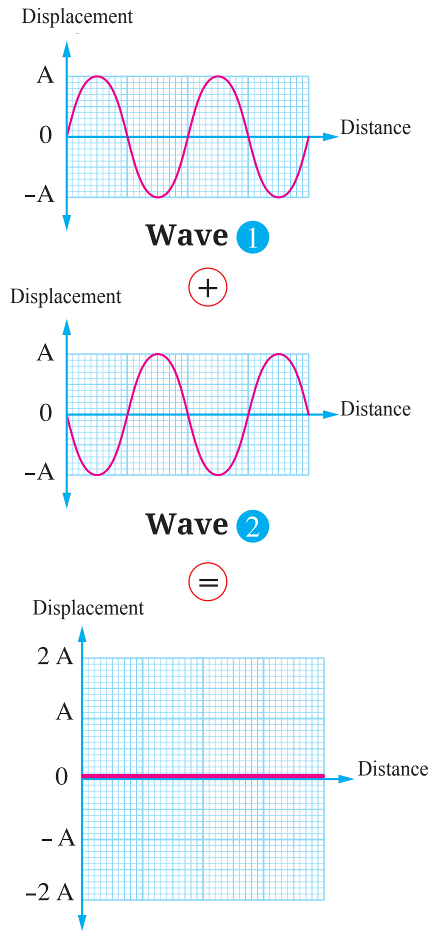
1. **Reinforcement** of the intensity of the two waves at certain positions **as a result of** the meeting of a crest from one wave with a crest from the other wave, or a trough from one wave with a trough from the other wave, and this is called **constructive interference** as shown in Figure (7).

2. **Cancellation** of the intensity of the two waves at other positions **as a result of** the meeting of a crest from one wave with a trough from the other wave, and this is called **destructive interference** as shown in Figure (8).



Resultant of constructive interference

Figure (7)



Resultant of destructive interference

Figure (8)

Thomas Young conducted an experiment to study the phenomenon of light interference, known as the double-slit experiment Double Slit Experiment, which is illustrated in Figure (9). In this figure, a monochromatic light source , i.e.,, i.e., the wavelength λ has a single fixed value and is located at a suitable distance from a barrier with a narrow rectangular opening S through which cylindrical waves pass toward a barrier with two narrow rectangular openings S_1 , S_2 acting as a double slit. The double-slit barrier is adjusted so that the two openings S_1 , S_2 on the same cylindrical wavefront, so the waves they emit have the same phase, as the two rectangular apertures behave like coherent sources, which are sources whose waves have the same frequency and amplitude and the same phase.

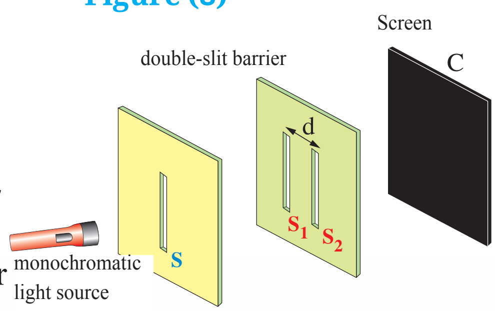


Figure (9)

Young's experiment before turning on the light source

And on the screen C, the waves of the two wave motions coming to it from S_1 , S_2 are superimposed

As a result of this superposition, bright regions appear interspersed with dark ones, known as interference fringes as in figure (10),

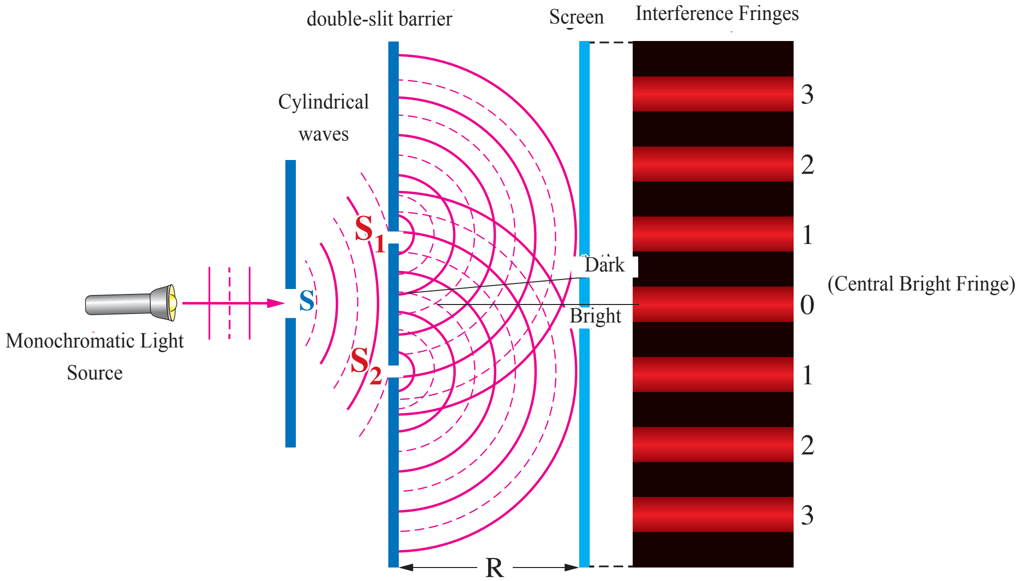


Figure (10)

Schematic diagram of Young's experiment

The distance between the centers of any two successive fringes Δy of the same type is determined by the relation:

$$\Delta y = \frac{\lambda R}{d} \qquad (5)$$

Where: λ is the wavelength of the monochromatic light used, R is the distance between the double slit and the screen prepared to receive the fringes, and d is the distance between S_1 , S_2,

Therefore, this experiment is used to determine the wavelength of any monochromatic light.

Example

In the double-slit experiment, if the distance between the two narrow rectangular slits is 1.5×10^{-4} m , and the distance between the slit and the screen prepared to receive the fringes is 0.75 m, and the distance between the centers of two successive bright fringes is 3 mm, **calculate** the wavelength of the monochromatic light used in angstroms.

Solution

$$\Delta y = \frac{\lambda R}{d} \quad , \quad 3 \times 10^{-3} = \frac{0.75 \times \lambda}{1.5 \times 10^{-4}}$$

$$\lambda = \frac{1.5 \times 10^{-4} \times 3 \times 10^{-3}}{0.75} = 6 \times 10^{-7} \text{ m} \quad , \quad \lambda = 6 \times 10^{-7} \times 10^{10} = 6000 \text{ Å}$$

Light diffraction

The direction of wave propagation changes (deviates from its direction) when it falls on a narrow slit or a sharp or pointy edge. For example, when monochromatic light falls on a circular aperture in a barrier, according to our knowledge about the propagation of light in straight lines, we expect a defined bright circular spot to form on the screen shown in the figure. However, a close study of the bright spot, i.e., studying the distribution of illumination on the screen, shows the presence of bright and dark fringes as in figure (11), and the central bright fringe is called the Airy Disk.

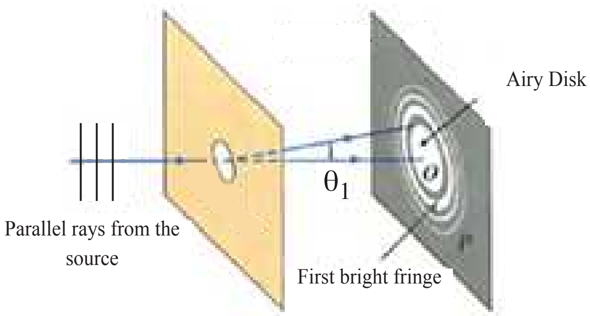


Figure (11)

Diffraction through a circular aperture

Figure (12) shows diffraction through a rectangular aperture, and in general, diffraction appears clearly if the wavelength is comparable to the dimensions of the obstacle's aperture, and vice versa.

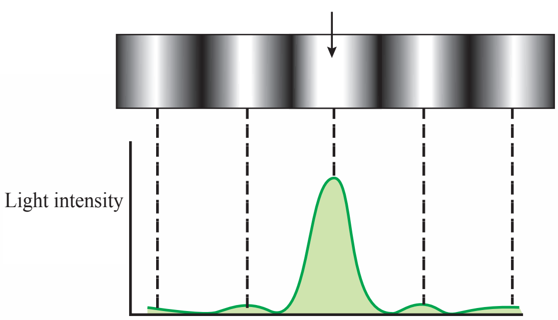


Figure (13)

Distribution of light intensity on the screen with the sequence of fringes resulting from diffraction through a rectangular aperture

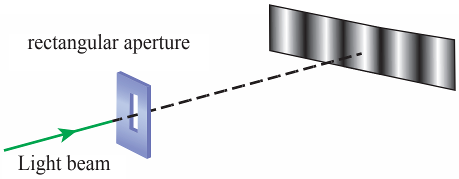


Figure (12)

Diffraction through a rectangular aperture

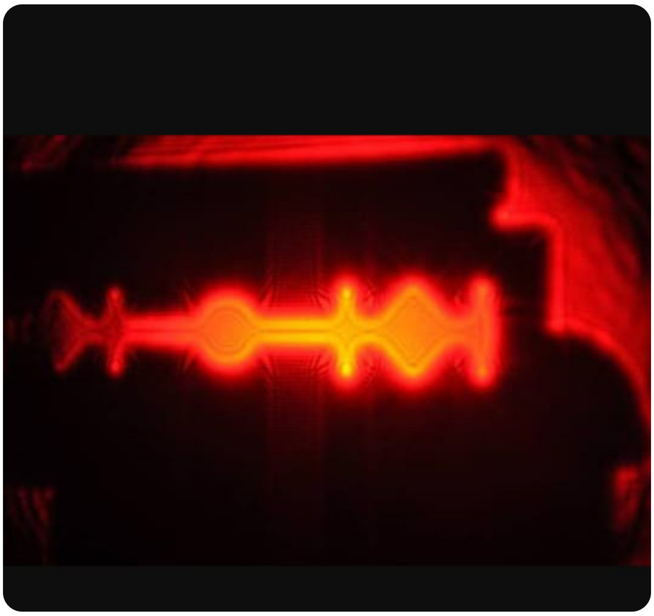


Figure (14)

Diffraction of light at a sharp edge

It is worth mentioning that there is no fundamental difference between the models of interference and diffraction, as both arise from the superposition of waves.

Light is a wave motion

It is clear to us from the previous paragraphs that light:

1. Propagates in straight lines.
2. Reflects when it meets a reflective surface according to the laws of reflection.
3. Refracts when it meets an interface between two transparent media according to the laws of refraction.
4. Light interferes, and interference results in an increase in light intensity at some positions (bright fringes) and a decrease in intensity at other positions (dark fringes).
5. Light diffracts (deviates from its path) when it passes through an aperture whose dimensions are comparable to the wavelength of light or a sharp (or pointy) edge.

These are the same general properties of waves, and therefore the propagation of light is in the form of wave motion.

Total reflection and the critical angle

When a light ray travels from a medium of higher optical density such as water (or glass) to a medium of lower optical density such as air, the refracted ray moves away from the normal as shown by the path of ray (B) in figure (15). As the angle of incidence increases in the medium of higher optical density (the one with the higher absolute refractive index), the angle of refraction increases in the medium of lower optical density (the one with the lower absolute refractive index), as shown by the path of ray (C) in figure (15).

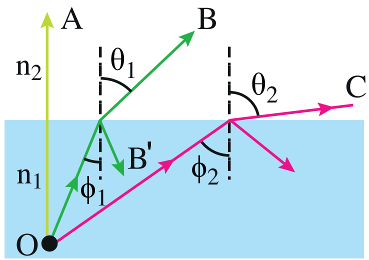


Figure (15)

And when the angle of incidence in the medium of higher optical density reaches a certain value ϕ_c, the angle of refraction in the medium of lower density reaches its maximum value and equals 90°, and at this point the refracted ray emerges coincident with the interface. The angle of incidence in this case is called the critical angle ϕ_c, which is the angle of incidence in the higher density medium corresponding to a refraction angle of 90° in the lower density medium.

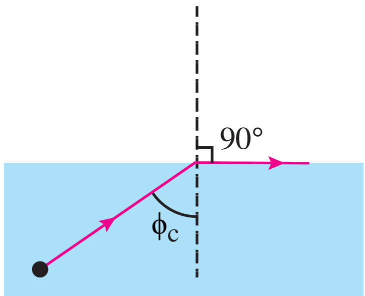


Figure (16)

By applying Snell's law in this case: $n_1 \sin \phi_c = n_2 \sin 90$

Among them

$$\sin \phi_c = \frac{n_2}{n_1} = {}_1n_2 \qquad (6)$$

Where: n_1 is the refractive index of the medium with higher optical density, n_2 is the refractive index of the medium with lower optical density, and ϕ_c is the critical angle between the two media.

And when the medium of lower optical density is air, $n_2 = 1$, and then the previous relation is written as:

$$\sin \phi_c = \frac{1}{n_1} \qquad (7)$$

Where: ϕ_c represents the critical angle for the medium with higher optical density, and n_1 is its absolute refractive index, Thus, the refractive index of the medium can be calculated by knowing its critical angle. If the angle of incidence in the medium of higher optical density exceeds the critical angle, the light ray does not pass into the second medium of lower optical density, but instead undergoes total internal reflection in the same medium, unlike any other angle of incidence less than the critical angle, where part of the light passes through and another part is reflected, as in figure (17).

Figure (17)
Total reflection

Example

If the refractive indices of glass and water are 1.6 and 1.33 respectively, calculate:

(a) The critical angle for glass. (b) The critical angle for water.

(c) The critical angle between glass and water.

Solution

(a) $$\sin \phi_c = \frac{1}{n_1} = \frac{1}{1.6} = 0.625$$

And from this: $$\phi_c = 38.68°$$

(b) $$\sin \phi_c = \frac{1}{n_2} = \frac{1}{1.33} = 0.7519$$

And from this: $$\phi_c = 48.76°$$

(c) $$\sin \phi_c = \frac{n_2}{n_1} = \frac{1.33}{1.6} = 0.8313$$

And from this: $$\phi_c = 56.23°$$

What if A light ray fell at an angle of incidence of 57° from water onto glass, Does total internal reflection occur for the ray?

Applications of total internal reflection

1 Optical fibers (fiber optics)

If we have a hollow tube and look from one end to see a luminous object at the other end, it can be seen. But if the hollow tube is bent, the luminous object cannot be seen.

So how can it be seen in this case? Assuming we place reflective mirrors at the points where the light ray strikes the inner wall of the tube, we can then see the luminous object. Similarly, optical fibers can be used: when a light ray falls at an angle greater than the critical angle, total internal reflections occur, allowing the ray to exit with its full energy from the other end despite the bending of these fibers.

Figure (18)
Optical fibers

An optical fiber is a thin solid rod made of a transparent material. If light enters from one end and strikes its inner wall at angles of incidence greater than the critical angle, it undergoes successive total internal reflections until it exits from the other end, as shown in figure (19).

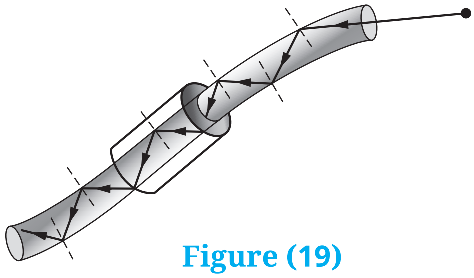


Figure (19)

Figure (20) shows a bundle consisting of thousands of fibers together, flexible enough to be bent, allowing them to reach places that are difficult to access, and can be used to transmit light with negligible loss in its intensity.


Figure (20)

Optical fibers are now receiving great interest. Fiber optics or optical fibers are now used in medical examinations such as medical endoscopes, Figure (21), which are used in diagnosis, as well as in performing surgical operations using a laser beam. Optical fibers and lasers are also used in communications by converting electrical signals into light pulses that can be transmitted efficiently through an optical fiber cable.


Figure (21)
Performing surgeries using medical endoscopes

Creative Thinking Prompt

- In addition to the use of optical fibers in the fields of communications and medicine, can optical fibers be used in other fields?

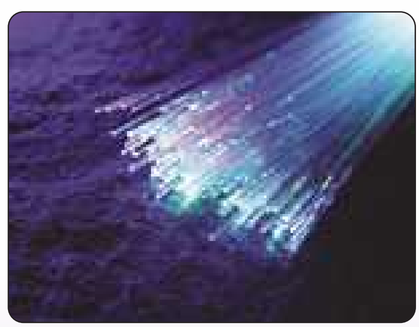


Figure (22)

Enrichment information (for reference only)

While light travels inside the optical fiber, the light rays may strike the wall of the fiber at an angle of incidence less than the critical angle, causing them to refract and leak out of the fiber, which reduces the efficiency of light transmission.

Therefore, the optical fiber is made of two layers (inner and outer), so that the refractive index of the outer layer is less than that of the inner layer, which helps increase the occurrence of total internal reflection and thus increases the efficiency of light transmission.

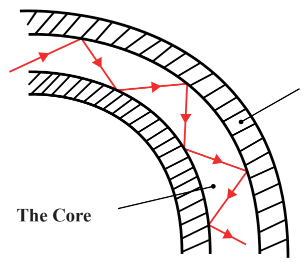
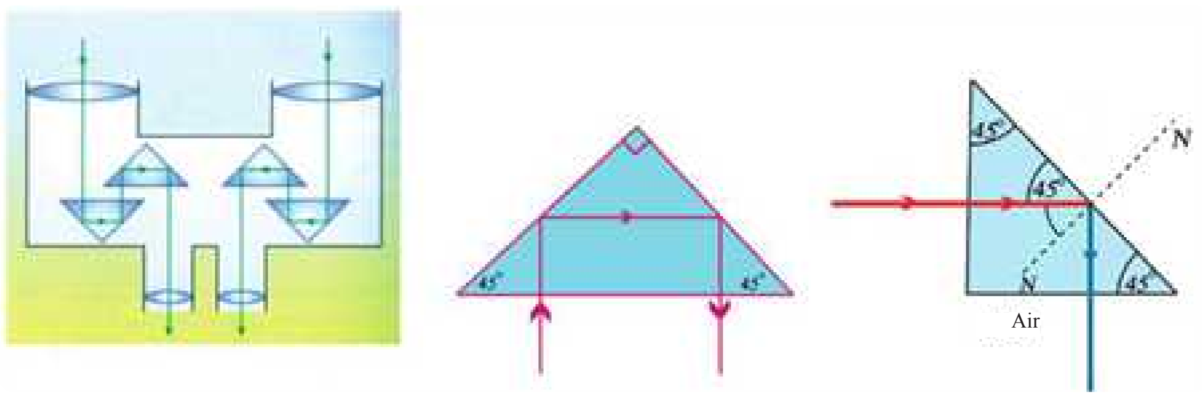


Figure (23)

2 Reflecting Prism

Since the critical angle between glass with an absolute refractive index of (1.5) and air is about 42°, a triangular glass prism with angles (45°, 45°, 90°) is used to change the path of a light beam by 90° or 180°. Such a prism is used in some optical devices such as the periscope used in submarines and in Figure (24).



c. Using the prism in binoculars

b. The reflecting prism changes the path of light by 180°

a. The reflecting prism changes the path of light by 90°

Figure (24)

Reflecting prism

And using the prism for this purpose is better than using a metallic reflecting surface (or a mirror).

1. Because light is totally internally reflected in the prism, and it is rare to find a metallic reflecting surface with 100 % efficiency.

② The metallic surface may lose its luster or shine, reducing its ability to reflect light, which does not happen in the prism. In practice, some light is lost upon entering or exiting the prism, but this can be avoided by coating the surface through which light enters or exits with a thin non-reflective film such as aluminum fluoride or magnesium fluoride (whose refractive index is less than that of glass).

③ Mirage

Mirage is a familiar phenomenon on hot days, It can be seen in summer on roads where the road appears to the car passenger as if it is covered with water, Figure (25 A), and it can also be observed in deserts where palm trees or hills appear as inverted images similar to those formed by reflection on a water surface, making the observer think there is water, Figure (25 B).

Figure (25 A)
Paved roads appear wet

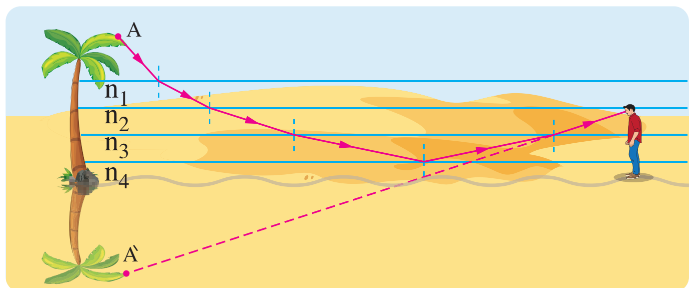


Figure (25 B)
Seeing the image of a palm tree in the desert suggests the presence of water

This phenomenon is explained as follows:

On very hot days, the temperature of the air layers adjacent to the ground rises, making their density less than that of the layers above them. Consequently, the refractive indices of the upper air layers are greater than those below. Therefore, if we trace a light ray coming from the top of a palm tree, for example, this ray, when moving from the upper layer to the one below, refracts away from the normal at the interface between the two layers.

As it passes from that layer to the next, its deviation increases, and thus the ray's deviation increases as it passes through successive air layers, taking a curved path. When its angle of incidence in one of the layers becomes greater than the critical angle for the layer below, the light ray undergoes total internal reflection, taking a curved path upward until it reaches the eye, which sees the image of the top of the palm tree along the path of the arriving ray. This explains why its image appears inverted (Figure 25 B) and the observer thinks there is water.

Deviation of light in the triangular prism

When a light ray such as ray (ab) falls on the face (XY) of a triangular prism, this ray refracts inside the prism, taking the path (bc) until it strikes the face (XZ) as in Figure (26), and then exits to the original medium in the direction (cd).

From this figure, we see that the light ray in the triangular prism refracts twice, once at the first face (XY) and again at the second face (XZ), and as a result, the ray deviates from its path by a certain angle called the angle of deviation α.

The angle of deviation : it is the acute angle between the extensions of the incident and emergent rays, denoted here by the symbol α.

And if the angle of incidence is ϕ_1, the angle of refraction at the first face is θ_1, the angle of incidence at the second face is ϕ_2, the angle of emergence is θ_2, and the prism's apex angle is A, then from the geometry of Figure (26) we find:

$\alpha = (\phi_1 - \theta_1) + (\theta_2 - \phi_2)$

$\alpha = (\phi_1 + \theta_2) - (\theta_1 + \phi_2)$

$e + A = 180°$

$e + \theta_1 + \phi_2 = 180°$

$$\therefore \quad A = \theta_1 + \phi_2 \qquad (8)$$

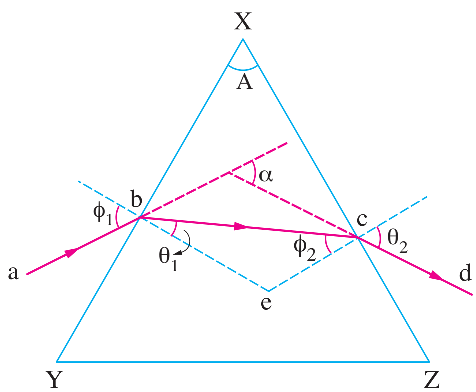


Figure (26)
The path of the light ray in a triangular prism

And by substituting from equation (8), we find that:

$$\alpha = \phi_1 + \theta_2 - A \qquad (9)$$

From this relationship, it is clear that the angle of deviation in a triangular prism with apex angle A depends on the angle of incidence ϕ_1.

It can be shown in practice that the angle of deviation gradually decreases as the angle of incidence increases until the angle of deviation reaches a certain limit known as the minimum deviation (α_o), after which the angle of deviation gradually increases as the angle of incidence increases, as in Figure (27).

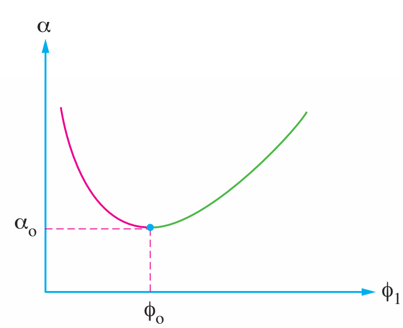


Figure (27)
The graphical relationship between the angle of deviation and the angle of incidence in the triangular prism

And at the position of minimum deviation, it can be practically and theoretically proven that:

$\phi_1 = \theta_2 = \phi_o$

$\theta_1 = \phi_2 = \theta_o$

And equations (8) and (9) become as follows:

$$A = 2\,\theta_o$$

From which $$\theta_o = \frac{A}{2}$$

From which $$\alpha_o = 2\,\phi_o - A$$

$$\phi_o = \frac{\alpha_o + A}{2}$$

In the case where the triangular prism is surrounded by air, its material's refractive index is:

$$n = \frac{\sin \phi_o}{\sin \theta_o}$$

By substituting θ_o , ϕ_o, we find that the refractive index of the prism material in the position of minimum deviation is determined by the relation:

$$n = \frac{\sin\left(\frac{\alpha_o + A}{2}\right)}{\sin\left(\frac{A}{2}\right)} \qquad (10)$$

Practical experiment to determine the path of a light ray through a triangular prism

Required tools:

1. A glass prism with apex angle 60°
2. Pins
3. Protractor
4. Ruler

Procedure:

1. Place the prism on a white sheet and mark its triangular base, then remove the prism and draw a line (ab) inclined on one of the prism's faces representing an incident ray at a certain angle of incidence.
2. Place the prism in its position, then look from the opposite side and determine the position of the emerging ray (cd) using pins, or by placing a ruler and aligning its edge with the image of the incident ray (ab), then draw a line (cd) along the edge of the ruler.

③ Remove the prism and then connect (bc), so the path of the light ray is (abcd) from air to glass to air again.

④ Extend the emerging ray (cd) in a straight line until it meets the extension of the incident ray (ab), so the acute angle between them is the angle of deviation α as shown in figure (28).

⑤ Measure each of the following: angle of incidence ϕ_1, angle of refraction θ_1, internal angle of incidence ϕ_2, angle of emergence θ_2, and angle of deviation α

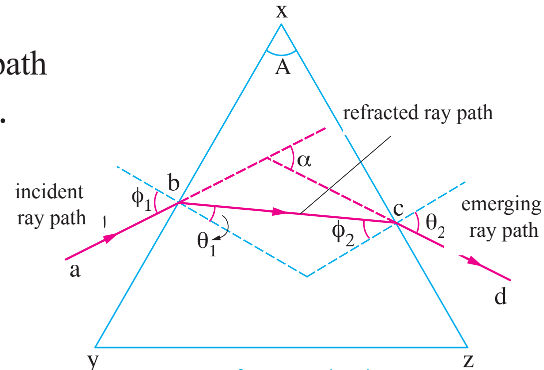


Figure (28)
The path of the light ray in a triangular prism

⑥ Repeat the previous procedure several times, changing the angle of incidence, and place the results in a table as follows:

Prism apex angle A	Angle of incidence ϕ_1	Angle of refraction θ_1	Internal angle of incidence ϕ_1	Angle of emergence θ_2	Angle of deviation α
....	....	....	....	....	....

Use equations (8) and (9) to calculate the values of α and A, and compare the results with the experimentally measured values.

Example

The adjacent figure represents a light ray incident at an angle of 45° on one face of an equilateral triangular prism with refractive index of its material 1.5, **calculate:**
(a) The angle of emergence of the light ray from the prism.
(b) The angle of deviation of the light ray.

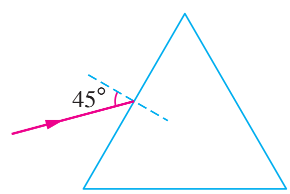


Figure (29)

Solution

(a) By applying Snell's law: $\because \sin\phi_1 = n \sin\theta_1$

$\therefore \sin\theta_1 = \frac{\sin 45}{1.5}$ $\therefore \theta_1 = 28.13°$

$\because A = \theta_1 + \phi_2$

$\therefore \phi_2 = A - \theta_1 = 60 - 28.13 = 31.87°$

$\because \sin\phi_c = \frac{1}{n} = \frac{1}{1.5}$

$\therefore \phi_c = 41.81°$

* By comparing the second angle of incidence (ϕ_2) with the critical angle of the prism material, we find that: $\phi_2 < \phi_c$

∴ The ray passes through the face of the prism and Snell's law applies.

∵ $\sin \theta_2 = n \sin \phi_2 = 1.5 \sin 31.87$ ∴ $\theta_2 = 52.37°$

∵ $\alpha = \phi_1 + \theta_2 - A$ ∴ $\alpha = 45 + 52.37 - 60 = 37.37°$ (B)

What if The angle of incidence ($\phi 1$) was gradually increased to 52.37°, what effect does this have on the angle of deviation of the beam?

Misconceptions

Some believe that the angle of light deviation (α) in a triangular prism increases by increasing the angle of incidence (ϕ_1) according to the relationship ($\alpha = \phi_1 + \theta_2 - A$)

In fact, the relationship between the two quantities is not as simple as it appears, since the value of (θ_2) also changes with the angle of incidence (ϕ_1).

Dispersion of light by the triangular prism

We concluded in the previous paragraph that in the position of minimum deviation, the refractive index of the prism material surrounded by air is determined by the relation:

$$n = \frac{\sin\left(\frac{\alpha_o + A}{2}\right)}{\sin\left(\frac{A}{2}\right)}$$

Where: n is the refractive index of the prism material, α_o is the angle of minimum deviation, and A is the prism apex angle.

Since the prism apex angle is constant, it is clear that a change in the refractive index of the prism material is accompanied by a change in the value of the minimum deviation angle; as the refractive index increases, the minimum deviation angle increases, and vice versa.

Since the refractive index n depends on the wavelength of the light passing through the prism, the minimum deviation angle also depends on the wavelength of this light.

Therefore, if a beam of white light falls on a triangular prism set in the position of minimum deviation, the light emerging from the prism disperses into the known spectrum colors as shown in Figure (30), From the figure, we see that violet light rays are the most deviated among visible light rays (the refractive index of the prism material is greater for violet light), and red light rays are the least deviated (the refractive index of the prism material is less for red light). The order of the visible spectrum colors into which white light disperses, from the prism apex to its base, is: red - orange - yellow - green - blue - indigo - violet.

Figure (30)

The prism disperses the colors of the spectrum

Enrichment information (for reference only)

Figure (31)

⋆ **Explanation of the phenomenon of the rainbow:**

When sunlight passes through water droplets suspended in the air after rainfall, the following occurs inside each droplet:

1. Light refracts when the ray enters from air into water.
2. The light disperses as the different colors of light refract at different angles, because each color has a different wavelength, and thus the refractive index of water varies according to each wavelength.
3. The light is totally reflected on the inner surface of the drop when it falls at angles of incidence greater than the critical angle.
4. The light refracts again when it exits the drop into the air, and reaches our eyes so we see the seven colors of the spectrum.

Developing critical thinking

The triangular prism disperses light into its components. Soap bubbles, DVDs, water droplets in air, and the layer of kerosene floating on the surface of water do the same. **Are** they all similar in how they disperse light?

Figure (32)

Dispersion of light on the surface of a DVD disc

Figure (33)

Dispersion of light in a soap bubble

Summary

First: Key definitions and concepts

- The two laws of reflection of light:

(1) Angle of incidence = angle of reflection.

(2) The incident light ray, the reflected light ray, and the normal drawn from the point of incidence on the reflecting surface all lie in one plane perpendicular to the reflecting surface.

- Light changes its direction of propagation when it falls at an acute angle on the interface between two transparent media due to the difference in the speed of light in the second medium v_2 compared to its speed in the first medium v_1, and the refraction of light follows these rules:

(1) The ratio of the sine of the angle of incidence in the first medium to the sine of the angle of refraction in the second medium is a constant for these two media, called the relative refractive index from the first medium to the second, denoted by ${}_1n_2$ and it is also equal to the ratio of the speed of light v_1 in the first medium to the speed of light v_2 in the second medium.

(2) The incident light ray, the refracted light ray, and the normal drawn from the point of incidence on the interface all lie in one plane perpendicular to the interface.

- The absolute refractive index of a medium is the ratio of the speed of light in vacuum to the speed of light in the medium.
- Snell's law of light states: The product of the absolute refractive index of the medium of incidence and the sine of the angle of incidence equals the product of the absolute refractive index of the medium of refraction and the sine of the angle of refraction.
- Interference: The phenomenon of the superposition of light waves emitted from two coherent sources, resulting in an increase in light intensity at some points (bright fringes) and the absence of light intensity at other points (dark fringes).
- Diffraction: The change in the direction of wave propagation when it falls on a narrow slit or a sharp or pointy edge.
- Light propagates as a wave motion, as light waves undergo reflection, refraction, interference, and diffraction.
- The critical angle: It is the angle of incidence in the medium of higher optical density that corresponds to an angle of refraction of 90° in the medium of lower optical density.
- The absolute refractive index of a medium equals the reciprocal of the sine of its critical angle when light passes from this medium to air or vacuum.

- Total reflection: When the angle of incidence of light in the medium of higher optical density is greater than the critical angle, the light does not pass into the medium of lower optical density but is totally reflected at the interface.
- Applications of total reflection (mirage phenomenon - reflecting prism - optical fibers).
- The deviation angle α is the acute angle between the extensions of the incident and emergent rays.

Second: Fundamental laws and equations

- The relative refractive index between two media:

$${}_1n_2 = \frac{\sin \phi}{\sin \theta} = \frac{n_2}{n_1} = \frac{v_1}{v_2}$$

- The absolute refractive index of a medium:

$$n = \frac{c}{v}$$

- Snell's law:

$$n_1 \sin \phi = n_2 \sin \theta$$

- In Young's double-slit experiment, the distance between the centers of any two consecutive fringes of the same type:

$$\Delta y = \frac{\lambda R}{d}$$

- The critical angle of a medium:

$$\sin \phi_c = \frac{1}{n}$$

- The apex angle of the triangular prism: $A = \theta_1 + \phi_2$
- The deviation angle of light in a triangular prism: $\alpha = \phi_1 + \theta_2 - A$
- In the position of minimum deviation for the triangular prism:

$$\phi_1 = \theta_2 = \phi_o$$

$$\theta_1 = \phi_2 = \theta_o$$

$$n = \frac{\sin \left(\frac{\alpha_o + A}{2}\right)}{\sin \left(\frac{A}{2}\right)}$$

Questions and problems

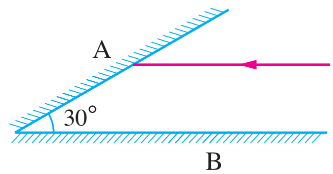
First: Complete the following statements

1. In Young's experiment, the distance between the centers of two consecutive fringes of the same type is determined by the relation ....

2. Snell's law states ....

Second: Choose the correct answer

1. In the adjacent figure, a light ray fell on mirror A so that it was parallel to mirror B, so when:



(A) The ray reflects off mirror A and falls on mirror B. The angle of incidence is ....

ⓐ 90° ⓑ 60°

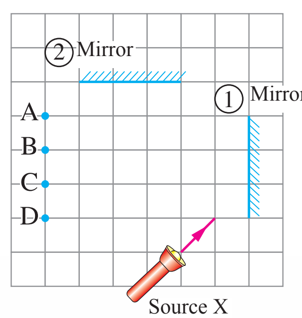
ⓒ 30° ⓓ 0°

(B) The ray reflected from mirror B falls again on mirror A The angle of incidence is ....

ⓐ 90° ⓑ 45°

ⓒ 30° ⓓ 0°

2. The adjacent figure shows, to a certain scale, a laser beam falling from source x towards the mirror ①, so the ray after reflecting from the mirror ② passes through point ....



ⓐ A ⓑ B

ⓒ C ⓓ D

3. The ratio of the sine of the angle of incidence in the first medium to the sine of the angle of refraction in the second medium is called ....

ⓐ The absolute refractive index of the first medium

ⓑ The absolute refractive index of the second medium

ⓒ The relative refractive index from the second medium to the first medium

ⓓ The relative refractive index from the first medium to the second medium

4. A light ray falls on a surface separating two media. If the angle of incidence in the first medium is 60º and the angle of refraction in the second medium is 30º, then the relative refractive index from the first medium to the second medium is ....

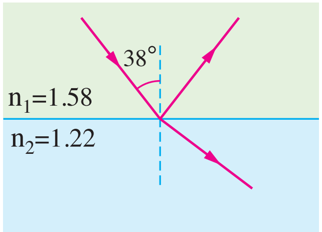
ⓐ $\sqrt{3}$ ⓑ $\frac{1}{2}$ ⓒ $\sqrt{2}$ ⓓ 2

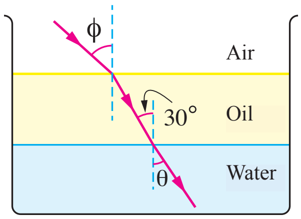
5. A light ray falls at an angle of 48.6º on one face of a rectangular glass block with a refractive index of 1.5, so the angle of refraction in the glass is ....

ⓐ 20º ⓑ 30º ⓒ 35º ⓓ 40º

6. A light ray falls on the interface between two media whose refractive indices are as shown in the adjacent figure, so the values of the angle of reflection and the angle of refraction are ....

	Angle of reflection	Angle of refraction
ⓐ	38°	68.38°
ⓑ	52.88°	38°
ⓒ	28.38°	38°
ⓓ	38°	52.88°



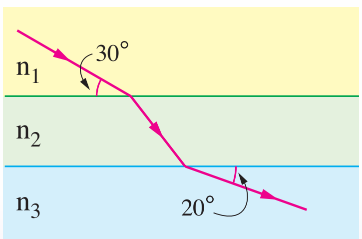


7. The adjacent figure shows the transition of a light ray from air to oil and then to water. If the absolute refractive index of oil is 1.48 and for water is 1.33, then the values of θ , ϕ are ....

	ϕ	θ
ⓐ	41.6°	33.81°
ⓑ	41.6°	41.6°
ⓒ	47.73°	33.81°
ⓓ	47.73°	41.6°

8. The adjacent figure shows the transition of a light ray through three different transparent media, so the relationship between:

(A) The absolute refractive indices of these media are ....



ⓐ $n_3 > n_1 > n_2$ ⓑ $n_1 > n_2 > n_3$

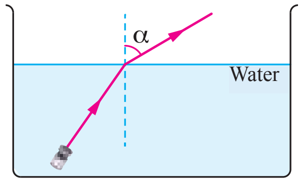
ⓒ $n_2 > n_1 > n_3$ ⓓ $n_2 > n_3 > n_1$

(B) The speed of light in the three media is ....

ⓐ $v_1 > v_2 > v_3$ ⓑ $v_2 < v_1 < v_3$

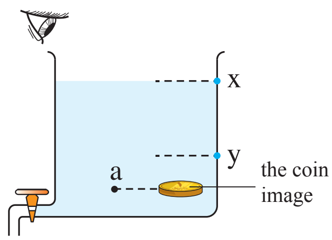
ⓒ $v_1 > v_3 > v_2$ ⓓ $v_3 < v_1 < v_2$

9. In the adjacent figure, a light ray passed from water to air and exited at an angle α. If a transparent liquid that does not mix with water and has a density less than that of water is slowly added so that it floats on the water surface, then the angle of emergence of the ray into the air will be ....



ⓐ Greater than α ⓑ Smaller than α ⓒ Equal to 90° ⓓ Equal to α

10. A person looks steadily at a coin placed at the bottom of a vessel filled with water up to level x, so the coin appears to him at a certain position (a) as in the adjacent figure. If the tap is opened so that the water gradually leaves the vessel until its surface reaches level y, the person sees the image of the coin ....



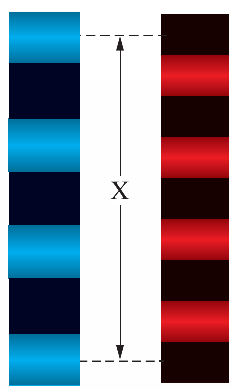
ⓐ Gradually rises upward ⓑ Gradually decreases downward

ⓒ At the bottom of the vessel ⓓ Remains fixed at its position (a)

11. In the double-slit experiment, if the distance between the slits is 10^{-4} m, and the distance between the centers of two successive fringes of the same type is 3.75 mm, and the screen receiving the interference fringe is at a distance of 0.75 m from the slit barrier, then the wavelength of the light used is ....

ⓐ 5000 Å ⓑ 5400 Å ⓒ 6000 Å ⓓ 6400 Å

12. Two attempts were made to perform the double-slit experiment: the first using monochromatic red light and the second using monochromatic blue light, with the distance between the slits kept constant. The adjacent figure represents the interference fringes formed in both attempts. If the distance between the screen and the double-slit barrier in the two cases is R_r, R_b respectively, then the ratio $\left(\frac{R_r}{R_b}\right)$ ....



Second attempt The first attempt

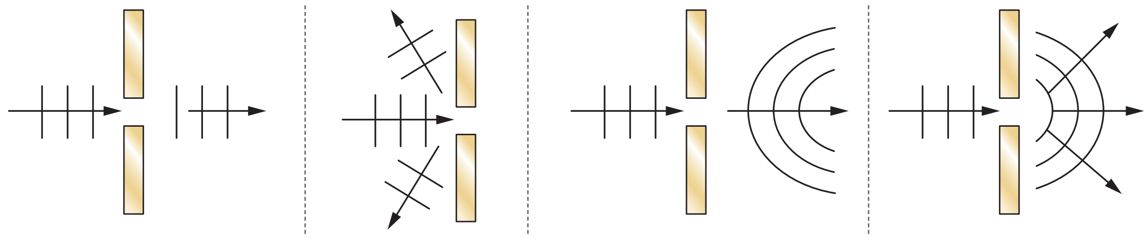
ⓐ Greater than one

ⓑ Less than one

ⓒ Equal to one

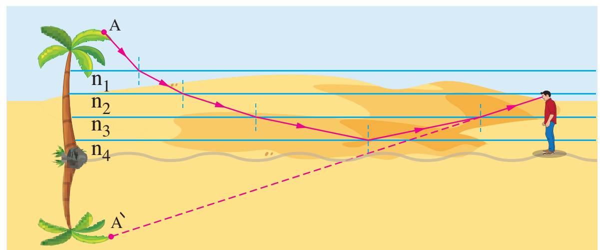
ⓓ Cannot be determined

13. Which of the following figures correctly represents the diffraction of light when it falls on a barrier with a small opening?



(a) (b) (c) (d)

14. The adjacent figure represents the occurrence of the mirage phenomenon. The correct order of the refractive indices of the air layers is..........



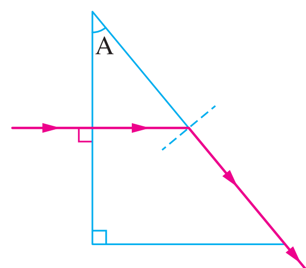
(a) $n_3 < n_2 < n_1$ (b) $n_1 < n_2 < n_3$

(c) $n_2 < n_1 < n_3$ (d) $n_3 < n_1 < n_2$

15. If the critical angle for a medium with respect to air is 45°, then the refractive index of this medium is ....

(a) 1.64 (b) 2 (c) 1.7 (d) $\sqrt{2}$

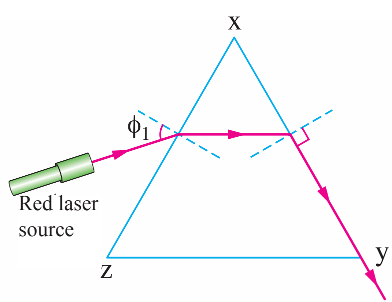
16. In the adjacent figure, a light ray passes through a triangular prism made of a transparent material at a speed of 0.8 c, where c is the speed of light in air. The angle A is approximately equal to ....



(a) 37° (b) 40°

(c) 50° (d) 53°

17. In the adjacent figure, if you are asked to replace the red laser source with a blue laser source so that the blue beam emerges tangent to the interface, how does the angle of incidence ϕ_1 change to achieve this?



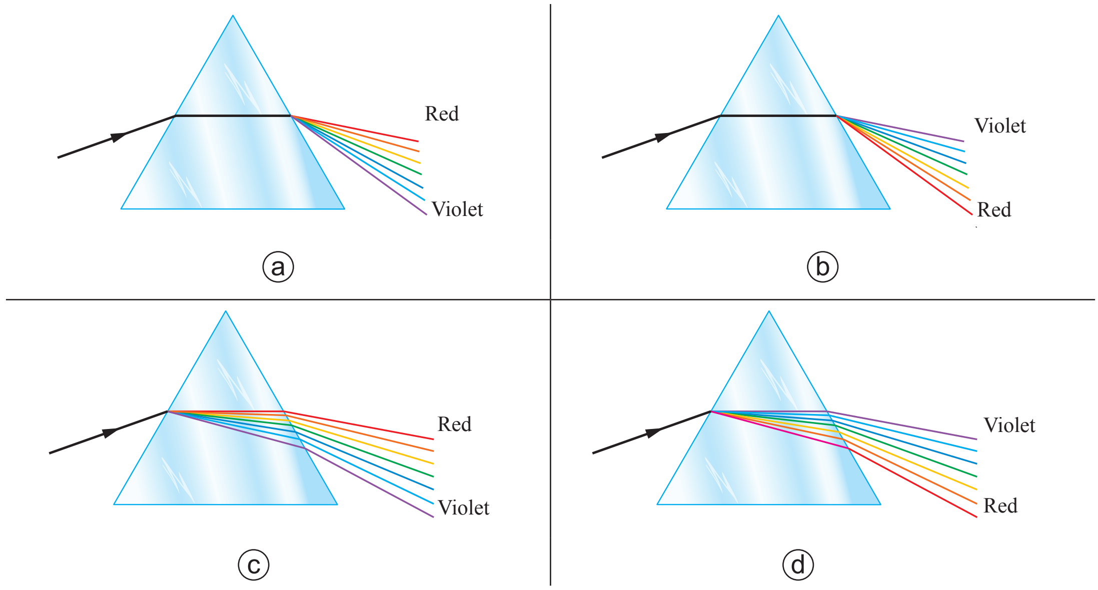
(a) Increase it

(b) Decrease it

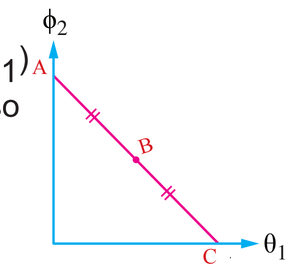
(c) Do not change it

(d) Cannot determine the answer

18. If a narrow beam of white light falls on one face of a triangular prism in the position of minimum deviation, which of the following figures correctly shows the dispersion of this light beam?



19. The adjacent graph represents the relationship between the second angle of incidence (ϕ_2) and the first angle of refraction (θ_1) when a light ray passes through an equilateral triangular prism, so the position of minimum deviation is represented by..........



ⓐ The point A ⓑ The point B
ⓒ The point C ⓓ The two points A, C

20. In an experiment to determine the minimum deviation in a triangular prism, it was found that this angle equals 48.2º. If the prism's apex angle is 58.8º, then the refractive index of its material is ....

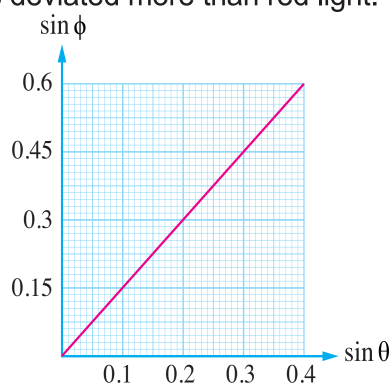
ⓐ 1.5 ⓑ 1.64 ⓒ 1.82 ⓓ 1.85

Third: Essay Questions

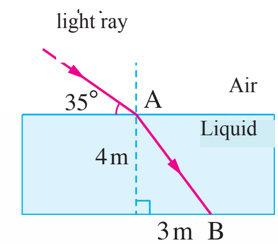
1. Explain why it can be said that light is a wave motion.
2. Define each of the following:
   (A) The relative refractive index between two media.
   (B) The absolute refractive index of a medium.
   (C) The critical angle. (D) The angle of deviation.
3. Explain an experiment that demonstrates the phenomenon of interference in light.

4. The double-slit experiment was conducted using red light, what happens to the distance between the centers of the formed fringes if:
   (A) The distance between the slits is decreased?
   (B) Blue light is used instead of red light?
   (C) The screen receiving the fringes is moved farther from the double-slit barrier?
5. Three spaced lamps were placed at the flat bottom of a swimming pool in a hotel. The first emits yellow light, the second emits red light, and the third emits blue light. Colored circular spots formed on the water surface with areas A_y, A_r, A_b respectively. Arrange the areas of the light circles on the water surface in ascending order, with an explanation of the reason for the difference in the area of each color's light circle from the others.
6. Explain the occurrence of the mirage phenomenon.
7. Derive the relationship used to find the minimum deviation angle of light (α_o) when it passes through a triangular prism with apex angle (A) and refractive index of its material (n_p) while it is immersed in a liquid such as water with refractive index (n_w).
8. Explain: When white light falls on a triangular prism, violet light is deviated more than red light.

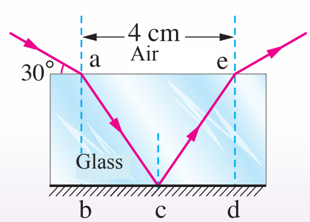
Fourth: Problems



1. The adjacent graph represents the relationship between the sine of the angle of incidence of a light ray in a transparent medium ① and the sine of its angle of refraction in the medium it enters ②, and if the speed of light in the medium ① is 2×10^8 m/s, calculate:
   (a) The relative refractive index from the medium ① to the medium ②.
   (b) The speed of light in the medium ②. (1.5, 1.33×10^8 m/s)

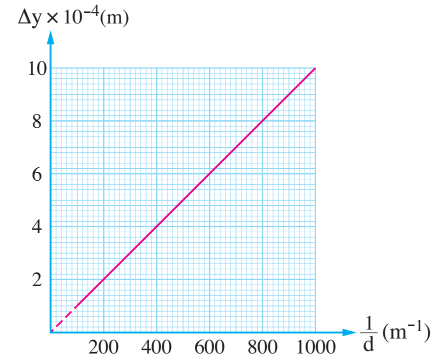


2. The adjacent figure shows a light ray moving from air into a layer of liquid with a thickness of 4 m. If you know that the speed of light in air equals 3×10^8 m/s , calculate:
   (a) The refractive index of the liquid.
   (b) The time taken by the ray to travel from point A to point B (1.37, 2.28×10^{-8} s)



3. The adjacent figure shows the path of a light ray incident on a rectangular glass block with an absolute refractive index $\sqrt{3}$ placed above a plane mirror until it emerges again into the air, so what is the thickness of the rectangular block ed or ab? (3.46 cm)

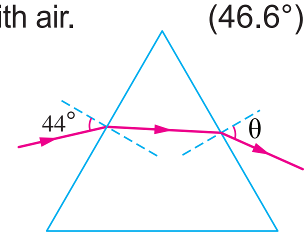
4. The adjacent graph represents the relationship between the distance between the centers of two successive bright fringes (Δy) and the reciprocal of the distance between the double slit $\left(\frac{1}{d}\right)$, if the distance between the double slit barrier and the fringe screen is 2 m, calculate the wavelength of the light used.



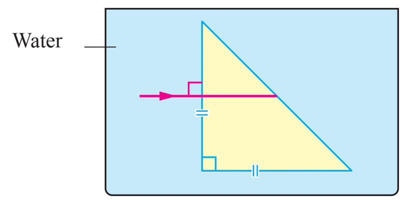
$(5 \times 10^{-7}$ m)

5. A light ray fell at an angle of incidence 54° from air onto the surface of a transparent material, part of it reflected and part refracted such that the reflected ray was perpendicular to the refracted ray. Calculate the critical angle of the transparent material with air. (46.6°)

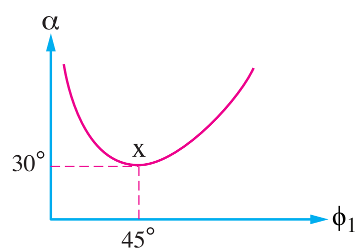
6. The adjacent figure shows the path of a light ray through an equilateral glass prism with a refractive index of its material 1.5. Calculate:
(a) The angle of emergence of the ray.
(b) The angle of deviation of the ray. (53.5°, 37.5°)



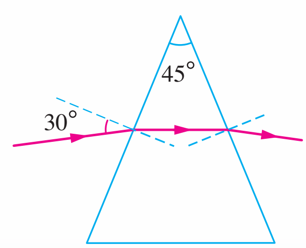
7. In the adjacent figure, trace the path of the incident light ray until it exits the prism, knowing that the critical angle of the prism material with air is 42° and the absolute refractive index of water is 1.33



8. The adjacent graph represents the relationship between the angle of deviation of a light ray (α) through a triangular prism and the first angle of incidence (ϕ_1) of the ray on one face of the prism. Calculate:
(a) The prism's apex angle.
(b) The absolute refractive index of the prism material.
(c) The angle of emergence of the ray at position x (60°, $\sqrt{2}$, 45°)



9. The adjacent figure shows an isosceles triangular prism with an apex angle of 45° made of a transparent material. A light ray fell on one of its faces at an angle of 30° and refracted inside the prism parallel to the base. Calculate:
(a) The angle of emergence of the light ray from the prism.
(b) The angle of deviation of the light ray.
(c) The refractive index of the prism material. (30°, 15°, 1.31)



Unit

Three

Circular motion

- **Chapter Four:** Laws of Circular Motion
- **Chapter Five:** Universal Gravity and Circular Motion

Chapter

Four

Laws of Circular Motion

Expected learning outcomes

By the end of this chapter, you will be able to:

1- *Identify the concept of uniform circular motion .*

2- *Deduce the factors that determine the magnitude of the centripetal force.*

3- *Calculate the centripetal force and the centripetal acceleration.*

4- *Analyze traffic instructions and their relation to the centripetal force.*

5- *Analyze some life situations related to the motion of a body in a circular path.*

Chapter Terms

- *Uniform Circular Motion*
- *Centripetal Acceleration*
- *The centripetal force*
- *Tangential Velocity*

Introduction

Motion in a circle is considered one of the most important types of periodic motion, such as the movement of some rides in amusement parks, the Earth's movement around the Sun, the Moon around the Earth, and others. What are the characteristics of motion in a circle? What are the most important mathematical relationships used to describe it? And what are the most significant life and technological applications related to it?

Uniform Circular Motion

Through your study of Newton's Second Law, you learned that when a force acts on a body moving at a constant speed, it acquires acceleration, meaning a change occurs in its speed. The change in speed depends on the direction of the applied force relative to the direction of motion, as follows:

When a force acts on a moving body in a straight line

If

- **The direction of the force is in the same direction of the motion** → **The magnitude of the velocity increases but its direction does not change**
- **The direction of the force is opposite to the direction of motion** → **The magnitude of the velocity decreases but its direction does not change**
- **The direction of the force is perpendicular to the direction of** → **The direction of the velocity changes but its magnitude does not change**

So when the racer (2) in figure (1) increases the flow of fuel, the motorcycle is affected by a force in the same direction as the motion, so its speed increases. But when the brakes are applied, the force is in the opposite direction to the motion, so the speed decreases. And when the racer (1) or (3) leans his bike to the right or left, a force perpendicular to the direction of motion is generated and this force is called the centripetal force, and thus the direction of motion changes and he moves in a circular path.

Figure (1)
Motion in curved paths

Practical experiment to demonstrate motion in a circle

Purpose of the experiment:

We have learned that the centripetal force is necessary for an object to rotate in a circular path, and this experiment aims to describe the motion of an object rotating in a circular path and to understand the concept of centripetal force.

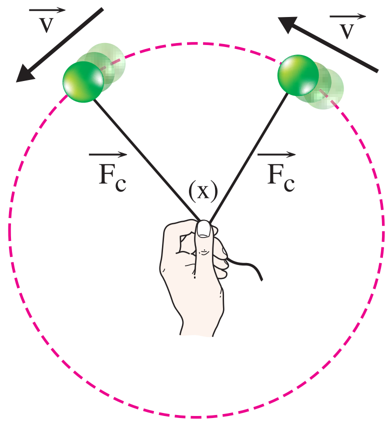


Figure (2)

Materials and tools:

1. A tennis ball.
2. A thread.

Procedure:

1. Tie a tennis ball to a thread with a length of about 120 cm and hold the thread at a certain point (x), and leave the rest of the thread at a suitable length.
2. Spin the ball in a horizontal plane at an appropriate speed, so that it moves along the circumference of a circle.
3. Let go of the thread suddenly from your hand and record the direction in which the ball moves.
4. Repeat the previous steps with different thread lengths (50 - 40 - 30 - 20 cm), with the help of your group members.

Notes:

Thread length	Description of the motion
20 cm	....
30 cm	....
40 cm	....
50 cm	....

- Did you feel the need to pull the thread inward for the ball to continue rotating in its path? (Yes/No).
- When you suddenly let go of the thread, did you notice that the ball continued in the circular path, or did it move in the direction of the tangential (linear) velocity in a straight line?
- Draw an arrow representing the direction of the ball's motion at the point that was the ball left the circumference of the circle.
- Explain the results you obtained.

From the above, we conclude that:

- For any object to move in a circular path, a force (F_c) must act on it perpendicular to the direction of its movement and in the direction of the center of the circle, in order to force it to continue in circular motion.
- If this force is absent, the object will move in the direction tangent to the circular path it was following at the moment of release, at a constant speed in magnitude and direction (in a straight line), and this speed is called the tangential velocity (v).

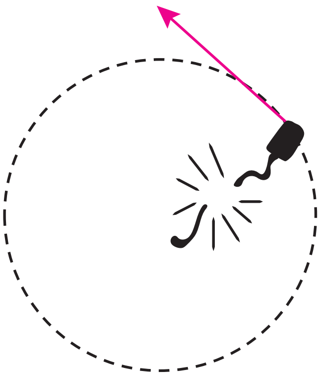


Figure (4)
The direction of the object's motion when the thread breaks

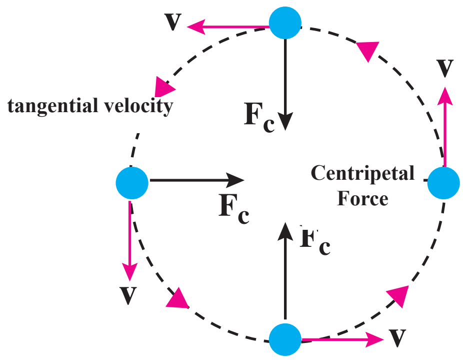


Figure (3)
The direction of force and velocity in circular motion

Types Of Centripetal Forces

When an object moves in a circular path at a constant speed in magnitude and variable in direction, this motion is called uniform circular motion, and the force that continuously acts in a direction perpendicular to the motion of the object is called the centripetal force. Centripetal force is not a new type of force; it is simply the name given to any force that acts perpendicular to the path of an object's motion and causes it to move in a circular path. Centripetal force can be a tension force, a physical attractive force, etc. Here are some examples of these forces:

Figure (5)
Why does the athlete feel a tension force in his arms while spinning?

1. **Tension force (F_T):** When an object is pulled using a rope or wire, a tension force arises in it. When the tension force is perpendicular to the direction of motion of an object moving at constant speed, it moves in a circular path, and the tension force is the same as the centripetal force.

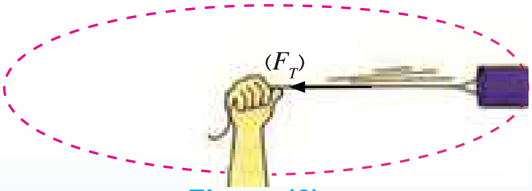


Figure (6)
The tension force in the thread acts as a centripetal force

② **Gravitational force (F_G):** A gravitational force arises between the Earth and the Sun, perpendicular to the direction of Earth's motion, so the Earth moves in a circular path around the Sun.

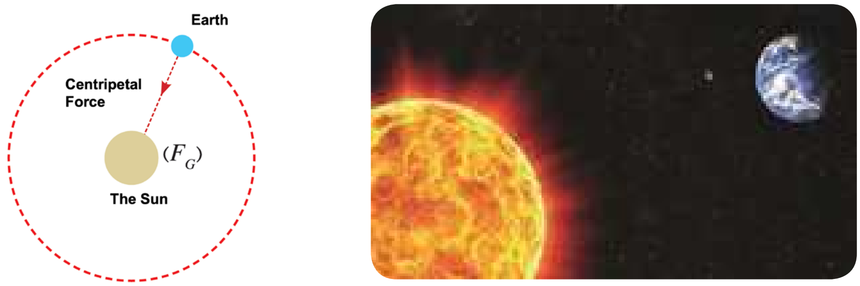


Figure (7)

The force of physical attraction acts as a centripetal force.

③ **Friction force (F_f):** When a car turns in a circular path or curve, an additional friction force arises between the road and the car's tires. This force acts perpendicularly to the direction of the car's motion and towards the center of the circular path. thus the car moves along the curved path.

Figure (8)

The friction force acts as a centripetal force.

Enrichment information (for reference only)

Some curves, such as parts of a car racing track or bridges, are designed so that the outer edge of the curve is at a higher level than its inner edge. What is the reason for that?

In the case where the car's circular path is inclined at an angle to the horizontal, a horizontal component of the reaction force is produced towards the center of the circle, which helps the car to turn. In this case, the centripetal force is the sum of the horizontal component of the reaction force and the horizontal component of the friction force where both act towards the center of rotation.

Figure (9)

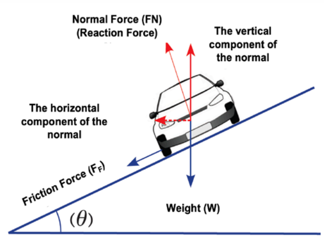


Figure (10)

The centripetal force is the sum of the components of the reaction and friction forces in the horizontal direction.

Developing critical thinking

In the roller coaster game shown in the figure, at which part of the circular path is the resultant force acting on the train greater: when it is at the top of the path or at its bottom? And why?

Figure (11)

Centripetal acceleration

When a force (F_c) acts perpendicularly to the direction of motion of an object of mass (m) and velocity (v), it moves in a circular path of radius (r), causing a change in the direction of velocity. Thus, the object has an acceleration (a_c) called centripetal acceleration, and its direction is the same as that of the centripetal force.

It is observed from figure (12) that the velocity (v) has a constant magnitude but its direction is continuously changing.

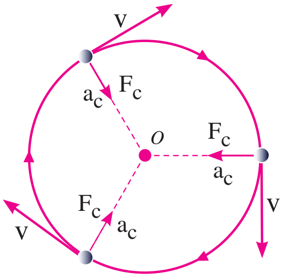


Figure (12)
Velocity vector and acceleration vector during uniform motion in a circular path

Centripetal acceleration (a_c) : is the acceleration acquired by the object in circular motion as a result of the change in the direction of velocity.

The centripetal acceleration (a_c) is calculated from the relation:

$$a_c = \frac{v^2}{r} \qquad (1)$$

Where: (v) is the magnitude of the linear velocity with which an object moves, (r) is the radius of the circular path.

Example

An object moves along the circumference of a horizontal circle with a radius of 2 m at a constant linear speed of 10 m/s. **Calculate** the centripetal acceleration with which the body moves.

Solution

$$a_c = \frac{v^2}{r} = \frac{(10)^2}{2} = 50 \text{ m/s}^2$$

Enrichment information (for reference only)

Derivation of the Magnitude of Centripetal Acceleration

It is observed from figure (13) that when the body moves from point (A) to point (B), the velocity (v) changes in direction but maintains its magnitude constant. Thus, the change in velocity (Δv) results only from the change in the direction of velocity.

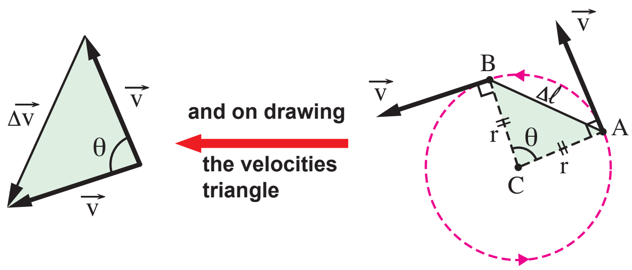


Figure (13)

Motion of a body from (A) to (B)

From the similarity of triangle (CAB) with the velocities triangle shown in figure (13), the following relation can be written:

$$\frac{\Delta \ell}{r} = \frac{v\Delta}{v} \qquad (1)$$

Where Δv is in the direction of the center of the circle.

$$\therefore \Delta v = \frac{\Delta \ell}{r}.v \qquad (2)$$

If the body moves from point (A) to point (B) in a time interval (Δt), then the acceleration towards the center (a_c) is calculated by dividing the equation (2) by (Δt):

$$\therefore a_c = \frac{v\Delta}{\Delta t} = v\frac{\Delta \ell}{\Delta t}\frac{1}{r}$$

And since $\frac{\Delta \ell}{\Delta t}$ equals (v), then the centripetal acceleration is:

$$\therefore a_c = \frac{v^2}{r}$$

Calculating the magnitude of the centripetal force (F_c)

From Newton's second law, the force is given by the relation (F = ma), that is:

The centripetal force during uniform circular motion = mass × centripetal acceleration

And by substituting the value of the centripetal acceleration from relation (1), we find that:

$$\therefore F_c = m \times \frac{v^2}{r} \qquad (2)$$

Calculating the value of the tangential velocity (v)

If we assume that an object completes a full revolution in the circular path in a time (T), which represents the periodic time then during this time it covers a distance equal to the circumference of the circle, which is (2 πr). Thus, the tangential velocity (rotational speed) can be calculated as follows:

$$v = \frac{\text{Distance}}{\text{Time}} = \frac{2\pi r}{T} \qquad (3)$$

This means that the tangential velocity (v) can be calculated if both the period (T) and the radius of rotation (r) are known.

The mini lab

Verifying the centripetal force relation:

* Tie a rubber stopper of mass (m) to a string, then pass the string through a metal or plastic tube (such as a pen tube), and then tie the other end to a weight of mass (M).
* When we move the rubber stopper in a circular path, the centripetal force arises from the tension in the string (F_T), which equals the weight of the hanging mass, **that is:**

$$F_c = F_T = Mg$$

* Using the above materials and a stopwatch, experimentally prove the validity of the relation: $F_c = Mg = m\frac{v^2}{r}$

Experiment tools

Figure (14)

Example

In the previous experiment, the mass of the rubber stopper was 13 g, and the stopper was rotated in a horizontal circular path of radius 0.93 m to make 50 revolutions in a time of 59 s. **Calculate the mass of the weight hanging at the other end of the string.**

(π = 3.14, g = 9.8 m/s^2)

Solution

Calculation of the period: $T = \frac{\text{Total time}}{\text{Number of revolutions}} = \frac{59}{50} = 1.18\ s$

Calculating velocity: $v = \frac{2\pi r}{T} = \frac{2 \times 3.14 \times 0.93}{1.18} = 4.9\ m/s$

Calculating the tension force: $F_c = m\frac{v^2}{r} = 0.013 \times \frac{(4.9)^2}{0.93} = 0.34$ N

Calculating the mass of the weight: $M = \frac{F_c}{g} = \frac{0.34}{9.8} = 0.035$ kg

What if The stopper was spun faster; what effect does this have on the radius of the stopper's rotation?

The factors on which the centripetal force depends

It is necessary to calculate the centripetal force when designing road and railway curves, so that cars and trains move along the curved path without slipping, and by studying the relationship ($F_c = \frac{mv^2}{r}$) it can be concluded that the centripetal force depends on the following factors:

1. **The mass of the object (m)**: The centripetal force is directly proportional to the mass (when r, v are constant), so the force required for a bicycle to move along a curved path is less than the force required for a truck to move along the same path. This explains why heavy transport vehicles are prohibited from some dangerous curves.

Figure (15)
Trailers and trucks are not allowed to pass

2. **Tangential velocity (v)**: The centripetal force is directly proportional to the square of the speed (when m and r are constant). The higher the speed of the car, the greater the centripetal force needed to move along the curved path. Therefore, road engineers set a specific speed for movement on curves that should not be exceeded.

Figure (16)
Maximum speed
On this curve is (80 km/h)

Figure (17) shows the effect of changing the speed of an object on the amount of centripetal force required for it to move along a curved path.

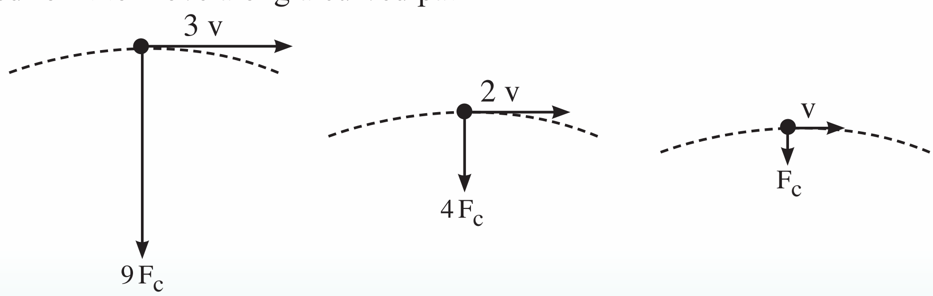


Figure (17)

③ **Radius of rotation (r)**: The centripetal force is inversely proportional to the radius of the path (when m and v are constant). The smaller the radius of the curve, the greater the centripetal force needed for the car to turn, and thus the danger of this curve increases. To avoid this, one should drive at a low speed on dangerous curves.

The following figure shows traffic instructions indicating the maximum speed of vehicles at some curves:

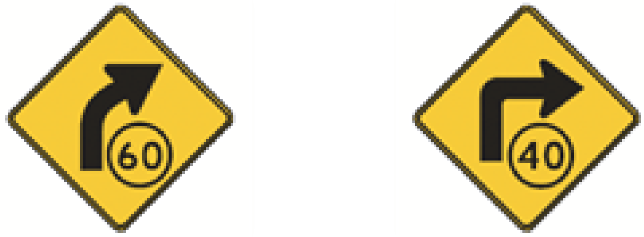


Figure (18)

What is the effect of decreasing the centripetal force on the radius of rotation?

When the centripetal force decreases, this means that the radius of the path in which the object moves will increase, because ($F_c \propto \frac{1}{r}$), meaning that the object will move away from the center of the circle, and if the centripetal force becomes zero, it will move in a straight line due to inertia.

If we assume that a car is moving along a curved path and the road is slippery, the frictional forces may not be sufficient to steer the car along the curved path, so the car will skid and the tires will slide towards the side of the road, and the car cannot continue along the curved path.

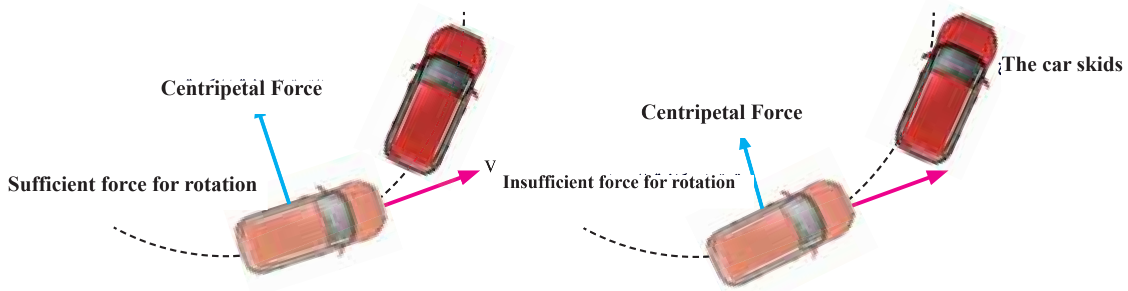


Figure (19)

The car slides off the curved path if the centripetal force is insufficient

Real-life applications

The phenomenon of objects moving away from the circular path, when the centripetal force is insufficient for circular motion, is utilized in many practical applications, such as drying clothes, making cotton candy, and the spinning barrel ride in amusement parks. For example, in drying clothes, water droplets are attached to the clothes with a certain force, and when the dryer spins at high speed, this force is not enough to keep the droplets in their orbit, so they move tangentially to the circumference of the rotation and separate from the clothes.

Figure (20)

When the dryer spins at a high speed, the water droplets are propelled in the direction tangent to the circumference of the rotation circle

Misconception

Some people believe that while an object moves in a circular path, a force pushes it outward called the centrifugal force.

In fact, this force does not actually exist, and the feeling of being pushed outward is due to inertia, which tries to make the object move in a straight line.

Example

A stone with a mass of 60 g is tied to a string of length 30 cm, **calculate** the centripetal force required for it to rotate at a speed of 3 m/s in a circular path. **What** do you expect to happen if the maximum tension the string can withstand is 1.5 N?

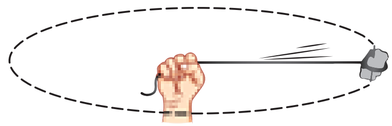


Figure (21)

Solution

Calculating the centripetal force:

$$F_c = m\frac{v^2}{r} = 0.06 \times \frac{(3)^2}{0.3} = 1.8 \text{ N}$$

Since the centripetal force is greater than the maximum tension the string can withstand, it will break. At that moment, the stone will move in a straight line tangent to the circular path it was following at the instant the string breaks.

Developing critical thinking

Centripetal force:

- Fill a bucket halfway with water and move it in a vertical circle. Does the water spill from the mouth of the bucket? And why?

Figure (22)

Creative Thinking Prompt

- Use the internet to research how centrifuges used in medical analysis work.
- Based on your research, discuss with your classmates, using examples: Does centrifugal force actually exist?

Figure (23)

Summary

First: Key definitions and concepts

- Uniform circular motion: It is the motion of an object in a circular path at a constant speed in magnitude, but changing in direction.
- Centripetal force: It is the force that continuously acts perpendicular to the motion of the object, causing it to move in a circular path.
- Centripetal acceleration: It is the acceleration acquired by the object in circular motion as a result of the change in the direction of velocity.
- Periodic time: It is the time interval during which the object completes a full revolution.

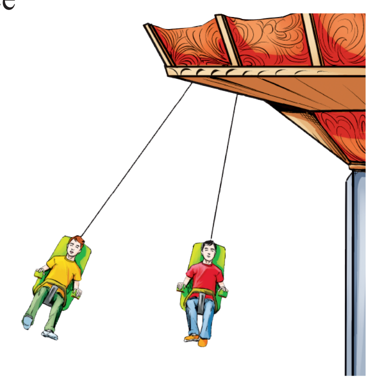
Second: Fundamental laws and equations

- Centripetal acceleration: $a_c = \frac{v^2}{r}$
- Centripetal force: $F_c = m\frac{v^2}{r}$
- Tangential speed: $v = \frac{2\pi r}{T}$

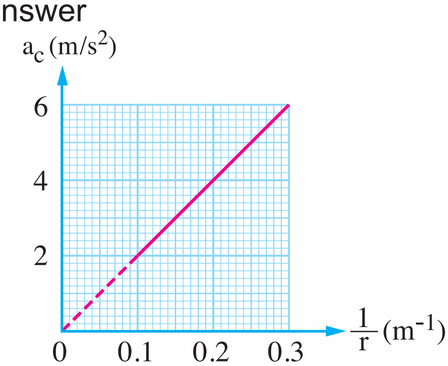
Questions and Problems

First: Choose the correct answer

1. The centripetal force acting on a car moving along a curve is produced by ....
   ⓐ The gravitational force of Earth on the car
   ⓑ The frictional force between the car's tires and the road
   ⓒ The inertia acting on the driver ⓓ The braking force



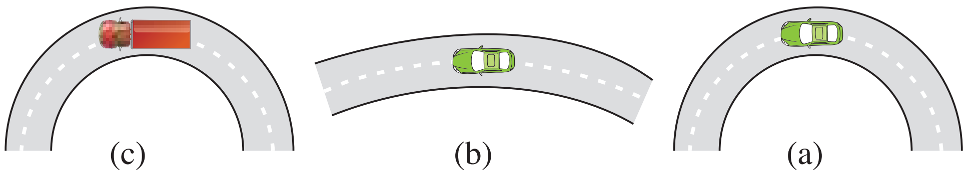
2. In one of the amusement park rides, the chairs rotate in a regular horizontal circular path. If one chair is at a distance of 1.5 m from the center and another is at a distance of 2 m from the center, and both are aligned with the center as shown, which one moves at a greater tangential speed?
   ⓐ The chair that is 1.5 m away from the center
   ⓑ The chair that is 2 m away from the center
   ⓒ Both have the same speed
   ⓓ The periodic time must be known to determine the answer



3. The opposite graph shows the relationship between the centripetal acceleration (a_c) with which a body moves in a horizontal circular path and the inverse of the radius of this path ($\frac{1}{r}$), then the tangential velocity with which the body moves equals ....
   ⓐ 4.47 m/s ⓑ 5.58 m/s
   ⓒ 3.13 m/s ⓓ 9.8 m/s

4. If the radius of the orbit of a particle moving in a circular path is increased to four times its original value, the centripetal force required to keep the particle's speed constant in its circular path ....
   ⓐ Decreases to half of what it was ⓑ Remains constant in magnitude
   ⓒ Increases to twice what it was ⓓ Decreases to a quarter of what it was

5. The following figure shows three cars a , b , c move in three horizontal curved paths with the same speed. If the masses of the cars are m , m , 3 m in order, and the radii of their circular paths are d , 2 d , d In order, the correct ranking of these cars in terms of their susceptibility to skidding is ....



ⓐ 2 < 1 < 3 ⓑ 1 < 2 < 3 ⓒ 3 < 1 < 2 ⓓ 3 < 2 < 1

Second: Essay questions

1. Write the scientific term indicated by each of the following statements:
   (a) The motion of a body along the circumference of a circle with constant speed but changing direction. (..........................)
   (b) The time taken by a body moving in a circular path to complete one full revolution. (..........................)
   (c) A force acting on a body moving in a circular path always directed toward the center and perpendicular to the direction of its linear velocity . (..........................)
2. Explain the following:
   (a) At a curve, the motorcyclist leans with his bike and body toward the center of the circular path.
   (b) At dangerous curves, some cars maintain their path in the curve and do not deviate from it.
   (c) Although a body moving in uniform circular motion is affected by acceleration, its linear speed remains constant in value.
   (d) The danger of moving at high speeds on road curves.
3. In the following two figures, identify in each case the type of centripetal force among (gravitational attraction, electric attraction, tension force, friction force):

Rotation in the flying chairs game

The movement of a train on a curve

4. When spinning a stone tied to the end of a string in a horizontal circular path, what is the direction of the force acting on it that keeps it in its circular path? What is the direction of motion at the moment the string breaks?

Third: Problems

1. An object of 100 g mass moves along the circumference of a circle with a radius of 50 cm in uniform circular motion, taking 90 s to complete 45 full revolutions. Calculate:

   (a) The periodic time. (b) The linear speed. (c) The centripetal acceleration. (2 s , 1.57 m/s , 4.9 m/s^2)

2. An object of 2 kg mass is tied to the end of a string to rotate in a horizontal circular path with a radius of 1.5 m making 3 revolutions in 9 s. Calculate:

   (a) The linear (tangential) speed.

   (b) The centripetal acceleration.

   (c) The tension force of the string on the body. (3.14 m/s , 6.57 m/s^2 , 13.14 N)

3. A car of 1000 kg mass moves at a constant speed of 5 m/s around a curve on a horizontal plane with a radius of 50 m, calculate the friction force that keeps the car moving around the curve. (500 N)

4. A cyclist moves in a circular path with a tangential speed of 13.2 m/s . If the radius of the path is 40 m and the force that keeps the bicycle in its circular path is 377 N, calculate the mass of the bicycle and rider together. (86.5 kg)

5. A racing car with a mass of 905 kg moves in a horizontal circle with a circumference of 3.25 km . Calculate the tangential speed of the car if the force required to maintain the car's circular motion is 2140 N (34.97 m/s)

Chapter

Five

Universal Gravity and Circular Motion

Expected learning outcomes

By the end of this chapter, you will be able to:

1- *Deduce the law of universal gravitation.*

2- *Explain the motion of the Moon around Earth in a fixed path.*

3- *Deduce the factors on which the orbital velocity of a satellite depends as it moves around a planet.*

Chapter Terms

- *Universal Gravitation*
- *Gravitational Constant*
- *Gravitational Field- Gravitational Field Intensity*
- *Satellite*
- *Orbital Velocity*

Introduction

In our study of uniform circular motion, we learned how objects move in a circular path due to a central force that keeps them in their path. But what is the source of this force in the case of the Moon orbiting Earth, or Earth orbiting the Sun?

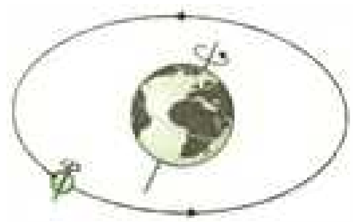


Figure (1)

The motion of the Moon around Earth

In this chapter, we will get closer to one of the great secrets of the universe, which is **the force of gravity** that affects the motion of objects from the smallest atom to the largest galaxies. We will discover how "Newton" was able to formulate a law that explains the rotation of planets in their orbits. Our understanding of this force is not limited to explaining natural phenomena only, but it is also the key to modern technologies such as launching satellites and space exploration.

Law of Universal Gravitation

Newton studied the nature of this attractive force and concluded that it depends on the masses of the attracting objects as well as the distance between them, as follows:

"Every physical object in the universe attracts any other object with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers."

The law is written as follows:

$$F = G\frac{Mm}{r^2} \quad (1)$$

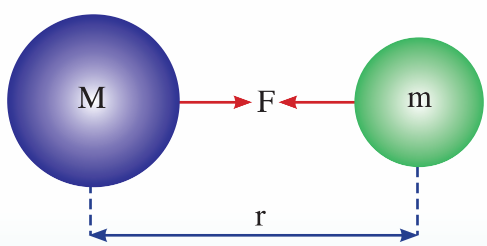


Figure (2)

Where: (r) is the distance between the centers of the two objects, (G) is the proportionality constant, a universal constant known as the universal gravitational constant, and its value is:

$G = 6.67 \times 10^{-11}\ N.m^2.kg^{-2}$

It is worth noting that the gravitational force is a mutual force between the two objects, as each attracts the other with the same force. Due to the generality of this law, it is known as the **law of universal gravitation**.

Example

Two identical spheres, each with a mass of 7.3 kg, the distance between their centers is 0.5 m. **Calculate** the mutual gravitational force between them and write the appropriate comment.

Solution

According to the law of universal gravitation, the gravitational force equals:

$$F = \frac{GMm}{r^2} = \frac{(6.67 \times 10^{-11})\,(7.3)^2}{(0.5)^2}$$

$F = 1.4 \times 10^{-8}$ N

In this example, we notice that the mutual gravitational force between the two spheres is very small because the value of the universal gravitational constant is very small. Therefore, the gravitational force between objects is only significant and large when the masses are large or the distances between the objects are small, or both together.

Gravitational Field

We have learned that the gravitational force is inversely proportional to the square of the distance between the centers of the two objects, so it decreases sharply until the distance between them reaches a point where the gravitational effect of each on the other disappears.

At that point, each of them is outside the gravitational field of the other object, and thus **the gravitational field** is defined as : "the region in which the gravitational force appears."

The intensity of the Earth's gravitational field at a point: is the gravitational force exerted by Earth on a mass of 1 kg at that point. It is denoted by the symbol “g” and numerically equals the acceleration due to gravity at that point. By applying the law of universal gravitation, we find that:

$$g = \frac{GM}{r^2} \qquad (2)$$

Knowing that: (M) is the mass of Earth = 5.98×10^{24} kg , and(r) is the radius of the path and equals (R + h),

Where: (R) is the radius of Earth = 6378 km, and (h) is the height above Earth's surface

From equation (2), deduce the factors on which the intensity of Earth's gravitational field at a point depends.

Satellites

It was mankind's dream to explore the space around him, and he kept developing observation devices and rockets that launch a spacecraft to orbit Earth or travel to greater distances to reach, for example another planet, such as Mars.

The world woke up on October 4, 1957 to the surprise of the successful launch of the Sputnik satellite into space as the first artificial satellite of planet Earth. This was followed by further successes in launching other satellites, and even landing on the surface of the Moon, and space exploration continues to achieve great success.

Figure (3)
Launching a rocket to place a satellite in its orbit

The idea of launching a satellite

(Isaac Newton) is considered the first to explain the scientific basis for launching satellites. He imagined that when a cannonball is fired horizontally from the top of a mountain, it will fall freely and take a curved path toward Earth. If the launch speed increases, it will reach Earth at a farther point and follow a less curved path. When the curvature of the cannonball's path equals the curvature of Earth's surface, it will orbit in a fixed path and become a satellite of Earth, resembling the Moon's orbit around it. Therefore, it is called a "Satellite"

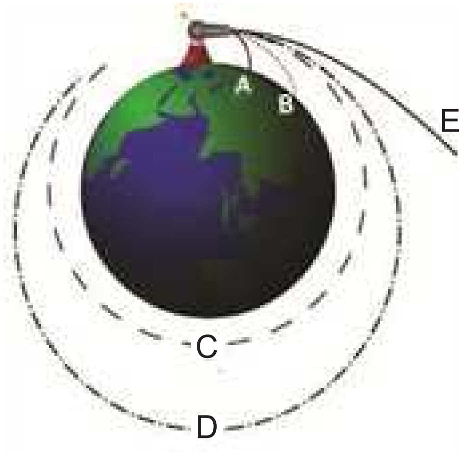


Figure (4)
Launching a projectile horizontally

Derivation of the orbital speed of the satellite

Suppose there is a satellite with mass (m) moving at a constant speed (v) in a circular orbit of radius (r) around Earth, which has a mass of (M), as shown in the figure:

We notice that the gravitational force between the satellite and Earth is perpendicular to the path of the satellite's motion and acts to keep it in its circular orbit. That is, the gravitational force between the satellite and Earth is the same as the centripetal force.

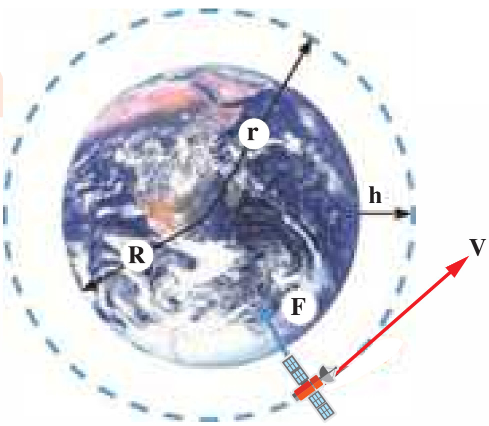


Figure (5)
The orbit of the satellite around Earth

So,

$$F = m\frac{v^2}{r} = G\frac{mM}{r^2}$$

$$\cancel{m}\frac{v^2}{r} = G \times \frac{\cancel{m}M}{r^2}$$

From the previous equation, it is clear that the speed of the satellite that keeps it in its orbit is:

$$v = \sqrt{G\frac{M}{r}} \qquad (3)$$

The value of the speed (v) from equation (3) represents the speed that must be given to the satellite so that it orbits Earth and is known as the orbital speed. (r) represents the radius of the orbit to which it is launched in space. If the height above Earth's surface is (h) and Earth's radius is (R), then the radius of the orbit (r) : $r = R + h$

The factors on which the orbital speed of a satellite depends as it moves around a planet:

From equation (3), it is clear that the speed of the satellite in its orbit does not depend on its mass but depends on the following factors:

- The mass of the planet it orbits.
- The height of the satellite above the center of the planet it orbits.

Figure (6)
The satellite around Earth

Enrichment information (for reference only)

The greater the mass of the satellite to be sent into space, the more powerful the rocket needed to launch it into its orbit and give it the necessary speed to revolve around Earth.

Developing critical thinking

Some satellites, such as communication satellites, are launched into an orbit that makes them appear stationary relative to a specific location on Earth's surface.

- How can the radius of this orbit be determined?

Example 1

The Moon revolves around Earth in a circular orbit with a radius of 3.85×10^5 km and completes a full cycle in 27.3 days. **Calculate** the mass of Earth

(gravitational constant 6.67×10^{-11} $m^3.kg^{-1}.s^{-2}$, $\pi = 3.14$)

Figure (7)

Solution

Calculation of the period: $T = 27.3 \times 24 \times 60 \times 60 = 2.36 \times 10^6$ s

Calculation of the moon's velocity: $v = \frac{2\pi r}{T} = \frac{2 \times 3.14 \times 3.85 \times 10^5 \times 10^3}{2.36 \times 10^6} = 1024.5$ m/s

Calculation of Earth's mass: $v^2 = G\frac{M}{r}$

So: $M = \frac{v^2 \times r}{G} = \frac{(1024.5)^2 \times 3.85 \times 10^5 \times 10^3}{6.67 \times 10^{-11}} = 6.06 \times 10^{24}$ kg

Example 2

An artificial satellite orbits Earth in a nearly circular orbit at an altitude of 940 km above Earth's surface. **Calculate** the orbital speed and the time required to complete a full revolution around Earth. (Knowing that: $G = 6.67 \times 10^{-11}$ $N.m^2 / kg^2$,

$\pi = 3.14$, R = 6360 km , $M = 6 \times 10^{24}$ kg)

Figure (8)

Solution

Calculation of the radius of the Moon's orbit around Earth:

$r = R + h = 6360 + 940 = 7300$ km $= 7.3 \times 10^6$ m Calculation of the orbital speed:

$$v = \sqrt{G\frac{M}{r}}$$

$$v = \sqrt{6.67 \times 10^{-11} \times \frac{6 \times 10^{24}}{7.3 \times 10^6}} = 7.4 \times 10^3 \text{ m/s}$$

Calculation of the period: $v = \frac{2\pi r}{T}$

$$T = \frac{2\pi r}{v} = \frac{2 \times 3.14 \times 7.3 \times 10^6}{7.4 \times 10^3} = 6195 \text{ s}$$

What if The radius of the satellite's orbit were twice the value given in the example, what effect would that have on its period?

The importance of satellites

The use of satellites has brought about a real revolution in many fields, as the satellite is considered a tall tower that can be used to transmit and receive radio waves. There are many types of satellites, including:

Figure (9)

The importance of satellites

1. **Communication satellites:** Allow television, radio, and telephone transmission to and from any place on Earth's surface.
2. **Astronomical satellites:** These are large telescopes that float in space and can photograph space accurately.
3. **Remote sensing satellites:** Used to study and monitor migratory birds, identify and map mineral resources, monitor agricultural crops to protect them from weather hazards, and study the formation of hurricanes.
4. **Reconnaissance and spy satellites:** Used to provide information needed by political and military leaders for decision-making and managing wars.

Developing critical thinking

Earth's gravity may cause objects to fall to Earth's surface (like meteorites), while at other times it may cause them (like satellites) to orbit Earth without reaching its surface. How is that?

Figure (10)

Misconceptions

Some people believe that satellites orbit Earth in a single orbit.

In fact, satellites orbit at different altitudes above Earth's surface. There are:

- **Low Earth Orbit satellites (LEO) at an approximate altitude from 200 km to 2000 km, used for imaging, remote sensing, and space stations.**
- **Medium Earth Orbit satellites (MEO) at an approximate altitude from 2000 km to 35000 km, often used in positioning systems.**
- **High altitude or geostationary satellites (GEO) at an altitude of about 36000 km, used in communications, television broadcasting, and meteorology.**

Summary

First: Key definitions and concepts

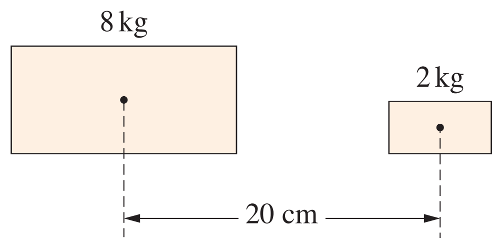
- Law of universal gravitation: Every physical object in the universe attracts any other object with a force directly proportional to the product of their masses and inversely proportional to the square of the distance between their centers.
- The gravitational field of an object: the region in which the gravitational force of the object appears.
- The intensity of Earth's gravitational field at a point: is the force with which Earth attracts a mass of 1 kg, and is numerically equal to the acceleration due to gravity at that point.

Second: Fundamental laws and equations

- Calculation of the gravitational force: $F = G\frac{Mm}{r^2}$
- Calculation of the intensity of Earth's gravitational field at a point: $g = \frac{GM}{r^2}$
- Calculation of the orbital speed of the satellite: $v = \sqrt{\frac{GM}{r}}$

Questions and Problems

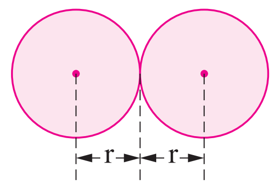
Firstly: Choose the correct answer



1. Two objects whose masses are 2 kg, 8 kg and the distance between them is 20 cm as shown in the adjacent figure. If you know that the universal gravitational constant is 6.67×10^{-11} N.m^2/kg^2, then the mutual gravitational force between them equals ....

   ⓐ 2.67×10^{-8} N   ⓑ 2.67×10^{-12} N

   ⓒ 5.34×10^{-9} N   ⓓ 5.34×10^{-11} N



2. In the adjacent figure, two identical spheres, each with mass m and radius r, are placed in contact. The magnitude of the gravitational force between them is given by the relation ....

   ⓐ $F = \frac{Gm^2}{r^2}$ ⓑ $F = \frac{Gm^2}{4\,r^2}$

   ⓒ $F = \frac{2\,Gm}{r^2}$ ⓓ $F = \frac{Gm^2}{2\,r^2}$

3. If the distance between the centers of two identical spheres is 1 m, and the gravitational force between them equals 10^{-8} N, then the mass of each is ....

   ($G = 6.67 \times 10^{-11}$ N.m^2/kg^2)

   ⓐ 1 kg   ⓑ 12.2 kg

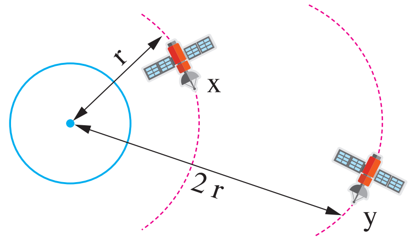
   ⓒ 2×10^5 kg   ⓓ 0.1 kg

4. If the distance between the centers of two objects is doubled and their masses remain constant, then the gravitational force between them ....

   ⓐ doubles   ⓑ becomes half its original value

   ⓒ becomes a quarter of its original value   ⓓ becomes four times its value

5. The adjacent figure shows two satellites y and x orbiting a planet. If the gravitational force exerted by the planet on both satellites is equal, then the ratio between the masses of the two satellites $\left(\frac{m_x}{m_y}\right)$ equals ....



ⓐ $\frac{1}{1}$ ⓑ $\frac{1}{2}$ ⓒ $\frac{1}{4}$ ⓓ $\frac{4}{1}$

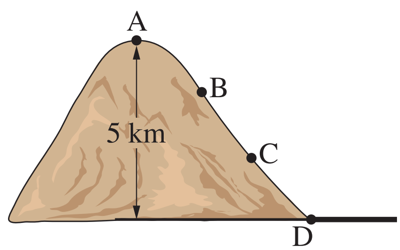
6. The acceleration due to Earth's gravity ....
   ⓐ is a universal constant
   ⓑ varies according to the altitude above Earth's surface
   ⓒ varies with the seasons
   ⓓ varies according to Earth's distance from the Sun

7. Two artificial satellites (A), (B) are orbiting Earth. If the orbital radius of satellite (A) is four times the orbital radius of satellite (B), then the ratio of the speed of satellite (A) to the speed of satellite (B) $\left(\frac{v_A}{v_B}\right)$ equals ....

ⓐ $\frac{2}{1}$ ⓑ $\frac{4}{1}$ ⓒ $\frac{1}{2}$ ⓓ $\frac{1}{4}$

Second: Essay Questions

1. In the adjacent figure, a mountain has a height of 5 km. At which of the points D, C, B, A is the intensity of Earth's gravitational field the lowest? And why?



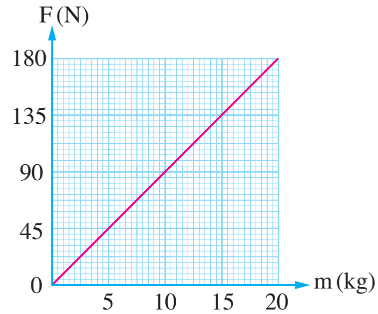
2. The International Space Station orbits Earth in an orbit of radius r such that it completes a full revolution around Earth in a time T. If a part with a mass of 0.1 of the station's mass separates from it, explain what happens to the orbital period of the station around Earth.

Third: Problems

1. If the mass of the planet Mercury is 3.3×10^{23} kg and its radius is 2.439×10^{6} m, what is the weight of an object with mass 65 kg on its surface and what is the weight of the same object on the surface of Earth?

   (Note: The universal gravitational constant $G = 6.67 \times 10^{-11}$ N.m^2.kg^{-2}, and the acceleration due to gravity at Earth's surface is $g = 9.8$ m/s^2) (240.5 N , 637 N)

2. Several objects of different masses are present on the surface of a planet with mass 4.88 × 10^{24} kg. The adjacent graph represents the relationship between the gravitational force (F) exerted by the planet on each of these objects and the mass of each body (m mass (m) of each object.



Calculate: (Note: G = 6.67 × 10^{-11} N.m^2/kg^2)

(a) The intensity of the gravitational field of this planet at its surface.

(b) The radius of the planet. (9 N/kg , 6 × 10^3 km)

3. An artificial satellite orbits at an altitude of h = 300 km above Earth's surface. Find: (Note: Earth's radius R = 6378 km, Earth's mass M = 6 × 10^{24} kg, universal gravitational constant G = 6.67 × 10^{-11} N.m^2.kg^{-2}, acceleration due to gravity at Earth's surface g = 9.8 m/s^2):

(a) Its speed in its orbit.

(b) The period of revolution of the satellite around Earth.

(c) The value of the acceleration due to gravity at its orbit.

(7.7 × 10^3 m/s , 5.45 × 10^3 s , 8.97 m/s^2)

4. At what altitude above Earth's surface should a satellite orbit so that its period of revolution around Earth equals the period of Earth's rotation about its axis?

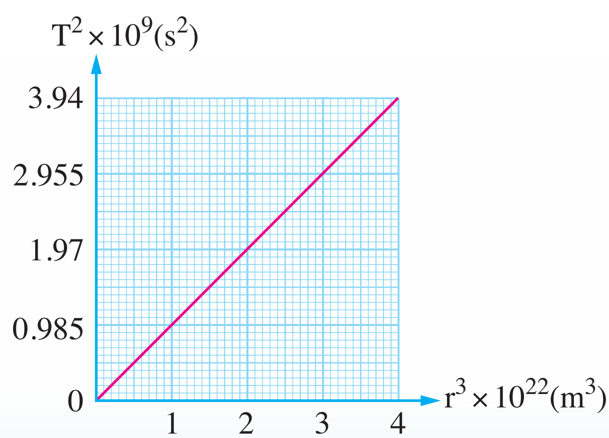
(Note: The universal gravitational constant G = 6.67 × 10^{-11} N.m^2.kg^{-2},

Earth's mass M = 5.98 × 10^{24} kg,

Earth's radius R = 6378 km) (3.59 × 10^7 m)

5. Several satellites orbit a planet in different orbits with different radii, and the adjacent graph represents the relationship between the square of the orbital period of the satellite around the planet (T^2) and the cube of the radius of the satellite's orbit (r^3). Calculate the mass of the planet.

(Knowing that: G = 6.67 × 10^{-11} N.m^2/kg^2)



(6 × 10^{24} kg)