Physics Year 1

SECTION

5

BEHAVIOUR OF LIGHT THROUGH DIFFERENT MEDIA

ENERGY

Waves

INTRODUCTION

Welcome back to the world of optics, or the behaviour of light. You will explore the beautiful concepts of refractive index, total internal reflection, and the interplay of real and apparent depth.

Total internal reflection is a fundamental concept in physics that occurs when a light wave hits a boundary between two media and is completely reflected back into the first medium.

The relationship between real depth, apparent depth, and refractive index can be established using the following formula: $\eta = \frac{\text{real depth (hr)}}{\text{apparent depth (ha)}}$

At the end of this section, you should be able to;

- Determine the refractive index of a medium.
- Explain total internal reflection.
- Establish the relationship between the real depth, apparent depth and the refractive index.

Key Ideas:

- Refractive index (**η**) is a measure of how much light bends when it enters a new material.
- Real depth refers to the actual distance between an object and the surface of a medium, like the distance between a coin in water and the water surface. Apparent depth is the perceived depth of an object when viewed through a medium like water. It is the depth that our eyes see and brains recognise, and it is always shallower than the real depth.
- Total Internal Reflection (TIR) occurs when light hits a boundary at a shallow angle. The light is completely reflected back into the first material.

REFRACTIVE INDEX (η)

Activity 5.1 Exploring refraction and apparent depth

Read the passage below and use it to define what is meant by the refractive index of a material.

One bright afternoon, Hopeson was spending the day by the lake with his friends. As they sat on the dock, dipping their toes in the cool, clear water, Hopeson saw a shiny coin at the bottom of the water.

"Hey, look! There's a coin down there," Hopeson exclaimed, pointing at the water. His friend Nyarkoah tilted her head and said, "Really? I don't see it. Where exactly?"

Hopeson directed "Right there, in the water. It's just a few inches down." Nyarkoah squinted her eyes and nodded. "I see it now. But wait, doesn't it look like the coin is closer to the surface than it actually is?"

"You're right!" Hopeson exclaimed. "That's really interesting. Let's take a closer look."

The two friends and Aishatu carefully lowered their hands into the water, keeping their eyes on the coin. As their fingers approached the coin, they noticed that it appeared to be closer to the surface than it actually was.

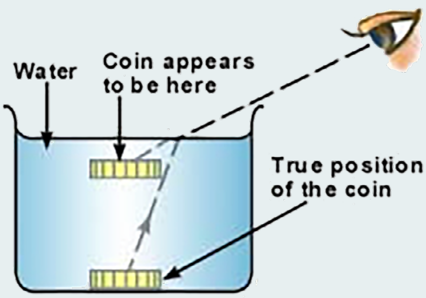


Fig 5.1: Apparent depth of a coin due to refraction in water

"Exactly!" Nyarkoah exclaimed. "The real depth of the coin is the actual distance from the surface to the coin, but the apparent depth is the distance it appears to be from the surface. The refractive index of the water is what causes this difference."

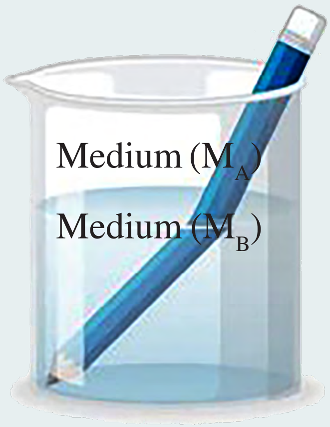


Fig 5.2: Refraction of light causing the apparent bending of a pencil in water

Observe the picture above carefully, does the pencil look bent?

The refractive index is a number that tells us how much light bends when it passes from one material medium into another, like from air into water or glass and vice versa. This bending of light is what makes the pencil appear bent in the picture above.

It can also be defined as the ratio of the speed of light in vacuum or free space (M_A in the diagram above) to the speed of light in another medium.

$$\eta = \frac{\text{speed of light } (M_A)}{\text{speed of light } (M_B)}$$

In other words, it measures how much a medium slows down or bends light as it travels through it. It is an important concept in physics as it plays a key role in understanding various concepts (phenomena) such as refraction, diffraction, and total internal reflection. Different materials have distinct refractive indices, which can be used to identify them. Refractive index can also be defined as the ratio of real depth to the apparent depth of a medium.

$$\eta = \frac{\text{real depth (hr)}}{\text{apparent depth (ha)}}$$

Types of Refractive Index

1. Absolute refractive index
2. Relative refractive index

Absolute refractive index is defined as a ratio of the speed of light in vacuum to a selected medium.

Relative refractive index is defined as the ratio of speeds of light in two different media.

If light enters any substance with a *higher* refractive index (such as from air into glass) it slows down its speed. The light bends *towards* the normal line. However, when light enters into a substance with a *lower* refractive index (such as from water into air) it speeds up. The light however bends *away* from the normal line.

Applications of Refraction

1. Designing Optical Instruments: Knowing the refractive index of different materials allows engineers to design lenses with specific focal lengths and curvatures to focus light accurately.
2. Fibre Optics: Refractive index plays a critical role in fibre optic cables, where light is guided through thin fibres by total internal reflection, which relies on the difference in refractive index between the fibre and its surroundings.
3. Creating a Rainbow Effect: Different colours of light have slightly different refractive indices. This means that when white light passes through a prism, it is separated into its constituent colours, creating a rainbow. This phenomenon is called dispersion.
4. Medical Imaging: Refractive index differences are utilised in techniques like MRI and CT scans to create images of the human body

Activity 5.2 Calculating the refractive index of various substances

Complete the table by calculating the absolute refractive index of the substances listed, using the speed of light.

Table 5.1: Refractive indices and speeds of light in different substances

Substance	Speed of light $\times 10^6$ (ms^{-1})	Refractive index
Air	300	1.00
Water	226	
Glass	200	
Diamond	125	

Activity 5.3 Experiment to explore the concepts of real and apparent depth using a coin and a transparent container of water.

Objective: To investigate the difference between real and apparent depth through observation of a coin submerged in water.

Materials Needed:

- Transparent container (e.g., a clear glass or plastic tank)
- Coin (or any small, flat object)
- Water
- Cardboard
- Pen and paper for recording observations

Procedure:

1. Place the coin in the bottom of the transparent container, as the far side relative to you.
2. View the coin from around 45 degrees above it.
3. Place a piece of cardboard in front of the container so that the coin is now obscured.
4. Fill the transparent container with water slowly, until the coin just comes into view.
5. Record the depth of water added to the container at the point that the coin became visible.
6. Repeat the experiment, this time viewing the coin from different angles. Record your findings and analyse the results.
7. Discuss how the angle of observation affects the perceived depth.

Activity 5.4 Solving real and apparent depth problems using refractive index

Problems using the refractive index formulae:

$$\eta = \frac{\text{speed of light } (M_A)}{\text{speed of light } (M_B)}$$

$$\eta = \frac{\text{real depth (hr)}}{\text{apparent depth (ha)}}$$

1. A pond is 100cm deep when a coin was placed into it, it was viewed or seen at 20cm from the surface of the water. calculate the refractive index of water and hence the displacement of the coin
2. A coin was thrown into a bucket of water which was 10cm deep. An observer saw the coin to have appeared on the 5cm mark from the top of the bucket. Calculate the refractive index of the water and hence the displacement of the coin.
3. Kofi and Ama after a physics class decided to go for a swim in a swimming pool. They noticed a coin at the bottom of the pool two meters deep. The coin appeared to be 1.4 meters from the surface of the water. What was the refractive index of water in the swimming pool?

Activity 5.5 Determining the refractive index of a material using Snell's law

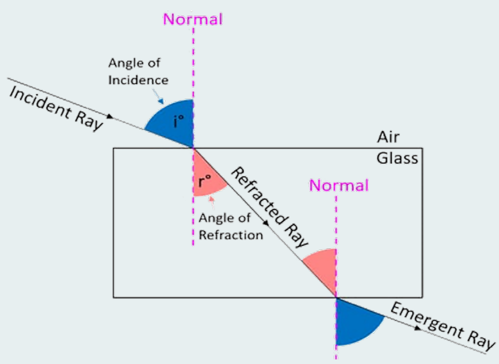


Fig 5.3: Refraction of light through a glass block

1. Using the diagram above, measure the angle of incidence 'i' and angle of refraction 'r' using a protractor and record it on the table below.
2. Use your calculator and find 'sin i' and 'sin r' of the measured angles. You can also find the refractive index using the final formula, $\eta = \frac{\sin i}{\sin r}$.

Complete the table below with these results.

Table 5.2: Table to record measured angles and calculated values

i	r	sin i	sin r	$\eta = \frac{\sin i}{\sin r}$

3. Use your calculator and press 'sin i' and 'sin r 'of the measured angles obtained and fill the empty spaces of the table below.

Table 5.3: Table to record various calculated refracted indices

i	r	sin i	sin r	$\eta = \frac{\sin i}{\sin r}$
20	13			
30	20			
40	26			
50	31			
60	36			
70	40			
80	42			

4. Plot a graph of sin i (*y* axis) against sin r (*x* axis) using the results in the second table.
5. Plot a line of best fit on your graph and then find the gradient of this line.
6. What do you notice about the value of the gradient?

Activity 5.6: Finding the refractive index from experimental data

Note: in the absence of practical equipment, you can use the interactive simulation linked using the QR code below:

https://phet.colorado.edu/sims/html/bending-light/latest/bending-light_all.html

Materials Needed

- Glass block
- Light source (e.g., laser pointer)
- Protractor
- Ruler
- Pencil

Procedure

1. Draw a diagram of the experimental setup, including the glass block, light source, and protractor.

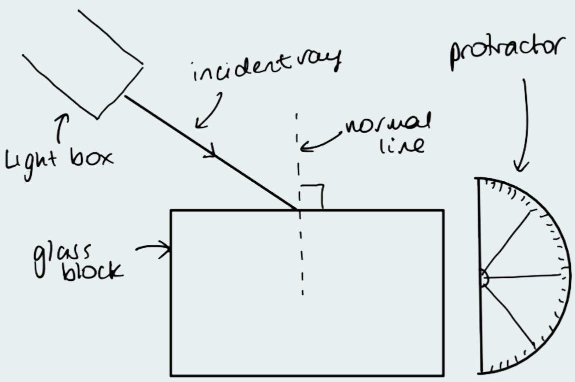


Fig 5.4: Schematic of the experimental setup

2. Shine the light source through the glass block at an angle.
3. Measure the angle of incidence (θ_i) using the protractor.
4. Measure the angle of refraction (θ_r) using the protractor.
5. Repeat steps 1-3 for different angles of incidence. Record the measurements in a table.

Table 5.4: Table to record observations made throughout activity 5.6

i	r	sin i	sin r

6. Plot a graph of sin i against sin r and use the gradient to find the refractive index of the glass block.

Activity 5.7: Problems using the refractive index formula

Refractive index formula:

$n_1 \sin\theta_1 = n_2 \sin\theta_2$

where n_1 is the refractive index of material 1 (which the light is initially traveling through) and n_2 is the refractive index of material 2 (which the light is entering).

1. A light ray traveling in air of refractive index 1.00 strikes the surface of a block of glass at an angle of 30°. The refracted ray makes an angle of 20° with the normal. What is the refractive index of the glass?
2. A light ray traveling in water strikes the surface of a diamond at an angle of 45°. What is the angle of refraction? (n_1 of water = 1.33, n_2 of diamond = 2.42)
3. A light ray traveling from water into glass enters the glass at an angle of incidence of 42 degrees and emerges at an angle of 55 degrees. The refractive index of the glass is 1.42. What is the refractive index of the water?

TOTAL INTERNAL REFLECTION

Total internal reflection is a fundamental concept in physics that occurs when a wave, typically light, hits a boundary between two mediums and is completely reflected back into the first medium. This phenomenon happens when the angle of incidence exceeds the critical angle, causing the light to be unable to pass through the boundary and instead bounce back.

Total internal reflection is commonly observed in optics, fibre optics, and even in nature, such as in the sparkle of diamonds or the mirage effect on hot roads. It has numerous applications, including medical imaging, telecommunications, and even in the design of optical instruments like microscopes and telescopes. Understanding total internal reflection is crucial for harnessing the power of light and its behaviour at the boundary of different mediums.

Conditions for occurrence of total internal reflection

1. The light must travel from the denser medium to less dense medium.
2. The angle of incidence in the denser medium must be greater than the critical angle.

TIR problems can still be solved using the formula $n_1 \sin \theta_1 = n_2 \sin \theta_2$, however θ_2 will always be equal to 90 degrees in the case of total internal reflection (as the light does not emerge from the first material).

Optical instruments that utilise total internal reflection

1. Periscopes
2. Optical fibres
3. Binoculars
4. Telescopes
5. Microscopes
6. Periscopes
7. Spectroscopes.

Natural examples of total internal reflection

1. Mirage
2. Brilliance of diamond

A mirage is a naturally occurring optical phenomenon in which light rays bend to produce a displaced image of distant objects or the sky. The word comes from English via the French mirage, from the Latin ‘mirari’, meaning “to look at, to wonder at”

Definition: ***A mirage is an optically illusive and deceptive image formed on a tarred mac road on a hot day or image formed on the sea on the cold day as a result of total internal reflection.***

Activity 5.8: Problems about TIR using the refractive index formula

$n_1 \sin \theta_1 = n_1 \sin \theta_2$

1. A light ray travels from a medium with a refractive index of 1.50 to a medium with a refractive index of 1.00. What is the critical angle for total internal reflection?
2. Calculate the critical angle of the medium of refractive index 1.800

Activity 5.9: Total Internal Reflection Practical

Materials needed:

- Source of light e.g. ray box or laser pointer
- Plain paper
- Protractor
- Semi-circular glass prism
- Pencil

Procedure:

1. Place the semi-circular glass block in the centre of the piece of paper and draw around it. Leave it in place.
2. Shine a ray of light towards the curved surface, ensuring that it hits the surface at 90 degrees (see diagram).
3. Increase the angle of the light as it hits the far surface (angle i in the diagram below) until the point at which no light appears to emerge from the block.
4. Mark the path of the light on to the piece of paper when the above condition is met.
5. Remove the glass block and continue drawing the marked ray of light until it hits the far boundary.
6. Measure the angle between this ray of light and the normal. This is your critical angle.

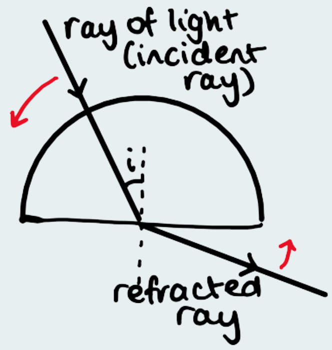


Fig 5.5: Refraction of light through a semi-circular block

Follow-up task:

Calculate the refractive index of the glass block using your measured value of the critical angle.

Discuss the effect that a larger refractive index would have on the critical angle.

Annex 5.1 – Solutions to some activities

Activity 5.1

The refractive index of a medium is a fundamental property that describes how light behaves when it passes through a particular material or substance.

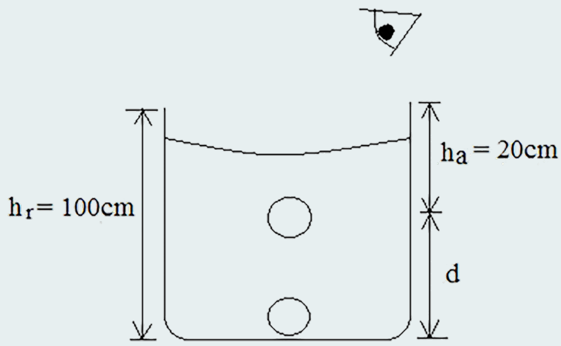
Activity 5.2

Table 5.5: Solution to Activity 5.2

Substance	Speed of light $\times 10^6$ (ms^{-1})	Refractive index
Air	300	1.00
Water	226	1.33
Glass	200	1.50
Diamond	125	2.40

Activity 5.4

a) Solution

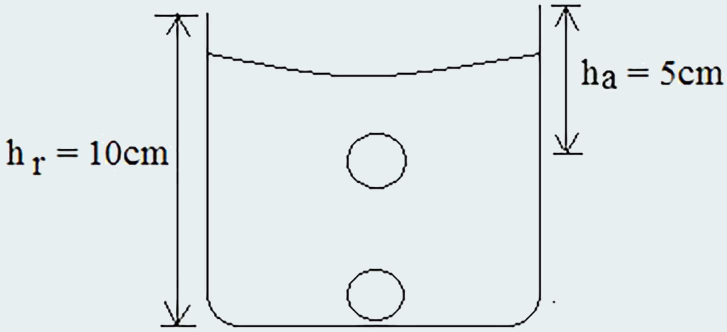


$$\eta = \frac{hr}{ha} = \frac{100}{20} = 5$$

Displacement = hr – ha

Displacement =100 – 20 = 80cm

b) Solution



$$\eta = \frac{\text{real depth (hr)}}{\text{apparant depth (ha)}}$$

$$\eta = \frac{10\ cm}{5\ cm} = 2$$

Displacement = hr – ha

Displacement= 10cm – 5cm = 5cm

7. Solution

$$\eta = \frac{\text{real depth (hr)}}{\text{apparant depth (ha)}} = \frac{2}{1.4} = 1.42$$

Activity 5.5

iii)

Table 5.6: Solution to Activity 5.5

i	r	sin i	sin r	$\eta = \frac{sini}{sinr}$
20	13	0.342	0.225	1.52
30	20	0.500	0.342	1.46
40	26	0.643	0.438	1.47
50	31	0.766	0.515	1.49
60	36	0.866	0.588	1.47
70	40	0.940	0.643	1.46
80	42	0.985	0.669	1.47

vi) The value of the gradient is equal to the value of the refractive index.

Activity 5.6

Draw or plot a graph of sin i values against sin r values which passes through the origin and hence your refractive index (η) using the slope of the graph.

1. $\eta = \frac{\sin i}{\sin r}$

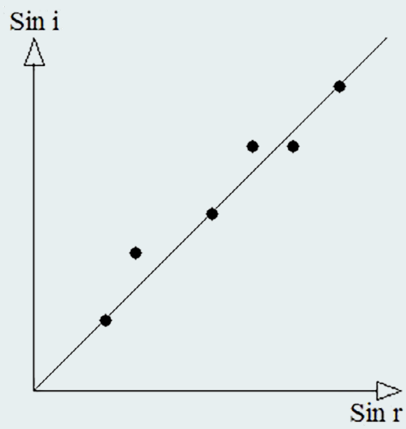


Fig 5.6

Activity 5.7

1. Solution:

Identify the knowns:

$n_1 = 1.00$ (air)

$\theta_1 = 30°$

$\theta_2 = 20°$

Apply the formula:

$n_1 \sin\theta_1 = n_2 \sin\theta_2$

$1.00\sin(30°) = n_2\sin(20°)$

Solve for n_2:

$n_2 = \frac{(1.00 \sin(30°))}{\sin(20°)} = 1.46$

Therefore, the refractive index of the glass is approximately 1.46.

2. Solution:

Identify the knowns:

$n_1 = 1.33$ (water)

$n_2 = 2.42$ (diamond)

$\theta_1 = 45°$

Apply the formula:

$n_1 \sin \theta_1 = n_2 \sin \theta_2$

$1.33 \sin (45°) = 2.42 \sin \theta_2$

make θ_2 the subject:

$$\sin \theta_2 = \frac{1.33 \sin(45°)}{2.42} = \frac{0.94}{2.42} = 0.389$$

$\sin \theta_2 = 0.389$

$\theta_2 = \sin^{-1} (0.389) = 22.7^o$

Therefore, the angle of refraction is approximately 22.7^o

3. $\eta_1 \sin\theta_1 = \eta_2 \sin\theta_2$

$\eta_1 \sin 42 = \eta_2 \sin 55$

$$\eta_1 = \frac{1.42 \sin 55}{\sin 42}$$

$= 1.74$

Activity 5.8

1. At the critical angle, the angle of refraction is 90°.

Apply the formula:

$\eta_1 \sin\theta_1 = \eta_2 \sin\theta_2$

$$\sin \theta c = \frac{1.00 \sin(90°)}{1.50} = 6.66 \times 10^{-3}$$

$\theta c = \sin^{-1} (6 \times 10^{-3}) = 41.8°$

Therefore, the critical angle for total internal reflection is approximately 41.8°.

2. $\sin c = \frac{1}{\eta}$

$\eta = 1.800$

$\sin c = \frac{1}{1.800}$

$\sin c = 0.5$

$c = \sin^{-1}(0.5)$

$c = 30^0$

Annex 5.2- Further information on refraction

Deriving the apparent depth formula

Consider the diagram below. An object is placed in a vessel of water and is observed at a different position by an observer.

If a coin was placed at a position C, and it was observed to have been appeared at a position B, the refractive index could be found using real depth of the object and the apparent depth.

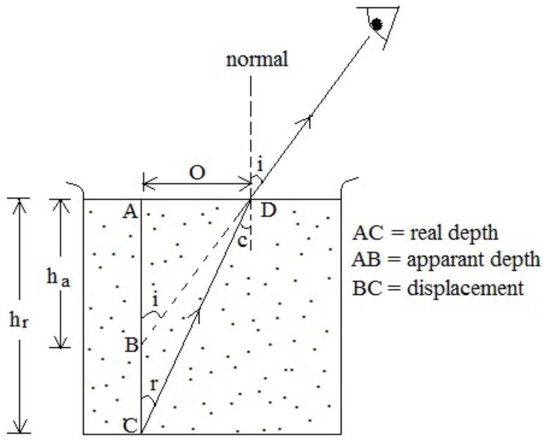


Fig 5.7: Diagram showing refraction and depth relationships in a water"

In triangle ABD and ACD

$\tan r = \frac{AD}{AC} = \frac{o}{hr}$ *and* $\tan i = \frac{o}{AB} = \frac{o}{ha}$

for small angles tan r = sin r

hence $\frac{\sin i}{\sin r} = \frac{\tan i}{\tan r} \rightarrow \frac{o/ha}{o/hr} = \frac{hr}{ha}$

$\eta = \frac{hr}{ha}$

$\eta = \frac{\text{real depth (hr)}}{\text{apparent depth (ha)}}$

Explanation of the brilliance of a diamond

Refractive index of diamond is 2.42, so the critical angle for diamond air interface is $24.4^{o.}$

Diamonds are cut in such a way that light falling on them from any surface undergoes total internal reflection at various faces and therefore remains within the diamond. Different incident rays travel along different paths and therefore come out of the diamond at different times and angles causing a sparkle effect. Hence diamonds shine very brilliantly.

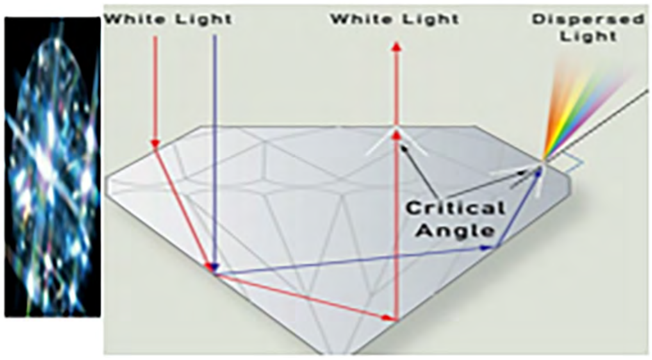


Fig 5.8: Dispersion and critical Angle in a diamond

Summary of the similarities and differences between TIR, refraction and reflection

Table 5.7: Comparison of Total Internal Reflection, Regular Reflection, and Refraction

Feature	Total Internal Reflection	Regular Reflection	Refraction
Definition	The complete reflection of light within a medium at a boundary with another medium, occurring when the angle of incidence is greater than the critical angle.	The bouncing back of light from a surface.	The bending of light as it passes from one medium to another.

Feature	Total Internal Reflection	Regular Reflection	Refraction
Occurs at Boundary	Between two media where light is passing from a more optically dense medium to a less dense one (e.g., water to air).	At any reflective surface (e.g., mirrors).	Between two media with different optical densities (e.g., air to water).
Angle of Incidence	Greater than the critical angle.	Not necessarily related to critical angle.	Usually less than the critical angle.
Critical Angle	Required; if the angle of incidence exceeds this angle, total internal reflection occurs.	Not applicable.	Not applicable.
Angle of Reflection	Equal to the angle of incidence.	Equal to the angle of incidence.	Not defined; depends on Snell's Law.
Angle of Refraction	None, as light is entirely reflected inside the medium.	Not applicable.	Changes according to Snell's Law.
Transmission of Light	No light passes through the boundary; all is reflected.	Light is reflected, and some may pass through if the surface is not perfectly reflective.	Light passes through the boundary and bends.
Medium	Light travels from a denser to a less dense medium.	Can occur between any reflective surfaces.	Light travels from one medium to another with different densities.
Applications	fibre optics, prisms, and certain types of lenses.	Mirrors, reflective coatings.	Lenses, glasses, water droplets (rainbows).

REVIEW QUESTION

Review Quesiton 5.1

1. A coin is placed in a bowl of water. Identify the name for the depth to which it sinks?
2. A coin is placed in a bowl of water. Identify the name for the depth to which it is viewed?
3. How is refractive index related to real depth and apparent depth?
4. The real depth of a fish swimming in a pond is 2 metres below the water surface. The refractive index of water is approximately 1.33. Calculate where the fish will be apparently (falsely) be seen.
5. What causes total internal reflection to occur?
6. What are some observable examples of total internal reflection?

ANSWERS TO REVIEW QUESTION

Review Question 5.1

1. Real depth refers to the actual distance between an object and the surface of a medium, like water. It's the true depth of the object as measured in a straight line from the object to the surface.
2. Apparent depth is the perceived depth of an object when viewed through a medium like water. It's the depth that our eyes register, and it's always shallower than the real depth.
3. The refractive index of a medium determines how much light bends when it passes from one medium to another. A higher refractive index means a greater bending of light. The relationship between refractive index, real depth (d), and apparent depth (d') is: $\eta = \frac{d}{d'}$

   or $\eta = \frac{h_r}{h_a}$ Where 'n' is the refractive index of the medium. This means that a higher refractive index leads to a smaller apparent depth compared to the real depth.
4. Using the formula, we can calculate the apparent depth of the fish:

   $\eta = \frac{h_r}{h_a}$

   $1.33 = \frac{2}{h_a}$

   $h_a = \frac{2m}{1.33} \approx 1.5$ m

   Therefore, the fish would appear to be about 1.5 meters below the surface of the water.
5. Total internal reflection is caused by the combination of two factors:
   - Refraction: When light travels from a denser medium to a less dense medium, it bends away from the normal (an imaginary line perpendicular to the surface).
   - Critical angle: As the angle of incidence increases, the angle of refraction also increases. At a certain angle, called the critical angle, the angle of refraction reaches 90 degrees. Beyond this angle,

the light cannot refract into the less dense medium and is instead reflected back into the denser medium.

6. Total internal reflection has several important applications, including:
   - Fibre optics: Light travels through thin, flexible fibres by undergoing total internal reflection at the fibre's boundary. This allows for efficient transmission of information over long distances.
   - Prisms: Prisms use total internal reflection to redirect light, as seen in binoculars and periscopes.
   - Diamonds: The brilliance of diamonds is due to total internal reflection, which traps light within the diamond and causes it to sparkle.
   - Medical imaging: Endoscopes use total internal reflection to allow doctors to view internal organs and cavities without surgery.

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