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0 (https://intercom.help/kognity)

TOPIC C
WAVE BEHAVIOUR

SUBTOPIC C.3
WAVE PHENOMENA

Student view

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C. Wave behaviour / C.3 Wave phenomena

The big picture

? Guiding question(s)

- How are observations of wave behaviours at a boundary between different media explained?
- How is the behaviour of waves passing through apertures represented?
- What happens when two waves meet at a point in space?

Keep the guiding questions in mind as you learn the science in this subtopic. You will be ready to answer them at the end of this subtopic. The guiding questions require you to pull together your knowledge and skills from different sections, to see the bigger picture and to build your conceptual understanding.

Waves, such as sound waves and electromagnetic waves, are all around us, and we often encounter them in our daily lives without realising it. The behaviour of waves is responsible for many of the phenomena we may come across, from the colours of a rainbow to echoes in a cave.

Waves can be bounced back when they hit a surface. They can spread out as they travel from one medium to another (**Figure 1**). Or waves can spread out as they travel through a gap or around a corner.

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Figure 1. A rainbow is caused by light waves being dispersed by rain drops.

Understanding the behaviour of waves is a crucial aspect of physics. How can we describe these wave behaviours?

Prior learning

Before you study this subtopic make sure that you understand the following:

- Wavelength, frequency, displacement, amplitude and wave speed (see subtopic C.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43778/)).
- Phase difference (see subtopic C.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43161/)).
- The nature of sound waves and electromagnetic waves (see subtopic C.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43778/)).

Practical skills

Once you have completed this subtopic, you can apply your knowledge of wave phenomena by going to Practical 6: Determining the refractive index (/study/app/math-aa-hl/sid-423-cid-762593/book/determining-refractive-index-id-46510/).

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Higher level (HL)

Practical skills

Once you have completed this subtopic, you can examine interference patterns by going to Practical 10: Investigating double-slit and double-source wave interference (HL) (/study/app/math-aa-hl/sid-423-cid-762593/book/investigating-double-slit-and-double-id-46754/).

C. Wave behaviour / C.3 Wave phenomena

Reflection, refraction and diffraction

C.3.1: Wavefronts and rays C.3.2: Reflection, refraction and transmission C.3.3: Wave diffraction
C.3.4: Wavefront-ray diagrams for refraction and diffraction

Learning outcomes

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

- Use the concepts of wavefronts and rays to describe travelling waves.
- Understand reflection, refraction, transmission and diffraction of waves.
- Use wavefront-ray diagrams to show behaviour of waves.

How does the nature of the medium affect the direction and speed of wave travel?

Wavefronts and rays

Wavefronts are imaginary surfaces that connect points on a wave that are in phase (see subtopic C.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43161/)). The distance between wavefronts represents the wavelength of the wave. For convention, the points represented on a wavefront are those of maximum displacement.

Rays are imaginary lines that show the direction of energy transfer in the wave as well as the direction of propagation.

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- In a plane wave, all the rays are parallel to each other, and we track a single ray.

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- In a spherical wave, the rays are along radial directions and are divergent.

Figure 1 shows a spherical wave and a plane wave.

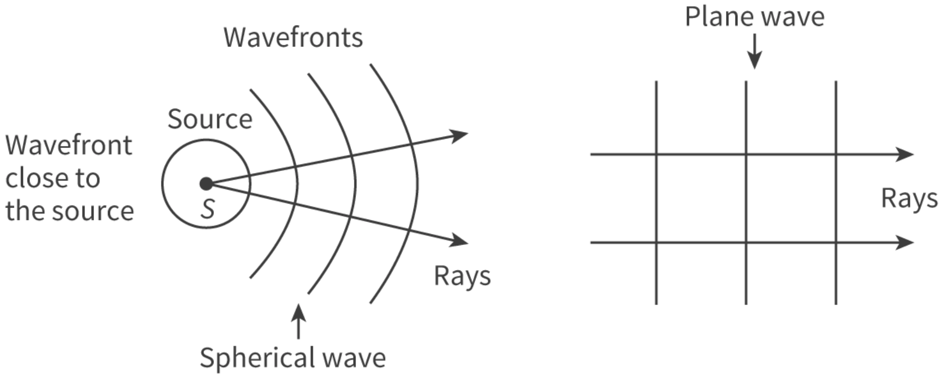

Figure 1. Spherical wave and plane wave.

More information for figure 1

The image shows two parts. On the left side, a spherical wave is depicted, originating from a source labeled 'S'. The wavefronts are represented by concentric circles spreading outward from the source, with arrows indicating the direction of 'rays' moving perpendicular to the wavefronts. A label reads "Wavefront close to the source" above one of the inner circles. On the right side, a plane wave is illustrated with parallel, straight lines that represent the wavefronts. Perpendicular arrows show the direction of the rays, with the label "Plane wave" at the top. The rays in both parts are consistently shown as perpendicular to the wavefronts.

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As shown in **Figure 1**, rays and wavefronts are always perpendicular to each other.

Reflection

When a wave hits a boundary between two different media, it can bounce off the boundary. This is known as reflection.

When a wave reflects, it follows the law of reflection, which states that the angle of incidence (the angle between the incident wave and the normal to the surface) is equal to the angle of reflection (the angle between the reflected wave and the normal to the surface).

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Study skills

The angle of incidence is the angle between the incoming (incident) ray and the normal. The normal is an imaginary line that is perpendicular (at 90°) to the surface at the point where the incident ray strikes. The angle of reflection is the angle between the reflected ray and the normal.

We can show reflection using a ray diagram (**Figure 2**). The angle of incidence, θ_1, equals the angle of reflection, θ_2.

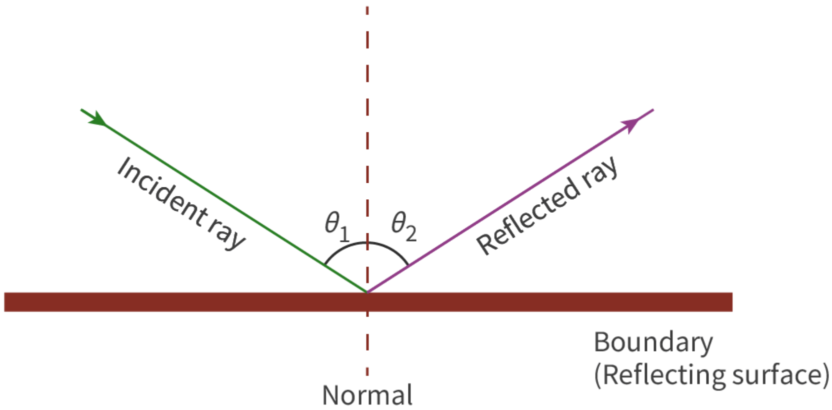

Figure 2. Ray diagram showing the law of reflection in which the angle of incidence (θ_1) equals the angle of reflection (θ_2).

More information for figure 2

This diagram illustrates the law of reflection. It shows a flat brown reflecting surface with a perpendicular dashed line labeled as the "Normal." To the left of this line, there is a green arrow pointing downward labeled "Incident ray," forming an angle labeled θ1 with the normal. To the right, a purple arrow labeled "Reflected ray" points upward, forming an angle labeled θ2 with the normal, equal to θ1. The boundary surface is labeled as "Boundary (Reflecting surface)."

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When drawing wavefronts on a ray diagram for reflection, remember these rules:

- Wavefronts are always perpendicular to rays.
- In a single medium, the distance between one wavefront and the next is constant (and equals the wavelength).

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view

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- Reflection does not change the wavelength of a wave.
- Wavefronts do not pass through a mirror.

The steps for drawing a wavefront-ray diagram are shown in four parts in **Figure 3**:

1. Draw incident wavefronts. These do not pass into the mirror.
2. To draw the reflected part of a wavefront, reflect the 'missing' part of the incident wavefront (shown as dotted lines) in the mirror. Do not include these dotted lines in your final diagram.
3. Draw all the reflected parts of the wavefronts.
4. You can add one or two completely reflected wavefronts. Part 4 of **Figure 3** uses different colours for the incident and reflected wavefronts to aid understanding, but you do not have to do this.

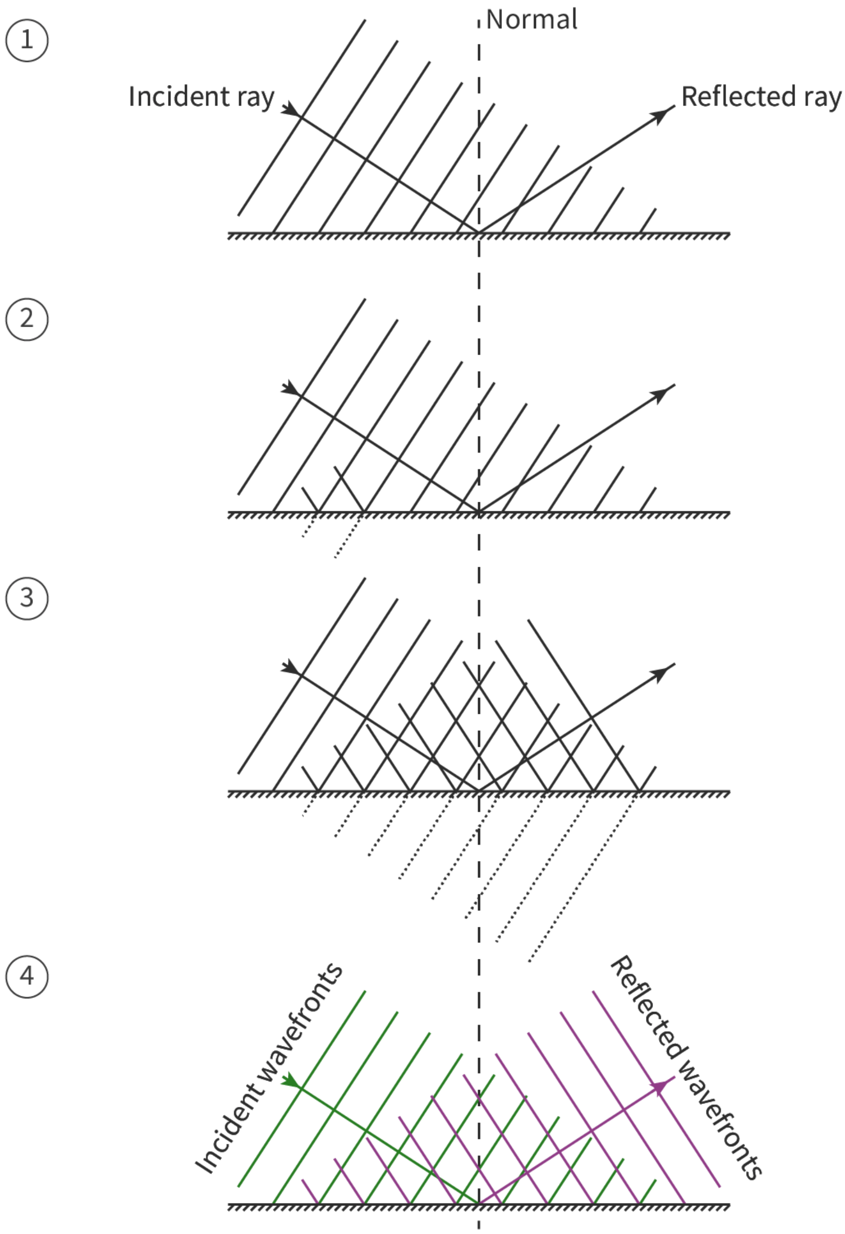

Figure 3. How to draw a wavefront-ray diagram for reflection.

Student view

More information for figure 3

The image is a comprehensive diagram showing the process of reflection using a wavefront-ray approach. It consists of four sections, labeled 1 to 4.

1. **Section 1:** Shows an incident ray approaching a reflective surface at an angle, labeled with 'Incident ray.' A dotted line labeled 'Normal' is perpendicular to the surface at the point of incidence. A reflected ray is shown diverging from the point of incidence at the same angle as the incident ray, labeled 'Reflected ray.' This section illustrates the law of reflection where the angle of incidence equals the angle of reflection.

2. **Section 2:** Similar to Section 1, it reinforces the concept of reflection, showing more rays parallel to the initial incident ray, all reflecting symmetrically across the normal.

3. **Section 3:** Further emphasizes the principles shown in Sections 1 and 2 with additional wavefronts drawn perpendicular to the rays, illustrating the change in orientation as they reflect.

4. **Section 4:** Completes the diagram with incident wavefronts represented as green lines and reflected wavefronts as purple lines. The wavefronts are perpendicular to the rays, demonstrating the concept of wavefront orientation before and after reflection, adhering neatly to the reflective surface. The labels 'Incident wavefronts' and 'Reflected wavefronts' identify respective sections of the diagram.

The diagram overall demonstrates the relationship between incident rays, normal lines, reflected rays, and the associated wavefronts in the context of reflection.

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Refraction

Imagine a light wave travelling through a medium and encountering a boundary with a different medium. If the angle of incidence is not perpendicular (at 90°) to the boundary, the direction of the wave will change as it enters the second medium. This is known as refraction.

Figure 4 shows a wavefront-ray diagram for the refraction of a light wave at the boundary between air and glass. How does the wavelength of the wave change as the wave crosses the boundary?

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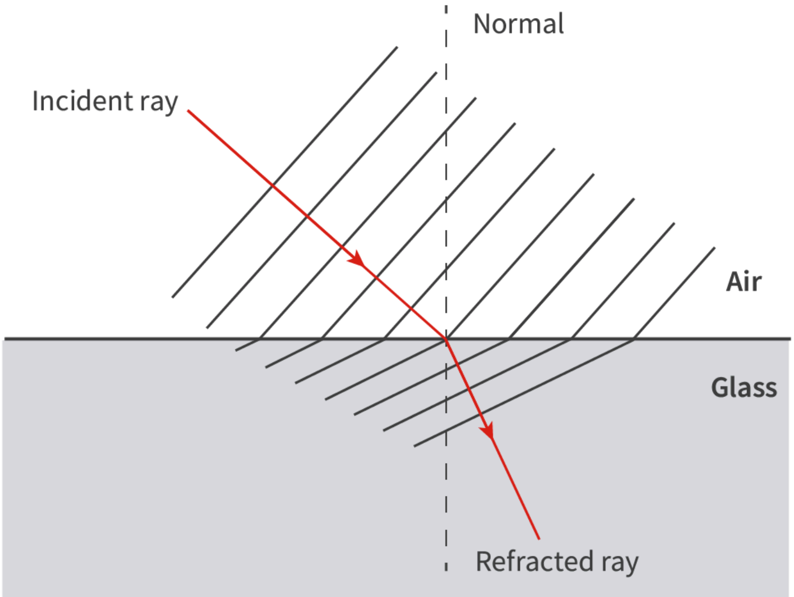

Figure 4. Wavefront-ray diagram for the refraction of a light wave.

More information for figure 4

The diagram illustrates the refraction of a light wave as it passes from air into glass. It features wavefronts represented by black lines. An incident ray approaches from the top left and hits the surface separating air and glass. At the boundary, the direction of the ray changes. The incident ray is marked with an arrow that bends towards the normal line when entering the glass. Below the boundary, in the glass, the wavefront lines are closer together compared to above in the air, indicating the decrease in wavelength upon refraction. Labels show 'Incident ray,' 'Normal,' and 'Refracted ray,' with the 'Normal' being a dotted vertical line. The top region is labeled 'Air' and the bottom region is labeled 'Glass.'

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We can see from **Figure 4** that the wavefronts in glass are closer together than the wavefronts in air. This means that the wavelength of the wave decreases as it moves from air into glass. This change in wavelength is a direct result of the change in speed of the wave.

The relationship between speed, wavelength and frequency for a wave is given by the wave speed equation (see subtopic C.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43778/)):

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view

$$v = f\lambda$$

Since the frequency of a light wave does not change when it refracts (frequency is a property of the source of the light), a decrease in wave speed means a decrease in wavelength, and an increase in wave speed means an increase in wavelength.

This change in speed is what causes the light wave to change direction. The different parts of the wavefront are slowed down (or sped up) by different amounts as they enter the new medium, which causes the wave to bend. The angle of refraction depends on the angle of incidence and the difference in speed between the two media.

The change in wave speed is due to differences in physical and molecular properties between the two media.

Study skills

It is important to remember what happens to a wave as it goes from one medium to another medium:

- If the wave slows down, it bends towards the normal.
- If the wave speeds up, it bends away from the normal.

When drawing wavefronts on a ray diagram for refraction remember these rules:

- Wavefronts are always perpendicular to rays.
- In a single medium, the distance between one wavefront and the next is constant (and equals the wavelength).

The steps for drawing a wavefront-ray diagram for refraction are shown in four parts of **Figure 5**:

1. Start by drawing a ray diagram. To make an accurate drawing (instead of a sketch) use Snell's law (see section C.3.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/snell's-law-critical-angle-and-total-internal-reflection-id-46612/)), which relates the angles of incidence and refraction to the wave speed in each medium.
2. Draw some incident wavefronts in Medium 1. End these wavefronts at the boundary with Medium 2.
3. To draw the refracted part of a wavefront continue the line into Medium 2, but change the direction of this part of the wavefront making it perpendicular to the ray in Medium 2. If

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you have drawn the rays correctly, you should find that the wavelength is longer in Medium 2 if the wave speeds up (as shown here) or shorter if the wave slows down.

4. You can add one or two completely refracted wavefronts. Part 4 of **Figure 5** uses different colours for the incident and refracted wavefronts to aid understanding, but you do not have to do this.

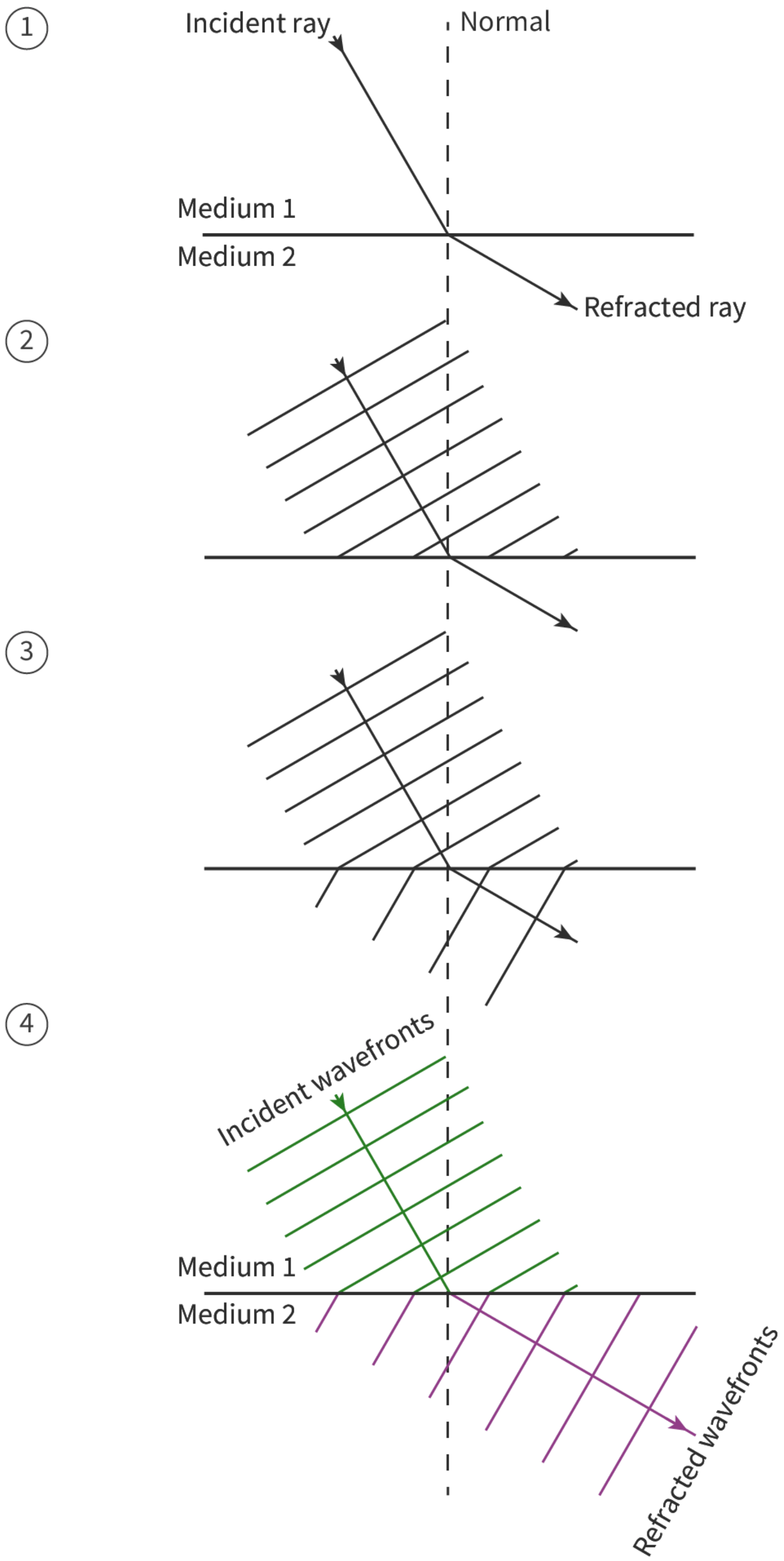

Figure 5. How to draw a wavefront-ray diagram for refraction.

More information for figure 5

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The diagram illustrates the concept of refraction using wavefront-ray diagrams and consists of four numbered sections:

1. The first section shows the incident ray hitting the boundary between two media labeled as Medium 1 and Medium 2, and then refracting as it continues into Medium 2. The ray approaches at an angle to the normal (a dotted vertical line) and is labeled.

2. In the second section, wavefronts are depicted as parallel lines approaching the boundary from Medium 1 and bending as they enter Medium 2.

3. The third section demonstrates the further refraction of wavefronts in Medium 2. The diagram shows the lines changing direction as they cross the boundary, illustrating the change in speed and direction due to the difference in mediums.

4. The final section shows the incident wavefronts in green approaching the boundary and the refracted wavefronts in purple diverging after crossing into Medium 2. Each section is visually labeled to indicate the separate parts of the diagram.

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White light is made up of different wavelengths of visible light. White light is refracted as it passes through a glass prism. This phenomenon is known as dispersion. It happens because the different wavelengths are refracted by different amounts, leading to the separation of the colours (**Interactive 1**). Colours with shorter wavelengths are refracted more than colours with longer wavelengths. The refraction of sunlight through water droplets is what causes a rainbow.

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Interactive 1. Refraction of White Light by a Prism.

More information for interactive 1

The animation depicts the refraction and dispersion of white light as it passes through a triangular glass prism. A single white beam enters the prism from the left side. Inside the prism, the light splits into multiple colored waves, representing different wavelengths of visible light. These waves exit the prism at different angles, creating a spectrum of colors. Colours with shorter wavelengths, such as violet and blue, bend more than those with longer wavelengths, like red and orange. The animation visually demonstrates how dispersion occurs due to varying refraction angles for different colors.

Water waves are refracted as they travel from deeper water to shallower water (or from shallower water to deeper water). As the water becomes shallower, the speed of the waves decreases (**Figure 6**).

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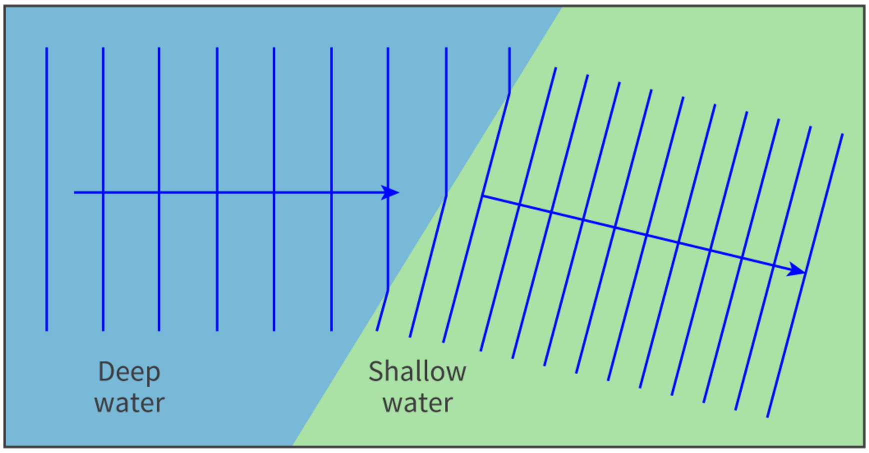

Figure 6. Refraction of water waves.

More information for figure 6

The diagram illustrates the concept of water wave refraction as waves move from deep to shallow water. On the left side, labeled 'Deep water,' blue vertical lines represent wave fronts that are evenly spaced and perpendicular to the direction of the wave's travel, indicated by a horizontal arrow. As the waves enter the area labeled 'Shallow water' on the right side, the wave fronts bend and become angled relative to their original direction, with the space between them decreasing. The arrow also shifts to indicate the change in direction due to refraction. This change illustrates how waves slow down as they move into shallower regions, causing them to refract, or bend, towards the normal line separating the water depths.

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Transmission

When a wave encounters a boundary between two media, the wave can be absorbed, reflected or transmitted (**Video 1**).

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Video 1. Absorption, reflection and transmission.

More information for video 1

The video explores how light interacts with different materials by being absorbed, reflected, transmitted, or refracted. It starts by showing 8 everyday objects like tissue paper, wax paper, plastic wrap, aluminum foil, cardboard, a bowl of water, a compact mirror, and an LED flashlight. When light shines on tissue paper, it glows softly but changes color—this is because tissue paper is translucent, allowing some light through but scattering it. Next, wax paper is tested: light passes through but comes out distorted, making it another example of a translucent material. Plastic wrap, on the other hand, is transparent—all light travels straight through without any changes, like looking through a clear window.

The video then demonstrates opaque materials. Aluminum foil blocks all light completely—it doesn't transmit anything! Instead, the foil reflects light rays, bouncing them back like a mirror. Similarly, cardboard is also opaque, but instead of reflecting light, it absorbs it, soaking up the energy like a sponge. These interactions show how materials can either stop light (opaque), let some light through (translucent), or allow all light through (transparent).

Finally, the video highlights how engineers use these properties creatively. For example, understanding reflection helps design laser security systems, while refraction in water or glass can split light into rainbows. By experimenting with how light behaves, engineers invent tools and technologies that solve real-world problems, proving that even something as simple as light can inspire big ideas!

Transmission is the process by which waves move through a boundary into a different medium, and continue travelling in the new medium. The proportion of wave energy that is transmitted depends on the properties of the two media and the angle of incidence of the wave. If the angle of incidence is not 90° to the normal, the wave will be refracted.

Figure 7 shows a summary of reflection, transmission, absorption and refraction.

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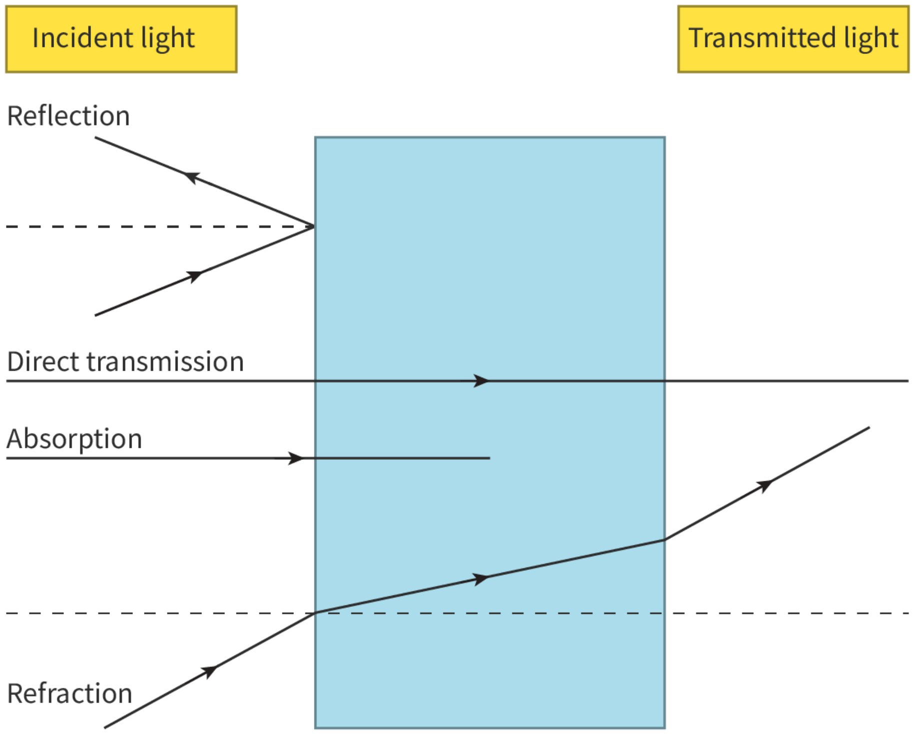

Figure 7. Reflection, direct transmission, absorption and refraction.

More information for figure 7

The image is a diagram showing how incident light interacts with a medium, illustrating four main concepts: reflection, direct transmission, absorption, and refraction. At the top left, the incident light is labeled in a yellow box. Reflection is represented by arrows bouncing back at an angle from the surface. Direct transmission is shown as a straight arrow passing directly through the medium. Absorption is depicted by an arrow entering but not passing through, indicating energy loss within the medium. Refraction is represented by an arrow changing direction as it exits the medium, illustrating the bending of light. At the top right, the transmitted light is labeled in another yellow box. The diagram visually demonstrates how light behaves when it encounters a material, emphasizing different light interactions.

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Diffraction

When waves arrive at a barrier with an opening, or at an obstacle of some limited width, they spread out as shown in **Figure 8**. This spreading out of the wavefronts beyond barriers and objects is known as diffraction.

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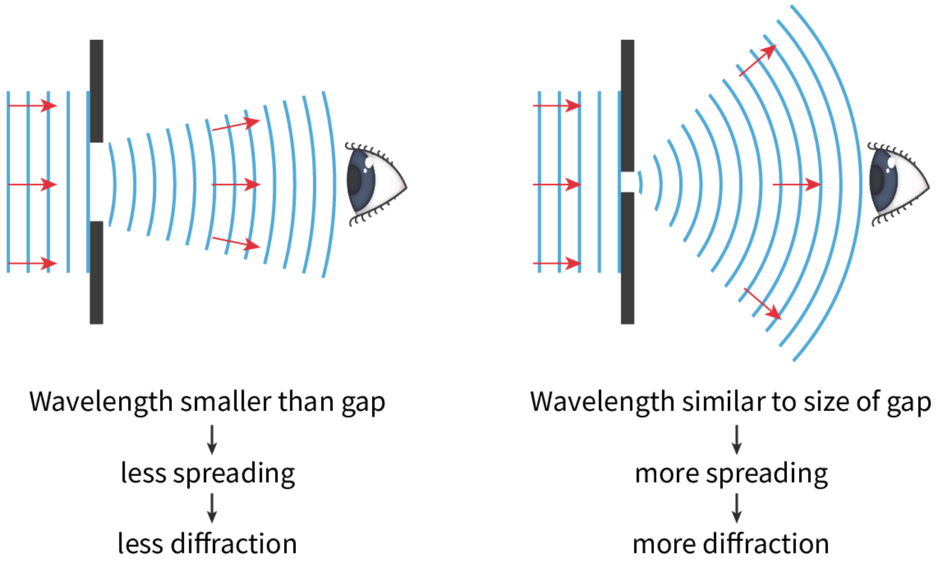

Figure 8. Diffraction of waves through an opening.

More information for figure 8

The image illustrates the concept of wave diffraction through openings with varying gaps. On the left side of the image, waves approach a barrier with a gap that is larger than the wavelength. The waves are represented by parallel lines before the gap and curved lines after the gap to depict less spreading and diffraction, labeled as "Wavelength smaller than gap - less spreading - less diffraction." On the right side, waves approach a barrier with a gap similar in size to the wavelength. The waves curve more noticeably after passing through the gap, indicating more spreading and diffraction, labeled as "Wavelength similar to size of gap - more spreading - more diffraction." An eye symbol is positioned to show an observation of the wave behavior.

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The extent of diffraction depends on the size of the opening in relation to the wavelength of the waves. More specifically, diffraction is more evident when the wavelength is greater than (or similar to) the size of the opening, as shown in **Figure 9**.

Examples of diffraction in real-life scenarios are:

- sound waves diffracting at a narrow door opening
- radio signals diffracting around a mountain
- water waves diffracting around jetties and breakwaters **(Figure 9)**.

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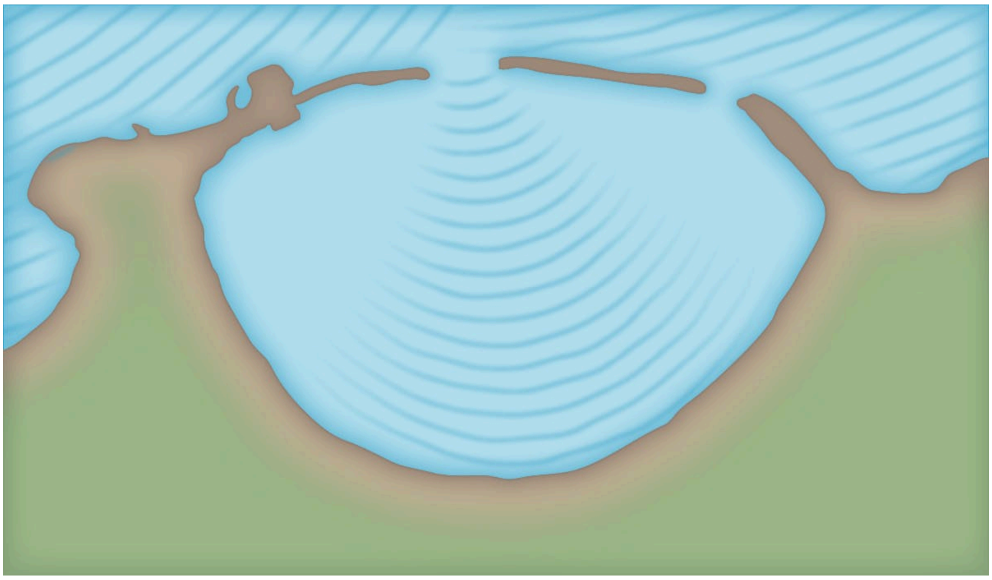

Figure 9. Diffraction of water waves.

More information for figure 9

The image depicts an illustration showing the diffraction of water waves as they enter a harbor. The harbor is outlined by land masses, which curve around the water, forming a semi-circular shape. As the water enters the harbor from the open sea, the waves become bent and spread out in circular patterns. The water inside the harbor shows curved wavefronts indicating the change in wave direction. The land masses are in shades of brown and green, indicating the coastal environment, while the water is depicted in blue tones. The image demonstrates the wave behavior as it interacts with obstacles like the harbor walls, illustrating the concept of diffraction.

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Worked example 1

The gap between a door and its frame measures 34 cm. What frequencies of sound are optimally diffracted?

Speed of sound = 340 m s^{-1}

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Solution steps	Calculations
Step 1: Understand that the effects of diffraction are more relevant when the wavelength of the waves is larger than (or comparable to) the size of the opening.	$\lambda \geqslant 34\ \text{cm} = 0.34\ \text{m}$
Step 2: Use the wave equation linking wave speed, frequency and wavelength (given in the data booklet) to calculate the frequency of sound corresponding to a wavelength $\lambda = 0.34$ m.	Wave equation $\rightarrow v = f\lambda$ Rearrange for f: $\begin{aligned} f &= \frac{v}{\lambda} \\ &= \frac{340}{0.34} \\ &= 1.0 \times 10^3\ \text{Hz (} \end{aligned}$
Step 3: Give the range of frequencies of sound that are optimally diffracted.	The frequencies of sound that are optimally diffracted are equal to 1.0×10^3 I lower.

As a comparison, visible light waves have much shorter wavelengths (and higher frequencies) than calculated in the above worked example. So, visible light does not diffract through the door gap, at least not significantly enough for us to notice.

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Creativity, activity, service

Strand: Activity
Learning outcome: Demonstrate how to initiate and plan a CAS experience

Think about how you could explain reflection, refraction and diffraction of waves to younger students. You could carry out experiments, produce a video or even act out scenes to demonstrate what happens to the waves.

Work through the activity to check your understanding of reflection, refraction and transmission.

Activity

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:** Thinking skills — Being curious about the natural world
- **Time required to complete activity:** 30 minutes
- **Activity type:** Individual activity

You are going to carry out some experiments to observe how a light wave behaves when it hits a boundary between two media.

Reflection:

1. Find a calm body of water or a clean mirror in a well-lit area.
2. Observe how light behaves when it hits the surface.
3. If you can, take a photograph, making sure to include the light source and the reflecting surface.

Refraction:

1. Half fill a clear glass with water.
2. Put a straight object, such as a straw or a pencil, into the water at an angle.
3. Observe how the object seems to bend at the water's surface.
4. If you can, take a photograph, ensuring that the part of the object in the water and the part outside of the water are visible.

Transmission:

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1. Find a window through which you can see clearly, preferably without any colour or texture.
2. Observe how you can see objects on the other side of the window.
3. If you can, take a photograph that shows the window and the view through it.

Create a presentation with each behaviour (reflection, refraction and transmission) on a different slide. For each behaviour, include:

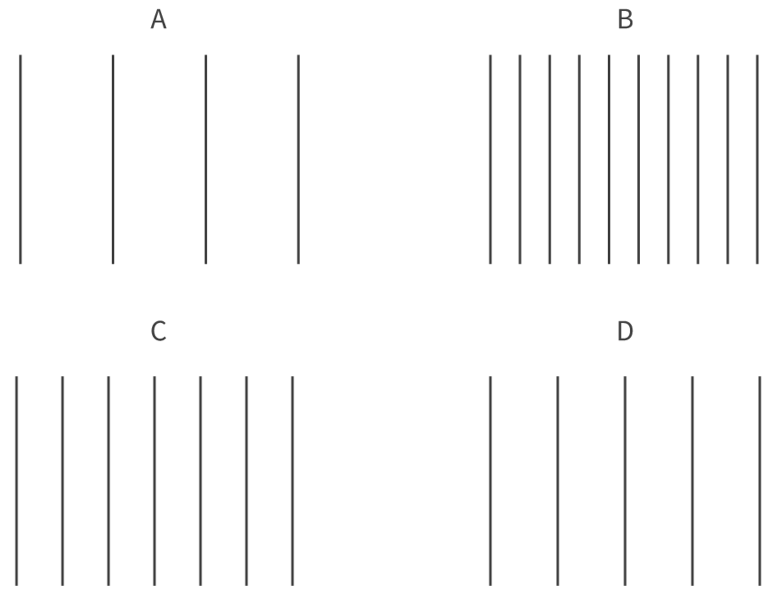
- a title identifying the behaviour
- a photograph of the behaviour (your own or taken from the internet)
- a short paragraph explaining what is happening to the light and why.

5 section questions

Question 1

SL HL Difficulty:

The waves in the wavefront diagrams all travel at the same speed.



More information

Which wave (A, B, C or D) has the lowest frequency?

1 A ✓

2 C

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3 B

4 D

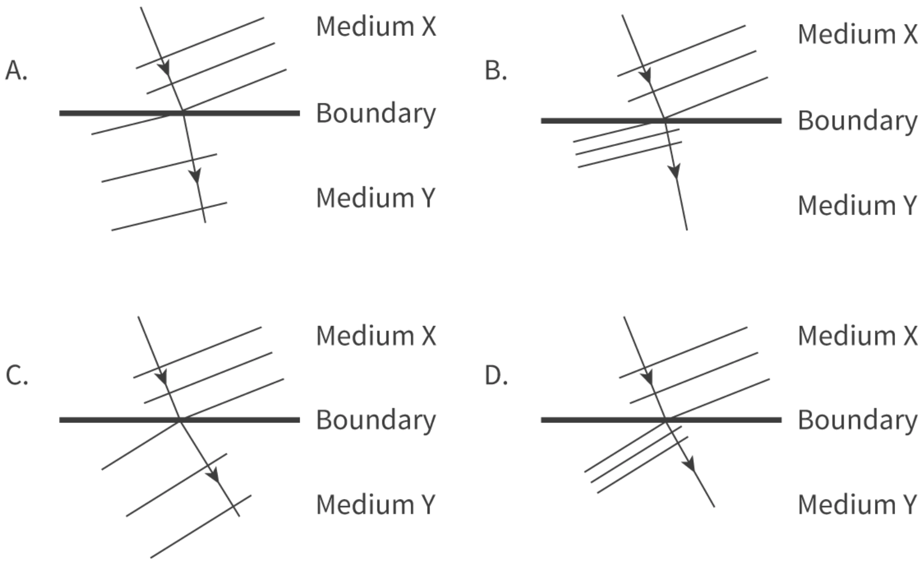
Explanation

Since $v = f\lambda$ and v is constant, the wave with the lowest frequency will have the smallest number of waves in the distance shown. The lowest value here is four for wave A.

Question 2

SL HL Difficulty:

The speed of a wave in medium X is less than the speed of the wave in medium Y.



More information

Which diagram (A, B, C or D) shows the refraction of the wave at the boundary between X and Y?

1 C ✓

2 A

3 B

4 D

Explanation

As the wave enters medium Y, its speed increases. Therefore, its wavelength increases (the distance between the wavefronts increases). The wave bends away from the normal.

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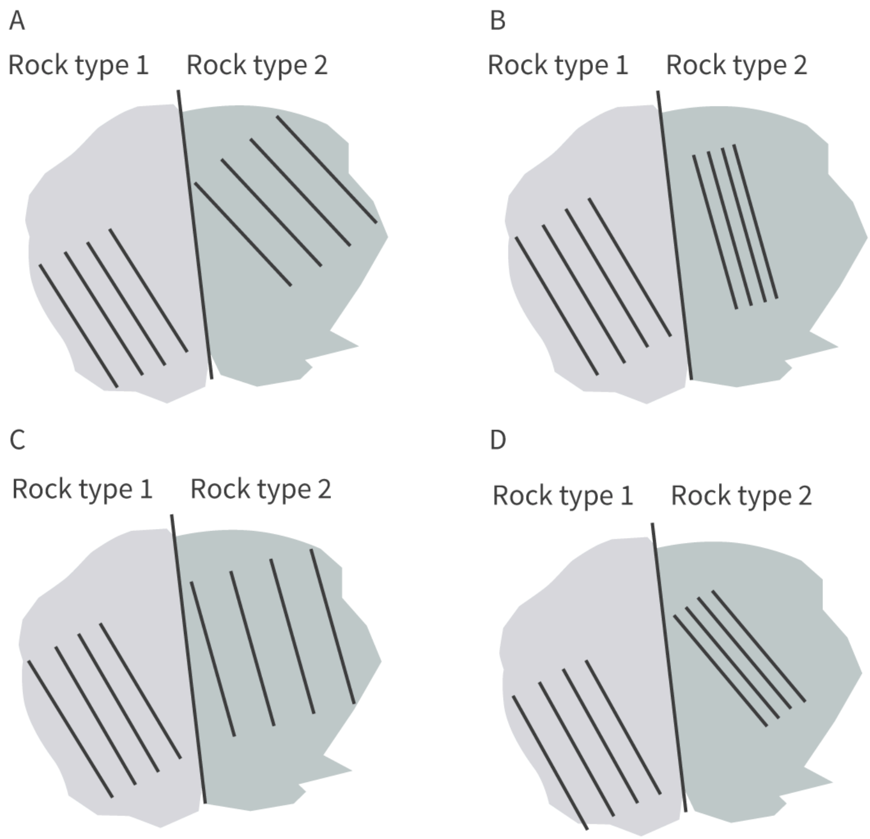
Question 3

SL HL Difficulty:

A pressure wave from an earthquake approaches the boundary between two different rock types. The speed of travel in rock type 2 is greater than the speed of travel in rock type 1. Which wavefront diagram (A, B, C or D) shows the wavefronts for the refracted wave?



More information

1 A ✓

2 B

3 C

4 D

Explanation

As the waves travel from rock type 1 to rock type 2, they speed up. This causes a change in direction and a change in the wavelength.

When wave speed increases, wavelength increases and the waves bend away from the normal. This combination is shown in diagram A.

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Question 4

SL HL Difficulty:

A flat mirror is positioned horizontally on a flat surface, 60 m away from the base of a tower. A light ray from the top of the tower reflects from the mirror at 90° into a student's eye on top of an identical tower.

Determine the height of the tower.

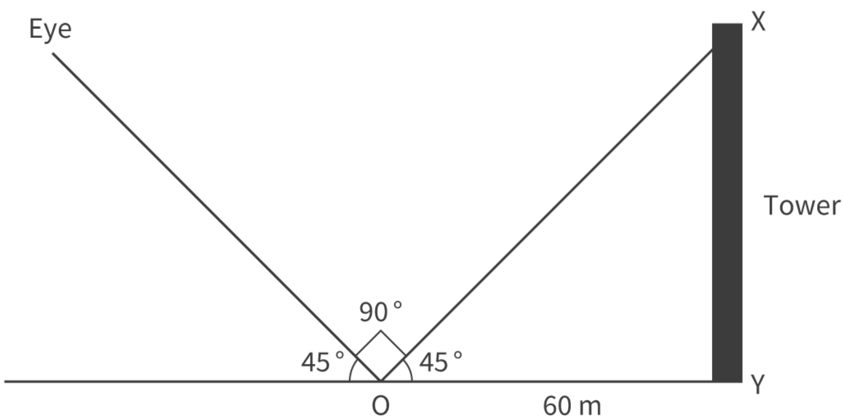
1 60 m ✓

2 30 m

3 90 m

4 120 m

Explanation



More information

The law of reflection states that the angle of incidence is equal to the angle of reflection. As you are told that the ray reflects from the mirror at an angle of 90°, then both the angle of incidence and the angle of reflection must be 45°.

Using trigonometry:

$$\tan 45 = \frac{XY}{OY}$$

$$1 = \frac{XY}{60}$$

$$= 60 \text{ m } (1 \text{ s.f.})$$

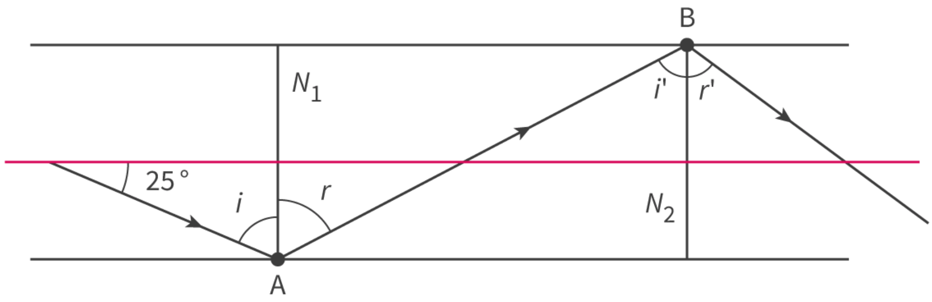
Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

Question 5

SL HL Difficulty:

A ray of light is reflected by two parallel mirrors at points A and B. The ray makes an angle of 25° with the axis of the two mirrors.



More information

Determine the angle of reflection, r', at point B? Give your answer to an appropriate number of significant figures.

The angle of reflection at point B is 1 65 ✓ °.

Accepted answers and explanation

#1 65

General explanation

The normals, N_1 and N_2, are normal to the reflecting mirrors and are perpendicular to the axis of the two-mirror system.

$$i = 90 - 25 = 65°$$

$$i = r = 65° \text{ (law of reflection)}$$

Angle r and angle i' are equal in size (they are alternate interior):

$$r = i' = r' = 65°$$

C. Wave behaviour / C.3 Wave phenomena

Snell's law, critical angle and total internal reflection

Student view

Overview
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Learning outcomes

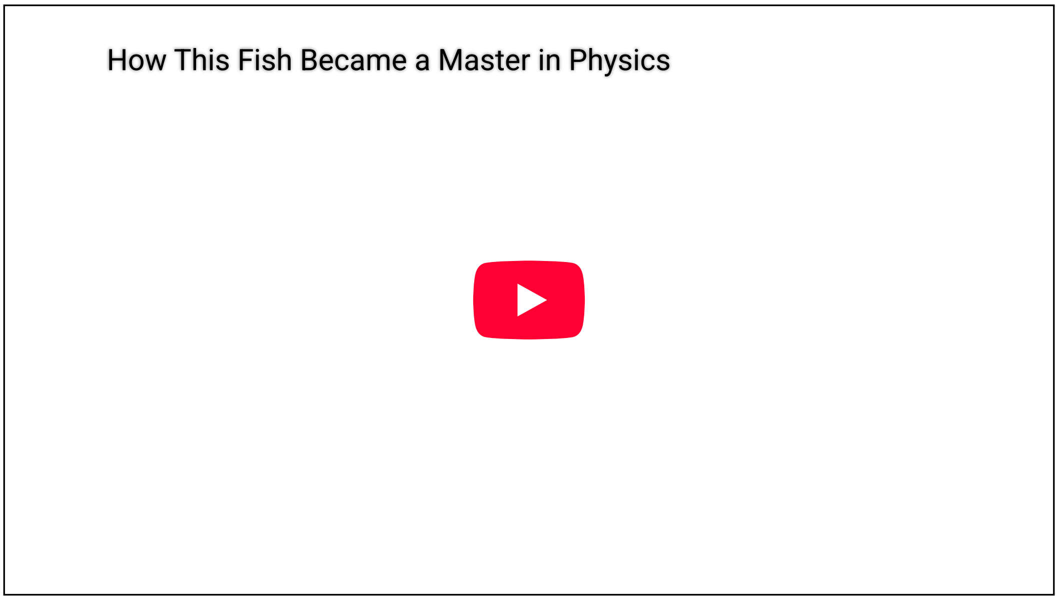
By the end of this section you should be able to:

- Understand the concepts of refractive index and critical angle.
- Understand Snell's law and use the equation:

$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}.$$

- Understand total internal reflection.

Video 1 shows the archerfish. They hunt by shooting out streams of water to bring down airborne insects.



Video 1. The archerfish.

The archerfish can do this because they understand the behaviour of light underwater. As they aim their water jets, their eyes remain submerged, and they account for the refraction of light that occurs when light enters the water. Even when the perceived angle of the target is 45°, they can correct for deviations as large as 25° to ensure their aim is accurate.

Student
view

How does the archerfish calculate the refraction of light so accurately? And can we use the same principles to predict how light will behave when it moves from one medium to a different another?

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

Refractive index

Light waves refract as they pass from one medium into a different medium. Refraction occurs because light waves travel at different speeds in different media (see section C.3.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/reflection-refraction-and-diffraction-id-46611/)).

Nature of Science

Aspect: Theories

The study of refraction dates back to ancient times, with the ancient Greeks being the first to observe the bending of light through transparent materials. However, it was not until the 17th century that the true nature of refraction was understood due to the work of French mathematician and physicist René Descartes.

Descartes was the first to explain refraction using the wave theory of light. He showed that when light passes from air into a medium, it slows down due to the properties of the medium, and this slowing down causes the light to bend. In the 19th century, Scottish physicist James Clerk Maxwell developed a mathematical model of electromagnetic waves that provided a more detailed explanation of refraction. He showed that the speed of light is determined by the properties of the medium, such as its refractive index.

The refractive index, n, of a medium is a measure of how much the medium can slow down light waves. It is the ratio of the speed of light in a vacuum to the speed of light in the medium:

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

where:

- n is the refractive index of the medium (n is a ratio so it is doesn't have units)
- c is the speed of light in a vacuum (3.00×10^8 m s^{-1})
- v is the speed of light in the medium in metres per second (m s^{-1})

The greater the refractive index of a medium, the more it slows down light, and the more the light is bent.

Student view

Overview
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The value of refractive index ranges from 1 in a vacuum to over 2 for diamond. The refractive index for a material is not constant but can vary based on different factors, such as temperature and pressure.

Making connections

Einstein's theory of special relativity (see subtopic A.5 HL (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-hl-id-45344/)) says that nothing can travel faster than the speed of light in a vacuum. This means that, in theory, the value of refractive index cannot be less than 1. However, refractive index measures the phase velocity of light, which is the speed at which the wave crests move. This phase velocity can be faster than the speed of light in a vacuum. The Earth's ionosphere, a type of plasma, has a refractive index of less than 1. This results in electromagnetic waves bending away from the normal, enabling long-distance radio communications due to the waves being refracted back towards the Earth.

Snell’s law

Figure 1 shows a wavefront-ray diagram for refraction.

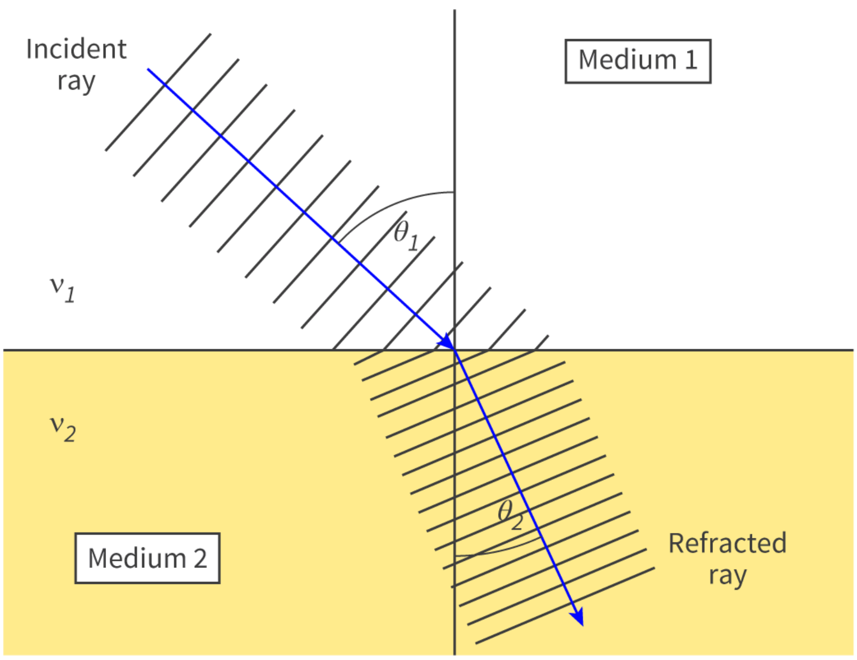

Figure 1. A wavefront-ray diagram for refraction.

More information for figure 1

Student view

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

The diagram illustrates how a wavefront changes direction as it passes from one medium to another, demonstrating the principle of refraction. At the top, labeled 'Medium 1,' the incident ray enters the diagram at an angle θ1 to the normal line, marked with several parallel wavefronts. The wave penetrates into 'Medium 2,' which is depicted as a yellow rectangle. As the wave transitions into the second medium, its direction changes, creating an angle θ2 with the normal, and the wavefronts refract accordingly. Labels indicate both the incident and refracted rays, as well as the velocities v1 and v2 for the respective media. This diagram is used to illustrate the concept of Snell's law, which relates the angles to the velocities and refractive indices of the two media.

[Generated by AI]

We use Snell's law to describe the relationship between the angle of incidence, θ_1, and the angle of refraction, θ_2. It states that the ratio of the sine of the angle of incidence to the sine of the angle of refraction is equal to the inverse ratio of the refractive indices of the two media and the ratio of the speed of the wave in the two media. This is shown mathematically in **Table 1**.

Table 1. Equation for Snell's law.

Equation	Symbols	Units
$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$	n_1 = refractive index of first medium	No units
	n_2 = refractive index of second medium	No units
	θ_1 = angle of incidence	degrees (°)
	θ_2 = angle of refraction	degrees (°)
	v_1 = speed of wave in first medium	metres per second ($m\,s^{-1}$)
	v_2 = speed of wave in second medium	metres per second ($m\,s^{-1}$)

Worked example 1

A light ray travels from air (n = 1.00) into a medium with a refractive index of 1.50. If the angle of incidence is 30.0°, determine the angle of refraction.

Student view

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Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation	$n_1 = 1.00$ $n_2 = 1.50$ $\theta_1 = 30.0^\circ$
Step 2: Write out the equation	$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1}$ $\sin\theta_2 = \frac{n_1 \sin\theta_1}{n_2}$
Step 3: Substitute the values given	$\sin\theta_2 = \frac{(1.00 \times \sin 30.0)}{1.50}$ = 0.333
Step 4: State the answer with appropriate units and the number of significant figures used in rounding	$\theta_2 = 19.47^\circ = 19.5^\circ (3\ \text{sf})$

Worked example 2

A ray of light passes from air into a medium. The angle of incidence is 45° and the angle of refraction is 30° Determine the ratio of the speed of light in air to the speed of light in the medium.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation	$\theta_1 = 45^\circ$ $\theta_2 = 30^\circ$
Step 2: Write out the equation	$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2}$

Student view

Overview
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Solution steps	Calculations
Step 3: Substitute the values given	$\frac{\sin 45}{\sin 30} = \frac{v_1}{v_2}$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding	$= \sqrt{2} = 1.4\ (2\ \text{sf})$ The speed of light in air is 1.4 times faster than the speed of light in the medium.

Critical angle and total internal reflection

Imagine that a light ray hits a boundary between a more dense medium (such as glass) and a less dense medium (such as air). As you increase the angle of incidence, θ_1, the angle of refraction, θ_2, increases until it become 90° and the ray is refracted along the boundary between the two media. The angle of incidence at which this occurs is known as the critical angle. The critical angle depends on the refractive index of each medium.

When the angle of incidence is greater than the critical angle, the light ray is reflected off the boundary and back into the more dense medium. This is known as total internal reflection.

Figure 2 shows refraction, the critical angle and total internal reflection.

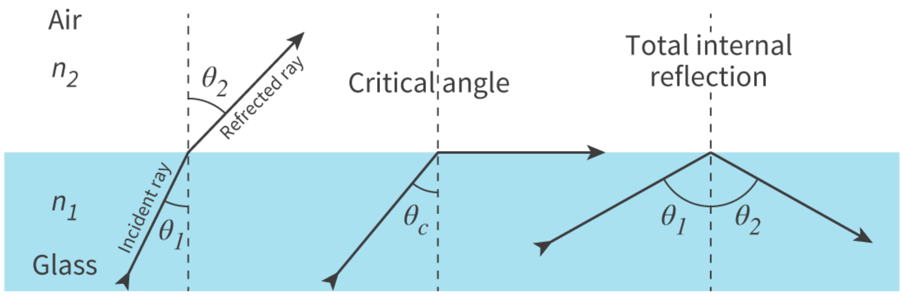

Figure 2. Refraction, critical angle and total internal reflection.

More information for figure 2

The diagram illustrates the principles of refraction, the critical angle, and total internal reflection. It consists of two main sections: air and glass, denoted by their refractive indices, n2 for air and n1 for glass. An incident ray strikes the glass surface at an angle θ1 and refracts at angle θ2 in the air. The critical angle θc is indicated where the refracted ray remains tangent to the surface. Total internal reflection occurs when the angle of incidence exceeds the critical angle, θc, resulting in the ray reflecting back into the glass. Arrows mark the path of the rays, labeled appropriately as incident ray, refracted ray, and reflected ray, illustrating the transition from refraction to internal reflection.

Student view

Overview
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[Generated by AI]

The conditions for total internal reflection are:

- The light must be passing from a medium with a higher refractive index into a medium with a lower refractive index.
- The angle of incidence must be greater than the critical angle.

International Mindedness

Total internal reflection has applications all over the world. Fibre optic cables use total internal reflection to transmit light signals over long distances (**Figure 3**).

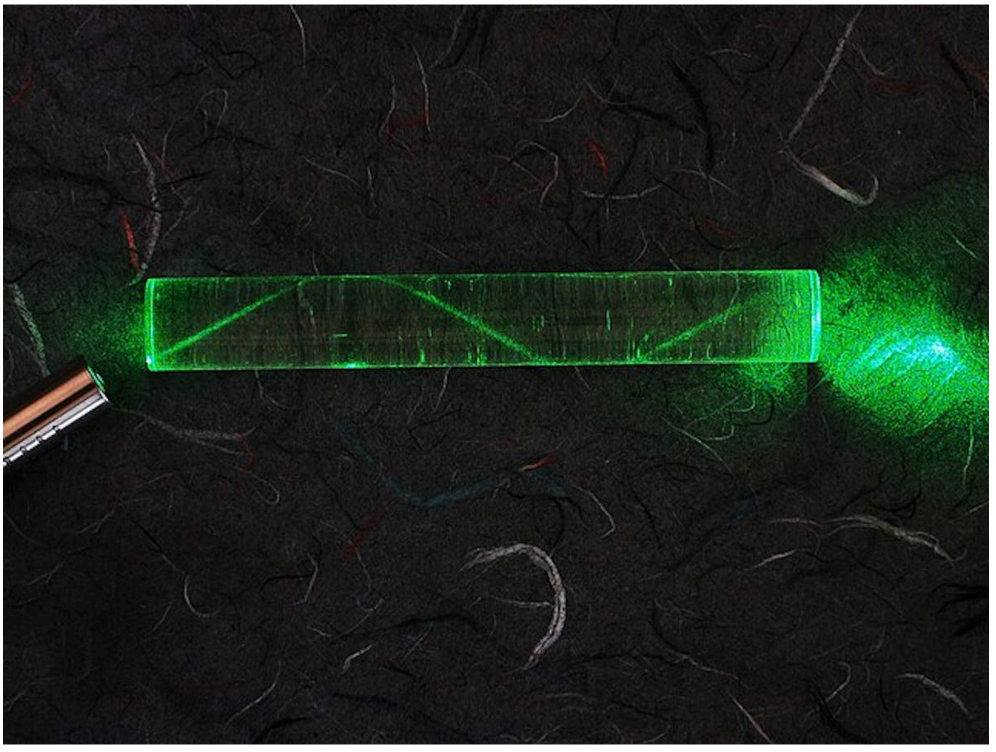

Figure 3. Total internal reflection in a fibre optic cable.

More information for figure 3

The image shows a demonstration of total internal reflection within a fiber optic cable. A green laser beam is directed into the cable and can be seen bouncing off the inner walls of the cable in a zigzag pattern, illustrating how light is transmitted through fiber optics by reflecting internally along the cable's length. The setup includes a visible light source on the left and the cable stretching horizontally across the image with the beam visibly traveling inside. The background is dark with some faint colorful fibers visible.

Student view

[Generated by AI]

For example, the Fibre-optic Link Around the Globe (FLAG) is a 28 000 kilometres long, mostly underwater cable, connecting countries such as India and the UK.

The critical angle can be found using Snell's law:

$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1}$$

The angle of refraction is 90°, and sin 90 = 1. The angle of incidence is now the critical angle, θ_c:

$$\frac{n_1}{n_2} = \frac{1}{\sin\theta_c}$$

Rearranging the equation gives us:

$$\sin\theta_c = \frac{n_2}{n_1}$$

Worked example 3

A light ray travels from a material with a refractive index of 1.50 into water, which has a refractive index of 1.33. Determine the critical angle.

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation	$n_1 = 1.50$ $n_2 = 1.33$
Step 2: Write out the equation	$\sin\theta_c = \frac{n_2}{n_1}$
Step 3: Substitute the values given	$\sin\theta_c = \left(\frac{1.33}{1.50}\right)$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding	$\text{critical angle} = 62.457^{\circ} = 62.5^{\circ}(3\text{ s.f.})$

Work through the activity to check your understanding of critical angle and total internal reflection.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20 minutes
- **Activity type:** Pair activity

Look at the simulation in **Interactive 1.** It shows a light ray as it travels from one medium into another medium.

Student view

Overview
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Interactive 1. Critical angle and total internal reflection simulation.
Credit: Tom Walsh

More information for interactive 1

An interactive titled, Critical Angle and Total Internal Reflection Simulation, demonstrates the refraction and reflection of light as it travels between two media with different refractive indices. It allows users to manipulate the angle of incidence and the refractive indices of the two materials to observe changes in the behavior of the light ray. The interactive represents the incident, reflected, and refracted rays, along with their corresponding angles, using color-coded annotations. At the bottom, checkboxes allow users to toggle specific visual elements, such as the refracted ray, reflected ray, angle of deviation, and percentage of light reflected and transmitted.

Users can adjust the angle of incidence using a slider (ranges from 0 to 90 degrees) or an input box to explore the transition from partial reflection to total internal reflection. When the angle reaches a critical value, the percentage of transmitted light drops to zero, and all the light is reflected into the initial medium. By gradually increasing and decreasing the angle, users can determine the exact critical angle where total internal reflection begins.

The refractive indices of both media can also be modified within predefined constraints, where the first medium must always have a higher refractive index than the second. This feature allows for the investigation of different material combinations and their corresponding critical angles. The simulation provides real-time calculations of the reflected and transmitted light percentages, reinforcing the principles of Snell's Law and total internal reflection.

A key part of the activity involves recording critical angles for different refractive index pairs and plotting a graph of sine values to determine the relationship between the angles of refraction and incidence. The resulting straight-line graph allows users to derive the refractive index of the first medium by calculating the gradient. This interactive is useful for understanding light behavior at interfaces, confirming theoretical predictions, and exploring practical applications of refraction and total internal reflection in optics.

Student view

1. Using the data entry boxes below the sliders, set the refractive index as $n_1 = 1.5$ and $n_2 = 1.33$.

Overview (/study/app/math-aa-hl/sid-423-cid-762593/c

2. Gradually increase the value of the 'Angle of incidence' slider until 'The Percent of Light Reflected' becomes 100%.
3. Use the data entry box below the 'Angle of incidence' slider to reduce the angle of incidence by 0.1° until you see the percentage of light reflected no longer equal 100%. Record the lowest value of angle of incidence that has 100% of light reflected. This is the critical angle. You can compare this value to the answer to **Worked example 3.**
4. Increase the angle of incidence further. What happens to the light ray?
5. Vary n_1 and n_2 to another six sets of values, but remember that n_1 has to be greater than n_2.
6. For each set of values, find the critical angle. Record the values of refractive index for each medium and the critical angle in a table.
7. Plot a graph of sin θ_1 (*x*-axis) against sin θ_2 (*y*-axis). What shape of graph do you get? How could you use this graph to determine the value for n_1?

The graph should be a straight line passing through the origin.

Using Snell's law:

$$\frac{n_1}{n_2} = \frac{\sin \theta_2}{\sin \theta_1}$$

The gradient is equal to $\frac{\sin \theta_2}{\sin \theta_1}$ and therefore also equal to $\frac{n_1}{n_2}$.

You can find n_1 by multiplying the gradient by n_2 .

5 section questions

Question 1

SL HL Difficulty:

Light travels from air into glass. The refractive index of glass is 1.5. Determine the speed of light in glass. Give your answer to an appropriate number of significant figures.

The speed of light in glass is 1 2.0 ✓ × 10^8 m s^{-1}

Accepted answers and explanation

#1 2.0

2

Student view

Overview
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General explanation

$$n = 1.5$$

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

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

$$= \frac{3.00\times10^8}{1.5}$$

$$= 2.0\times10^8 \text{ m s}^{-1}(2 \text{ s. f.})$$

Question 2

SL HL Difficulty:

Light travels from a medium with a greater refractive index into a medium with a lower refractive index. What is the angle of incidence at which the light is refracted at an angle of 90° to the normal called?

critical angle ✓

Accepted answers

critical angle

Explanation

The critical angle is the angle of incidence at which light is refracted at an angle of 90° to the normal (along the boundary between the two media).

Question 3

SL HL Difficulty:

The 1 refractive index ✓ of a medium is defined as the ratio of the speed of light in a 2 vacuum ✓ to the speed of light in the medium.

Accepted answers and explanation

#1 refractive index

#2 vacuum

General explanation

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

Student
view

Question 4

SL HL Difficulty:

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

What is the angle of refraction when a light ray passes from air (n = 1.00) into water (n = 1.33) at an angle of incidence of 45°?

1 32.1 ° ✓

2 44.3 °

3 62.0 °

4 93.1 °

Explanation

$$n_1 = 1.00$$

$$n_2 = 1.33$$

$$\theta_1 = 45^\circ$$

$$\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1}$$

$$\sin\theta_2 = \frac{n_1 \sin\theta_1}{n_2}$$

$$\theta_2 = \sin^{-1}\left(\frac{n_1 \sin\theta_1}{n_2}\right)$$

$$= \sin^{-1}\left[\frac{(1.00 \times \sin 45)}{1.33}\right]$$

$$= 32.12^\circ = 32.1^\circ (3\text{ sf})$$

Question 5

SL HL Difficulty:

The refractive index of glass is $\frac{3}{2}$ and the refractive index of water is $\frac{4}{3}$. What is the critical angle for light travelling from glass to water?

1 $\sin^{-1}\left(\frac{8}{9}\right)$ ✓

2 $\sin^{-1}\left(\frac{2}{3}\right)$

3 $\sin^{-1}\left(\frac{3}{4}\right)$

4 $\sin^{-1}\left(\frac{1}{2}\right)$

Explanation

Student view

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(/study/app/math-aa-hl/sid-423-cid-762593/c

$$n_1 = \frac{3}{2}$$

$$n_2 = \frac{4}{3}$$

$$\begin{aligned}\theta_1 &= \sin^{-1}\left(\frac{n_2}{n_1}\right)\\ &= \sin^{-1}\left(\frac{\frac{4}{3}}{\frac{3}{2}}\right)\\ &= \sin^{-1}\left(\frac{8}{9}\right)\end{aligned}$$

C. Wave behaviour / C.3 Wave phenomena

Superposition of waves and Young's double slit interference

C.3.7: Superposition of waves and wave pulses C.3.8: Double-source interference and coherent sources C.3.9: Constructive interference C.3.10: Destructive interference C.3.11: Young's double-slit interference

Learning outcomes

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

- Understand the superposition of wave pulses and travelling waves.
- Know that coherent sources are needed for double-source interference.
- Know the conditions for constructive interference and destructive interference and use the equations:

  path difference = $n\lambda$

  and

  path difference = $\left(n + \frac{1}{2}\right)\lambda$
- Understand Young's double-slit interference and use the equation: $s = \frac{\lambda D}{d}$

Movie theatres have sound speakers that produce sound waves. These sound waves meet and interact.

Student view

Overview
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Imagine you are at a movie screening (**Figure 1**). If you get up and move around the theatre during the movie, the volume of the sound will change as you move around. It will be louder in some areas and quieter in other areas. Why does this happen?

Figure 1. Sound speakers in a movie theatre produce sound waves that interact.

Properties of waves

Waves have properties that determine their behaviour and interactions (see subtopic C.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/snell's-law-critical-angle-and-total-internal-reflection-id-46612/)) (**Figure 2**).

- Crest: The highest point of a wave, where the maximum displacement from its equilibrium position occurs.
- Trough: The lowest point of a wave, where the minimum displacement from its equilibrium position occurs.
- Amplitude: The maximum displacement of a wave from its equilibrium position.
- Wavelength, λ: The distance between two consecutive crests (or troughs) in a wave, measured in metres (m).
- Frequency, f: The number of oscillations a wave makes in one second, measured in hertz (Hz).
- Wave speed, v: The speed at which a wave travels through a medium, measured in metres per second (m s^{-1}).

Student view

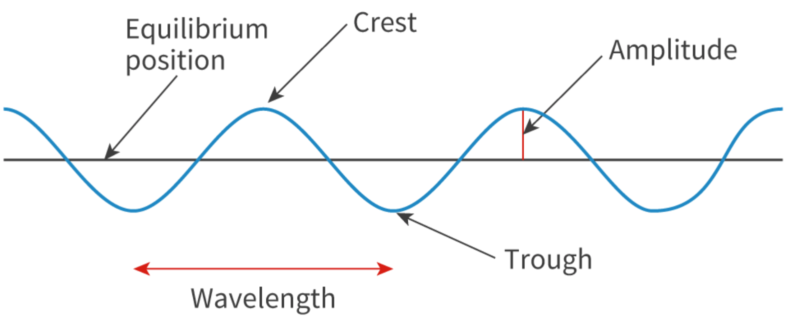

Figure 2. The properties of a wave.

More information for figure 2

The diagram illustrates the properties of a wave. It features a sinusoidal wave with labels indicating key parts and measurements. The wave's central line is marked as the "Equilibrium position." Above this line is the "Crest," the highest point of the wave. Below the line is the "Trough," the lowest point. The horizontal distance between two successive crests or troughs is labeled "Wavelength," indicated by a double-headed arrow. Additionally, the vertical distance from the equilibrium position to the crest is labeled "Amplitude." Each of these labels is connected to the corresponding part of the wave by arrows, providing a clear layout of the wave's structure and its properties.

[Generated by AI]

Superposition of waves

Wave pulses are short-duration, single oscillations. When two wave pulses, travelling in opposite directions through a medium, pass through each other, their displacements add together at every point in space to produce a combined wave pulse. This is called superposition. After their interaction, the waves pulses continue to travel on their way.

Use the simulation in **Interactive 1** to investigate the superposition of wave pulses. Use the sliders to change the height (amplitude) of the pulses and the width (wavelength) of the pulses. Consider the following questions:

- What happens when the wave pulses meet?
- Would you describe the wave pulses as passing through each other or bouncing off each other?
- What happens when a trough exactly overlaps (superposes) a crest of the same amplitude and pulse width? (Tip: Use slow motion by adjusting the Animation Speed slider.)
- What happens when a crest meets a crest of the same amplitude and pulse width?
- What can you do deduce about the amplitude at the moment of overlap?

Overview
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Interactive 1. Superposition of wave pulses simulation.

Credit: Tom Walsh

More information for interactive 1

The interactive simulation titled, Superposition of wave pulses simulation, illustrates the superposition of wave pulses, allowing users to manipulate various parameters and observe how waves interact. It features two wave pulses traveling towards each other, with controls to adjust their heights (amplitudes) and widths (wavelengths). The pulses can be displayed individually, helping users visualize their contributions to the overall wave behavior.

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A time control slider allows users to step through different moments of the interaction. The animation speed slider provides the option to slow down or speed up the motion, making it easier to observe the details of the interaction. When the pulses meet, their amplitudes combine according to the principle of superposition. Users can investigate how the pulses either constructively or destructively interfere. If two crests or two troughs overlap, the resultant wave has a higher amplitude. If a crest and a trough of the same amplitude and width meet, they cancel each other out, creating a momentary flat wave.

After the pulses pass through each other, they continue moving in their original directions, maintaining their shapes. This illustrates that wave pulses do not bounce off one another but pass through unchanged after interaction. The simulation encourages the exploration of different amplitude and width settings to analyze varying levels of constructive and destructive interference.

By adjusting the parameters and observing the interactions, users can develop an understanding of fundamental wave behavior. Through these observations, the simulation demonstrates key wave phenomena, such as interference and amplitude summation, reinforcing concepts in wave physics.

Student view

Overview
(/study/app/math-aa-hl/sid-423-cid-762593/c

The superposition of travelling waves works in the same way. When two (or more) waves superpose, they can interfere.

International Mindedness

Lasers (Light Amplification by Stimulated Emission of Radiation) use the principles of wave interference and diffraction to produce light that is coherent (the waves are in phase) and monochromatic (has a single wavelength). This technology has revolutionised various fields all over the world, including medicine (laser surgery), telecommunications (fibre optics), manufacturing (laser cutting), and entertainment (laser shows).

Constructive interference

When two waves with amplitude A travel towards each other, they superimpose, giving rise to a resultant wave with amplitude $2A$, as shown in **Figure 3**. The two waves will then emerge unchanged on the other side. This is known as constructive interference, and it happens when the amplitude of the resultant wave is greater than the amplitude of any of the individual waves.

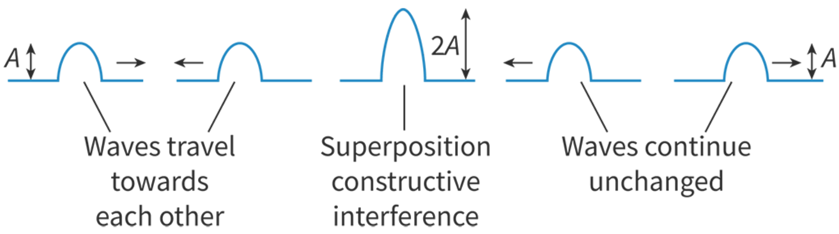


Figure 3. Constructive interference.

More information for figure 3

The image is a diagram illustrating the concept of constructive interference. It shows two waves moving towards each other. As they intersect, a resultant wave with a larger amplitude than either of the individual waves is formed. The two original waves are depicted in blue and are identical in shape and size, mirroring each other around a central axis. The resultant wave is shown in black and is the sum of the amplitudes of the two blue waves. After the point of intersection, the waves continue unchanged. This visually represents how constructive interference increases the amplitude of the waves temporarily during their intersection.

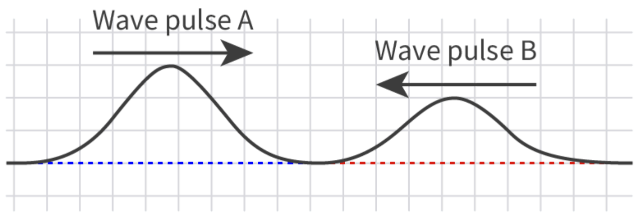
[Generated by AI]

Student view

To determine the displacement of the resultant wave, we add together the displacements of the individual waves.

Worked example 1

Two waves pulses are travelling through a medium in opposite directions and interfere constructively. The wave pulses are in phase and have the same wavelength of 4 cm. The amplitude of wave pulse A is 3 cm and the amplitude of wave pulse B is 2 cm.



More information

The diagram depicts two wave pulses traveling through a medium in opposite directions, labeled as Wave pulse A and Wave pulse B. Wave pulse A is moving towards the right, while Wave pulse B is moving towards the left. Both wave pulses are shown on a grid and are in phase, indicating constructive interference. Wave pulse A has a larger amplitude of 3 cm, while wave pulse B has an amplitude of 2 cm. Their wavelengths are the same, measuring 4 cm each. The diagram visually represents the interference, with the resultant wave expected to have a combined amplitude greater than the individual pulses.

[Generated by AI]

Determine the wavelength and amplitude of the resultant wave pulse.

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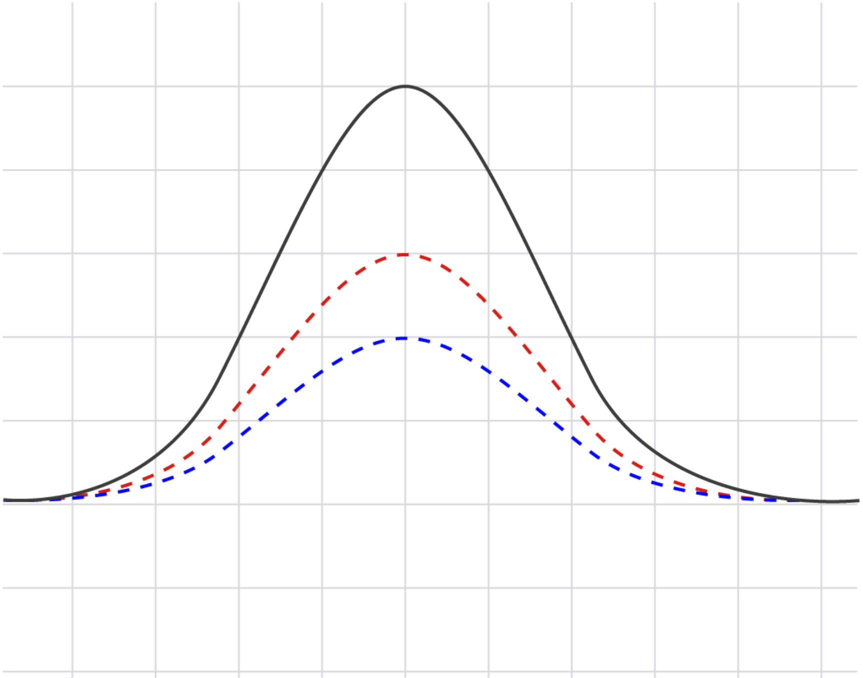

Wave pulse A and wave pulse B have the same wavelength, so the wavelength of the resultant wave pulse will be 4 cm.

amplitude of resultant wave pulse = amplitude of wave pulse A + amplitude of wave pulse B

= 3 + 2

= 5 cm (1 s.f.)

Destructive interference

In destructive interference, the crest of one wave meets the trough of another wave – in this case, the waves are said to be in antiphase (**Figure 4**). This results in a wave with a reduced (if the amplitudes are different) or zero amplitude (if the amplitudes are the same).

For example, when two waves with amplitude A travel towards each other and the crest of one wave meets the trough of the other wave, the resultant wave has zero amplitude, as shown in **Figure 4**. The two waves will then emerge unchanged on the other side.

Student
view

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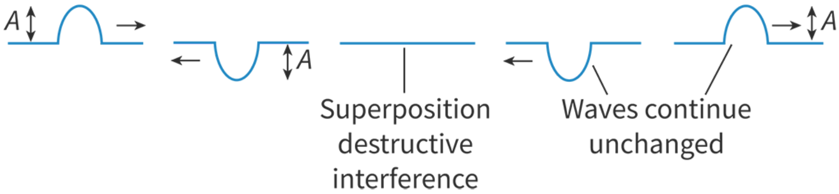

Figure 4. Destructive interference.

More information for figure 4

The image illustrates a destructive interference scenario involving two waves. The first wave is shown traveling from left to right with a certain amplitude, and the second wave travels from right to left. When the crest of the first wave coincides with the trough of the second wave, the result is a wave with zero amplitude, visually depicted as a flat line in the middle of the image. After this interference, both waves continue to travel unchanged in their respective directions post-interference, as indicated by the continuation of their wave patterns beyond the intersection point.

[Generated by AI]

To determine the displacement of the resultant wave, we subtract the displacements of the individual waves.

Path difference

The path difference between two waves is the difference in distance travelled by one wave compared to the other wave. It is measured in terms of wavelength.

In **Figure 5**, two waves are emitted by each of the two sources, S_1 and S_2. The waves have the same frequency, the same amplitude and are in phase when emitted by the sources. The waves meet at point P_1 in antiphase (i.e. a crest meets a trough), so destructive interference happens, and the resultant wave has zero amplitude. Looking at the blue wave, we can express the distance between S_2 and P_1 in terms of number of wavelengths: $S_2P_1 = 6.5\lambda$. We can do the same thing for the distance between S_1 and P_1, now looking at the purple wave: $S_1P_1 = 6\lambda$. The path difference between the two waves at P_1 is:

$$\text{Path difference at } P_1 = S_2P_1 - S_1P_1 = 6.5\lambda - 6\lambda = 0.5\lambda = \frac{\lambda}{2}.$$

The waves meet at point P_2 in phase (i.e. a trough meets a trough), so constructive interference happens, and the resultant wave has double the amplitude as the individual waves. We can once again look at the distances travelled by the two waves to get to point P_2, and express them in

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terms of number of wavelengths. We get: $S_2P_2 = 6\lambda$ and $S_1P_2 = 7\lambda$. So, the path difference between the two waves at P_2 is:

Path difference at $P_2 = S_1P_2 - S_2P_2 = 7\lambda - 6\lambda = \lambda$.

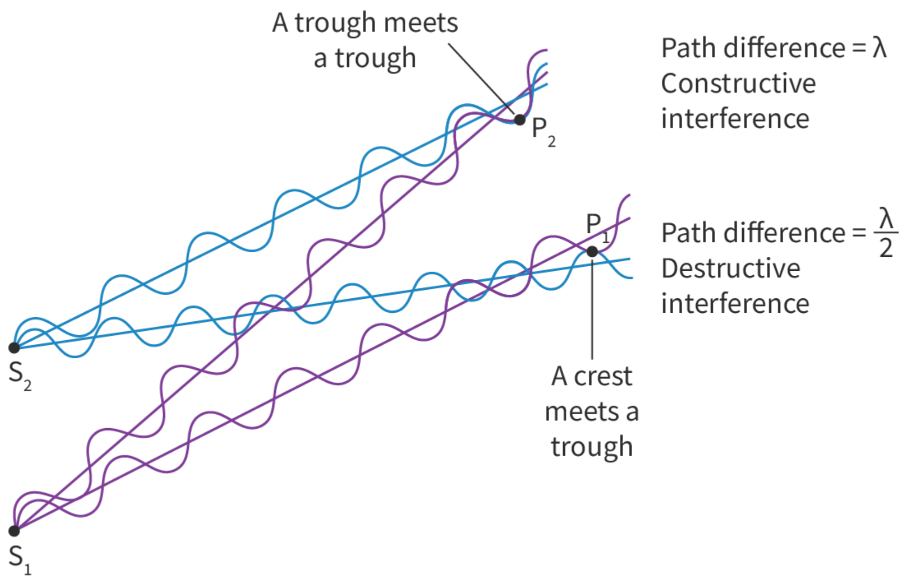

Figure 5. Path difference of waves emitted by two sources.

More information for figure 5

The image is a diagram illustrating the path difference of waves emitted by two sources, labeled as S1 and S2. Two curving lines extend from these sources, indicating the trajectory of waves. The path difference at point P2 between the two paths is calculated as S1P2 minus S2P2, equating to 7λ minus 6λ, resulting in λ. The diagram visually demonstrates constructive interference, where the path difference equals a whole number of wavelengths, causing the crests and troughs of one wave to align with those of another.

[Generated by AI]

Constructive interference occurs when the path difference between two waves is a whole number of wavelengths – the crest (and trough) of one wave meets the crest (and trough) of another wave. The equation for the path difference for constructive interference is shown in **Table 1**.

Table 1. Equation for path difference for constructive interference.

Student view

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Equation	Symbols	Units
path difference = $n\lambda$	n = integer (1, 2, 3...)	no units
	λ = wavelength	metres (m)

Destructive interference occurs when the path difference between the waves is a half-integer multiple of the wavelength. The equation for the path difference for destructive interference is shown in **Table 2**.

Table 2. Equation for path difference for destructive interference.

Equation	Symbols	Units
path difference = $\left(n+\frac{1}{2}\right)\lambda$	n = integer (1, 2, 3...)	unitless
	λ = wavelength	metres (m)

Double-source interference

Double-source interference occurs when two sources produce waves that interfere. **Figure 6** shows two sound speakers producing sound waves. The sound waves interfere to produce an interference pattern. To get the clearest interference pattern, the waves from the two sources need to be coherent. This means that they have the same wavelength (frequency) and have a constant phase difference. An example of a coherent source of light is laser light (e.g. red laser light or blue laser light). As opposed to the light emitted by a filament light bulb, laser light contains light waves of a single frequency, and it is therefore said to be monochromatic (which means 'of one colour').

Student view

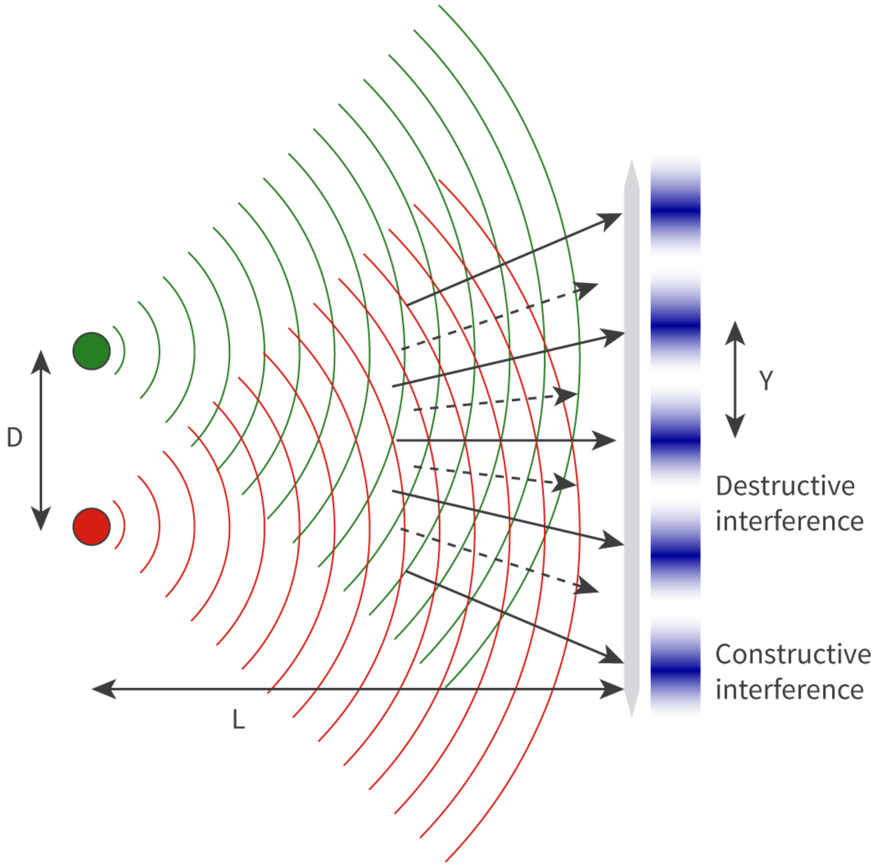

Figure 6. Double-source interference of sound waves.

More information for figure 6

The diagram shows two sound sources located at the left side of the image, each represented by a red and a green circle, emitting sound waves. The waves are depicted as concentric circles expanding outward from each source. To the right, there is a barrier where the waves converge, creating a pattern of interference. Areas of constructive interference are marked as regions where the waves overlap in phase, producing brighter bands, while destructive interference is where the waves are out of phase, shown as darker regions. The distance between the two sources is labeled as 'D', and the horizontal distance to the barrier is labeled as 'L'. Both constructive and destructive interference patterns are labeled on the barrier.

[Generated by AI]

We can see from **Figure 6**, that the two sound waves interfere constructively and destructively at different points. This is because of the path difference at that point between the waves:

- If path difference is $n\lambda$, then the waves interfere constructively.
- If path difference is $\left(n + \frac{1}{2}\right)\lambda$, then the waves interfere destructively.

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For sound waves, constructive interference means the sound gets louder (greater amplitude), and destructive interference means the sound gets quieter (smaller amplitude). This is why if you move around in a movie theatre, the volume of the sound may appear to fluctuate.

Young's double-slit interference

Young's double-slit experiment, conducted by Thomas Young in 1801, provided evidence for the wave nature of light and laid the foundation for our understanding of wave interference.

Theory of Knowledge

In science, realism is the view that well-confirmed scientific theories are true or approximately true. Antirealism is the view that scientific theories are approximately true or not true at all. Light can behave as a wave and as a particle, which can challenge our intuitive understanding of the nature of reality. This raises questions about the nature of scientific knowledge and whether it accurately represents an objective reality, or if it is merely a useful tool for making sense of our experiences.

In the double-slit experiment, a monochromatic coherent light source (such as a laser) emits light waves towards a screen with two narrow slits. When the light waves pass through these slits, they act as two coherent light sources. The light waves interfere, creating an interference pattern on the optical screen. The interference pattern consists of alternating dark and light fringes (bands) (**Figure 7**).

Student view

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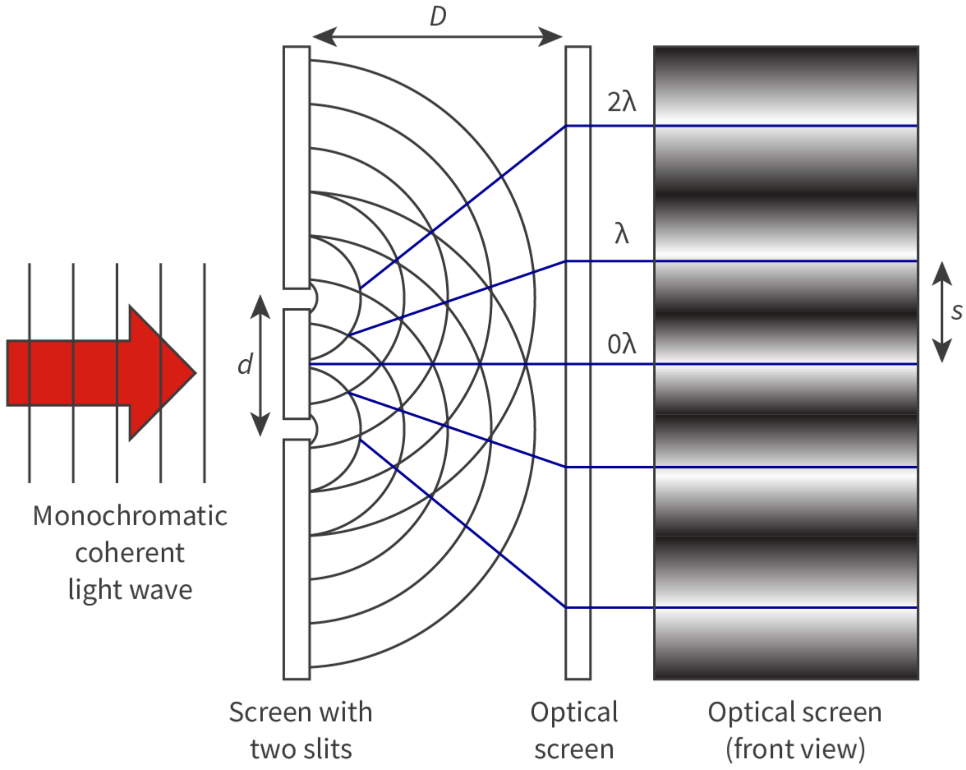

Figure 7. Young's double-slit interference pattern.

More information for figure 7

This diagram illustrates Young's double-slit experiment. On the left, a monochromatic coherent light wave is shown approaching a barrier with two narrow slits. The slits are labeled 'd' and serve as the initial points from which the light waves emanate. Lines indicate the wavefronts of light emerging from the slits, spreading outwards and overlapping. Five key lines are drawn extending from the slits to the right, marked with spacing: 0λ, λ, and 2λ, indicating wave interference distances. To the right of the barrier, an optical screen displays the interference pattern with alternating light and dark fringes. These fringes are depicted as horizontal bands parallel to the slits. The dark and light bands represent the interference maxima and minima.

[Generated by AI]

The light fringes (maxima) are where the light waves interfere constructively and the dark fringes (minima) are where the light waves interfere destructively.

Figure 8 shows the path difference between the light waves at the first bright fringe (path difference = λ).

Student view

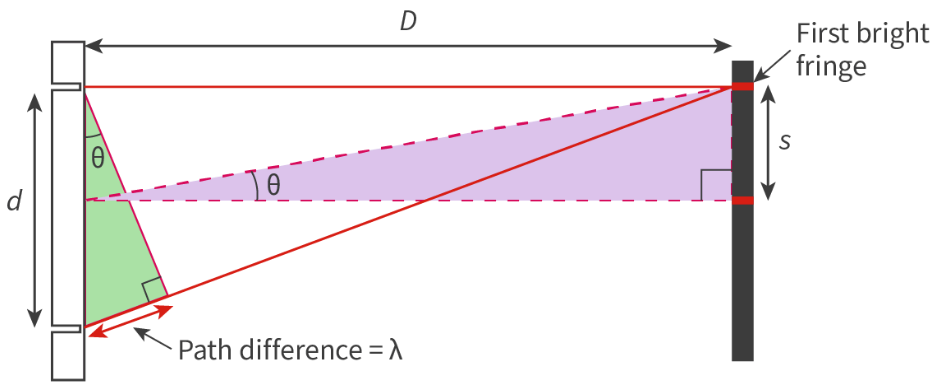

Figure 8. Two-slit interference showing path difference.

More information for figure 8

The image illustrates a two-slit interference pattern with the path difference labeled. On the left side, two slits are shown with a separation labeled 'd'. Light waves emerge from these slits and meet at a point on the screen labeled as the 'First bright fringe' on the right, creating an interference pattern. The path difference, indicated as (λ), represents the extra distance one wave travels relative to the other. Angles (θ) are marked next to the paths, illustrating the divergence from the perpendicular path to the slits. Several arrows indicate distances and angles, with annotations on the paths, highlighting elements essential to understanding the interference pattern such as path length differences and light deflection angles.

[Generated by AI]

The separation of fringes (distance between two light fringes or two dark fringes) can be determined using the equation in **Table 3**.

Table 3. Equation for separation of fringes.

Equation	Symbols	Units
$s = \frac{\lambda D}{d}$	s = separation of fringes	metres (m)
	λ = wavelength	metres (m)
	D = distance from slits to screen	metres (m)
	d = separation of slits	metres (m)

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Worked example 2

In a double-slit experiment, the distance between the two slits is 0.50 mm, and the distance between the screen and the slits is 1.5 m. The separation of the fringes is 1.8 mm. Determine the wavelength of the light source.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation	$d = 0.50\text{ mm} = 0.0005\text{ m}$ $D = 1.5\text{ m}$ $s = 1.8\text{ mm} = 0.0018\text{ m}$
Step 2: Write out the equation and rearrange to find λ	$s = \frac{\lambda D}{d} \lambda = \frac{sd}{D}$
Step 3: Substitute the values given	$= \frac{(0.0018\times0.0005)}{1.5}$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding	$= 6.0\times10^{-7}\text{ m }(2\text{ s.f.})$

Work through the activity to check your understanding of interference of waves.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 15 minutes
- **Activity type:** Pair activity

You are going to use the simulation in **Interactive 2** to investigate Young's double-slit interference of light waves.

Student view

Interactive 2. Investigate Young's Double-Slit Interference of Light Waves.

More information for interactive 2

This interactive simulation is designed to explore the phenomenon of wave interference, with a particular focus on Young's double-slit experiment, which demonstrates the wave nature of light. In this simulation, users can manipulate the properties of waves such as frequency, amplitude, and wavelength to observe how waves interact and form interference patterns. The simulation illustrates how both constructive and destructive interference occurs. Constructive interference happens when waves are in phase, resulting in the waves combining to form a larger wave. Destructive interference occurs when waves are out-of-phase, leading to cancellation and areas of no wave displacement.

Users can adjust the amplitude, frequency, and wavelength of the waves using sliders. These changes directly influence the resulting interference patterns. The simulation provides an opportunity to experiment with both single-source and multiple-source interference. When the waves are in phase, constructive interference amplifies the waves. When the waves are out of phase, destructive interference results in cancellation.

The focus of the simulation is on Young's double-slit interference, where light waves pass through two slits and create an interference pattern on a screen. Users can adjust the slit width and slit separation to observe how these factors influence the pattern. The frequency slider alters the frequency of the waves, and the distance between the slits and the screen can be changed to see how it affects the fringe separation. The resulting interference pattern consists of alternating bright fringes (constructive interference) and dark fringes (destructive interference), demonstrating the core principles of interference in wave phenomena.

In the simulation, users can observe wave displacement across a grid. Areas of high displacement correspond to constructive interference, while areas of low or no displacement correspond to destructive interference. Clicking on different points in the grid helps users see how waves interact at

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specific locations, visually demonstrating how interference occurs at various points in space.

This simulation also includes accessibility features, such as keyboard navigation and alternative text for visual elements, ensuring compatibility with screen readers. For users who need an alternative experience, a text-based description of the interference patterns and key observations is available. Additionally, a downloadable dataset is provided for further analysis of the wave interactions.

Through this interactive, students will learn how Young's double-slit experiment provides evidence for the wave nature of light. They will explore the conditions for constructive interference and destructive interference and understand how to calculate the path difference between two waves. The simulation demonstrates the importance of coherent sources in producing clear interference patterns. By adjusting the slit width and slit separation, users can observe firsthand how these factors influence the interference pattern.

By experimenting with different wave properties and analyzing the resulting interference patterns, students will gain a deeper understanding of how waves behave and interact. The simulation reinforces key physics concepts, such as the nature of coherent sources, the conditions required for constructive and destructive interference, and how wave properties like wavelength and frequency affect the resulting interference patterns.

1. Select the 'Slits' tab. Select 'Light Generator' (i.e. the laser picture on the right). Select 'Two Slits' in the drop-down menu. Select 'Screen' and 'Intensity'. The 'Frequency' slider should be in the middle of green.
2. Click the green button to start the simulation. Look at the interference pattern formed on the screen. Identify the regions of constructive interference and destructive interference.
3. Use the 'Slit Width' and 'Slit Separation' sliders to change the width of the slits and the distance between the slits. Use the green double arrow slider to change the distance between the slits and the screen. How does changing each variable affect the interference pattern?

5 section questions

Question 1

SL HL Difficulty:

Two waves, each with a wavelength of 4 cm, are travelling in opposite directions through a medium. The path difference between the two waves is 6 cm. Determine whether the waves will undergo constructive or destructive interference.

The waves will undergo 1 destructive ✓ interference.

Accepted answers and explanation

#1 destructive

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view

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General explanation

To determine whether the waves will undergo constructive or destructive interference, compare the path difference with the wavelength of the waves. The path difference is 6 cm and the wavelength is 4 cm.

6 cm = 1.5 × 4 cm, which is a half-integer multiple of the wavelength

Therefore, the waves undergo destructive interference.

Question 2

SL HL Difficulty:

Constructive interference occurs when two waves are 1 in ✓ phase and the crest of one wave meets the 2 crest ✓ of another wave, resulting in a wave with a greater amplitude.

Destructive interference occurs when two waves are 3 out of ✓ phase and the crest of one wave meets the 4 trough ✓ of another wave, resulting in a wave with a smaller or zero amplitude.

Accepted answers and explanation

#1 in

#2 crest

#3 out of

#4 trough

General explanation

Constructive interference occurs when two waves are in phase and the crest of one wave meets the crest of another wave, resulting in a wave with a greater amplitude.

Destructive interference occurs when two waves are out phase and the crest of one wave meets the trough of another wave, resulting in a wave with a smaller or zero amplitude.

Question 3

SL HL Difficulty:

Red laser light of wavelength 650 nm is shone through two slits. The separation of the slits is 0.20 mm. The distance between the slits and the screen is 1.2 m. Determine the separation of the bright fringes. Give your answer to an appropriate number of significant figures.

The separation of the bright fringes is 1 3.9 ✓ mm

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Accepted answers and explanation

#1 3.9
4

General explanation

$$\lambda = 650 \text{ nm} = 6.5\times10^{-7} \text{ m}$$

$$d = 0.2 \text{ mm} = 0.0002 \text{ m}$$

$$D = 1.2 \text{ m}$$

$$s = \frac{\lambda D}{d}$$

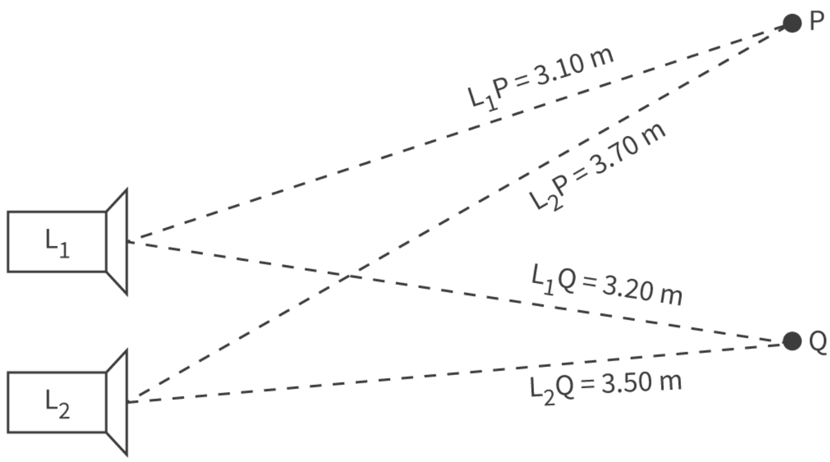
$$= \frac{(6.5\times10^{-7}\times1.2)}{0.0002}$$

$$= 3.9\times10^{-3} \text{ m} = 3.9 \text{ mm (2 sf)}$$

Question 4

SL HL Difficulty:

Two loudspeakers, L_1 and L_2, produce coherent sound waves. The wavelength of the sound is 0.60 m. The waves interfere and are observed at points P and Q.



More information

Which row of the table shows the intensity of the sound at P and the intensity of the sound at Q?

	Intensity at P	Intensity at Q
A	Maximum	Maximum
B	Maximum	Minimum

Student view

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	Intensity at P	Intensity at Q
C	Minimum	Maximum
D	Minimum	Minimum

1 B ✓

2 A

3 C

4 D

Explanation

To determine whether the intensity is a maximum or a minimum, determine the path difference:

path difference at point P = 3.70 — 3.10 = 0.60 m

path difference at point Q = 3.50 — 3.20 = 0.30 m

Compare the path difference to the wavelength (λ = 0.60 m):

point P: 0.60 = 1 × λ

point Q: 0.30 = ½ × λ

The waves constructively interfere at point P, so it is maximum intensity.

The waves destructively interfere at point Q, so it is minimum intensity

Question 5

SL HL Difficulty:

Wave generators placed at position P and position Q produce water waves of wavelength 4 m. Each generator produces a wave with an amplitude of 2 m at position R. Distances PR and QR are shown in the diagram.

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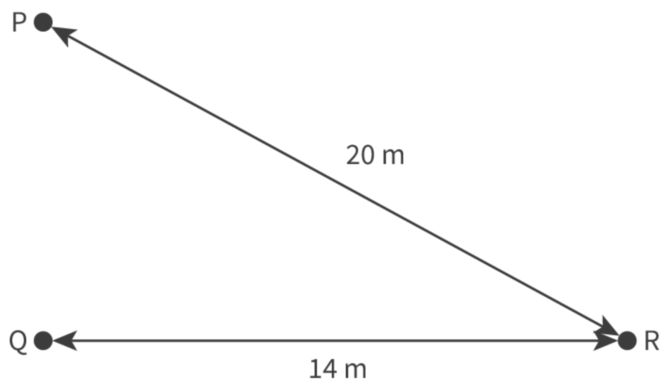

More information

Both wave generators now operate together in phase. Determine the amplitude of the resulting wave at R. Give your answer to an appropriate number of significant figures.

The amplitude of the resulting wave is 1 0 m.

Accepted answers and explanation

#1 0

General explanation

The path difference between the waves generated from P and Q at position R is the absolute difference between PR and QR:

$$\text{path difference at R} = 20 - 14 = 6$$

As $\lambda = 4\text{ m}$,

$$\frac{\text{path difference}}{\lambda} = \frac{6}{4} = 1.5$$

This means that the waves undergo destructive interference at R.

Each wave generator produces a wave with an amplitude of 2 m at position R, so:

$$\begin{aligned}\text{amplitude of resulting wave} &= \text{amplitude of P wave} - \text{amplitude of Q wave}\\ &= 2 - 2\\ &= 0\text{ m (1 s.f.)}\end{aligned}$$

C. Wave behaviour / C.3 Wave phenomena

Single and multi-slit diffraction (HL)

Student view

C.3.12: Single-slit diffraction (HL) C.3.13: Single-slit pattern modulation of double slit interference pattern (HL)
C.3.14: Interference patterns from multiple slits and diffraction gratings (HL)

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Higher level (HL)

Learning outcomes

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

- Understand single slit diffraction and use the equation:

$$\theta = \frac{\lambda}{b}$$

- Describe how the double-slit interference pattern is modulated by the single slit interference pattern.
- Understand the interference patterns produced by multiple slits and diffraction gratings and use the equation:

$$n\lambda = d\sin\theta$$

Single-slit diffraction

When monochromatic coherent light waves pass through a single narrow slit, the waves diffract and interfere, forming a pattern. **Figure 1** shows the difference between a single-slit interference pattern and a double-slit interference pattern (see section C.3.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/superposition-of-waves-and-young's-double-slit-interference-id-46613/)).

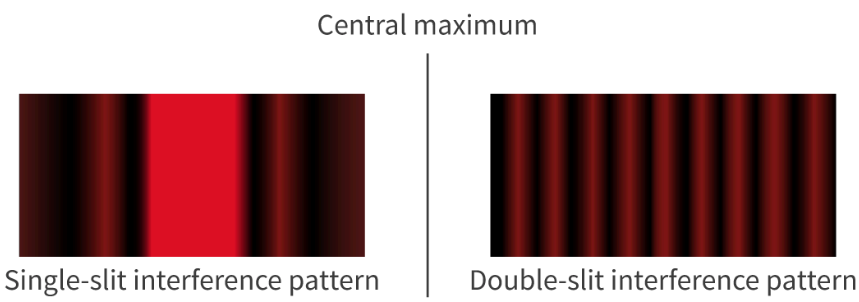

Figure 1. Single-slit and double-slit diffraction patterns.

More information for figure 1

The image depicts two types of light interference patterns: single-slit and double-slit. On the left, the single-slit interference pattern shows a prominent central bright region, known as the central maximum, flanked by several dimmer, smaller fringes. These fringe patterns represent the areas of constructive and destructive interference created by waves passing through a single slit. On the right, the double-slit interference pattern exhibits a series of closely spaced, evenly bright and dark fringes. This pattern is due to the constructive and

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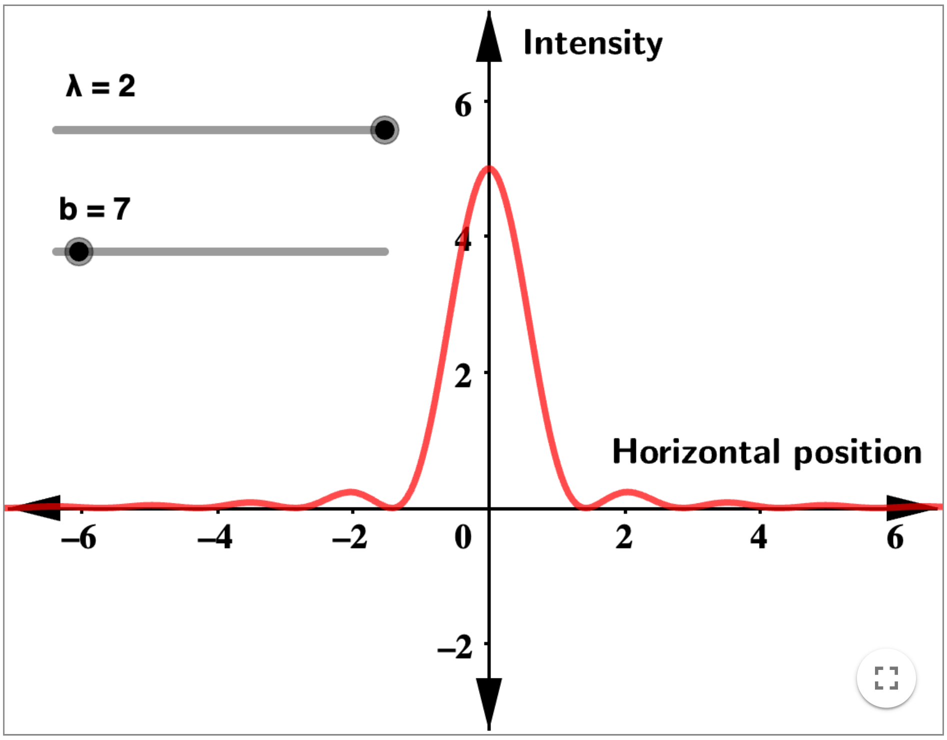
destructive interference resulting from light passing through two slits, creating more frequent interference points compared to the single-slit setup. The image visually highlights the difference in fringe spacing and brightness between the two interference types.

[Generated by AI]

We can see from **Figure 1**, that a single-slit interference pattern has a central bright fringe (central maximum), with smaller, dimmer fringes on either side. The bright fringes are due to constructive interference and the dark fringes are due to destructive interference (see section C.2.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/sound-waves-and-electromagnetic-waves-id-44907/)).

The intensity of light is greatest in the central maximum and decreases with each successive maximum. Use the simulation in **Interactive 1** to investigate light intensity in single-slit diffraction. Use the sliders to change the wavelength, λ, and slit width, b. What happens to the intensity pattern (and the width of the central maximum)?



Interactive 1. Single-slit diffraction simulation.

More information for interactive 1

The interactive titled "Single-Slit Diffraction Simulation" allows users to explore how monochromatic light behaves when passing through slits of varying widths, revealing the resulting diffraction patterns. As light passes through a narrow slit, it diffracts and forms a series of bright and dark fringes. The central bright fringe, or central maximum, is the brightest and is surrounded by progressively dimmer fringes. The intensity of light is highest at the center and diminishes with each successive maximum. The simulation provides users with the ability to adjust the wavelength of the light and the slit width, offering valuable insight into how these factors

Student view

influence the diffraction pattern.

The graph in the simulation represents light intensity as a function of the angle at which the diffracted light reaches the screen. The x-axis represents the angle of diffraction, measured in radians or degrees, showing the angle between the central maximum and the other diffraction maxima (bright fringes). The y-axis represents light intensity, indicating how the intensity changes as the angle increases. The wavelength slider on the top left allows the users to toggle the wavelength (λ) of the light used for the single slit diffraction and the slit width slider below the wavelength slider allows the user to adjust the width (b) of the slits used for the single slit diffraction.

For single-slit diffraction, increasing the slit width results in a narrower central maximum and closer fringes. Decreasing the slit width makes the diffraction effects stronger, causing the central maximum to widen. Increasing the wavelength leads to a more spread-out diffraction pattern, while decreasing it makes fringes more closely packed. The intensity decreases for each successive maximum, with the first bright fringe being much dimmer than the central maximum.

For instance, when using a wavelength of 500 nm (visible light) and a slit width of 0.4 mm, the simulation helps calculate the angle at which the first dark fringe (minimum) occurs. The angle between the central maximum and the first dark fringe can be calculated using the equation $b\sin(\theta) = m\lambda$, where b is the slit width, θ is the angle, m is the order of the minimum, and λ is the wavelength of light.

The simulation effectively visualizes the wave nature of light and demonstrates how single-slit diffraction produces characteristic interference patterns. It allows users to manipulate key parameters, providing insight into how slit width and wavelength affect diffraction.

Study skills

In a single-slit interference pattern, the central maximum has an angular width that is twice as wide as the other bright fringes. In a double-slit interference pattern, the bright fringes have equal width.

Figure 2 shows how the single-slit interference pattern is produced. It shows the light ray for a wave travelling from the top of a slit of width b, and the ray for a wave travelling from the middle of the same slit. The top ray travels a shorter distance to the screen compared to the middle ray, so there is a path difference between the two waves. These two waves form the first dark fringe (i.e. the first minimum on either side of the central bright fringe shown in **Figure 1**) when they interfere destructively, hence when their path difference x is:

$$x = \frac{\lambda}{2}$$

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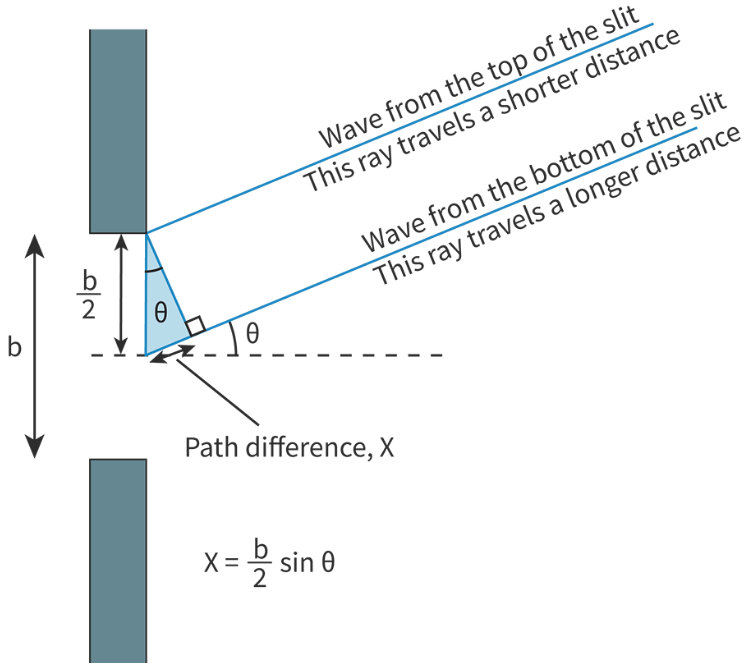

Figure 2. Path difference in single slit interference.

More information for figure 2

The diagram illustrates the concept of path difference in a single slit interference setup. It includes a central slit where light waves pass through. On the left side is the starting point, labeled with an angle θ, formed between the horizontal axis and the line representing one of the wavefronts. The light waves are depicted as lines propagating outward from the slit. The path difference is shown as the difference in distance between the two wavefronts at the slit, noted as 'x = λ/2'. This path difference is a crucial aspect of understanding interference patterns, where 'b' is the slit width and 'θ' is the angle of diffraction. The components relate to the calculation of path difference using trigonometry, as indicated by the surrounding text instructions.

[Generated by AI]

From the diagram in **Figure 2**, we can see that, using trigonometry, the path difference x can be expressed in terms of the slit width b and the angle θ as follows:

$$x = \frac{b}{2}\sin\theta$$

Equating the two expressions for the path difference, we get:

$$\frac{\lambda}{2} = \frac{b}{2}\sin\theta$$

The distance between the slit and the screen is several orders of magnitudes larger than the slit width, which means that the angle θ is very small. We can therefore use the small angle approximation $\sin\theta \sim \theta$, and we can also multiply both sides of the equation by 2, so the last equation becomes:

$$\lambda = b\theta$$

Student view

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So, the angle between the central maximum and the first dark fringe (minimum) can be calculated as shown in **Table 1**.

Table 1. Equation for angle between central maximum and first dark fringe.

Equation	Symbols	Units
$\theta = \frac{\lambda}{b}$	θ = angle between central maximum and first dark fringe	radians (rad)
	λ = wavelength	metres (m)
	b = width of slit	metres (m)

You can see from the equation that the larger the slit width, the smaller the angle between the central maximum and the first dark fringe:

- The larger the slit width, the narrower the width of the central maximum and the greater the intensity of the central maximum.
- The smaller the slit width, the greater the width of the central maximum and the lower the intensity of the central maximum.

Note that in Interactive 1, the y-axis is normalised and given as an arbitrary value, meaning it will always show the same maximum intensity. In other sources, you might see it as I / I_0 or just labelled as 1.

Study skills

The θ in the single slit equation refers to the angle from the central maximum to the first dark fringe, not the separation between consecutive light or dark fringes as in Young's double-slit interference.

Worked example 1

A student shines laser light through a single slit to observe the interference pattern using a spectrometer. The angle between the central maximum and the first dark fringe is 0.0025 rad. The width of the slit is 0.4 mm. Determine the wavelength of the laser light.

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Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation	$\theta = 0.0025 \text{ rad}$ $b = 0.4 \text{ mm} = 0.0004 \text{ m}$
Step 2: Write out the equation and rearrange to find λ	$\theta = \frac{\lambda}{b}$ $\lambda = \theta b$
Step 3: Substitute the values given	$= 0.0025 \times 0.00004$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding	$= 1 \times 10^{-6} \text{ m (1 sf)}$

Figure 3 shows the pattern of light intensity for single-slit diffraction and double-slit diffraction.

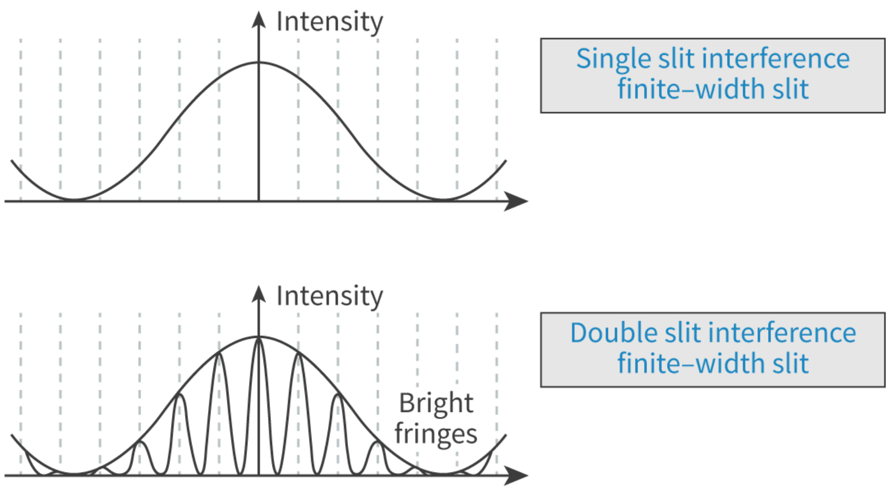

Figure 3. Light intensity patterns for single-slit and double-slit interference.

More information for figure 3

The image shows two graphs comparing light intensity patterns for single-slit and double-slit interference.

In the top graph, labeled 'Single slit interference,' there is a smooth, bell-shaped curve representing the intensity distribution for a single-slit with a finite width. The curve peaks at the center, showing a single central maximum.

Student view

In the bottom graph, labeled 'Double slit interference,' the pattern shows multiple peaks and troughs, indicating a series of bright and dark fringes. This graph also features a central maximum similar to the single-slit graph, but with additional maxima and minima across the spectrum, demonstrating the interference pattern from two slits. The term 'Bright fringes' appears beside the peaks, indicating areas of constructive interference where the intensity is higher.

[Generated by AI]

Comparing the images above you can observe a highly intense central maximum, less intense secondary maxima, and the same position for these maxima. However, there are also additional maxima and minima within the original pattern.

In double-slit diffraction, the pattern created by the double slits overlaps the patterns of each single slit (**Figure 4**). This is known as modulation.

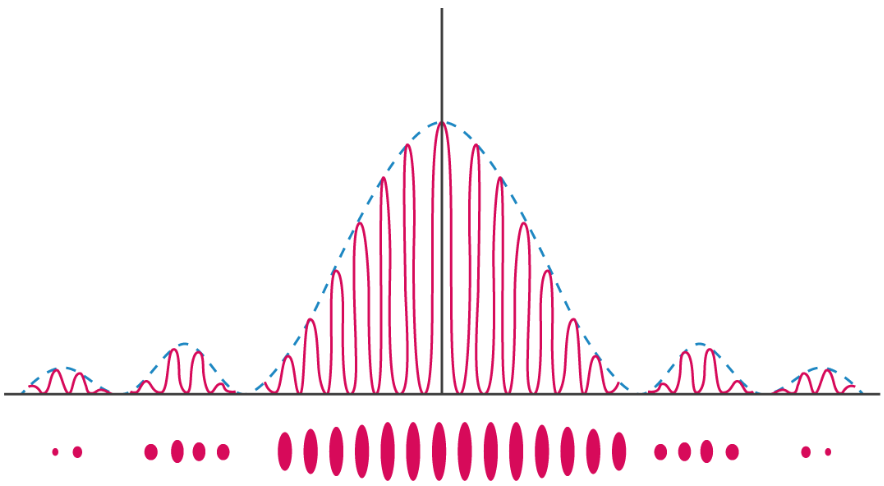

Figure 4. The double-slit intensity pattern is modulated by the single-slit intensity pattern.

More information for figure 4

The image is a graph depicting a modulated double-slit diffraction intensity pattern. The horizontal axis represents the position along the observation screen, while the vertical axis measures the light intensity. Superimposed on the graph are two sets of wave patterns. The blue dashed line represents the single-slit diffraction envelope, exhibiting a broad central peak with diminishing intensity towards the edges. The red solid line represents the detailed double-slit interference pattern, showing multiple smaller peaks within the envelope, indicating constructive and destructive interference points. The overall shape is modulated, with the amplitude of the smaller peaks falling under the single-slit pattern. This visualization illustrates how the interference pattern from two slits is convolved with the intensity distribution of a single slit.

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Multiple-slit and diffraction grating interference

When monochromatic light passes through several equally spaced slits, the interference patterns produced by each slit combine to form a more complex interference pattern. **Figure 5** shows the intensity profiles corresponding diffraction through a single slit, a double slit, three slits and five slits.

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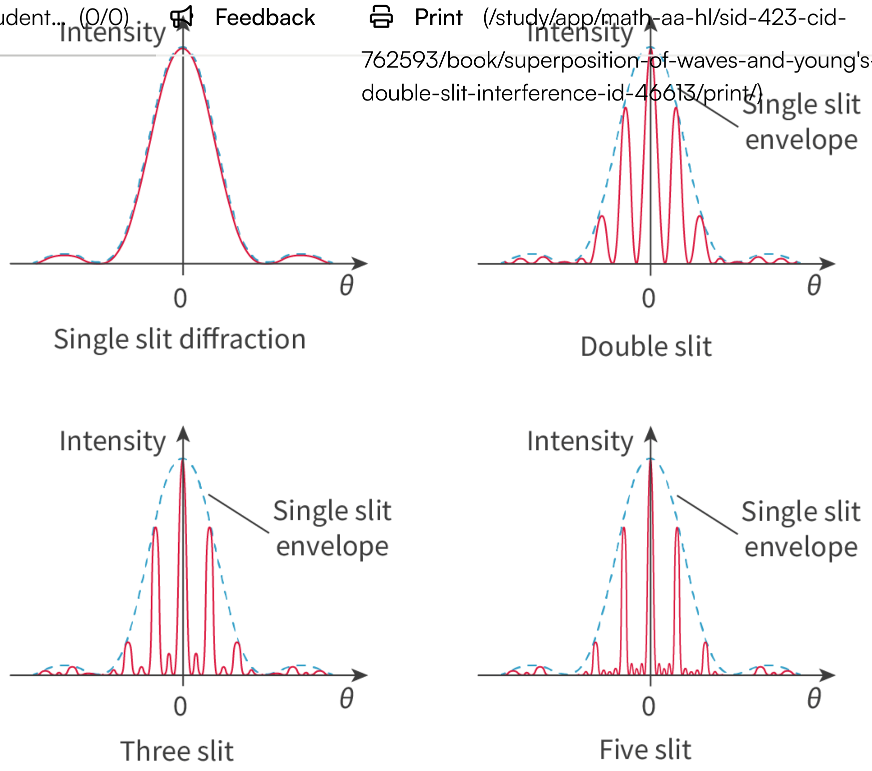

Figure 5. Diffraction through a single slit, double slit, three slits and five slits.

More information for figure 5

The image consists of four separate graphs showing the diffraction patterns for light passing through different numbers of slits: single, double, three, and five. Each graph plots Intensity (y-axis) against angle θ (x-axis).

1. **Single Slit Diffraction**: This graph shows a broad central peak with diminishing side peaks. The intensity profile forms a wide triangle centered at angle 0, representing the single-slit diffraction pattern.
2. **Double Slit**: This graph has the same broad envelope of the single slit but with smaller, closely spaced oscillations within the larger central peak, representing the interference pattern due to two slits.
3. **Three Slit**: The pattern becomes more complex, with multiple small peaks within the single-slit envelope. This indicates increased interference effects due to the additional slit.
4. **Five Slit**: The interference pattern is even more intricate, with many small peaks. The main envelope still resembles that of the single slit, but with far more detailed oscillations inside.

In all graphs, the baseline is marked at 0 degrees, and the intensity decreases symmetrically in either direction, with the phenomenon becoming visually complex as the number of slits increases.

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The pattern becomes more intricate as the number of slits increases. For a double-slit, the interference pattern is a series of modulated peaks within the envelope of the single slit diffraction pattern.

Three slits create a fourth-order maximum, and the distance between the first and last maximum becomes slightly greater.

Even though the maximum is still at the same place, close to the maximum the additional distance travelled by the light from the more distant slit causes destructive interference to occur closer to the maximum. Therefore, the maxima remain in the same place, but they become narrower. Furthermore, because there are more slits, there is more light incident on the screen, which increases the intensity of the peaks. This pattern continues as the number of slits increases, which results in narrower maxima and small secondary maxima modulations appearing between them.

The relationship between intensity and amplitude of a wave is given by the equation:

$$I \propto A^2$$

This means that the intensity of a wave is proportional to the square of its amplitude. So, if the amplitude of a wave is tripled (as in the case of three coherent sources adding together), the intensity of the resulting wave would be nine times greater ($3^2 = 9$).

This is why, in a multi-slit interference setup, the intensity of the central maximum (where constructive interference is at its peak) increases dramatically with the number of slits. Each additional slit contributes to the amplitude of the wave at that point, and thus the intensity increases with the square of the number of slits. In **Figure 5**, the graphs have been drawn with the same intensity to illustrate the differences in the profiles. However, if the diagrams were to scale, the intensity of the five-slit profile would actually be 25 times higher than the single-slit intensity.

The equation for multiple-slit diffraction is given in **Table 2**.

Table 2. Equation for multiple-slit diffraction.

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Equation	Symbols	Units
$n\lambda = d\sin\theta$	n = order of maxima (1, 2, 3, etc.)	Unitless
	λ = wavelength	metres (m)
	θ = angle between maxima and normal	degrees (°) or radians (rad)
	d = distance between slits	m metres (m)

A diffraction grating has a large number of equally spaced slits, with the widths of the slits considered negligible.

Study skills

Diffraction gratings often quote '1000 lines per mm'. To use this information in the equation above, you need to convert this data into the distance between the slits:

$$d = \frac{1\ \text{(line)}}{1000\ \text{(lines/mm)}} = 1 \times 10^{-3}\ \text{mm} = 1 \times 10^{-6}\ \text{m}$$

Worked example 2

Laser light of wavelength 450 nm is incident on a diffraction grating with 1000 lines per mm. Determine the angle to the normal that the second order maximum is detected. Give your answer to two significant figures.

Solution steps	Calculations
Step 1: Write out the values given in the question and convert the values to the units required for the equation	$\lambda = 450\ \text{nm} = 4.5\times10^{-7}\ \text{m}$ $n = 2$ $d = \frac{1}{1000} = 1.0\times10^{-6}\ \text{m}$
Step 2: Write out the equation and rearrange to find sin θ	$n\lambda = d\sin\theta$ $\sin\theta = \frac{n\lambda}{d}$

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Solution steps	Calculations
Step 3: Substitute the values given	$= \frac{(2\times4.5\times10^{-7})}{1.0\times10^{-6}}$
Step 4: State the answer with appropriate units and the number of significant figures used in rounding	$\theta = 64.16^{\circ} = 64^{\circ}(2\text{ s. f. })$

The interference pattern from a diffraction grating is much more defined and precise than the interference pattern from a smaller number of slits. **Figure 6** shows the diffraction grating interference pattern for monochromatic light and white light.

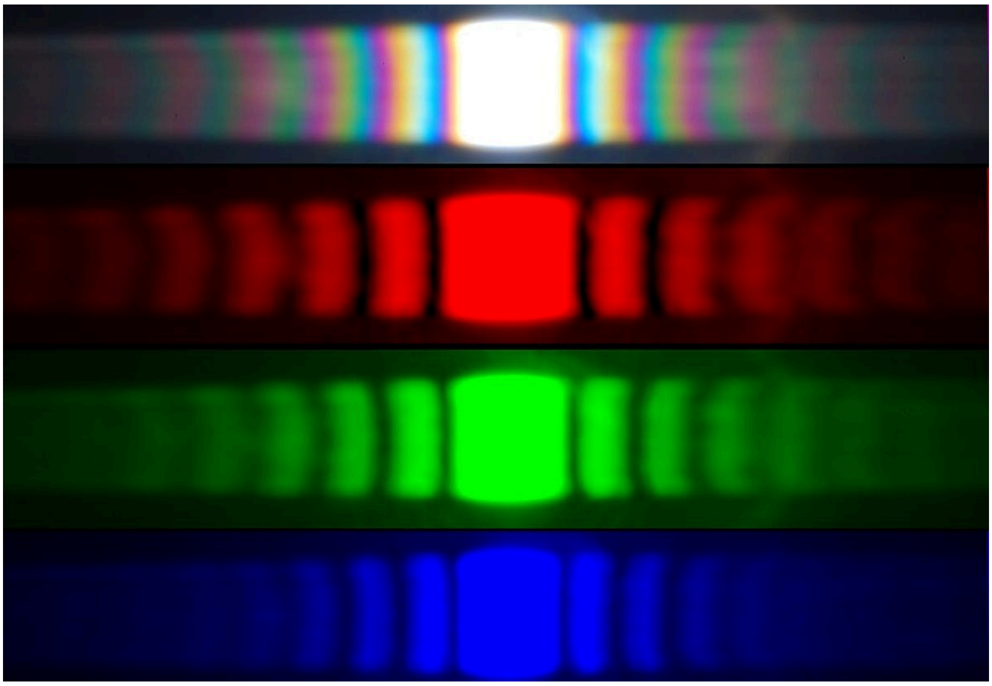

Figure 6. Diffraction grating interference pattern for monochromatic and white light.

More information for figure 6

The image shows four distinct sections, each illustrating diffraction grating interference patterns for different types of light. The top section displays the pattern for white light, characterized by a central bright white fringe with 'rainbow' fringes on either side due to different wavelengths being diffracted by different amounts. The remaining three sections show bright central fringes for monochromatic light in red, green, and blue. In each case, the central bright fringe is most intense, with fainter fringes diminishing in intensity further from the center. These patterns are aligned horizontally across the image and highlight how different colors or types of light produce distinct diffraction patterns.

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We can see from **Figure 6**, that the diffraction grating interference pattern for monochromatic light is a series of bright fringes of equal width, with fainter lines in between them. The central bright line is zero order ($n = 0$) and either side of the central line are the higher orders ($n = 1, 2$, etc.). The diffraction grating interference pattern for white light has a central white fringe and 'rainbow' fringes on either side. The 'rainbow' fringes are due to the fact that the different wavelengths of light in white light are diffracted by different amounts.

Work through the activity to check your understanding of multiple-slit diffraction interference patterns.

Activity

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:** Thinking skills — Being curious about the natural world
- **Time required to complete activity:** 20 minutes
- **Activity type:** Pair activity

You are going to use this simulation (https://demonstrations.wolfram.com/MultipleSlitDiffractionPattern/) to investigate multiple-slit interference of light waves.

1. Set the number of slits to 5 and observe the intensity pattern. Identify the central maximum and the secondary maxima.
2. Change the number of slits to 7. How does the intensity pattern change? How does the fringe spacing change and the intensity of the fringes?
3. Focus on the secondary minima. Can you count how many there are for 5 slits versus 7 slits? How does the number of slits affect the number of secondary minima?
4. Use the slider to change the slit width. How does this change influence the intensity pattern?
5. Use the slider to change the slit spacing. Describe the effect of changing only this variable.

5 section questions

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Question 1

SL HL Difficulty:

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Which row in the table correctly describes the change in width and intensity of the central maximum when the slit width **increases** in single-slit diffraction?

	Width of central maximum	Intensity
A	Increases	Decreases
B	Decreases	Decreases
C	Decreases	Increases
D	Increases	Increases

1 C ✓

2 A

3 B

4 D

Explanation

In single-slit diffraction, the larger the slit width, the narrower the width of the central maximum and the greater the intensity of the central maximum.

Question 2

HL Difficulty:

In a single-slit diffraction experiment, monochromatic light passes through a slit of width 0.1 mm. The first dark fringe (minima) is observed at an angle of 0.005 radians from the central maximum. Determine the wavelength of the light. Give your answer to a suitable number of significant figures.

The wavelength of the light is 1 500 ✓ nm

Accepted answers and explanation

#1 500

General explanation

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$\theta = 0.005 \text{ rad}$

$b = 0.1 \text{ mm} = 0.0001 \text{ m}$

$\theta = \frac{\lambda}{b}$

$\lambda = \theta b$

$= 0.005 \times 0.0001$

$= 5 \times 10^{-7} \text{ m} = 500 \text{ nm (1 sf)}$

Question 3

HL Difficulty:

In a single-slit diffraction experiment, the angular width of the first order maximum is found to be 0.02 rad. If the width of the slit is 0.0001 m, determine the wavelength of the light used in the experiment.
Give your answer in μm without units, to an appropriate number of significant figures.

1

Accepted answers

1 , one, 1 um, 1 micron, 0.000001 m, 0.000001 metres, 0.000001 meters

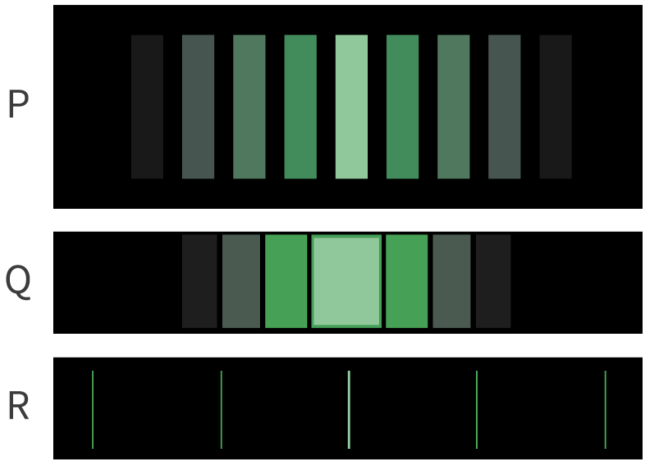
Explanation

The correct answer is λ = (0.0001 m) * (0.02/2) = 0.000001m, based on the small angle approximation of the formula for the angular position of minima in a single-slit diffraction pattern and considering the angle is half the angular width of the central maximum.

Question 4

HL Difficulty:

Red light is incident on a diffraction grating, a double-slit and a single-slit. The patterns produced on the screen are shown.



More information

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Which row in the table correctly identifies patterns P, Q and R?

	P	Q	R
A	Diffraction grating	Double-slit	Single-slit
B	Double-slit	Single-slit	Diffraction grating
C	Double-slit	Double-slit	Diffraction grating
D	Diffraction grating	Single-slit	Double-slit

1 B ✓

2 A

3 C

4 D

Explanation

The spacing in R is evidence for a diffraction grating. The central maximum in Q is wider than the other light fringes, which is evidence for a single slit. P shows a uniform width for all the light fringes, which is evidence for a double-slit.

Question 5

HL Difficulty:

The graph shows the intensity pattern for the interference of monochromatic light passing through N slits.

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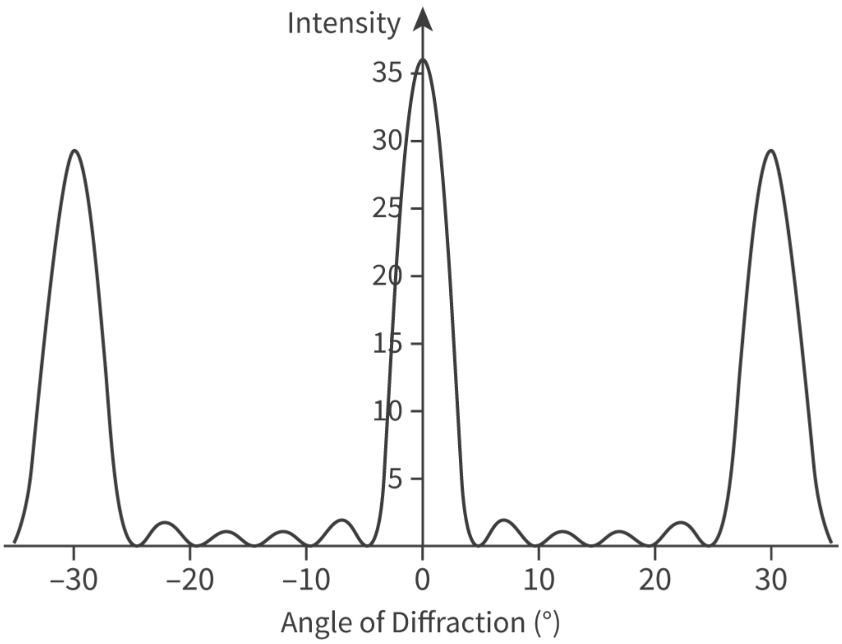

More information

Determine the correct relationship between the slit separation d and wavelength λ.

1 $d = 2\lambda$ ✓

2 $d = \frac{\lambda}{4}$

3 $d = \frac{\lambda}{2}$

4 $d = 4\lambda$

Explanation

If we know the order of the bright fringe (n), the angular position of the bright fringe (θ) we can use the formula for multi-slit interference to find the relationship between the slit separation (d) and the wavelength (λ). The formula is:

$$n\lambda = d \sin\theta$$

For the central maximum (the zeroth order maximum), $n = 0$ and thus $\sin\theta = 0$, meaning the angle θ is 0 degrees.

For the first order maximum, $n = 1$ the angle of diffraction, θ, is 30 degrees.

Substituting these values into the equation gives us:

$$\lambda = d \sin 30$$

Since $\sin 30 = 0.5$, the equation simplifies to:

Student view

$$\lambda = 0.5d$$

$$d = 2\lambda$$

So, for this specific interference pattern with a 30-degree angle between the central maximum and the first order maximum, the slit separation is twice the wavelength of the light.

Summary and key terms

- Wavefronts and rays can be used to describe travelling waves. Wavefronts show points on a wave that are in phase. Rays show the direction of wave travel.
- When a wave hits a boundary between two different media it can be absorbed, reflected or transmitted.
- The law of reflection states that the angle of incidence is equal to the angle of reflection.
- When a wave hits a boundary between two different media at an angle and is transmitted, it will be refracted because the speed of the wave changes.
- Diffraction is the bending of a wave when it travels around a body or through an aperture.
- The refractive index of a medium is a measure of how much the medium can slow down light, and it is the ratio of the speed of light in a vacuum to the speed of light in the medium.
- Snell's law describes the relationship between the angle of incidence and the angle of refraction. The ratio of the sine of the angle of incidence to the sine of the angle of refraction is equal to the ratio of the refractive indices of the two media and the ratio of the speed of the wave in the two media.
- When light travels from a more dense medium into a less dense medium, the critical angle is the angle of incidence that make the light refract along the boundary between the two materials. When the angle of incidence is greater than the critical angle, light undergoes total internal reflection.
- When two waves pass through each other, they superpose. Depending on the path difference, they can constructively interfere or destructively interfere.
- To get the clearest double-source interference pattern, the two sources need to be coherent. They need to have the same wavelength and be in phase.
- A Young's double-slit interference is produced by shining a monochromatic light through two slits, producing a series of light and dark fringes.

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Higher level (HL)

- A single-slit interference pattern has a central bright maximum with narrower bright fringes on either side. The intensity of light is greatest in the central maximum and decreases with each successive maximum. The width of the slit affects the intensity of the central maximum and its width.
- For double-slit diffraction, the double-slit interference pattern is modulated by the single-slit interference patterns from each slit.

Key terms

Review these key terms. Do you know them all? Fill in as many gaps as you can using the terms in this list.

1. The ______ states that the angle of incidence is equal to the angle of ______.
2. ______ is the bending of waves as they travel around a body or through an aperture.
3. ______ is the bending of waves as they pass from one medium into a different medium, and it occurs because the ______ of the waves changes.
4. When a light ray travels from a more dense medium into a less dense medium, the ______ is the angle of incidence at which the light ray is refracted along the ______ between the two media.
5. ______ interference occurs when the path difference between two waves is a whole number of wavelengths.
6. ______ interference occurs when two waves are out of ______.
7. The ______ of a medium is the ratio of the speed of light in a ______ to the speed of light in the medium.

Constructive | refractive index | speed | phase | law of reflection | reflection | Destructive | Diffraction | Refraction | vacuum | boundary | critical angle

Check

Interactive 1. Properties of Wave.

Student view

Checklist

What you should know

At the end of this subtopic you should be able to:

- Use the concepts of wavefronts and rays to describe travelling waves.
- Understand reflection, refraction, transmission and diffraction of waves.
- Use wavefront-ray diagrams to show behaviour of waves.
- Understand the concepts of refractive index and critical angle.
- Understand Snell's law and use the equation: $\frac{n_1}{n_2} = \frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1}$.
- Understand total internal reflection.
- Understand the superposition of wave pulses and travelling waves.
- Know that coherent sources are needed for double-source interference.
- Know the conditions for constructive interference and destructive interference and use the equations: path difference = $n\lambda$ and path difference = $(n + ½)\lambda$.
- Understand Young's double-slit interference and use the equation: $s = \lambda D/d$.

Higher level (HL)

- Understand single slit diffraction and use the equation: $\theta = \frac{\lambda}{b}$.
- Describe how the double-slit interference pattern is modulated by the single slit interference pattern.
- Understand the interference patterns produced by multiple slits and diffraction gratings and use the equation: $n\lambda = d\sin\theta$.

Practical skills

Once you have completed this subtopic, go to Practical 6: Determining the refractive index (/study/app/math-aa-hl/sid-423-cid-762593/book/determining-refractive-index-id-46510/) in which you will measure and analyse the refraction of light.

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Higher level (HL)

Practical skills

Once you have completed this subtopic, go to Practical 10: Investigating double-slit and double-source wave interference (HL) (/study/app/math-aa-hl/sid-423-cid-762593/book/investigating-double-slit-and-double-id-46754/) in which you can experimentally measure the wavelength of light.

C. Wave behaviour / C.3 Wave phenomena

Investigation

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/investigation-id-46617/print/) Assign

- **IB learner profile attribute:** Inquirer
- **Approaches to learning:** Thinking skills – Applying key ideas and facts in new contexts
- **Time required to complete activity:** 1 hour
- **Activity type:** Group activity

Your task

In this activity you will construct a CD spectrometer and use it to investigate the behaviour of light waves as they pass through different media and apertures.

Inquiry prompts

- How do the spectral lines emitted by various light sources (e.g. sunlight, LED lights, fluorescent lights) change as they pass through the spectrometer? What does this tell us about the behaviour of waves at the boundary between different media?
- How does the angle at which light enters the spectrometer affect the spectral lines observed? What does this reveal about the behaviour of waves passing through apertures?
- Observe and describe what happens when the spectral lines of two different light sources meet at a point within the spectrometer. What can we learn from this about the behaviour of waves when they meet at a point in space?

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Use the CD spectrometer to analyse the spectral lines in various real-world settings, such as the sunlight filtering through different coloured glasses or the light from a fire.

Materials

- An old CD
- A cardboard box
- A sharp knife or scissors
- A ruler
- A pencil
- Various light sources (sunlight, LED light, fluorescent light, etc.).

Procedure

For a visual guide on how to construct a CD spectrometer and conduct this experiment, refer to **Video 1**.

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/single-and-multi-slit-diffraction-hl-id-46614/print/) Assign

Video 1. Make your own CD spectrometer.

Extension: Theory of Knowledge discussion

Discuss the significance of observation and experimentation in scientific inquiry and how different views and interpretations can shape our comprehension of the world.

Extension: Nature of Science discussion

Investigate the evolution and refinement of scientific models and the importance of assessing the validity and reliability of evidence supporting scientific claims. Discuss practical applications of scientific knowledge, such as the usage of spectrometers in various fields like

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astronomy and chemistry.

Through this inquiry task, you can gain a deeper understanding of spectral lines and how a spectrometer works. You will also understand how different light sources produce different spectral lines, providing insights into their composition.

C. Wave behaviour / C.3 Wave phenomena

Reflection

Section Student… (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/reflection-id-47879/print/) Assign

Teacher instructions

The goal of this section is to encourage students to reflect on their learning and conceptual understanding of the subject at the end of this subtopic. It asks them to go back to the guiding questions posed at the start of the subtopic and assess how confident they now are in answering them. What have they learned, and what outstanding questions do they have? Are they able to see the bigger picture and the connections between the different topics?

Students can submit their reflections to you by clicking on 'Submit'. You will then see their answers in the 'Insights' part of the Kognity platform.

Reflection

Now that you've completed this subtopic, let's come back to the guiding questions introduced in The big picture (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-44900/).

- How are observations of wave behaviours at a boundary between different media explained?
- How is the behaviour of waves passing through apertures represented?
- What happens when two waves meet at a point in space?

With these questions in mind, take a moment to reflect on your learning so far and type your reflections into the space provided.

You can use the following questions to guide you:

- What main points have you learned from this subtopic?
- Is anything unclear? What questions do you still have?

Student view

- How confident do you feel in answering the guiding questions?
- What connections do you see between this subtopic and other parts of the course?

Once you submit your response, you won't be able to edit it.

0/2000

Submit

Rate subtopic C.3 Wave phenomena

Help us improve the content and user experience.