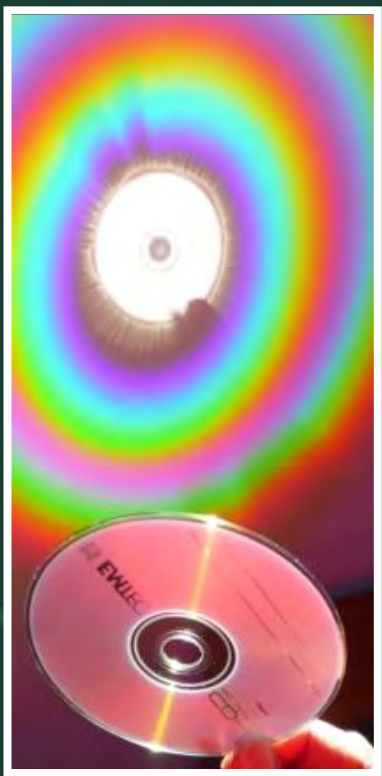
Te Kura
Te Aho o Te Kura Pounamu
The Correspondence School

TE MĀTAURANGA AHUPŪNGAO

PHYSICS



PH3031

WAVES AND INTERFERENCE

NCEA LEVEL 3

2013/1

PHYSICS

NCEA LEVEL 3

Expected time to complete work
This work will take you about 12 hours to complete.

You will work towards the following standard:
Achievement Standard AS91523 (Version 1) Physics 3.3
Demonstrate understanding of wave systems

Level 3, External
4 credits

In this topic you will focus on the following learning outcomes:

- describing the basic characteristics of waves
- explaining the Doppler effect, the change in frequency of sound due to movement of its source, and solving numerical problems relating to this
- explaining phenomena and solving problems involving the interference and diffraction of waves and light.

You will complete work towards this standard in this topic.

- Standing waves and resonance PH3032

CONTENTS

HOW TO DO THE WORK

When you see:

Complete the activity.

Check your answers in the Answer Guide at the back of this booklet.

Use the Topic webpage or the Internet.

Hands-on activity. Complete these practical activities to strengthen your learning.

Caution! Read the safety instructions carefully.

You will need:

- a pen, pencil, ruler
- a computer with Internet connection will be very useful
- a laser pointer*
- a pair of diffraction glasses*
- a CD*
- two pencils
- two rubber bands
- a strong light source
- a white wall or a paper screen
- a table lamp
- a candle
- a tape measure or ruler
- a sharp knife
- sticky tape.

*Contained in the Waves equipment box supplied to eligible Te Kura students.

Resource overview

This topic provides an introduction to waves and interference. You will get most out of your studies if you use the write-in booklet alongside a computer with an Internet connection, using the Topic webpage. It is possible to study this topic using just the booklet if you read the explanations and the answers very carefully.

Interesting extras, which are not essential for passing the NCEA Achievement Standard, are marked in lilac boxes like this. You may skip these if you are short of time.

Mark your own answers, using the Answer guide. Try to think critically about the physics involved.

Computer-based activities

Te Kura's Online Teaching and Learning site, OTLE, has many supporting materials that will aid your learning. Log on to this site to enhance your understanding of the subject matter.

The Physics Education Technology (PhET) teaching simulations are some of the most powerful learning tools you can use on a computer. Activities that use these simulations appear in many Te Kura physics topics.
You can run these simulations online or install them on your computer.

To run a simulation online:

- click on the link on the OTLE Topic webpage or use a search engine such as Google to search for 'PhET' and the name of the simulation.

To install PhET on your computer:

- download and install PhET from http://phet.colorado.edu/get_phet/full_install.php (this is recommended if you don't have fast Internet) or install PhET from a disc – ask your teacher to send a disc to you.

1 WAVE BASICS

LEARNING INTENTIONS

In this lesson you will learn to:

- describe a wave in terms of the motion of particles as it travels.

INTRODUCTION

Waves are very common in nature and are very important to us. Animals and humans explore our environment through light and sound waves. All of our communication devices – such as cell phones, television sets and radios, use waves. Waves are the most important means of transferring energy, including the energy from the Sun to the Earth. This lesson introduces the concepts and the terminology of wave motion.

WAVE MOTION

The concept of wave motion is introduced in NCEA level 2 Physics. If you have not studied level 2, or feel you need to revise, you can access the level 2 materials through the links on the Topic webpage. If you need help and you don't have access to OTLE, contact your teacher.

DESCRIBING WAVES

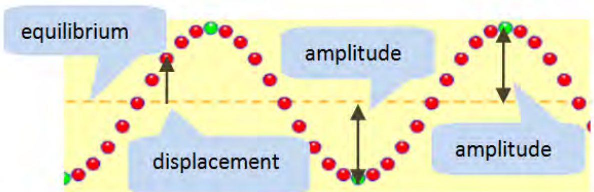
When you clap your hands, the air between your hands is compressed rapidly. A **wave pulse** travels across the room. The air particles do not travel across the room in that time, but the energy does.

A **wave** is a series of **oscillations** that travel through a medium. An oscillation at the source of the wave causes particles in the medium to oscillate. Connections between the particles pass the oscillations from one particle to the next. The wave spreads, or **propagates**.

If you are on a swing, an oscillation is one to-and-fro swing, as shown by the arrows in the diagram below.

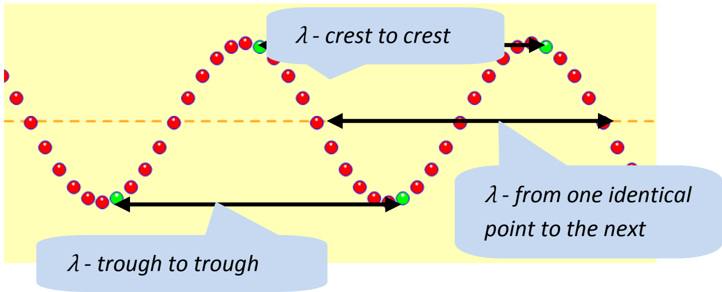
The central point from which each particle oscillates is called the **equilibrium position**. The **displacement** of a particle is its distance at any given moment from the equilibrium position.

The **amplitude** of a wave, (A), is the maximum displacement of a particle from its equilibrium position.



WAVELENGTH

One wavelength (λ) is the distance from a crest to the next crest or from one trough to the next trough. It is the distance between two adjacent points on a wave that have identical movements (they oscillate in step with each other, **in phase**).



The symbol for wavelength is λ, (said as 'lamb-dah') and it is measured in metres.

1B QUICK QUIZ: DESCRIBINGWAVES

Test yourself to see how many words you can remember.

a. a regular, repeated back-and-forth movement ____________________

b. the distance moved by a particle ____________________

c. the maximum distance moved by an oscillating particle ____________________

d. a short duration wave ____________________

e. the material which carries the wave ____________________

f. a disturbance that travels through a medium from one location to another ____________________

Check your answers.

DESCRIBING OSCILLATIONS

PERIOD

The **period** (T) of an oscillation is the time taken for one complete oscillation. If a swing takes 3.0 s to go from one extreme position to the other and back to the starting position, then its period is 3.0^{o} s.

Example: A flag flutters in the wind 12 times in 6.0 seconds. Calculate the period of the oscillation of the flag.

Answer

$$\text{Period } (T) = \frac{\text{time taken}}{\text{number of oscillations}} = \frac{6.0}{12} = 0.50\text{ s}$$

FREQUENCY

The **frequency** (f) is the number of oscillations in one second. The unit of measurement for frequency is **hertz** (**Hz**). If the time period for an oscillation is 0.5 seconds, then its frequency is 2.0^{o} Hz.

$$\text{frequency } (f) = \frac{\text{number of oscillations}}{\text{time taken}} = \frac{1}{0.5} = 2.0\text{ Hz}$$

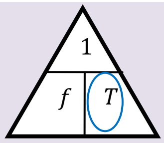
HOW IS THE FREQUENCY RELATED TO THE PERIOD?

Frequency is the reciprocal of the period.

$$f = \frac{1}{T}$$

MATHS HELP!

The frequency–period relationship can be written in a triangle as shown. If you circle the quantity you require, then the other two quantities are automatically arranged correctly.



$$T = \frac{1}{f} \qquad f = \frac{1}{T} \qquad 1 = fT$$

Example: A boy bounces up and down on a trampoline. He makes 8.0 back-and-forth movements in 28 s. Calculate the frequency and period of his oscillations.

Answer

Frequency: Number of oscillations = 8.0

Time taken = 28 s

$$\text{Frequency } (f) = \frac{\text{number of oscillations}}{\text{time (seconds)}}$$

$$\text{Frequency } (f) = \frac{8.0}{28.0} = 3.5\ \text{Hz}$$

Period:

$$T = \frac{1}{f}$$

$$T = \frac{1}{3.5} = 0.26\ \text{Hz}$$

HERTZ IN YOUR HOME

If you look for technical details about almost any electronic equipment you will find 'Hz'. Here are some examples:

- $'{\sim}50/60\ \text{Hz}'$ on the bottom of a toaster. T*he toaster is designed to work with a mains electricity supply that has current oscillating at 50 to 60 Hz.*
- Radio Hauraki broadcasts on 99.0 MHz. *This is the frequency of the radio waves used to carry the signal from this radio station.*
- Headphones are designed for frequencies from 100 Hz to 18 kHz. *These are the frequencies of the sound waves the headphones can produce.*

KILO- MEGA- GIGA...

High frequencies are usually written with a prefix (a bit before the main word) to save writing lots of zeros.

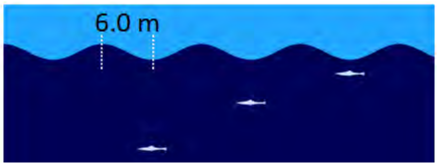
1 **kilo**hertz	= 1 kHz	= 1000 Hz
1 **mega**hertz	= 1 MHz	= 1 000 000 Hz
1 **giga**hertz	= 1 GHz	= 1000 MHz = 1.0 x10^9 Hz

1C QUICK QUIZ: OSCILLATIONS

1. The number of back-and-forth vibrations made in every second is called _______________ and is measured in_________________.
2. There are 24 wave crests passing a point in a lake in 5.0 minutes. The horizontal distance between the top of a crest and the bottom of a trough is 6.0 m.

   a. What is the frequency of the water waves?

   ____



   b. What is the wavelength of the water waves?

   ____

   c. A piece of driftwood is floating in the lake. The vertical distance between the lowest position of the driftwood and the highest position of the drift wood is 1.2 m. What is the amplitude of the wave?

   ____

3. During a high tide the water under a wharf rises 1.8 m. The time between a low tide and a high tide is roughly 6 hours.

   a. What is the period of the tide?

   ____

   b. What is the frequency of the tide?

   ____

   c. What is the amplitude of the tide?

   ____

4. A radio station broadcasts on a frequency of 567 kHz.

   a. How many hertz are there in 567 kHz?

   ____

   b. Calculate the period of the waves. Give your answer to three significant figures in standard form. (If you have not learned how many significant figures to use, or how to work in standard form, refer to lesson 9.)

   ____

   ____

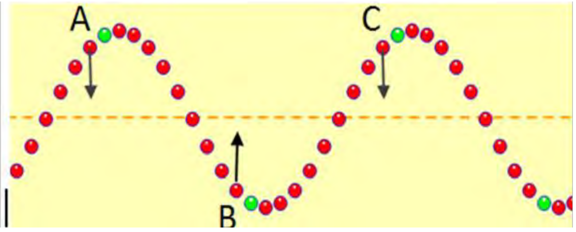
Check your answers.

WAVE PHASE

Phase is a concept used to describe a particular moment in the cycle of an oscillation. One complete oscillation (once round the cycle), is 360°.

Two points are in phase if they move exactly in step with each other (they are at the same part of the oscillation at the same time).

Here is a screen shot from the PhET *Wave on a string* simulation. Particles A and C are **in phase** because, at the instant of the screen shot, they have the same displacement and they are both moving down. They are one wavelength apart. Particles which are a whole multiple of a wavelength ($n\lambda$) apart are always in phase. A phase difference of 360°, 720° and so on means that the particles move in phase.



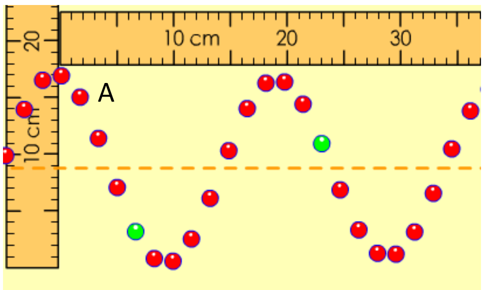
Particles that are out of phase are not in step with each other, although their movements are similar and have the same time period. For example, the particles A and B in the diagram above are out of phase and are moving oppositely to each other – when A is moving down, B is moving up and vice versa. Because particles A and B are out of phase by 180°, they are in **antiphase** with each other. Particles move in antiphase if they are separated by half a wavelength ($\frac{1}{2}\lambda$), or any whole number of wavelength plus half a wavelength ($n\lambda + \frac{1}{2}\lambda$).

1D QUICK QUIZ: WAVE PHASE

1. This diagram shows a transverse wave through a rope.State the wavelength and the amplitude of the wave.

   ____

   ____



2. On the diagram mark the positions of the following particles:
   a. the next particle in phase with particle A
   b. a particle that is $\frac{1}{2}$ cycle (180°) out of phase with particle A
   c. a particle that is $1\frac{1}{2}$ cycles out of phase with particle A.

Check your answers.

KEY POINTS

- A wave is a series of oscillations that travel through a medium.
- The distance and direction of the movement of a particle in the wave is its displacement. The maximum displacement is the amplitude.
- The frequency (f) (the number of oscillations per second) of the wave is the same as the frequency of the source.
- The time period (T) (the time to make one oscillation) is related to frequency: $T = \frac{1}{f}$.
- Wavelength (λ) is the distance between two adjacent points that are moving in phase. It is the distance from one crest to the next crest or one trough to the next trough.
- Phase describes a particular moment in the cycle of an oscillation. Particles which are in phase move in step with one another. In a wave, particles which are in phase are $n\lambda$ apart. Particles which are in antiphase move oppositely. In a wave, particles are in antiphase when they are $n\lambda + \frac{1}{2}\lambda$ apart.

2 WAVE MOTION

LEARNING INTENTIONS

In this lesson you will learn to:

- describe the characteristics of transverse and longitudinal waves
- define wave speed and solve numerical problems relating to wave speed, frequency and wavelength.

INTRODUCTION

Most electronic communication – cell-phone networks, radio and television – uses electromagnetic waves. Electromagnetic waves travel at the speed of light; that is, 300 million metres per second. This is why text messages are delivered so fast. This lesson looks at the characteristics of waves and how the speed of a wave relates to its frequency and its wavelength.

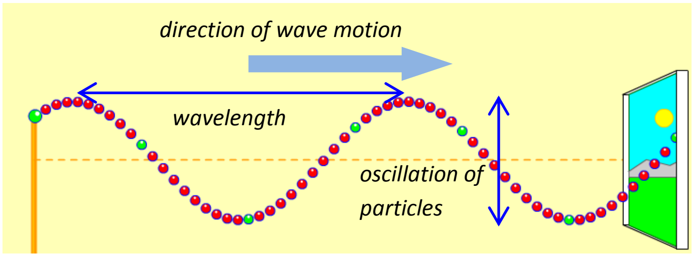
MECHANICAL WAVES

Mechanical waves are waves which propagate through a material medium (solid, liquid, or gas). The speed of a wave in a medium depends on the elastic properties of the medium. Mechanical waves can be **longitudinal** or **transverse**.

TRANSVERSE WAVES

The wave in this diagram is moving from left to right and the particles are moving up and down. This is an example of **transverse wave** motion.

In transverse wave motion the particles of the medium vibrate at right angles to the direction in which the wave travels.

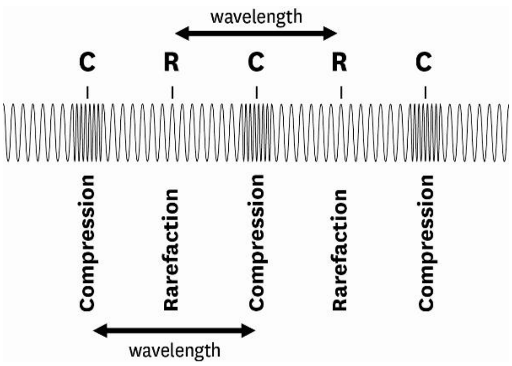


One wavelength (λ) is the distance between two adjacent crests or between two adjacent troughs.

LONGITUDINAL WAVES

In a longitudinal wave the particles vibrate parallel to the direction of wave motion.

This diagram shows a snapshot of a longitudinal wave as it moves along a slinky spring. As the wave travels along the spring, the coils of the spring move back and forth.



The part where the coil is squeezed is called a compression (C).

The part where the coil is stretched is called a rarefaction (R).

One wavelength (λ) is the distance between two nearby compressions or between two nearby rarefactions.

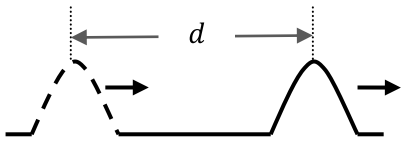
WAVE SPEED

Water dripping into a bowl produces ripples (waves). The waves move horizontally although the particles in the wave move (approximately) up and down.
The speed of the ripple across the bowl is not the same as the speed of the water particles.

The speed of a wave can be measured by timing a wave crest as it travels a fixed distance.

$$v = \frac{d}{t}$$

v = velocity of the wave, in m s^{-1}
d = distance moved by the pulse, in m
t = time taken to travel the distance

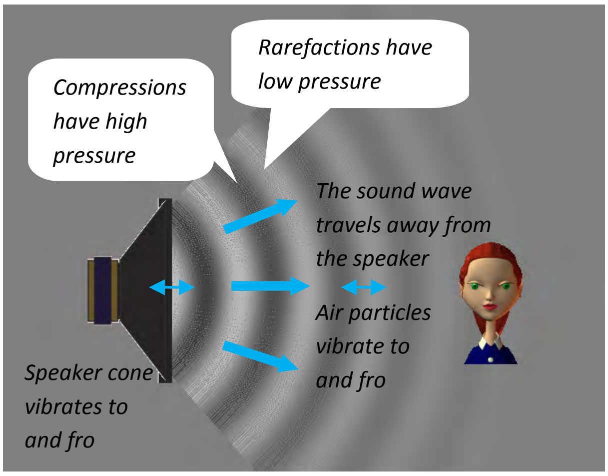


Example: A wave in a pond travels 24 metres in 3.0 seconds. Calculate the speed of the wave.
Answer
d = 24 m, t =3.0 s

$$v = \frac{d}{t} = \frac{24}{3.0} = 8.0 \text{ m s}^{-1}$$

SOUND WAVES

Sound waves are longitudinal waves produced by pressure variations in a material (usually air). A speaker produces sound when its cone vibrates. The vibrating cone pushes air particles. Each particle collides with the next, and so energy travels away from the speaker.

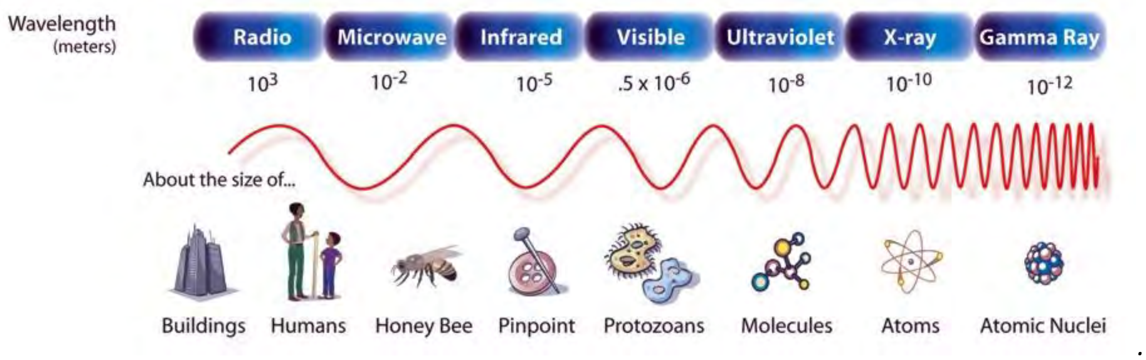


The speed of sound in air depends on humidity, temperature and pressure. It is usually between 320 and 340 m s^{-1}.
Increasing the amplitude of a sound wave makes it louder.
The loudness (volume) of a sound relates to the sound wave's amplitude.
Increasing the frequency of a sound wave makes it higher pitched.

ELECTROMAGNETIC WAVES

When you listen to the radio, watch television, or cook dinner in a microwave oven, you use electromagnetic waves. Light is part of a series of waves called the **electromagnetic spectrum**.

Electromagnetic waves are transverse. In radio circuits they are produced by the oscillation of electrically charged particles. Unlike all other waves, they do not require a medium to travel – they can travel through empty space as well as through air and other substances. In a vacuum all types of electromagnetic waves travel at the same speed: $3.0 \times 10^{8}\ \mathrm{m\ s^{-1}}$. Because air slows the waves down very little, the speed of electromagnetic radiation in air is also this speed.



The electromagnetic spectrum

Electromagnetic waves come in a huge range of sizes. At one end of the spectrum are radio waves, which have a very low frequency and long wavelengths. At the other end of the spectrum are high-frequency (short wavelength) gamma rays. Visible light (the radiation you can detect with your eyes) is a small part of this spectrum. Red light has the longest visible wavelength; violet has the shortest.

WAVE PARTICLE DUALITY

Electromagnetic waves are quite unlike mechanical waves. They are not continuous – they carry energy in discrete lumps called **photons.** Light is a stream of particles *and* a type of wave. It is both particles and waves – a phenomenon called **wave–particle duality**.

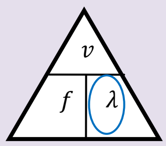
The energy of a photon of electromagnetic radiation is proportional to its frequency. High-frequency radiations, such as X-rays and gamma radiation (emitted by radioactive materials) have high-energy photons. Photons of lower frequency radiation, such as microwaves, have much less energy.

THE WAVE EQUATION

Wave velocity depends on the medium through which the wave is travelling. If the medium does not change, the wave velocity does not change. The wave frequency depends on the frequency of the wave source. The frequency cannot change once a wave has left the source. If the frequency is increased, more waves are produced per second. Because the velocity of the waves does not change, the wavelength decreases. Similarly, when the frequency is decreased, there are fewer waves produced per second, and the wavelength increases.

MATHS HELP!

The wave equation can be written in a triangle as shown. If you circle the quantity you require, then the other two quantities are automatically arranged correctly.



Example 1: A cell-phone tower transmits at a frequency of 850 MHz. The speed of the wave in air is $3.0 \text{ X } 10^8$ m s^{-1}. Calculate the length of the waves transmitted from the cell-phone tower.

Answer

f = 850 MHz = 850 x 10^9 Hz; $v = 3.0 \text{ X } 10^8 \text{ m s}^{-1}$

Wavelength λ = ?

$$v = f\lambda$$
$$\lambda = \frac{v}{f}$$
$$= \frac{3.0 \text{ X } 10^8}{850 \times 10^9}$$
$$\lambda = 3.5 \times 10^{-4} \text{ m}$$

Technique: Avoid rounding errors

You often need to round numbers in your answer to a problem to ensure that you do not give your answer to a higher level of accuracy than the data that was used in the problem. To avoid increased error in the calculation, it is best not to round until you have a final answer. In the example above, the data is given to three significant figures, so the final answer is rounded to three significant figures too. (See lesson 9 for more details.)

2A CHECK YOUR UNDERSTANDING: WAVES AND SOUND

1. The speed of sound in water is 1480 m s^{-1}. Calculate the time it takes for a sound wave to travel 50.0 m in a pool. Give your answer to the appropriate number of significant figures.

____

____

2. When a cover for a cricket pitch is shaken, the pulse generated travels at a speed of 2.35 m s^{-1} for 4.0 s. Calculate how far the pulse travels. Give your answer to the appropriate number of significant figures.

____

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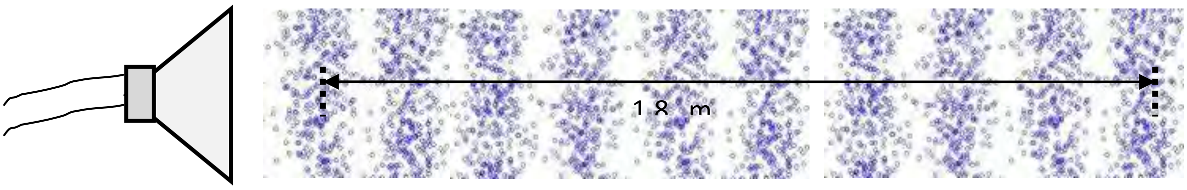
3. The diagram below shows the arrangement of smoke particles in air at an instant in time when a series of sound waves travels through smoke-filled air. The frequency of the sound wave is 364 Hz.



   a. Describe the movement of one smoke particle when the sound waves travel through the smoke-filled air.

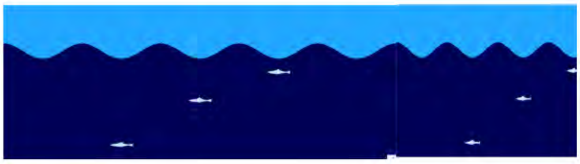
   ____

b. Calculate the period of the sound wave.

c. Use the information in the diagram to calculate the speed of the sound waves in smoke-filled air.

4. This diagram shows waves created by a breeze on the surface of a lake.

a. Describe how the water waves on the surface of the lake are different to the sound waves in air in terms of the motion of the particles.



b. The waves travel from the centre of the lake to the shore. A piece of wood bobs up and down 12 times a minute in the lake. The speed of the wave at the centre of the lake is 0.80 m s^{-1}. As the wave nears the shore its speed and wavelength decreases. The wavelength when it reaches the shore is 3/4 of the wavelength in the centre of the lake. Calculate the wavelength of the waves near the shore.

Check your answers.

KEY POINTS

- In transverse wave motion the particles of the medium vibrate at right angles to the direction in which the wave travels.
- In a longitudinal wave the particles vibrate parallel to the direction of wave motion.
- Velocity (v) is the distance travelled by a wave-front per second.
- The velocity of a wave depends on the type of wave and the medium it travels through. The speed of the wave remains the same unless the medium changes. The speed is $v = f\lambda$.

3 THE DOPPLER EFFECT

LEARNING INTENTIONS

In this lesson you will learn to:

- explain the Doppler effect – the change in frequency of the sound heard when a source moves towards or away from a listener
- solve numerical problems relating to the Doppler effect
- describe some uses of the Doppler effect.

INTRODUCTION

An ambulance, with its siren on, comes down the road. As it passes, a person standing on a footpath will hear the pitch of the siren drop. If you watch a Formula 1 race on TV you can hear the cars making a characteristic 'neee-yow' sound as they pass the microphone.

These frequency changes are due to the Doppler effect, an effect that is widely used in modern technology. This lesson is about the Doppler effect and its applications.

The sound of this Formula 1 car changes pitch as it passes an observer

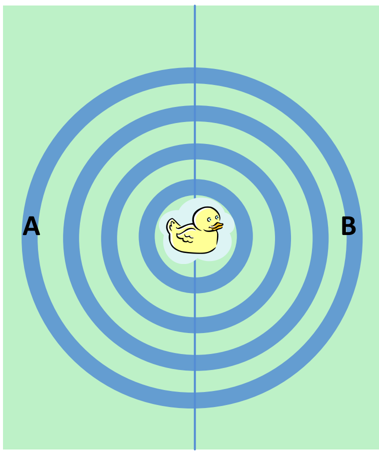
THE DOPPLER EFFECT IN RIPPLES

3A DOPPLER DUCK

Use the Topic webpage to see a video which shows the Doppler effect in water ripples, and an explanation of the effect. If you do not have access to the Internet, read the text below carefully.

DUCK ON WATER

The diagram shows the ripples made by a duck bobbing up and down on the surface of water with a constant frequency. The water is still and the duck stays in the same spot. Its motion creates waves that travel outward. The constant frequency of the motion generates waves of equal wavelengths. The constant velocity of the waves keeps the ripples circular.



Ripples from a stationary source

The number of waves passing per second through points A and B are the same. Because frequency is the number of waves per second, the frequency of the waves arriving at A and B are the same.

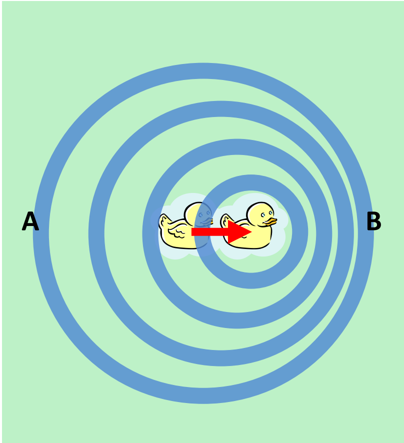
Now the duck continues to bob, but it also moves slowly across the pond. The ripples are generated at the same frequency and travel at the same speed as before (it makes circular ripples). The duck's movement causes the waves in front of it to 'bunch up' and the waves behind it to spread out.

The wavelength of the waves is longer behind the duck and shorter in front of the duck

Fewer ripples arrive each second at A and more arrive each second at B.

A lower frequency is detected at A because the source is moving away.

A higher frequency is detected at B because the source is approaching.



Ripples from a moving source

SOUND WAVES AND THE DOPPLER EFFECT

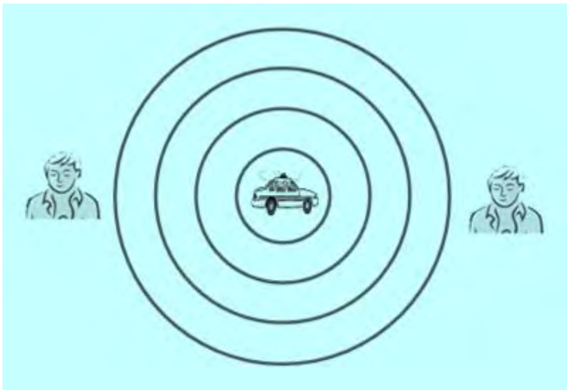
3B DOPPLER SOUNDS

Use the Topic webpage to watch animations and hear sound caused by the Doppler effect. If you do not have access to the Internet, read the text below carefully.

When you hear sound waves your brain detects the frequency of the waves that move hairs in the inner ear. (You don't measure the wavelength of the sound waves, you sense the frequency.) Musical notes are defined in terms of frequency.

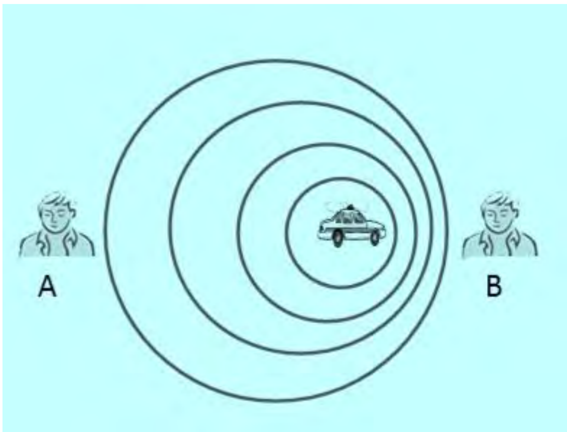
In this diagram the sound waves from the siren on a stationary police car spread out evenly in all directions. The speed of sound in the air is constant (provided temperature and humidity of the air do not change), so the wave fronts are spherical.

The frequency of sound heard by the two observers is the same, wherever they stand, because they both receive the same number of waves per second. Both observers hear a sound of the same pitch.



Stationary police car

The police car moves toward observer B. The siren continues to produce the same number of waves per second but these waves are fitted into a shorter distance, so they are bunched up. The wavelength is shorter and, because the waves continue to move at the same speed, observer B receives more waves per second. Hence the frequency heard by listener B is higher than the frequency at the source.



Moving police car

Behind the police car, the distance between observer A and the source of the sound is increasing. The siren still produces the same number of waves per second, but these waves are fitted into a longer distance, so they spread out and the wavelength becomes bigger. Observer A receives fewer waves per second, so the frequency heard is lower.

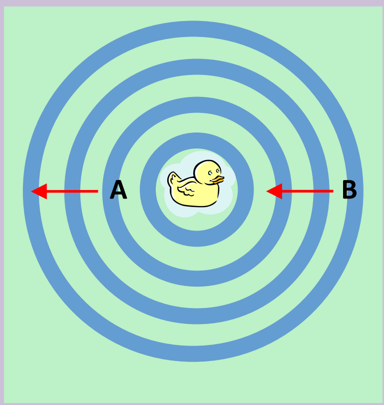
WHO OR WHAT IS AN OBSERVER?

The Doppler effect may be detected with any type of wave. The 'observer' may be a person listening or looking at a star, but it could also be a piece of kit such as a microphone, a radio receiver or a special telescope. The 'observer' simply needs to be able to sense the frequency of the waves. It is anything that can make a measurement.

MOVING OBSERVER

There is also a Doppler effect if the source of waves is stationary and the observer moves. You might have noticed this effect if you have driven past a house where the alarm was sounding.
Because the source is stationary the waves spread out evenly.
By approaching the source (B) you move into wave-fronts more frequently.
Similarly, as you move away from the source (A) you move into wave-fronts less frequently.

If you drive past a sounding alarm, the pitch of the alarm goes from a higher note to a lower one.



Ripples from a stationary source

CALCULATING DOPPLER SHIFT

The frequency measured by a detector (such as a microphone) or an observer (such as a person listening to the sound) is called the **apparent frequency.**

> The difference between the frequency of a source and the apparent frequency caused by the **relative** motion of the wave source and the detector is called **Doppler shift.**

The two important words here are **apparent** and **relative**. We use the term **relative motion** because the Doppler effect takes place whenever the distance between the source and the observer changes. It does not matter whether the source, the observer, or both, are moving – the waves will be Doppler-shifted.

CHRISTIAN DOPPLER

The Doppler effect was proposed by Christian Doppler in 1842. Doppler's proposition was tested by CHD Buys Ballot in 1845. Buys Ballot used two groups of trumpeters: one group was stationary at a train station and one group was moving on an open train car. Both groups of musicians held the same note. However, as the train approached the station, it was obvious that the frequency of the two notes didn't match. This proved Doppler's hypothesis.

Christian Doppler (1803-1853)

3C QUICK QUIZ: DOPPLER SOUNDS

1. A car is stationary in a car park, playing loud music. The bass drumbeat has a frequency of 2.0 Hz. The speed of sound in the air is 340 m s^{-1}.
   a. Calculate the time period for the drumbeat.

   ___

   b. Calculate the time period between wave-fronts 1 and 3.

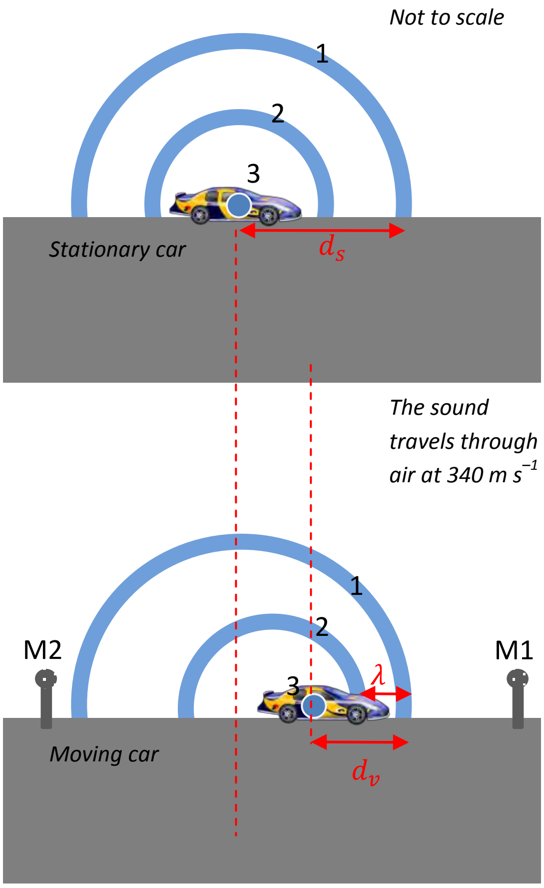
   ___

   c. Calculate the wavelength of the sound waves.

   ___

   d. Calculate the distance between waves 1 and 3 (d_s).

   ___



2. The car is now moving at 30 m s^{-1}.
   a. Calculate the distance moved by the car in 2.0 s.

   ___

   b. Calculate the distance between wave-fronts 1 and 3 in front of the car (d_v).

   ___

   c. Calculate the distance between the wave-fronts in front of the car (λ).

   ___

3. Use your answer to (2 c) to calculate the frequency detected by microphone M1.

   ___

   ___

4. Apply the reasoning you used in questions 2 and 3 to calculate the frequency detected by microphone M2.

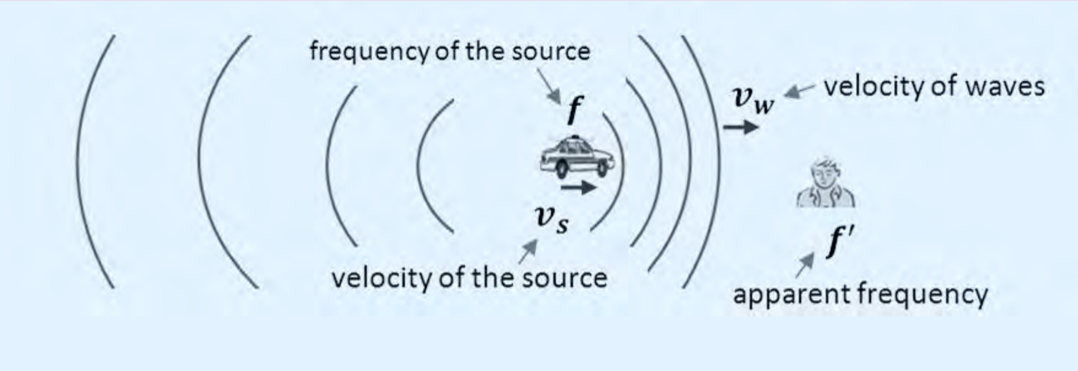
   ___

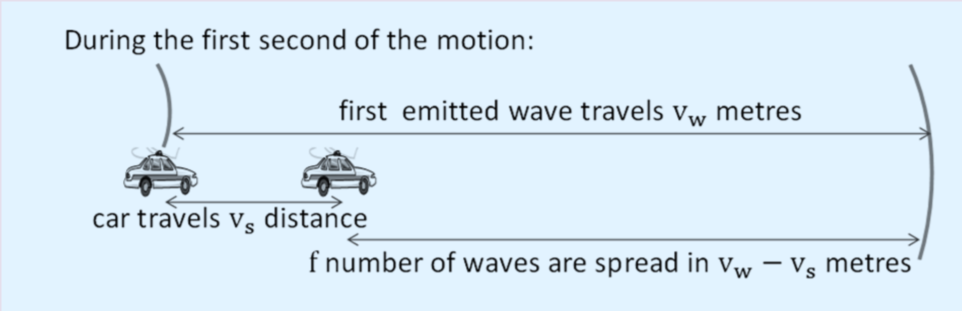
   ___

Check your answers.

DOPPLER FORMULAE

Now we'll see how an equation can be derived mathematically. The principle is the same as that in activity 3C, but now we'll use letters instead of numbers.
Consider a police car travelling at velocity v_s and making waves at frequency f, which travel at speed v_w. The speed of the waves is not altered by the motion of the source. The observer detects frequency f'.





Because frequency is the number of waves per second, at the end of the first second of the car's motion the source would have emitted f of wave-fronts.
The distance travelled by a wave-front:

$$d = v_w \times t$$

In one second:

a wave-front travels $d = v_w \times 1 = v_w$ metres
the car travels $v_s \times 1 = v_s$ metres.

The distance between the first and last waves emitted in one second period is $v_w - v_s$ metres.
There are f number of waves in this distance.

$$\text{The new wavelength } \lambda' = \frac{distance}{number\ of\ waves} = \frac{v_w - v_s}{f}$$

The wavelength of the waves approaching the listener the apparent wavelength, λ', is less than the original wavelength, λ.
The velocity of the wave in air: $v_w = f'\lambda'$
Because the wave velocity is fixed, a change in wavelength causes a change in frequency.
The apparent frequency: $f' = \frac{v_w}{\lambda'} = \frac{v_w}{\frac{v_w - v_s}{f}}$.
Rearranging this formula gives apparent frequency:

$$f' = f\frac{v_w}{v_w - v_s}$$

f' is the apparent frequency of a wave from a source that is travelling **toward** an observer.

Example : An ambulance siren has a frequency of 6.00×10^3 Hz. It moves towards Sam at 30.0 m s^{-1}. The speed of the sound in air = 340 m s^{-1}.

a. Calculate the wavelength of the sound from the siren.
b. Explain why the wavelength of the waves approaching Sam is less than the wavelength of the siren.
c. Calculate the apparent frequency of the sound that Sam hears.
d. Calculate the apparent wavelength of the sound approaching Sam.

Answer

$f = 6.00 \times 10^3 \text{ Hz};\quad v_w = 340 \text{ m s}^{-1};\qquad v_s = 30 \text{ m s}^{-1}$

a.

$$v_w = f\lambda$$

$$\lambda = \frac{v_w}{f}$$

$$\lambda = \frac{340}{6.00\ \times 10^3} = 0.0567 \text{ m}$$

b. As the ambulance moves, the distance between Sam and the ambulance decreases but the same number of waves are fitted into a lesser distance. This causes the wavelength to be smaller.

c.

$$f' = f\frac{v_w}{v_w - v_s}$$

$$f' = 6.00\ \times\ 10^3(\frac{340}{340 - 30})$$

$$f' = 6.58\ \times 10^3 \text{ Hz}$$

d.

$$\lambda' = \frac{v_w -\ v_s}{f} = \frac{340 -\ 30}{6.00\ \times 10^3} = 0.0517 \text{ m}$$

Alternatively, use your answer to (c) and apply:

$$v_w = f'\lambda'$$

$$\lambda' = \frac{v_w}{f'} = \frac{340}{6.58\ \times 10^3} = 0.0517 \text{ m}$$

Example : A steam train's whistle makes a frequency of 600 Hz. Calculate the speed of the train when the whistle is heard to make a frequency of 620 Hz. Assume that the speed of sound in the air is 320 m s^{-1}.

Answer

$f = 600 \text{ Hz};\quad f' = 620 \text{ Hz};\quad v_w = 320 \text{ m s}^{-1};\quad v_s = ?$

The higher frequency tells us that the whistle is approaching, so we use the equation:

$$f' = f\frac{v_w}{v_w - v_s}$$

v_s is required, so the equation can be rearranged:

$$v_w - v_s = f\frac{v_w}{f'}$$

$$-v_s = f\frac{v_w}{f'} - v_w$$

$$v_s = v_w - f\frac{v_w}{f'}$$

$$v_s = v_w\left(1 - \frac{f}{f'}\right)$$

$$v_s = 320\left(1 - \frac{600}{620}\right)$$

$$v_s = 10.3 \text{ m s}^{-1}$$

Alternatively, you could start by substituting the numbers into the equation:

$$620 = 600\left(\frac{320}{320 - v_s}\right)$$

$$\frac{620}{600} = \left(\frac{320}{320 - v_s}\right)$$

$$1.033 = \left(\frac{320}{320 - v_s}\right)$$

$$1.033\,(320 - v_s) = 320$$

$$330.67 - 1.033v_s = 320$$

$$-1.033v_s = 320 - 330.67 = -10.67$$

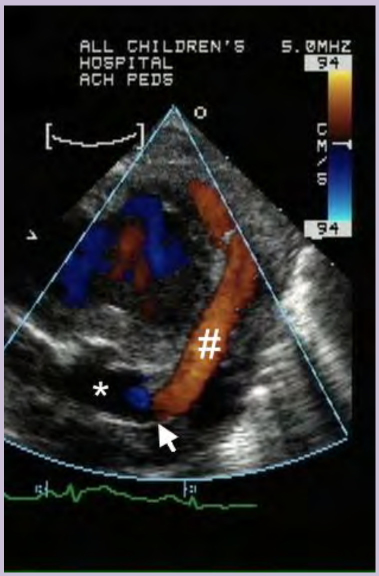
$$1.033v_s = 10.67$$

$$v_s = \frac{10.67}{1.033} = 10.3 \text{ m s}^{-1}$$

DOPPLER ULTRASOUND

Ultrasound is sound at a frequency too high to be heard by human ears. Because sound waves travel very well in water, they can travel through the human body. The echoes from organs can be detected and used to create images.
When ultrasonic sound waves bounce off moving blood cells in flowing blood, they act as moving sources, so the reflected sound waves are Doppler-shifted.
This shift can be used to determine the direction of blood flow.

The image on the right shows blood flow from a coronary artery into the left ventricle, clearly showing that the patient has a hole (a fistula) linking the artery with the heart chamber.



The Doppler shift from moving blood is an important tool for helping to diagnose heart problems.

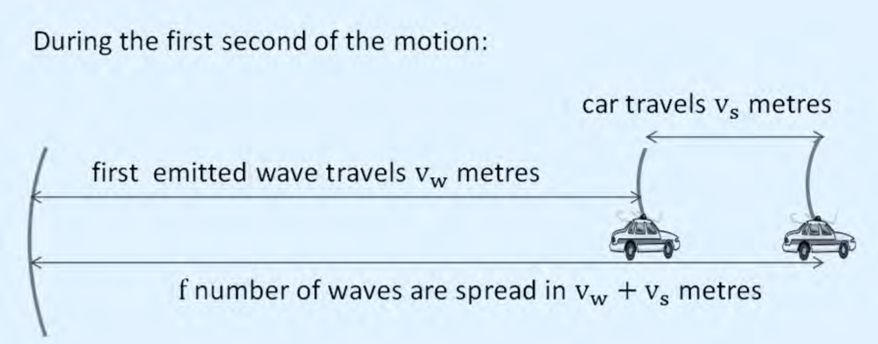
CALCULATING THE FREQUENCY DETECTED FROM A RECEDING SOURCE

When a wave source is moving away from a detector (receding), the wave length of the waves increases due to the movement of the source. The apparent frequency (f') is less than the frequency of the source (f). It can be calculated using the equation:

$$f' = f\frac{v_w}{v_w + v_s}$$

When the car is moving away from the listener, the first wave is emitted at the beginning of the first second and the last wave is emitted at the end of it. During this time the car travels v_s metres. The distance between the car and the first emitted wave is $v_w + v_s$ metres. During this time the car would have emitted f number of waves, which are spread out in $v_w + v_s$ distance.

$$\text{The new wavelength} = \frac{distance}{number\ of\ waves}$$



$$\lambda' = \frac{v_w + v_s}{f}$$

The velocity of the wave in air is v_w $\mathrm{m\ s^{-1}}$, which remains constant for given physical conditions. The wavelength of the waves approaching the listener (the apparent wavelength) is λ', which is larger than the original wavelength, λ. Since the apparent wavelength is larger, the apparent frequency, f', is smaller than the frequency of the wave from the siren.

The velocity of the wave in air: $v_w = f'\lambda'$

The apparent frequency:

$$f' = \frac{v_w}{\lambda'} = \frac{v_w}{\frac{v_w + v_s}{f}}$$

Rearranging this formula gives apparent frequency:

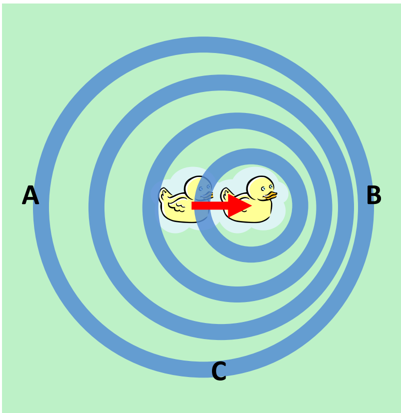
$$f' = f\frac{v_w}{v_w + v_s}$$

GENERAL FORMULA

When a detector is stationary in a wave medium, the apparent frequency of a source of waves (f') is related to the true frequency of the waves (f) by the equation:

$$f' = f\frac{v_w}{v_w \pm v_s}$$

where v_w is the velocity of the waves through the medium and v_s is the velocity of the source in a direction away from (+) or toward () the detector.



At A the frequency detected is lower than the source, because λ is increased.
At B the frequency detected is higher than the source, because λ is decreased.
At C there is no motion toward or away from the detector, so f and λ do not change.

Example: A boy in a skate park is near a stationary police car that has turned on its siren. The wavelength of the sound waves in air produced by the siren is 0.242 m, and the frequency is 1.40×10^3 Hz.

1. Calculate the speed of the sound from the car.
2. The car moves away from the boy at 30.0 m s^{-1}. Compare the wavelength of the waves approaching the boy from the moving car with the wavelength of the waves from the stationary car. Explain your answer.
3. Calculate the apparent frequency of the sound heard by the boy.

Answer

1. $f = 1.40 \times 10^3$ Hz; $\lambda = 0.243$ m; $v_w = ?$

$$v_w = f\lambda = 1.40 \times 10^3 \times 0.243$$

$$v_w = 388.8 = 389 \text{ m s}^{-1}$$

2. The wavelength of the waves approaching the boy when the car is moving away from him is larger than the wavelength of the waves from the siren when it is stationary. This is because when the car is moving away from the boy, the distance between them increases. The number of waves produced by the siren per second remains constant, so the waves are spread through a longer distance, making the wavelength larger.

3. $f = 1.40 \text{ x} 10^3$ Hz ; $v_s = 30 \text{ ms}^{-1}$; $v_w = 388.8 \text{ ms}^{-1}$ $f' = ?$

$$f' = f\frac{v_w}{v_w - v_s}$$

$$f' = 1.40 \times 10^3 \left(\frac{340}{340 + 30}\right)$$

$$f' = 1.28 \times 10^3 \text{ Hz}$$

3D CHECK YOUR UNDERSTANDING

1. The sound from the air horn of a stationary car has a frequency of 1250 Hz. The driver sounds the horn as he drives the car down the road past a person standing by the side of the road.
   a. Describe the change in frequency experienced by the listener as the car passes her. Explain your answer.

b. At one instant the car is travelling directly towards the observer at 13.9 m s^{-1}. Calculate the wavelength of the waves approaching the observer at that instant. The speed of sound in the air is 335 m s^{-1}.

2. Jack and Lena have a model aircraft that they are flying horizontally in circles on the end of a 10.0 m long wire. The model aircraft has a constant speed of 12.0 m s^{-1}. The plane has a noisy engine that emits a sound of frequency 3.00 kHz. The speed of sound in the air is 330 m s^{-1}.

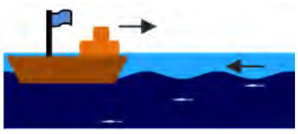
a. Jack notices that the sound from the plane varies in loudness and pitch. On the diagram, clearly mark the section of the circular track of the plane where Jack would hear an increasing frequency.

b. Lena, who is holding the plane's control wire at the centre of the circle, hears a constant loudness and pitch. Explain why Jack hears these variations in sound, and Lena does not.

c. Calculate the wavelength of the sound waves that Lena hears from the plane.

d. Calculate the maximum frequency of the sound that Jack hears.

3. Water waves of wavelength 1.2 m are moving across the surface of a lake at 1.5 m s^{-1} as shown in this diagram. A motor boat is moving against the direction of the waves at 2.0 m s^{-1}.



a. Calculate the frequency of the waves.

b. Explain why the waves strike the bow of the boat more frequently than the value you calculated in (a).

4. As John is driving he hears a fire-engine siren coming from a few hundred meters behind him. He pulls over and waits for the fire engine to pass. The fire engine passes him at a constant speed of 31.0 m s^{-1}. The frequency of the siren is 900 Hz. The speed of sound in the air is 330 m s^{-1}. The frequency shift (Δf) is the difference between the frequency detected from the approaching fire engine and the frequency detected from the receding fire engine. Calculate the frequency shift heard by John.

Check your answers.

ELECTROMAGNETIC RADIATION

Electromagnetic radiation is unlike sound or water waves because it travels without any medium – it travels in a vacuum. We cannot tell whether the source is moving or if the observer is moving – there is only relative motion. This is an important feature of Einstein's theory of relativity.

In the visible spectrum (light that we can detect with our eyes) red light has the longest wavelength and blue light has the shortest wavelength. When astronomers study the characteristic spectra from galaxies they often find that the light has slightly longer wavelengths than we would expect from a stationary source. The shift to longer wavelengths is called **red shift** (it might not actually be red!). Red shift indicates that the observer on Earth and the galaxy being observed are getting further apart. A **blue shift** (to shorter wavelengths) is caused when the source and the observer are getting closer.

The Doppler equations used so far in this topic are not strictly true for electromagnetic radiation, but they can be used to provide an approximate value for the relative speed between a source of electromagnetic radiation and an observer.

SPEED CAMERAS

Speed cameras and hand-held radar guns use Doppler shifts of radio waves reflecting off cars to measure their speed.

For example, a police officer aims his radar gun at an approaching vehicle. The gun sends out a burst of waves at a particular frequency. The waves strike the vehicle and bounce back toward the radar gun.

The radar gun contains a detector which compares the frequency of the returning waves with the emitted waves. If the car is moving toward the gun, the frequency of the returning waves will be higher than the frequency of the source. The faster the car travels, the higher the frequency of the returning waves.

The difference between the emitted frequency and the reflected frequency is used to determine the speed of the vehicle. A computer inside the gun performs the calculation instantly and displays the speed to the officer.

Speed camera

3E TORNADO WATCHING

1. Meteorologists are scientists who study the weather. They can study the motion of weather features such as tornadoes by transmitting radio waves toward the feature, and then analysing the reflected waves. Explain how you could use the Doppler effect to determine the speed of an approaching tornado.

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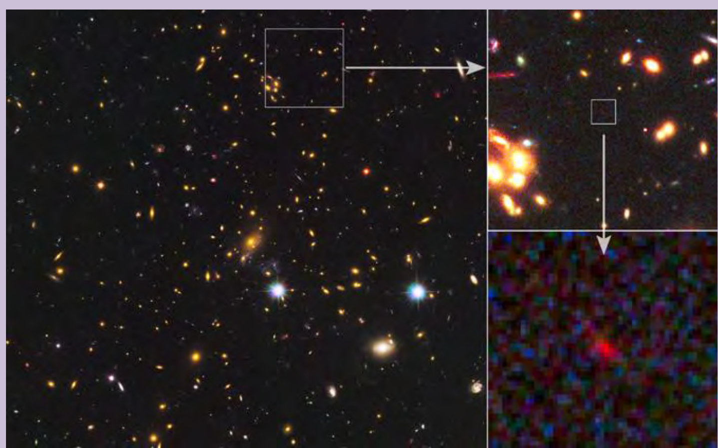
Check your answers.

COSMOLOGICAL RED SHIFT

Astronomers are able to measure Doppler shifts to find out about the Universe.
The light from objects that are moving toward or away from Earth have spectra-shifted because of their motion.

There are many other strange changes to the frequencies of well-known spectra caused by the expansion of space.
There are links to information about cosmological red shift on the Topic webpage. You can also learn more about it by studying the Stars topic, PH3022



Measurements of light from the galaxy indicate that the light has been travelling for 13.2 billion years.

KEY POINTS

- The apparent change in the pitch of sound caused by the relative motion between the source waves and the detector is called the **Doppler effect.**
- When a source of waves approaches a detector, the frequency of the waves detected is higher than the frequency of the source because the wavelength decreases.
$$f' = f\frac{v_w}{v_w - v_s}$$
- When a source of waves recedes from a detector, the frequency of the sound detected is lower than the frequency of the source because the wavelength increases.
$$f' = f\frac{v_w}{v_w + v_s}$$
- The general formula provided in NCEA exams is: $f' = f\frac{v_w}{v_w \pm v_s}$
- Electromagnetic radiation travels differently because it does not require a medium. These formulae are only approximately correct for electromagnetic radiation.

4 SUPERPOSITION AND DIFFRACTION

LEARNING INTENTIONS

In this lesson you will learn to:

- explain the superposition of waves in terms of phase difference
- describe the diffraction of waves.

INTRODUCTION

You might have noticed that when an incoming wave on a beach meets a retreating wave, they combine to form a bigger wave. Unlike particles, waves can travel through each other. When there are two waves in the same position the effect is called superposition, and that is the subject of this lesson.

SUPERPOSITION

4A

SUPERPOSITION IN ONE DIMENSION

The concept of superposition is introduced in NCEA level 2 Physics. If you have not studied level 2, or feel you need to revise, you can access the level 2 materials through the links on the Topic webpage. If you need help and you don't have access to OTLE, contact your teacher.

4B

ONLINE ACTIVITY: SUPERPOSITION ON A STRING

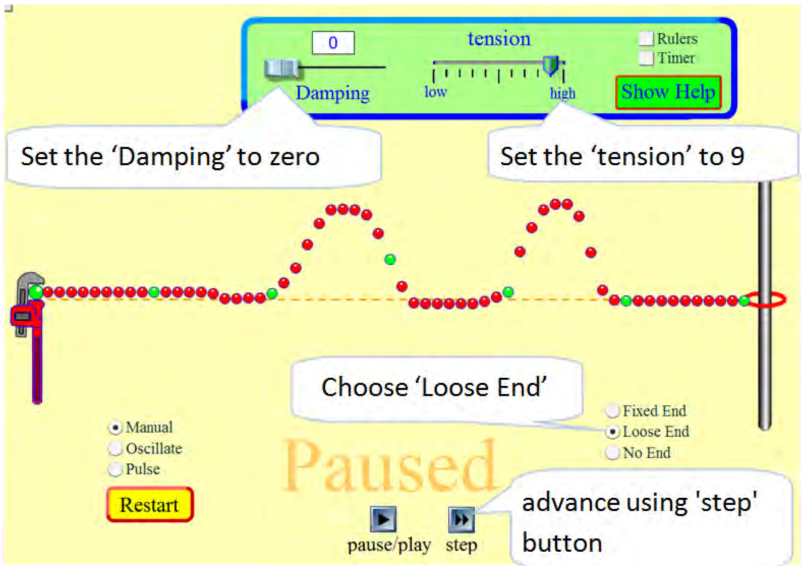
Run the PhET simulation 'Wave on a string'. This is linked to the Topic webpage

1. Set up the screen as shown.

2. Wiggle the wrench (spanner) to send two different wave pulses along the string.

3. When the first wave reflects off the pole and begins to return, click on the 'Pause/Play' button.

4. Now use the 'step' button to advance slowly until the waves overlap.
   Describe what happens when the waves superpose on each other.



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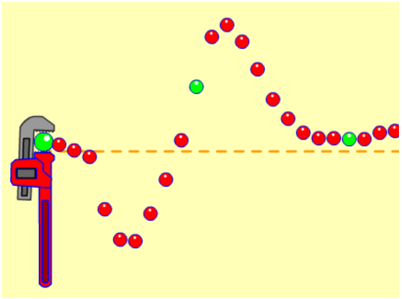
5. Keep using the 'step' button to advance the simulation. One of the waves will reflect off the spanner. Advance until both waves overlap again.
   Describe what happens when the waves superpose on each other.

   ____

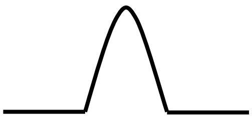
   ____



Check your answers.

Constructive interference takes place when the superposing particles are in phase. The displacements of each particle add to create a larger pulse. The amplitude of the resulting pulse or wave is the sum of the amplitudes of the two initial pulses.

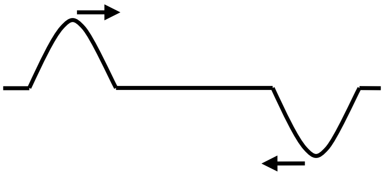
Two pulses are travelling towards each other.



When they meet, the amplitude of the resulting pulse is the sum of the amplitudes of the two initial pulses.

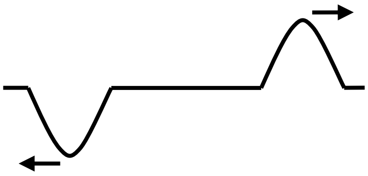
After meeting, each pulse continues along its original direction of travel and their original amplitudes are unchanged.

Destructive interference takes place when the superposing particles are out of phase by 180^{o}. If the displacements of the particles are equal and opposite, they add up to zero displacement. The sketch shows the destructive interference of two pulses.



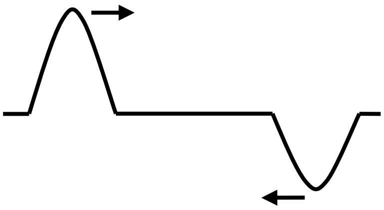
Two pulses are travelling towards each other. The waves have the same amplitude.

When they meet they cancel out each other momentarily.

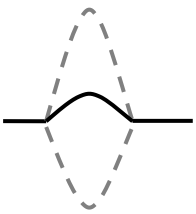


After meeting, each pulse continues along its original direction of travel, and the original amplitudes are unchanged.

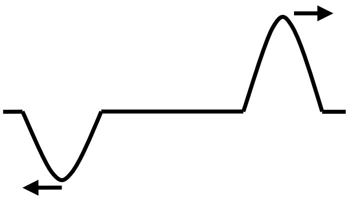
If the amplitudes of the pulses are different, there is a partial cancellation of the two pulses. The amplitude of the resulting pulse is still the sum of the amplitudes of the two initial pulses as shown in the following sketch.



Two pulses are travelling toward each other. The waves have different amplitudes.



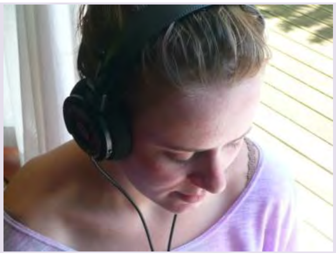
When the pulses meet, a partial cancellation takes place. The new pulse has the sum of the amplitudes of the two initial pulses.



After meeting, each pulse continues along its original direction of travel and their original amplitudes remain unchanged.

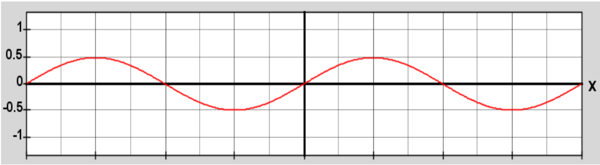
NOISE-CANCELLING HEADPHONES

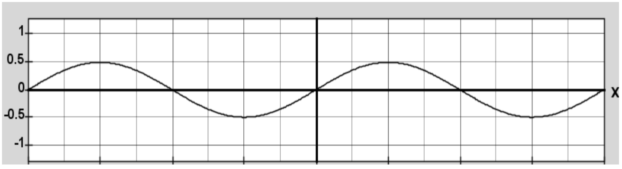
Noise-cancelling headphones use an idea known as active noise control. One or more microphones near the ear (inside the headphone), detect the background noise. A computer analyses the waveform of the background noise, and speakers generate an identical sound wave in antiphase. The background noise and the sound from the speakers cancel each other.



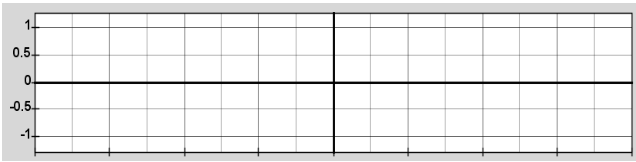
4C CHECK YOUR UNDERSTANDING:SUPERPOSITION

1. The diagrams below show a pair of waves.
   a. Are the waves in phase or out of phase? ______________________________

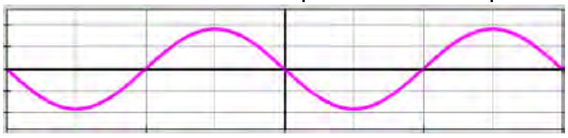




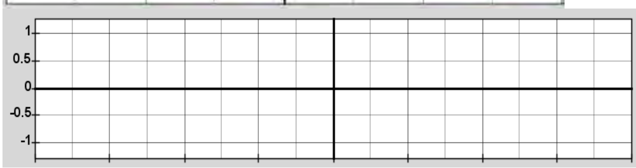
   b. In the space given, draw the resultant wave when both waves meet.



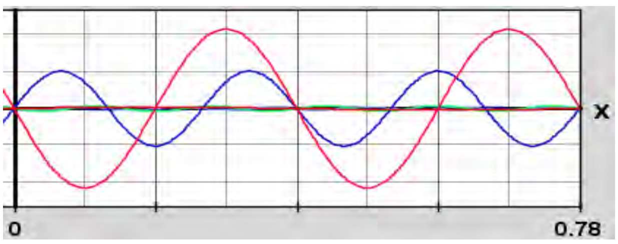
2. The diagrams below show a pair of waves.
   a. Are the waves in phase or out of phase? ______________________________

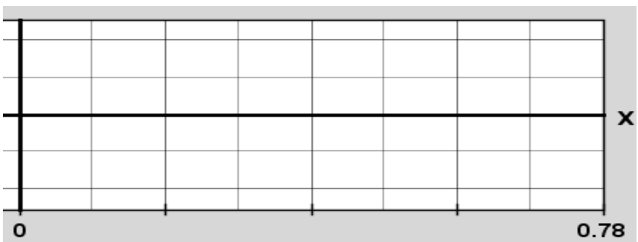


   b. In the space given, draw the resultant wave when both waves meet.



3. The diagram below shows two waves at a given instant. In the space given, sketch a rough shape of the superposed wave of these two waves





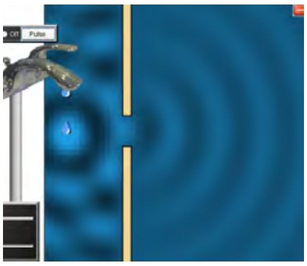
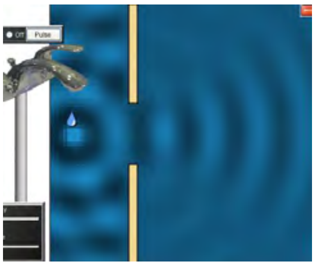
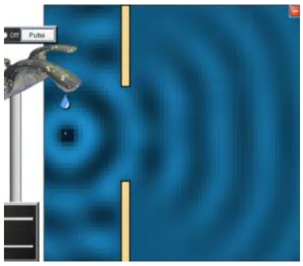
Check your answers.

RIPPLES AND GAPS

4D ONLINE ACTIVITY: DIFFRACTION OF RIPPLES

Run the PhET simulation 'Wave interference'. This is linked to the Topic webpage. (See page 2 for full instructions on how to run PhET simulations.)

1. Play the simulation and watch the shape of the waves that come out of the gap.
2. Now change the slit width to 2.5 and watch the shape of the waves that come out of the gap.
3. Repeat step 2 for a slit width of 3.75.

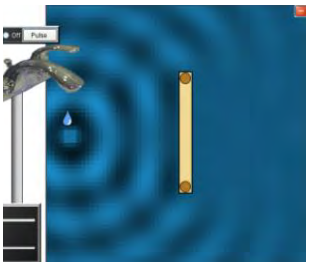
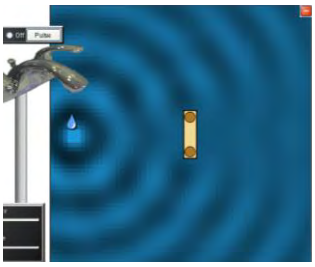
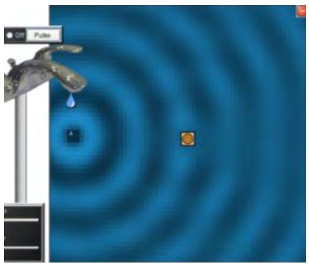




4. Describe how the shape of the wave changes as the slit width is increased.

____

____

5. Click on 'No Barrier' and 'Add Wall'. Drag the wall into the positions shown.

6. Describe how the wall affects the ripples.

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____

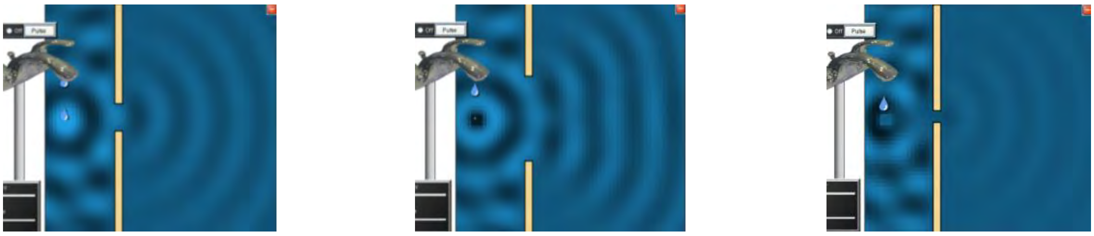
7. Describe what happens as you make the wall smaller.

Leave the simulation running. You will use it again later in this lesson.

Check your answers.

DIFFRACTION OF WAVES

If you throw a stone into a pond the ripples spread out in a circle. Waves spread out from all points of a disturbance. When a barrier blocks part of the wave-front, the remaining, unblocked section of the wave-front spreads out into the ‘shadow’ created by the barrier. The spreading out of waves as they pass a barrier is called **diffraction**. Diffraction does not change the speed, the wavelength or the frequency of the wave. Only the direction is changed.



This spreading out is most noticeable if the gap is about the same as the wavelength. When the gap is much larger than the wavelength, most of the wave energy goes straight through. When the gap is much smaller than the wavelength, most of the wave energy is reflected.

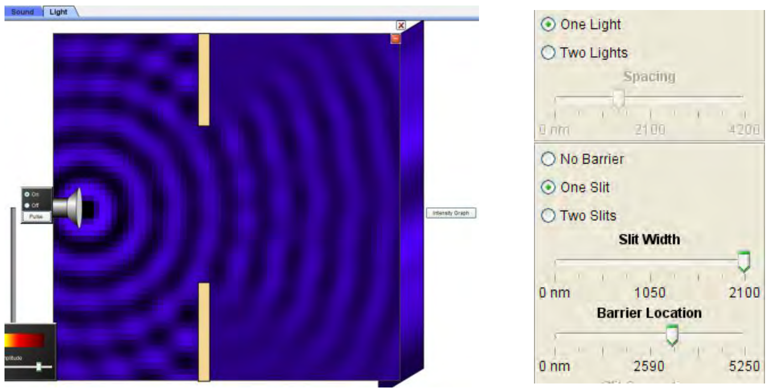
4E ONLINE ACTIVITY: DIFFRACTION IN DETAIL

Run the PhET simulation ‘Wave interference’. This is linked to the Topic webpage. (See page 2 for full instructions on how to run PhET simulations.)

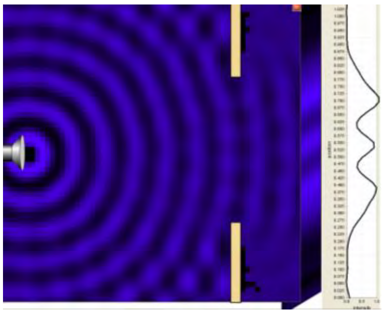
1. Click the ‘Light’ tab at the top of the screen.

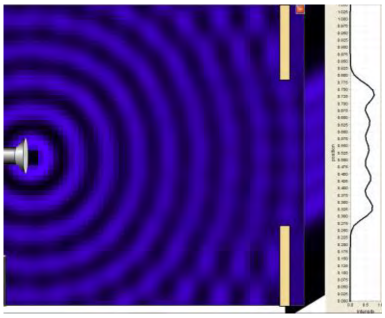
2. Set up the screen as shown, with one light, one slit and a large slit width.

3. Notice how the intensity of the diffracted waves varies slightly as the waves interfere with each other.



4. Investigate the diffraction patterns that would be seen if light was shone at a screen through the gap. Choose ‘show screen’ and ‘intensity graph’.





You will see that the diffraction pattern from a single slit shows the effects of interference. The precise pattern is very complicated. (You do not have to explain the details for NCEA.)

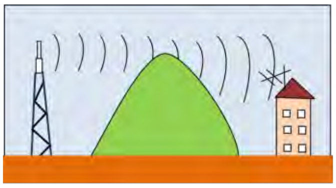
5. Explain the formation of dark bands in the light that travels through the slit.

Check your answers.

4F CHECK YOUR UNDERSTANDING

1. Explain how the relative size of the wavelength and the gap width affect the degree of diffraction at a gap.

2. Radio stations broadcast in AM and FM frequencies. AM frequencies are in kHz and FM frequencies are in MHz.



   a. Compare the wavelengths of AM and FM frequencies.

   b. Explain why houses in valleys receive a better signal from AM frequency broadcast than FM frequency broadcast.

Check your answers.

KEY POINTS

- Superposition describes what happens when one wave is superimposed on ('sits on top of') another. The displacement of the medium at each point is the sum of the displacements of the superposing waves.
- Constructive interference takes place where in-phase waves meet, creating a large amplitude motion.
- Destructive interference takes place where antiphase waves meet. If the two waves have the same amplitude and are in antiphase, there is zero amplitude, and no motion.
- Diffraction is the spreading of waves as they pass an obstacle. When waves spread out as they go through a gap, the amount of diffraction is greatest if the width of the gap is equal to the wavelength. Obstacles that are smaller than the wavelength have no significant effect on the waves.

5 INTERFERENCE PATTERNS

LEARNING INTENTIONS

In this lesson you will learn to:

- discuss the conditions required to produce an interference pattern
- describe and explain how two sources cause interference patterns.

INTRODUCTION

In the last lesson you studied how waves interact when they meet. In this lesson you will learn how two sources of waves can produce a steady interference pattern.

OBSERVING INTERFERENCE PATTERNS

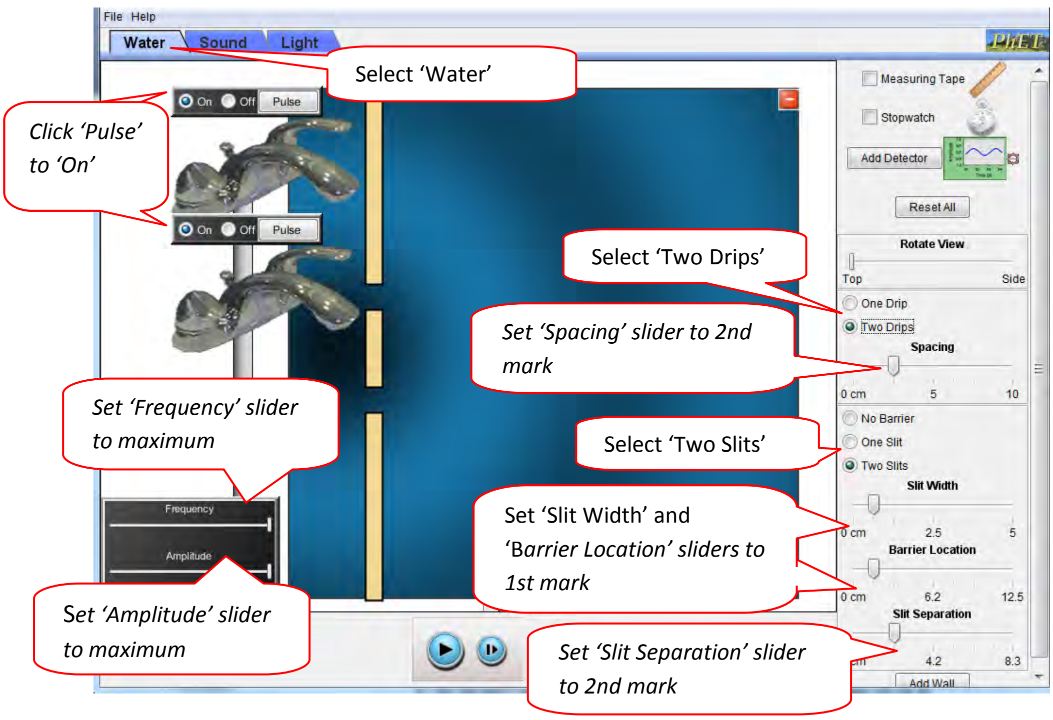
Superposition occurs whenever two waves of the same type travel through each other. However, there is only a clear interference pattern if the waves make a lasting difference to each other. To produce a steady interference pattern:

- The waves must have the same frequency (identical wavelength).
- The sources of the two waves must have a steady phase relationship – they must either be in phase or have some other constant phase difference. Sources of waves that have a constant phase relationship are **coherent sources.**

5A ONLINE ACTIVITY: INTERFERENCE PATTERNS

Run the PhET simulation 'Wave interference'. This is linked to the Topic webpage. (See page 2 for full instructions on how to run PhET simulations.)

1. Select 'Pause' and set up the simulation as shown.



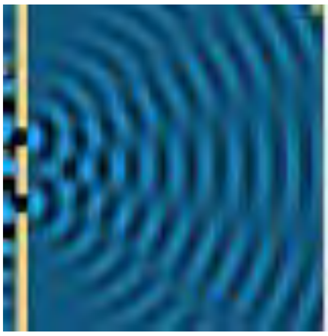
2. Click the 'Play' button to start the wave motion.

3. Explain how these waves meet the two conditions for an observable interference pattern.

4.
   a. Describe what is happening in areas where you see large ripples.

   b. Describe what is happening in areas where you see calm water.

5. On this image mark the areas where reinforcement (constructive interference) and cancellation (destructive interference) take place.



6. Set the 'Amplitude' slider to half way. Describe how changing the amplitude affects the distance between the areas of calm water.

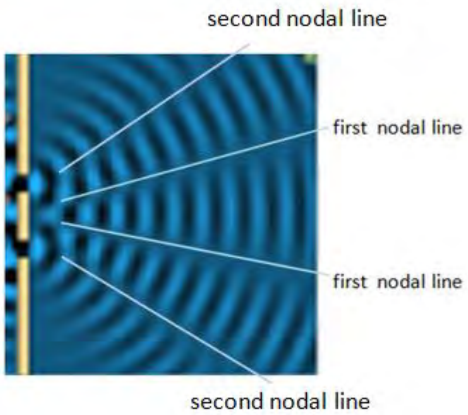
7. Decrease the 'Frequency' slider to ¾. Describe how changing the frequency affects the distance between the areas of calm water.

Check your answers.

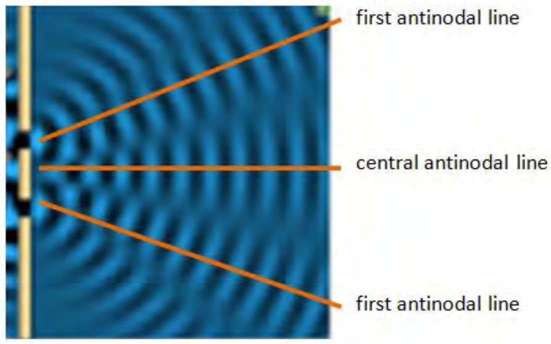
EXPLAINING INTERFERENCE PATTERNS

Destructive interference takes place where waves arrive in **antiphase**; that is, where a crest from one source arrives at exactly the same time as a trough from the other source.

Points at which destructive interference takes place are called **nodes**. These are the points of no movement. A **nodal line** joins a series of nodes. In a ripple tank, calm water is seen along these lines.

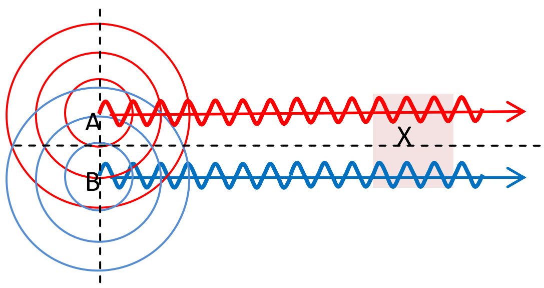


Constructive interference takes place where waves arrive in phase. When the crest of one wave meets the crest of another wave, they reinforce to produce a larger crest. Similarly, when two troughs meet they reinforce to produce a larger trough. Points at which constructive interference takes place are called **antinodes**. An **antinodal line** joins a series of nodes. In a ripple tank, large ripples flow along these lines.

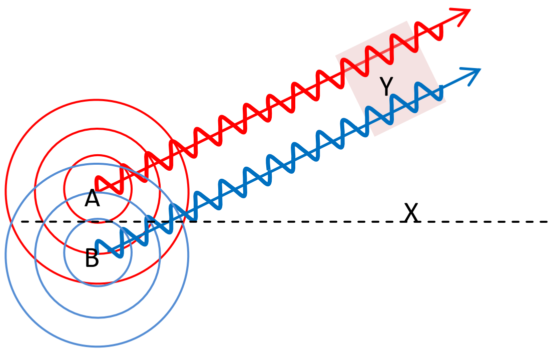


INTERFERENCE AND PATH DIFFERENCE

Sources A and B in the diagram produce waves in phase with one another. Imagine you are standing at point X, equidistant from both sources. The waves from each source take the same time to reach you and they travel the same distance from the source to reach you. Because the path difference (the difference between AX and BX) is zero, the waves reach you in phase and you will be at the point of constructive interference. X is on the **zero order** antinodal line, at a point of zero path difference.

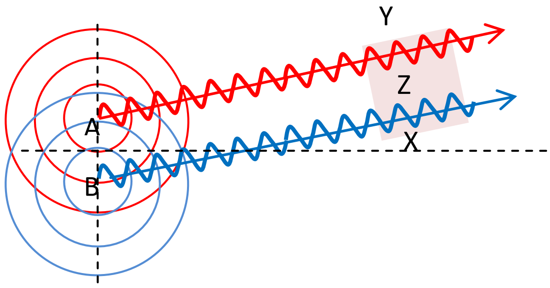


Now imagine you are standing at the point Y; your distance from B is greater than your distance from A. The path AY is 10 wavelengths long (10λ). Path BY is 11 wavelengths long (11λ). The path difference (BY–AY) is one wavelength (1λ). The waves arrive at Y in phase with each other, so they reinforce to form a large wave: an antinode. Your position is on one of the first-order antinodal lines, where the path difference is 1λ.



If the path difference is exactly a whole number of wavelengths, the waves arrive with the same phase difference as they left the source. If the sources are in phase, constructive interference occurs when the path difference is $n\lambda$, where n is an integer called the 'order' for an antinodal line.

Now imagine you are standing at the point Z. Your distance from B is greater than your distance from A by exactly half a wavelength. The waves arrive at Z out of phase, so they cancel each other out to create a node.



If the path difference is ½ λ, 1½ λ, 2½ λ and so on, waves from in-phase sources arrive out of phase and there is destructive interference. Nodes occur where the path difference is $\left(n+\frac{1}{2}\right)\lambda$.

Example: Water waves from two sources, that are coherent and in phase, arrive at a boat. The wavelength of the waves is 2.2 m. A person in a dingy is 14.2 m from one location and 8.7 m from the other. Determine whether the boat is at a nodal or antinodal position and describe the motion of the boat.

Answer

$\lambda = 2.2\text{ m};\quad d_1 = 11.2\text{ m};\quad d_2 = 8.7\text{ m}$

$$\text{Path difference} = d_1 - d_2 = 14.2 - 8.7 = 5.5\text{ m}$$

Number of wavelengths:

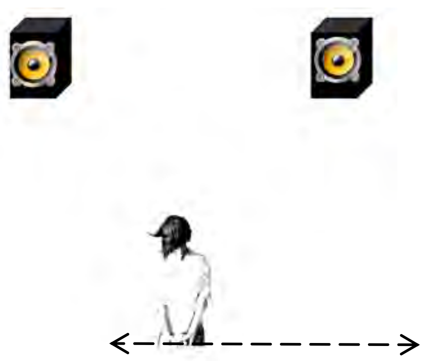
$$= \frac{5.5}{2.2} = 2.5$$

Because the path difference is 2.5λ, the waves will arrive at both locations in antiphase, so the boat will be at a nodal point, where the waves tend to cancel. The amplitude of the waves from the closer location will be slightly larger than the waves from the further location, so there will be small waves.

INTERFERENCE OF SOUND WAVES

When sound waves from different sources arrive at the same time in a given spot, they interfere with each other.

The diagram shows two speakers which are producing sounds of the same amplitude and wavelength, in phase with each other. They are equidistant from the person standing in front of them. She will hear a loud sound due to constructive interference.



In locations where the compressions and rarefactions are out of phase, their interaction creates a wave with a soft sound due to destructive interference.

If the listener moves to the left or right she will hear a soft sound due to destructive interference. By continuing in the same direction she will hear soft and loud sounds which are caused by interference of waves from the speakers.

5B DEMONSTRATIONS OF 2-D INTERFERENCE

Use the Topic webpage to watch video demonstrations which show interference from ripples and from loudspeakers.

BUILDING DESIGN

Sound waves from different speakers can interfere so destructively with each other that they produce dead spots or places where no sound is heard. Dead spots occur when the compressions of one wave line up with the rarefactions from another wave and cancel each other. Sound engineers who design theatres or auditoriums must take sound-wave interference into account. The shape of the building and the materials used to build it are chosen based on interference patterns. The speakers are placed to avoid interference of sound so every member of the audience is able to hear loud, clear sounds.

The domed roofs of the Sydney opera house affected the sound inside by creating interference patterns.

Example: Two speakers placed side by side at a distance of 1.0 m generate waves of frequency 200 Hz. The speed of sound in the air is 340 m s^{-1}. A person is 8.0 m from one speaker and 5.6 m from the other.

a. Calculate the wavelength of the waves in air.

b. Will the person hear a loud sound or a soft sound?

Answer

a.

$$\lambda = \frac{v}{f} = \frac{340}{200} = 1.6 \text{ m}$$

b. The path difference = longer distance – shorter distance = 8.0 -5.6 = 2.4

$$\text{path difference} = 8.0 - 5.6 = 2.4$$

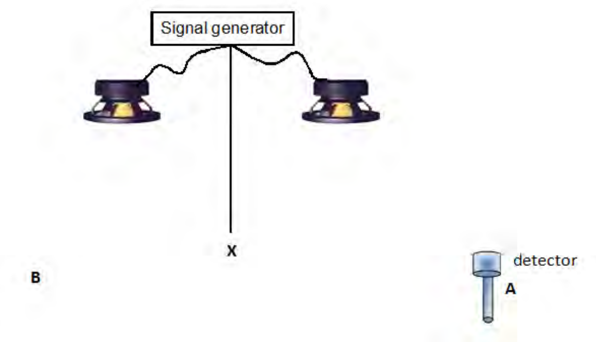
In this path there are:

$$\frac{2.4}{1.6} = 1.5 \text{ waves}$$

Because there is half the number of waves in the path difference there is destructive interference, so the person will hear a soft sound.

5C CHECK YOUR UNDERSTANDING: SOUND INTERFERENCE

1. Two small identical speakers are set up in a room where reflection is negligible. The speakers are connected to a signal generator and produce identical sounds of single frequency. They are wired to emit the sound in phase with one another. A sound detector moves slowly from A to B in front of the speakers as shown in the diagram. It records the intensity of the sound as it moves.



a. As the detector moves along the line AB, the intensity of the sound repeatedly increases and decreases. Explain this change in intensity and identify the position of the loudest sound.

b. How would the intensity of sound at X change if one speaker was out of phase with the other by 180^{o}? Explain your answer.

Check your answers.

CALCULATION OF WAVELENGTH

This diagram shows constructive interference where the path difference to the detector from the sources is 1λ.

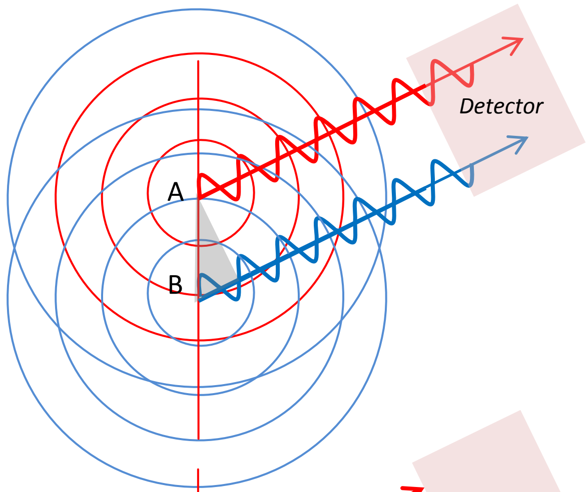
The extra distance travelled by the waves from B is shown by the shaded triangle.

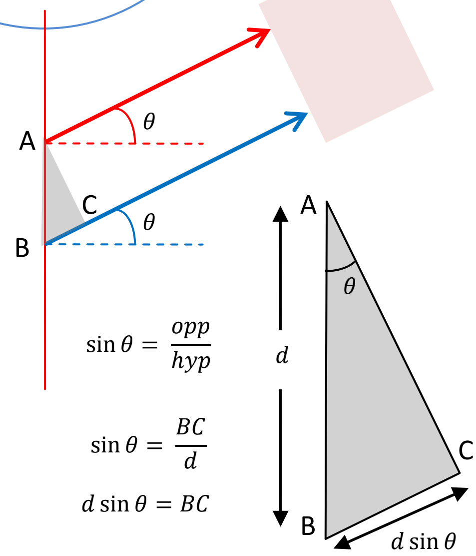
When the sources are in phase, constructive interference occurs when:

$$\text{path difference} = n\lambda$$

The diagram shows how we can apply trigonometry to the shaded triangle ABC. This shows that the path difference ($n\lambda$) is related to the distance between the sources (d) and the angle θ:

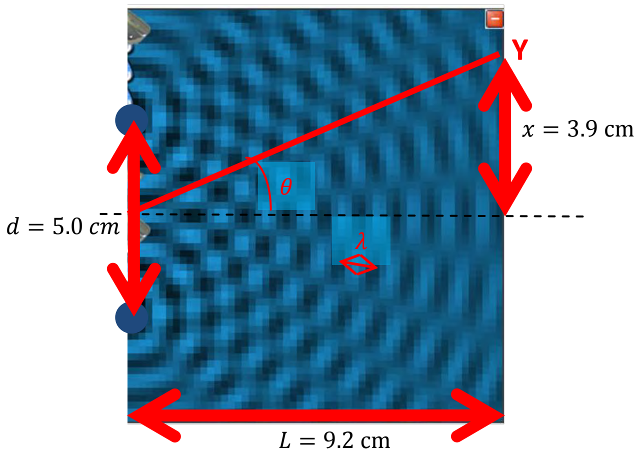
$$n\lambda = d\sin\theta$$





Example: A student sets up a ripple tank to study two-source interference. The distance (L) from the sources to the end of the tank is 9.2 cm. The distance between the sources (d) is 5.0 cm. The student measures the distance from a maximum (antinode) to the zeroth antinodal line (x) as 3.9 cm.

a. Calculate the angle θ.
b. State the order of the maximum which appears at Y.
c. Calculate the wavelength of the waves, λ



Answer

a.

$$\tan\theta = \frac{opp}{hyp} = \frac{3.9\text{ cm}}{9.2\text{ cm}} = 0.4239$$
$$\theta = \tan^{-1} 0.4239$$
$$\theta = 23°$$

b. 2

c.

$$n\lambda = d\sin\theta$$
$$\lambda = \frac{(5\times10^{-2}\text{m})\sin 23°}{2}$$
$$\lambda = 9.8\times10^{-3}\text{m}$$

5D CHECK YOUR UNDERSTANDING

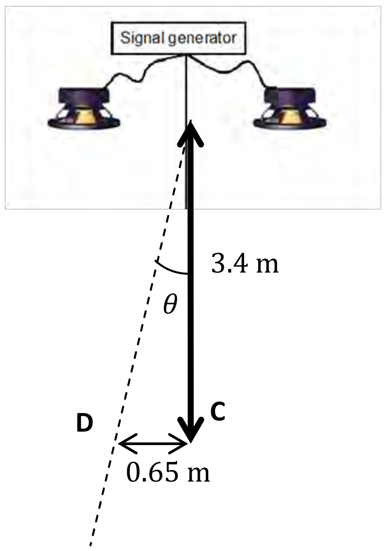
1. Two small identical speakers emit a constant tone of frequency 500 Hz. The speed of sound in the air is 340 m s^{-1}.

   a. Calculate the wavelength of the sound waves emitted by the speakers.

   ____

   ____

   ____

   b. A student, who is 3.4 m from the speakers, locates the central maximum at C. He then locates the next maximum at D, 65 cm from C, as shown in the diagram. Use this information to calculate the angle θ, between the zeroth and the first-order antinodal lines.

   ____

c. Use your answer to (b) to calculate the separation of the speakers.

Check your answers.

KEY POINTS

- To produce a steady interference pattern, waves must have approximately the same amplitude and they must be coherent (that is, the waves must have the same frequency and a constant phase relationship).
- The separation of nodal and antinodal lines increases if the wavelength is increased or if the sources are brought closer together.
- When the sources are in phase, constructive interference occurs when:

$$\text{path difference from sources} = n\lambda$$

- The path difference ($n\lambda$) is related to the distance between the sources (d) and the angle θ, so, for constructive interference from sources that are moving in phase:

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

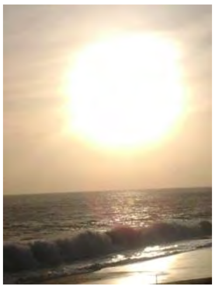
6 INTERFERENCE OF LIGHT

LEARNING INTENTIONS

In this lesson you will learn to:

- describe how to produce a two-source interference pattern with light
- explain how this interference pattern provides evidence of the wave nature of light
- carry out calculations related to double-slit interference.

INTRODUCTION



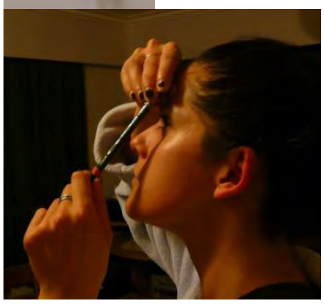
Is light a series of waves or a stream of particles? The exact nature of light is a mystery that has puzzled scientists for centuries. Some ancient Greek thinkers believed that every visible object emits a steady stream of particles while others, such as Aristotle, maintained that light travels in a manner similar to that of waves in the ocean. Although there have been many modifications to the theory of nature of light over the years, the essence of the dispute established by the Greek philosophers remains to this day. This lesson introduces you to the first experiment that was conducted to prove that light travels in waves.

Caution!
In the following experiments you will use a laser. You must never point the laser at a person's eye – it can cause blindness. Also make sure that the reflected laser beam does not hit your eye. Always keep the laser away from small children. Te Kura is not responsible for any misuse of the laser.

SINGLE-SLIT DIFFRACTION

6A

HANDS-ON ACTIVITY: DIFFRACTION AT A SINGLE SLIT



What you need:

1. two pencils
2. two rubber bands
3. a strong light source such as a bright sky or light bulb
4. a laser pointer*
5. a white wall or a white paper screen.

*Contained in the wave equipment box.

What you do:

1. Hold the pencils together and wrap a rubber band around one end. At the other end, wrap the second rubber band around one of the pencils, and then wrap the rest of the rubber band around both of them. This will create a small gap between the pencils.
2. Hold the pencils about 8–10 cm from one eye and close the other eye. Look through the gap between the pencils toward a bright window or a bright light bulb. Squeeze the pencils together. You should see very fine dark and bright lines in the gap.

Use the idea of diffraction and interference to explain the appearance of the lines.

3. Hold the pencil 20 cm from a white wall or a screen made from a white piece of A4 paper stuck on to a cereal box. Hold the laser head against the pencil and shine the laser through the gap at about the middle of the pencils.

4. Make sure the beam is at 90^{o} to the wall or screen. The laser beam will create a spot on the screen. (You will get a better result if you do this at night or in a dark room.)

5. Slowly move away until you see very fine red and black bands on both sides of the centre spot of the laser. You need to jiggle the laser a bit to get this pattern. When you a get a good pattern, stop moving.
How does the shape of the laser spot change as you move away from the screen?

6. When you can see fine red and black bands on both sides of the centre spot, stay in that position. Watching the screen carefully as you move the laser beam gradually along the gap between the pencils to the narrow end of the gap. How does the spacing between the red and black bands change?

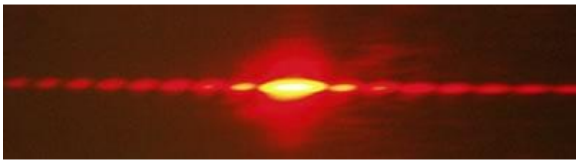
Check your answers.

SINGLE-SLIT DIFFRACTION

The faint bright and dark lines that run parallel to the pencils are created by light waves. The light diffracts at the edges of the pencils and, as it travels to your eye, it interferes to produce bright and dark bands. The bright lines are caused by constructive interference of the light waves where the waves arrive in phase and are reinforced. The dark lines are caused by the destructive interference of light waves where they arrive out of phase by 180^{o} and cancel each other out.

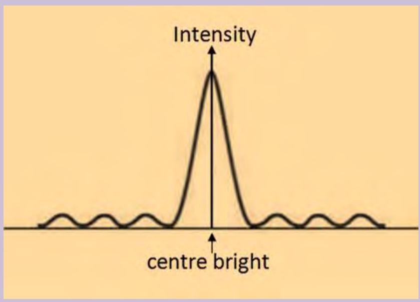
Light from a cloudy sky, photographed as it diffracts from a pencil gap.

The laser beam forms a bright spot with dark and bright bands on either side. These are caused by interference of the diffracted light from the pencil edges.



Diffraction pattern from a laser point passing through the gap between two pencils.

In lesson 4 you used a PhET simulation to study diffraction. The PhET activity shows that the precise pattern depends on many variables. Fraunhofer diffraction is the name of the well-defined pattern produced when light from a very distant object travels through a slit.



A Fraunhofer diffraction pattern: the central spot is the brightest. The light intensity decreases rapidly on either side. The bands are very close to each other.

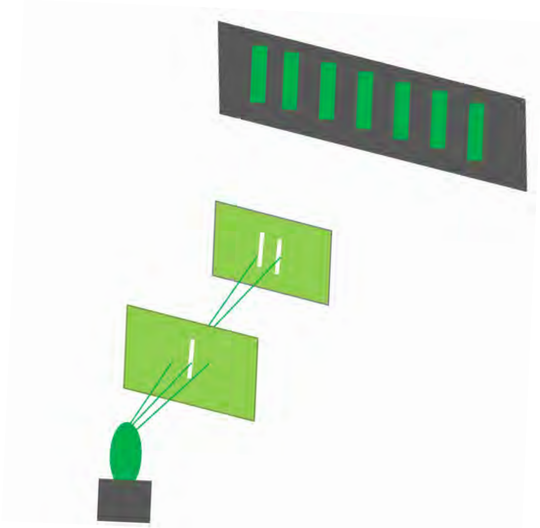
Joseph Fraunhofer was a Bavarian glassmaker who designed and built telescopes in the early 19th century. He developed the spectrometer and invented the diffraction grating.

YOUNG'S DOUBLE-SLIT EXPERIMENT

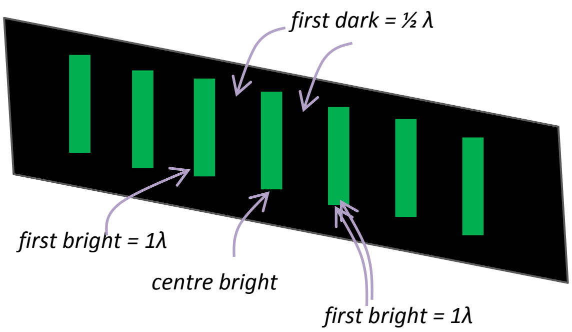
A steady interference pattern is only produced if the sources are coherent. That means they have the same frequency (wavelength) and they are either in phase or have a constant phase difference.

A simple experiment of the interference of light was first demonstrated by Thomas Young in 1801. It provided evidence that light is a wave. First the light falls on a screen with a narrow single slit.This slit ensures that the light comes from a tiny, coherent region of the source.

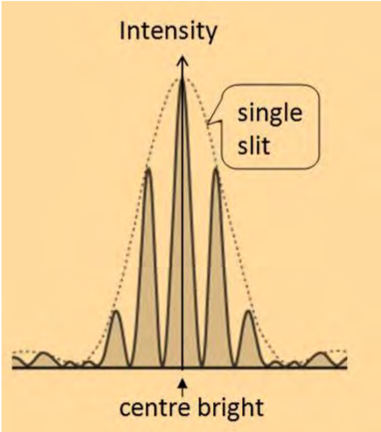
The diffracted light waves from the single slit hit a screen that contains two narrow, parallel slits. The waves diffracting from the double slits originate from the same wave front and are therefore always coherent and in phase.



A pattern of dark and light bands was formed on a screen placed well away from the double slit. (Young called these lines 'fringes'.) The bright bands are areas of constructive interference (antinodes). Here, the waves arrive in phase to cause reinforcement. The dark bands are areas of destructive interference (nodes). Here the waves arrive out of phase by $180°$ to cause cancellation.



This graph compares the brightness and the bandwidth of a double-slit interference with a single slit one. The main feature of single-slit interference is that the centre band is the brightest and the widest of all bands. In a double-slit interference the central band is still the brightest and the intensity of the other bright bands varies as the distance from the centre is increased. Notice that the bandwidth in this case is much smaller than that of a single slit.



6B INTERFERENCE OF LIGHT

1. Explain why interference of light can be observed if one source of light is split into two, but it cannot be observed when two separate sources are shone across each other.

___

___

___

___

Check your answers.

THE INTERFERENCE EQUATION FOR SMALL ANGLES

This diagram shows an interference pattern produced from light from two coherent, in-phase sources separated by distance d.

The wavelength of the light (λ) can be calculated using the interference formula:

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

In this case θ is the angle between the zeroth and the second antinodal lines.

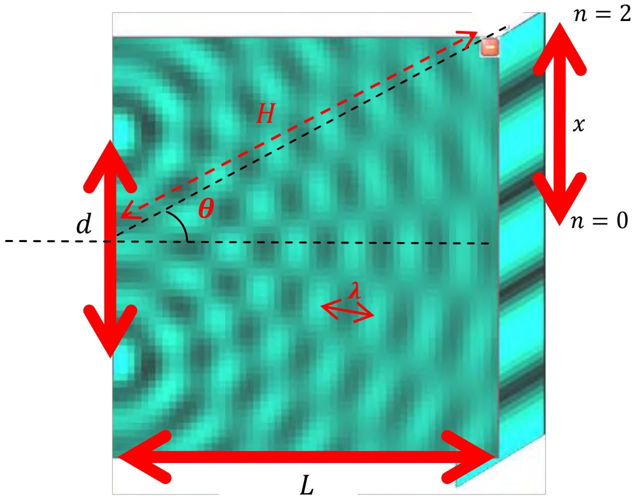
$$2\lambda = d\sin\theta$$

When L is much larger than x, at angles of θ less than about 4°:

$$\tan\theta \approx \sin\theta$$

Because:

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



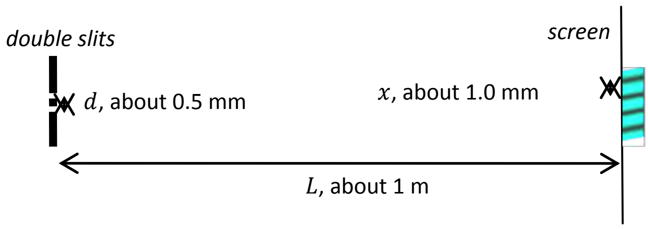
$$\tan\theta = \frac{opposite}{adjacent} = \frac{x}{L}$$

$$\sin\theta = \frac{opposite}{hypoteneuse} = \frac{x}{H}$$

When L is much larger than x:

$$n\lambda = \frac{dx}{L}$$

x = distance from central fringe (m)
n = an integer, the order of the fringe
d = distance between the slits (m)
L = distance from the screen to the double slit (m)



It is difficult to make a pair of slits closer than about 0.5 mm and still have them wide enough to make a visible pattern. Because the wavelength of light is so small, the slits need to be about a metre from the screen to make a pattern of fringes 1 mm apart. For this arrangement θ is well under 4°, so the approximation is valid.

MEASURING THE WAVELENGTH OF LIGHT

Young's double-slit experiment provides a method for measuring the wavelength of light.

We can measure the quantities d and L and x in an experiment, so we can calculate λ:

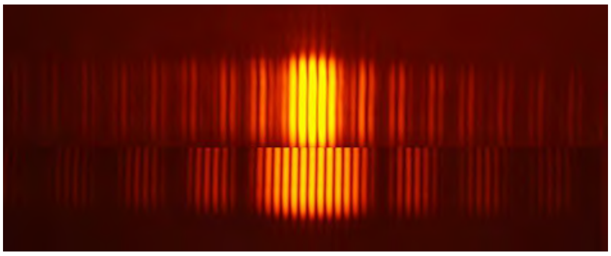
$$n\lambda = \frac{dx}{L}$$

White light contains different colours – it does not have a single wavelength. It is a mixture of colours with different wavelengths. The wavelengths visible to the human eye range between 3.5×10^{-7} m and 7.8×10^{-7} m. If white light is used to observe Young's fringes the central line is white, but the others have 'rainbow' edges because each colour of light produces fringes spaced in proportion to its wavelength.

6C ONLINE ACTIVITY: EXPERIMENTS WITH LIGHT

Use the links on the Topic webpage to watch laboratory demonstrations showing diffraction and interference using different colours of light.

These two photographs were taken by using a digital camera to replace the screen. The yellow light is from a sodium lamp (a yellow street light), which is useful because it only has one wavelength.
The separation of the slits was 0.25 mm for both photographs.
The two photographs show the effect of slit width.
The top pattern was produced by 0.08 mm slits, the bottom pattern by 0.04 mm slits. The camera was 15 cm behind the slits.



Example 1: A screen is placed 1.37m from a double slit. The yellow light travelling through the double slit causes an interference pattern on the screen. The third bright yellow band is seen on the screen 0.250 cm from the central one. If the slits were cut 0.0960 cm apart, calculate the wavelength of this light.

Answer

$L = 13.7$ m; $\quad n = 3$; $\quad x = 0.250$ cm $= 0.00250$ m; $\quad d = 0.0960$ cm $= 9.60 \times 10^{-4}$m

$$n\lambda = \frac{dx}{L}$$

$$3\lambda = \frac{9.60 \times 10^{-4} \times 0.00250}{1.37} = 1.75 \times 10^{-6}$$

$$\lambda = \frac{1.75 \times 10^{-6}}{3} = 5.84 \times 10^{-7} \text{ m}$$

Example 2: In a Young's double-slit experiment, light of wavelength 400×10^{-9} m is used. The distance between the slits is 0.10 mm and the screen is placed 1.0 m from the slit.

a. Calculate the separation of the bright bands.
b. Explain whether the distance between the bright bands will increase or decrease if the wavelength of the light is higher. Assume all other factors are unaltered.

Answer

a. $\lambda = 400 \times 10^{-9}$m; $\quad d = \frac{0.10 \text{ mm}}{1000} = 1.0 \times 10^{-4}$ m; $\quad L = 1.0$ m; $\quad x = ?$

If x is the distance between the first and the central band, then the value of $n = 1$.

$$n\lambda = \frac{d \times x}{L}$$

$$1 \times 400 \times 10^{-9} = \frac{1 \times 1.0 \times 10^{-4} \times x}{1.0}$$

$$x = \frac{1 \times 400 \times 10^{-9} \times 1.0}{1.0 \times 10^{-4}} = 4.0 \times 10^{-3} \text{ m}$$

b. The distance will increase because, in the interference equation, the wavelength and the distance between the bands are directly proportional provided all other factors remain the same.

6D CHECK YOUR UNDERSTANDING: WAVELENGTH OF LIGHT

1. Choose the correct word.

   In an experiment to observe Young's fringes, the separation (x) of the bright bands is increased if:

   a. the slit separation (d) / is *increased/decreased*

   b. the wavelength of light (λ) is *increased/decreased*

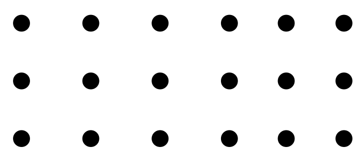
   c. the distance (L) from the screen to the double slit is *increased/decreased*.

2. A double slit of width 0.050 cm is placed 5.0 m from a screen.

   a. How far from the central band will the first bright violet light form when the slit is illuminated with a violet light of wavelength 350 nm. (1 nm = 1.00×10^{-9} m)

   b. The violet light is replaced with a red light of wavelength 700 nm. Show that the first red band from the centre will appear at twice the distance as the first violet band.

3. When you shine a laser through a fine mesh material onto a wall, it creates a pattern of dots.

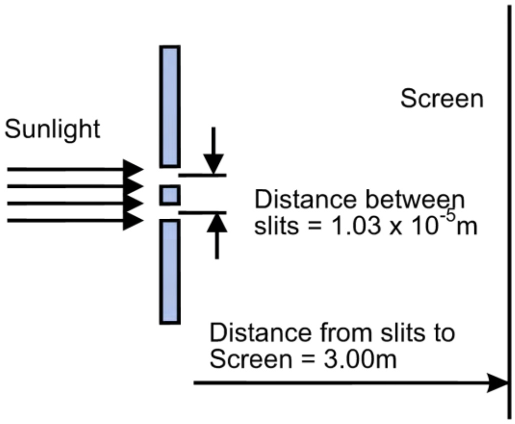
   

   a. Explain why this pattern forms.

   b. How will the pattern change if the mesh material and the laser are moved back from the wall? Explain your answer.

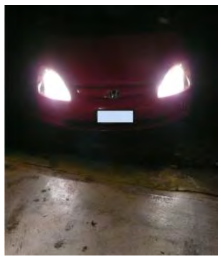
   c. The laser is replaced by another laser of a shorter wavelength. Explain how this will change the pattern.

4. Young's double-slit experiment is carried out with sunlight shining through a double-slit screen.
   a. Explain why the fringes that are produced using sunlight have blurred, coloured edges.



   b. When the sunlight is replaced with a hand-held laser of light wavelength 431 x10^{-9} m, a pattern is produced on the screen. Describe the pattern (with a sketch or in words).
   c. Calculate the distance between the two dark bands seen on either side of the central band.

   d. A car has two identical head lamps that light up the road evenly. Explain why wave cancellation means the driver cannot see any dark patches on the road.



Check your answers.

KEY POINTS

- To produce a steady interference pattern there must be coherent (constant phase relationship) waves with similar amplitudes arriving in the same place from at least two sources.
- Young's double-slit experiment provides evidence that supports the wave nature of light.
- When $x \ll L$, the condition of constructive interference $n\lambda = d\sin\theta$ can be written as:

$$n\lambda = \frac{dx}{L}$$

where $x$is the distance between the n^{th} antinodal line and the central line, λ is the wavelength, the slits separation is d and the distance between the slits and the screen is L.

7 DIFFRACTION GRATINGS

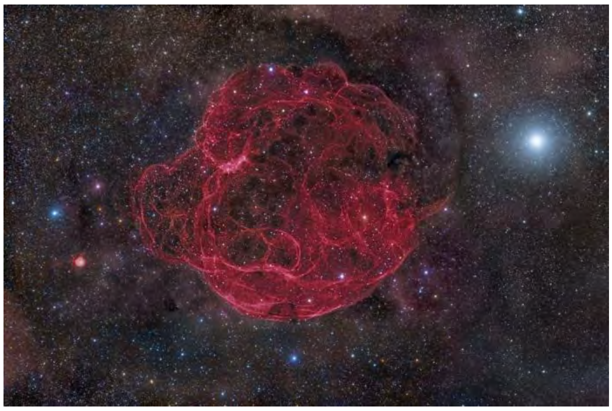
LEARNING INTENTIONS

In this lesson you will learn to:

- describe and explain the interference patterns produced by multiple slits and diffraction gratings
- solve problems relating to interference patterns from slits
- outline the uses of diffraction-grating spectrometers in astronomy.

INTRODUCTION

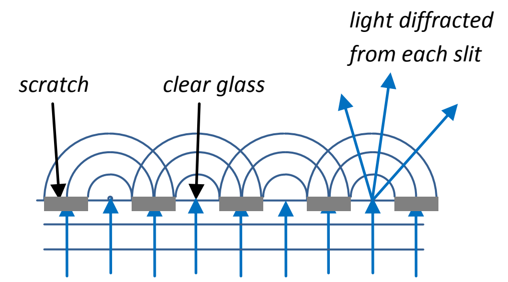
Luminous objects (those that give off their own light) produce specific wavelengths of light. By analysing the wavelengths emitted by the object, we can determine what the object is made of, how hot it is and how fast it is moving towards Earth (by measuring Doppler shift). The study of spectra (the range of wavelengths emitted and absorbed by an object) is called spectroscopy. The key element in an astronomical spectrometer that separates light waves by their wavelength is a diffraction grating, which is the subject of this lesson.



Supernova remnant Simeis 147, with colourful stars in the background. We can determine a star's composition by studying the wavelengths of the light it emits

DIFFRACTION GRATINGS

A diffraction grating is a screen with multiple narrow parallel slits. Light diffracts as it goes through each slit, providing multiple sources of coherent light. Because there are lots of slits, they can be very narrow and very close together and still let plenty of light through. The diffracted light interferes to create a very sharp interference pattern.



Grating used to be made with special ruling engines which scratched very fine lines on a piece of glass.

HOW BIG IS THE SPACING?

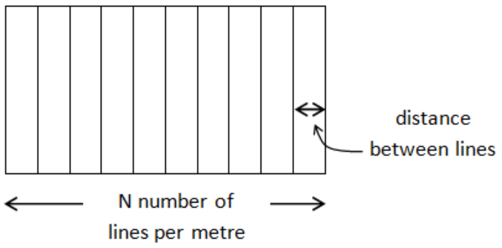
A typical spectrometer grating could have as many as 10 000 slits in 1 cm, and thus the slit separation is much smaller than that used in the double-slit interference experiment.

If a grating is marked as '6 000 lines per centimetre', the distance between two adjacent slits is $\frac{1\text{ cm}}{6000}$. Because $1\text{ cm} = \frac{1.0}{100} = 0.01\text{ m}$, the distance between two adjacent slits in a metre is = $\frac{0.01\text{ cm}}{6000.}$. This is equal to $1.67 \times 10^{-7}\text{ m}$.

If there are N lines per **metre**, the slit width d in metres is:

$$d = \frac{1}{N}$$

Normally N is given as the number of lines per 1 cm or 1 mm. You need to convert 1 cm or 1 mm into metres before you use the above formula.



7A QUICK QUIZ: DIFFRACTION GRATINGS

1. A diffraction grating has 10 000 lines per cm. Calculate the spacing between the lines.

2. What is the slit width for a diffraction grating which has 400 lines/mm?

3. The slit width for a diffraction grating is 1.45×10^{-5}m. How many lines are there in 1.0 cm of the grating?

Check your answers.

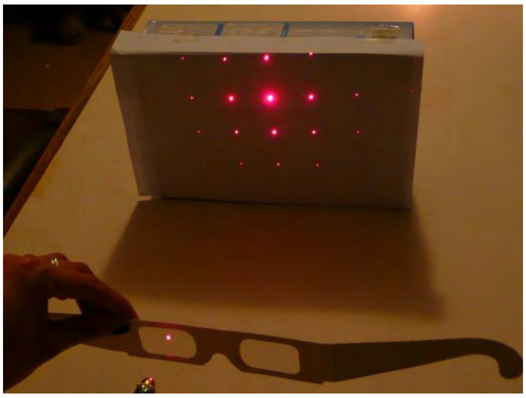
7B HANDS-ON ACTIVITY: DIFFRACTION OF LASER LIGHT

Caution! Never point the laser, or a reflection of the laser, at a person's eye. Do not look down the laser beam. Always keep the laser away from small children.

What you need:

- a laser pointer*
- diffraction glasses*
- a white paper screen.

*Contained in the wave equipment box.



What you do:

1. Make a screen (for example, by attaching an A4 sheet of paper to a cereal box).

2. Hold the laser pointer about 30 cm from the screen and shine it through one of the transparent segments of the glasses as shown in the photograph. You will see a pattern like the one shown.

3. Slowly move the laser and the glasses away from the screen while watching the bright spots. The distance between two adjacent horizontal spots *increases/decreases/stays the same.*

4. Look at the central (brightest) row of horizontal spots.
   a. Record the number of spots on one side of the centre spot. ________
   b. The first spot on either side of the centre spot is called the first order and the next one is the second order. In the space given, sketch one of the horizontal set of spots seen and label the orders.

5. Explain how a bright spot is formed.

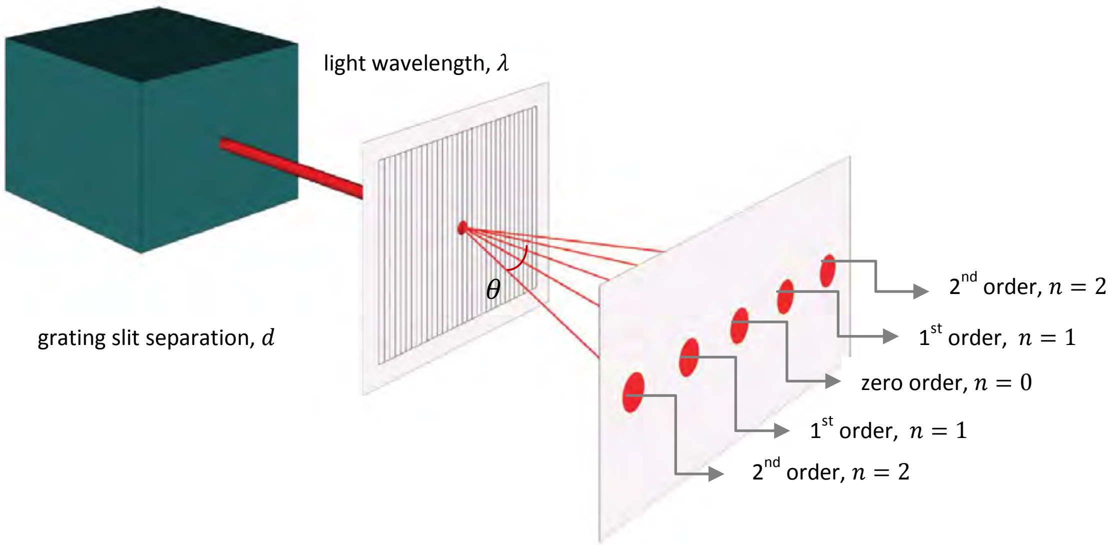
____

____

____

Check your answers.

INTERFERENCE PATTERNS FROM A DIFFRACTION GRATING



The diagram above shows the pattern of light on a screen from a laser shone through a diffraction grating with vertical slits. The laser light is monochromatic (single-coloured), so it contains only one wavelength.

The bright spots form by constructive interference, exactly as they do from two slits. Bright spot spots form where the waves, from all the slits, arrive in-phase, with a path difference of $n\lambda$ (where n can be 0, 1, 2, 3 …)

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

WAVELENGTH OF LASER LIGHT

1. The photograph on the right was taken using a 633 nm laser through a grid of 150 slits, width 0.0625 mm, 0.25 mm separation between their centres.

   Calculate the angle between the first antinodal line and the central maximum (the zeroth antinodal line).

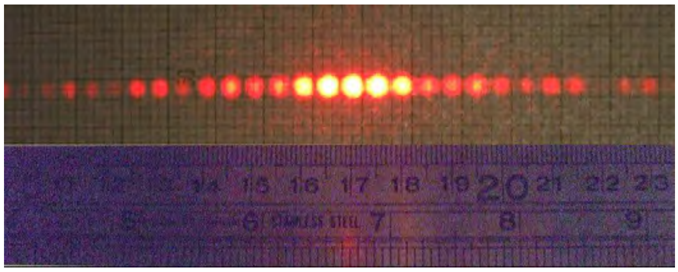


Photo: Shim'on (talk) and Slava Rybka.

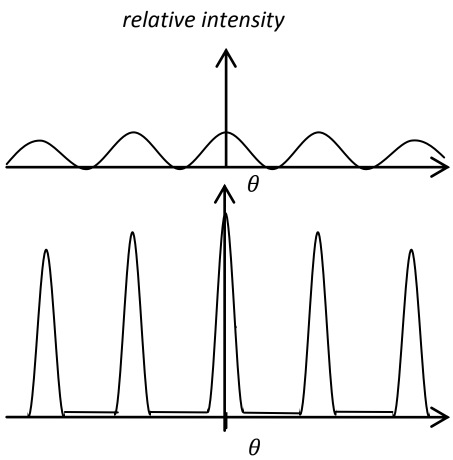
Check your answers.

COMPARISON WITH DOUBLE-SLIT INTERFERENCE

The diffraction grating has advantages over the double-slit method of measuring wavelength, in that:

1. the beam passes through more than two slits, so the bright bands are brighter
2. the maxima are more sharply defined
3. the angles between the bright bands are larger, so they can be measured with greater precision.

The positions of the bright spots depend on the wavelength and the slit separation. The positions are due to constructive interference from all slits.
The most striking difference between the double-slit pattern and the pattern from a diffraction grating is the lack of light at other angles.
The double-slit pattern shows a gradual change from maximum to minimum intensity. But the grating has precise angles at which light appears. For all other angles there is total destructive interference. This is because the waves reaching the screen differ progressively in phase, so at all angles (except the 'constructive' angles), there are waves in antiphase which cancel.



Graphs of intensity vs diffraction angle for a double slit and for 10 slits with same slit separation.

HOW MANY DIFFRACTION LINES?

The narrow lines of a diffraction grating can diffract light in all directions from the slit, up to 90° from the central line.

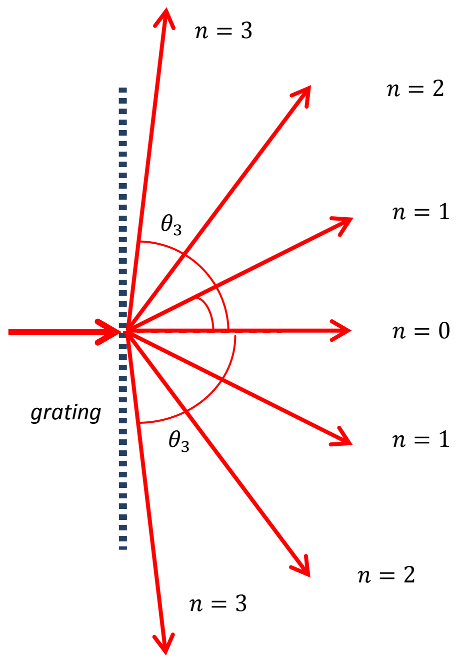
The maximum value for $\theta$is 90°:

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

$$n\lambda = d\sin 90°$$

$\sin 90° = 1,$ so the maximum value of n can be calculated:

$$n\lambda = d$$



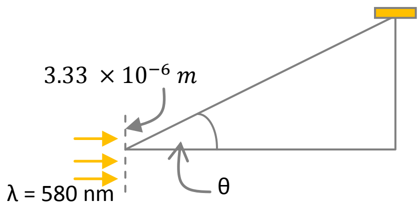
Example: A diffraction grating has 300.0 lines per mm. It is illuminated by light of wavelength 580° nm.

a. Calculate the angle of diffraction for the first order maxima.

b. How many maxima will form?

Answer

a. λ = 580 nm = 580 x10^{-9} m; *d* = 300 lines per mm



There are 300 lines per mm, so

$$d = \frac{1}{N} = \frac{1}{300} = 3.33 \times 10^{-3} \text{ per mm}$$

The number of lines per metre is

$$\frac{3.33 \times 10^{-3}}{1000} = 3.33 \times 10^{-6}$$

For the first order n = 1. The angle for the first order maximum is:

$$3.33 \times 10^{-3} \sin\theta = 1 \times 580 \text{ x } 10^{-9}$$

$$\sin\theta = \frac{1 \times 580 \times 10^{-9}}{3.33 \times 10^{-6}} = 0.1742$$

$$\theta = \sin^{-1}(0.159) = 10.0°$$

b. The greatest number of maxima is formed when $\theta = 90°$. The highest order maximum is:

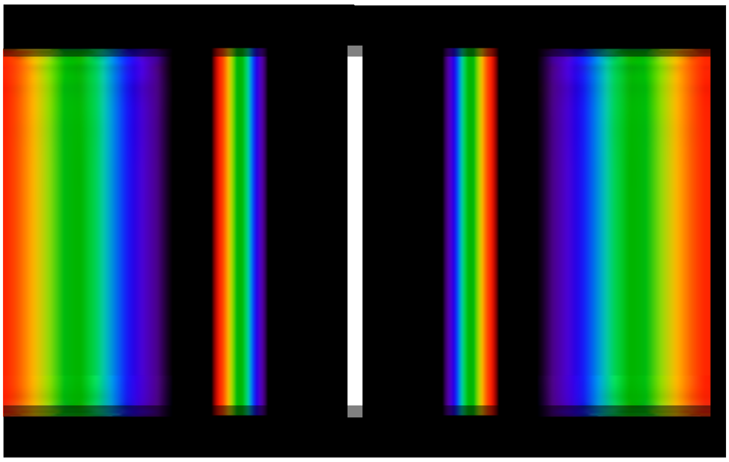
$$n = \frac{d}{\lambda} = \frac{3.33 \times 10^{-6}}{530 \text{ x } 10^{-9}} (= 6.28) = 6$$

(Because the orders of maxima have to be whole numbers, the maximum order has to be 6. If the answer to the problem had been 6.87, the maximum order would still be 6, although the nearest whole number is 7.)

DIFFRACTION OF WHITE LIGHT

Visible light that appears white is actually a mixture of colours – it contains a range of wavelengths. A diffraction grating can be used to split light into different wavelengths for analysis. Prisms can also separate light into different colours, but diffraction gratings can separate them by a larger angle, so most spectrometers use diffraction gratings. As the beam passes through the diffraction grating, different wavelengths of light are directed in different directions.

The picture shows the pattern on a screen when white light is shone through a diffraction grating. The centre band is called the centre maximum or zero order and it is bright white. The waves arrive here in phase and the path difference is zero; so the value of n = 0.



There is a dark band on either side of the central band where the waves arrive out of phase to create cancellation.

For the first spectrum of colours, either to the left or to the right, the path difference is 1λ. For the second set of spectra the path difference is 2λ.

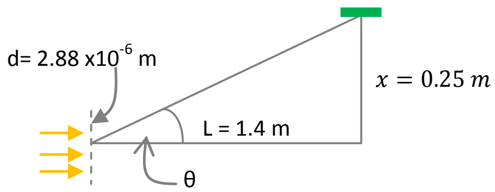
The violet light has the smallest diffraction angle because it has the shortest wavelength. Red light has the largest diffraction angle because the wavelength of the red light is largest. The larger the wavelength, the larger the diffraction angle for all orders.

Example: A pure white light is shone onto a screen through a diffraction grating of spacing 2.88×10^{6} m. The screen is placed 1.4 m from the grating. The green part of the first order spectrum is seen 2.5 cm from the centre. Calculate the wavelength of the green light.

Answer

$$d = 2.88 \times 10^{-6}\ \text{m}; \quad n = 1; \quad \lambda = ?$$

From the diagram:



$$\tan\theta = \frac{x}{L} = \frac{0.25}{1.4}$$

$$\theta = \tan^{-1}\left(\frac{0.25}{1.4}\right) = 10.02°$$

$$3.0 \times 10^{-6} \times \sin 10.02° = 1 \times \lambda$$

$$\lambda = 5.21 \times 10^{-7} = 521\ \text{nm}$$

HANDS-ON ACTIVITY: DIFFRACTION OF WHITE LIGHT

What you need:

- at least one type of electric light (such as a table lamp)
- diffraction glasses*

*Contained in your wave equipment box.

Three different types of electric light: incandescent, compact fluorescent and led. Compare the spectra from different lamps if you can.

What you do:

1. Draw the curtains in the room to make it dark. Angle the table lamp toward you and turn it on.

2. Put the glasses on and look at the table lamp. You will see coloured spectra of the light in all directions. Look at the spectra on the horizontal level.
   a. How many spectra are there on one side of the lamp? _______________
   b. Write down the colours seen in their order for the first horizontal spectrum on your left.
   ____

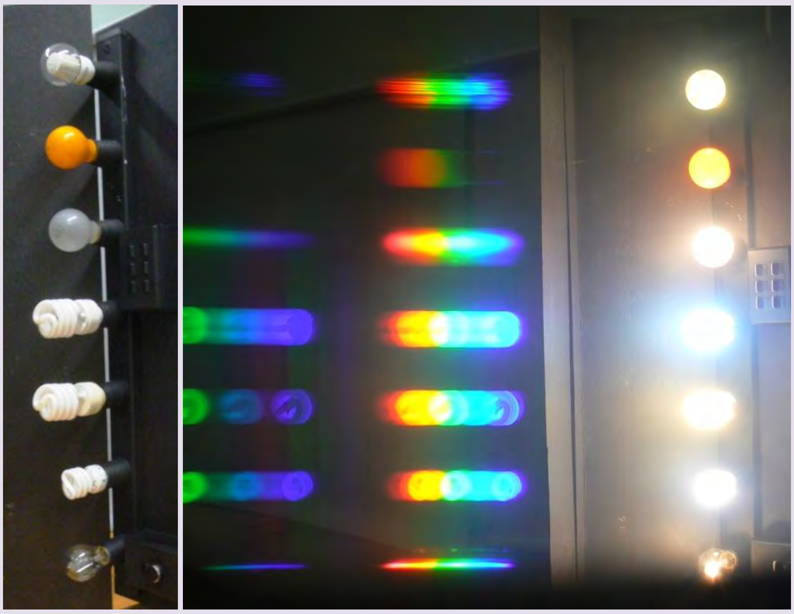
3. Walk slowly back from the light while watching the spectra on the horizontal level. Write down how the spacing between the spectra changes when you move away from it.

   ____

Check your answers.

WHAT IS 'WHITE LIGHT'?

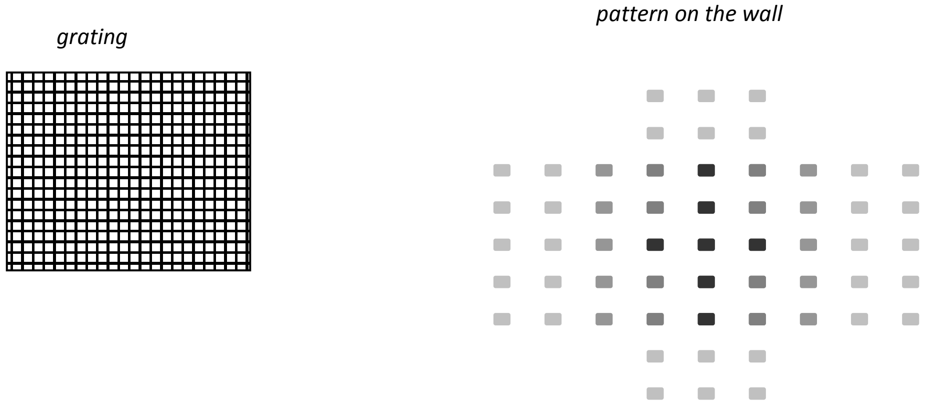
If you look at a piece of white paper in daylight it looks white. In artificial light it will also appear to be white, but if you could compare the two directly you would see a difference. Candles and incandescent lamps are much more orange than daylight. Other artificial lights (such as fluorescent and l.e.d. lights) produce a mixture of distinct wavelengths to make artificial daylight, or a warmer, more orange light.



A row of electric lights, viewed through diffraction glasses.All but the yellow lamp are 'white' but there spectra are different showing that the 'white' is made with slightly different mixes of colours.

7E CHECK YOUR UNDERSTANDING

1. A laser beam is shone through a diffraction grating which contains horizontal and vertical lines. The observed pattern of bright spots is shown below.



   a. Explain why the laser light spreads out in the vertical and horizontal directions.

   b. Explain why no interference pattern is observed if the mesh has holes that are 2.0 mm apart.

   c. Explain how the dark places between the bright spots in the pattern are produced.

2. The laser is now shone through a diffraction grating that has 650 lines per mm.
How about:

   a. A diffraction grating and a double-slit (with slit separation of 0.10 mm) both produce interference patterns. State and explain three differences between these interference patterns.

b. Explain why it is better to use a diffraction grating than a double slit to check the laser's wavelength.

c. When white light is shone through the grating, coloured spectra are formed. Explain the appearance of these colours.

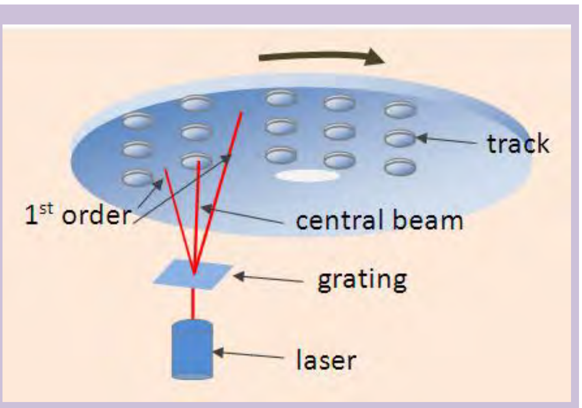
Check your answers.

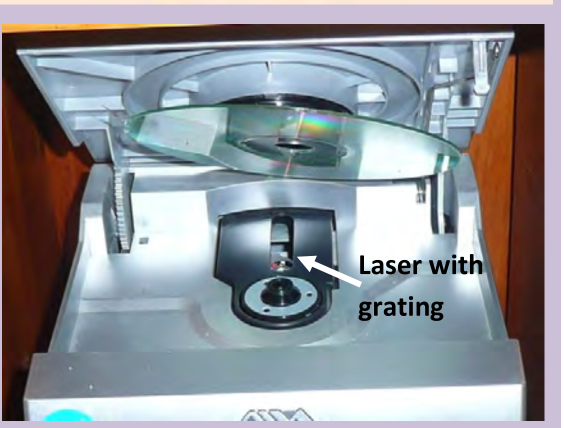
DIFFRACTION GRATING IN CD TRACKING

The pickup laser in a CD player has to move at a steady pace across the CD to pick up the signals properly. When a CD is burned, bumps and pits are created to store the digital data. The bumps on the outside of the CD move past the laser more quickly than those on the inside of the CD. A tracking system within the CD player makes sure that the laser stays pointed where it is supposed to, and a spindle motor varies the speed of the disc so that the bumps pass over the laser at the same rate throughout the playing time.

A diffraction grating can be used in a three-beam method to keep the beam on a CD on track.

The diffraction grating attached to the laser lens creates three beams. The central maximum of the diffraction pattern is used to read the information on the CD. The two first-order maxima are used for steering.





KEY POINTS

- A diffraction grating consists of thousands of parallel slits.
- When a monochromatic light is shone through a diffraction grating it produces sharp, bright and widely spaced intense spots of light.
- When a white light is shone through a diffraction grating it produces a series of coloured spectra. This separation of colours is caused by different wavelengths of light constructively interfering in different directions.
- Diffraction gratings are used analyse light. Study of the intensity of light from an object at different wavelengths can tell the composition of materials, their temperature and their motion (due to Doppler shift).

8 USING DIFFRACTION

LEARNING INTENTIONS

In this lesson you will learn to:

- analyse light using diffraction grating
- describe how diffraction can be used for information storage and measurement
- describe how interference can produce colourful effects.

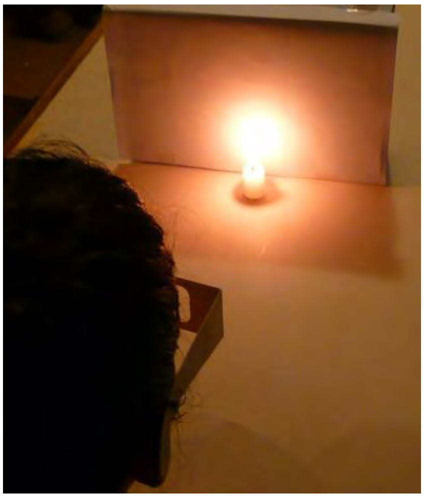
INTRODUCTION

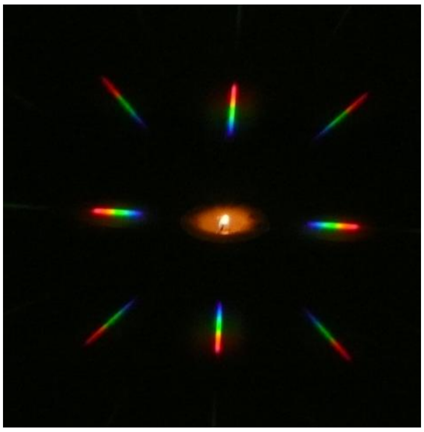
This lessons teaches you how to use diffraction grating as a simple spectrometer to measure the wavelength of light of different colours.

ANALYSING LIGHT

8A

HANDS-ON ACTIVITY: WAVELENGTH OF VIOLET LIGHT





What you need:

- a candle*
- diffraction glass*
- a screen
- a ruler.

*Contained in your wave equipment box.

What you do:

1. Make a screen as in activity 7B.

2. Place the candle 30 cm from the edge of the table.

3. Draw a vertical line down the middle of the screen and place it behind the candle, as close as possible but far enough that the paper will not catch fire when the candle is lit. Make sure that the vertical line is in line with the candlewick.

4. Light the candle. Put the diffraction glasses on and look at the burning candle from the edge of the table. Make sure you are 30 cm away from the candle.

5. For the spectrum that you see on the horizontal level, mark the boundary of the violet and the blue bands on the screen with a pencil. Blow out the candle, remove the screen and measure the distance between the two violet bands in cm. Half of the value of this distance is ________ cm.

6. The width between two slits in the diffraction glass is 2.85×10^{-6} m and you were looking at the first-order spectrum whose order is $n = 1$.

7. Calculate the wavelength of the violet light.

8. Compare your value with the average value for violet light, which is about 4.0×10^{-7} m.

Check your answers.

COMPACT DISCS

A standard CD can store up to 74 minutes of music, although most CDs contain only about 50 minutes. The data is recorded on one side of the CD in the form of a continuous spiral starting from the inside and moving outward. In the next activity you will calculate the distance between two tracks.

8B HANDS-ON ACTIVITY: MEASURING THE WIDTH OF A CD TRACK

Caution! Never point the laser, or a reflection of the laser, at a person's eye. Do not look down the laser beam. Always keep the laser away from small children.

What you need:

- a laser light*
- a CD*
- a screen
- a ruler
- a sharp knife
- sticky tape
- a small box (such as your PH3030K box) to support the laser.

*Contained in the wave equipment box.

What you do:

1. Use a sharp knife to scratch a small section of the coating off the painted side of the CD. Stick a piece of sticky tape onto the scratched area, press hard on it and then peel it off. This will remove all the paint fragments from the surface.

2. Tape the laser onto the narrow side of the box, close to the front end. Tape the CD in front of the laser so the light will shine through the scratched area.

3. Place a screen 15 cm from the CD. Turn the laser on. You will see three red dots on the screen. Turn the CD to move the dots into a horizontal line. Mark the positions of the right and left spots on the screen.
   Measure this distance and find half of its value. ________ cm.

4. The wavelength of the laser beam is 6.50 x10^{-7} m and the spots on the screen are the first–order maxima. Calculate the wavelength of the violet light.

   ____

   ____

   ____

5. The actual value of the track width is 1.6 x 10^{-6} m. How does your value compare with this?

   ____

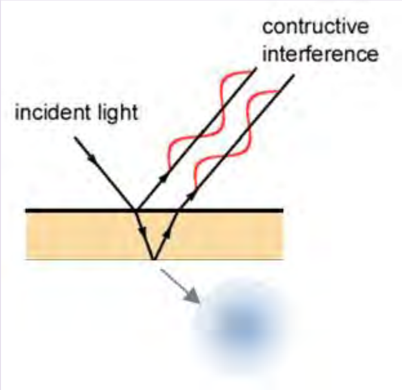
   ____

Check your answers.

DIFFRACTION BY REFLECTION

It is very common to see rainbow patterns when you look at the surface of a CD, soap bubbles or paua shells. All of these effects are created by constructive and destructive interference of the reflected light.

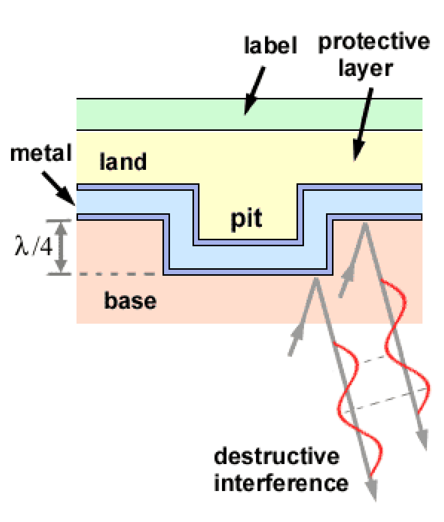
When white light strikes the film of a soap bubble, most of the light passes through, but some is reflected off the top and bottom layers of the film. Light that reflects off the top layer of a film of oil travels a slightly shorter distance than the light that reflects off the bottom layer – as shown in this diagram. At a particular film thickness, you will see constructive interference. We see a colour because the reflected light from the top and the bottom layer arrive in phase to cause constructive interference. For example, if the film is just the right thickness, a red light wave will bounce off the top and bottom layers in phase and the two resulting waves will combine to double the amount of red light. If they reflect out of phase by 180°, the red will be eliminated. This is why you see only some colours.



A CD has three layers – a transparent base, a metal layer and a top protective coating. When sunlight falls on a CD, reflective diffraction causes constructive interference of certain colours. When you look at a CD, the angle of the CD to the light source determines the path difference and hence the reflected colours.

READING CD–DVD DATA

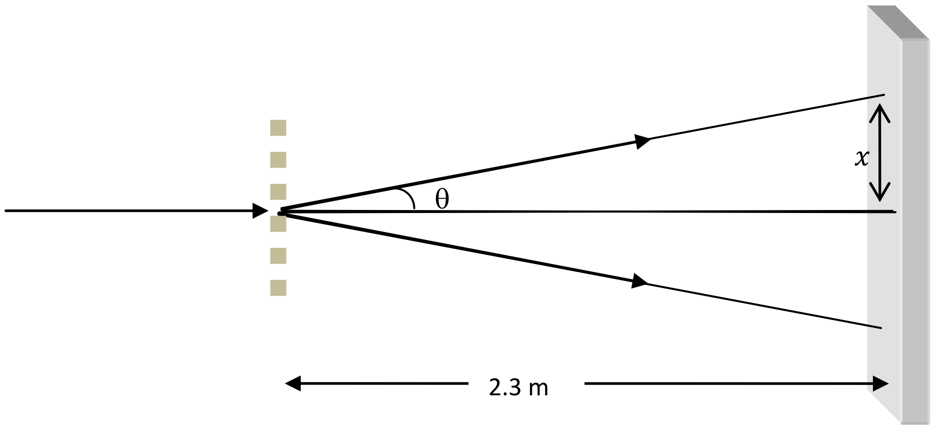
The surface of the CD or DVD, where the data is stored, has 'pits' and 'lands' in circular tracks. The data is read by a laser beam. When the beam travels from the base and reaches the pits, the pits on the metal layer reflect the beam like a mirror. The depth of a pit is 1/4 of the wavelength of the laser. Laser rays reflected by both pits and lands have a path difference of half the wavelength which leads to destructive interference, hence a low signal output. The path difference is zero for two rays both reflected by the pits, or both by the lands. Constructive interference occurs and a strong signal is generated. A digital code of strong and weak signals is converted into sound by a music CD player.



8C

CHECK YOUR UNDERSTANDING

1. A red laser with a wavelength of 640 nm (6.40×10^{-7} m) is shone at a diffraction grating. The screen is 2.3 m from the grating. The grating has 3 000 lines per cm.



a. Calculate the angle of diffraction for the first order.

b. Calculate the distance x between $n = 0$ and $n = 1$ maxima.

c. How would the pattern change if the slit separation was reduced? Explain your answer.

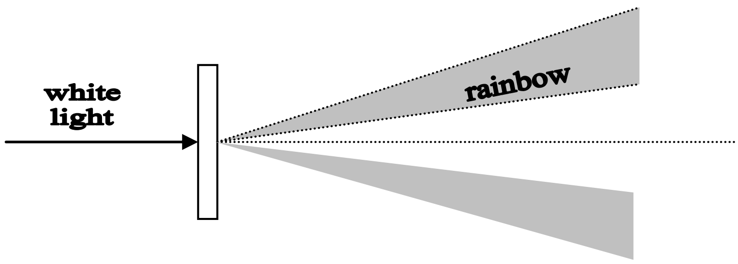
d. The red laser is replaced with a green laser of wavelength 532 nm. How would this affect the pattern on the screen? Explain your answer.

2. Visible light of wavelength 550 nm falls on a diffraction grating and produces its second-order diffraction maxima at an angle of 45.0^{o} relative to the incident direction of the light.
   a. Calculate the slit separation in the grating.

   b. At what angle is the first minimum produced?

   c. Calculate the possible number of maxima formed.

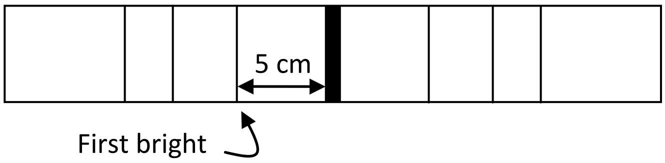
3. A white light source illuminates a diffraction grating with 1000 lines per mm. A series of spectra are seen on the screen.



Here are some common visible light wavelengths:
λred = 7.00×10^{-7}m; λgreen = 5.00×10^{-7}m; λblue = 4.50×10^{-7}m.

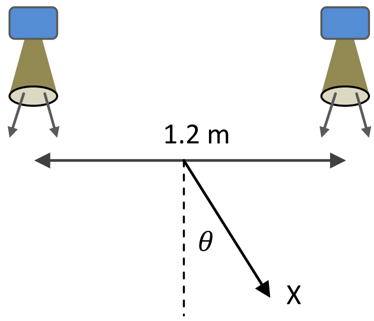
a. Calculate the number of full spectra that can be produced with this grating.

b. An astronomer uses a diffraction grating to analyse the light from a star. He uses diffraction grating that has 1 000 lines per mm, and the grating is 10 cm from the screen. The first-order bright line forms 5.0 cm from the central maximum. Show that this is caused by light of wavelength 5.00×10^{-7} m.



c. Explain why the analysis of the spectra of the star light is so important to astronomers.

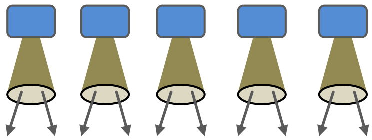
4. The owner of a car wants to customise it. She fits two air horns (sound sources) onto the roof. The distance between them is 1.20 m. The horns emit sound waves in phase with each other and with a wavelength of 0.20 m. An interface sound pattern forms in front of the sound sources. Point X is directly in front and is the same distance from each horn.



a. Will point X be a position of loudness or quietness? Explain.

b. Point Y is positioned on the third nodal point measured from Point X. Calculate the value of the angle θ.

c. The owner now decides to further customise her car. She adds three more horns so that there are now five across the roof, spaced 0.30 m apart. Compare and contrast the sound pattern produced in front of the car by this setup with the one produced by the setup in (a).



Check your answers.

KEY POINTS

- Diffraction patterns have a number of uses for information storage and accurate measurement.

9 SIGNIFICANT FIGURES AND STANDARD FORM

LEARNING INTENTIONS

In this lesson you will learn to:

- identify the number of significant figures in a given set of data
- apply rules that will help you to round the final answer to the correct number of significant figures to the accepted standard
- use standard form notation

SIGNIFICANT FIGURES

Significant figures are very important in physics calculations. They represent the accuracy of the data and hence the final answer. Each given measurement has a certain number of significant figures. Calculations done on these measurements must follow the rules for significant figures. Recognising significant figures is important in the examination because you need to write your final answers to the correct number of significant figures.

HOW TO FIND THE NUMBER OF SIGNIFICANT FIGURES IN A NUMBER

The rules for determining the number of significant figures in a given measurement are as follows.

- Digits from 1–9 are always significant. For example, 467 km has 3 significant figures.
- Zeros between two other significant digits are always significant. For example, 407 km has 3 significant figures and 0.5007 has 4 significant figures.
- Zeros used solely for marking the decimal point (placeholders) are not significant. For example, 0.0004 km has 1 significant figure. This is because the zeroes on the left of the 4 are only decimal holders, so they are not significant.
- One or more additional zeros to the right of both the decimal place and another significant digit are significant. For example, 0.000400 km has 3 significant figures.
- There are some exceptions. For example, 100 is considered to be 1 significant figure if zeros are considered as place holders, and as 3 significant figures if they are not. On the other hand, to avoid the ambiguity, we can write 100 in standadrd form, as 1×10^2, which has 1 significant figure.

STANDARD FORM

Standard form is a good way to write a number and make its significant figures very clear. It is also a good way of handling large and small numbers. Most calculators can be set to write answers in standard form.

Any number written in standard form has one digit to the left of the decimal place, and any further significant figures are written after the decimal place. Powers of ten are then used to express the size of the number. For example:

456000 , a number which has an accuracy to four significant figures can be written as 4.560×10^5. 0.0034 is written as 3.4×10^{-3}. 20 000, accurate to 1 s.f. is written as 2×10^4. Notice how standard form avoids the ambiguity of the placeholder zeros in 20 000 which are not significant.

9A CHECK YOUR UNDERSTANDING

Complete the following table by writing the number in standard form. Identify the number of significant figures , giving a brief reason why the figures are significant. The first row is done for you.

Data	Standard form	Number of significant figures	Reason
6893 m	6.893×10^3	4	All non-zero digits are always significant.
9007 kg			
5.00 cm			
0.007 mm			
0.005001 g			

Check your answers.

CALCULATIONS AND SIGNIFICANT FIGURES

Each recorded value contains a certain number of significant figures. When we do calculations our answers cannot be more accurate than the measurements that they are based on. We follow certain rules whenever we do calculations using the given data. They are given below.

HOW TO FIND THE NUMBER OF SIGNIFICANT FIGURES IN A CALCULATED VALUE

1. **Adding and subtracting**

   When adding or subtracting the given data, the final answer can only show as many decimal places as the measurement that has the fewest decimal places.

   Example: $9.15 \text{ cm} + 19.81 \text{ cm} + 3.4 \text{ cm} = 32.36 \text{ cm}$

   Look at the original data to see the number of decimal places shown in each value.
   3.4 has the fewest decimal places. We must round our answer, 32.36, to one decimal place.
   Therefore the final answer is 32.4 cm

2. **Multiplying and dividing**

   When multiplying or dividing, round the calculated answer until you have the same number of significant figures as the measurement with the fewest significant figures.

   Example: $22.37 \text{ cm} \times 3.10 \text{ cm} \times 85.75 \text{ cm} = 5946.50525 \text{ cm}^3$

   Look at the original data to check the number of significant figures in each value:

   22.37 has 4 significant figures.
   3.10 has 3 significant figures – the fewest
   85.75 has 4 significant figures.

   Our answer can only show 3 significant figures because that is the fewest significant figures in the given data.
   5946.50525 shows 9 significant figures, but we must round to show only 3 significant figures. Our final answer becomes 5950 cm^3. In this case zero is not significant.
   You can avoid ambiguity if you write your answer as 5.95×10^2 cm^3 (or 5950 cm^3 3 s.f.)

9B CHECK YOUR UNDERSTANDING

Complete the table below by calculating the given data and rounding the answer to the correct number of significant figures.

Data for calculation	Calculated value	Rounded answer
$39.64 + 1.3$		
$1.954 - 193$		
$\dfrac{3.84 \times 21.69}{2.9 \times 1.63}$		
$\dfrac{23.5 - 21.3}{1.58}$		
$\dfrac{4.83 \times 12.3 \times 10^3}{2.4 \times 986}$		

Check your answers.

KEY POINTS

- Significant figures are very important in physics calculations. They represent the accuracy of the data and hence the final answer.
- Rounding the final answer of a mathematical calculation to the correct number of significant figures is important to represent the accuracy of the data.

10 TEACHER-MARKED ASSIGNMENT

LEARNING INTENTIONS

In this lesson you will learn to:

- review your progress over this topic and practise exam-type questions.

INTRODUCTION

In this lesson you will need the Teacher Marked Assignment (TMA) PH3031A. If you did not receive this with your booklet, contact your teacher, or download it from the Topic webpage.

REVIEW AND SELF-ASSESSMENT

Take a quick look back at all the lessons you have completed in this topic. Think about what you have learned. If you believe that you have reached the learning objectives for this Topic, continue on and complete the TMA.

If you have tried all the activities, but you do not feel that you are ready to be tested against the learning objectives, make sure you have tried all the activities. You could also check the Topic webpage on OTLE and look for extra help and tutorials. If none of this works, contact your teacher.

WHEN YOU HAVE FINISHED

When you have finished the TMA, fill in the Self Assessment section and the cover sheet, sign the authenticity statement and send the TMA to your teacher. Do not send the completed topic booklet unless you need your teacher to look at something. When you are working at NCEA level 3 it is important to keep your topic booklets for reference.

By post:

Put the completed TMA in the plastic envelope provided. Make sure that the address card shows the Te Aho o Te Kura Pounamu (The Correspondence School) address. Seal the envelope with tape before you post it.

By email:

Scan or photograph the completed TMA, including feedback sheet and the cover sheet, and email to your teacher. The standard format for Te Kura teacher email addresses is:
firstname.lastname@tekura.school.nz
If you aren't sure who your teacher is, call 0800 65 99 88.

Before you finish this topic you should have agreed your next steps with your teacher. If you do not have your next set of study materials, contact your teacher immediately. If you are not sure what to do next, ask your teacher for advice.

ANSWER GUIDE

1B QUICK QUIZ: DESCRIBINGWAVES

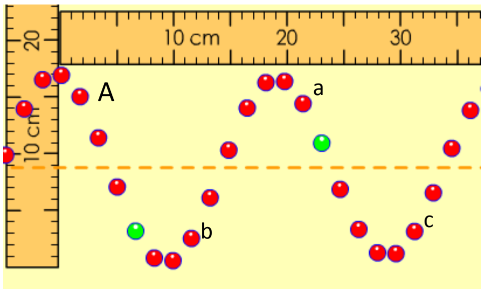
1.
   a. oscillation
   b. displacement
   c. amplitude
   d. pulse
   e. medium
   f. wave

1C QUICK QUIZ: OSCILLATIONS

1. The number of back-and-forth vibrations made in every second is called **frequency** and is measured in **hertz**.
2.
   a. $f = \frac{24}{5\times60} = 0.080 \text{ Hz}$
   b. $\lambda = 6.0 \times 2 = 12 \text{ m}$
   d. $\text{Amplitude} = \frac{1.2}{2} = 0.6 \text{ m}$
3.
   a. The time between two low tides is the period, which is roughly 12 hours.
   b. $f = \frac{1}{T} = \frac{1}{12} = 0.083 \text{ Hz}$
   c. Amplitude = $\frac{1.8}{2} = 0.90 \text{ m}$
4. a. $567 \times 1000 = 567\,000 \text{ Hz}$
   b. T = $\frac{1}{f}$ so, T = $\frac{1}{567000}$ = 1.8×10^{8} s

1D QUICK QUIZ: WAVE PHASE

1. Wavelength = 19 cm   amplitude = 9 cm.
2. See diagram.



2A CHECK YOUR UNDERSTANDING: WAVES AND SOUND

1. $\frac{d}{v} = \frac{50.0}{1480} = 0.0338 \text{ s}$
2. $d = v \times t = 2.35 \times 4.0 = 9.4 \text{ m}$
3.
   a. The particle will move (oscillate) back and forth in the direction of the wave motion.
   b. $T = \frac{1}{364} = 0.0027 \text{ s}$
   c. $\lambda = \frac{1.8}{0.90} = 0.20 \text{ m}$

$$v = f\lambda = 364 \times 0.20 = 328 \text{ m s}^{-1}$$

4.

a. Water waves are transverse waves in which the particles move roughly up and down. In sound waves, the particles move back and forth, parallel to the direction of wave travel.

b. $f = \frac{12}{60} = 0.20 \text{ Hz}$

$\lambda = \frac{v}{f} = \frac{0.80}{0.20} = 4.0 \text{ m}$, wavelength near the shore $= ¾ \times 4 = 3.0 \text{ m}$

3C DOPPLER SOUNDS

1.

a. $T = \frac{1}{f} = \frac{1}{2.0} = 0.5 \text{ s}$

b. $2T = 2 \times 0.5 = 1.0 \text{ s}$

c. $v = f\lambda$

$$\lambda = \frac{v}{f} = \frac{340}{2} = 170 \text{ m}$$

d. distance is $2\lambda = 2 \times 170 = 340 \text{ m}$

2.

a. $2 \times 30 = 60 \text{ m}$

b. $340 - 60 = 280 \text{ m}$

c. $\lambda = \frac{280}{2} = 140 \text{ m}$

3. $v = f\lambda$

$$f = \frac{v}{\lambda} = \frac{340}{140} = 2.4 \text{ Hz}$$

4. The wavelengths behind the car will increase from 170 to 200 m.

$$f = \frac{v}{\lambda} = \frac{340}{200} = 1.7 \text{ Hz}$$

3D CHECK YOUR UNDERSTANDING

1.

a. As the horn passes, the person hears the pitch drop. That is, as the horn approaches, the horn moves toward the sound waves it is emitting, so the wave fronts become bunched up. When the horn moves away, it moves in the opposite direction to the sound waves travelling toward the observer, so the wavelength is stretched out. $v = f\lambda$. Because the v is unchanged, the increase in λ causes the decrease in f.

b. $f = 1250 \text{ Hz}$; $f' = ?$ $v_w = 335\ m\,s^{-1}$; $v_s = 13.9 \text{ m s}^{-1}$

Note: There are two different approaches to this question. Both are correct.

$$f' = f\frac{v_w}{v_w - v_s}$$

$$= 1250\left(\frac{335}{335-13.9}\right) = 1304 \text{ Hz}$$

$$\lambda' = \frac{v}{f'} = \frac{335}{1304} = 0.257 \text{ m}$$

In 1 s, 1250 waves travel

$(335 - 13.9)$ m

$$\lambda = \frac{335 - 13.9}{1250} = 0.257 \text{ m}$$

2.

a. The red line shows the position of the plane from which Jack would hear a higher frequency – caused by Doppler shift. In these points it is coming toward him.

b. Lena hears a sound of the same frequency because the plane is at a constant distance from her all the time – there is no relative motion between her and the plane. Jack hears the frequency increasing and decreasing because the plane flies toward/away from him, causing waves to bunch up or spread out.

$$v = f\lambda$$

$$\lambda = \frac{v_w}{f} = \frac{330}{3.00 \times 10^3} = 0.110 \text{ m}$$

c. The highest relative velocity between Jack and the plane is 12.0 m s^{-1}

$$f' = f\frac{v_w}{v_w - v_s}$$

$$f' = 3.00 \times 10^3 \left(\frac{330}{330 - 12}\right) = 3110 \text{ Hz}$$

d.

$$f = \frac{v_w}{\lambda} = \frac{1.5}{1.2} = 1.3 \text{ Hz}$$

3.

a. $f = \frac{v_w}{\lambda} = \frac{1.5}{1.2} = 1.3$ Hz.If the boat was still, it would be hit by 1.3 waves per second.

b. Because it is moving into the waves, it will hit them more frequently.

The relative speed is $1.5 + 2.0 = 3.5$. The wavelength of the waves remains constant.

$$f = \frac{v_w}{\lambda} = \frac{3.5}{1.2} = 2.9 \text{ Hz.}$$

4. When the engine approaches him, John hears a frequency of:

$$f' = f\frac{v_w}{v_w - v_s}$$

$$f' = 900\left(\frac{330}{330-31}\right) = 993.31 \text{ Hz}$$

When the engine leaves him, John hears a frequency of:

$$f' = f\frac{v_w}{v_w + v_s}$$

$$f' = 900\left(\frac{330}{330+31}\right) = 822.71 \text{ Hz}$$

Frequency shift = $993.31 - 822.71 = 170.59 = 171$ Hz

3E TORNADO WATCHING

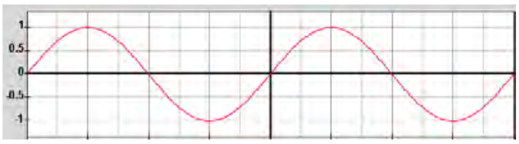
1. When the tornado is approaching, the waves that reflect off it have a shorter wavelength than the original waves. This means that the frequency received will be greater than the original frequency. The amount of frequency shift can give the speed of the tornado.

4B ONLINE ACTIVITY: SUPERPOSITION ON A STRING

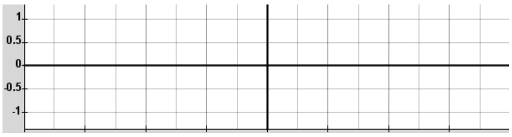
4. They add together to create a wave of large amplitude.
5. They cancel each other to create no wave.

4C CHECK YOUR UNDERSTANDING:SUPERPOSITION

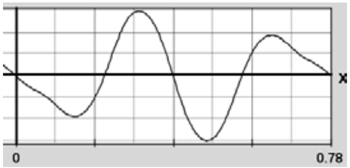
1. a. In phase



b. Out of phase (by 180°).



c.



4D ONLINE ACTIVITY: DIFFRACTION OF RIPPLES

4. As the slit width increases, the waves-fronts are less curved.
5. The wall reflects the ripples that hit it. The wave-fronts that do not hit the wall spread into the 'wave shadow' created by the wall.
6. As the wall is made smaller it has less effect on the waves. When the wall is very small there is very little 'wave shadow'.

4E ONLINE ACTIVITY: DIFFRACTION IN DETAIL

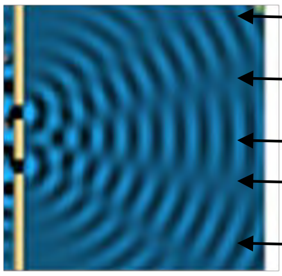
5. The dark bands are formed by destructive interference between waves from different parts of the slit.

4F CHECK YOUR UNDERSTANDING

1. If the wavelength is about the same as the gap width, waves will diffract through a large angle. If the wavelength is much smaller than the gap width, there is little diffraction because most of the wave energy goes straight through the gap. If the gap is much smaller than the wavelength, very little wave energy goes through the gap.
2.
   a. AM waves are longer than FM waves.
   b. Because AM radio waves have longer wavelengths, they bend around the hills. They diffract through a larger angle than FM waves, which have shorter wavelengths.

5A ONLINE ACTIVITY: INTERFERENCE PATTERNS

3. The waves are coherent because the two taps drip at the same time and the waves diffract from the slits. The waves have similar amplitude.
4.
   a. Constructive interference (reinforcement).
   b. Destructive interference (cancellation).
5.



Amplitude does not affect the spacing between the lines of calm water.

6. Decreasing frequency increases the wavelength. This increases the distance between the lines of calm water.

5C CHECK YOUR UNDERSTANDING: SOUND INTERFERENCE

1.
   a. As the detector moves along, the path difference from the detector to the speakers changes. If the path difference is a whole number of wavelengths, then the signal will be strong due to constructive reinforcement. If the path difference has an extra half wavelength, then destructive reinforcement will take place.
   b. It will be quiet at X because waves will arrive in out of phase by 180° (antiphase) and they will therefore cancel each other out.

5D CHECK YOUR UNDERSTANDING

1.
   a. $\lambda = \frac{v}{f} = \frac{340}{500} = 0.68 \text{ m}$
   b. $\tan\theta = \frac{0.65}{3.4}$

      $\theta = 10.8°$
   c.

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

$$n = 1$$

$$d = \frac{\lambda}{\sin\theta} = \frac{0.68}{\sin 10.8°} = 0.128 \text{ m}$$

6A ONLINE ACTIVITY: DIFFRACTION AT A SINGLE SLIT

2. The light diffracts at the edges of the pencils because the diffracted light from different parts of the slits interferes to produce bright and dark bands. The bright lines are caused by constructive interference of the light waves where the waves arrive in phase and reinforce. The dark lines are caused by the destructive interference of light waves where they arrive out of phase by 180° and cancel each other out.
5. The spot spreads out as the beam moves away from the screen
6. The distance between the bands increases as the gap gets narrower.

6B INTERFERENCE OF LIGHT

1. Interference can be only observed if the sources are coherent. Splitting a source of light into two will provide two identical coherent sources.

6D CHECK YOUR UNDERSTANDING: WAVELENGTH OF LIGHT

1.
   a. decreased
   b. increased
   c. increased

2.
   a. $d = 0.050 \times 10^{-2}\text{m};\quad L = 5.0\text{ m};\quad n = 1;\quad \lambda = 350 \times 10^{-9}\text{m}\quad x = ?$

   $L \gg x$, (the distance to the screen is much greater than the separation of the maxima)so:

$$n\lambda = \frac{dx}{L}$$

$$x = \frac{n\lambda L}{d}$$

$$x = \frac{1 \times 350 \times 10^{-9} \times 5.0}{0.050 \times 10^{-2}} = 3.5 \times 10^{-3}\text{m}$$

   b. $d,\ n,\ L,$ and λ are all the same as in part (a). You can do the working in numbers or symbols:

$$x = \frac{n\lambda L}{d}$$

$$x_{700} = \frac{1 \times 700 \times 10^{-9} \times 5.0}{0.050 \times 10^{-2}}$$

$$x_{700} = 7.0 \times 10^{-3}\text{m}$$

$$\frac{x_{700}}{x_{350}} = \frac{7.0 \times 10^{-3}}{3.5 \times 10^{-3}} = 2$$

OR

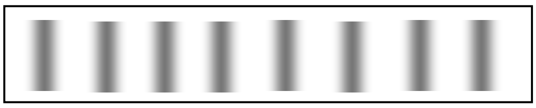
$$x = \frac{n\lambda L}{d}$$

$$\frac{x_{700}}{x_{350}} = \frac{\frac{nL}{d}\lambda_{700}}{\frac{nL}{d}\lambda_{350}} = \frac{\lambda_{700}}{\lambda_{350}} = \frac{7.0 \times 10^{-3}}{3.5 \times 10^{-3}} = 2$$

3. No scale is given in this question, so we can't be sure whether $\gg x$. (It is safer not to use the small angle approximation in your answer.)
   a. The light waves diffract when they emerge from the mesh material and interfere. The pattern of dots is the interference patterns produced when waves which are in-phase reinforce. Where there are no dots there is destructive interference by out-of-phase waves.
   b. The dots will move further apart. The angle between the antinodal lines and the mesh is fixed, so increasing the distance from the mesh increases the separation of the dots.
   c. $n\lambda = d\sin\theta$. By decreasing λ, and keeping n and d fixed, $\sin\theta$ must decrease in proportion, thereby decreasing θ and moving the dots closer.

4.
   a. Sunlight is made up of many different wavelengths (or frequencies) of light and each wavelength diffracts at its own angle.
   b. evenly spaced bands

      Alternatively, you could sketch a diagram as shown here.



   c. There are at least two approaches to solving this when $x \ll L$:

For destructive interference at the dark band next to the central maximum:

$$\frac{1}{2}\lambda = \frac{d\,x}{L}$$

$$\frac{1}{2}431\times 10^{-9} = \frac{1.03\times\ 10^{-5}\times\ x}{3.0}$$

$$x = \frac{\left(1-\frac{1}{2}\right)\times 431\times\ 10^{-9}\ \times\ 3.00}{1.03\times\ 10^{-5}}$$

$$x =\ 0.0627\ \text{m}$$

The distance between the two dark bands is:

$$2x =\ 2\times 0.0627\ \text{m} = 0.125\ \text{m}$$

or

Close to the central maximum the separation of bright bands is the same as the separation of dark bands, so the separation of dark bands can be calculated using:

$$x = \frac{n\lambda L}{d}$$

$$x = \frac{1\times 431\times\ 10^{-9}\times 3.00}{1.03\times\ 10^{-5}}$$

$$x = 0.126\ \text{m}$$

d. Light from the two head lamps is incoherent – the lamps emit light waves which have no fixed phase relationship.

7A QUICK QUIZ: DIFFRACTION GRATINGS

1. $d = \frac{1}{N} = \frac{0.01}{10\ 000} = 1.0\times 10^{-6}\text{m}$
2. $d = \frac{1}{N} = \frac{0.001}{400} = 2.5\ \times 10^{-6}\text{m}$
3. $\text{N} = \frac{1}{d} = \frac{1}{1.45\times 10^{-5}} = 6897\ \text{per metre}\ \rightarrow\ \frac{6897}{100} = 69\ \text{per cm}$

7B HANDS-ON ACTIVITY: DIFFRACTION OF LASER LIGHT

3. increases.
4. a. You can probably see two.

   b. 

5. The bright spots are formed by light from two sources arriving in phase and reinforcing.

7C WAVELENGTH OF LASER LIGHT

1. $n = 1\quad \lambda = 633\times 10^{-9}\text{m}\quad d = 0.25\times 10^{-3}\text{m}\ \sin\theta$

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

$$\sin\theta = \frac{n\lambda}{d} = \frac{1\times 633\times 10^{-9}}{0.25\times 10^{-3}} = 0.00253$$

$$\theta = 0.145°$$

7D HANDS-ON ACTIVITY: DIFFRACTION OF WHITE LIGHT

2.
   a. There are 2 but you can see 1 more if the room is dark enough.
   b. For each order spectrum, the blue-violet colours are nearest the central line and red light is furthest away from the central line.

3. The spacing increases.

7E CHECK YOUR UNDERSTANDING

1.
   a. The horizontal rows produce vertical interference pattern and the vertical rows produce horizontal interference pattern.
   b. Interference is only observed when the distance between the sources is close together compared with the wavelength. Because 2.0mm is much greater than the wavelength, the antinodes are too close to be seen separately.
   c. Light diffracts as it passes through the holes. The diffracted waves arrive out of phase by 180°, causing destructive interference.
2.
   a. For a pattern produced by diffraction grating:
      i. maxima are brighter due to more sources
      ii. maxima are further apart due to sources being closer
      iii. maxima are more defined due to more sources causing complete cancellation at more angles.
   b. The diffraction grating causes sharper, brighter maxima, which spread out a lot more than a double slit. The bigger angle and better visibility give more accurate data to calculate the wavelength.
   c. Different wavelengths in the white light diffract at different angles, thus causing a separation of colours

8A HANDS-ON ACTIVITY: WAVELENGTH OF VIOLET LIGHT

5. 4.2 ∓ 0.2 cm or closer to this value is acceptable.
7. From the diagram $\tan\theta = \frac{x}{L} = \frac{4.2}{30}$

   $\theta = \tan^{-1}\left(\frac{4.2}{30}\right) = 7.97°$

   $2.85 \text{ x} 10^{-6} \times \sin 7.97° = 1 \times \lambda$

   $\lambda = 3.95 \times 10^{-7} = 395 \text{ nm}$ (Or a similar value based on your data.)
8. This is a reasonable value, taking into consideration the difficulty of locating the middle position of the violet band.

8B HANDS-ON ACTIVITY: MEASURING THE WIDTH OF A CD TRACK

3. 7.5 ∓ 0.3 cm or closer to this value is acceptable.
4. From the diagram, $\tan\theta = \frac{x}{L} = \frac{4.2}{30}$

   $\theta = tan^{-1}\left(\frac{7.5}{15}\right) = 25.56^{\circ}$

   $d \times \sin 25.56^{\circ} = 1 \times 6.50 \text{ x } 10^{-7}$

   $d = 1.46 \times 10^{-6} = 1.46\ \mu m$ (Or a value closer to this is also acceptable.)
5. This is reasonable value taking into account the possible measurement errors.

8C CHECK YOUR UNDERSTANDING

1.
   a. $d = \frac{1}{N} = \frac{0.01}{3000} = 3.33 \times 10^{-6} \text{ m}$

      $3.33 \times 10^{-6} \times \sin\theta = 1 \times 6.40 \text{ x } 10^{-7}$

      $\theta = 11.3°$
   b. $x = \tan 11.3° \times 2.3 = 0.46 \text{ m}$
   c. $\sin\theta = \frac{\text{n} \times \lambda}{d}$. If d is decreased then $\sin\theta$ increases. This means the bands spread out further.

d. $\sin\theta = \frac{n \times \lambda}{d}$. If λ is decreased then $\sin\theta$ also decreases. This means the bands will be closer.

2.

a. $d = \frac{2 \times 550 \times 10^{-9}}{\sin 45} = 1.16 \times 10^{-6}\text{m}$

b. $\sin\theta = \frac{1 \times 550 \times 10^{-9}}{1.16 \times 10^{-6}} = 0.7069$

$\theta = 47.4^{\circ}$

c. $n = \frac{d}{\lambda} = \frac{1. \times 10^{-6}}{550 \times 10^{-9}} = 2$

3.

a. Red is the last colour in a spectrum. We need to find how many red bands are formed.

$$d = \frac{1}{N} = \frac{0.001}{1000} = 1.0 \times 10^{-6}\text{ m}$$

$$n = \frac{\text{d}}{\lambda} = \frac{1.0 \times 10^{-6}}{7.00 \times 10^{-7}} = 1.4. \text{Hence there are only 2 full spectra to be seen}$$

b. $\theta = \tan^{-1}\left(\frac{5}{10}\right) = 26.56°$

$$d = \frac{1}{N} = \frac{0.001}{1000} = 1.0 \times 10^{-6}\ m$$

$$\lambda = \frac{d \times \sin\theta}{\text{n}} = \frac{1.0 \times 10^{-6} \times \sin 26.56}{1} = 4.31 \times 10^{-7}\text{ m}$$

c. By comparing interference patterns of starlight and the same interference patterns from known elements in the lab on Earth, it is possible to determine the composition of the elements in the star. The continuous spectrum also indicates the temperature of the star. The Doppler shift of the spectra indicates the motion of the star (and its age in an expanding Universe).

4.

a. This point will be louder because the two sources are in phase. This means that crests will meet crests and troughs will meet troughs and so the point will be antinodal.

b. Because the point is nodal and *n* = 3, the path difference is (3- ½) λ.

$$\sin\theta = \frac{(3 - ½) \times 0.20}{1.2} = 0.4167$$

$$\theta = \sin^{-1} 0.4167 = 24.6^{\circ}$$

c. Antinodal points are spaced further apart because the horns are closer together. The sound maxima will be louder and located in a much more precise direction (that is, the loud areas will be narrower).

9A CHECK YOUR UNDERSTANDING

Data	Standard form	No. of significant figures	Reason
6893 m	6.893×10^3	4	All non-zero digits are always significant.
9007 kg	9.007×10^3	4	Zeroes between 2 significant digits are significant
5.00 cm	5.00×10^0	3	Additional zeros to the right of decimal and significant digits are significant
0.007 mm	7×10^3	1	Placeholders are not significant
0.005001 g	5.001×10^3	4	Zeros between 2 significant digits are significant

9B CHECK YOUR UNDERSTANDING

Data for calculation	Calculated value	Rounded answer
$39.64 + 1.3$	40.94	40.9
$1.954 - 193$	−191.046	−191
$\frac{3.84 \times 21.69}{2.9 \times 1.63}$	17.61997...	18
$\frac{23.5 - 21.3}{1.58}$	1.3924......	1.4*
$\frac{4.83 \times 12.3 \times 10^3}{2.4 \times 986}$	25.1052...	25

*This has a mix of subtraction and division, with different rules, so you must do them separately. 23.5 – 21.3 = 2.2 (with one decimal place) and then, dividing 2.2 by 1.58, the answer is 1.4 with 2 significant figures. The limiting factor is 2.2, with 2 significant figures, so the final answer should have 2 significant figures.

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USEFUL INFORMATION

EQUATIONS

This information will be provided in the resource booklet in the NCEA examination

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

$$n\lambda = \frac{dx}{L}$$

$$v = f\lambda$$

$$f' = f\frac{v_w}{v_w \pm v_s}$$

$$f = \frac{1}{T}$$

$$f_{beat} = f_1 - f_2$$

Other useful equations:

$$v = \frac{d}{t}$$

$$\sin\theta = \frac{opp}{hyp}$$

Area of a circle

$$A = \pi r^2$$

Speed of light $= 3.00 \times 10^8$ m s^{-1}

OTHER INTERESTING INFORMATION

Speed of sound:

Dry air at 0^o = 331 m s^{-1}
Dry air at 20^o = 343 m s^{-1}
Dry air at 40^o = 355 m s^{-1}
At 15 000m above sea level (cruising altitude of long haul flights) = 295 m s^{-1}

Pure water at 20^o: 1482 m s^{-1}
Sea water: 1560 m s^{-1}

Tsunami waves in deep water: 260 m s^{-1}
Tsunmai waves in shallow water: 10 m s^{-1}

Concrete: 3500 m s^{-1}
Structural steel: 4510 m s^{-1}
Primary earthquake waves: 6000-13000 m s^{-1}

Secondary earthquake waves: 3500-7500 m s^{-1}