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# The big picture

## ? Guiding question(s)

- How can the Doppler effect be explained both qualitatively and quantitatively?
- What are some practical applications of the Doppler effect?
- Why are there differences when applying the Doppler effect to different types of waves?

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

Have you ever stood by the side of a road when a fast car passes and noticed that the sound the car makes as it approaches is different to the sound it makes after it has passed? Watch **Video 1**, which shows race cars on a track.

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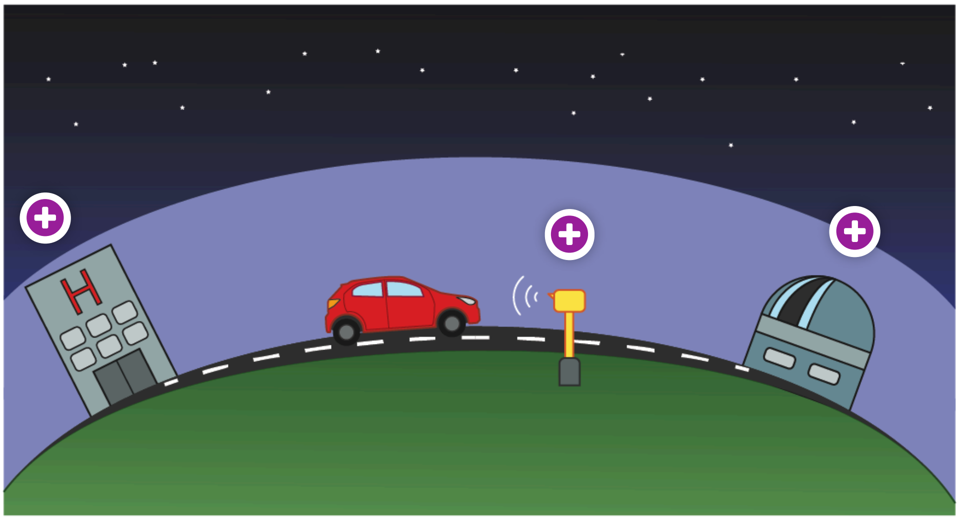
**Video 1.** What happens to the sound as the cars pass?

More information for video 1

The video shows a racetrack with high-speed race cars zooming past. It serves as an effective illustration of the Doppler Effect, emphasizing how the sound of the cars changes as they move. As the cars approach the viewer or listener, the sound rises in pitch, indicating a higher frequency. Conversely, as the cars moves away, the pitch drops, demonstrating a lower frequency.

As the cars race past the camera, you hear the change in sound we often associate with speed. What happens to the sound waves is related to the relative velocity difference between the cameraperson and the racing car. At the end of the video, when the camera is inside the car and the relative speed between the car and the camera is $0\,m\,s^{-1}$, the pitch of the sound is constant.

Click on the images in **Interactive 1** to see uses of the Doppler effect.






**Interactive 1.** Uses of Doppler Effect in Medicine, Speed Cameras and Satellite Imagery.

More information for interactive 1

This interactive consists of an image that highlights various uses of the Doppler effect. The layout is divided into sections where the user can interact with '+' (buttons) hotspots to explore different scenarios in which the Doppler effect is applied.

The hotspot at the left-hand side opens a visual of a hospital building labeled with an "H," tilted slightly on the curved surface of the Earth under a starry sky, representing medical diagnostics. The accompanying text reads, "The Doppler effect can be used to detect

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blood flow in the body without the need for intrusive instruments. This has applications from cancer detection to treating heart disease."

The hotspot in the middle opens a visual of a red car driving along a curved road, with a yellow radar speed detector emitting curved signal lines, illustrating the use of Doppler radar in monitoring vehicle speed. The accompanying text reads, "Radar speed guns and speed cameras use the Doppler effect with radio waves in order to detect speeding vehicles." The visual shows

The hotspot at the right-hand side opens a visual of an observatory dome, tilted on the curve of the Earth beneath a star-filled night sky, symbolizing the role of astronomical instruments in measuring stellar motion using the Doppler effect. The accompanying text reads, "Satellites detecting atomic spectra from stars, like the Hubble Space Telescope, use the Doppler effect in order to determine if they are moving away from or towards us, and at what rate. This has applications from finding the relative motion of a star to providing evidence for the Big Bang theory." The visual features

### International Mindedness

The satellite imagery that you read about in **Interactive 1** — produced by the Hubble Space Telescope (and now the James Webb Space Telecope or JWST) — was largely funded by taxpayers' money because it was a US government led project. Now, the images shared around the world are open source and globally available. Should the American people have ownership over these images, or is the contribution to global science too important to worry about ownership?

### Prior learning

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

- The wave equation (see subtopic C.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43778/)).
- Wavefronts and waveforms (see subtopic C.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43778/)).

C. Wave behaviour / C.5 Doppler effect

# The Doppler effect

C.5.1: Doppler effect for sound waves and electromagnetic waves C.5.2: Representation in terms of wavefront diagrams

### Learning outcomes

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

- Explain the Doppler effect and its effect on the perception of sound waves and electromagnetic waves.

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- Use wavefront diagrams to represent the Doppler effect when the source is moving or the observer is moving.

Imagine a bird flying alongside a slow-moving train (**Figure 1**). The bird is flying at the same speed as the train. What does this look like to an observer inside the train and an observer outside the train on the platform?

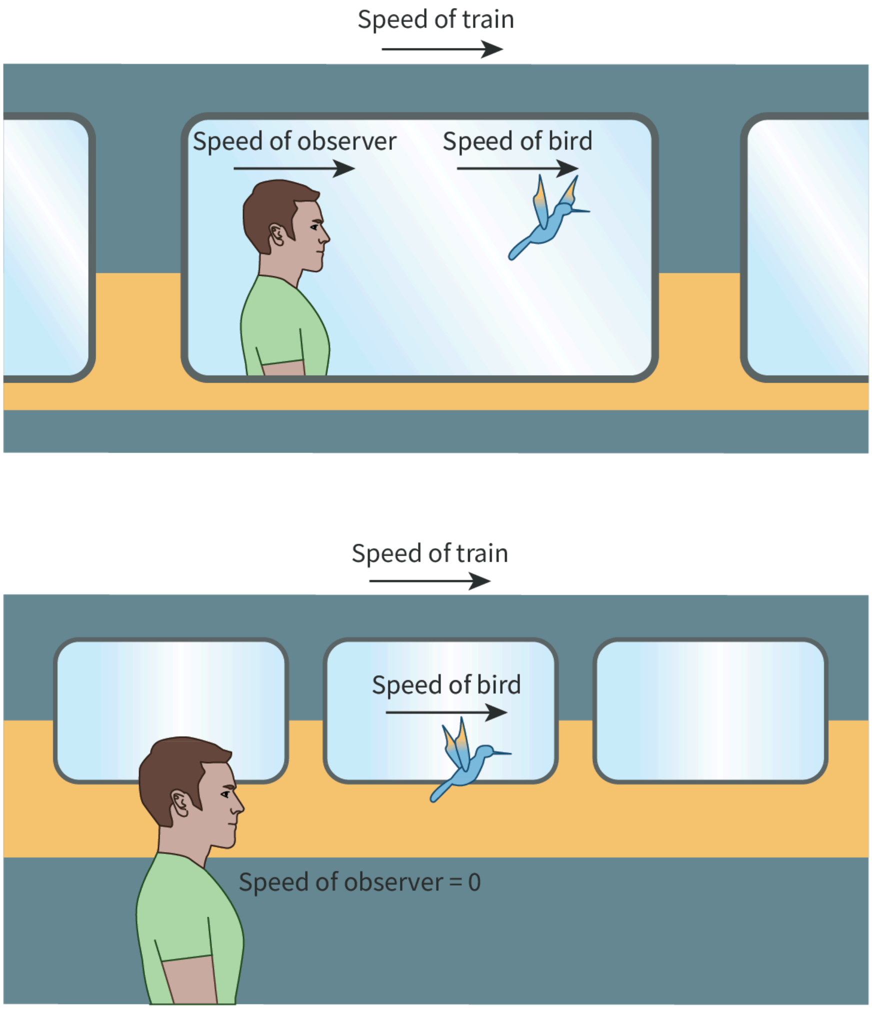


**Figure 1.** Observing the motion of a train and a bird from two different reference frames.

More information for figure 1

The image consists of two panels depicting a bird flying next to a moving train, viewed from two different perspectives.

In the top panel, an observer is inside the train. The bird flies beside the train at the same speed, and an arrow indicates the speed of the train and the observer, both in the same direction. Another arrow, in the opposite direction, shows the speed of the bird relative to the inside observer, making the bird appear stationary relative to the train.

In the bottom panel, the observer is outside the train, on a platform. The observer, standing still, sees two arrows: one, from left to right, showing the train's speed, and another, parallel and in the same direction, indicating the bird's speed, demonstrating the bird moving alongside the train.

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## Reference frames

- To the observer inside the moving train. the bird appears to be hovering, so it has a velocity of 0 m $s^{-1}$ relative to the observer.
- To the observer on the platform watching the train go past, the bird has a relative velocity which is the same speed as the train. The bird looks like it is moving.

In each case, the bird has the same motion – it is flying at the same speed as the train. However, each observer views the motion of the bird differently. This is because they have a different reference frame (see subtopic A.5 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-hl-id-45344/)).

Relative motion between the source of the wave and the observer is the basis of the Doppler effect. When we deal with the Doppler effect, it is important to always think of the waves from the observer's perspective. Sometimes the observer will be moving, and sometimes the source will be moving. The reference frame has a big impact on how we perceive the waves.

All waves can undergo the Doppler effect, including electromagnetic waves and sound waves. In this section, we will look at sound waves.

### Nature of Science

**Aspects:**

- Observations
- Measurement

In physics, our observations of an event often depend on our reference frame. In **Video 1** in The big picture (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-45337/), the pitch of the sound we hear from a race car is different depending on where we are relative to the car.

When we determine the gravitational potential energy of an object (see subtopic A.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43083/)), we use the equation:

$$\Delta E_\mathrm{p} = mg\Delta h$$

With what reference is the height measured? The ground below the object or the centre of the Earth? If we were looking at the Earth from outside the Solar System, we might use the Sun as a reference frame.

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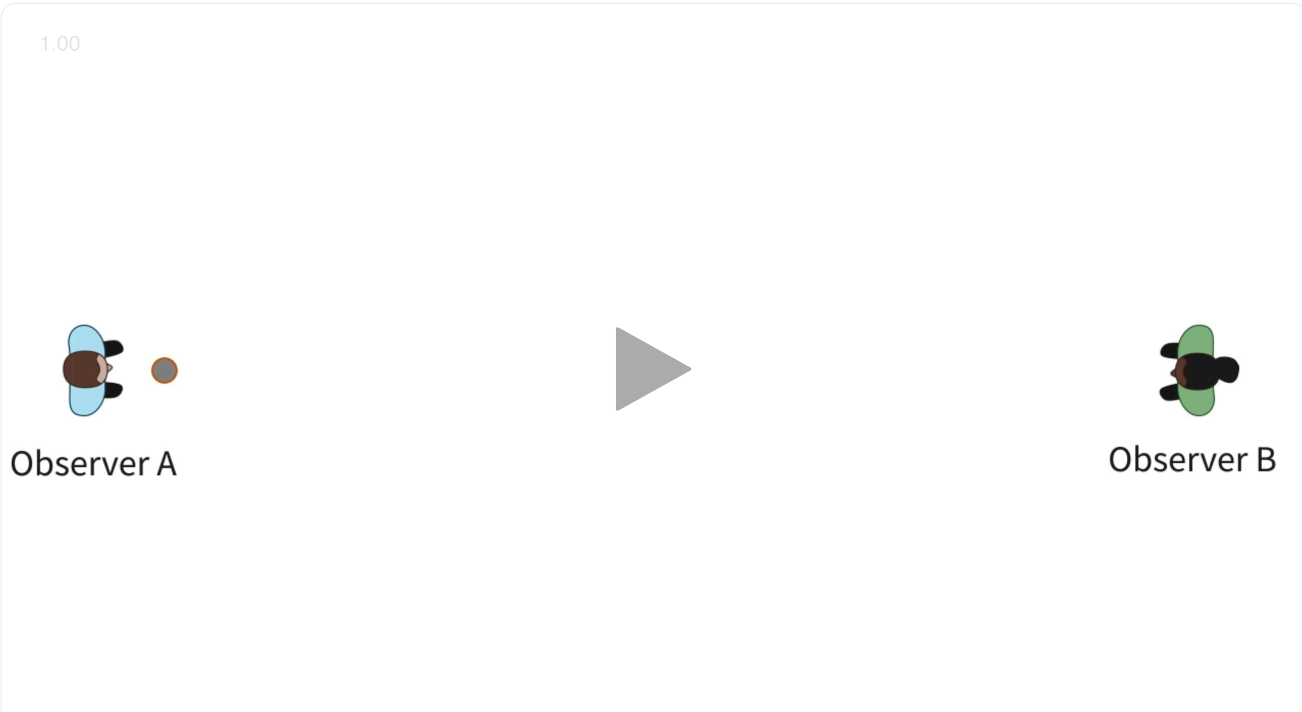
The Doppler effect, named after Christian Andreas Doppler, is the effect of motion on the observation of waves.

The Doppler effect is the change in the observed frequency of a wave based on the relative motion between the source and the observer. This change in observed frequency is from the perspective of the observer and not the source. If the source was observing itself, it would not notice any change in observed frequency.

### Study skills

You will not be required to discuss situations where both the source **and** the observer are moving.

**Interactive 1** shows a wavefront diagram with a moving source and two stationary observers.




**Interactive 1.** Wavefront Diagram with a Moving Source and Two Stationary Observers.

More information for interactive 1

This interactivity features a video-based animation demonstrating the Doppler effect using a simple illustration. The interface includes standard video controls along the bottom bar, such as play/pause, a progress timeline, sound control, and a fullscreen toggle in the bottom right corner.

The animation shows a moving sound source situated between two stationary observers labeled Observer A (on the left) and Observer B (on the right). As the source travels from left to right, it emits circular wavefronts representing sound waves. These wavefronts appear compressed (closer together) in the direction the source is moving — toward Observer B — and spread out in the direction it's leaving — toward Observer A.

This visual illustrates the Doppler effect, where the perceived frequency of sound increases for the observer the source is approaching and decreases for the observer it is moving away from. The denser wavefronts near Observer B indicate a higher frequency, while the more spaced-out wavefronts near Observer A represent a lower frequency. The video effectively captures how motion affects sound wave perception based on the observer's position relative to the source.

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In **Interactive 1**, you can see that for Observer B, the wavefronts appear closer together. In a certain amount of time, many more sound waves reach them. Therefore, the sound waves reach Observer B **more frequently**. For Observer A, the wavefronts appear further apart. In a certain amount of time, fewer sound waves reach them. Therefore, the sound waves reach Observer A **less frequently**.

- For Observer B, the frequency of the sound waves has increased and the wavelength has decreased.
- For Observer A, the frequency of the sound waves has decreased and the wavelength has increased.

### Exercise 1

Click a question to answer

For a moving source, the observer perceives a change in the frequency and the wavelength of the sound wave, but no change in the speed.

### Creativity, activity, service

**Strand:** Activity
**Learning outcome:** Demonstrate that challenges have been undertaken, developing new skills in the process

As the speed of a moving source of sound increases, the wavefronts ahead of the source get closer and closer together. What would happen if the source reached the speed of sound? Impressive photos of jets doing this show the dramatic effect of the overlapping wavefronts.

**Figure 2.** Jet flying at speed of sound.
Credit: Alextov, Getty Images

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What would happen to the sound heard by an observer who the plane was flying directly towards? What about directly away from? What would it sound like to the person on the plane? Can you create a piece of music, a sound effect or a poem about one of these experiences?

**Interactive 2** shows a wavefront diagram with a stationary source and two moving observers.

**Interactive 2.** Wavefront Diagram with a Stationary Source and Two Moving Observers.

More information for interactive 2

This interactivity features a video that visually demonstrates the Doppler effect using two moving observers, labeled A and B, and a stationary wave source placed in the center. The interface includes standard video playback controls at the bottom, including a play/pause button, progress timeline, mute option, and fullscreen toggle.

At the start of the animation, the source is placed at the center, emitting circular wavefronts that radiate outward uniformly. Observer A is positioned to the left of the source, while Observer B is to the right of the source. As the animation progresses, both observers begin to move from left to right in a straight line, maintaining constant speed.

As the wavefronts expand outward from the stationary source, their spacing remains consistent in all directions. However, due to their linear motion, Observer A moves toward the incoming wavefronts, encountering them more frequently. This results in Observer A perceiving a higher frequency (or pitch). In contrast, Observer B moves away from the source, causing the wavefronts to reach them less frequently. As a result, Observer B perceives a lower frequency.

In **Interactive 2**, you can see that the wavefronts are the same distance apart for Observer A and Observer B. This means that the observed wavelength has not changed. Observer A is moving towards the source, so the wavefronts reach them much **more frequently**. Observer B is moving away from the source, so the wavefronts reach them much **less frequently**.

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- For Observer A, the frequency of the sound waves has increased.
- For Observer B, the frequency of the sound waves has decreased.

We calculate the speed of sound using the wave equation (C.2 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43778/)):

$$v = f\lambda$$

For Observer A, the frequency has increased, but the wavelength has not changed. This means that Observer A perceives the speed of the sound waves to be faster. For Observer B, the frequency has decreased, but the wavelength has not changed. This means that Observer B perceives the speed of the sound waves to be slower.

For a moving observer, the observer perceives a change in the frequency and the speed of the sound wave, but no change in the wavelength.

Imagine two people are running along a road marked with lines every 5 metres (**Figure 3**). They are running at different speeds.

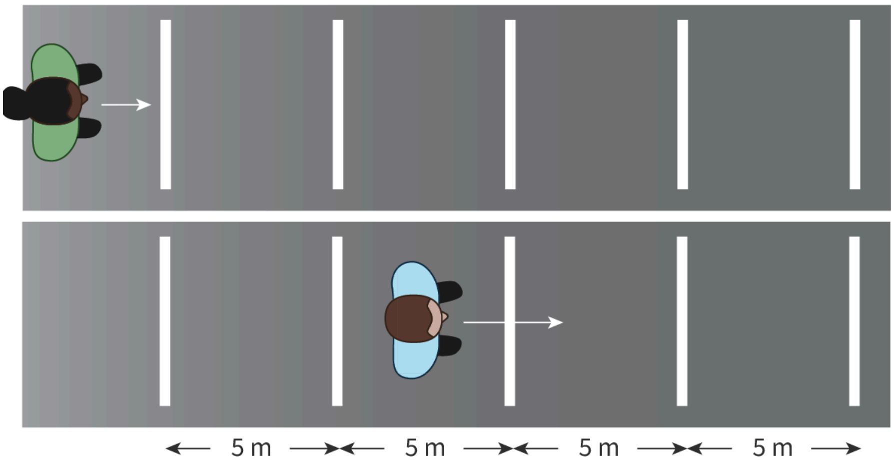


**Figure 3.** Running at different speeds over equally spaced lines.

More information for figure 3

The image shows two runners on a road divided into two segments, each with equally spaced lines every 5 meters. The upper part of the image has a person in green running left to right, while in the lower part, another person in blue is running in the opposite direction. Both sections of the road feature the same spacing between lines, illustrating the concept of moving across equidistant lines at different speeds.

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Each runner will cross these lines with different frequencies, although the distance between the lines remains 5 m. The distance between lines is always the same, just like the distance between wavefronts for a moving observer.

**Table 1** shows the velocity of a runner, the time it takes for them to run between lines and the distance between the lines.

**Table 1.** Velocity, time and distance.

| Velocity of runner, $v$ (m s$^{-1}$) | Time to run between lines, $t$ (s) | Distance between lines, $s = vt$ (m) |
|---|---|---|
| 1 | 5.00 | 1 × 5.00 = 5 |
| 3 | 1.67 | 3 × 1.67 = 5 |
| 5 | 1.00 | 5 × 1.00 = 5 |

From each runners' perspective, the distance between lines does not change. However, the rate at which they encounter the lines changes (**Table 2**).

**Table 2.** Velocity and number of lines encountered per second.

| Velocity (m s$^{-1}$) | Lines encountered per second |
|---|---|
| 1 | $\frac{1}{5} = 0.2$ |
| 3 | $\frac{3}{5} = 0.6$ |
| 5 | $\frac{5}{5} = 1$ |

As a runner increases their velocity, the number of lines encountered per second increases. Applying this to sound waves, we know that an increase in encountered wavefronts per second corresponds to an increase in perceived frequency.

# Double Doppler effect

What happens if the source and the observer are the same? For example, the speed camera and the blood flow monitor in **Interactive 1** The big picture (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-45337/) emit and receive waves. This is known as the double Doppler effect.

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Bats and dolphins use the double Doppler effect to detect prey or objects around them. This is known as echolocation. The different wave properties of the echo allow the bats and dolphins to locate the object or prey the waves reflect off.

In order to observe a Doppler effect, there must be a relative difference in the velocity of the source and the observer:

- The source is moving, and sound is reflected off a stationary object.
- The source is stationary, and sound is reflected off a moving object.

In this case, we deal with the problem in two stages:

1. What happens to the waves as they move towards the object?
2. What happens to the waves when they are reflected back towards the observer?

Consider the situation where a bat produces ultrasonic sound waves as it flies towards a stationary wall (**Figure 4**).

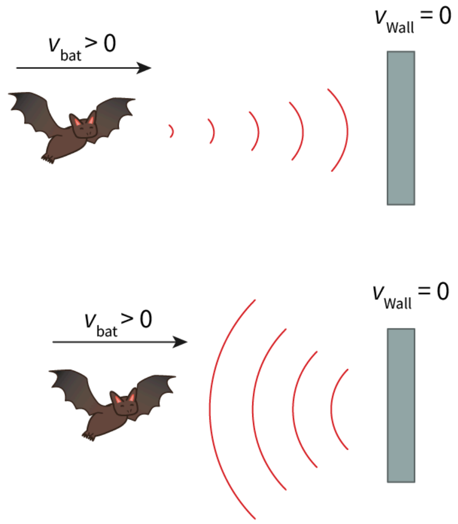


**Figure 4.** A bat flying towards a wall.

More information for figure 4

The image illustrates two scenarios of a bat flying towards a stationary wall. In both scenarios, the bat is generating ultrasonic sound waves. The top part shows the bat moving with a velocity greater than zero (v_bat > 0) towards the wall with a velocity of zero (v_wall = 0). The sound waves are depicted as red concentric arcs spreading outward from the bat. In the bottom part, the same setup is shown with larger arcs indicating sound waves, emphasizing the moving source of the waves towards the stationary observer, the wall.

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The source of the sound waves (the bat) is moving. The observer (the wall) is stationary. The wall will observe an increase in frequency (moving source, stationary observer).

The wall reflects the sound wave. The bat (now the observer) is moving towards the wall (now the source). The bat observes a greater increase in frequency (moving observer, stationary source).

Alternatively, you can visualise this situation as the bat is flying towards its ‘image’ on the wall, so initial there is a moving observer (the bat) and then a stationary source (the bat’s image).

Where the bat is flying away from the wall, or an object, such as prey, is moving away, we use the same logic to work out how the frequency is affected.

Work through the activity to check your understanding of the Doppler effect.

## Nature of Science

**Aspect:**

- Measurement
- Global impact of science

Medical professionals use specialised machines that use the Doppler effect to image how blood flows through arteries and veins, or how fluid moves in the eye or in sports injuries, or inside a cyst, which can indicate if the cyst is cancerous or not. (http://www.genesis.net.au/~ajs/projects/medical_physics/graphics/ultrasound_doppler.jpg)**Figure 5** shows the Doppler effect being used to image the rate of blood flow in the vessels of an adult human.

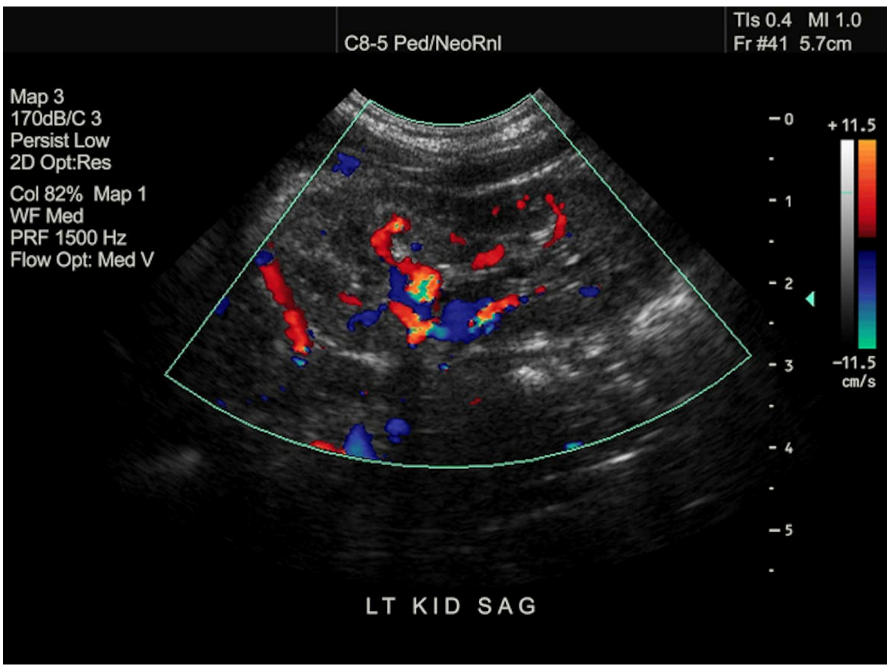


**Figure 5.** Doppler effect being used to image the rate of blood flow in the kidney of a child.
Credit: UrsaHoogle, Getty Images

Student view

More information for figure 5

The image is an ultrasound scan using the Doppler effect to show blood flow in a child's kidney. It displays a triangular section in the center indicating the direction and speed of blood flow through vessels. Different colors on the image, such as red and blue, represent varying velocities and directions of flow, indicating arterial and venous flows, respectively. The image includes a color scale on the right side showing values from -11.5 to +11.5 cm/s, which is used to interpret flow velocities. On the left, there are various settings including "Map 3," "170dB/C 3," among others, which appear related to the operational settings of the ultrasound machine. The bottom of the image is labeled "LT KID SAG," possibly indicating a longitudinal sagittal section of the left kidney.

[Generated by AI]

## Activity

- **IB learner profile attribute:**
  - Knowledgeable
  - Thinker
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 20—30 minutes
- **Activity type:** Individual activity

You are going to use this Doppler effect and sonic boom (https://ophysics.com/w11.html) simulation to investigate the Doppler effect. Note that the source frequency is always 343 Hz.

**Task 1: Moving source and stationary observer**

1. Set the 'Source Velocity' to 62 m s$^{-1}$ using the slider. Then click 'Start'.
2. Record the 'Perceived Frequency' and 'Perceived λ' before and after the source passes the observer in a table similar to **Table 3.**
3. Change the 'Source Velocity' to the velocities in **Table 3** and repeat Step 2 for each velocity.

**Table 3.** Data table for Task 1.

| Source velocity (m s$^{-1}$) | Before source passes observer | | After source passes observer | |
|---|---|---|---|---|
| | Perceived $f$ (Hz) | Perceived $\lambda$ (m) | Perceived $f$ (Hz) | Perceived $\lambda$ (m) |
| 62 | | | | |
| 123 | | | | |
| 182 | | | | |

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| Source velocity (m $s^{-1}$) | Before source passes observer | | After source passes observer | |
|---|---|---|---|---|
| | **Perceived *f* (Hz)** | **Perceived *λ* (m)** | **Perceived *f* (Hz)** | **Perceived *λ* (m)** |
| 240 | | | | |
| 302 | | | | |

4. How do the frequency and wavelength before the source passes the observer change with increasing velocity of the source?
5. How do the frequency and wavelength after the source passes the observer change with increasing velocity of the source?
6. Can you show that the speed of sound is constant for each velocity?

**Task 2: Stationary source and moving observer**

1. Set the 'Observer Velocity' to −62 m $s^{-1}$ using the slider and set the 'Source Velocity' to 0 m $s^{-1}$. Then click 'Start'.
2. Record the 'Perceived Frequency' and 'Perceived λ' before and after the observer passes the source in a table similar to **Table 4.**
3. Change the ' Observer Velocity' to the velocities in **Table 4** and repeat Step 2 for each velocity.

**Table 4.** Data table for Task 2.

| Observer velocity (m $s^{-1}$) | Before observer passes source | | After observer passes source | |
|---|---|---|---|---|
| | **Perceived *f* (Hz)** | **Perceived *λ* (m)** | **Perceived *f* (Hz)** | **Perceived *λ* (m)** |
| −62 | | | | |
| −123 | | | | |
| −182 | | | | |
| −240 | | | | |
| −302 | | | | |

4. How do the frequency and wavelength before the observer passes the source change with increasing velocity?
5. How do the frequency and wavelength after the observer passes the source change with increasing velocity?

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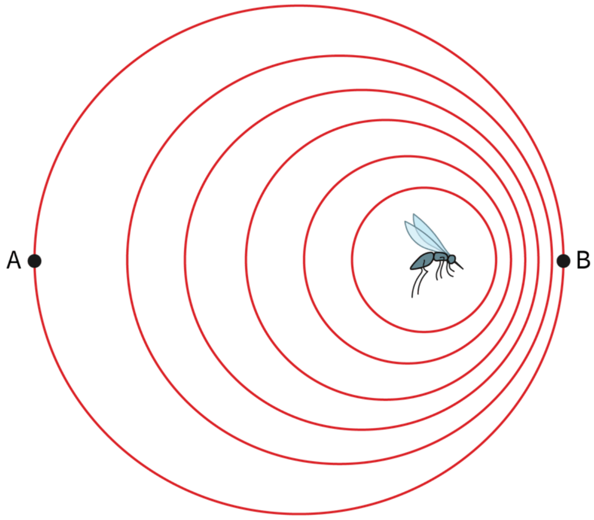
**Question 1**

SL HL Difficulty:

A mosquito generates sound by beating its wings.




More information

Which statement correctly describes the relative velocities of the mosquito and the observers?

1 The mosquito is moving to the right. The observers are stationary. ✓

2 The mosquito is moving to the left. The observers are stationary.

3 The mosquito is stationary. Observer A is moving to the right.

4 The mosquito is stationary. Observer B is moving to the left.

**Explanation**

Observer B observes waves with a shorter wavelength (wavefronts are closer together) than observer A, so the mosquito must be moving towards B and away from A. This means the mosquito must be moving to the right and both observers are stationary.

**Question 2**

SL HL Difficulty:

A fire engine approaches you as you wait at a bus stop. As it passes, the observed 1 frequency ✓ of the waves decreases.

**Accepted answers and explanation**

#1 frequency
frequencies

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**General explanation**

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You are a stationary observer and the fire engine is a moving source. As the fire engine passes you, the frequency of the waves decreases.

**Question 3**

SL HL Difficulty:

A spacecraft with a solar sail is launched into space. Solar sails propel the spacecraft at very high speeds away from the Earth. The spacecraft has radio equipment to relay images and information back to the Earth. When an observatory on the Earth detects the radio waves, what will they notice?

1 The observed wavelength increases and the observed frequency decreases. ✓

2 The observed wavelength decreases and the observed frequency decreases.

3 The observed wavelength increases and the observed frequency increases.

4 The observed wavelength decreases and the observed frequency increases.

**Explanation**

The radio waves are emitted by a moving source (the spacecraft) and detected by a stationary observer (the observatory on the Earth). The wavelength increases and the frequency decreases.

**Question 4**

SL HL Difficulty:

A bat uses echolocation to detect prey. The bat is flying towards a tree with a stationary insect on it, and the bat is producing ultrasonic sound waves. The frequency of the waves observed by the insect is 1 greater ✓ than that produced by the bat. The waves reflect off the insect and back to the bat, which observes a 2 greater ✓ frequency again than that of the insect.

**Accepted answers and explanation**

#1 greater
bigger
larger
higher

#2 greater
bigger
larger
higher

**General explanation**

As the bat (moving source) flies towards the insect (stationary observer), the frequency observed by the insect is greater than that produced.

The bat (moving observer) is flying towards the insect (stationary source). The frequency observed by the bat is greater still.

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**Question 5**

SL HL Difficulty:

Sound waves from a 2.50 kHz siren are detected 1 km away. The frequency recorded by the observer is 2.51 kHz. The speed recorded by the observer is greater than the speed of sound. What is the relative motion between the source and the observer?

1 The observer is moving towards a stationary source. ✓

2 The observer is moving away from a stationary source.

3 The source is moving towards a stationary observer.

4 The source is moving away from a stationary observer.

**Explanation**

The frequency has increased, meaning the observer and the source are moving closer together. As the speed of sound has changed, the observer is moving. In the case of a moving source, the speed of sound is constant, so a moving observer is the only solution here.

C. Wave behaviour / C.5 Doppler effect

# Light and the Doppler effect

C.5.3: Relative changes observed for a light wave C.5.4: Shifts in spectral lines

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/light-and-the-doppler-effect-id-45339/print/) Assign

## Learning outcomes

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

- Determine the relative change in frequency and wavelength for a light wave using the equations:

$$\frac{\Delta f}{f} = \frac{\Delta \lambda}{\lambda} \approx \frac{v}{c}$$

- Explain that shifts in spectral lines from stars and galaxies give information about their motion in space.

The speed of light is $3.00 \times 10^8$ m s$^{-1}$ (given in section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/) of the DP physics data booklet). In comparison, the speed of sound is relatively slow (343 m s$^{-1}$) and the fastest aircraft, the NASA X-43 Jet, travels at 3111 m s$^{-1}$,

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which is 0.00001 × the speed of light! Do sound waves and light waves behave in the same way when they are affected by the Doppler effect?

# Doppler effect and light

The Doppler effect depends on the relative velocity between the source and the observer (see section C.5.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-doppler-effect-id-45338/)). For example, if an observer is travelling in a plane at the speed of sound, the sound waves travel relative to the observer at 0 m s$^{-1}$. If the waves were visible, they would appear stationary from the reference frame of the observer on the plane.

Electromagnetic radiation, such as light, is different. Whatever reference frame you view light from, it appears to be travelling at the speed of light. Even if you are travelling at 99% the speed of light, the light passing you in either direction is travelling at the speed of light.

We can use the equation in **Table 1** to determine the relative change in frequency or wavelength for a light wave.

**Table 1.** Equation for relative change in frequency or wavelength for a light wave.

| Equation | Symbols | Units |
|---|---|---|
| $\frac{\Delta f}{f}=\frac{\Delta\lambda}{\lambda}\approx\frac{v}{c}$ | $\Delta f$ = change in frequency | hertz (Hz) |
| | $f$ = frequency emitted by the source | hertz (Hz) |
| | $\Delta\lambda$ = change in wavelength | metres (m) |
| | $\lambda$ = wavelength emitted by the source | metres (m) |
| | $v$ = velocity of the source | metres per second (m s$^{-1}$) |
| | $c$ = speed of light in a vacuum ($3.00 \times 10^8$ m s$^{-1}$) | Given in section 1.6.3 (/study/app/math-aa-hl/sid-423-cid-762593/book/fundamental-constants-id-45155/)of the DP physics data booklet |

## Worked example 1

Student view

A distant star emits radio waves of frequency 1.4 GHz. It is observed by an astronomer on Earth who measures the frequency to be 1.3 GHz. How fast is the star moving away from Earth?

Overview
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| Solution steps | Calculations |
|---|---|
| **Step 1:** Write out the values given in the question and convert the values to the units required for the equation. | $f = 1.4\times10^9\ \text{Hz}$<br>$\Delta f = 0.1\times10^9\ \text{Hz}$<br>$c = 3.0\times10^8\ \text{m s}^{-1}$ |
| **Step 2:** Write out the equation. | $\frac{\Delta f}{f} \approx \frac{v}{c}$ |
| **Step 3:** Substitute the values given. | $\frac{0.1}{1.4}\times3\times10^8 \approx v$ |
| **Step 4:** State the answer with appropriate units and the number of significant figures used in rounding. | $2.1\times10^7\ \text{m s}^{-1}$ |

The equations tell us that the relative change in frequency (or wavelength) can give us an estimate for the velocity of the moving object.

One of the applications of these equations is to determine the velocity of faraway stars and galaxies.

If the wavelengths of the light waves coming from the star are greater than expected, then the velocity of the star is positive and it is moving away from the Earth:

$$\begin{aligned}\frac{\Delta\lambda}{\lambda} &= \frac{\lambda_{\text{observed}} - \lambda_{\text{expected}}}{\lambda_{\text{expected}}}\\ &= \text{positive velocity}\end{aligned}$$

If the wavelengths of the light waves coming from the star are smaller than expected, then the velocity of the star is negative and it is moving towards the Earth.

$$\begin{aligned}\frac{\Delta\lambda}{\lambda} &= \frac{\lambda_{\text{observed}} - \lambda_{\text{expected}}}{\lambda_{\text{expected}}}\\ &= \text{negative velocity}\end{aligned}$$

# Spectral lines

The light emitted by a star (its emission spectrum) has lines, called spectral lines, that show the wavelengths of light emitted when the electrons of particular elements lose energy (subtopic E.1 (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-43191/)).

Student view

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**Figure 1** shows the expected spectral lines for a particular star. Different wavelengths have different colours. Longer wavelengths are at the red end of the spectrum, and shorter wavelengths are at the blue end.

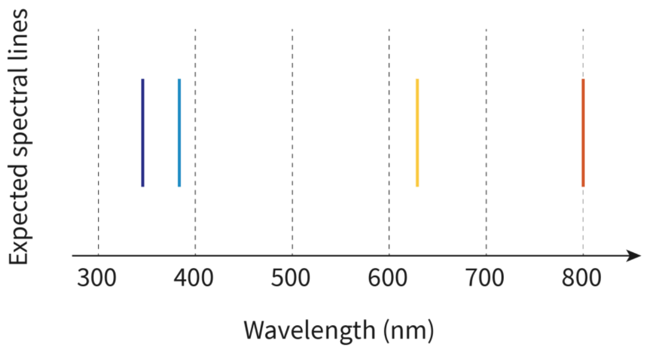


**Figure 1.** Spectral lines for a star.

More information for figure 1

The image shows a graph representing the expected spectral lines for a star across different wavelengths measured in nanometers (nm). The X-axis is labeled "Wavelength (nm)" and ranges from 300 nm to 800 nm, marked at intervals of 100 nm. The Y-axis is labeled "Expected spectral lines." There are three vertical lines corresponding to different wavelengths. The first line is at approximately 400 nm, another at approximately 600 nm, and the third at approximately 800 nm. Each line represents a spectral line and is color-coded, indicating different colors associated with the wavelengths, moving from shorter to longer wavelengths across the visible spectrum. The graph illustrates how different spectral lines correspond to specific wavelengths of light emitted by the star.

[Generated by AI]

What do you think happens to the spectral lines if the star is moving away from the Earth or moving towards the Earth?

### Theory of Knowledge

Is the star moving away from Earth, or is the Earth moving away from the star? Is there any way to tell? Will the Doppler effect give different answers? Is there one absolute truth, or does it just depend on the frame of reference?

**Figure 2** shows light moving away from and towards a person.

Student view

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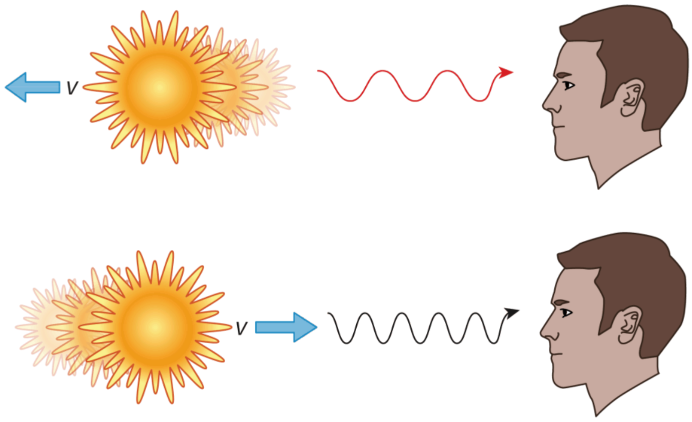


**Figure 2.** Light moving away from a person and towards a person.

More information for figure 2

The diagram shows two scenarios of a light source and a person. In the top scenario, the light source is moving away from the person, indicated by a blue arrow pointing left marked with 'v'. The waves emanating from the light are shown in red with longer wavelengths. In the lower scenario, the light source is moving towards the person, indicated by a blue arrow pointing right, also marked with 'v'. The waves in this case are black with shorter wavelengths. This illustrates the Doppler effect with light, where the movement of the light source relative to the observer changes the perceived wavelength.

[Generated by AI]

- If the light wave is moving away from us, the wavelength appears to be longer (red end of the spectrum).
- If the light wave is moving towards us, the wavelength appears to be shorter (blue end of the spectrum).

**Figure 3** shows the spectral lines for a star moving away from the Earth and towards the Earth.

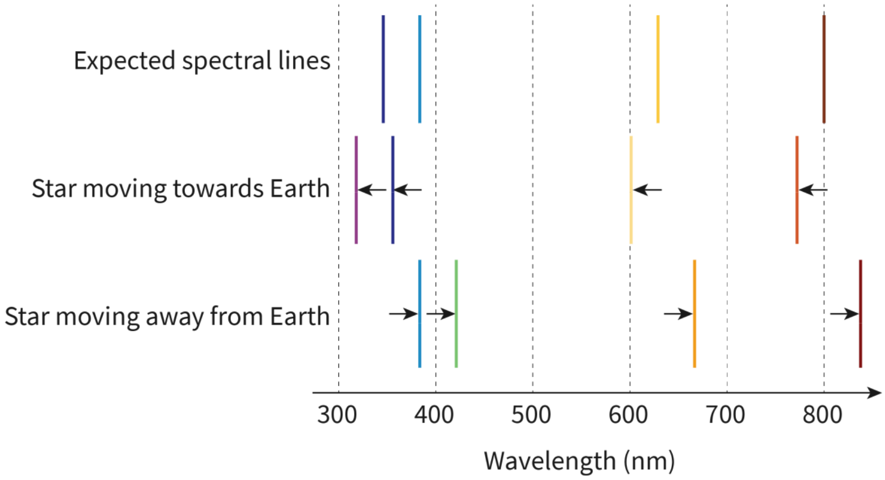


**Figure 3.** Spectral lines for a star moving away from the Earth and a star moving towards the Earth.

More information for figure 3

Student
view

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The image shows a graph illustrating how spectral lines shift for stars moving towards and away from Earth. The x-axis represents wavelength in nanometers (nm), ranging from 300 to 800 nm. Three sets of spectral lines are depicted:

1. The expected spectral lines are shown vertically at specific wavelengths across the graph.
2. For a star moving towards Earth (blue shift), the lines shift towards shorter wavelengths, indicated by arrows pointing left towards the blue end of the spectrum.
3. For a star moving away from Earth (red shift), the lines move towards longer wavelengths, shown by arrows pointing right towards the red end of the spectrum.

Overall, the graphic demonstrates that the greater the relative velocity between the Earth and the star, the more significant the shift in the spectral lines.

[Generated by AI]

You can see from **Figure 3** that the spectral lines for a star moving towards the Earth are shifted towards the blue end of the spectrum (known as blueshift). The spectral lines for a star moving away from the Earth are shifted towards the red end of the spectrum (known as redshift). The greater the relative velocity between the Earth and the star, the greater the shift of the spectral lines.

By looking at the motion of objects in space, we can model what we think the Universe looked like in the past and what we think the Universe will look like in the future. Redshift in spectral lines from stars is evidence for the Big Bang theory, which states that the Universe expanded outwards from a single dense point, and that galaxies are travelling away from each other as space expands.

Work through the activity to check your understanding of the Doppler effect and light.

## Activity

- **IB learner profile attribute:**
  - Knowledgeable
  - Communicator
- **Approaches to learning:**
  - Thinking skills — Providing a reasoned argument to support conclusions
  - Communication skills — Applying interpretive techniques to different forms of media
- **Time required to complete activity:** 20—30 minutes
- **Activity type:** Group activity

Student view

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Work in a group of three. Decide who will be A, B and C, and look at the source material for your letter. You have 3—5 minutes to look through your source material, and to try and understand what you are looking at and what it might mean.

The source material for A is

Source material A (https://d3vrb2m3yrmyfi.cloudfront.net/media/edusys_2/content_uploads/Physics C5.1.2 ACTIVITY Doppler (source A).2cc6afd4a629bdad7a2c.pdf)

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The source material for B is

Source material B (https://d3vrb2m3yrmyfi.cloudfront.net/media/edusys_2/content_uploads/Physics C5.1.2 ACTIVITY Doppler (source B).bdc908f37887db99ec54.pdf)

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The source material for C is

Source material C (https://d3vrb2m3yrmyfi.cloudfront.net/media/edusys_2/content_uploads/Physics C5.1.2 ACTIVITY Doppler (source C).96e5c1330038218918b6.pdf)

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In your group, discuss the following questions:

- What does your data show?
- What do you think your data means?
- How do you think your data could be applied?

If your source has an image, you could describe the features of the image. If your source has equations, you could describe what the equations find.

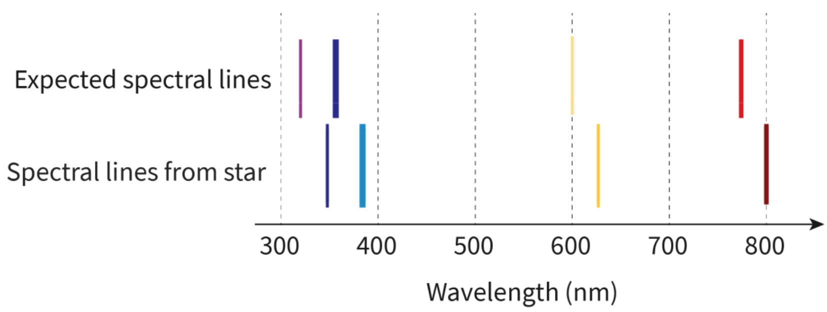
Look at sources A, B and C as a group. Write a paragraph describing what you can learn from the sources, using data and images from the sources to help you. Try to make links between the data in the sources.

## 6 section questions

**Question 1**

SL HL Difficulty:

The diagram shows the spectral lines from a distant star compared to the expected spectral lines.




Student view

Overview
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More information

Which statement about the star is correct?

1 The star is moving away from us and its spectral lines are redshifted. ✓

2 The star is moving towards us and its spectral lines are redshifted.

3 The star is moving away from us and its spectral lines are blueshifted.

4 The star is moving towards us and its spectral lines are blueshifted.

**Explanation**

The spectral lines from the star have been shifted towards longer wavelengths (red end of the spectrum), so they have been redshifted. Redshift occurs for objects that are moving away from the Earth, so the star is moving away from us.

**Question 2**

SL HL Difficulty:

A star is moving towards the Earth at 450 km $s^{-1}$. Which statement is true about the star's spectral lines?

1 The spectral lines will be blueshifted as the star is moving towards us. ✓

2 The spectral lines will be redshifted as the star is moving towards us.

3 The spectral lines will be blueshifted as the star is moving away from us.

4 The spectral lines will be redshifted as the star is moving away from us.

**Explanation**

The star is moving towards us, so its spectral lines will be blueshifted.

**Question 3**

SL HL Difficulty:

If a galaxy is moving away from us, its spectral lines are shifted towards 1 longer ✓ wavelengths. If a galaxy is moving towards us, its spectral lines are shifted towards 2 shorter ✓ wavelengths.

**Accepted answers and explanation**

#1 longer
bigger
larger

Student view

greater

#2 shorter

smaller

**General explanation**

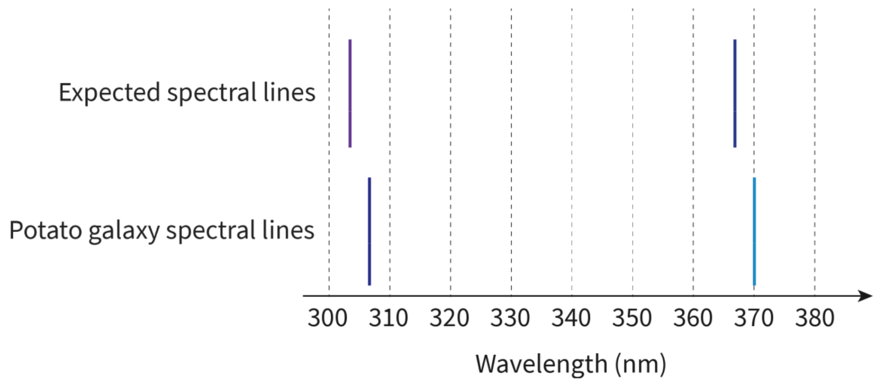
If a galaxy is moving away from us, then its wavelengths are shifted towards longer wavelengths (red end of the spectrum). If a galaxy is moving towards us, then its wavelengths are shifted towards shorter wavelengths (blue end of the spectrum).



**Question 4**

SL HL Difficulty:

The diagram shows the spectral lines from a galaxy called the Potato Galaxy, compared to predicted spectral lines.




More information

What velocity is the Potato Galaxy moving relative to the Earth?

1 2500 km $s^{-1}$ away from us ✓

2 2500 km $s^{-1}$ towards us

3 51 000 km $s^{-1}$ away from us

4 51 000 km $s^{-1}$ towards us

**Explanation**

As the spectral lines of the Potato Galaxy are shifted to the right, the change in wavelength is a positive value, leading to a positive velocity, so the galaxy is moving away from the Earth. Read off the diagram the shift in wavelength.

$\lambda = 367 \text{ nm}$

$c = 3.00\times10^{8} \text{ m s}^{-1}$

$\Delta\lambda = 3 \text{ nm}$

The choice of which spectral line to use is arbitrary in this case as there are only two, however were there more I would select the middle lines as our test line to get an average velocity.

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Thus calculating:

$$\frac{\Delta\lambda}{\lambda} \approx \frac{v}{c}$$

$$\begin{aligned} v &= \frac{c\Delta\lambda}{\lambda} \\ &= \frac{3.00 \times 10^8 \times 3}{367} \\ &= 2\,452\,316 \text{ m s}^{-1} \\ &= 2500 \text{ km s}^{-1} \text{ (2 s.f.)} \end{aligned}$$

**Question 5**

SL HL Difficulty:

When travelling at 95% the speed of light, you conduct an experiment to measure the speed of light outside your spacecraft. What value will you measure the speed of light as?

The speed of light is 1 3.00 ✓ $\times 10^8$ m s$^{-1}$.

**Accepted answers and explanation**

#1 3.00

3

3.0

**General explanation**

The speed of light is always measured as the speed of light. It does not matter how fast or slow you are travelling during this experiment; the speed of light will be measured as the speed of light.

**Question 6**

SL HL Difficulty:

A new star is discovered in the Andromeda Galaxy, and its light is analysed. The following data is collected:

$\lambda_{\text{observed}}$ = 410 nm

$f_{\text{expected}}$ = 7.11 × 10$^{14}$ Hz

What is the velocity of the star relative to the Earth? Give your answer to an appropriate number of significant figures.

The velocity of the star is 1 8500 ✓ km s$^{-1}$.

Student view

**Accepted answers and explanation**

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#1 8500

8.5x10^3

8.5*10^3

**General explanation**

$$\lambda_{\text{observed}} = 410 \text{ nm} \\ = 4.10\times10^{-7} \text{ m}$$

$$f_{\text{expected}} = f = 7.11\times10^{14} \text{ Hz}$$

$$c = 3.00\times10^{8} \text{ m s}^{-1}$$

Expected wavelength:

$$c = f\lambda$$

$$\lambda = \frac{c}{f} = \frac{3.00\times10^{8}}{7.11\times10^{14}} = 4.22\times10^{-7} \text{ m}$$

Change in wavelength:

$$\Delta\lambda = 4.10\times10^{-7} - 4.22\times10^{-7} = -1.2\times10^{-8} \text{ m}$$

$$\frac{\Delta\lambda}{\lambda} \approx \frac{v}{c}$$

$$v \approx 3.00 \times 10^{8} \times \frac{-1.2 \times 10^{-8}}{4.22 \times 10^{-7}}$$

$$v \approx -8.53 \times 10^{6} \text{ m s}^{-1} = -8500 \text{ km s}^{-1} \text{ (2 s.f.)}$$

C. Wave behaviour / C.5 Doppler effect

# Calculating Doppler (HL)

C.5.5: Observed frequency for sound waves and mechanical waves (HL)

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/calculating-doppler-hl-id-45340/print/) Assign

## Higher level (HL)

### Learning outcomes

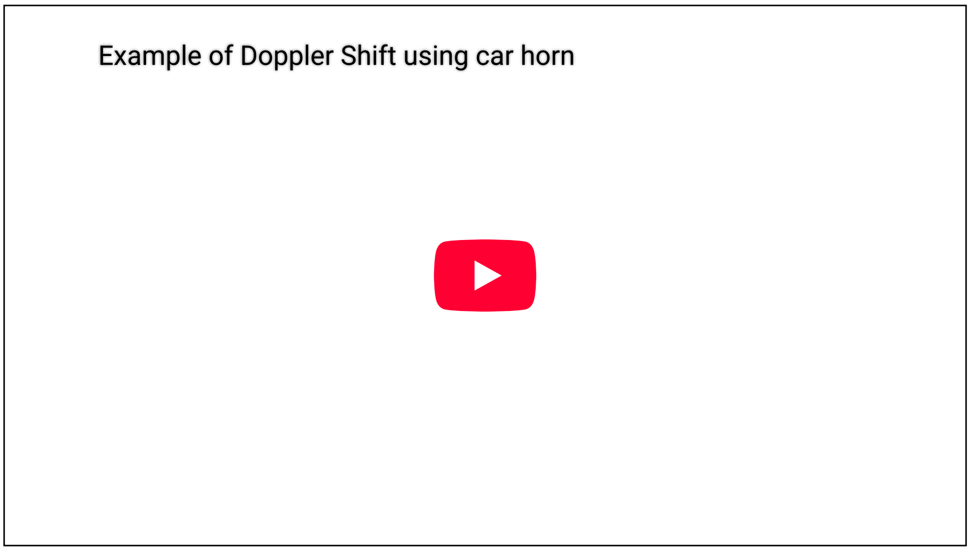
At the end of this section you should be able to determine the observed frequency of waves for a moving source or a moving observer using:

$$f' = f\left(\frac{v}{(v \pm u_{\text{s}})}\right) \text{ and } f' = f\left(\frac{(v \pm u_{\text{o}})}{v}\right)$$

Student view

## Engage

What sound does a fast car make when it drives past you? What about a car sounding its horn? Watch **Video 1** to remind yourself. Could you tell from measuring the sound how fast the car was going?




**Video 1.** Car sounding its horn.

More information for video 1

A car sounding its horn is featured in this video to demonstrate the Doppler effect. Set against the backdrop of an empty road, a dark blue minivan begins to approach from a distance, driving steadily along the right-hand lane. As it nears, the sound of its horn becomes audible. The tone of the horn noticeably shifts in pitch as the vehicle passes by and continues down the road. This change in pitch—higher as the vehicle approaches, and lower as it recedes—is a direct illustration of the Doppler effect.

The Doppler effect is a phenomenon where the frequency of a wave changes based on the relative motion between the source and the observer. In this case, the wave in question is the sound wave emitted by the car's horn. When the minivan is moving toward the listener, the sound waves are compressed, causing the pitch to rise. As it moves away, the waves are stretched, lowering the pitch. The video provides a real-world, observable example of this effect, allowing for a clear auditory comparison of the pitch before, during, and after the vehicle passes by.

Using an understanding of the Doppler effect, we can measure these sound changes and calculate the speed of the car. Let's find out how.

## Moving source

We are going to derive an equation to determine the observed frequency of waves (mechanical waves or sound waves) from a moving source.

### Study skills

In this section, we will use a lot of variables in the equations, so they are shown in **Table 1.**

**Table 1.** Variables.

Overview
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| Symbol | Unit | Description |
|---|---|---|
| $s$ | m | Distance between source and observer |
| $f$ | Hz | Emitted frequency |
| $f'$ | Hz | Observed frequency |
| $\lambda$ | m | Emitted wavelength |
| $\lambda'$ | m | Observed wavelength |
| $v$ | $\text{ms}^{-1}$ | Velocity of the wave |
| $u_s$ | $\text{ms}^{-1}$ | Velocity of the source |
| $u_o$ | $\text{ms}^{-1}$ | Velocity of the observer |

**Figure 1** shows a sound wave emitted from a moving source.

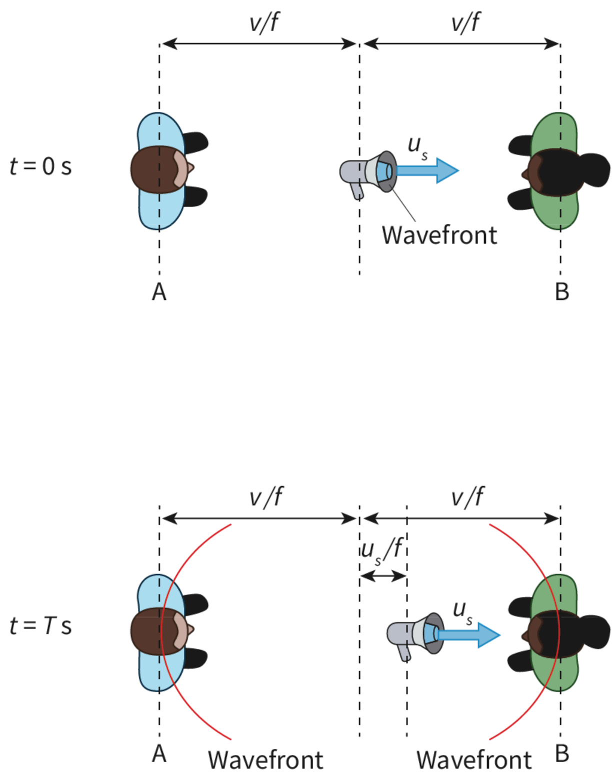


**Figure 1.** A sound wave emitted from a moving source.

More information for figure 1

This diagram illustrates the propagation of a sound wave from a moving source at two different times. In the top section of the diagram, marked as ( t = 0 ) seconds, the source emits sound waves that are shown as concentric curves propagating towards two observers, labeled A and B. The distance between the source and each observer is equal, marked as ( v/f ),

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where ( v ) represents the wave speed and ( f ) is the frequency.

In the lower section, marked as ( t = T ) seconds, the wave has reached the observers. The distance between the source and observer A is still ( v/f ) but the wave shows a shifted closer wavefront between the source and observer B. This additional shift is calculated as ( u_s/f' ), indicating the source's speed ( u_s ) affecting the wave frequency ( f' ). An arrow points rightward from the source, denoting its direction of movement. The wavefronts in this scenario are slightly bent, indicating the Doppler effect with respect to the moving source and observers in both diagrams.

[Generated by AI]

At time $t = T$ later, the wave has reached the two observers ($T$ is the time period of the wave). The speed of the wave is $v$, and the speed of the source is $u_{\text{s}}$.

We know that:

$$s = vt$$

and when the time is one complete time period,

$$\begin{aligned} t &= T \\ &= \frac{1}{f} \end{aligned}$$

So:

$$s = \frac{v}{f}$$

Distance between source and observer A is:

$$s = \frac{v}{f} + \frac{u_{\text{s}}}{f}$$

Distance between source and observer B is:

$$s = \frac{v}{f} - \frac{u_{\text{s}}}{f}$$

For observer A, the wavelength appears longer, and for observer B, the wavelength appears shorter. This is known as the apparent wavelength, $\lambda'$.

The wave equation is:

$$v = f\lambda$$

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

Apparent wavelength for observer A:

$$\lambda' = \frac{(v + u_{\text{s}})}{f}$$

Apparent wavelength for observer B:

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$$\lambda' = \frac{(v - u_s)}{f}$$

Putting this back into the wave equation, we can determine the apparent frequency of the wave. Note that observer B receives waves more frequently than observer A as the source is moving towards observer B.

Apparent frequency for observer A:

$$f' = \frac{v}{\lambda'}$$

$$f' = \frac{v}{\left[\frac{(v + u_s)}{f}\right]}$$

$$f' = f\left[\frac{v}{(v + u_s)}\right]$$

Apparent frequency for observer B:

$$f' = \frac{v}{\lambda'}$$

$$f' = \frac{v}{\left[\frac{(v - u_s)}{f}\right]}$$

$$f' = f\left[\frac{v}{(v - u_s)}\right]$$

Note that the derivation of this equation is not a requirement of the DP physics course, but it is included to aid understanding.

The general equation for observed frequency of a moving source is shown in **Table 2**.

**Table 2.** Equation for observed frequency of a moving source.

| Equation | Symbols | Units |
|---|---|---|
| $f' = f\left[\frac{v}{(v \pm u_s)}\right]$ | $f'$ = observed frequency | hertz (Hz) |
| | $f$ = frequency emitted by the source | hertz (Hz) |
| | $v$ = velocity of the wave | metres per second (m s$^{-1}$) |
| | $u_s$ = velocity of the source | metres per second (m s$^{-1}$) |

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### Study skills

This equation is given to you in section 1.6.C (/study/app/math-aa-hl/sid-423-cid-762593/book/wave-behaviour-id-45162/) of the DP physics data booklet. However, you need to determine whether the sign is positive or negative for the situation you are evaluating.

## Worked example 1

A motorbike is approaching a person at a bus stop at a constant speed of 50 km $h^{-1}$. The motorbike engine is producing a consistent frequency of 1500 Hz. Calculate the frequency heard by the person as the motorbike moves towards, and then away from them.

(Speed of sound in air is approximately 342 m $s^{-1}$.)

| Solution steps | Calculations |
|---|---|
| **Step 1:** Write out the values given in the question and convert the values to the units required for the equation. | $u_s = 50\ \text{km/h}$<br>$= 13.9\ \text{m s}^{-1}$<br><br>$f = 1500\ \text{Hz}$<br><br>$v = 342\ \text{m s}^{-1}$<br><br>There is a moving source (motorbike) and stationary observer (person).<br><br>The source is moving towards the observer then away from the observer. |
| **Step 2:** Determine the observed frequency when the source is moving towards the observer. | As the motorbike moves towards the person, the wavefronts become closer together. The wavefronts reach them more frequently. The equation should maximise $f'$:<br><br>$f' = f\left[\frac{v}{(v-u_s)}\right]$<br>$= 1500\times\left[\frac{342}{(342-13.9)}\right]$<br>$= 1563.5\ \text{Hz}$<br>$= 1600\ \text{Hz (2 s.f.)}$ |

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| Solution steps | Calculations |
|---|---|
| **Step 3:** Determine the observed frequency when the source is moving away from the observer. | As the bike moves away from the person, the wavefronts become further apart. The wavefronts reach them less frequently. The equation should minimise $f'$: $$f' = f\left[\frac{v}{(v+u_s)}\right]$$ $$= 1500\times\left[\frac{342}{(342+13.9)}\right]$$ $$= 1441.4\text{ Hz}$$ $$= 1400\text{ Hz (2 s.f.)}$$ |

## Moving observer

Now, we are going to derive an equation to determine the observed frequency of waves for a moving observer.

**Figure 2** shows a sound wave emitted from a stationary source. Observer A and observer B are moving towards the left. Observer A is moving away from the source, while observer B is moving towards the source.

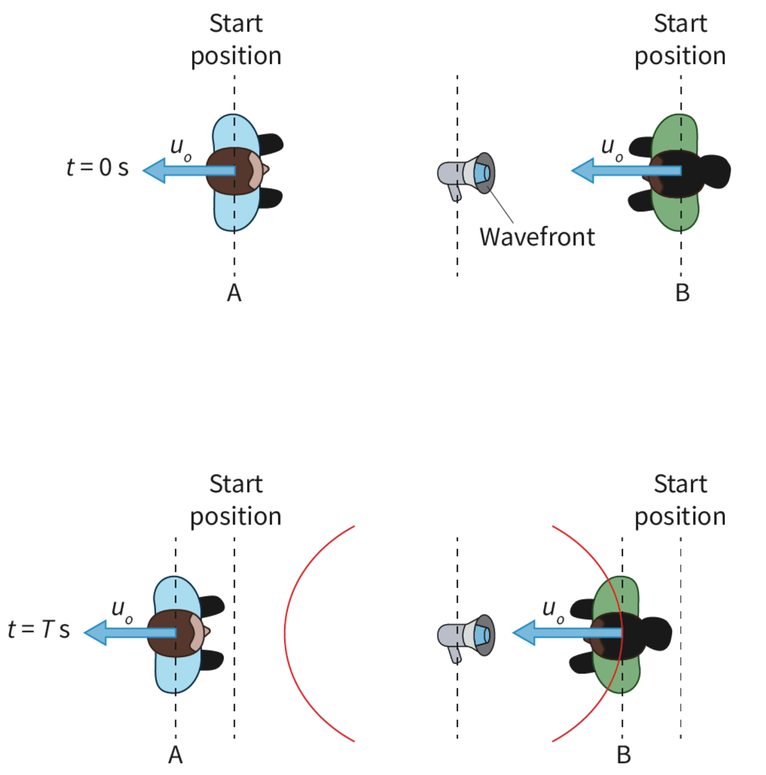


**Figure 2.** A sound wave emitted from a stationary source.

More information for figure 2

The diagram illustrates two observers, A and B, relative to a sound wave emitted from a stationary source. Observer A is depicted moving to the left, away from the source, with labeled velocity ( u_o ). Observer B is also moving to the left but towards the source, also

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

with velocity ( u_o ). This is illustrated in two stages: at time ( t = 0 ) seconds, both observers are at their start positions, while at time ( t = T ), they have moved further to the left relative to their initial positions and relative to the sound wave. The wavefronts are shown as curved lines emanating from the source toward the positions of the observers at both time intervals.

[Generated by AI]

At time $t = T$ later, the wave has reached the two observers ($T$ is the time period of the wave). The speed of the wave is $v$, and the speed of the observers is $u_o$.

We can see from **Figure 2** that the sound wave has reached observer B, but it is still some distance away from observer A.

**Figure 3** shows the wave after time $t = 2T$.

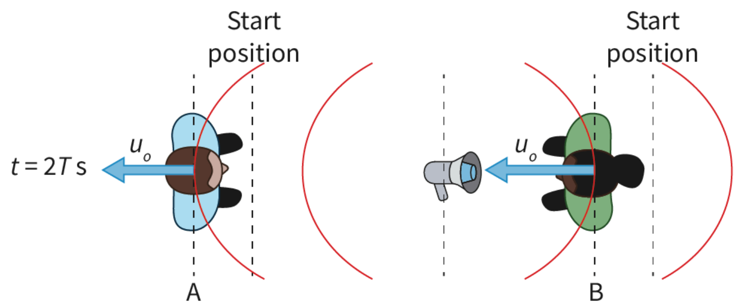


**Figure 3.** A sound wave emitted from a stationary source after $t = 2T$.

More information for figure 3

The diagram illustrates a sound wave emitted from a stationary source over time ( t = 2T ). On the left, there is a depiction labeled 'A' with an individual facing right and a blue arrow pointing left labeled ( u_0 ), representing the initial velocity of the sound wave. The individual's start position and the proceeding sound wave are marked by arcs around the figure. On the right, a similar depiction is labeled 'B' with another individual facing left. The sound wave for this individual, also starting at a position marked by arcs, moves towards them with an arrow labeled ( u_0 ) pointing towards the individual. This represents the movement and interaction of sound waves with observers at two different positions.

[Generated by AI]

- For observer A, only one of the wavefronts has reached them in time $2T$.
- For observer B, two wavefronts have reached or passed them in time $2T$.

For a moving observer, the apparent frequency of the sound changes. For observer A, the relative speed between the source and the observer $(v - u_o)$ is slower, as they are moving away from each other. For observer B, the relative speed between the waves and the observer $(v + u_o)$ is faster, as they are moving towards each other. Thus we can write:

Apparent frequency for observer A:

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$$f' = \frac{(v - u_o)}{\lambda}$$

Apparent frequency for observer B:

$$f' = \frac{(v + u_o)}{\lambda}$$

For a moving observer, the wavelength does not appear to change – it is the speed of sound that appears to change:

$$v - u_o = f'\lambda$$

Remember that:

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

For observer A (relative speed of sound is decreased):

$$v - u_o = f'\left(\frac{v}{f}\right)$$

$$f' = \left[\frac{(v - u_o)}{\left(\frac{v}{f}\right)}\right]$$

$$f' = f\left[\frac{(v - u_o)}{v}\right]$$

For observer B (relative speed of sound is increased):

$$v + u_o = f'\left(\frac{v}{f}\right)$$

$$f' = \left[\frac{(v + u_o)}{\left(\frac{v}{f}\right)}\right]$$

$$f' = f\left[\frac{(v + u_o)}{v}\right]$$

Note that the derivation of this equation is not a requirement of the DP physics course, but it is included to aid understanding.

The general equation for observed frequency for a moving observer is shown in **Table 3**.

**Table 3.** Equation for observed frequency for a moving observer.

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| Equation | Symbols | Units |
|---|---|---|
| $f' = f\left[\frac{(v \pm u_o)}{v}\right]$ | $f'$ = observed frequency | hertz (Hz) |
| | $f$ = frequency emitted by the source | hertz (Hz) |
| | $v$ = velocity of the wave | metres per second (m s$^{-1}$) |
| | $u_o$ = velocity of the observer | metres per second (m s$^{-1}$) |

### Study skills

The equation for observed frequency is given with a plus or minus sign to show whether the observed frequency will increase or decrease. If you are struggling to remember, try thinking of a race car.

- As the race car moves towards you, the frequency increases, meaning $f'$ is greater than $f$.
- As the race car moves away from you, the frequency decreases, meaning $f'$ is less than $f$.

Then, consider what the plus or minus sign will do to the magnitude of the fraction and how it will affect $f'$.

## Worked example 2

A runner is moving at 8.00 m s$^{-1}$ away from a crying baby. If the sound he hears has a frequency of 3370 Hz, what was the emitted frequency of the crying? Sound waves move at 330 m s$^{-1}$.

| Solution steps | Calculations |
|---|---|
| **Step 1:** Write down the known quantities using the appropriate symbols. | Velocity of the observer $\rightarrow u_0 = 8.00\text{ m s}^{-1}$<br>Observed frequency $\rightarrow f' = 3370\text{ Hz}$<br>Speed of sound $\rightarrow 330\text{ m s}^{-1}$ |
| **Step 2:** In section 1.6.C (/study/app/math-aa-hl/sid-423-cid-762593/book/wave-behaviour-id-45162/) of the IB physics data booklet, choose the right Doppler effect equation. | This is a question about a stationary source (i.e. the crying baby) and a moving observer (i.e. the runner), so the equation to be used is:<br>$f' = f\left(\frac{v \pm u_0}{v}\right)$ |

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| Solution steps | Calculations |
| --- | --- |
| **Step 3:** Choose the right sign to be used. | Since the runner is moving away from the crying baby, the observed frequency $f'$ is less than the actual frequency of the crying $f$, so the minus sign must be used in the equation: $$f' = f\left(\frac{v - u_0}{v}\right)$$ |
| **Step 4:** Rearrange the equation, substitute the numerical values and calculate $f$. | $$f = f'\left(\frac{v}{v - u_0}\right)$$ $$= 3370 \times \left(\frac{330}{330 - 8.00}\right)$$ $$= 3450 \text{ Hz } (3 \text{ s.f.})$$ |

Work through the activity to check your understanding of observed frequency.

## Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Applying key ideas and facts in new contexts
- **Time required to complete activity:** 5—10 minutes
- **Activity type:** Individual activity

Sort the equations in **Interactive 1** into the correct order of derivation for the equation for observed frequency for a moving source and stationary observer.

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Sort the paragraphs

$$f' = \frac{v}{\left(\frac{(v \pm u_s)}{f}\right)}$$

$$f' = f\left(\frac{v}{(v \pm u_s)}\right)$$

$$s = \left(\frac{v}{f}\right) \pm \left(\frac{u_s}{f}\right)$$

$$\lambda' = \frac{(v \pm u_s)}{f}$$

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

Check

**Interactive 1.** What is the correct order of derivation for the equation?

More information for interactive 1

This is a sorting-style interactivity that allows users to sort a series of equations into the correct order to derive the observed frequency for a moving source and a stationary observer, a common scenario in Doppler effect problems. The interface presents five rectangular boxes, each containing one or more mathematical expressions. These boxes can be reordered using the up and down arrows on the right side of each one. The goal is to move these equations up or down in the correct logical sequence to understand how the Doppler shift formula is derived.

The first box contains the equation, $\lambda' = \left(\frac{v \pm u_S}{f}\right)$ which represents the wavelength observed when the source is moving with speed $u_S$, and $v$ is the speed of sound. The second box shows the fundamental wave equation, $v = f\lambda$, and its rearranged form, $f = \frac{u}{\lambda}$, establishing the relationship between wave speed $v$, frequency $f$, and wavelength $\lambda$. The third box shows, $f' = \left(\frac{v}{\frac{v \pm u_S}{f}}\right)$, which is an intermediate step in deriving the observed frequency using the modified wavelength. The fourth box contains the distance equation, $S = \left(\frac{v}{f} \pm \frac{u_S}{f}\right)$, which shows how the displacement $s$ in one period incorporates both the wave speed and source speed. The fifth box contains the equation, $f' = f\left(\frac{v}{v \pm u_S}\right)$ which is the final simplified form of the Doppler effect equation for a moving source and stationary observer.

To interact with this activity, users click the up or down arrow buttons on each equation box to rearrange them into a sequence that logically leads to the observed frequency formula. The "Check" button at the bottom allows users to submit their sequence and verify its correctness. This interactivity provides a

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hands-on way to reinforce the derivation of the Doppler effect formula by guiding learners through the key concepts and transformations involved.

Solution:

Here is the correct order of derivation for the observed frequency.

1. $S = \left(\frac{v}{f} \pm \frac{u_S}{f}\right)$
2. $\lambda' = \left(\frac{v \pm u_S}{f}\right)$
3. $v = f\lambda, f = \frac{u}{\lambda}$
4. $f' = \left(\frac{v}{\frac{v \pm u_S}{f}}\right)$
5. $f' = f\left(\frac{v}{v \pm u_S}\right)$

This interactivity promotes conceptual understanding of how motion influences wave perception. Rather than simply memorizing the Doppler formula, students develop insight into the physical meaning behind each algebraic step, reinforcing the importance of wave motion and reference frames.

## 5 section questions

**Question 1**

HL Difficulty:

For a source moving towards a stationary observer, the observed 1 wavelength ✓ decreases and the observed 2 frequency ✓ of the wave increases.

**Accepted answers and explanation**

#1 wavelength

#2 frequency

**General explanation**

If a source is moving towards a stationary observer then the wavelength appears to decrease. The frequency of the wave appears to increase. The speed of sound does not change so wavelength and frequency are inversely related.

**Question 2**

HL Difficulty:

The sound of a flying hummingbird is detected by a stationary microphone and recorded on a computer. The hummingbird is flying towards the microphone.

Which statement is correct?

1 The observed frequency is greater and the observed wavelength is shorter ✓

2 The observed frequency is greater and the observed wavelength is longer

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3 The observed frequency is lower and the observed wavelength is shorter

4 The observed frequency is lower and the observed wavelength is longer

### Explanation

The hummingbird is a moving source and the microphone is a stationary observer.

As the hummingbird is moving towards the microphone, the frequency will increase.

The speed of sound does not change so wavelength and frequency are inversely related. This means that the wavelength must decrease.

**Question 3**

HL Difficulty:

A raccoon runs towards a person. The person runs away from the raccoon. The raccoon stops and makes a friendly noise, but the person keeps running.

Which equation should be used to determine the frequency of the raccoon's call?

1 $f' = f\left[\frac{(v - u_o)}{v}\right]$ ✓

2 $f' = f\left[\frac{v}{(v + u_s)}\right]$

3 $f' = f\left[\frac{v}{(v - u_s)}\right]$

4 $f' = f\left[\frac{(v + u_o)}{v}\right]$

### Explanation

Moving observer (person) and a stationary source (raccoon):

$$f' = f\left[\frac{(v \pm u_o)}{v}\right]$$

The observer is moving away from the source so the frequency decreases:

$$f' = f\left[\frac{(v - u_o)}{v}\right]$$

**Question 4**

HL Difficulty:

A motorbike travels along a road at 14 m s$^{-1}$. The sound of the engine has a frequency of 171 Hz. A stationary person sees and hears the motorbike go past. Determine the observed frequency of the engine sound after the motorbike has passed the person. Give your answer to an appropriate number of significant figures.

(Speed of sound in air is approximately 342 m s$^{-1}$.)

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The observed frequency of the engine is 1 160 ✓ Hz

**Accepted answers and explanation**

#1 160

**General explanation**

$v = 342 \text{ m s}^{-1}$

$u_s = 14 \text{ m s}^{-1}$

$f = 171 \text{ Hz}$

Moving source (motorbike) and stationary observer (person):

$$f' = f\left[\frac{v}{(v \pm u_s)}\right]$$

The source is moving away from the observer:

$$\begin{aligned} f' &= f\left[\frac{v}{(v + u_s)}\right] \\ &= 171 \times \left[\frac{342}{(342 + 14)}\right] \\ &= 164.3 \text{ Hz} \\ &= 160 \text{ Hz (2 s.f.)} \end{aligned}$$

**Question 5**

HL Difficulty:

A bat hanging in a tree emits ultrasound at a frequency of 61 kHz. The ultrasound reflects off a moth flying towards the bat at 7.0 m s$^{-1}$. Determine the frequency of the reflected wave detected by the bat. Give your answer to an appropriate number of significant figures.

(Speed of sound = 342 m s$^{-1}$)

The frequency of the reflected wave is 1 64 ✓ kHz.

**Accepted answers and explanation**

#1 64

64 kHz

**General explanation**

$v = 342 \text{ m s}^{-1}$

$$\begin{aligned} f &= 61 \text{ kHz} \\ &= 61\,000 \text{ Hz} \end{aligned}$$

$u_o = 7.0 \text{ m s}^{-1}$

Stationary source (bat) and moving observer (moth):

$$\begin{aligned} f' &= f\left[\frac{(v + u_o)}{v}\right] \\ &= 61\,000 \times \left[\frac{(342 + 7.0)}{342}\right] \\ &= 62\,249 \text{ Hz} \end{aligned}$$

Stationary observer (bat) and moving source (moth):

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$$
\begin{aligned}
f' &= f\left[\frac{v}{(v-u_s)}\right]\\
&= 62\,249\left[\frac{342}{(342-7.0)}\right]\\
&= 63\,550\ \text{Hz}\\
&= 64\ \text{kHz (2 s.f.)}
\end{aligned}
$$

C. Wave behaviour / C.5 Doppler effect

# Summary and key terms

Section Student… (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/summary-and-key-terms-id-45341/print/) Assign

- The Doppler effect is the perceived change in frequency, relative speed or wavelength of a wave due to relative motion between the source and the observer.
- The Doppler effect affects all waves, including mechanical waves, sound waves and electromagnetic waves.
- Wavefront diagrams can be used to represent the Doppler effect for a moving source and a moving observer.
- The relative change in frequency or wavelength for an electromagnetic wave due to the Doppler effect can be determined using:

$$\frac{\Delta f}{f} = \frac{\Delta\lambda}{\lambda} \approx \frac{v}{c}$$

- Spectral lines can be redshifted or blueshifted, which gives us information about the motion of stars and galaxies.

## Higher level (HL)

For sound waves and mechanical waves, the observed frequency from a moving source and for a moving observer can be determined using:

$$f' = f\left[\frac{v}{(v \pm u_s)}\right] \text{ and } f' = f\left[\frac{(v \pm u_o)}{v}\right]$$

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## Key terms

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

1. The ______ is the change in the observed frequency of a wave as the result of the relative motion between two bodies.
2. The specific perspective from which an observer analyses a situation is called the ______.
3. ______ is when wavelengths of light are shifted towards shorter wavelengths than expected.
4. When a source produces a wave that reflects off an object and is received by the source again, this is known as the ______.
5. The ______ for a star show the wavelengths of light emitted by different elements losing electrons.
6. ______ is when wavelengths of light are shifted towards longer wavelengths than expected.

Blueshift | Redshift | spectral lines | reference frame | Doppler effect | double Doppler effect

Check

**Interactive 1.** Wave Behavior and Observational Perspectives.

C. Wave behaviour / C.5 Doppler effect

# Checklist

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/checklist-id-45342/print/) Assign

## What you should know

After studying this subtopic, you should be able to:

- Explain the Doppler effect and its effect on the perception of sound waves and electromagnetic waves.
- Use wavefront diagrams to represent the Doppler effect when the source is moving or the observer is moving.
- Determine the relative change in frequency and wavelength for a light wave using the equations:

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$$\frac{\Delta f}{f} = \frac{\Delta \lambda}{\lambda} \approx \frac{v}{c}$$

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- Explain that shifts in spectral lines from stars and galaxies give information about their motion in space.

### Higher level (HL)

- Determine the observed frequency of waves for a moving source or a moving observer using:

$$f' = f\left(\frac{v}{(v \pm u_s)}\right) \text{ and } f' = f\left(\frac{(v \pm u_o)}{v}\right)$$

C. Wave behaviour / C.5 Doppler effect

# Investigation

Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/nvestigation-id-45343/print/) Assign

- **IB learner profile attribute:**
  - Knowledgeable
  - Thinker
- **Approaches to learning:** Thinking skills – Applying key ideas and facts in new contexts
- **Time required to complete activity:** 30–45 minutes
- **Activity type:** Group activity

## Your task

You are going to use the Doppler effect to determine your arm speed (the maximum speed you can move your arm).

You will need access to a tone generator and an audio analysis program (see below for links). You will need other devices to operate these such as laptops or smartphones. Alternatively, you could use either a datalogger or a cathode ray oscilloscope if your school has them.

### Tone generator

- Web-based: Online Tone Generator (https://onlinetonegenerator.com)
- Apps:
  - Phyphox (https://phyphox.org)

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- Physics Toolbox Sensor Suite (https://apps.apple.com/us/app/physics-toolbox-sensor-suite/id1128914250)

Or, you could use a simple buzzer or toy that makes a continuous sound (remember it has to be a constant tone).

## Audio analysis program

- Audacity (https://www.audacityteam.org)

Write down how fast you expect the speed of your arm to be. Express this as m $s^{-1}$.

Set a frequency, $f$, of 600–900 Hz in the tone generator and make sure the volume is high enough for the computer to record the sound.

Open the audio analysis program on the computer. Holding one arm as far as you can from the computer, hit the record button in the audio analysis program with your other hand. Then move the tone generator as quickly as you can towards the microphone on the computer. This will record the tone being generated as the tone generator approaches the computer.

Consider how you can gather the best data possible. What are the sources of error or uncertainty in your data collection methodology?

Repeat the experiment and save the audio file.

Determine the observed frequency, $f'$, of the wave. Then use the following equation to determine your arm speed:

$$u_{\mathrm{s}} = v\left(1 - \frac{f}{f'}\right)$$

where:

- $u_{\mathrm{s}}$ is your arm speed
- $v$ is the speed of sound in air (342 m $s^{-1}$)
- $f$ is the frequency of the tone generator
- $f'$ is the frequency observed by the audio analysis program

**Figure 1** shows a screenshot from the Audacity program.

Student view

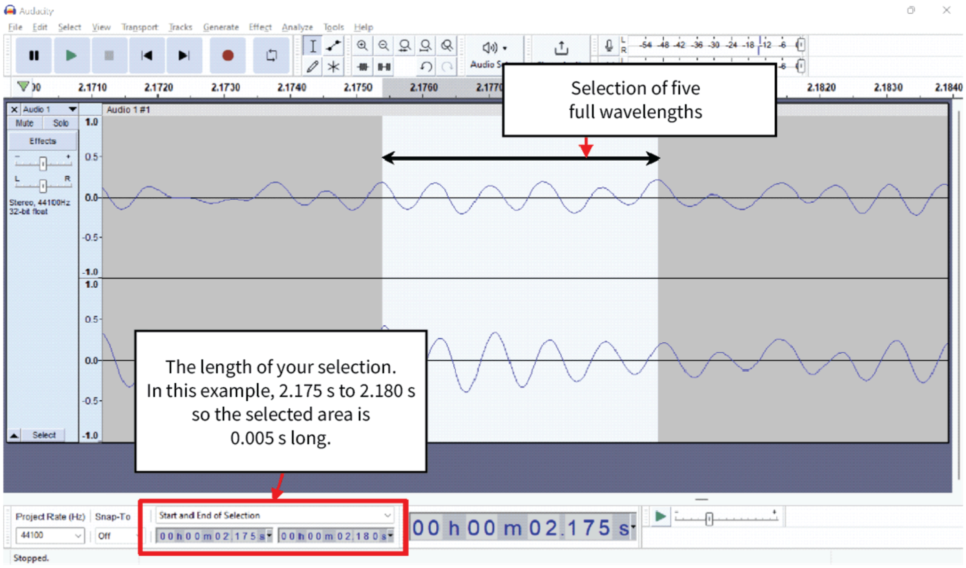


**Figure 1.** Screenshot from Audacity.

The original frequency, $f$, of the tone generator was 942 Hz.

**In Figure 1**, there are five full wavelengths in 0.005 s. This means that the observed frequency, $f'$, is:

$$\begin{aligned} f' &= \frac{5}{0.005} \\ &= 1000 \text{ Hz} \end{aligned}$$

$$\begin{aligned} u_s &= v\left(1 - \frac{f}{f'}\right) \\ &= 342 \times \left(1 - \frac{942}{1000}\right) \\ &= 19.8 \text{ m s}^{-1} \end{aligned}$$

Once you have calculated your arm speed:

- Compare the estimated value of arm speed to the calculated value. How accurate do you think the calculated value is?
- What do you think are the measurement errors in the measured values?
- What are the limitations of this method of determining arm speed?

C. Wave behaviour / C.5 Doppler effect

# Reflection

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Section Student... (0/0) Feedback Print (/study/app/math-aa-hl/sid-423-cid-762593/book/reflection-id-47881/print/) Assign

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## Teacher instructions

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

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

## Reflection

Now that you've completed this subtopic, let's come back to the guiding questions introduced in The big picture (/study/app/math-aa-hl/sid-423-cid-762593/book/the-big-picture-id-45337/).

- How can the Doppler effect be explained both qualitatively and quantitatively?
- What are some practical applications of the Doppler effect?
- Why are there differences when applying the Doppler effect to different types of waves?

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

You can use the following questions to guide you:

- What main points have you learned from this subtopic?
- Is anything unclear? What questions do you still have?
- How confident do you feel in answering the guiding questions?
- What connections do you see between this subtopic and other parts of the course?

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

0/2000

Submit

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## Rate subtopic C.5 Doppler effect

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