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A Level Physics Summer Independent Learning Activity

Welcome to A Level Physics, please complete the following tasks ready for your first day at New College. You can either write on the document electronically, print the document out or write your notes and answers on paper to bring in for your first lesson in September.

The activity is split into 4 sections:

TASK 1: GCSE Waves Review

TASK 2: GCSE Waves Exam Questions

TASK 3: A Level Waves Introduction

TASK 4: A Level Waves Exam Questions

Task 5: Articles to read (this is optional and will **not** form part of the assessment)

Mark Schemes to the questions are found at the back of the document

Please be aware that you will have an **assessment** on these topics shortly after beginning your A level Physics course and the knowledge covered is essential to understanding the subsequent content.

TASK 1: GCSE Waves Review

Part 1. Read through the Bitesize pages on Progressive waves.
https://www.bbc.co.uk/bitesize/guides/zgf97p3/revision/1

Part 2. Read through the notes on Longitudinal and Transverse waves.
https://www.bbc.co.uk/bitesize/guides/z9bw6yc/revision/1

Part 3. Complete the notes on wave basics

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Wave Basics

All waves transfer ____

Waves are created by

____

There are two types of waves; transverse and longitudinal.

In a transverse wave the oscillations are ________________to the direction that the wave travels in.

In a longitudinal wave the oscillations are _________________ to the direction that the wave travels in.

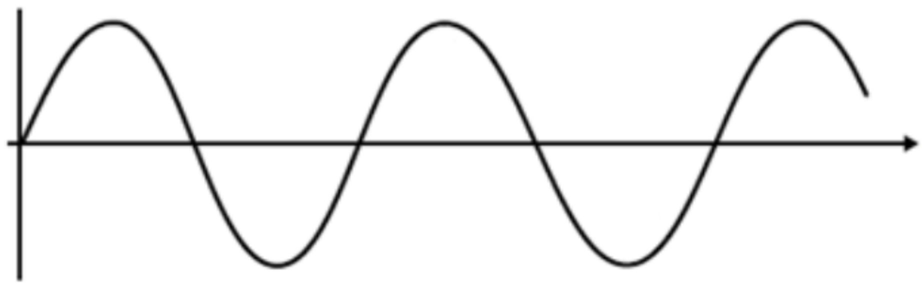
Examples of transverse waves are ____

____

Examples of longitudinal waves are ____

____

The diagram below is an example of a ____ wave.



The diagram below is an example of a ____ wave.

What do the following terms mean? Add them to the appropriate diagram above (if possible).

Peak ____

Trough ____

Compression ____

Rarefaction ____

Wavelength ____

Amplitude ____

Frequency ____

Wave speed ____

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$$v = f \times \lambda$$

Symbol	Quantity	Units	Unit Symbol
v			
f			
λ			

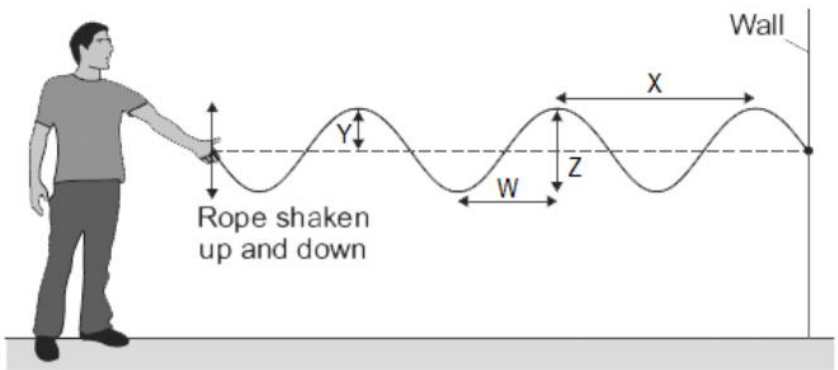
Complete this table by calculating the missing values.

v	f	λ
	3	1.2
	8	0.015
336		0.8
40		0.8
340	850	
300 000 000	500 000 000	

The diagram shows waves being produced on a rope. The waves are not reflected by the wall. Draw an arrow on the diagram to show the direction in which the waves transfer energy. Which of the labelled arrows show the:

Amplitude? ___________

Wavelength? ___________



State which type of wave is shown in the diagram and explain how you can tell?

____

____

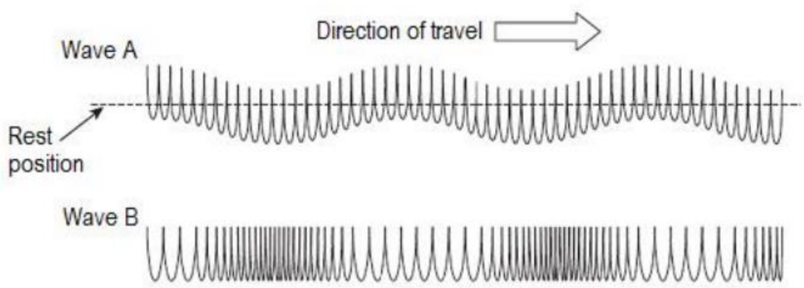
The diagram shows two ways in which a wave can travel along a slinky spring. Clearly indicate and label the wavelength of Wave A and Wave B

Which a longitudinal wave?

____

Which is a transverse wave?

____



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Complete the table by writing the initials of the waves of the EM spectrum and colours of the visible section into the correct boxes.

	X		Visible Light									R
						G	Y					

As we go from left to right in the table above the wavelength of the waves

____

As we go from left to right in the table above the frequency of the waves

____

As we go from left to right in the table above the energy of the waves

____

As we go from left to right in the table above the speed of the waves

____

Circle the correct values for the range of wavelengths of the electromagnetic spectrum.

The longest EM wavelength is around				The shortest EM wavelength is around			
10^{15} m	10^{4} m	10 m	10^{-6} m	10^{6} m	10 m	10^{-4} m	10^{-15} m

Use	EM Wave	Use	EM Wave
Sending a text from a mobile phone		To sterilise surgical equipment	
Taking a photograph of a tree		A medical tracer injected into a patient	
Killing cancerous cells inside a patient		Security ink used to mark your property	
Turning off a television with a remote control		Producing shadow images of bones	
Broadcasting a movie by satellite		Broadcasting a local radio show	
In sunbeds to give a sun tan		Turning a piece of bread into toast	
Taking a thermal photograph of a human		Cooking food in a microwave oven	

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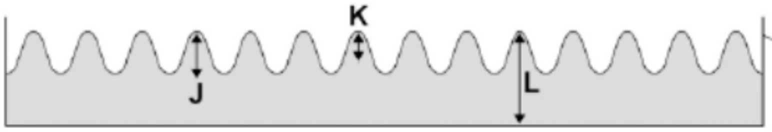
TASK 2: GCSE Waves Exam Questions.   Wave Basics

Q1. Small water waves are created in a ripple tank by a wooden bar. The wooden bar vibrates up and down hitting the surface of the water.

The figure below shows a cross-section of the ripple tank and water.



Q1(a) Which letter shows the amplitude of a water wave? Tick **one** box.

J ☐

K ☐

L ☐

(1)

Q1(b) The speed of the wooden bar is changed so that the bar hits the water fewer times each second.
What happens to the frequency of the waves produced? Tick one box.

Increases ☐

Does not change ☐

Decreases ☐

(1)

Q1(c) Describe how the wavelength of the water waves in a ripple tank can be measured accurately.

....

....

....

....

.... **(2)**

Q1(d) The water waves in a ripple tank have a wavelength of 1.2 cm and a frequency of 18.5 Hz.
How does the speed of these water waves compare to the typical speed of a person walking?

....

....

....

....

(4)

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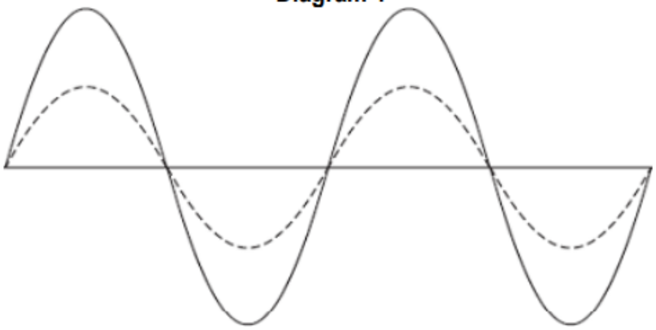
Q2(a) **Diagram 1** shows two waves.

Diagram 1



Q2(ai) Name **one** wave quantity that is the same for the two waves.

.... **(1)**

Q2(aii) Name **one** wave quantity that is different for the two waves.

.... **(1)**

Q2(aiii) The waves in **Diagram 1** are transverse.

Which **one** of the following types of wave is **not** a transverse wave?

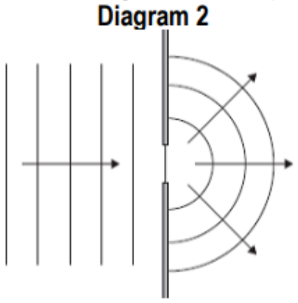
Draw a ring around the correct answer.

gamma rays **sound** **visible light**

(1)

Q2(b) **Diagram 2** shows water waves in a ripple tank moving towards and passing through a gap in a barrier.

Diagram 2



Every second, 8 waves pass through the gap in the barrier. The waves have a wavelength of 0.015 metres.

Calculate the speed of the water waves and give the unit.

....

....

....

Speed = ... **(3)**

Q2(c) Bats use the reflection of high pitched sound waves to determine the position of objects.
State the name given to reflected sound waves.

.... **(1)**

Q2(d) The bat emits a sound wave with a frequency of 25.0 kHz and a wavelength of 0.0136 metres.
Calculate the speed of this sound wave.

....

....

....

Speed = ... m/s **(2)**

Q2(e) Sound waves are longitudinal. Describe a longitudinal sound wave.

....

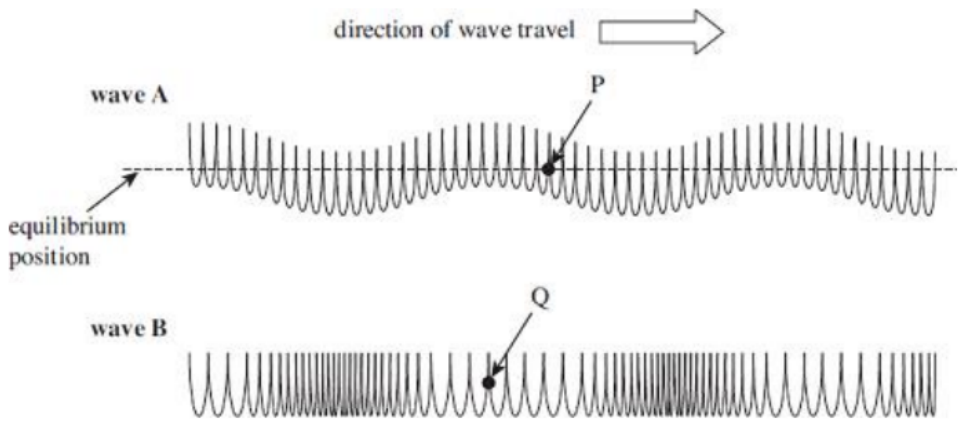
....

....

.... **(2)**

(Total 11 marks)

Q3. The figure below shows two ways in which a wave can travel along a slinky spring.



Q3(a) State and explain which wave is longitudinal.

....

....

.... **(2)**

Q3(b) On the figure above,

Q3(bi) clearly indicate and label the wavelength of **wave B** **(1)**

Q3(bii) use arrows to show the direction in which the points **P** and **Q** are about to move as each wave moves to the right. **(2)**

Q3(ci) State the difference between a longitudinal wave and a transverse wave.

....

....

....

.... **(2)**

Q3(cii) State an example of a transverse wave.

.... **(1)**

Q3(ciii) State an example of a longitudinal wave.

.... **(1)**

Q3(e) Sound with a frequency of 560 Hz travels through steel with a speed of 4800 m/s.
Calculate the wavelength of the sound wave.

....

....

.... **(2)**

(Total 11 marks)

The EM Spectrum

Q4. **Diagram 1** shows four of the seven types of wave in the electromagnetic spectrum.

Diagram 1

J	**K**	**L**	Visible light	Infrared	Microwaves	Radio waves

Q4(a) The **four** types of electromagnetic wave named in **Diagram 1** above are used for communication.

Q4(ai) Which type of electromagnetic wave is used when a traffic signal communicates with a car driver?

.... **(1)**

Q4(aii) Which type of electromagnetic wave is used to communicate with a satellite in space?

.... **(1)**

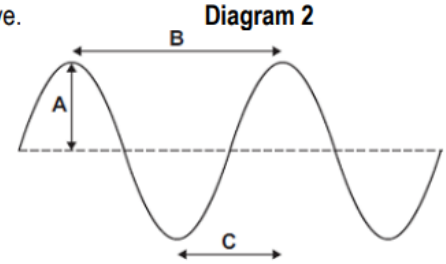
Q4(b) Gamma rays are part of the electromagnetic spectrum.
Which letter, **J**, **K** or **L**, shows the position of gamma rays in the electromagnetic spectrum?
Draw a ring around the correct answer.

J **K** **L**

(1)

Q4(c) **Diagram 2** shows an infrared wave.

Diagram 2



Q4(ci) Which **one** of the arrows, labelled **A**, **B** or **C**, shows the wavelength of the wave?

Write the correct answer, **A**, **B** or **C**, in the box. ☐

(1)

Q4(cii) Draw a ring around the correct answer to complete the sentence.

The wavelength of infrared waves is [shorter than / the same as / longer than] the wavelength of radio waves.

(1)

Q4(d) Mobile phone networks send signals using microwaves. Some people think the energy a person's head absorbs when using a mobile phone may be harmful to health.

Q4(di) Scientists have compared the health of people who use mobile phones with the health of people who do not use mobile phones. Which **one** of the following statements gives a reason why scientists have done this? Tick (✓) **one** box.

To find out if using a mobile phone is harmful to health. ☐

To find out if mobile phones give out radiation. ☐

To find out why some people are healthy. ☐

(1)

Q4(dii) The table gives the specific absorption rate (SAR) value for two different mobile phones.

The SAR value is a measure of the maximum energy a person's head absorbs when a mobile phone is used.

Mobile Phone	SAR value in W/kg
X	0.28
Y	1.35

A parent buys mobile phone **X** for her daughter.
Using the information in the table, suggest why buying mobile phone **X** was the best choice.

....

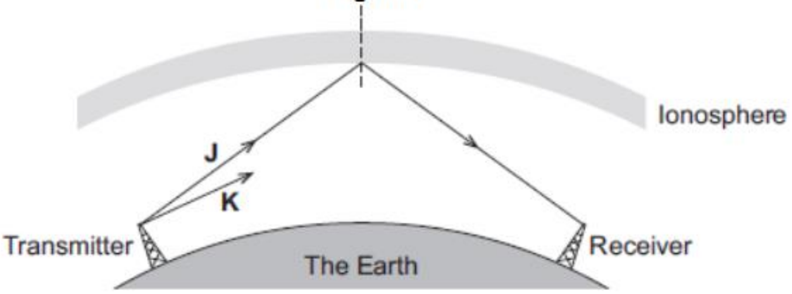
....

.... **(2)**

Q4(e) Different parts of the electromagnetic spectrum are useful for different methods of communication.

Figure 1 shows a transmitter emitting two electromagnetic waves, **J** and **K**.

Figure 1



Wave **J** is reflected by a layer in the atmosphere called the ionosphere.

Q4(ei) Wave **K** will also be reflected by the ionosphere.

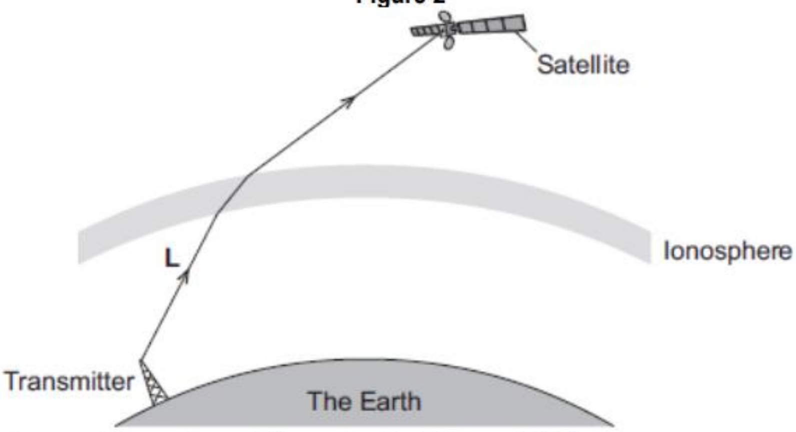
On **Figure 1**, draw the path of wave **K** to show that it **does not** reach the receiver. **(2)**

Q4(eii) What is the name given to the dashed line in **Figure 1**?

.... **(1)**

Q4(f) **Figure 2** shows a transmitter sending a signal to a satellite orbiting the Earth.

Figure 2



Q4(fi) Which type of electromagnetic wave is used to send a signal to a satellite?
Draw a ring around the correct answer.

gamma **microwave** **ultraviolet**

(1)

Q4(fii) What name is given to the process that occurs as wave **L** passes into the ionosphere?
Draw a ring around the correct answer.

diffraction **reflection** **refraction**

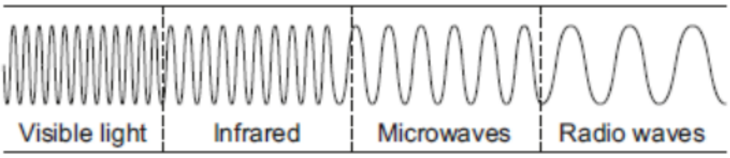
(1)

Q4(g) Waves **J**, **K** and **L** are electromagnetic waves.
What are **two** properties of **all** electromagnetic waves? Tick (✓) **two** boxes.

Property	**Tick (✓)**
All electromagnetic waves are longitudinal.	
All electromagnetic waves are transverse.	
All electromagnetic waves are mechanical.	
All electromagnetic waves have the same speed in a vacuum.	
All electromagnetic waves have the same frequency.	

(2)
(Total 15 marks)

Q5. Infrared and microwaves are two types of electromagnetic radiation.
The diagram below shows the positions of the two types of radiation within part of the electromagnetic spectrum.



Q5(a) Name **one** type of electromagnetic radiation which has more energy than infrared.

.... **(1)**

Q5(b) Use the correct answer from the box to complete each sentence.
Each answer may be used once, more than once or not at all.

greater than	less than	the same as

The wavelength of infrared is .... the wavelength of microwaves.

The frequency of microwaves is .... the frequency of infrared.

The speed of microwaves in a vacuum is .... the speed of infrared in a vacuum. **(3)**

Q5(c) Some scientists think that there is a link between using a mobile phone and some types of illness. Other scientists disagree. They say that the evidence is limited and unreliable.

Q5(ci) Suggest what scientists could do to show a link between using a mobile phone and illness.

....

.... **(1)**

Q5(cii) How could scientists improve the reliability of the evidence?

....

.... **(1)**

Q5(ciii) Complete the following passage by drawing a ring around the word in the box that is correct.
There has been little or no experimental research into the health of children who use mobile phones.

This is partly because of the [economic / environmental / ethical] issues involved in using children in scientific research.

(1)

Q5(d) Before being sold, new mobile phones must be tested and given a SAR value.
The SAR value is a measure of the energy absorbed by the head while a mobile phone is being used.
The table gives the SAR value for three mobile phones made by different companies.
To be sold in the UK, a mobile phone must have a SAR value lower than 2.0 W/kg.

Mobile phone	SAR value in W/kg
J	0.18
K	0.86
L	1.40

Q5(di) All companies use the same test to measure a SAR value.
Why is using the same test important?

....

.... **(1)**

Q5(dii) Would the companies that make the mobile phones, **J**, **K** and **L**, be correct to claim that these three phones are totally safe to use?

Answer yes or no. ....

Give a reason for your answer.

....

.... **(1)**

Q5(e) Devices designed to protect a mobile phone user from microwave radiation are now available.
Why is it important that these devices are tested by scientists who are **not** working for the company that makes the devices?

....

.... **(1)**

(Total 10 marks)

Q6(a) Microwaves and visible light are two types of electromagnetic wave. Both can be used for communications.

Q6(ai) Give **two** properties that are common to both visible light and microwaves.

....

....

.... **(2)**

Q6(aii) Name **two** more types of electromagnetic wave that can be used for communications.

.... and .... **(1)**

Q6(b) Wi-Fi is a system that joins computers to the internet without using wires. Microwaves, with a wavelength of 12.5 cm, are used to link a computer to a device called a router. Microwaves travel through the air at 300 000 000 m/s.
Calculate the frequency of the microwaves used to link the computer to the router.
Show clearly how you work out your answer and give the unit.

....

....

....

Frequency = ... **(3)**

Q6(c) Wi-Fi is used widely in schools. However, not everyone thinks that this is a good idea.
A politician commented on the increasing use of WiFi. He said: 'I believe that these systems may be harmful to children.'
However, one group of scientists said that there is no reason why Wi-Fi should not be used in schools. These scientists also suggested that there is a need for further research.

Q6(ci) Suggest what the politician could have done to persuade people that what he said was not just an opinion.

....

.... **(1)**

Q6(cii) Why did the group of scientists suggest that there is a need for further research?

....

.... **(1)**

(Total 8 marks)

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TASK 3: A Level Waves Introduction Part 1.

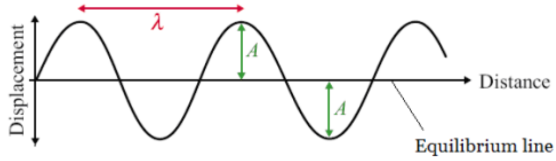
Read through the notes on Progressive waves and then watch and make extra notes on the video linked below – '14 – Progressive Waves': https://www.youtube.com/watch?v=MngDwyyrPpw

Part 2. Read through the notes on Longitudinal and Transverse waves and then watch and make extra notes on the video linked below – `15 – Longitudinal and Transverse waves': https://www.youtube.com/watch?v=mP2xDykybPE

Both tasks, 1 and 2, should take a minimum of 1 hour each. You will be tested on the content in September so pause / rewind / repeat the video as many time as you need to ensure you know the content.

1 - Progressive Waves

Waves



All waves are caused by oscillations and all transfer energy without transferring matter. This means that a water wave can transfer energy to you sitting on the shore without the water particles far out to sea moving to the beach.

Here is a diagram of a wave; it is one type of wave called a transverse wave. A wave consists of something (usually particles) oscillating from an equilibrium point. The wave can be described as progressive; this means it is moving outwards from the source.

We will now look at some basic measurements and characteristics of waves.

Amplitude, A, **measured in metres, m**

The amplitude of a wave is the maximum displacement of the particles from the equilibrium position.

Wavelength, λ, **measured in metres, m**

The wavelength of a wave is the minimum distance between 2 points which are in phase. It can be measured between two adjacent peaks, troughs or any point on a wave and the same point one wave later.

Time Period, T, **measured in seconds, s**

This is simply the time is takes for one complete oscillation to happen. Like wavelength it can be measured as the time it takes between two adjacent peaks, troughs or to get back to the same point on the wave.

Frequency, f , **measured in Hertz, Hz**

Frequency is a measure of how often something happens, in this case how many complete waves occur in every second. It is linked to time period of the wave by the following equations: $T = \frac{1}{f}$ and $\boxed{f = \frac{1}{T}}$

Wave Speed, c, **measured in metres per second, m s^{-1}**

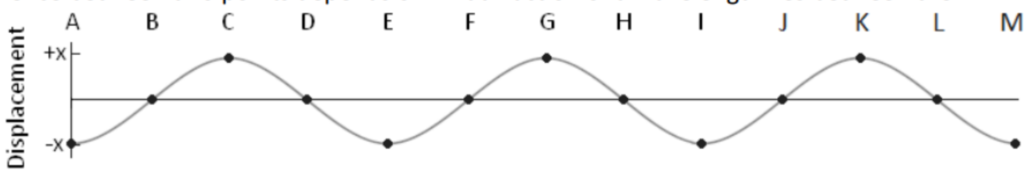
The speed of a wave can be calculated using the following equations: $\boxed{c = f\lambda}$

Here c represents the speed of the wave, f the frequency and λ the wavelength.

Phase Difference **is measured in degrees, °**

If we look at two particles a wavelength apart (such as C and G) we would see that they are oscillating in time with each other. We say that they are *completely in phase*. Two points half a wavelength apart (such as I and K) we would see that they are always moving in opposite directions. We say that they are *completely out of phase*.

The phase difference between two points depends on what fraction of a wavelength lies between them



	B	C	D	E	F	G	H	I	J	K	L	M
Phase Difference from A (degrees)	90	180	270	360	450	540	630	720	810	900	990	1080

Path Difference **is measured in wavelengths, λ**

If two light waves leave a bulb and hit a screen the difference in how far the waves have travelled is called the path difference. Path difference is measured in terms of wavelengths.

	B	C	D	E	F	G	H	I	J	K	L	M
Path Difference from A	¼λ	½λ	¾λ	1λ	1¼λ	1½λ	1¾λ	2λ	2¼λ	2½λ	2¾λ	3λ

So two waves leaving A with one making it to F and the other to J will have a path difference of 1 wavelength (1λ).

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My notes on Progressive Waves	
Questions (2. After writing your notes, what questions could you be asked?)	My notes (1. write your notes here)

Summary (definitions I must learn, key ideas I must remember).

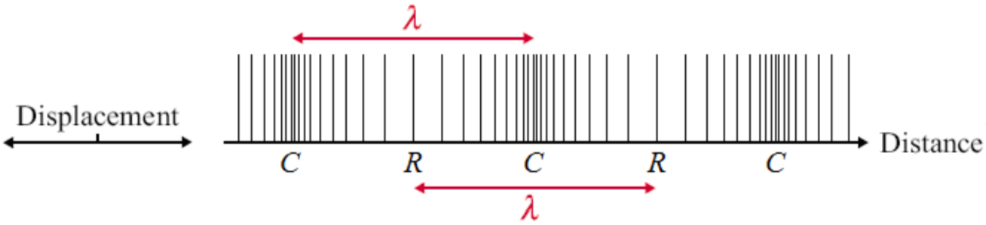
2 - Longitudinal and Transverse waves.

Waves

All waves are caused by oscillations and all transfer energy without transferring matter. This means that a sound wave can transfer energy to your eardrum from a far speaker without the air particles by the speaker moving into your ear. We will now look at the two types of waves and how they are different

Longitudinal Waves

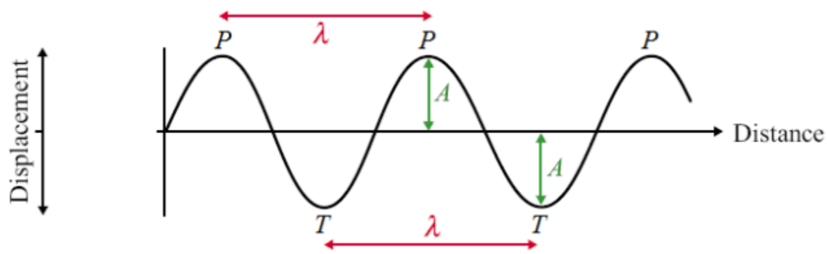
Here is a longitudinal wave; the oscillations are parallel to the direction of propagation (travel).
Where the particles are close together we call a compression and where they are spread we call a rarefaction.
The wavelength is the distance from one compression or rarefaction to the next.
The amplitude is the maximum distance the particle moves from its equilibrium position to the right of left.



Example: sound waves

Transverse Waves

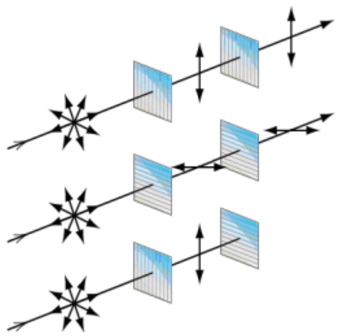
Here is a transverse wave; the oscillations are perpendicular to the direction of propagation.
Where the particles are displaced above the equilibrium position we call a peak and below we call a trough.
The wavelength is the distance from one peak or trough to the next.
The amplitude is the maximum distance the particle moves from its equilibrium position up or down.



Examples: water waves,Mexican waves and waves of the EM spectrum

EM waves are produced from varying electric and magnetic field.

Polarisation Polarisation restricts the oscillations of a wave to one plane. In the diagrams the light is initially oscillating in all directions. A piece of Polaroid only allows light to oscillate in the same direction as it.



- In the top diagram the light passes through a vertical plane Polaroid and becomes polarized in the vertical plane. This can then pass through the second vertical Polaroid.
- In the middle diagram the light becomes polarized in the horizontal plane.
- In the bottom diagram the light becomes vertically polarized but this cannot pass through a horizontal plane Polaroid.

This is proof that the waves of the EM spectrum are transverse waves. If they were longitudinal waves the forwards and backwards motion would not be stopped by crossed pieces of Polaroid; the bottom set up would emit light.

Applications

TV aerials get the best reception when they point to the transmission source so they absorb the maximum amount of the radio waves.

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My notes on Longitudinal and Transverse Waves	
Questions (2. After writing your notes, what questions could you be asked?)	My notes (1. write your notes here)

Summary (definitions I must learn, key ideas I must remember).

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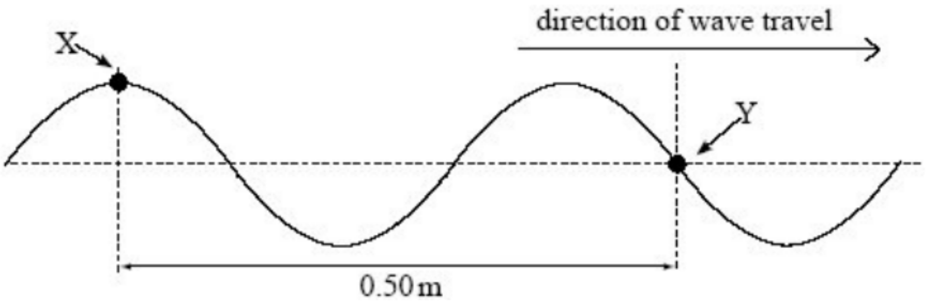
TASK 4: A Level Waves Exam Questions

Q1. Complete the first column in the table to show which of the waves listed are transverse and which are longitudinal.
Complete the second column to show which waves can be polarised.

type of wave	transverse or longitudinal	can be polarised (answer yes or no)
light		
microwaves		
ultrasound		

(Total 3 marks)

Q2. (a) The diagram below represents a progressive wave travelling from left to right on a stretched string.



(i) Calculate the wavelength of the wave.

answer .... m
(1)

(ii) The frequency of the wave is 22 Hz. Calculate the speed of the wave.

answer............................m s^{-1}
(2)

(iii) State the phase difference between points X and Y on the string, giving an appropriate unit.

answer ....

(2)

(b) Describe how the displacement of point Y on the string varies in the next half-period.

....

....

....

....

....

....

(2)

(Total 7 marks)

Q3.(a) State the difference between *transverse* and *longitudinal* waves.

....

....

....

....

(2)

(b) State what is meant by *polarisation*.

....

....

....

....

(2)

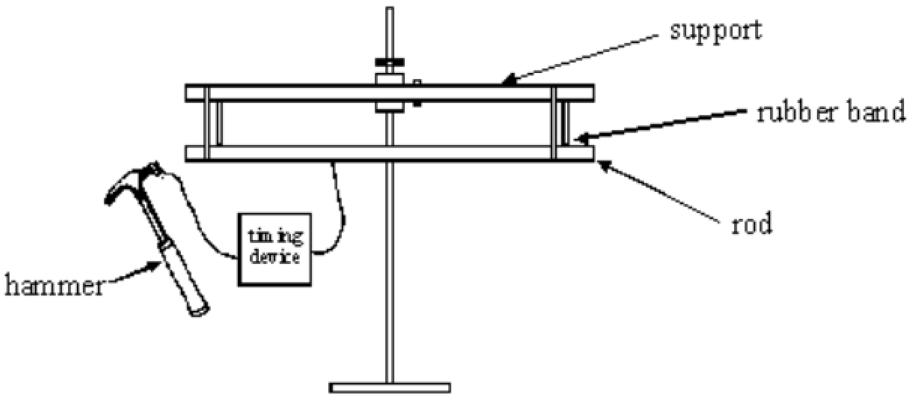
(c) Explain why polarisation can be used to distinguish between transverse and longitudinal waves.

....

....

(2)

Q4. The diagram below shows a hammer being struck against the end of a horizontal metal rod. A pulse of sound travels along the rod from where the hammer strikes it to the far end and back again. The sound pulse throws the hammer and rod apart when it returns. An electrical timing circuit measures the time for which the hammer and the rod are in contact.



(a) Circle the word below that describes the type of wave that travels along the rod.

transverse **longitudinal**

(1)

(b) State the name of the effect that causes the sound pulse to return to the hammer.

....

(1)

(c) The rod is 0.45 m long and the time for which the hammer is in contact with the rod is 1.6×10^{-4} s. Calculate the speed of sound in the rod.

Speed of sound ....

(3)
(Total 5 marks)

Q5. The least distance between two points of a progressive transverse wave which have a phase difference of 60° (or $\frac{\pi}{3}$ rad) is 0.050 m. If the frequency of the wave is 500 Hz, what is the speed of the wave?

A 25 m s^{-1}

B 75 m s^{-1}

C 150 m s^{-1}

D 1666 m s^{-1}

(Total 1 mark)

Q6. By approximately how many times is the wavelength of audible sound waves greater than the wavelength of light waves?

A 10^2

B 10^6

C 10^{10}

D 10^{14}

(Total 1 mark)

Q7. The speed of sound in water is 1500 m s^{-1}. For a sound wave in water having frequency 2500 Hz, what is the minimum distance between two points at which the vibrations are 60° out of phase?

A 0.05 m

B 0.10 m

C 0.15 m

D 0.20 m

(Total 1 mark)

Q8. Which one of the following types of wave **cannot** be polarised?

A radio

B ultraviolet

C microwave

D ultrasonic

(Total 1 mark)

Q9. A wave of frequency 5 Hz travels at 8 km s^{-1} through a medium.

What is the phase difference, in radians, between two points 2 km apart?

A 0°

B $\frac{\pi}{2}$ or 90°

C π or 180°

D $\frac{3\pi}{2}$ or 270°

(Total 1 mark)

TASK 5: Articles to Read (Optional)

Structural colour

Mike Follows

We perceive colour all around us, and animals use it to attract mates or warn off predators. Mike Follows explains how colour can be produced without chemical pigments

EXAM LINKS

The terms in bold link to topics in the AQA, Edexcel, OCR, WJEC and CCEA A-level specifications, as well as the IB, Pre-U and SQA exam specifications.

Structural colours are produced by **superposition** and **interference** when **light waves** undergo multiple **reflection**.

Colours are associated with different wavelengths of visible light. Some colours are due to *pigments* that absorb light at particular wavelengths. For example, a substance impregnated with a pigment that absorbs blue light will look yellow when illuminated with white light, because white minus blue gives yellow. Bioluminescent creatures such as fireflies, on the other hand, emit light due to a *chemical reaction*.

But most of the colour we see is *structural colour*, produced when light interacts with microscopic particles or microstructures. This interaction can include scattering, dispersion, diffraction and interference. Diffraction gratings, thin films or multilayers (of thin films) and other structures that repeat themselves can give rise to colours that change depending on the viewing angle. This is called *iridescence*. Because there is none of the absorption of light associated with pigments, structural colours can be startlingly vivid.

Structural colour was discovered by Robert Hooke. In his 1665 book *Micrographia* he described the iridescence of a peacock's tail feathers as 'fantastical'. He was astonished that the colours disappeared when he immersed the feathers in water, demonstrating that pigments played no role. Some creatures can change their structural colour. For example, chameleons

can change the spacing between guanine crystals in their skin, which changes the wavelength (and colour) of the light reflected.

New developments in materials technology are bringing us structurally coloured fabrics. The dress shown in Figure 1 is made from Morphotex — a fabric inspired by the morpho butterfly. The colour is produced without chemical dye, and changes subtly with viewing angle.

Structural colours all around us

Scattering of light by particles that are much smaller than the wavelength of light is called Rayleigh scattering (p. 34). The sky is blue because of Rayleigh scattering by air molecules (e.g. nitrogen and oxygen), which scatter blue light more strongly than red. When the Sun is overhead, sunlight passes through the 10 km thickness of the atmosphere. When the Sun is close to the horizon, sunlight has a longer journey through the atmosphere, so more blue light is scattered out of our line of sight to the Sun, which leaves it looking red.

Scattering by particles with sizes comparable to the wavelength of light is known as Mie scattering. Mie scattering by water droplets accounts for the white or grey appearance of clouds. The Lycurgus Cup, a Roman artefact dating from around 400 AD (Figure 2), is another example of structural colour due to Mie scattering from randomly distributed particles. The glass of the cup is dichroic — it is an opaque jade green when it reflects light and a translucent ruby colour when it transmits light. X-ray analysis shows that the light scattering is due to 50–100 μm diameter silver-gold alloy nanoparticles, with the precious metals present in concentrations of around 100 parts per million (ppm). Some Venetian glass gives a brilliant red colour due to scattering from dispersed gold nanoparticles.

Rainbows form when raindrops disperse and reflect light. Dispersion — the separation of white light into its component colours — occurs because higher-frequency light (the blue end of the visible spectrum) is refracted more than low-frequency (red) light. As shown in Figure 3, the light entering the raindrop is dispersed and totally internally reflected at least once off the back surface of the raindrop. It is then refracted again as it leaves the raindrop.

Soap bubbles

The colours of a soap bubble arise because light is reflected from both sides of a thin film. The colour depends on the angle from which a surface is seen.

Imagine a light ray striking the film of soap at normal incidence (i.e. at right angles to the surface) so that both the incident ray and reflected rays are normal to the soap film. Some light reflects off the outer (or top) surface of the film, retracing the path of the incident ray. Of the light transmitted, some reflects off the inner (bottom) surface of the film.

Figure 2 The Lycurgus Cup **(a)** when it reflects light and **(b)** when it transmits light

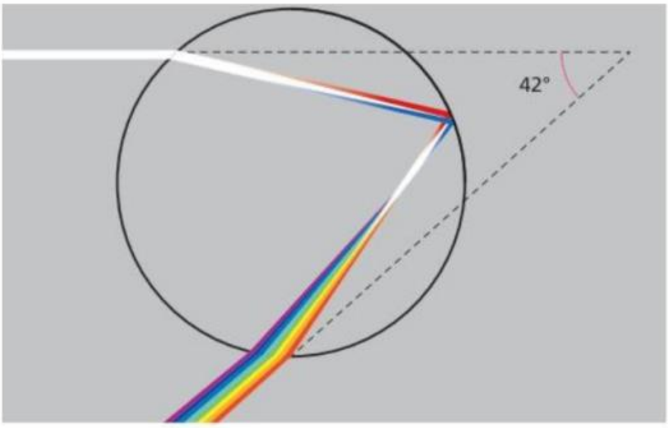


Figure 3 Light that is dispersed and totally internally reflected in a raindrop contributes to a rainbow

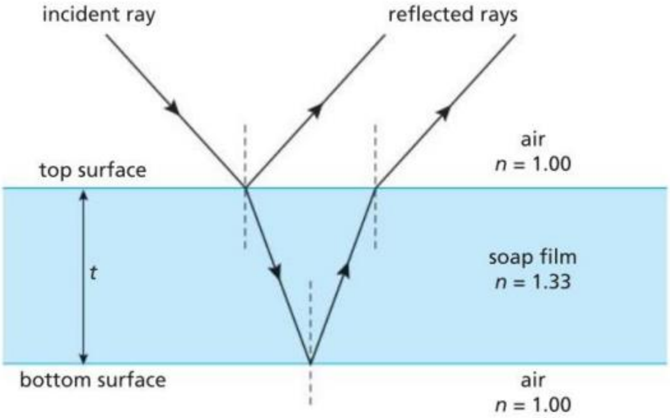


Figure 4 A ray of light reflected off the top and bottom surfaces of a soap film

Figure 4 shows this with not-quite normal incidence, making it easier to see what is going on.

The two reflected rays interfere, as discussed in Box 1. The transmitted ray has travelled an extra distance corresponding to twice the thickness of the film. Ignoring the role of phase shift for a moment, the two reflected rays will constructively interfere when their path difference is an integer (whole) number of wavelengths, so that a crest from one reflected ray coincides with a crest from the other reflected ray:

$$m\lambda = 2nt \qquad (1)$$

where m is an integer, λ is the wavelength, n is the refractive index of the soap film and t is its thickness. Equation 1 shows that the wavelength (and therefore colour) of the reflected light depends on the thickness of the film.

Box 1 Interference

Interference results from the superposition of waves, when two or more waves meet at a given point in space. The displacement at that point is the *algebraic* sum of the individual displacements due to each wave.

Imagine two waves with identical amplitude and frequency. In Figure 1.1a the crest of one wave (solid line) meets the trough from the second wave (dotted line) and we have destructive interference: the sum of a crest and a trough is zero and the two waves are cancelled at that point. In Figure 1.1b the crest from one wave (solid line) meets a crest from a second wave (dotted line). The resultant wave has double the amplitude and we have constructive interference.

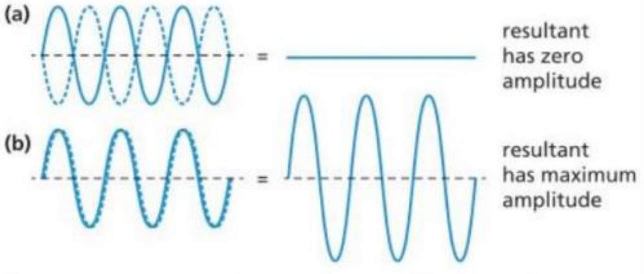


Figure 1.1 **(a)** Destructive interference. **(b)** Constructive interference

A slight complication is that the light reflecting off the top surface of the soap film undergoes a 180° phase shift (so that a crest becomes a trough and vice versa). This happens when any wave encounters a medium of higher refractive index, so the condition for constructive interference requires a slight modification to Equation 1, though the essential physics remains the same:

$$(m - \tfrac{1}{2})\lambda = 2nt \qquad (2)$$

Increasing the thickness increases the wavelength that produces constructive interference, so the colour will change from, say, green to yellow.

Multilayers

Multiple thin films are the most common method for producing vivid, metallic colours in biological systems. The wing casings of many beetles are a good example. Increasing the number of layers leads to more intense colours, but costs more energy because the beetle has to grow more body tissue.

Multilayers can be either narrowband (Figure 5a) or broadband (Figure 5b). For simplicity, refraction at the boundaries between layers is not shown. The layers in narrowband multilayers have

A large soap bubble

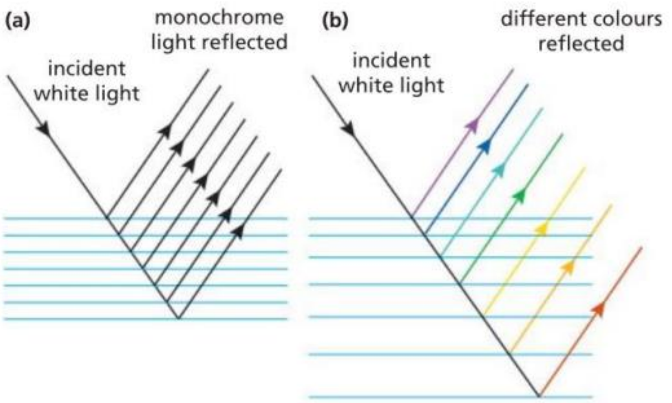


Figure 5 Multilayers: **(a)** narrowband and **(b)** broadband

a uniform thickness and reflect light over a narrow range of wavelengths (and hence colours). If the lowest layer is dark, it absorbs any remaining light, making the reflected colour very vivid. In contrast, the scales of silver-coloured fish have broadband multilayers whose layers vary in thickness. Thick layers reflect red light while thin layers reflect violet, as shown. This means that almost all wavelengths are reflected and, by reflecting virtually all the light in their environment, these fish are much less visible, providing the best possible camouflage in the open ocean, where there is nowhere to hide. Goldfish reflect all colours except the blue end of the spectrum.

Photonic crystals

Sometimes multilayers are referred to as photonic crystals. Natural selection over millions of years has led to photonic crystals with multilayers in one, two and three dimensions, as shown left to right in Figure 6. The diagram shows just two different values of refractive index (represented as two colours) with layers of uniform thickness in all dimensions. Reality is much more complicated and subtle, providing a genuine challenge to researchers attempting to mimic their physical properties, as the following examples illustrate.

Nature's colour tricks: reflecting bowls

Each 100 µm wing scale of the emerald swallowtail butterfly has a honeycomb array of dimples a few micrometres across. These dimples or bowls are lined with a stack of thin films, with eleven layers of protein separated by air, each 75 nm thick. A yellow dot is reflected when light incident along the normal strikes the bottom of each bowl. Two 45° reflections off opposite sides of the bowl result in the retro-reflection of a blue ring, as shown in Figure 7. The result is iridescence, where increasing the viewing angle from 0° to 45° shifts the reflected colour from

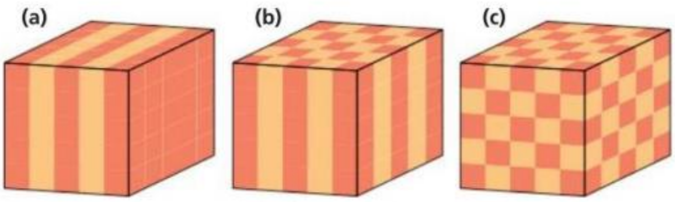
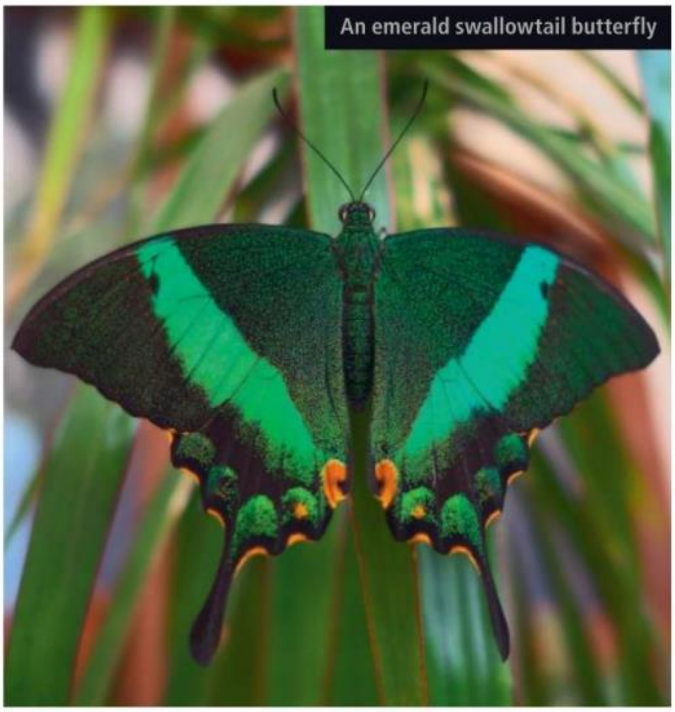


Figure 6 Photonic crystals: **(a)** in one dimension, **(b)** in two dimensions and **(c)** in three dimensions



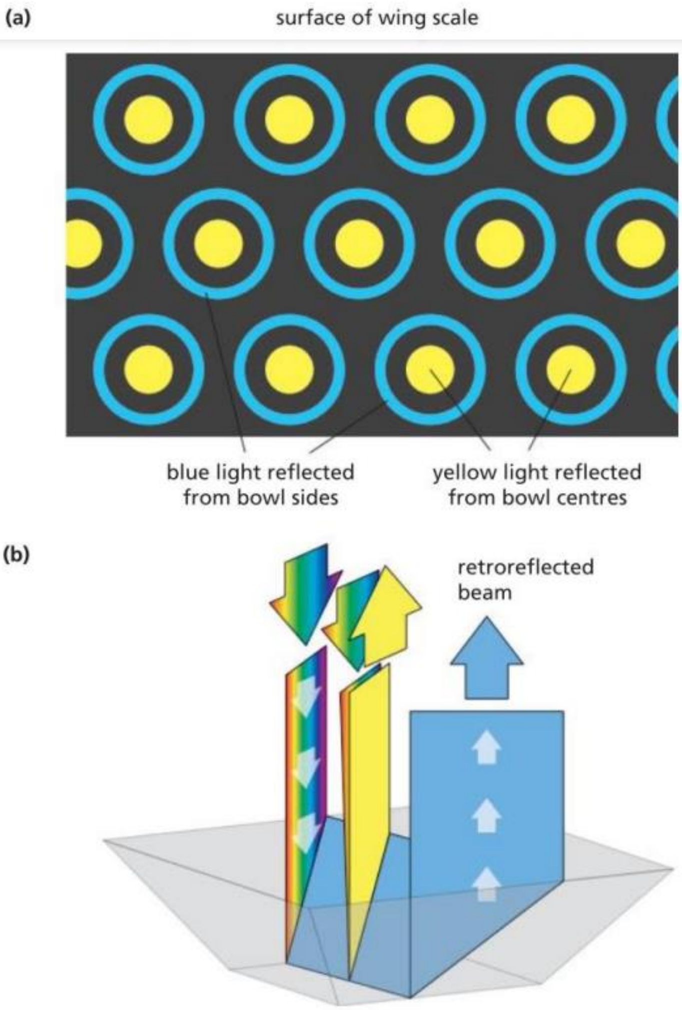


Figure 7 **(a)** The structural colours produced by the honeycomb array on the wing scale of an emerald swallowtail butterfly.
(b) A ray diagram to show what is happening in an individual bowl

The iridescent dogbane leaf beetle

yellow to blue. Our naked eyes are unable to resolve the spots from the rings, so the colours are mixed and we perceive the wing as green.

Each reflection changes the polarisation of light. Seen through crossed polarising filters, the yellow dot disappears, leaving the blue ring. This is how it works. Light is polarised (using a Polaroid filter) and shone onto the wing. The reflection is viewed through another Polaroid (an analyser) held with its plane of polarisation perpendicular to the first Polaroid. The yellow light cannot pass through the analyser but the blue light can because its plane of polarisation is rotated through 45° both times it is reflected off the side of the bowl, so that its plane of polarisation is parallel to that of the analyser. (See At a glance, Physics Review Vol. 28, No. 4, pp. 16–17.) This would be difficult to counterfeit, so a team at Georgia Institute of Technology in the USA is trying to mimic this structure for use on bank notes.

Morpho butterflies: living jewels

The dorsal (top) side of a male morpho butterfly's wings are an iridescent cobalt blue (Figure 8a) and can be seen from several hundred metres. Closing the wings hides the dazzling display from potential predators. This is the butterfly that gives its name to the Morphotex™ fabric shown in Figure 1.

Each morpho wing scale is composed of photonic crystals, typically 5 μm across. Each crystal is composed of a microscopic 'Christmas tree' protein structure (Figure 8b). It is difficult to model mathematically how light interacts with each crystal but, if each branch of the tree acts as a thin film about 110 nm thick, there is a reflectance maximum at 49°. Each crystal has a slightly different orientation, the layers within each crystal are not parallel and the thickness within each layer varies — characteristics referred to as 'fabrication noise' by researchers struggling to replicate the structure and its properties. Scientists are trying to fabricate such tree structures for use as chemical sensors. Wetting the surface would change the ratio of the refractive indices and shift the location of the reflectance maxima.

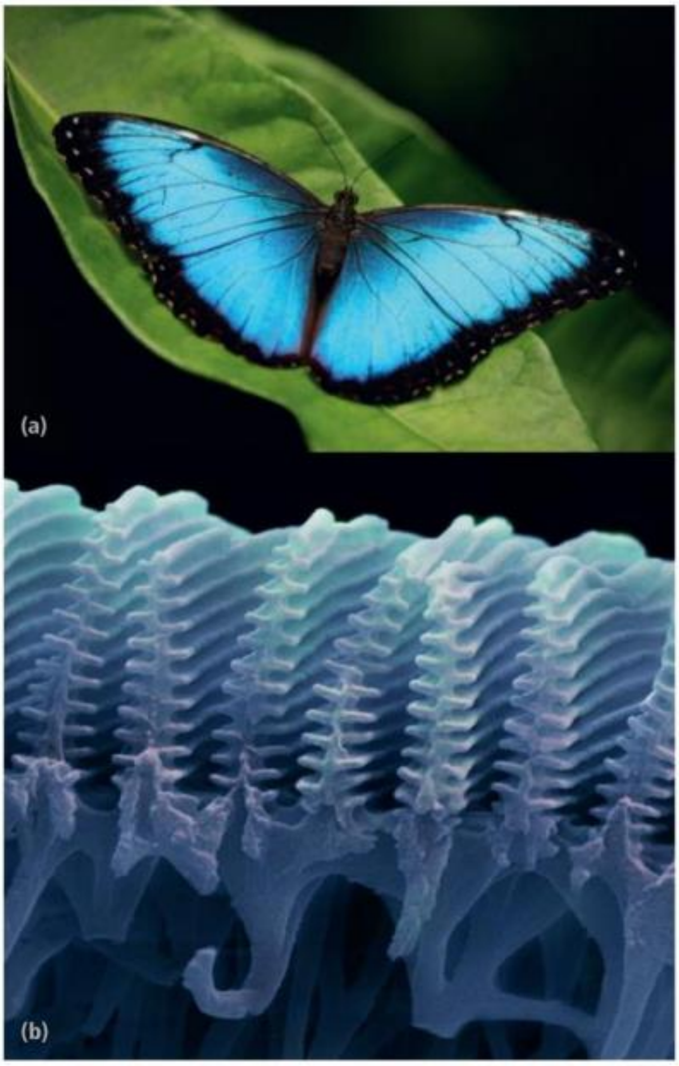


Figure 8 **(a)** The cobalt-blue wings of a morpho butterfly. **(b)** A scanning electron micrograph showing the 'Christmas tree' structure

Final comments

One advantage of new materials designed to have structural colour is that dyes are not used, saving water and energy, and reducing pollution. Structurally coloured clothes are colourfast, so they do not fade with repeated washing or exposure to UV light. Plastics would be much easier to recycle if surface structures replaced chemical pigments — these are under development. So structural colours are not only pleasing to look at, but can also help us address some important environmental issues.

RESOURCES

The photograph in Figure 1 was provided by Donna Sgro, textile designer and lecturer at the University of Technology, Sydney, Australia. See for more information and images.

Mike Follows teaches physics at King Edward's School, Birmingham, and is a keen science author.

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Opening doors to a brighter future

Measuring gravity's effect on time

Peter Main

The faulty launch of a pair of satellites gave an opportunity to measure how gravity affects the passage of time. The results agreed with the predictions of Einstein's theory of general relativity

Exam links

The terms in bold link to topics in the **AQA**, **Edexcel**, **OCR**, **WJEC** and **CCEA** A-level specifications, as well as the **IB**, **Pre-U** and **SQA** exam specifications.

Two satellites in elliptical **orbits** were used to measure **time dilation** in a **gravitational field**.

When things go wrong at the launch of a satellite, they usually go very wrong, leading to the loss of the satellite or rendering it useless for the job it was designed to do. However, the faulty launch of a pair of satellites in 2014 from the European Space Agency (ESA) launch site in French Guiana turned out to be the start of an ambitious and unplanned experiment.

The satellites were destined for the Global Navigational Satellite System, known as the Galileo Project, which is the European equivalent of the American GPS. A frozen fuel line in the fourth stage of the *Soyuz* rocket meant the satellites were launched in the wrong direction, into highly elliptical orbits that were totally unsuitable for their intended purpose. What happened next was a most remarkable recovery of a failed launch which, incidentally, presented an opportunity to test an important feature of Einstein's theory of general relativity.

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Recovery of orbital stability

The satellites were meant to be in the same circular orbit 23 000 km above the Earth's surface but displaced 180° from each other. Instead, they were in a highly elliptical orbit with a closest approach to Earth (perigee) of 13 700 km, rising to a furthest distance (apogee) of 25 900 km. In addition, the orbit was incorrectly inclined to the Earth's equator. There was a substantial list of things to do to determine the actual orbit, reorient antennae to set up robust radio links, bring the satellites under control and make them safe. All this was achieved in about a month, then further action to change the orbit and recover the situation could begin.

The satellites had enough fuel on board for small course corrections during their planned 12-year life span, but that was insufficient to move them into their correct orbit. A recovery plan was devised by a collaboration of space-flight specialists from Germany, France, Italy and Britain. One of the concerns was the lowest orbital height of 13 700 km, exposing the satellites to the harmful radiation of the Van Allen radiation belts (see below). Such intense radiation would degrade the satellites' electronics, leading to premature failure.

The recovery scheme therefore involved a series of manoeuvres, which raised the lowest point of the orbit by more than 3500 km.

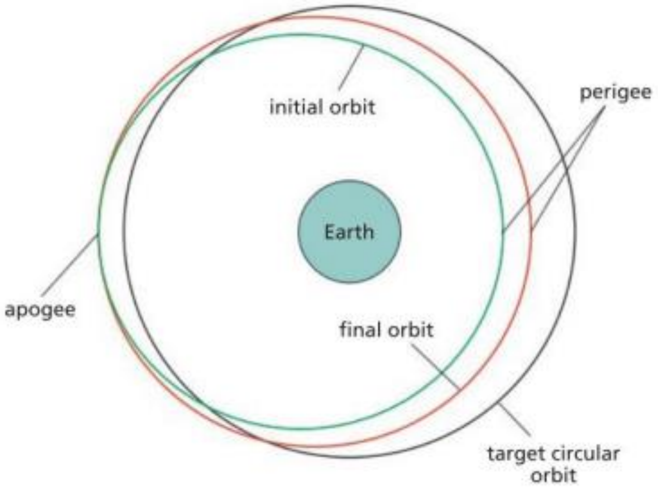

Figure 1 The initial, target and final satellite orbits. The Earth's centre of gravity is at one focus of the elliptical orbits

This greatly reduced the satellites' radiation exposure, ensuring a long-term reliable performance. In addition, the orbit was more circular, which helped the satellites to fit into the Galileo navigational system and gradually positioned them to be 180° from each other round the orbit. It took about 7 months to achieve this.

Figure 1 shows the initial and final orbits of the satellites as well as the desired orbit. Now the satellites were in a position where, with a certain amount of ingenuity, they could be used for their original purpose.

The Van Allen radiation belts

The discovery of the Van Allen radiation belts makes an interesting story. In January 1958, at the height of the Cold War, the USA launched its first Earth satellite, *Explorer 1*. It was 3 months after the Russians had launched their first satellite, *Sputnik 1*, and 2 months after *Sputnik 2* was successfully launched. The Americans were desperate to catch up with the Soviet Union, but they had been held back by launch failures.

James Van Allen of Iowa University was given the urgent job of designing the scientific payload of *Explorer 1*, which he made as basic and as light as possible. In fact, the satellite just contained some temperature sensors, an acoustic sensor and a Geiger counter with a tape recorder, as well as the essential communications equipment. The tape recorder was to record the output of the Geiger counter while the satellite was out of contact with the ground station.

Van Allen was expecting to detect only cosmic rays with the Geiger counter, but instead it recorded a rapid build-up of radiation, and then suddenly nothing. It was thought (and confirmed later) that the radiation was so intense that it had overwhelmed the counter, making it unable to register anything. It is now well known that the Earth is surrounded by radiation belts consisting of energetic charged particles, mostly electrons, captured from the solar wind by the Earth's magnetic field. Although the Americans were second into space, they were the first to make a discovery about the Earth's space environment.

A cross-section of the radiation belts is shown in Figure 2. There are three altogether and they clearly follow the shape of the Earth's magnetic field. Their closest approach to the Earth's surface is near the magnetic poles, where they can interact with the upper atmosphere to give rise to the aurora borealis (northern lights) and aurora australis (southern lights).

The experiment

Now back to the satellites. Because they were designed to be used in a navigational system, they contained atomic clocks, which were highly accurate — to 1 second in about 30 million years, or roughly 0.1 nanoseconds per day (1 nanosecond = 10^{-9} s). Einstein's theory of gravity — his theory of general relativity (Physics Review Vol. 29, No. 3, pp 2–6) — predicts that time progresses at a rate that depends upon the strength of the gravitational field.

The satellites were in an orbit that changed height from about 17 000 km to 26 000 km. Over that distance the acceleration due to Earth's gravity changes by a factor of 1.9. So, according to the theory, from the point of view of an observer on Earth, the clocks in the satellites would run faster at a height of 26 000 km than they would at 17 000 km. The difference in rate, although tiny, should be quite measurable with the instruments onboard. This is known as gravitational time dilation and is the basis of the redshift used by astronomers.

It should be pointed out that there is no doubt about Einstein's theory because it has been used by astronomers and cosmologists for a long time with spectacular success. However, this aspect of the theory — the change in the rate at which time passes — has rarely been measured directly. The last time was over 40 years ago by *Gravity Probe A* (see below). All other applications, such as its successful use in the GPS system, have simply assumed the theory to be correct and accepted its predictions. These satellites in an elliptical orbit therefore presented an unexpected but golden opportunity to test Einstein's theory to a much higher precision than was previously possible. This could only be done because the experiment did not interfere with the normal running of the satellites.

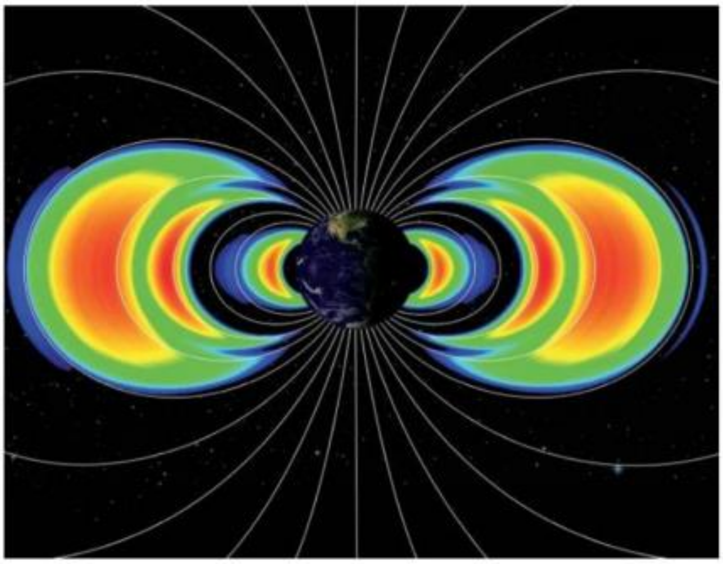

Figure 2 Cross-section of the Van Allen radiation belts superimposed on the Earth's magnetic field lines

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Gravity Probe A

The last occasion when time dilation was measured accurately was in 1976. It was a space-based experiment, carried out by NASA and the Smithsonian Astrophysical Observatory. The space probe, carrying a hydrogen maser, was launched into a suborbital flight lasting just under 2 hours and reaching a height of 10 000 km. A maser is like a laser except that it produces microwaves instead of visible light. The microwaves in this case had an extremely stable frequency, equivalent to a clock that is accurate to 1 second in 50 million years.

The frequency of the microwaves received from the probe was not only altered by time dilation, but also by the Doppler shift caused by the probe moving relative to the ground. After correction for the Doppler shift and an adjustment given by special relativity, the frequency was compared with that produced by an identical maser on the ground. The frequency difference was then compared with that predicted by general relativity. It was found that the maser frequency increased in the weaker gravitational field along the probe's path by an amount predicted by Einstein's theory to a precision of about 100 parts per million — ten times better than the previous determination of the effect.

Procedure and results

To reduce experimental error, it was important to know the position and movement of each of the navigation satellites as accurately as possible. This was done by taking laser-ranging measurements. Each satellite was already fitted with laser retroreflectors, sometimes called corner cube reflectors (Box 1). Their properties mean that a beam of light will always be reflected back to its source, no matter what the angle of incidence might be. Using laser ranging, it became clear that the greatest source of error in predicting the position of the

Box 1 Retroreflectors

A retroreflector is a device that reflects light back to its source, for any direction of incidence. It consists of three mutually perpendicular reflective surfaces, arranged to form the corner of a cube. Figure 1.1 illustrates this and shows two different rays being reflected back along their direction of incidence. Astronauts on the *Apollo 11, 14* and *15* missions left retroreflectors on the Moon as part of the Lunar Laser Ranging Experiment, which measures the distance between Earth and Moon to millimetre precision (Physics Review Vol 18, No. 1, pp. 12–15).

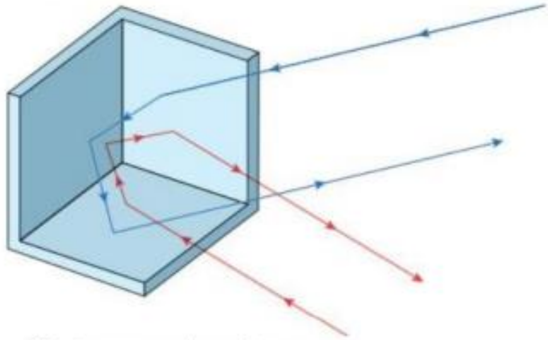
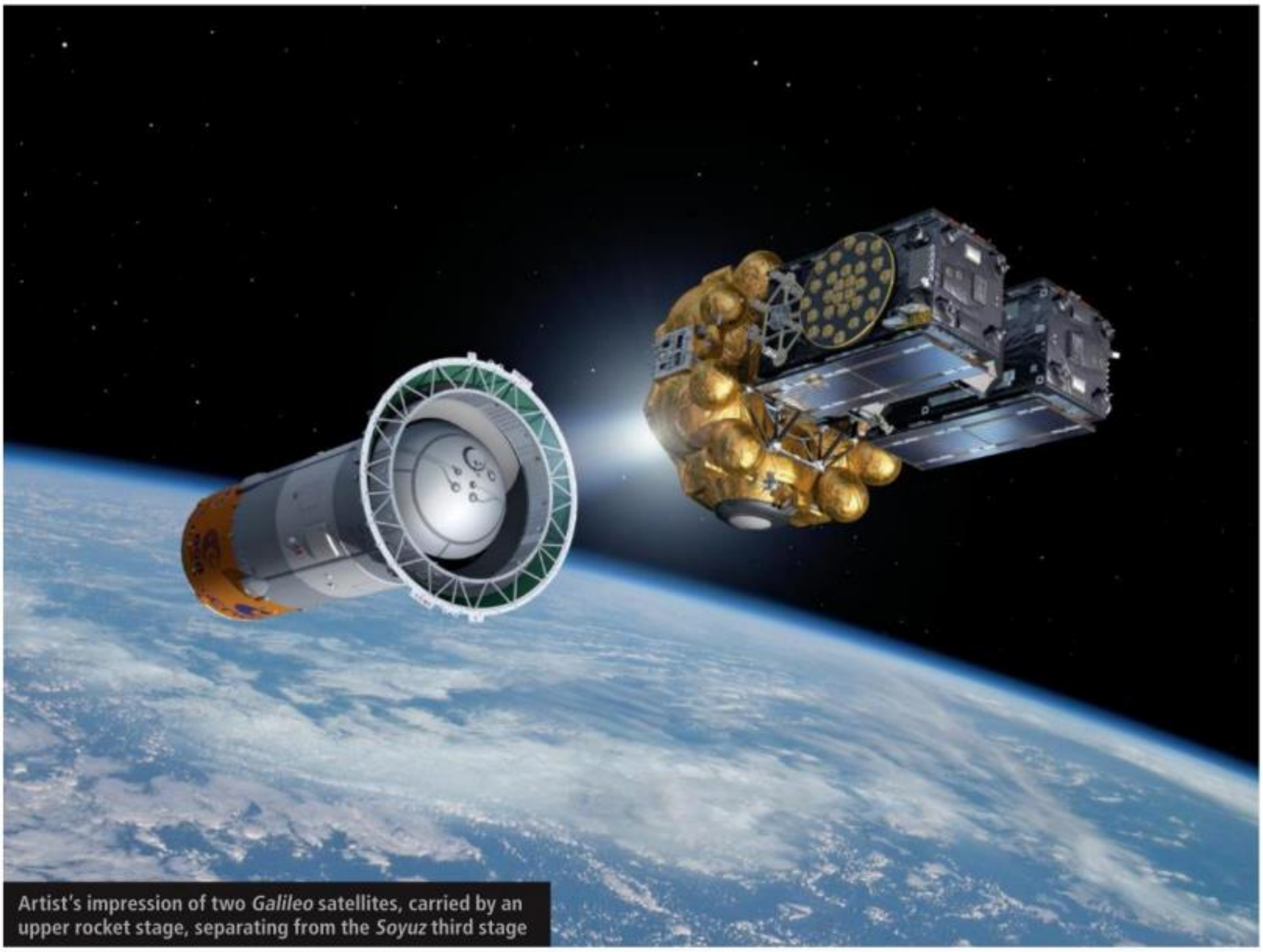


Figure 1.1 A corner cube reflector

Artist's impression of a fully operational *Galileo* satellite.



Artist's impression of two *Galileo* satellites, carried by an upper rocket stage, separating from the *Soyuz* third stage

satellite was due to the effect of the Sun's radiation. Photons possess momentum and they impart momentum to any surface on which they are incident, including the satellite. Ignoring this effect could put the predicted position of the satellite in error by about 1 km per day.

The atomic clock frequency of each satellite was recorded as a function of height for 1000 days and compared with the frequency of an identical atomic clock on the ground. The difference in frequency was then compared with the prediction of general relativity. It was found that general relativity predicted the gravitational time dilation correct to about 20 parts per million — the most precise determination to date and five times better than that obtained previously.

Comment

Why bother testing a theory that has performed so well for about 100 years? The testing continues — there is now an experiment on the International Space Station that aims to improve the measurement of time dilation to a precision of about two parts per million. This is a factor of ten better than using the navigation satellites. Physics progresses when a theory gives inaccurate or wrong predictions. Experiments can then be devised that will show what went wrong, enabling physicists to amend the inaccurate theory or develop a new one.

References and further reading

The inside story of the faulty launch, recovery and exploitation of the satellites:

An excellent video of the time dilation experiment:

The theory of gravity is certainly worth testing because there are aspects of gravity that remain a mystery. For example, neither dark matter nor dark energy can be explained. Finding an inaccurate prediction of general relativity will hopefully give clues as to where to look for a better theory.

A related problem is that no way has yet been found to combine general relativity with the highly successful quantum theory to produce a theory of quantum gravity. It appears that our formulation of either general relativity or quantum theory (or both) must change before that can happen. The person who achieves this will certainly deserve a Nobel prize.

Peter Main is on the academic staff of the University of York and is also a member of the Physics Review editorial board.

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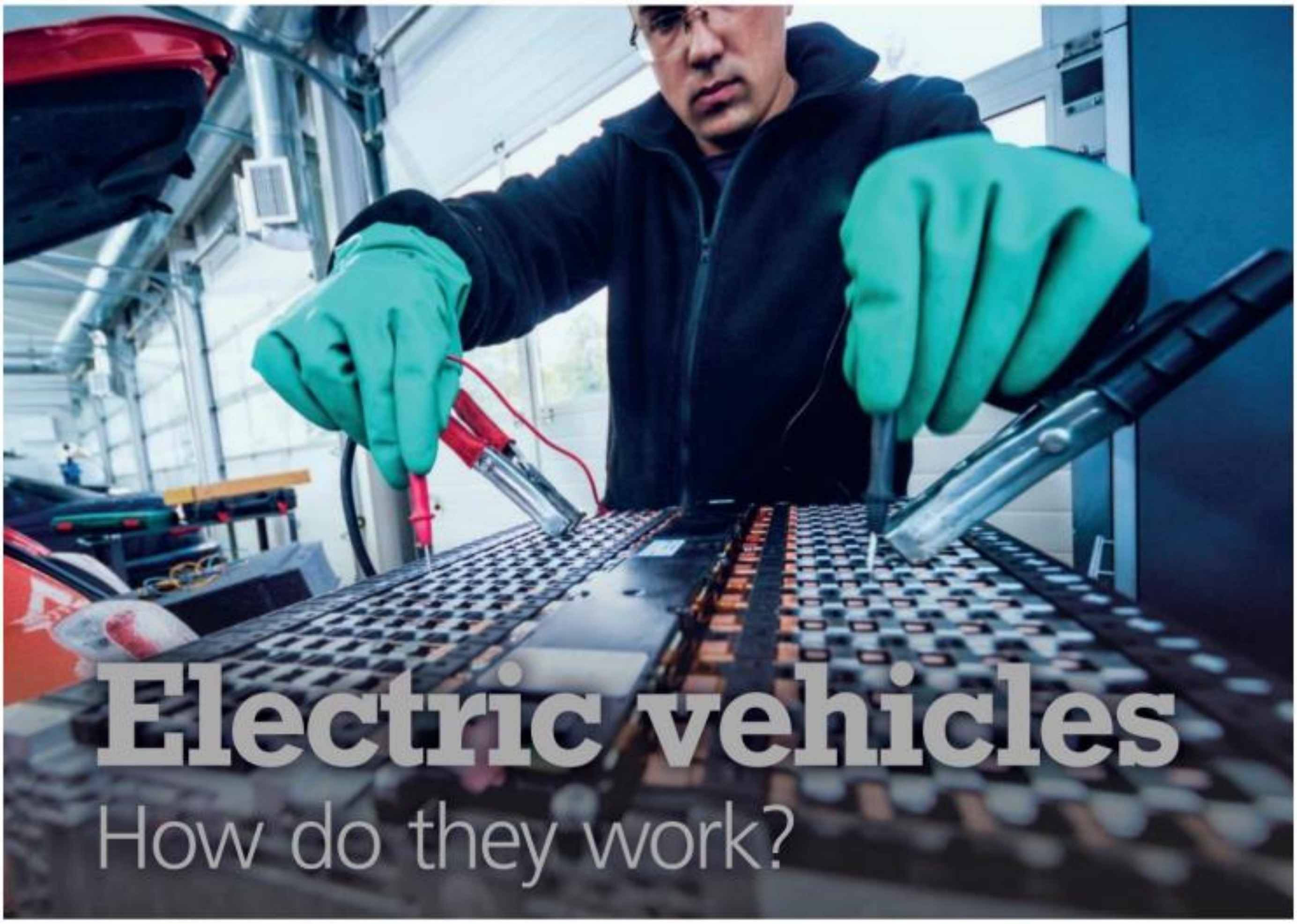

Electric vehicles

How do they work?

Susan Street

Susan Street looks at the development of the electric vehicle (EV), considers the physics involved in the rechargeable battery and the motor, and discusses the importance of this engineering revolution

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Exam links

The terms in bold link to topics in the **AQA**, **Edexcel**, **OCR**, **WJEC** and **CCEA** A-level specifications, as well as the **IB**, **Pre-U** and **SQA** exam specifications.

The performance of EVs and rechargeable batteries is described in terms of **charge**, **energy** and **power** in **electric circuits**, **efficiency**, and **electromagnetic induction**.

You may be surprised to read that EVs have been around in Britain for over a century. The first all-electric car with a rechargeable battery was invented in 1884 by Shropshire ironworker Thomas Parker (better known for electrifying the London Underground). His lead-acid battery is still used in every petrol or diesel car, but the internal combustion engine soon delivered a much longer-range journey and by 1935 EVs had all but disappeared.

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This century has seen a revival in EV manufacture, driven by the need to improve air quality and cut carbon emissions, and by the development of better batteries.

Types of EV

There are three types of electric vehicle:

- The hybrid electric vehicle (HEV) has a petrol or diesel engine and an electric motor to reduce fuel consumption. The battery is recharged as the brakes are applied.
- The battery in the plug-in hybrid electric vehicle (PHEV) is recharged from the National Grid, and its electric motor drives the wheels. Its petrol engine is a back-up for driving the wheels and charging the battery.
- The all-electric vehicle (EV or AEV) uses a rechargeable battery to operate a high-power electric motor to drive the wheels.

Portable energy

Cells and batteries are portable energy stores. A cell's emf is the amount of energy that it transfers to each coulomb of charge (Box 1). The way the chemicals in the cells release and move electric charge determines both the cell's emf and the potential difference (pd) it delivers to a working circuit. (The pd is slightly lower than the emf because energy is dissipated in the cell as a result of its internal resistance — see *Skillset* on pages 6–8.)

When cells are joined in series to make a battery, the battery emf is the sum of the individual cell emfs, and the pd it supplies is the sum of the cell pds.

Box 1 summarises some key electrical equations and SI units. To compare car batteries, we use larger units of charge, energy and power. Three quantities are typically used to measure battery performance: *charge capacity*, *energy density* and *efficiency*.

Charge capacity is the total charge that flows through a battery while it is operating. One ampere-hour (Ah) is the charge that flows when a battery provides a current of 1 amp for 1 hour:

$$1\,\text{Ah} = 3600\,\text{C}$$

Energy output and storage are measured in kilowatt-hours, kWh, the unit found on domestic energy bills. 1 kWh is the energy transferred by a device with a power of 1 kW operating for 1 hour:

$$1\,\text{kWh} = 3.6 \times 10^6\,\text{J}$$

If we know current in amperes and and pd in volts, then:

$$\text{power in kW} = \frac{\text{current in A} \times \text{pd in V}}{1000} \times \text{number of cells} \quad (1)$$

$$\text{energy stored in a battery (kWh)} = \frac{\text{battery charge capacity} \times \text{pd}}{1000} \times \text{number of cells} \quad (2)$$

A battery's energy density is its total stored energy divided by its mass, usually expressed in kWh per kg:

$$\text{energy density} = \frac{\text{energy stored in kWh}}{\text{mass of battery in kg}} \quad (3)$$

Box 1 Electrical equations and SI units

In SI units, charge, q, is expressed in coulombs (C) and current, I, in amperes (A). Current is the rate of flow of charge:

$$I = \frac{q}{t} \quad (1.1)$$

$$1\,\text{A} = 1\,\text{C}\,\text{s}^{-1}$$

$$q = It \quad (1.1a)$$

$$1\,\text{C} = 1\,\text{A}\,\text{s}$$

Power, P, is the rate of transfer of energy, E; it has SI units of watts (W).

$$P = \frac{E}{t} \quad (1.2)$$

$$1\,\text{W} = 1\,\text{J}\,\text{s}^{-1}$$

$$E = Pt \quad (1.2a)$$

$$1\,\text{J} = 1\,\text{W}\,\text{s}$$

Potential difference, V, and emf are measures of the energy, E, transferred per unit charge, and have SI units of volts (V).

$$V = \frac{E}{q} \quad (1.3)$$

$$1\,\text{V} = 1\,\text{J}\,\text{C}^{-1}$$

power = joules per coulomb × coulombs per second

$$P = VI \quad (1.4)$$

$$E = qV = VIt \quad (1.5)$$

An early electric vehicle

A battery's efficiency is defined as:

$$\text{battery efficiency} = \frac{\text{useful energy output during discharge}}{\text{energy transferred during charging}} \quad (4)$$

Efficiency is often expressed as a percentage.

The rechargeable battery

The main components of each cell are:

- a chemical solution (an electrolyte) that conducts electricity due to the presence of charged atoms (ions)
- plates (electrodes) that allow a chemical reaction to take place in the electrolyte and provide contacts for electrons to enter and leave the cell

Parker's electrolyte was dilute sulfuric acid; one electrode was lead and the other lead coated with lead dioxide. His solution contained positive ions (H^+) and sulfate ions (SO_4^{2-}). He connected six 2.1 V cells in series to make a 12.6 V battery. Lead-acid batteries are typically 70% efficient and have an energy density of 30–40 Wh kg^{-1}, which is too low for modern EVs.

The main successor to Parker's battery is the lithium-ion (Li-ion) battery. The electrolyte is an organic solution of lithium. One electrode is a lithium metal oxide with manganese, nickel and cobalt added to increase charge density and give stability. The other electrode is graphite.

The positive ions are lithium Li^{2+}. During discharge they move from anode to cathode through the electrolyte and a separator, which is a polymer barrier full of tiny (30–100 nm) pores holding electrolyte but allowing the ions to pass. Lithium ions are absorbed by the cathode, electrons are released from the anode and the resulting flow of electrons in the external circuit allows the motor to do work. Charging is the reverse process. Electrons are drawn away from the cathode and positive ions are attracted to the anode until it is packed with ions and the cell is fully charged again.

The Li-ion battery is 80–90% efficient and, since lithium has a low density (533 kg m^{-3}), it has an energy density of 200 Wh kg^{-1}. It is the go-to battery for EVs.

The Nissan Leaf

One popular EV is the Nissan Leaf, first produced in 2010. It is a good example of recent achievements in this field.

The basic Leaf has a Li-ion battery pack containing 48 modules (connected in series) of four cells (two in series and two in parallel) under the seats. Each cell of 3.75 V is rated at 32.5 Ah. Using Equation 2 to calculate the energy stored:

$$\text{energy} = 32.5\,\text{Ah} \times 3.75\,\text{V} \times 48 \times 4 = 23\,400\,\text{Wh} = 23.4\,\text{kWh}$$

Only 80% of this is available because Li-ion batteries are destroyed if completely discharged. The storage capacity is temperature dependent, increasing in hot weather.

The Li-ion battery discharges as it delivers an electric current to the motor. To recharge the cells, an electric current in the opposite direction is used to reverse the chemical reaction and increase the stored energy.

Recharging the battery

The main method of recharge is from an external electricity supply.

There are two on-board charging inlets under a flap in the bonnet. The cabling and connector depend upon the power rating of the supply you are using. Off-board charging cables are supplied at rapid-charging stations, with electronics that match up to the car's inlet with a 'handshake'. Fast on-board charging at home or at the workplace involves connecting a cable to a highly rated socket. For overnight slow charging in the home, a three-pin socket is sufficient. Table 1 compares how long it *can* take (official and real-world data vary) to charge a 24 kWh Li-ion battery to 80% capacity with different supply power ratings.

The motor and transmission

When a wire carries an electric current in a magnetic field, it experiences a force at right angles to both the current and field. When the wire is coiled and mounted on a shaft it becomes the rotor (rotating drive) of a motor, spinning within a surrounding magnetic field provided by a stationary electromagnet called the stator.

EV motors use alternating current (AC) to supply the stator so its magnetic field alternates too. To produce a constant rotation rate in one direction, the rotor must be synchronised with the stator's changing magnetic field (see 'Dynamos in cars — why AC?', PHYSICS REVIEW Vol. 26, No. 3, pp. 18–21).

The synchronous AC motor in the basic Leaf has a power of 80 kW (compare this with a maximum of 1.4 kW for a rechargeable power drill). It produces a twisting force (torque) of 280 Nm to a drive shaft that turns the wheels. The maximum rate of rotation is 10.4×10^3 revolutions per minute (rpm), varying as the car accelerates and decelerates. A single reducing gear with a ratio of 8:1 reduces this maximum to 1.3×10^3 rpm. An electric motor can provide maximum torque even at low speeds, so a conventional gearbox is not needed. With a wheel diameter of 63.6 cm, the vehicle's top speed is about $156\,\text{km}\,\text{h}^{-1}$.

Table 1 Battery charging times

Charging type	Power rating/kW	Time/hours
Rapid	50	0.5
Fast	22	1.5
Fast (home)	7	4
Slow	3	12

An inverter is included between the battery and the motor unit. This is an electronic controller that uses signals from the single 'epedal' to speed up the motor for acceleration when the pedal is pushed down and causes the motor to act as a generator when the pressure on the pedal is released for deceleration, at the same time discharging or recharging the battery, respectively. It also converts the direct current (DC) from the battery into AC for driving the motor and AC back to DC again for battery charging.

Regenerative braking uses the motor as a dynamo, reducing the vehicle's kinetic energy and recharging the battery. As regenerative braking gets less effective as speed decreases, standard friction brakes are applied for the final halt or for an emergency stop.

Performance

To increase efficiency, drag caused by air resistance is reduced as much as possible. The Leaf has a tapered nose, a flat underbody and two rear spoilers, giving the vehicle a drag coefficient of 0.28 — similar to that of a bullet.

A common performance measure for EVs is kWh used per 100 km. A typical figure for combined city and open road driving is about 18 kWh per 100 km: a fully charged 24 kWh battery should give a range of about 130 km.

There are losses within the charging system in the vehicle but in principle a more highly rated battery drives a more powerful motor and delivers a longer journey. All the measurements are fraught with variables, such as terrain, speed and driver competence.

Next steps

As demand for EVs rises, the network of street charging stations in towns and cities and multi-charging-point stations countrywide is expanding, with maps and apps available for drivers to plan for longer journeys. Check out your local availability at Zap-Map ( ). In the home, wall chargers for EVs will become the norm.


A rapid charge port

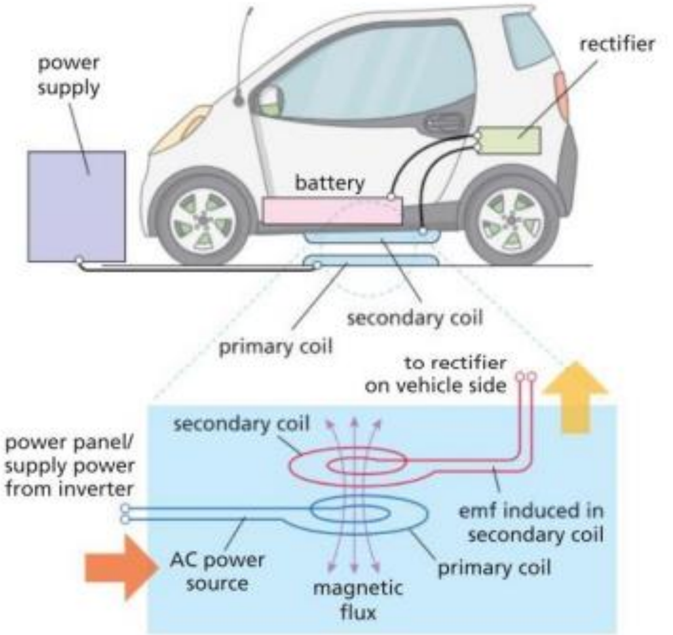

Figure 1 Wireless recharge

Manufacturers are vying to design more efficient vehicles, both domestic and commercial, with longer ranges. The next generation Leafs, for example, have 40 kWh and 62 kWh batteries.

Future EVs might use a wireless charging system with an air transformer. At a chosen parking space, for example outside the home or workplace, an alternating magnetic field is generated with mains AC in a primary coil fixed in the ground (Figure 1). The changing magnetic flux is directed vertically and links with a secondary coil attached to the base of the car above it, where it induces a secondary current, which is fed to an AC/DC rectifier in the car's charging port. The challenge will be to install the necessary charging infrastructure, to make it efficient and to ensure that the National Grid can supply sufficient energy when required (see 'Will electric cars break the National Grid?', Physics Review Vol. 28, No. 3, pp. 8–11).

The environment

The AEV is emission free at the point of use — it has no exhaust. The clamour to reduce greenhouse gases is rising as climate change bites. The UK government has adopted a 'Road to Zero' strategy that aims for:

- 50% EV (PHEV and EV) new car sales by 2030
- no new petrol/diesel cars in production by 2040
- 100% EV by 2050

Whether these targets can be achieved will depend to a certain extent on the necessary charging infrastructure.

Across Europe the installation of thousands of charging stations is well underway. However, electric cars are only as green as their power supply. Worldwide, a concerted approach to halt the burning of fossil fuels, both on the roads and at the power stations, is the ultimate aim for tomorrow's drivers.

Susan Street is a former physics teacher.

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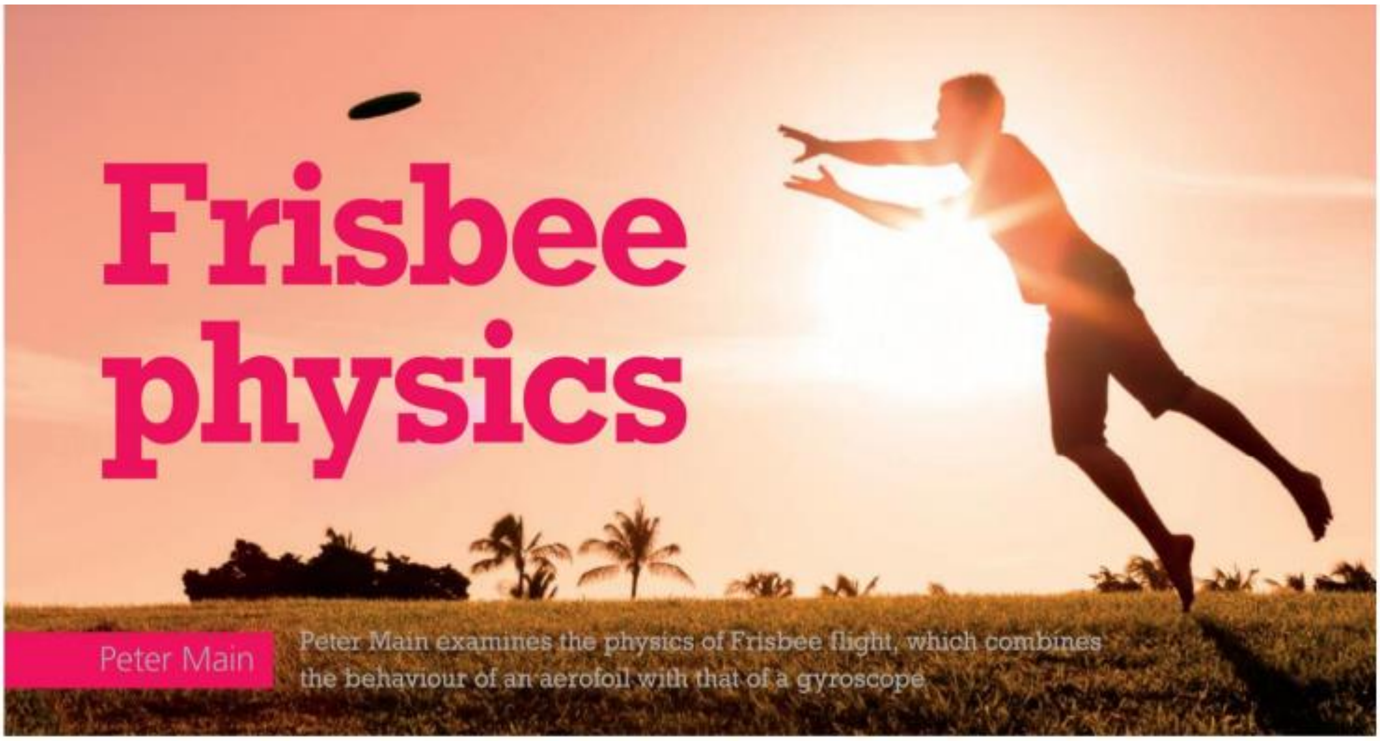


Frisbee physics

Peter Main

Peter Main examines the physics of Frisbee flight, which combines the behaviour of an aerofoil with that of a gyroscope

> **Exam links**
>
> The terms in bold link to topics in the AQA, Edexcel, OCR, WJEC and CCEA A-level specifications, as well as the IB, Pre-U and SQA exam specifications.
>
> The **conservation** of **mass**, **energy** and **momentum**, together with **Newton's second and third laws of motion**, help explain the lift provided by an aerofoil. Spin stablises a Frisbee flight because of of **angular momentum conservation**.

For decades Frisbees have been a source of fun for people of all ages. A skilful thrower can make them follow interesting curved trajectories, go in a straight line or even appear to hover in mid-air. These simple plastic discs can be thrown long distances and, best of all, are inexpensive — over

The entertaining aspects of a Frisbee can be explained in terms of just two physical concepts — it is both an aerofoil and a gyroscope.

The Frisbee story

Before we get into the physics, there is an interesting story about how Frisbees started. It all began in 1871 in William Russell Frisbie's small bakery in Connecticut, USA. Frisbie's delicious fruit pies were popular at the nearby Yale University. The students enjoyed throwing the empty metal pie plates around when they discovered they could make them fly long distances. The plates quickly became known as 'Frisbies'.

Production of the plastic flying discs started in the 1950s when they were marketed by the Wham-O Manufacturing Company in California. They called them 'Frisbees' — the slight change in name was to avoid trademark problems. Note that Frisbee is a registered trademark of Wham-O Manufacturing, hence the capital letter. Other firms manufacture them but are not allowed to call them Frisbees — they are known as 'flying discs'.

Aerodynamic lift

A Frisbee acts as an aerofoil as it flies through the air. A common example of an aerofoil is an aeroplane wing, which provides lift to an aircraft. How it provides lift is quite complicated, involving conservation of mass, energy and momentum. There is no straightforward explanation, and many textbooks make mistakes when they attempt a simplification.

The original Frisbie's pie tin

PhysicsReviewExtras

Get practice-for-exam questions based on this article at

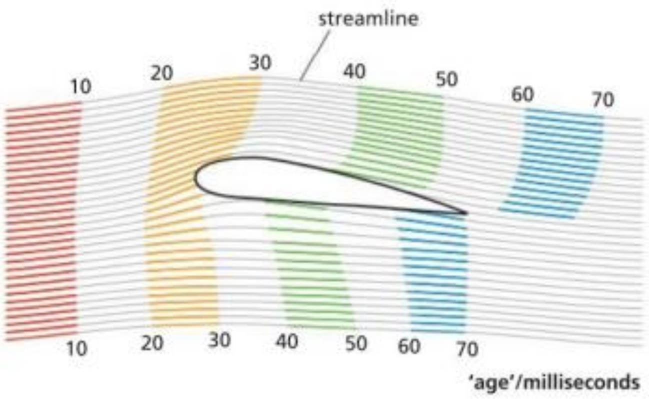


Figure 1 The calculated flow of air over an aerofoil. The air follows streamlines with varying speed

Let us just accept the accurately calculated flow of air over a wing, as shown in Figure 1. The air flows from left to right, following the continuous streamlines. Vertical slices of air, initially at equal time intervals, are represented by streamers of different colours. The streamers are stretched out over the top of the wing, showing that the air has increased its speed. In fact, the maximum velocity produced by the aerofoil is approximately twice that of the undisturbed air.

Conversely, the slices of air travelling along the underside of the wing are going more slowly. This means the two parts of each slice do not meet after travelling around the wing. Figure 1 shows that the upper part of the blue slice has moved well ahead of the lower part when it reaches the back of the wing.

Along a streamline, the static air pressure, p, is related to the dynamic pressure (kinetic energy per unit volume), $\frac{1}{2}v^2\rho$, by conservation of energy, giving the equation:

$$p + \tfrac{1}{2}v^2\rho = \text{constant} \qquad (1)$$

where v is the speed of the air and ρ is its density. The equation shows that if v is increased, then p must decrease to compensate. The faster-flowing air on top of the wing must therefore be at a lower pressure than the slower air underneath. This difference in pressure creates the upward force on the wing that we call lift.

A flying Frisbee and an aircraft wing are both aerofoils

Another way of looking at this is by considering the rising air immediately in front of the wing compared with the air immediately behind the wing, which is falling. Clearly, there has been a change of momentum of the air. The rate of change of momentum, according to Newton's second law of motion, is proportional to, and in the same direction as, the applied force. The force must therefore be in a downward direction. The force is exerted by the wing and Newton's third law tells us there must be an equal upward force on the wing, which is the lift.

Notice that neither of these interpretations of Figure 1 explains how the flow pattern occurs in the first place. A nice animated diagram of the flow of air over an aerofoil can be found at _(force).

Forces on the Frisbee

The total aerodynamic force on a flying disc can most conveniently be described in terms of the two components of *lift* and *drag*. The drag force is in a direction exactly opposite from the direction of flight, and the lift force is upwards at right angles to this. The vector sum of the two is the total aerodynamic force on the disc, which acts through the *centre of pressure*. Because the air pressure changes across the disc, the centre of pressure does not correspond to the geometric centre of the disc, but is closer to the leading edge, as seen in Figure 2.

The remaining force on the disc is its *weight*, the gravitational force that acts vertically downwards through the *centre of mass*. By symmetry, the centre of mass coincides with the geometric centre of the disc. Since the centre of pressure and the centre of mass do not coincide, the forces acting through them tend to flip the Frisbee over. With a successful throw this does not happen, so we need to discover what keeps it stable.

Gyroscope

You may well have played with a spinning top or a gyroscope. Their behaviour can be quite fascinating. One of the first things to consider is the rate of spin, which is a scalar quantity and can be expressed in radians per second. If the direction of the axis of rotation is included in the description it becomes a vector quantity, with the vector pointing along the rotation axis. It is then called the *angular velocity*.

In linear motion, multiplying velocity by mass gives momentum. The equivalent in rotational motion is angular momentum, which is also a vector quantity. When a Frisbee is thrown, it is given a lot of spin, so it has a substantial amount of angular momentum.

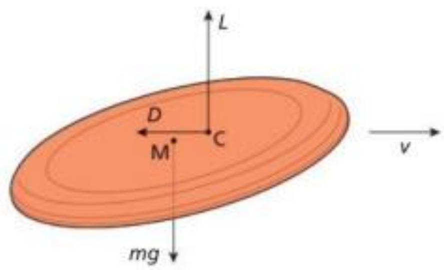


Figure 2 The forces acting on a Frisbee travelling with a velocity v. M is the centre of mass through which the weight, mg, acts. C is the centre of pressure through which the forces of lift, L, and drag, D, act

Gyroscopic action helps to keep the Frisbee stable in flight

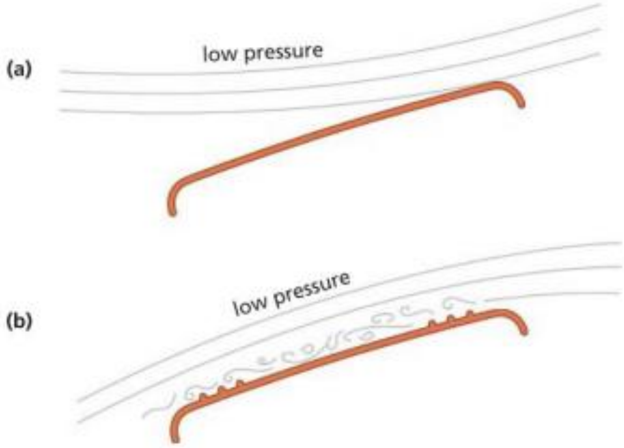


Figure 3 **Streamlines showing the effect on airflow of surface ridges: (a) without ridges, (b) with ridges**

Moment of inertia in rotational motion is equivalent to mass in linear motion. For a point mass m at a distance r from the axis of rotation, its *moment of inertia I* is:

$$I = mr^2 \quad (2)$$

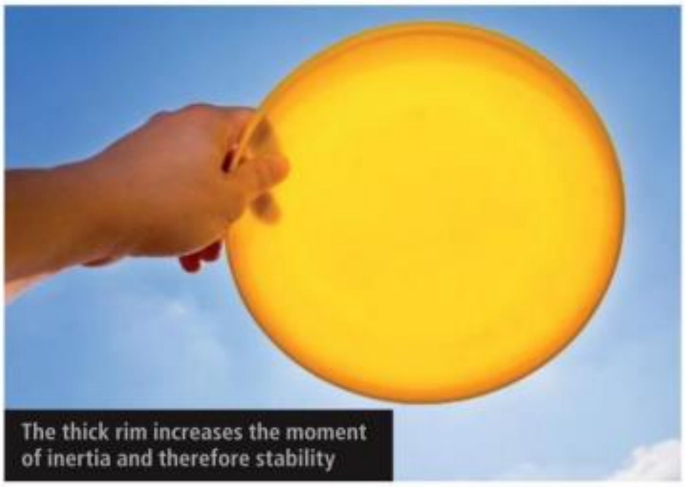
Multiplying angular velocity, ω, by moment of inertia, I, gives *angular momentum*:

$$L = I\omega \quad (3)$$

Just as linear momentum is conserved when no external resultant force acts, angular momentum is also conserved when there is no turning force (torque) acting on an object. This requires that both the rate of spin and the direction of the axis of rotation do not change (ignoring friction with the air). Requiring the axis of rotation to remain constant is exactly what is needed to stabilise the Frisbee and stop it from flipping over. Without spin, the Frisbee cannot fly.

Construction

The shape and construction of a Frisbee have important effects on its performance. We have already seen that its shape allows it to act as an aerofoil, but let us look at the purpose of the thick rim. First, and most important, it allows us to grip and throw the disc. Without it, the throw would be a lot less effective.



The thick rim increases the moment of inertia and therefore stability

In addition, and more to do with physics, the effect of the thick rim is to concentrate a lot of the Frisbee's mass far from the rotation axis. Consequently, it increases the moment of inertia and so contributes significantly to the stability of the Frisbee in flight.

Another effect of the rim is partially to turn the Frisbee into a parachute, albeit a rather poor one, helping it to almost hover in the air by slowing its descent.

On the top surface of some flying disc models there are several concentric ridges, which produce turbulence at the leading edge. The significance of the resultant turbulent layer of air is that it follows the contours of the spinning disc. This keeps the low-pressure air immediately above it close to the disc, enhancing the lift force. Without turbulence, the low-pressure air flowing over the disc no longer stays close to the top surface and some of the lift force is lost (Figure 3). Loss of any lift simply means the Frisbee will not fly so far.

The ridges also allow the Frisbee to be thrown at a higher angle of attack, so increasing its aerodynamic capabilities. They change the aerodynamics of the disc in the same way that the seam of a cricket ball enables swing bowling. All these enhancements to the flight of the Frisbee enable it to be thrown much further than a ball at the same initial velocity.

Record throw

The popularity of the Frisbee is such that it has spawned a host of new ways of using it. There are many trick 'shots' worth seeing on sites such as YouTube, and it has also given rise to a popular team sport called Ultimate. Some public parks and sports centres have disc golf courses, where flying discs are thrown with the object of landing them in small baskets. If you want something slightly different, try an Aerobie flying ring, which is the result of some serious aerodynamic calculations. It is in the *Guinness Book of World Records* for the longest throw of 406 metres, it has even been thrown across Niagara Falls and, remarkably, can stay aloft for over 30 seconds — all thanks to some fantastic physics.

Peter Main is on the academic staff of the University of York and is also a member of the Physics Review editorial board.

Physics SIL
Task 2 Mark Schemes

Q1. (a) K 1

(b) Decreases 1

(c) use a metre rule / 30 cm ruler to measure across 10 (projected) waves

accept any practical number of waves number for 10 1

and then divide by 10 1

(d) 1.2 cm = 0.012 m 1

18.5 × 0.012 = 0.22(2) (m / s) 1

*allow 0.22(2) with no working shown for **2** marks*

typical walking speed = 1.5m / s

accept any value e.g. in the range 0.7 to 2.0 m / s 1

so the water waves are slower (than a typical walking speed)

this cannot score on its own 1

[8]

Q2. (a) (i) wavelength

accept frequency

accept speed 1

(ii) amplitude

accept energy

height is insufficient 1

(iii) sound 1

(b) 0.12

*allow **1** mark for correct substitution, ie 8 × 0.015 provided no subsequent step shown* 2

metre per second **or** m/s **or** metre/second

*do **not** accept mps*

units must be consistent with numerical answers 1

(c) echo(es) 1

(d) 340 (m/s)

*allow **1** mark for correct substitution ie 25 000 × 0.0136 provided no subsequent step*

or

*allow **1** mark for a correct calculation showing an incorrect value from conversion to hertz × 0.0136*

*an answer of 0.34 gains **1** mark* 2

(e) (a wave where the) oscillations are parallel to the direction of energy transfer

both marking points may appear as labels on a diagram
accept vibrations for oscillations
accept in same direction as for parallel to
allow direction of wave (motion) for direction of energy transfer
*allow **1** mark for a correct calculation showing an incorrect value from conversion to hertz × 0.0136*

1

causing (areas of) compression and rarefaction
accept correct description in terms of particles
mechanical wave is insufficient
needs a medium to travel through is insufficient

1

[11]

Q3. (a) (wave) **B**
(the parts of the) spring oscillate / move back and forth **<u>in direction of / parallel to</u>** wave travel
OR
mention of <u>compressions and rarefactions</u>

2

(b) (i) (double ended arrow / line / brackets) from between two points in phase

1

(ii) wave A: arrow vertically upwards
wave B: arrow horizontally to the left

2

(c) (i) loose distinction e.g. one has oscillations parallel to the wave direction and the other has oscillations in the same direction as the wave

1

transverse -vibrations perpendicular to direction of propagation
longitudinal -vibrations in same direction as direction of propagation

1

(ii) any example of transverse wave

1

(iii) any example of longitudinal wave

1

(d) $v = f\lambda$

1

8.6 m

1

[11]

Q4. (a) (i) (visible) light
accept visible

1

(ii) microwaves

1

(b) J

1

(c) (i) B

1

(ii) shorter than

1

(d) (i) To find out if using a mobile phone is harmful to health

1

(ii) any **two** from:
- (X has a) low(er) SAR value
  "it" refers to mobile phone
  accept has a low(er) rate
- (maximum) energy absorbed (by the head) is less
  accept energy emitted (by phone) is less
  accept radiation for energy

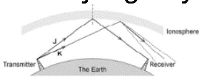
- (if mobiles are harmful) less likely to cause harm
  accept will not cause harm
  accept it is safer

2

(e) (i) reflection of wave **K** at or within the ionosphere
allow dashed lines

1

angle i = angle r
'judge by eye'



tolerance for the reflected ray is between the first e and last r
ignore arrows
a reflected ray to the receiver doesn't score 2nd mark
additional rays shown don't score 2nd mark

1

(ii) normal

1

(f) (i) microwave

1

(ii) refraction

1

(g) All electromagnetic waves are transverse.

1

All electromagnetic waves have the same speed in a vacuum.

1

[15]

Q5. (a) any **one** from:
- (visible) light
- UV / ultra violet
- X-ray
- gamma / γ-ray

1

(b) less than

1

less than

1

the same as

1

(c) (i) compare (the health of) mobile phone users with non-mobile phone users
must be an implied comparison between users and non-users
any idea of doing an experiment negates the mark

1

(ii) increase the sample size
accept use more people
accept have a large sample size
repeat the research / test is neutral

1

(iii) ethical

1

(d) (i) so the phones can be compared (fairly)
a fair test is insufficient
accept different tests (may) give different results
*do **not** accept to make the results reliable, unless qualified*
eg all variables are controlled
*do **not** accept bias unless qualified*

1

(ii) yes all are below the legal limit / 2 (W/kg)

or no and any **one** from:

- even absorbing a small amount of energy may be harmful
  accept microwaves for energy
  accept emits energy absorbed by head / other parts of body
- no proof that small amounts of energy are not harmful
  accept because the SAR value is not 0 (W/kg)

1

(e) any **one** from:

- to get an independent opinion
- company scientists may be biased
  accept company scientists may manipulate results

1

[10]

Q6. (a) (i) any **two** from:

- travel at the same speed (through a vacuum)
  accept travel at the speed of light
  accept air for vacuum
- can travel through a vacuum / space
  *do **not** accept air for vacuum*
- transfer energy
- can be reflected
- can be refracted
- can be diffracted
- can be absorbed
- can be transmitted
- transverse
  accept any other property common to electromagnetic waves
  accept travel at the same speed through a vacuum for both marks
  *do **not** accept both radiated from the Sun*

2

(ii) infra red

both required for the mark

radio(waves)

accept IR for infra red

1

(b) 2 400 000 000

*correct transformation and substitution gains **1** mark*

ie $\frac{300000000}{0.125}$ ***or*** $\frac{300000000}{12.5}$

*an answer of 24 000 000 gains **1** mark*

***either** 2 400 000 kHz*

***or** 2 400 MHz scores **3** marks but the symbol only scores the 3rd mark if it is correct in every detail*

2

hertz

accept Hz

*do **not** accept hz*

1

(c) (i) presented (scientific) evidence / data

do an experiment / investigation is insufficient

1

(ii) to find out if there is a hazard (or not)

accept to find out if it is safe

accept not enough evidence to make a decision

not enough evidence is insufficient

1

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[8]

Task 4 Mark Schemes

M1. transverse yes — B1

transverse yes — B1

longitudinal no — B1

[3]

M2. (a) (i) 0.4(0) m **(1)**

(ii) speed (= frequency × wavelength) = 22 × 0.4(0) ecf **(1)**
= 8.8 (m s^{-1}) **(1)**

(ii) 90 or 450 (1) ° or **degrees (1)**
or 0.5π or 2.5π or 5π/2 **(1)** **rad**(ians)
or **r** or ^{r} **(1)** no R, Rad, etc

5

(b) displacement of Y will be a **positive (or 'up') maximum** at 1/4 of a period (or cycle) (0.0114 s) **(1)**
returns to original position (at 0.5 of a period or cycle) (owtte) **(1)**

2

[7]

M3.(a) transverse: vibration / displacement / disturbance not movement is perpendicular to direction of travel — **B1**

longitudinal: vibration / displacement / disturbance not movement is parallel to (same) direction of travel — **B1**

C1 for idea of transverse and longitudinal being perpendicular

(2)

(b) restriction of vibration / idea of how polarisation occurs — **B1**

single plane / same orientation – diagram may help — **B1**

(2)

(c) only transverse can be polarised / longitudinal cannot — **B1**

idea of being able to restrict vibration to single plane
or longitudinal not being perpendicular to motion
or longitudinal vibrating in direction of travel — **B1**

(2)

[6]

M4. (a) longitudinal — B1

(b) reflection — B1

(c) use of speed = distance/time — C1

(0.45 **or** 0.9)/1.6 × 10^{-4} **or** 0.45/0.8 × 10^{-4} — C1

= 5.6 km s^{-1} [5.625] — A1

[5]

M5.C

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[1]

M6. B [1]

M7. B [1]

M8. D [1]

M9. B [1]