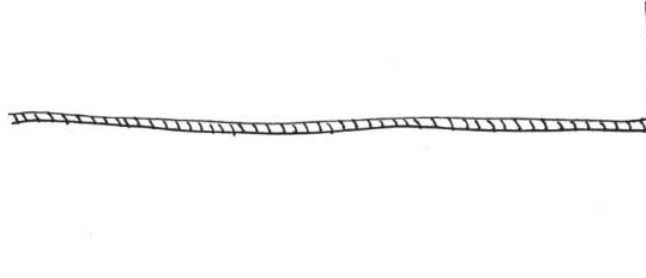




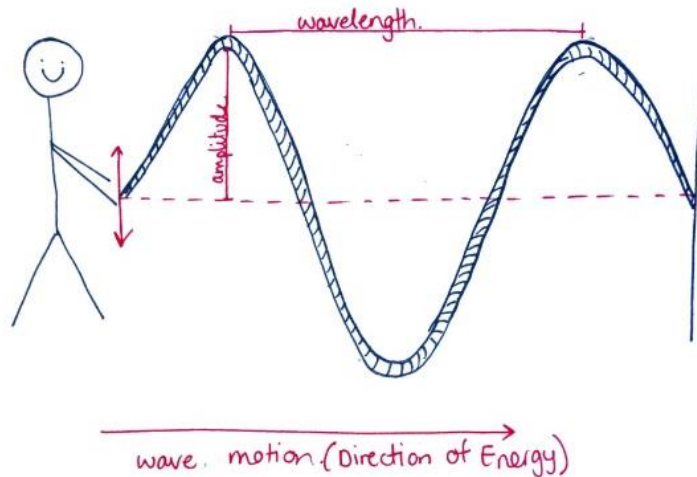
## WAVE CHARACTERISTICS

### CONTENT

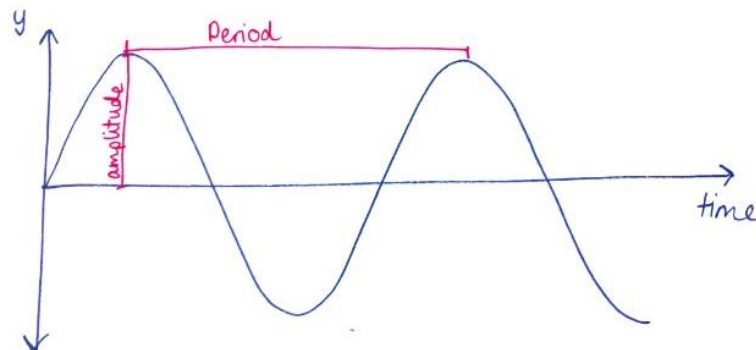
Waves transfer energy and can come in many different shapes. Some waves need a medium (e.g. a material) for propagation, whilst some waves can travel in a vacuum (i.e. do not require a medium). We can understand the type of wave and the way it transfers energy by plotting the wave: a plot of the displacement as a function of time (called the displacement-time graph) and a plot of displacement and the position of the wave (called the displacement-position graph). Consider a rope where one end is fixed to a wall. When the rope isn't being moved up or down it is just a flat line, this is its equilibrium position, as shown below.



When side not attached to the wall is moved up and down, a wave is created, as seen below.



To plot a displacement-time graph, we consider one point on the wave. Then we plot how that point moves from the equilibrium position over time. So, for our rope example, the displacement as a function of time graph involves plotting time on the x-axis and displacement on the y-axis, as shown below:



Displacement-time graph

When plotting the position of the wave, we plot the y-position of the wave against the x-position of the wave (see graph below). For the rope example, the graphs look very similar but they are actually showing different information.

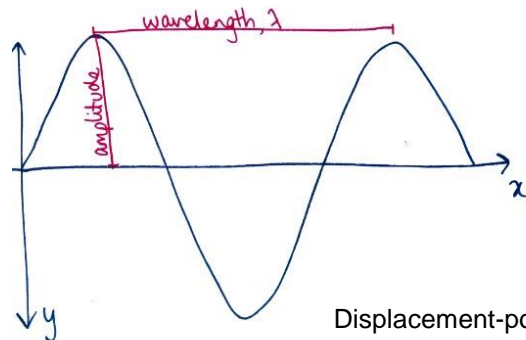


There are 6 main properties of waves that we can calculate from these graphs:

- **Velocity ( $v$ )**  
The velocity of the wave, calculated by multiplying the frequency and the wavelength together (m/s)
- **Frequency ( $f$ )**  
The frequency is the number of waves that pass through a fixed point every second (Hz)
- **Period ( $T$ )**  
The period is the time taken for one full oscillation to complete (s)
- **Wavelength ( $\lambda$ )**  
Wavelength is the distance of one full oscillation of the wave (m), easily measured from crest to crest or trough to trough
- **Amplitude**  
The amplitude is the height of the wave, the maximum displacement from the equilibrium position (m)

On the displacement-time graph, we can determine the amplitude and the period. To calculate the amplitude, we measure the distance from the  $y=0$  to the first crest, as shown in the graph. The period can be measured from finding the difference between two closest identical points on the wave (e.g. from crest to crest or trough to trough).

On a displacement-position graph, we can determine the amplitude of the wave as well as the wavelength. The wavelength is found using the same technique as the period but since we are now plotting the x-position on the x-axis, not the time, the wavelength can be easily calculated by measuring the distance between two adjacent crests or troughs.



Displacement-position graph

Note that we cannot measure the frequency or period directly from a displacement-position graph. To calculate the frequency of the wave, we can use two equations - either the equation for velocity ( $v = f\lambda$ ) or that of the period. The frequency and period are inversely related. So, in addition to the aforementioned equation, we can also calculate the frequency using the equation:

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



### EXAMPLE 1

A wave is travelling with a frequency of 50Hz and a wavelength of 0.25m. What is the velocity of the wave?

- ⇒ Let us start by writing all the known information, and what we wish to calculate to determine the appropriate formula:

Variable	Value
Frequency ( $f$ )	50 Hz
Wavelength ( $\lambda$ )	0.25m
Velocity ( $v$ )	???

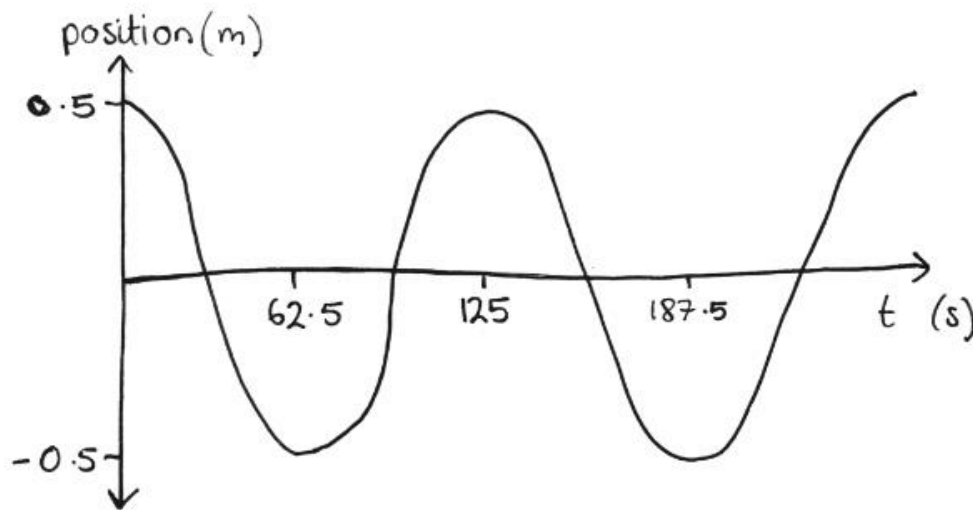
- ⇒ Now it is clear that we need to use  $v = f\lambda$  as the equation for velocity.

$$\begin{aligned} v &= f\lambda \\ &= 50 \times 0.25 \\ &= 12.5 \text{ m/s} \end{aligned}$$

- ⇒ So, the velocity is 12.5m/s in the positive direction.

### EXAMPLE 2

Using the displacement-time graph below, determine the frequency of the wave.



- ⇒ Firstly, we decide which formula to use. Since we want to calculate the frequency and have a displacement-time graph, we will use the formula  $f = \frac{1}{T}$ .
- ⇒ Now, from the graph we can see the period is 125s (difference between two adjacent crests), thus we can calculate the frequency as follows:

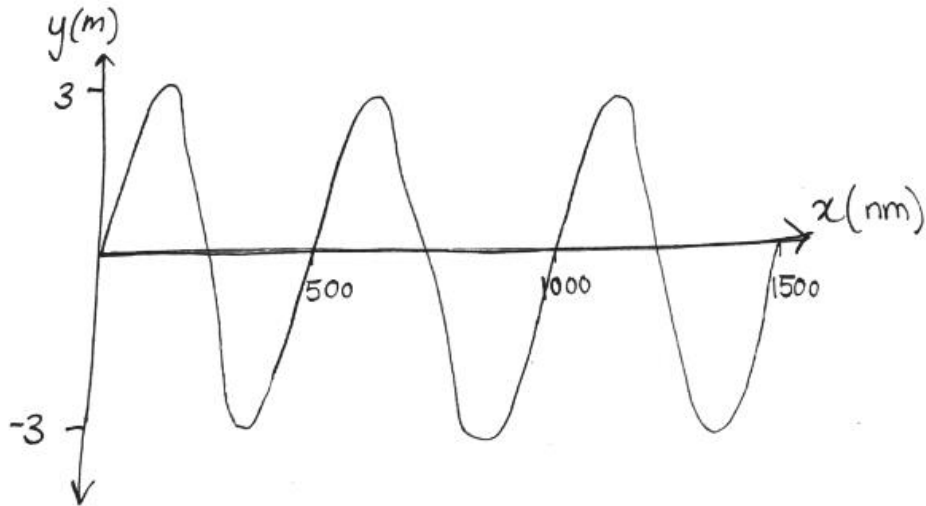
$$\begin{aligned} f &= \frac{1}{T} \\ &= \frac{1}{125} \\ &= 0.008 \text{ s}^{-1} \\ &= 0.008 \text{ Hz} \end{aligned}$$



### EXAMPLE 3

A periodic wave has a wavelength 500m and amplitude 3m. Plot a displacement-position graph for the wave.

⇒ Since we are plotting a displacement-position graph, we know our axis are going to be the x-position and y-position:





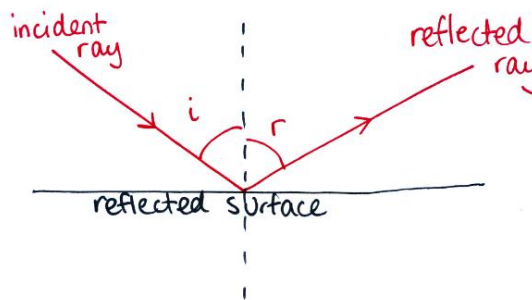
## WAVE BEHAVIOURS

### CONTENT

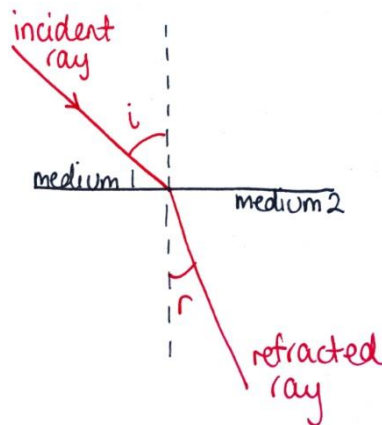
Waves behave differently when they reach a barrier or a new medium. These behaviours can be sorted into **reflection**, **refraction**, **diffraction** or **superposition**. We will be looking at superposition later.

When a wave encounters a barrier, the wave can be **reflected**. This means the wave 'bounces' off the barrier and changes direction. An example of this is when light hits a mirror. If you shine a torch at a mirror the light reflects off the surface and you can see a 'picture' of the torch in the mirror.

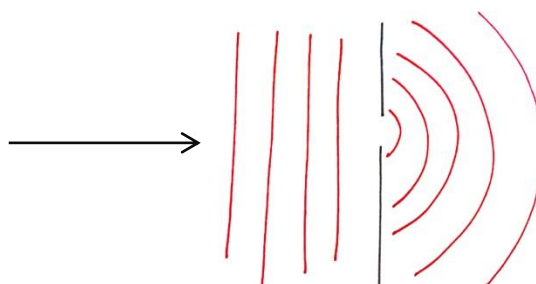
When a ray hits the surface, this is called the incident ray and the angle the ray hits the surface is called the angle of incidence,  $i$ . The angle of incidence is measured from the normal to the surface. Once the ray is reflected it is called the reflected ray and the angle of the ray is called the angle of reflection,  $r$ . This is also measured from the normal of the surface. The angle of incidence is equal to the angle of reflection.



Sometimes, instead of being entirely reflected, a wave can pass through into a different medium and it is **refracted**. Refraction is when the light 'bends' in the new medium. Similar to a reflected wave, there is also an incident ray and angle of incidence as well as a refracted ray and angle of refraction. The only difference is the refracted ray is not entirely reflected off the surface, instead travels through the new medium.

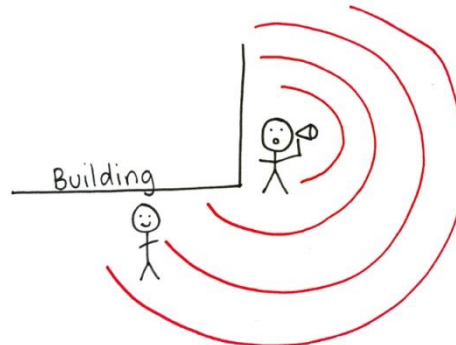


When waves pass through an opening they can also bend around the obstacles or change directions. This is called **diffraction**. For example, if straight water waves are travelling through the water and then pass through a slit the waves change direction and the water waves spread out, like in the diagram below.





Waves can also be diffracted around an obstacle. For example, if you are standing next to a building and shouting into a megaphone, around the corner, your voice can be heard. This is because the sound waves are being bent around the corner of the building.



The angle of diffraction is directly proportional to wavelength. The longer the wavelength, the greater the amount of diffraction, i.e. the more the wave can 'bend' around the obstacle.

### EXAMPLE 1

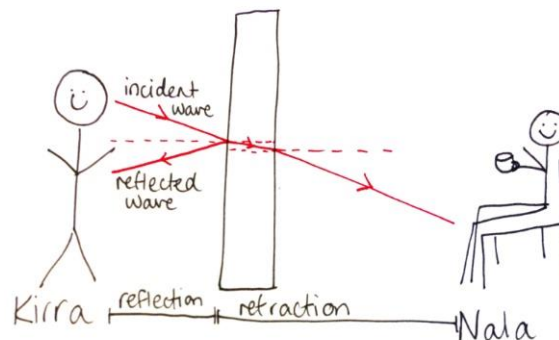
If a hiker is lost in a forest and wishes to send out a distress sound, should they use a high frequency or low frequency sound (assuming the waves have the same velocity) to bend around the trees in the forest? Explain your reasoning.

- ⇒ Given the hiker needs the signal to travel as far as possible and avoid being blocked by a large tree, we need to determine which of the two sound signals can 'bend' around the trees more. So, let us look at how the wavelength is related to the frequency so we can determine which signal will be able to diffract around larger trees.
- ⇒ We know the equation for velocity of a wave is  $v = f\lambda$  and we also know the velocity of the waves are the same. If we increase the frequency of the wave, the wavelength must decrease to keep the velocity constant. Likewise, if we decrease the frequency of the wave, the wavelength must increase.
- ⇒ This means, the lower the frequency, the longer the wavelength.
- ⇒ So, the hiker is best sending out a low frequency (longer wavelength) signal because the longer the wavelength, the more the sound waves can 'bend' around the trees.

### EXAMPLE 2

Kirra is looking at a window of a café, trying to see if her friend, Nala, is already waiting inside. Kirra notices she can see Nala inside but can also see her reflection in the window. Explain this behaviour of light.

- ⇒ Since Kirra can see both Nala and herself in the window, there must be a combination of behaviours involved.
- ⇒ Firstly, Kirra can see herself which means that at least some of the incident light wave is being reflected. However, since Kirra can also see Nala inside the café, light waves must also be travelling through the



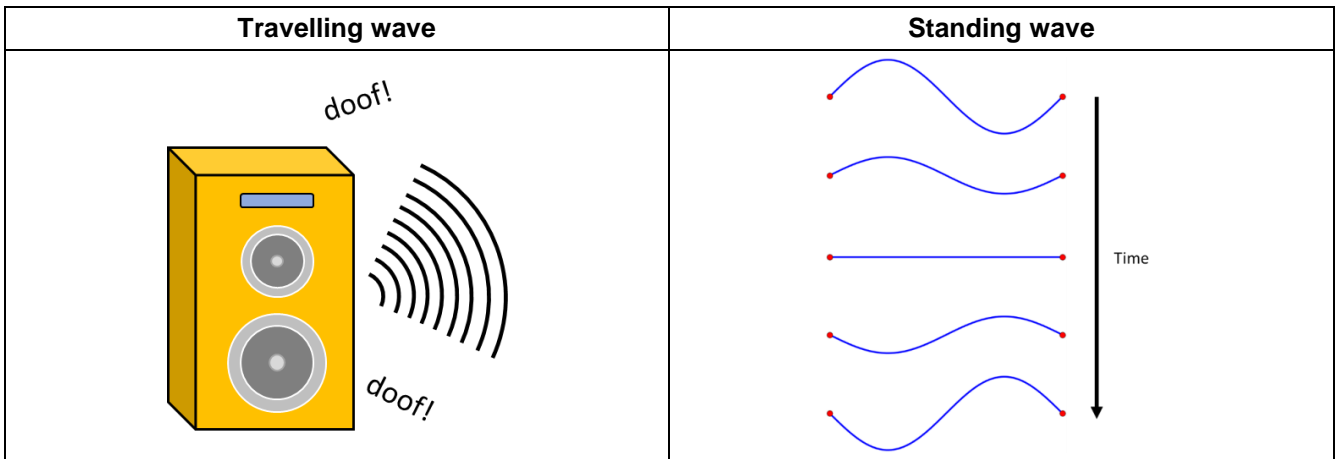
glass (being refracted). This is demonstrated in the diagram below. This is called partial reflection and refraction.



## WAVE SUPERPOSITION

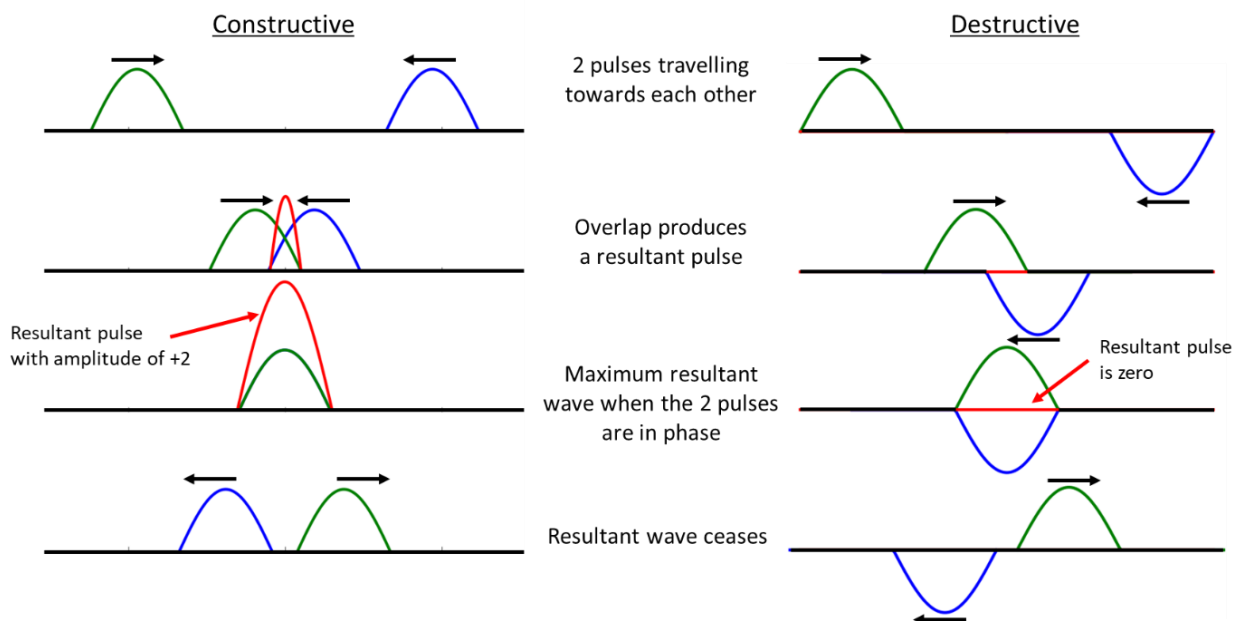
### CONTENT – TRAVELLING AND STANDING WAVE

When we think of waves, we associate the word with waves on the beach or a Mexican wave. The definition of waves in physics states that waves are oscillations that propagate in space and matter. The most common type of waves we encounter in our daily lives are mechanical waves. These include sound waves and wave motion in a string. Sound waves are an example of a travelling wave whereas a wave propagating in a string is an example of a standing wave. The position of a standing wave does not change while a travelling wave moves through space and matter.



### CONTENT – WAVE SUPERPOSITION

When two waves overlap, they combine to produce a resultant wave. This phenomenon is called the *principle of superposition* or *wave superposition*. The amplitude of the resultant wave increases when the two interacting waves are in phase, and it decreases when they are out of phase. To illustrate, consider two pulses with an amplitude of +1 travelling towards each other. When the two pulses start overlapping, the amplitude of the two pulses starts adding up following the superposition principle. When the two pulses reach maximum overlap (i.e. in phase), the resultant pulse will have an amplitude of +2. This behaviour is known as *constructive interference*. When the pulses have amplitudes in opposite directions, as shown in the diagram, the resultant pulse will have an amplitude of zero. This behaviour is known as *destructive interference*. The diagram illustrates the two

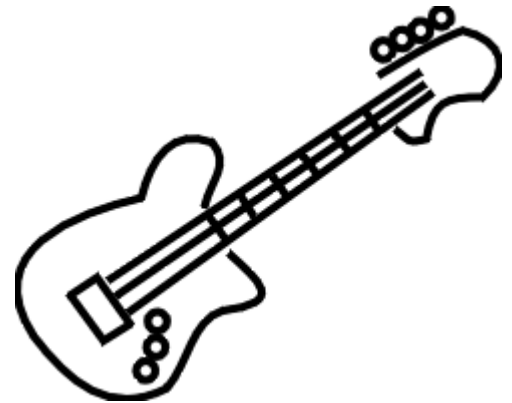




phenomena.

### REAL WORLD EXAMPLE

A real-world example of wave superposition at play is in musical instruments like the guitar. If you pluck the first string (string *E*: the thinnest) on the guitar, the string will vibrate and produce a sound. If you then pluck the second string (string *B*), you will create another sound different to the first string. Suppose now you pluck both string *E* and *B* at the same time, the sound that you will hear will be different than that of the sound produced by plucking strings *E* and *B* separately. This is because the sound wave generated by strings *E* and *B* add up to create a resultant sound wave (*wave superposition*). Different sounds can be created through a combination of strings and notes when you put your fingers on the guitar neck. These sets of notes are known as guitar chords.

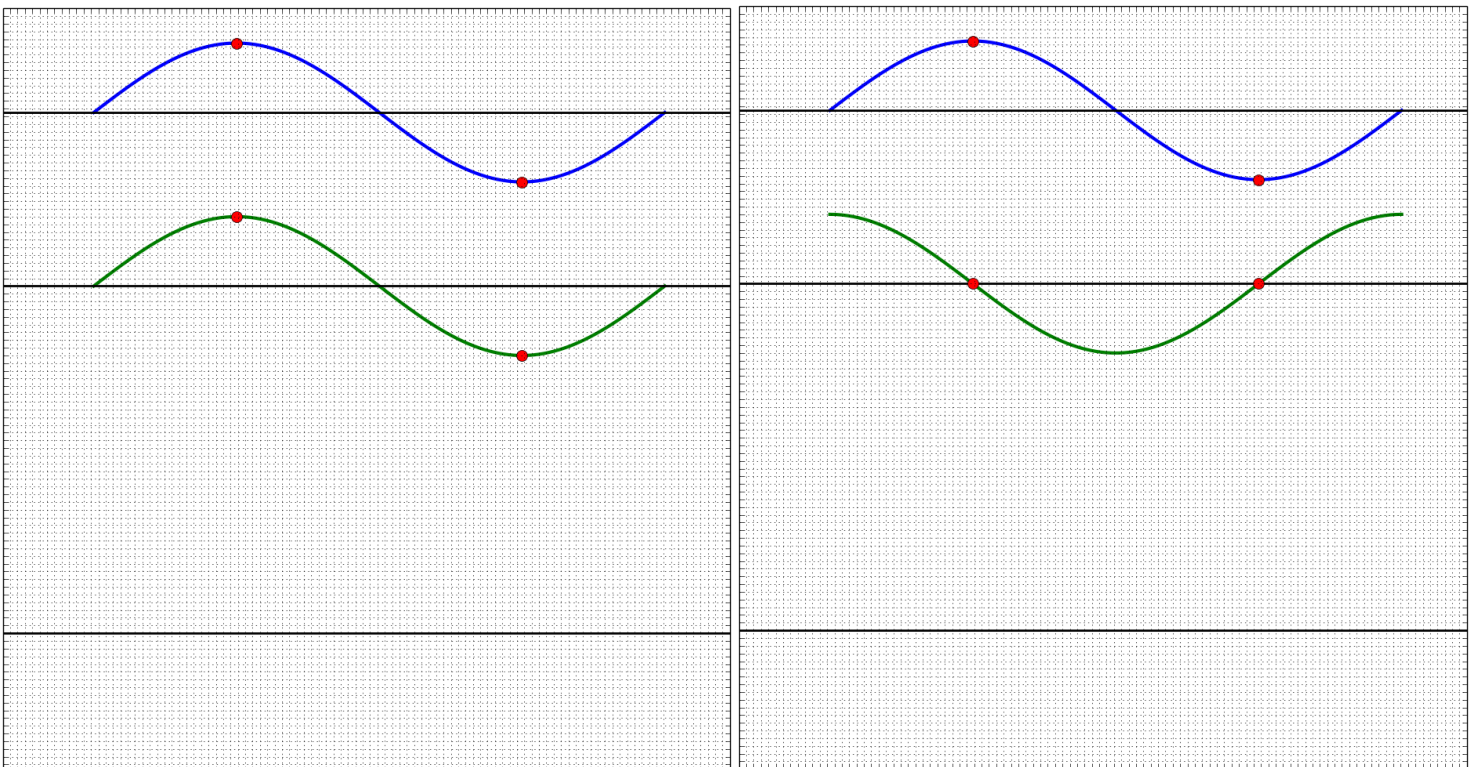


### QUESTION – INTERNET RESEARCH

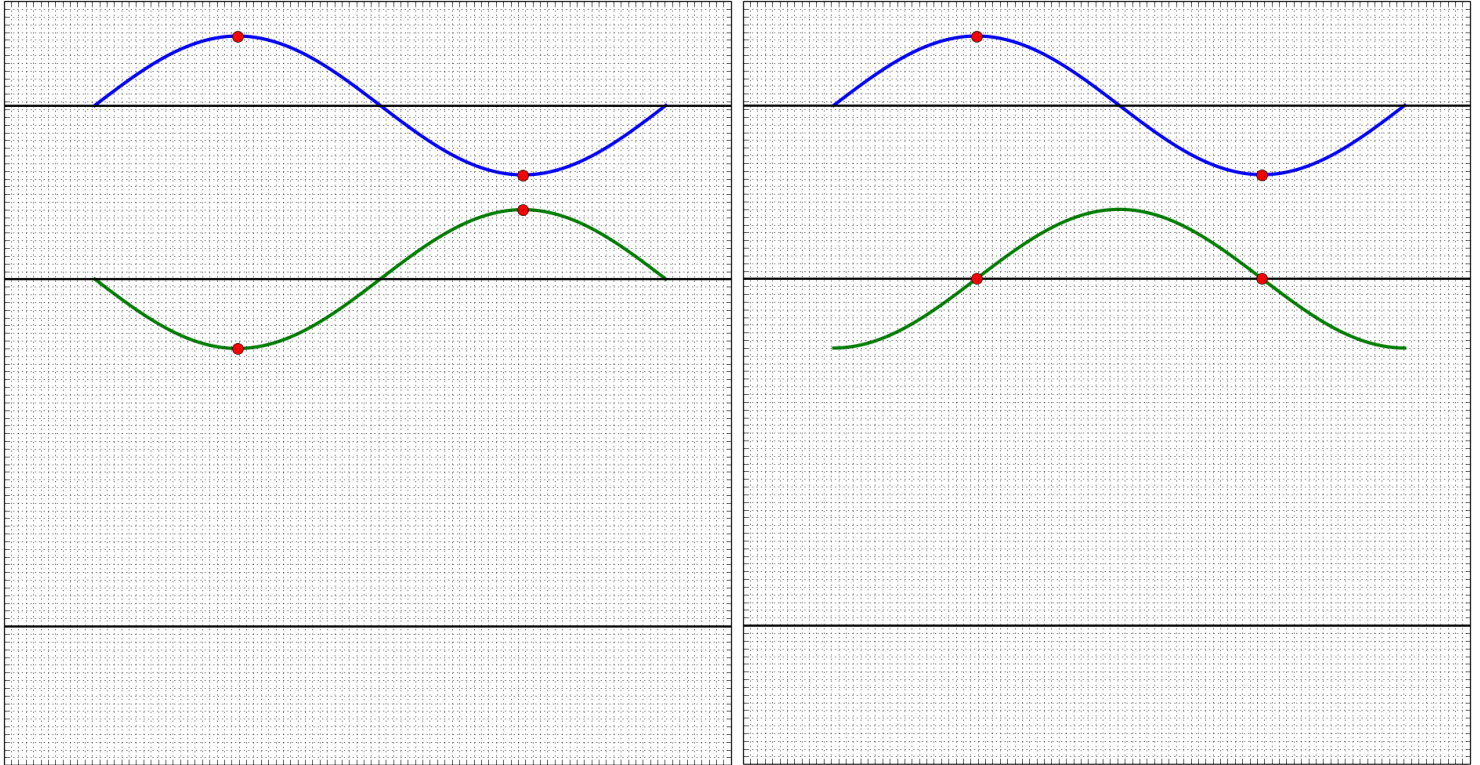
How do noise-cancelling headphones work?

### QUESTION – PENCIL

Using the principle of superposition draw the resultant wave produced by the two standing waves below.









# Investigation: Wave Behaviours

## INTRODUCTION

It's hard to find a playground that doesn't have a swing set and swinging is always heaps of fun. But what makes the swing go higher and faster? How can we push someone so that they swing higher and have a better time?



Image by 'wsilver' <https://www.flickr.com/photos/psycho-pics/2722836221/in/faves-120056317@N06/> Licence: <https://creativecommons.org/licenses/by/2.0/>

We know that when we push someone on a swing it is best to push them from when they are highest and on their way back down to the ground. But how often should you push them so that the person swinging goes as high as possible?

In this experiment, we will try to analyse the motions of a swing using a pendulum. This is a mechanical system and the pendulum is a harmonic oscillator. We will be measuring the natural frequency of a pendulum and determining the frequency of pushes that improve the swinging motion of the pendulum the most. We will also be considering the energy transformations of this system. Things to think about before the experiment: at what point of a swing do you think you are moving the fastest?

## 1. QUESTIONING AND PREDICTING

So, let us think about the aim of this investigation.

1. What is the natural frequency the pendulum wishes to swing at?
2. What frequency of an added regular force increases the swinging motion the most?



### HYPOTHESIS

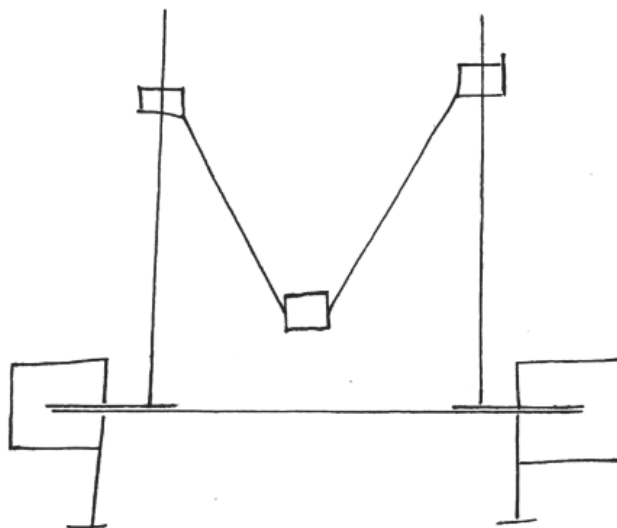
The regular pushing force will be most effective at increasing the swinging motion at a frequency (that matches the natural swing/is fastest/is slowest)

## 2. PLANNING INVESTIGATION

This investigation has been planned for you.

We will use one pendulum and find the frequency of pushes that naturally increases the amplitude of the swinging pendulum.

1. Set up your apparatus as shown in the picture below:



2. Place a 1 meter ruler horizontally against the wall. This will give you a scale for measuring the displacement of the object.
3. Use a smartphone or digital camera to record a video of the mass swinging from the time when it is released.
4. Raise one mass up a small angle and release it to let it swing.
5. The frame rate (in frames per second) of the recording is a fixed value which you can get from the camera settings. Find this value. Convert this to the time per frame. (For example, if the video is recorded at 30 fps, each frame lasts for  $1/30^{\text{th}}$  of a second.)
6. Look at the video frame by frame. What is the position of your object against each ruler for each frame?
7. Record the object's horizontal position and vertical position at each frame in the table on the next page. If there are a large number of frames, you may wish to take data every five or ten frames.
8. Repeat the experiment but 'bump' the mass at a consistent rate and force so that the pendulum keeps swinging smoothly and the amplitude of the pendulum increased. Make sure the hand is only moving in the horizontal direction.

Some groups may choose to download the free app 'VidAnalysis Free' for androids or the app 'Vernier Video Physics' for iPhones and analyse the video within the app to create graphs of the x-positions and y-positions over time.

### 3. CONDUCTING INVESTIGATION

For each pendulum, you should take a video that clearly shows the mass swinging and the scale of the ruler until the object hits the floor and the motion of the hand hitting the mass. Choose suitable time intervals and record the horizontal displacement of the mass and the horizontal displacement of the hand when applicable.

No input:

Time (s)	Horizontal Displacement (m)	Any other comments on motion of object and taking the video

Input frequency:

Mass displacement:

Time (s)	Horizontal Displacement of mass (m)	Any other comments on motion of object and taking the video

Hand displacement:

Time (s)	Horizontal Displacement of hand (m)	Any other comments on motion of object and taking the video

**Did you make any changes to the method? Did you have design problems to solve? Did you have some 'smart' ways of doing the investigation?**

#### 4. PROCESSING AND ANALYSING

Plot the displacement of the mass versus time on graph paper or using a spreadsheet program for the horizontal displacement. Plot the displacement of the hand (when used) versus time as well.

What shape are each of the displacement-time graphs of the mass and the hand? What shape would you expect the velocity-time graphs to be (remember the velocity is the change in displacement over the change in time)?

Try plotting the velocity-time graph of the pendulum mass for two periods of oscillation.

Finding the frequency of oscillation requires us to know the period of the oscillation. Mark on your graph a point where the displacement is a maximum and record the value of the time at that point, then record the time at the next maximum point on the graph. What is the difference between those times? To improve the validity of this period, record the time it takes for your pendulum to complete 10 full oscillations. Using the formula,

$$T = \frac{t}{10},$$

where  $T$  is the period of one oscillation and  $t$  is time for 10 full oscillations, calculate the time for one oscillation.

Repeat this for the input force of the hand too.

What shape do you expect the velocity-time plots to be for both the mass and the hand?

#### 5. PROBLEM SOLVING

- ⇒ Consider the energy transformations (always has constant mechanical energy, but the kinetic is max when position is zero and zero when still at max distance vice versa for the potential energy)

This is the section where we think about the results and what they mean.



When we let the pendulum swing it has a periodic motion. Each pendulum has a natural frequency at which it wants to oscillate. We can calculate it using:

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

where  $f$  is the frequency and  $T$  is the period. The period is measured in seconds as the time for the pendulum to complete one oscillation (the time we measured in our analysis)

What was the natural frequency of the pendulum?

\_\_\_\_\_

What was the frequency of the optimal input force?

\_\_\_\_\_

What can you say about these two frequencies?

The **amplitude** of the pendulum is the maximum displacement of the mass during the oscillation.

The **natural frequency** of oscillation is the frequency your pendulum wishes to oscillate at. No matter how high you begin the oscillation at or how hard you push the mass at the beginning, it will always oscillate with this frequency.

The **driving frequency** of a harmonic oscillator is the frequency of the input force, how frequently you pushed the pendulum in this case.

What relationship did you observe between the driving frequency and the natural frequency which increased the amplitude of your pendulum?

## 6. CONCLUSIONS

The natural frequency of the pendulum was \_\_\_\_\_.

The frequency of the driving force that increased the amplitude was \_\_\_\_\_.

The total energy of the system stays the same and the kinetic and potential energies \_\_\_\_\_.



# Investigation: Interference of Sound Waves

## INTRODUCTION

A speaker produces sound waves using a vibrating cone which changes the pressure of the air around it. The wave travels outwards in every direction and eventually reaches your ears.

Sound waves have the same properties as other types of waves, such as reflection and interference. Interference occurs when two waves are passing through the same position. These can be waves from two different sources, or a wave from one source plus its reflection. Both constructive and destructive interference are possible. This will affect the loudness of the sound you hear.

In this experiment, we will investigate the interference of sound waves produced by speakers and how the result varies with position. We will use the interference pattern to find the wavelength of a tone and compare it with the theoretical wavelength.

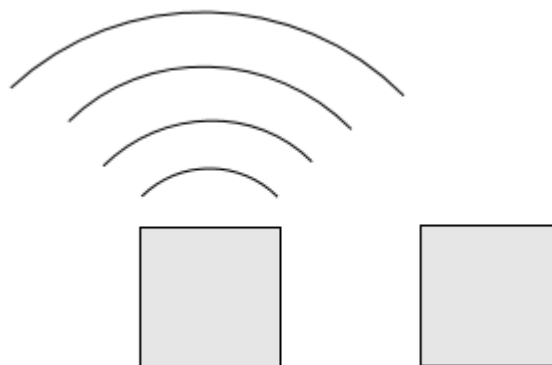
## 1. QUESTIONING AND PREDICTING

Let us think about the aim of this investigation.

1. What conditions are needed to produce interference between sound waves?
2. Where will constructive interference occur?
3. Where will destructive interference occur?

This diagram shows the wavefronts coming out of a speaker. Sketch what happens as they get further from the speaker.

Sketch the wavefronts coming from the second speaker (which is playing the same sound) and describe the results of the interference.



## HYPOTHESIS

Regions where the waves interfere constructively will sound \_\_\_\_\_ (louder/quieter).

Regions where the waves interfere destructively will sound \_\_\_\_\_ (louder/quieter).

The spacing of maxima and minima depends on \_\_\_\_\_.

## 2. PLANNING INVESTIGATION

This investigation has been planned for you. It is most suited to being performed by a whole class.

### Part A: Interference between two sources

You will need a pure (sine wave) tone to be played through two speakers. This can be created by a signal generator, or by an online app/recording. The frequency should be about 340 Hz in order to produce a wavelength of about 1 metre – this will make it easier to find distinct points of interference.

1. Place the speakers on a desk, facing in the same direction about a metre apart, and play the tone.
2. Have one student stand approximately the same distance from both speakers, at least a metre away. The student should find the location where the resulting tone sounds the loudest and place masking tape or a chalk mark on the floor<sup>1</sup>.
3. Get a second student to start from the first mark<sup>2</sup> and find a nearby point where the sound is loudest. Mark the location.
4. After 5-10 points of constructive interference have been found, repeat steps 2-4, this time finding locations where the sound is quietest. Mark these locations so they can be distinguished from the maxima.

### Part B: Interference with a reflection

For this section you will need only one speaker, plus a strongly reflective surface such as a sheet of metal or tile. You should also use a small power meter, such as a smartphone app, to measure the resulting volume in order not to block the wave.

1. Place the tile approximately two wavelengths away from the speaker and play the tone.

---

<sup>1</sup> If it is difficult or impractical for students to find regions of constructive/destructive interference by ear, a power meter can be used to measure the loudness in decibels at different locations. Smartphone apps can perform this task.

<sup>2</sup> Tip: Ensure all students listen to/measure the volume at approximately the same height above the ground; sound waves travel in three dimensions and we are interested in the 2D pattern at one height.





2. Move the sensor/meter along the path of the sound to find the loudest and quietest regions.
3. Adjust the position of the reflector until the greatest difference between maximum and minimum volume is observed. This indicates that a standing wave has been formed.
4. Mark the positions of maxima and minima on the floor using masking tape.

### 3. CONDUCTING INVESTIGATION

After each part, take a photograph or draw a scale diagram showing where the regions of constructive and destructive interference occur as marked by the students. Compare the pattern obtained from Part A of the experiment with the pattern you drew in Section 1. On your photograph/diagram, sketch the locations of wavefronts from each speaker which would give you the pattern.

If time permits, you should perform this investigation for multiple wavelengths in order to compare results.

**Did you make any changes to the method? Did you have design problems to solve? Did you have some 'smart' ways of doing the investigation?**

### 4. PROCESSING AND ANALYSING

What do you observe about the spacing of the loudest and quietest points compared to the wavelength of the sound? Do they change with wavelength?

Measure the distance between the wavefronts. How does it compare to the approximate known wavelength of the sound?

Observe the pattern of maxima and minima obtained in Part B of the experiment. What can you say about the spacing between them? The distance between two neighbouring maxima or two neighbouring minima of the standing wave is equal to half the wavelength of the sound wave.

## 5. PROBLEM SOLVING

One way to think about the wavelength of a sound wave is as the distance between wavefronts. The shorter the wavelength (i.e. the higher the frequency), the further apart the wavefronts are. This will in turn affect the spacing of the interference maxima (completely constructive) and minima (completely destructive).

In Part A of the experiment, we used the characteristics of interference between two waves of the same wavelength in order to locate the wavefronts and hence make an experimental measurement of the wavelength.

In Part B of the experiment, we used the property of reflection to effectively 'create' a second wave travelling in the opposite direction. If we fit a certain number of wavelengths between the source and the reflector, we can create a standing wave where the maxima and minima are always in the same place. An animation of this can be seen at:

[https://commons.wikimedia.org/wiki/File:Standing\\_wave\\_2.gif](https://commons.wikimedia.org/wiki/File:Standing_wave_2.gif)

The distance between neighbouring maxima/minima gives half the wavelength.

Because we know the speed of sound in air, knowing the frequency of our generated sine wave allows us to make a theoretical calculation of wavelength using the wave equation:

$$v = f\lambda$$

Where  $v$  is the speed of sound ( $\approx 340$  m/s) and  $f$  is the frequency in Hz.

The theoretical wavelength can now be compared to the experimentally measured wavelength.

## 6. CONCLUSIONS

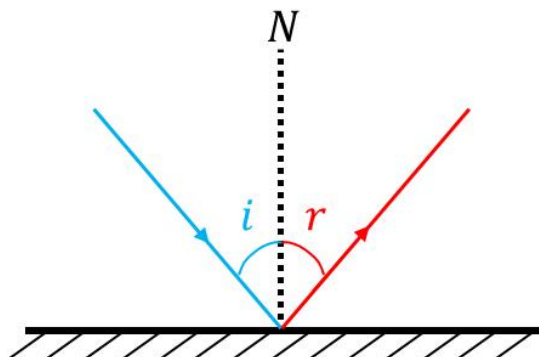
Interference of sound waves with the same frequency can be measured via the loudness of the sound.

The spacing of maxima and minima depends on wavelength. The longer the wavelength, the \_\_\_\_\_ (closer/further) the maxima and minima.

## RAY MODEL OF LIGHT

### CONTENT – REFLECTION

When light strikes a boundary between two materials, some of it will be reflected, and some will be refracted. In the ray model of light, the path light travels in is represented as a straight line which we call a ray. The ray continues in a straight path until it hits the boundary of an interface. When light hits a boundary, at least some of the light is reflected. The Law of Reflection states that the incident ray (incoming ray, marked blue in the diagram on the right), reflected ray (marked red) and the normal,  $N$ , lie on the same plane. If the angle of incidence is  $i$  with respect to the normal, then the angle of reflection is  $r$  and these two angles are equal. Reflection according to the ray model of light is illustrated in the diagram on the right. Reflection can take place from smooth/flat surfaces, or from irregular/bumpy surfaces. In both cases, the rays obey the Law of Reflection. The Law of Reflection is exploited in devices such as mirrors, microscopes and telescope where incoming light bounces off a reflective surface (in the latter two cases inside a cylinder tube).



### CONTENT – REFRACTION

Refraction is the bending of a light ray as it passes from one medium to another. The ray bends towards the normal if its speed decreases as it moves into a different medium, whereas it bends away from the normal if its speed increases with a change in medium. As explained in detail below the refractive index is essential for determining the bending of light towards or away from the normal.

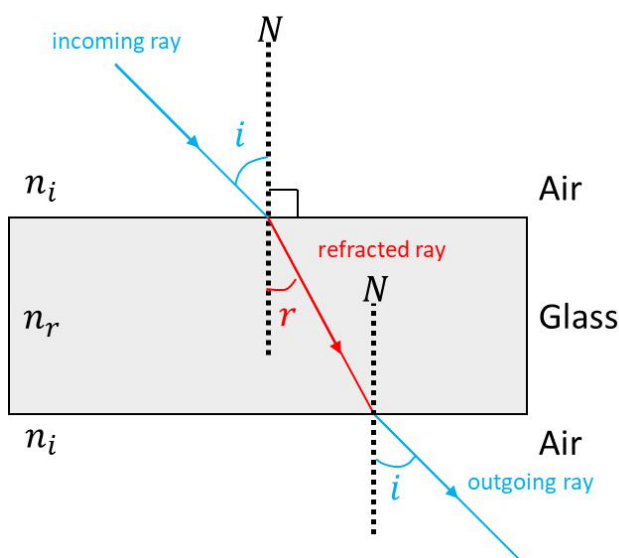
The speed of light, written as the symbol  $c$ , in vacuum or in air is  $3.0 \times 10^8$  m/s. When light enters a material (through an interface) its speed can increase or decrease. The speed changes depending on the refractive index of the material. If  $x$  represents the medium and  $v_x$  is the speed of light in the medium, then the refractive index of the material is

$$n_x = \frac{c}{v_x}$$

If the refractive index is equal to 1.0, then the speed of light in medium  $x$  is the same as it is in air and no bending of the light ray occurs. The larger the refractive index the slower the speed of light is in the medium. When light enters a medium with a refractive greater than 1.0 the path of the ray changes. The relationship that describes the light ray entering a medium from one medium to another is called Snell's law:

$$n_1 \sin(i) = n_2 \sin(r)$$

$i$  is angle of the incident (incoming) ray,  $r$  is the angle of the refracted ray and  $n_1$  and  $n_2$  are the refractive indices for the two medium the light ray travels in. The diagram below illustrates Snell's law for a light ray entering a glass medium from air.





The light ray travels in a path towards the air-glass interface at an incident angle  $i$  with respect to the normal (line perpendicular to glass surface). The path of the ray is altered due to the refractive index of the material and the refracted angle is  $r$ . Once the ray reaches the end of the glass medium the ray's path will refract again so as to be parallel to its path before entering the glass. The angle of the outgoing ray is the same as the angle of the incoming ray,  $i$ .

### QUESTION 1

Light travels from air into flint glass with an angle of incidence of  $30^\circ$ . If the refractive index of glass is 1.66 and that of air is 1.00, what is the angle of the refracted ray?

⇒ Start by writing down Snell's law

$$n_1 \sin(i) = n_2 \sin(r)$$

⇒ Rearrange the equation

$$\sin(r) = \frac{n_1}{n_2} \sin(i)$$

⇒ To make  $r$  the subject, take the inverse sine

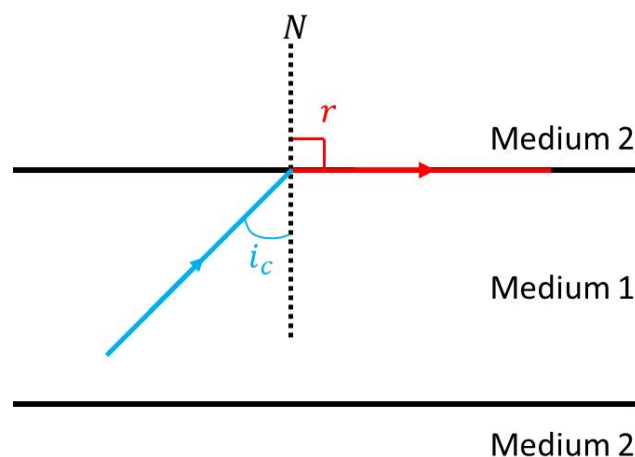
$$r = \sin^{-1}\left(\frac{n_1}{n_2} \sin(i)\right)$$

⇒ Putting in all the numbers for the refracted indices and incident angle, the refracted angle is

$$\begin{aligned} r &= \sin^{-1}\left(\frac{1.00}{1.66} \sin(30^\circ)\right) \\ &= 17.5^\circ \end{aligned}$$

### CONTENT – TOTAL INTERNAL REFLECTION

When light travels from an optically denser material to one less dense, (as, for example, from glass to air) the refracted ray is bent away from the normal to the surface. As the angle of incidence increases a situation will be reached where the refracted ray lies along the surface between the two materials (i.e. the refracted angle is  $i_r = 90^\circ$ ). This angle of incidence is called the critical angle  $i_c$ . Below is a diagram illustrating the critical angle of the incoming ray at an interface.

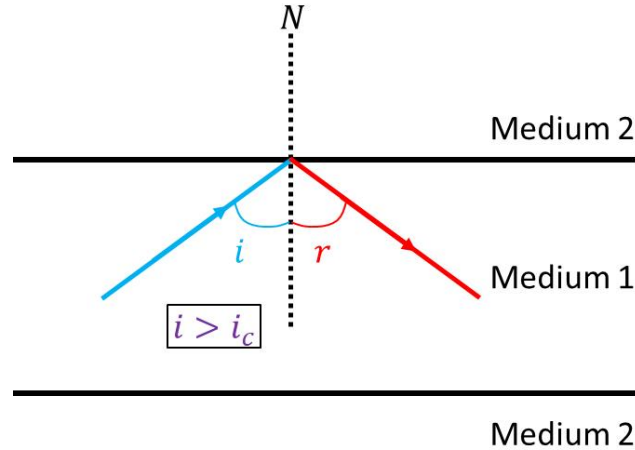


Applying Snell's law to the situation above, the right-hand side of the equation becomes  $n_2 \sin(90^\circ) = n_2$ . If medium 2 is air the refractive index is equal to  $n_2 = 1.00$ . Thus, the sine of the critical angle is

$$\sin(i_c) = \frac{1}{n_x}$$



To determine the critical angle, we take the inverse of the sine of the right-hand side. At angles greater than the critical angle all the light is reflected, so no light escapes the optically denser material. This phenomenon is called total internal reflection (TIR). As illustrated below, any such ray obeys the Law of Reflection with the angle of incidence  $i$  equal to the angle of reflection  $r$ .



### QUESTION 2

Light travelling inside crown glass with a refractive index of  $n = 1.50$  approaches the glass-air interface. What is the minimum angle of incidence needed for the light to be totally reflected (i.e. critical angle  $i_c$ )?

⇒ We first write down the equation for the critical angle

$$\sin(i_c) = \frac{1}{n_x}$$

⇒ Rearranging to make the critical angle the subject

$$i_c = \sin^{-1}\left(\frac{1}{n_x}\right)$$

⇒ Substituting the refractive index of glass is

$$\begin{aligned} i_c &= \sin^{-1}\left(\frac{1}{1.50}\right) \\ &= 41.8^\circ \end{aligned}$$

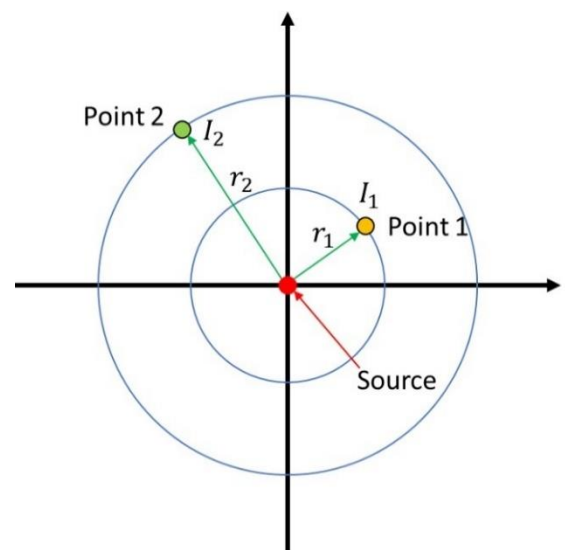
⇒ Therefore, the angle of incidence needs to be at least  $41.8^\circ$  for total internal reflection to occur.

### CONTENT – LIGHT INTENSITY

As light travels in space, the intensity (power per unit area) of the light will gradually decrease. Thus, the light intensity is greater the closer you are to the light source. This is demonstrated in real life when you see an oncoming car at night the headlights are very faint. As the car comes closer to you, the headlights become very bright. The intensity,  $I$ , is inversely proportional to the square of the distance,  $r^2$ , and this relationship is called the inverse-square law

$$I \propto \frac{1}{r^2}$$

The reason for the relationship is that the light is spread out over the surface of an expanding sphere. Following the inverse-square law, the intensities of light at two points,  $r_1$  and  $r_2$  from a point source at the origin,  $O$ , is given by





$$I_1 r_1^2 = I_2 r_2^2$$

The intensity multiplied by the distance squared must be equal at the two points because the light intensity at any point cannot be greater than the intensity at the source (i.e. conservation). Thus, if the distance  $r_2$  is greater than  $r_1$  the intensity  $I_2$  must be smaller than  $I_1$  to compensate.

### Question 3

If the intensity of light at 0.5 m from a source is 100 W/m<sup>2</sup>, what is the intensity of light at 3.0 m away from the source?

⇒ The inverse-square law that the relationship of the intensities at two points is

$$I_1 r_1^2 = I_2 r_2^2$$

⇒ We want to find the intensity at point 2, thus rearrange to make  $I_2$  the subject

$$I_2 = \frac{r_1^2}{r_2^2} I_1$$

⇒ Substituting the known values, we get an intensity of

$$\begin{aligned} I_2 &= \frac{(0.5 \text{ m})^2}{(3.0 \text{ m})^2} \times 100 \text{ W/m}^2 \\ &= 2.78 \text{ W/m}^2 \end{aligned}$$

### QUESTION 4 - Internet RESEARCH

Explain how the phenomenon of total internal reflection is used in fibre optics technology?

### QUESTION 5 - Internet RESEARCH

How is the inverse-square law of light used in photography?

## TEMPERATURE

### CONTENT – TEMPERATURE AND KINETIC ENERGY

What is temperature? In our everyday life experience temperature is a measure of the degree of ‘hotness’ or ‘coldness’ of an object. The term ‘heat’ refers to *energy* (or more specifically *thermal energy*) and is related to temperature. The SI unit of heat or thermal energy is Joule (J). The temperature of an object can be increased by adding thermal energy to it, and it can also be decreased by removing thermal energy from the object. However, heat and temperature are not the same quantities. The temperature of an object determines the average kinetic energy of all particles (i.e. atoms and molecules) in the object. The higher the temperature, the larger the kinetic energy (particles on average moves faster). If two objects are in thermal contact, thermal energy will be transferred from the object at the higher temperature to the object at the lower temperature.

### QUESTION 1

Consider heating two beakers of water using a Bunsen burner – keeping all variables the same and simply changing the amount of water being heated. If the amount of water in Beaker A is 50 mL and in Beaker B 100 mL, which beaker will have a higher temperature after 1 minute?

### CONTENT – TEMPERATURE SCALES

If temperature is an indicator of the average kinetic energy of particles in an object, how then should we report the value of temperature? Would a news outlet report on the temperature in Joules? Most likely not because it is not something that is humanly relatable. Thus, temperature scales were invented for convenience. For historical reasons, there are three temperature scales available used for measuring temperature – Fahrenheit, Celsius and Kelvin. The SI unit of temperature is Kelvin (K), and at 0 K all the particles in an object stop moving (zero thermal energy).

One or more fixed points are required for these three temperature scales. In the SI system, the triple boiling point of water is used as the internationally accepted fixed point; the temperature scale is defined by assigning the value of 273.15 K to this triple point.

The table below shows the **lower** (*melting point of ice*) and **upper** (*boiling point of water*) points of the three scales. For the Celsius and the Fahrenheit scales, they are fixed points.

Temperature scale	Lower fixed point	Upper fixed point
Fahrenheit	32 °F	212 °F
Celsius	0 °C	100 °C
Kelvin	273.15 K	373.15 K

The temperature measured in Celsius can be converted to the Kelvin scale adding 273.15 K to each reading on the Celsius scale. Fahrenheit measurement can be converted to Celsius by  $T(^{\circ}\text{C}) = (T(^{\circ}\text{F}) - 32) \times \frac{5}{9}$ .

### QUESTION 2

Convert the following temperatures from:

Celsius to Kelvin:

- a) 26 °C
- b) 92 °C

Fahrenheit to Celsius:

- c) 85 °F
- d) 54 °F

### QUESTION 3 INTERNET RESEARCH

When was the first thermometer made?



## THERMAL EQUILIBRIUM

### CONCEPT

Two objects are said to be in *thermal equilibrium* if they are in contact with each other, and no heat transfer occurs. To understand this, consider a hot iron object placed in a container of cold water illustrated in the

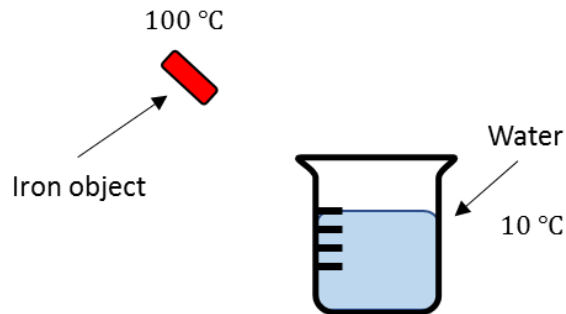
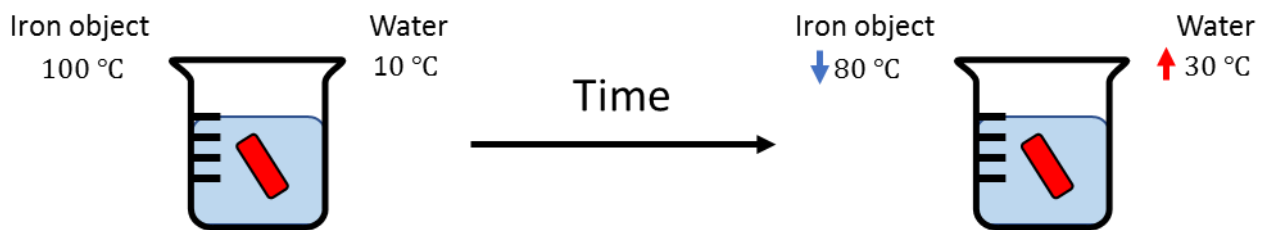
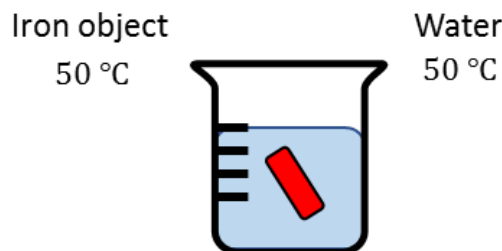


diagram below.

The iron has a higher temperature than the temperature of the cold water. When the iron object is dipped into the container (thermal contact) heat transfer occurs. Thermal energy is passed from the iron to the cold water. The iron object slowly loses heat while the cold water gains heat.



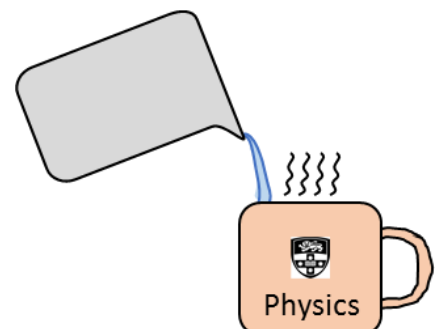
The heat transfer stops when both the iron object and water reaches the same temperature.



When this happens, the iron object and water are said to be in a state of *thermal equilibrium*.

### EXAMPLE – REAL WORLD

The example above can be applied to a common real-world example: your coffee mug. When you pour hot water into the coffee mug, the hot water transfers energy (heat) to the mug. As a result, the temperature of the mug will increase. The temperature of the hot water will continue to decrease as the mug gets hotter. After some time, the temperature of the water and mug will be the same. Thus the two are in thermal equilibrium.





## SPECIFIC HEAT CAPACITY

### CONTENT

The previous two topics deal with heat or thermal energy and the difference between temperature and internal energy (the kinetic energy of particles within an object). The symbol for thermal energy is  $Q$  and has units of joules (J). A change in temperature results in a change in thermal energy. Writing the mass of an object as  $m$ , the initial and final temperatures of the object  $T_1$  and  $T_2$  and the resulting change in thermal energy as  $Q$ , we have the equation

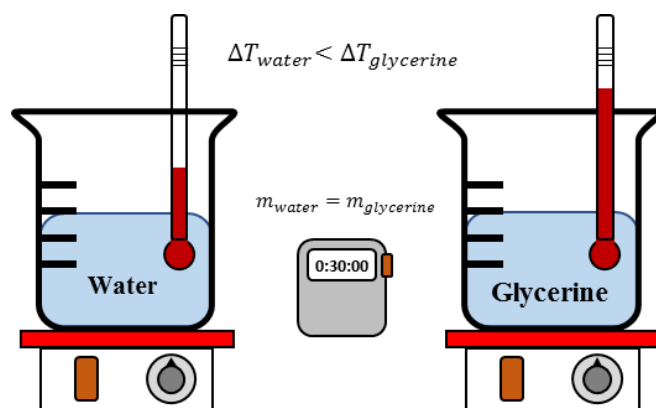
$$Q = mc(T_2 - T_1)$$

$$Q = mc\Delta T$$

In this equation,  $c$  is a property of matter called the specific heat capacity. The specific heat capacity is defined as the amount of thermal energy needed to raise the temperature of a 1 kg object by 1 °C. The SI unit for specific heat is J/(kg.°C). Different materials will behave differently to a change in temperature and is described by the value of the specific heat capacity. The change in temperature  $\Delta T$  can either be positive or negative depending on whether thermal energy is entering or leaving the body.

### EXAMPLE - LABORATORY

Consider equal masses of 1 kg of water and glycerine in separate beakers, both initially at the same temperature  $T_1$ .



As both beakers are heated the temperatures as shown by the thermometers will increase. However, the increase shown on the thermometer in the glycerine will be greater than that shown on the thermometer in the water. This is because the specific heat of glycerine is less than that of water ( $c_{\text{water}} = 4184 \text{ J}/(\text{kg}.\text{°C})$  and  $c_{\text{glycerine}} = 2430 \text{ J}/(\text{kg}.\text{°C})$ ).

### QUESTION 1 - INTERNET RESEARCH

Track down and compare the specific heat capacities of common substances – water, alcohol, ice, aluminium, iron, copper, gold, mercury, wood and steel.

### QUESTION 2

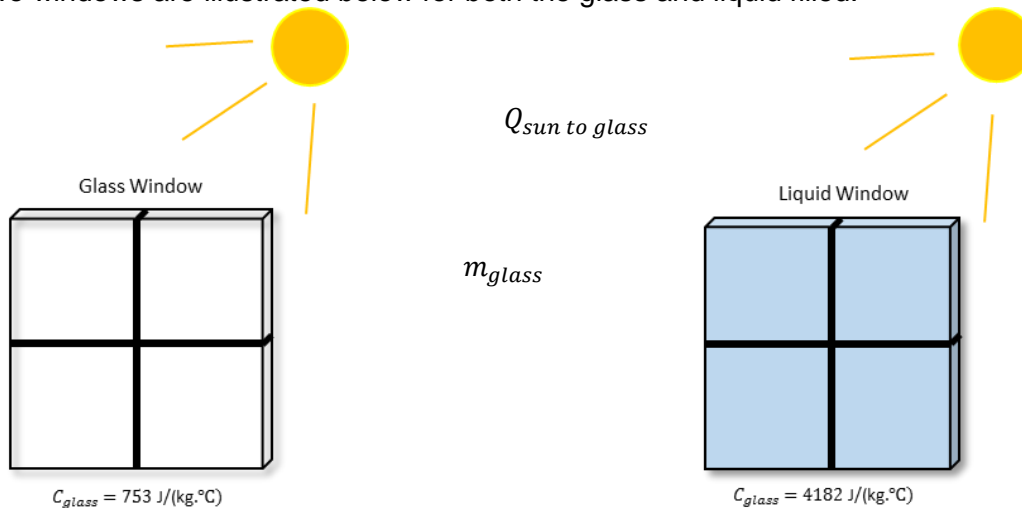
If we take 10 g of water and add 700 J by heating it, what will be the rise in its temperature? (Remember that the SI unit of mass is kg.)



**EXAMPLE - REAL WORLD**

In an attempt to reduce electric bills for homes, some innovators have developed liquid filled windows to cool houses in summer and help keep them warm in winter explain how a water-filled window can cool the house in summer but the opposite in winter. Is it better to use alcohol than water for the liquid instead? The specific heat of glass is  $c_{glass} = 753 \text{ J}/(\text{kg}\cdot^{\circ}\text{C})$ , water is  $c_{water} = 4184 \text{ J}/(\text{kg}\cdot^{\circ}\text{C})$  and alcohol is  $c_{alcohol} = 2440 \text{ J}/(\text{kg}\cdot^{\circ}\text{C})$ .

⇒ The two windows are illustrated below for both the glass and liquid filled.



⇒ Both windows should receive the same amount of thermal energy from the sun. Starting with the equation

$$Q = mc\Delta T$$

⇒ Rearrange to get the change in temperature

$$\Delta T = \frac{Q}{mc}$$

⇒ The change in temperatures for the two windows then becomes

$$\Delta T_{glass} = \frac{Q}{m \times 753}$$

$$\Delta T_{water} = \frac{Q}{m \times 4184}$$

$$\Delta T_{glass} > \Delta T_{water}$$

Since the specific heat capacity of glass is about 5x smaller than water

⇒ Therefore, the liquid filled window will have a change in temperature about five times smaller than the glass window.

⇒ If alcohol is used instead of water then the change in temperature is:

$$\Delta T_{alcohol} = \frac{Q}{m \times 2440}$$

$$\Delta T_{water} = \frac{Q}{m \times 4184}$$

$$\Delta T_{alcohol} > \Delta T_{water}$$

Since the specific heat capacity of alcohol is about 2x smaller than water

⇒ If we were to use alcohol to fill the window, the change in temperature would be about twice the change for the water-filled window. Therefore, it would be better to use water.



# Investigation: Thermal Conductivity

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## INTRODUCTION

For understanding the concept of thermal conductivity, let's take an example - consider walking barefoot on a tiled floor and on a carpet. Which surface feels 'colder' to walk on? Walking on a tiled floor 'feels' colder than walking on a carpet. The differences in sensations are to do with the composition of both the tiled floor and the carpet. The tiled floor is made up of a different material than the carpet; hence the rate at which heat transfer occurs is not the same for both these surfaces. When heat transfer occurs between two objects that are in contact, we refer to this transfer of heat as *thermal conduction*.

What really happens when you stand barefoot on a tiled floor in winter? Think about the molecules in the two bodies that are in contact – what is their kinetic energy?

In this experiment, we will model and predict quantitatively energy transfer from hot objects by the process of thermal conductivity. Before carrying out the experiment, undertake an internet research activity to find the thermal conductivity values for a range of metals. What do you observe?

## 1. QUESTIONING AND PREDICTING

Think about the following questions to formulate an aim for the investigation that you will undertake:

1. What factors does thermal conductivity depend on?
2. Will heat transfer occur at the same rate for two substances made up of the same material, but of different thickness?
3. Do you think all substances (for example metals) conduct heat at the same rate?

## HYPOTHESIS

Thermal conductivity varies/does not vary for different metals.  
Different metals conduct heat at (different/same) rates.

## 2. PLANNING INVESTIGATION

This investigation has been planned for you.

In this experiment, we will investigate if different metals conduct heat at different or same rates. To this end, we will use a range of metal wires of same length and thickness, a Bunsen burner, wax blobs and paper clips of equal size, heat proof mat, matches, stop watch, tripod and safety glasses.

Before undertaking any science experiment, it is important to do a risk assessment to assess any risks and devise strategies to mitigate those risks. Complete the table below.

Potential risks	Strategies to mitigate the risks

The steps below outline the procedure for carrying out the experiment.

1. Place the Bunsen burner on a heat proof mat and ensure that the air hole of the Bunsen burner is closed (*Recall* the difference between the safety flame and blue flame of a Bunsen burner.)
2. Place a tripod stand on top of the Bunsen burner.
3. Arrange a range of metal wires on top of the tripod stand ensuring that they all get exposed to the heat from the Bunsen burner in the same way, when we'll light the Bunsen burner in Step 5.
4. Place a wax blob at the end of each wire and attach a paper clip to each blob of wax.
5. Have a stop watch ready (you can use one on your phone) and light the Bunsen burner.
6. Record the time taken for the wax to melt resulting in the paper clip to fall from each wire. When will you stop recording the time? When the Wax starts melting or when the paper clip falls?

### 3. CONDUCTING INVESTIGATION

Record your results in the table below.

Metals	Time (s)

Is your experiment 'reliable'? Why/why not?  
Can you think of any errors that likely affected your results?  
How can you improve the experiment?



#### 4. PROCESSING AND ANALYSING

Plot the results on a graph paper or in Microsoft Excel. Will you make a line graph or a column/ bar graph? What graph would best represent your results?

What were the independent, dependent and control variables in your experiment?

Is your experiment valid?

#### 5. PROBLEM SOLVING

Refer to the worksheet on Energy Transfer, and work with the following equation:

$$P = \frac{Q}{t} = \frac{kA\Delta T}{d} = \frac{kA(T_2 - T_1)}{d}$$

What do the different components of the thermal conduction equation mean?

As an extension to this experiment, plan another investigation to test if same metals with varying thickness conduct heat at the same time. What could be your hypothesis?

Thermal conductivity varies/does not vary for same metals with varying thickness  
Same metals with varying thickness conduct heat at (different/same) rates.

#### 6. CONCLUSIONS

Fill in the blanks with one or many words.

Different metals conduct heat at \_\_\_\_\_ rates.

Thermal conductivity is \_\_\_\_\_ for different metals.

Thermal conductivity \_\_\_\_\_ for same metals with varying thickness.

Same metals with varying thickness conduct heat at \_\_\_\_\_ rates.

# Investigation: Latent Heat of Vaporisation

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## INTRODUCTION

When we want to increase the temperature of a substance, we need to supply heat. The amount of heat energy it takes to raise the temperature by one degree depends on the heat capacity.

Something different happens when we reach a phase change. If you take ice out of the freezer, it warms up until it starts to melt – and then stays at  $0^{\circ}\text{C}$  until it finishes melting! Does this mean that heat has stopped transferring to the ice?

In this experiment, we will analyse the heat transfer involved when water boils. We will be looking at what happens to the temperature of the water, and how much energy it takes to convert water into steam.

## 1. QUESTIONING AND PREDICTING

Let us think about the aim of this investigation.

1. How does the temperature of water change when it is near or at its boiling point?
2. How much energy do we have to supply to boil a certain volume of water?

## HYPOTHESIS

The temperature will \_\_\_\_\_ (increase/remain constant) once the water reaches its boiling point.

The amount of energy needed to boil a given volume of water is a constant.

## 2. PLANNING INVESTIGATION

This investigation has been planned for you.

Each group will be given a Bunsen burner, a stopwatch, a beaker of water and a thermometer. There will be a weighing scale available for use. First, we must determine the rate at which the Bunsen burner supplies heat to the water.

1. Measure and record the temperature of the water before heating.
2. Measure the initial mass of the water. (Hint: find the mass of an empty beaker and subtract this from your measured value.)
3. Heat the water over the burner for one minute. Ensure it does not begin to boil at this stage.
4. Remove the beaker from the heat source. Stir gently to ensure the temperature is consistent and record the increased temperature.



5. Use the equation  $\Delta Q = mc\Delta T$  to determine how much heat was transferred to the water in one minute. Use the value  $c = 4.18 \text{ kJ/kg/}^\circ\text{C}$ .

You can now assume the burner provides heat to the water at this constant rate. In the second phase of the experiment, we will examine how much heat is required to boil a certain mass of water.

6. Continue heating the water until it reaches boiling point at  $100^\circ\text{C}$ . Start timing on the stopwatch.
7. Record the temperature every 20 seconds and observe any trends.
8. After approximately three minutes, remove the beaker from the heat source. Determine the mass of water which remains in the beaker.
9. Use your value for the rate of heating (from step 5) to determine how much heat was required to boil off the difference in mass.
10. Using the equation  $Q = mL$ , calculate the latent heat of vaporisation  $L$  for water in  $\text{kJ/kg}$ .

### 3. CONDUCTING INVESTIGATION

Each group should fill in the following as you go:

Initial mass of water: \_\_\_\_\_

Initial temperature of water: \_\_\_\_\_

Temperature of water after heating: \_\_\_\_\_

Record the observations of temperature while boiling the water:

Final mass of water: \_\_\_\_\_

Final mass – initial mass: \_\_\_\_\_

**Did you make any changes to the method? What safety considerations were important? Did you have some 'smart' ways of doing the investigation?**

#### 4. PROCESSING AND ANALYSING

Before we can work out how much energy was supplied to boil the water, we have to know the approximate rate at which heat is transferred from the Bunsen burner to the water.

If a mass  $m$  of water is heated by an amount  $\Delta T$ , then we can calculate how much heat was supplied in one minute, using the known value of the heat capacity of water  $c = 4.18 \text{ kJ/kg/}^\circ\text{C}$ .

The equation to use is  $\Delta Q = mc\Delta T$ .

Therefore  $Q$  kilojoules are supplied per minute. When you move on to boiling the water, you can determine the heat transferred to the water by multiplying this factor by the number of minutes during which it was boiling.

To determine the latent heat of vaporisation, divide this amount of heat by the mass of water lost to find the answer in kJ/kg. Note that sometimes this quantity is expressed in J/kg or J/g.

#### 5. PROBLEM SOLVING

When a substance is undergoing a phase change, its temperature remains constant. However, in the case of melting or evaporation, heat energy must still be entering the system. The latent heat  $L$  of vaporisation is a quantity which describes how much energy is needed to evaporate a kilogram of water once it has reached its boiling point.

There is also a corresponding quality, the latent heat of fusion, which relates to the solid  $\rightarrow$  liquid phase transition.

For water, the latent heat of **fusion** is 334 kJ/kg.

The latent heat of **vaporisation** is 2,230 kJ/kg. How does this compare to the answer you found?

#### 6. CONCLUSIONS

During a phase change from liquid to gas, the temperature of a substance \_\_\_\_\_.

The experimentally measured latent heat of vaporisation of water is \_\_\_\_\_.



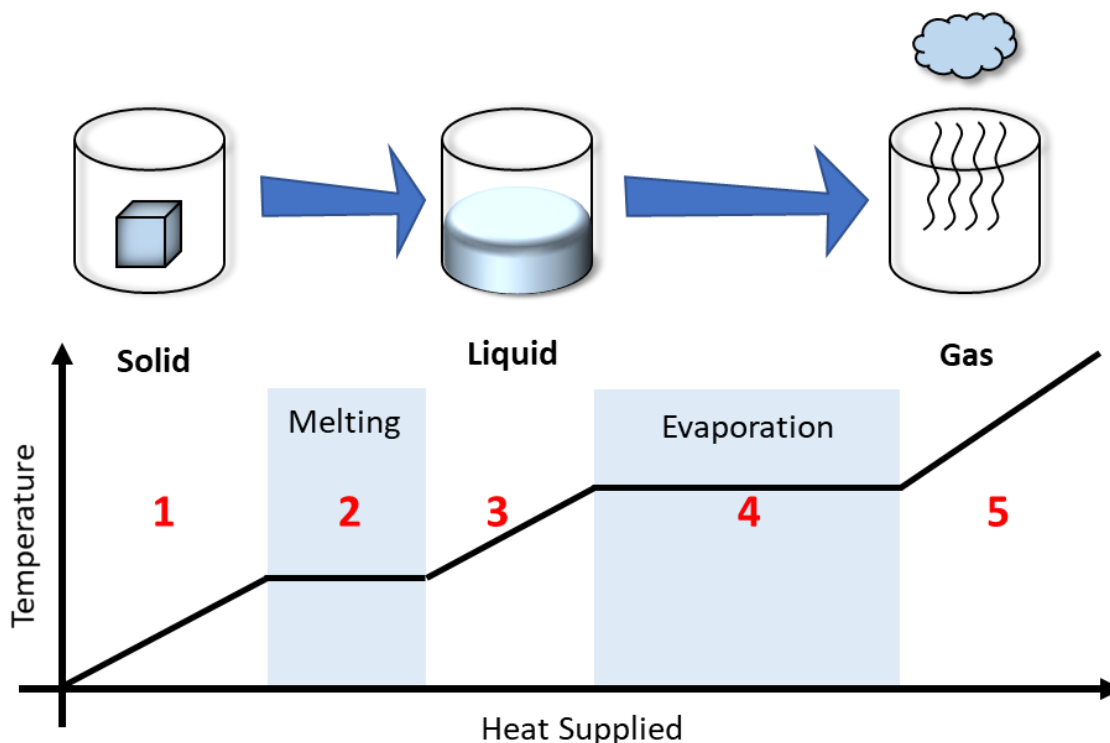
## LATENT HEAT

### CONTENT

Matter exists in different states, and the three common states are solids, liquids and gases. Matter in one state can transition to another state; a phenomenon called *phase change*. When a substance changes phase, thermal energy is absorbed by the substance from its surroundings. The temperature of the substance, however, remains constant during the phase change. The heat or thermal energy per unit mass is called the latent heat of the phase change. For historical reasons the latent heat for *melting* (solid → liquid) is called the **latent heat of fusion** and *evaporation* (liquid → gas) is called **latent heat of vaporisation**. The thermal energy required or released due to phase change is given by

$$Q = mL$$

where  $Q$  is the thermal energy,  $m$  is the mass and  $L$  is the latent heat. The units of latent heat are joule per kilogram (J/kg). Below is a diagram showing the different processes for water.



Following the diagram above:

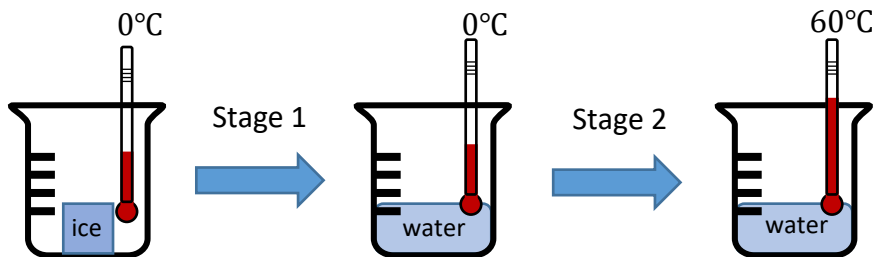
1. At low temperatures, water is in the solid form we call 'ice'. Adding thermal energy to ice will increase the temperature of the ice.
2. At some stage, the ice will **melt** into liquid (i.e. undergo a phase change) but the temperature will remain the same during this process.
3. With further thermal energy added, the temperature of the liquid will rise again.
4. At a much higher temperature, the liquid will start to **evaporate** into gas (a second phase change). The temperature will also not change during this process similar to melting.
5. Once the phase change is complete, the temperature of the gas will increase.



### WORKED EXAMPLE - ICE TO WATER

How much energy, as heat flow, is required to change 0.40 kg of ice at 0°C into the water at 60°C? The latent heat of fusion of water is 335,000 J/kg, and the specific heat is 4184 J/(kg.°C).

⇒ Let's break down the question into stages. The ice melts into the water without any change in temperature (a phase change). After this, the water temperature is increased from 0°C to 60°C.



⇒ Let's now write down all the information we are given or know

- |   |   |
|---|---|
| <ul style="list-style-type: none"> <li>• Energy due to phase change <math>Q = mL</math></li> <li>• Energy from heating <math>Q = mC(T_f - T_i)</math></li> <li>• Mass of water and ice, <math>m_{ice} = m_{water} = 0.40 \text{ kg}</math></li> </ul> | <ul style="list-style-type: none"> <li>• Temperature changes from <math>T_i = 0^\circ\text{C}</math> to <math>T_f = 60^\circ\text{C}</math></li> <li>• Latent heat of fusion is <math>L = 335,000 \text{ J/kg}</math></li> <li>• Specific heat of water is <math>C = 4184 \text{ J/(kg.}^\circ\text{C)}</math></li> </ul> |
|---|---|

⇒ Starting with **stage 1** we find the amount of energy required to melt the ice.

Energy from melting the ice = mass of ice × latent heat of ice

$$\begin{aligned} Q_{ice} &= mL \\ &= (0.40 \text{ kg}) \times (335,000 \text{ J/kg}) \\ &= 0.134 \text{ MJ} \end{aligned}$$

⇒ Moving to **stage 2** we find the thermal energy required to raise the temperature of the water from 0°C to 60°C

Energy from heating water = mass of water × specific heat of water × temperature change

$$\begin{aligned} Q_{Water} &= mC(T_f - T_i) \\ &= (0.40 \text{ kg}) \times (4184 \text{ J/(kg.}^\circ\text{C)}) \times (60^\circ\text{C} - 0^\circ\text{C}) \\ &= 0.1004 \text{ MJ} \end{aligned}$$

⇒ Finally, the total heat flow required is the sum of the energies from the two stages.

Total heat flow required = Energy of ice melting + Energy of heating water

$$\begin{aligned} Q_{Total} &= Q_{ice} + Q_{Water} \\ &= 0.134 \text{ MJ} + 0.1004 \text{ MJ} \\ &= 0.23 \text{ MJ} \end{aligned}$$

## ENERGY TRANSFER

### CONTENT

When thermal energy is absorbed or released from an object a change in temperature results. When an object receives thermal energy, the energy is obtained from a source. However, the thermal energy must be transferred from the source to the object. This process is called '**energy transfer**', and there are three mechanisms in which energy is transferred from one object to another.

### CONDUCTION

In this mechanism, energy is transferred through direct/physical contact. For example, if you touch a hot stove, thermal energy will be transferred from the hot surface to your hand. We can determine the rate of **thermal conduction** (labelled as  $P$ , with units joules/second, or watts) by using the equation

$$P = \frac{Q}{t} = \frac{kA\Delta T}{d} = \frac{kA(T_1 - T_2)}{d}$$

where  $Q$  is thermal energy,  $t$  is the time,  $k$  is thermal conductivity of a material,  $A$  is the cross-sectional area where heat transfer occurs,  $d$  is the thickness and  $\Delta T$  is the difference in temperature between two objects. Each material will have a different thermal conductivity value (e.g. copper has a high thermal conductivity in comparison to wood), and the unit is watts per meter kelvin  $W/(m.K)$ . From the equation above the thermal conduction  $P$  is inversely proportional to the thickness  $d$ . This means that a higher thermal conductivity will result in a higher rate of conduction and larger thickness will result in a lower rate of conduction.



Figure 1.

**Think:** Taking the above equation into account, explain why thick clothing keeps your body warmer than thin clothing (made out of the same material) in winters?

### CONVECTION

Higher temperatures will translate to higher kinetic energy. Using boiling water in a pot as an example (image on the right), water molecules that are closer to the bottom will have a higher kinetic energy. With a higher energy, the water molecules will move and collide with other molecules more often causing the molecules to be further apart. This results in a lower density and consequent rising through the rest of the liquid (like an inflatable ball released at the bottom of the pool). This process is called **convection currents** where the heated fluid moves away from the heat source, in turn carrying and transferring energy. The transfer of energy results in the increase of temperature of water in the pot.

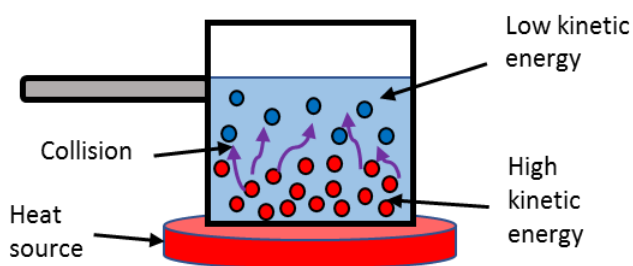


Figure 2.



## RADIATION

We experience energy transfer due to radiation almost every day. When we stand outside in the sun, we feel ‘warm’ because the energy from the sun is transferred to your body. To discern the difference between thermal and other electromagnetic signals (like x-rays or gamma ( $\gamma$ )-rays) we refer to this as **thermal radiation**. For example, when a stove is on, we can feel ‘heat’ when we stand near it. Why? Because the stove is emitting infrared waves into the air and you just happened to be standing nearby. The infrared waves will cause the molecules in your body to move faster, which explains your body heating up.

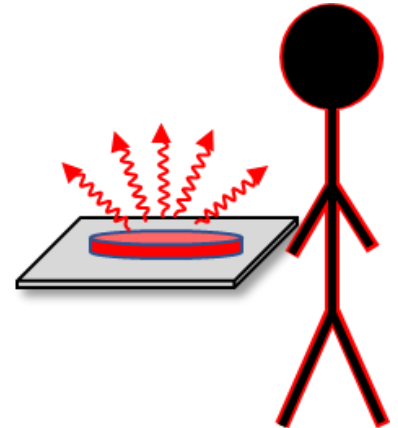
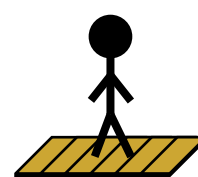
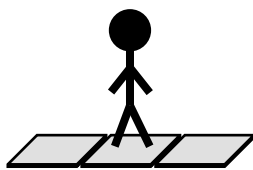
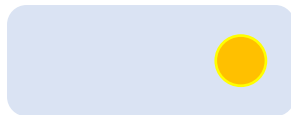


Figure 3.

## EXAMPLE - REAL WORLD

On a hot sunny day on the beach, you walk barefoot on a concrete path. After some time your feet get hot, and you run to a wooden platform. On this surface, your feet are not as ‘hot’ as it was on the concrete surface. Why is it ‘cooler’ to stand on the wooden surface? What would happen if it is during a cold night instead? (The thermal conductivity for concrete is  $1.7 \text{ W}/(\text{m}\cdot\text{K})$  and wood is  $0.17 \text{ W}/(\text{m}\cdot\text{K})$ )



⇒ For this question, we start with the thermal conductivity equation

$$P = \kappa \frac{A\Delta T}{d}$$

⇒ Concrete and wood have different thermal conductivity (i.e.  $\kappa$ )

$$\kappa_{\text{concrete}} = 1.70 \text{ W}/(\text{m}\cdot\text{K})$$

$$\kappa_{\text{wood}} = 0.17 \text{ W}/(\text{m}\cdot\text{K})$$

⇒ The thermal conductance from both surfaces are

$$P_{\text{concrete}} = 1.70 \times \frac{A\Delta T}{d}$$

$$P_{\text{wood}} = 0.17 \times \frac{A\Delta T}{d}$$

$$P_{\text{concrete}} \approx 10 \times P_{\text{wood}}$$

⇒ This means that the concrete surface absorbs heat from the sun about 10x faster than the



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wooden surface. Thus, the concrete surface is hotter than the wooden platform.

⇒ In a cold night the scenario becomes:



- ⇒ The reverse will happen, that is the concrete surface will feel 'colder' than the wooden surface. The concrete surface will release thermal energy 10x faster than the wooden surface. This is also because the thermal conductivity of concrete is 10x larger than wood.
- ⇒ In this example, we see that heat transfer goes both ways (absorbs or releases thermal energy) and we can feel this through direct contact with the surface of an object.