# ESAT Physics Prep

# Week 6 – Waves

ANSWERS

Week 1 – Electricity

Week 2 – Magnetism

Week 3 – Mechanics

Week 4 – Thermal physics

Week 5 – Matter

**Week 6 – Waves**

Week 7 – Radioactivity

There is one sample ESAT test – note that they use the same questions from NSAA 2020 specimen paper. Past NSAA & ENGAA questions are the most relevant.

**There are no calculators in the ESAT.**

# Waves spec

## P6. Waves

P6.1 Wave properties:

a. Understand the transfer of energy without net movement of matter.
b. Know and understand transverse and longitudinal waves.
c. Know and understand the terms: *peak*, *trough*, *compression* and *rarefaction*.
d. Recall examples of waves, including electromagnetic waves and sound.
e. Know and be able to use the terms: *amplitude*, *wavelength*, *frequency* and *period*.
f. Know and be able to apply: $\text{frequency} = \frac{1}{\text{period}}$, $f = \frac{1}{T}$
g. Know and be able to apply: $\text{wave speed} = \frac{\text{distance}}{\text{time}}$
h. Know and be able to apply: wave speed = frequency × wavelength, $v = f\lambda$

P6.2 Wave behaviour:

a. Know and understand reflection at a surface.
b. Know and understand refraction at a boundary.
c. Know and understand the effect of reflection and refraction on the speed, frequency, wavelength and direction of waves.
d. Know and understand the analogy of reflection and refraction of light with that of water waves.
e. Know and understand the Doppler effect.

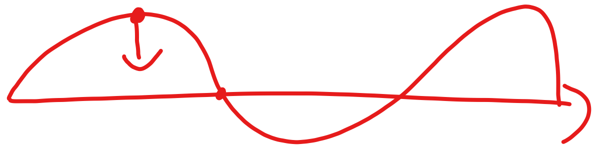
P6.3 Optics:

a. Draw and interpret ray diagrams to describe reflection in plane mirrors.
b. Know and be able to apply: angle of incidence = angle of reflection
c. Draw and interpret ray diagrams for refraction at a planar boundary.
d. Know and be able to interpret angle of incidence and angle of refraction.
e. Know and understand the effect of refraction on wave direction (away from or towards the normal) and speed (increasing or decreasing).

P6.4 Sound waves:

a. Understand the production of sound waves by a vibrating source.
b. Understand the need for a medium.
c. Understand qualitatively the relation of loudness to amplitude and pitch to frequency.
d. Know and understand longitudinal waves.
e. Understand that reflection causes echoes.
f. Recall that the range of human hearing is 20 Hz to 20 kHz.
g. Know and understand ultrasound and its uses (sonar and medical scanning).

$T = \frac{1}{12}$



# Q16 ENGAA 2023

**16** A transverse wave with an amplitude of 3.0 cm travels along a stretched string. The wave has a frequency of 12 Hz and a wavelength of 0.25 m.

What is the average speed of a particle in the string as the string oscillates during a time of 2.0 s?

↳ up + down

same average speed as 1.0 s

**A** $36\ \text{cm s}^{-1}$

**B** $72\ \text{cm s}^{-1}$

**C** $125\ \text{cm s}^{-1}$

**D** $144\ \text{cm s}^{-1}$

**E** $300\ \text{cm s}^{-1}$

in each T a particle travels $4 \times 3.0\text{cm} = 12\text{cm}$

in each second: $\frac{1}{\frac{1}{12}} = 12$ time periods

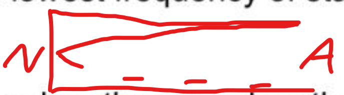
$12 \times 12 = 144\text{cm/s}$

# Q22 ENGAA 2023

Two pipes contain air at the same temperature and pressure.

node antinode

A stationary sound wave is formed in the first pipe, which is closed at one end and open at the other end. The lowest frequency of stationary sound wave that can be formed in this pipe is 4000 Hz.




$\lambda = 4L$

antinodes

The second pipe has the same length as the first pipe, but is open at both ends.

What is the lowest frequency of stationary sound wave that can be formed in the second pipe?

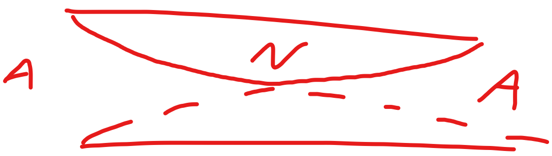
**A** 1000 Hz

**B** 2000 Hz

**C** 4000 Hz

**D** 8000 Hz

**E** 16 000 Hz




$\lambda = 2L$

$\lambda$ has decreased by a factor of 2

$v = f\lambda$

$\uparrow\times 2 \quad \downarrow\times 2$

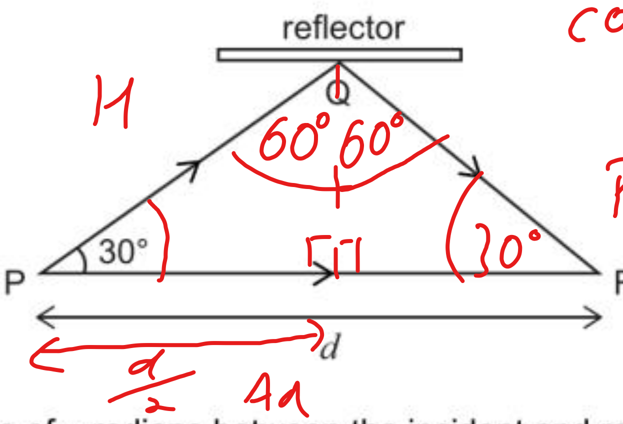
# Q38 ENGAA 2023

A sound wave can travel from a source at P to a detector at R directly or by reflecting at Q.

The angle between PR and PQ is 30° and the distance from P to R is $d$ as shown.

$\cos 30 = \dfrac{\frac{d}{2}}{PQ}$

$PQ = \dfrac{\frac{d}{2}}{\frac{\sqrt{3}}{2}} = \dfrac{d}{\sqrt{3}}$




There is a phase difference of $\pi$ radians between the incident and reflected wave at Q.

Waves that reach R via Q are in phase with waves that reach R directly from P.

Which expression gives the greatest wavelength of sound waves for which this is true?

**A** $2d\left(\dfrac{2}{\sqrt{3}}-1\right)$

**B** $d\left(\dfrac{2}{\sqrt{3}}-1\right)$

**C** $d(2-\sqrt{3})$

**D** $\dfrac{4d}{\sqrt{3}}$

**E** $\dfrac{2d}{\sqrt{3}}$

$P.d. = \dfrac{\lambda}{2}$

$PR = d$

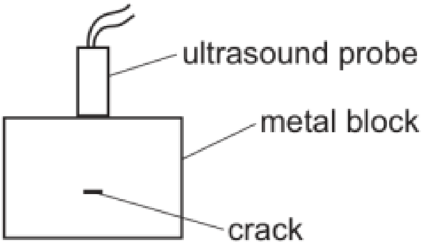
$PQ + QR = \dfrac{2d}{\sqrt{3}}$

$\dfrac{2d}{\sqrt{3}} - d = \dfrac{\lambda}{2}$

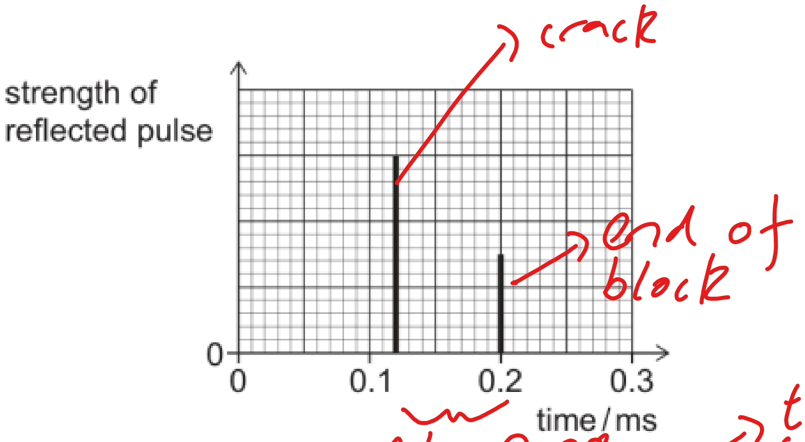
$\lambda = 2d\left(\dfrac{2}{\sqrt{3}} - 1\right)$

# Q6 ENGAA 2022

Ultrasound is used to find a crack inside a cuboid block of metal. An ultrasound probe is held in contact with the top surface of the metal block and perpendicular to the surface. A short pulse of ultrasound is sent into the metal block at time $t = 0$ ms and reflects from both the crack and the bottom surface of the metal block.




The times between the emission of the ultrasound pulse and the return of the reflections to the probe, and the strengths of the reflected pulses, are measured. The results are shown on the graph.




$\Delta t = 0.08$ ms → this is double the time for ultrasound to go between them

The speed of ultrasound in the metal is 5000 m s$^{-1}$.

What is the distance between the **bottom surface** of the metal block and the crack?

$v = \frac{s}{t} \Rightarrow s = vt = 5000 \times (0.04 \times 10^{-3}) = 5 \times 0.04 = 0.2$ m

**A** 0.2 m

**B** 0.3 m

**C** 0.4 m

**D** 0.5 m

**E** 0.6 m

**F** 1.0 m

# Q12 ENGAA 2022

**12** A transverse wave on a string has a speed of $500\,m\,s^{-1}$.

The horizontal distance between two points P and Q on the wave is 4.0 m, as shown in the diagram.

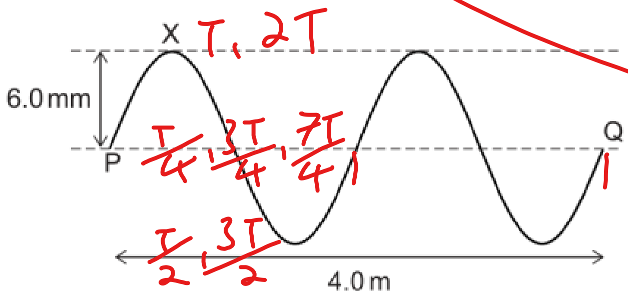
$2\lambda = 4.0\,m$

$\lambda = 2.0\,m$

$v = f\lambda$

$f = \frac{v}{\lambda} = \frac{500}{2.0} = 250\,Hz$

$T = \frac{1}{f} = \frac{1}{250} = 0.004\,s = 4\,ms$




At time $t = 0$ ms, point X on the string is at its maximum displacement of 6.0 mm above equilibrium.

What is the displacement of point X at time $t = 7.0$ ms?

$\frac{7T}{4}$

**A** 6.0 mm above equilibrium

**B** between 0 mm and 6.0 mm above equilibrium

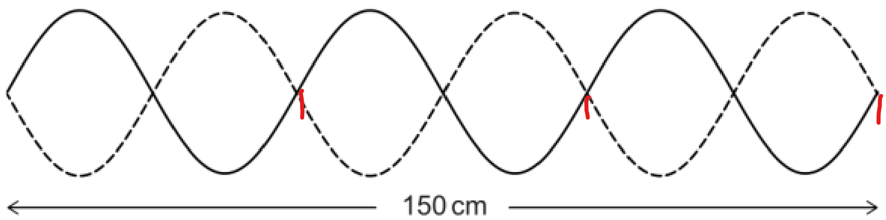
**C** 0 mm

**D** between 0 mm and 6.0 mm below equilibrium

**E** 6.0 mm below equilibrium

# Q22 ENGAA 2022

The diagram represents a stationary wave in a medium.




$3\lambda = 150\,cm$

$\lambda = 50\,cm = 0.5\,m$

The transverse waves that are creating the stationary wave travel at a speed of $300\,m\,s^{-1}$ through the medium.

What is the frequency of the transverse waves?

$v = f\lambda$

$f = \frac{v}{\lambda} = \frac{300}{0.5} = 600\,Hz$

**A** 75 Hz

**B** 150 Hz

**C** 200 Hz

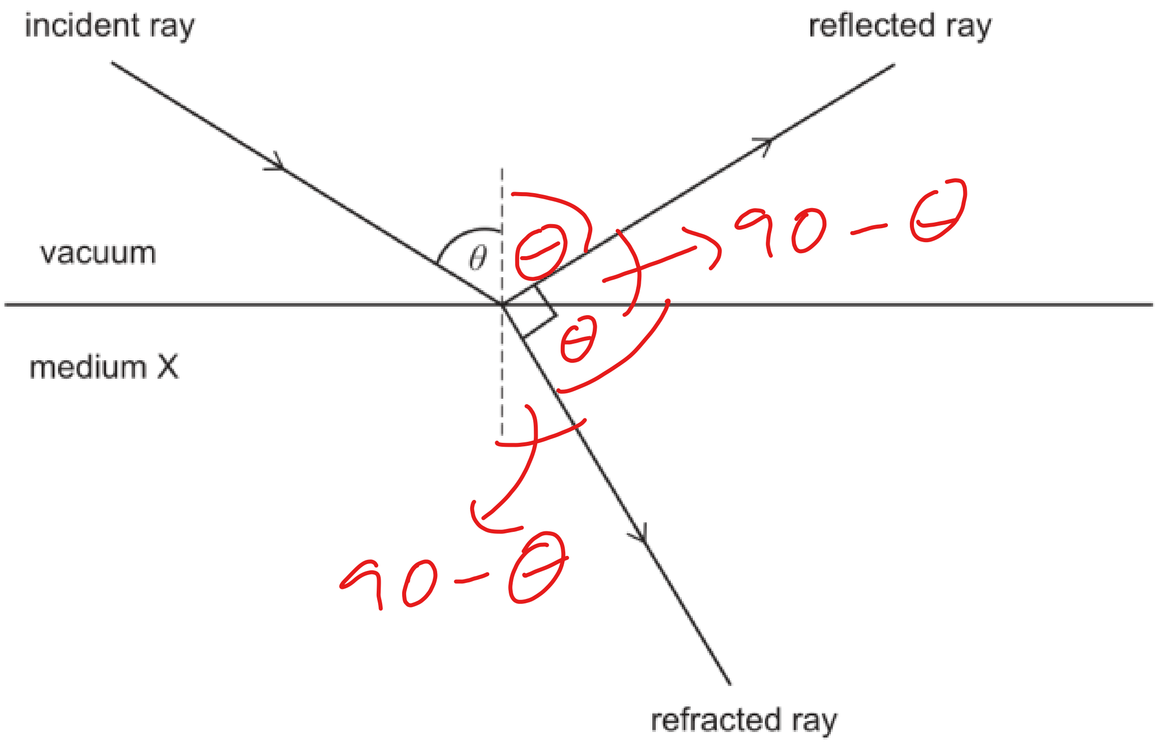
**D** 450 Hz

**E** 600 Hz

**F** 1200 Hz

# Q26 ENGAA 2022

A ray of light is incident on a boundary between a vacuum and medium X at an angle $\theta$ as shown:




The incident ray is partially reflected and partially refracted. The angle between the reflected and refracted rays is 90°.

What is the refractive index of medium X?

**A** $\sin\theta$

**B** $\dfrac{1}{\sin\theta}$

**C** $\cos\theta$

**D** $\dfrac{1}{\cos\theta}$

**E** $\tan\theta$

**F** $\dfrac{1}{\tan\theta}$

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$n_1 = 1,\ \theta_1 = \theta,\ \theta_2 = 90-\theta$$

$$\sin\theta = n_2 \sin(90-\theta)$$

$$n_2 = \frac{\sin\theta}{\sin(90-\theta)} = \frac{\sin\theta}{\cos\theta} = \tan\theta$$

# Q12 ENGAA 2021

**12** A ship travels into a wave that is travelling in the opposite direction to the ship.

The ship has a horizontal speed of $8.0\,\mathrm{m\,s^{-1}}$. The speed of the wave is $3.0\,\mathrm{m\,s^{-1}}$.

The front of the ship rises and falls with a time period of 8.0 s.

$\rightarrow f = \frac{1}{T} = \frac{1}{8}$

What is the wavelength of the wave?

**A** $\frac{3}{8}$ m

**B** $\frac{5}{8}$ m

**C** 1.0 m

**D** $\frac{11}{8}$ m

**E** 24 m

**F** 40 m

**G** 64 m

**H** 88 m

Relative speed = 11.0 m/s

$v = f\lambda$

$\lambda = \frac{v}{f} = \frac{11.0}{\frac{1}{8}}$

$= 88$ m

# Q20 ENGAA 2021

$v = s/t \Rightarrow s = vt$

$L$

$L - s$ $\quad$ $s$

**20** A pulse of ultrasound travels from one end of a solid uniform rod of length $L$, starting at time $t = 0$.

The pulse is partially reflected by a crack in the rod and partially by the far end of the rod.

These two reflected pulses travel back along the rod, arriving at the end from which they started at times $t_1$ and $t_2$, where $t_2 > t_1$.

What is the distance between the crack and the **far end** of the rod?

**A** $\dfrac{t_1}{t_2}L$

**B** $\dfrac{t_2}{t_1}L$

**C** $\dfrac{t_1}{2t_2}L$

**D** $\dfrac{t_2}{2t_1}L$

**E** $\dfrac{(t_2 - t_1)}{t_2}L$

**F** $\dfrac{(t_2 - t_1)}{2t_2}L$

$$v = \frac{2L}{t_2}$$

$$s = \left(\frac{t_2 - t_1}{2}\right) v$$

$$s = \left(\frac{t_2 - t_1}{\cancel{2}}\right) \frac{\cancel{2}L}{t_2}$$

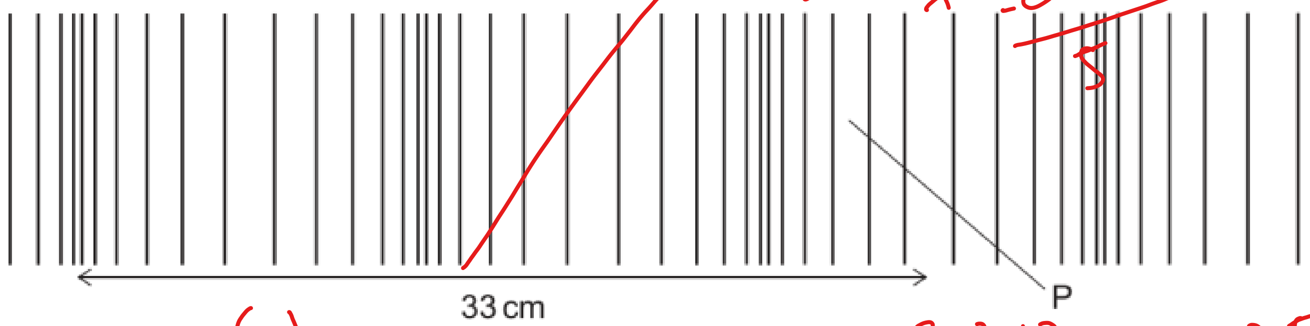
$$= (t_2 - t_1)\frac{L}{t_2}$$

# Q24 ENGAA 2021

A sound wave is travelling from left to right in air. The diagram represents the wave at a particular instant, and a distance of 33 cm is labelled.

$\frac{5\lambda}{2} = 0.33\,m$

$\lambda = \frac{0.66}{5}$




$v = f\lambda$

$f = \frac{v}{\lambda} = \frac{330}{\frac{0.66}{5}} = 2500\ Hz$

The speed of sound in air is 330 m s$^{-1}$.

What is the frequency of the sound and in which direction has the air at P been displaced from its mean position?

| | *frequency of sound* / Hz | *displacement of air at P* |
|---|---|---|
| **A** | 1000 | to the left |
| **B** | 2500 | to the left |
| **C** | 5000 | to the left |
| **D** | 1000 | to the right |
| **E** | 2500 | to the right |
| **F** | 5000 | to the right |

# Q14 ENGAA 2020

**14** P and Q are two fixed points on the surface of the ocean which are 6.0 m apart.

An ocean wave travels in the direction P to Q.

The wave has a frequency of 0.50 Hz and travels at a constant speed. $\rightarrow T = 2\,s$

A wave peak passes Q at time $t = 0$ s.

The next wave peak travelling towards Q passes P at time $t = 0.80$ s. $\rightarrow$ passes Q 2 s earlier

What is the speed of the wave?

$\Rightarrow$ Takes $(2 - 0.80) = 1.2\,s$ to go 6.0 m

**A** $2.1\,ms^{-1}$

**B** $3.4\,ms^{-1}$

**C** $5.0\,ms^{-1}$

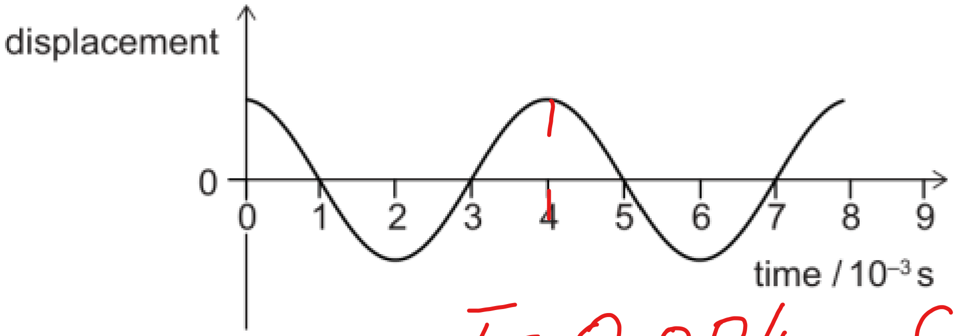
**D** $7.5\,ms^{-1}$

**E** $20\,ms^{-1}$

$v = \frac{s}{t} = \frac{6.0}{1.2} = 5\,m/s$

# Q26 ENGAA 2020

The graph shows how the displacement due to a wave in air varies with time.




$T = 0.004\,s,\ f = 250\,Hz$

The speed of the wave in air is $300\,m\,s^{-1}$.

$v = f\lambda$

$\lambda = \frac{v}{f} = \frac{300}{250} = 1.2\,m$

The wave now travels into water.

$$\frac{\text{wave speed in air}}{\text{wave speed in water}} = 0.2$$

What is the wavelength of the wave in water?

speed ×5 in water

$v = f \times \lambda$

$\uparrow \times 5 = \uparrow \times 5$

$\lambda = 1.2 \times 5 = 6.0\,m$

**A** $\frac{1}{6}$ m

**B** $\frac{2}{9}$ m

**C** $\frac{5}{6}$ m

**D** $\frac{9}{10}$ m

**E** $\frac{10}{9}$ m

**F** $\frac{6}{5}$ m

**G** $\frac{9}{2}$ m

H 6.0 m

# Q4 ENGAA 2019

**4** Two electromagnetic waves P and Q travel in a vacuum and the ratio of their wavelengths is:

$$\frac{\text{wavelength of P}}{\text{wavelength of Q}} = 1.0 \times 10^{8}$$

$f_p < f_q$

Which row in the table shows the ratio of their speeds, the ratio of their frequencies, and identifies the possible natures of P and Q?

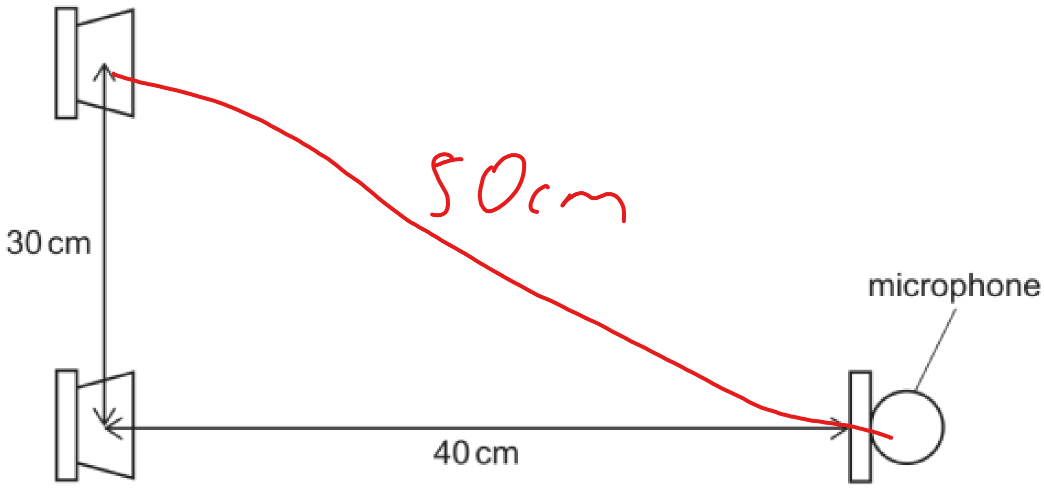
| | $\frac{\textit{speed of P}}{\textit{speed of Q}}$ | $\frac{\textit{frequency of P}}{\textit{frequency of Q}}$ | *nature of* P | *nature of* Q |
|---|---|---|---|---|
| **A** | 1.0 | $1.0 \times 10^{-8}$ | microwave | X-ray |
| **B** | 1.0 | $1.0 \times 10^{-8}$ | microwave | radio wave |
| **C** | 1.0 | $1.0 \times 10^{8}$ | infrared | ultraviolet |
| **D** | 1.0 | $1.0 \times 10^{8}$ | visible light | infrared |
| **E** | $1.0 \times 10^{8}$ | 1.0 | gamma | X-ray |
| **F** | $1.0 \times 10^{8}$ | 1.0 | gamma | infrared |
| **G** | $1.0 \times 10^{8}$ | $1.0 \times 10^{16}$ | infrared | radio wave |
| **H** | $1.0 \times 10^{8}$ | $1.0 \times 10^{16}$ | visible light | ultraviolet |

# Q30 ENGAA 2019

Two small loudspeakers are placed side by side 30 cm apart.

They are connected to the same signal generator so that they emit sound of frequency 400 Hz in phase with one another.

The sounds both reach a microphone placed 40 cm directly in front of one of the two loudspeakers as shown.




What is the phase difference between waves from the loudspeakers as they arrive at the microphone?

(speed of sound = $320\,\text{m}\,\text{s}^{-1}$)

$v = f\lambda$

$\lambda = \frac{v}{f} = \frac{320}{400} = 0.8\,\text{m}$

**A** 30°

**B** 36°

**C** 45°

**D** 60°

**E** 72°

**F** 90°

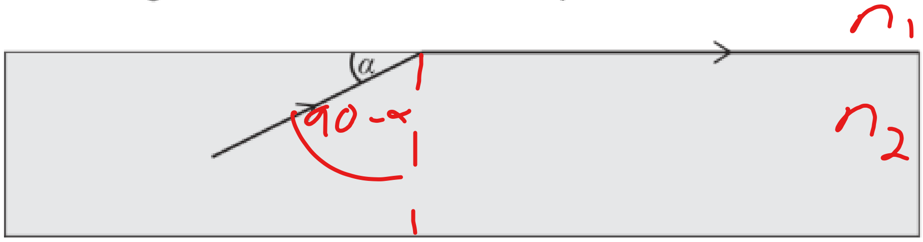
p.d. $= 0.5 - 0.4 = 0.1\,\text{m}$

$\frac{0.1}{0.8} \times 360 = 45°$

# Q38 ENGAA 2019

Light travelling in a transparent liquid strikes the surface from below. The angle between the surface of the liquid and the direction of travel of the light is $\alpha$.

The light then travels along the surface between the liquid and the air as shown in the diagram.




Now, light travelling in air strikes the surface from above so that the angle between the surface and the direction of travel of this light is also $\alpha$.

After the light strikes the surface from above, the angle between the surface and the direction of travel of the refracted light is $\beta$.

Which expression gives $\beta$?

(all angles are in degrees)

**A** $\cos\beta = \cos^2\alpha$

**B** $\cos\beta = \cos\alpha \sin^{-1}\left(\frac{1}{\alpha}\right)$

**C** $\sin\beta = \sin^2\alpha$

**D** $\beta = 90 - (90 - \alpha)^2$

**E** $\beta = 0$

**F** $\beta = \alpha$

$$\sin(90-\alpha) = \frac{1}{n_2}$$

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

$$\sin(90-\alpha) = n_2 \sin(90-\beta)$$

$$\sin(90-\alpha) = \frac{1}{\sin(90-\alpha)} \sin(90-\beta)$$

$$\cos^2\alpha = \cos\beta$$

$v = f\lambda \quad f = v/\lambda$

# Q6 ENGAA 2018

When travelling in a vacuum, visible light has a wavelength between 400 nm and 700 nm.

The speed of light in a vacuum is $3.0 \times 10^8 \text{ m s}^{-1}$. smallest $\lambda$ = max $f$

What can be concluded about **ultraviolet** radiation from this information?

$$f = \frac{3.0 \times 10^8}{400 \times 10^{-9}} = 7.5 \times 10^{14} \text{ Hz}$$

**A** It has a **maximum** frequency of $2.7 \times 10^{14}$ Hz

**B** It has a **maximum** frequency of $4.3 \times 10^{14}$ Hz

**C** It has a **maximum** frequency of $7.5 \times 10^{14}$ Hz ✓

**D** It has a **maximum** frequency of $1.0 \times 10^{15}$ Hz

**E** It has a **minimum** frequency of $2.7 \times 10^{14}$ Hz

**F** It has a **minimum** frequency of $4.3 \times 10^{14}$ Hz

**G** It has a **minimum** frequency of $7.5 \times 10^{14}$ Hz

**H** It has a **minimum** frequency of $1.0 \times 10^{15}$ Hz

# Q18 ENGAA 2018

goes up + down

**18** A transverse wave with an amplitude of 4.0 cm and a frequency of 10 Hz travels along a rope at a speed of $2.4 \text{ m s}^{-1}$.

$\hookrightarrow T = 0.1$ s

What is the total distance travelled by a particle in the rope in a time of 20 s?

$\hookrightarrow 200\,T$

**A** 2.4 m

**B** 4.8 m

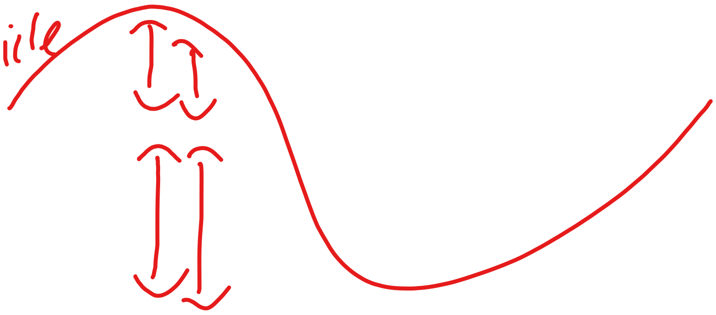
**C** 8.0 m

**D** 16 m

**E** 32 m

**F** 48 m

Each $T$ particle travels $4A$ $= 16$ cm $= 0.16$

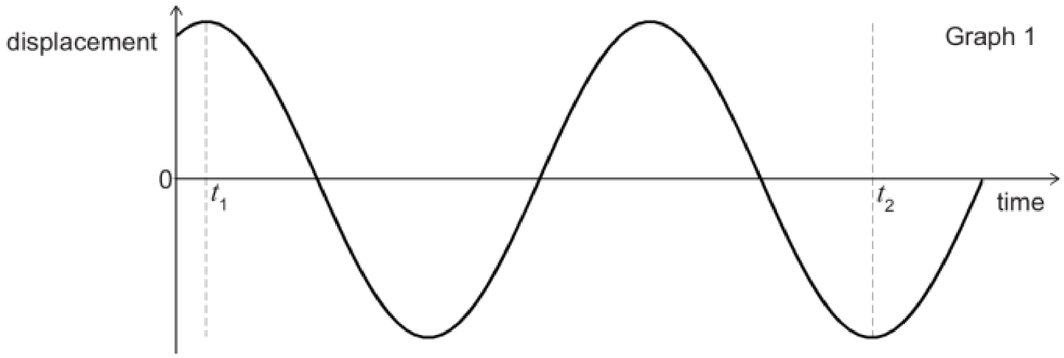


$0.16 \times 200 = 32$ m

# Q18 ENGAA 2017

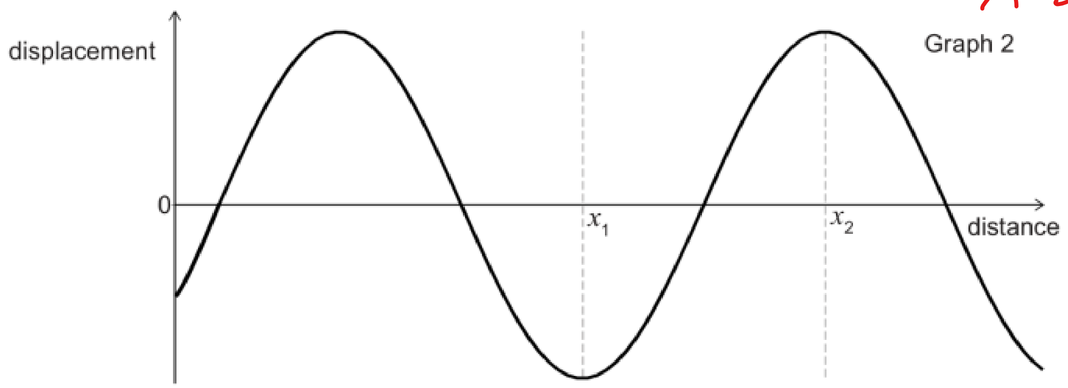
$\frac{3T}{2} = t_2 - t_1 \quad T = \frac{2(t_2 - t_1)}{3}$

**18** Graph 1 shows how the displacement of one of the particles of a medium varies with time in seconds as a wave travels through the medium.




Graph 2 shows how the displacement varies with distance in metres at one time for the same wave.

$\lambda = 2(x_2 - x_1)$




Which expression gives the speed in $\mathrm{m\,s^{-1}}$ of the wave?

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

$$v = \frac{\cancel{2}(x_2 - x_1)}{\frac{\cancel{2}(t_2 - t_1)}{3}} = \frac{3(x_2 - x_1)}{(t_2 - t_1)}$$

**A** $\dfrac{4(x_2 - x_1)}{3(t_2 - t_1)}$

**B** $\dfrac{3(x_2 - x_1)}{2(t_2 - t_1)}$

**C** $\dfrac{2(x_2 - x_1)}{t_2 - t_1}$

**D** $\dfrac{8(x_2 - x_1)}{3(t_2 - t_1)}$

**E** $\dfrac{3(x_2 - x_1)}{t_2 - t_1}$

**F** $\dfrac{6(x_2 - x_1)}{t_2 - t_1}$

$T = 0.2s$

## Q12 ENGAA 2016

**12** A transverse wave travelling through a medium has a frequency of 5.0 Hz, a wavelength of 4.0 cm and an amplitude of 3.0 cm.

What is the total distance travelled by a particle of the medium in one minute? → 300 T

in each T travels

$4A = 12cm$

$12 \times 300 = 3600cm$

**A** 900 cm

**B** 1200 cm

**C** 1800 cm

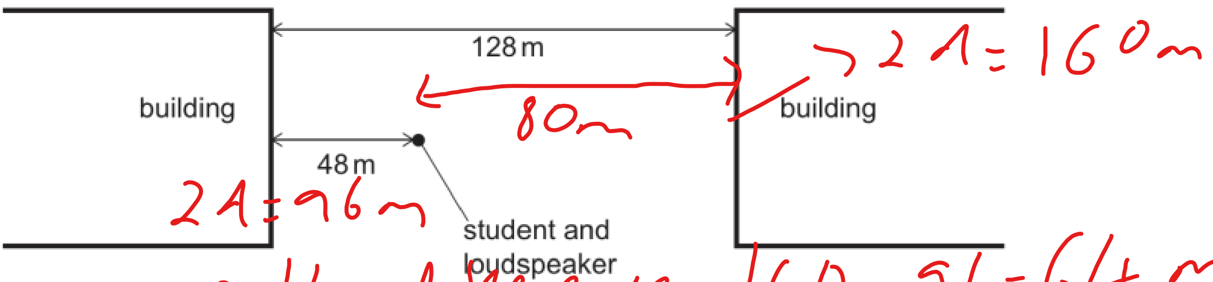
**D** 2400 cm

**E** 3600 cm

**F** 4800 cm

## Q28 ENGAA 2016

**28** A student carries out an experiment to measure the speed of sound. A loudspeaker that emits sound in all directions is placed between two buildings that are 128 m apart as shown. The student and loudspeaker are 48 m from one of the buildings.




path difference = 160 − 96 = 64 m

The loudspeaker is connected to a signal generator that causes it to emit regular clicks. The student notices that each click results in two echoes, one from each building. The rate at which the clicks are produced is gradually increased from zero until each echo coincides with a new click being emitted by the loudspeaker.

What is the frequency of emission of clicks when this happens?

(The speed of sound in air = 320 m s$^{-1}$.)

$\lambda = \frac{v}{f} = \frac{320}{f}$

**A** 2.0 Hz $\lambda = 160m$ ✗

**B** 2.5 Hz

**C** 3.3 Hz

**D** 4.0 Hz $\lambda = 80m$

**E** 5.3 Hz

**F** 6.7 Hz

**G** 10 Hz $\lambda = 32m$

want pd to be integer of λ and distance to buildings to be integer of λ