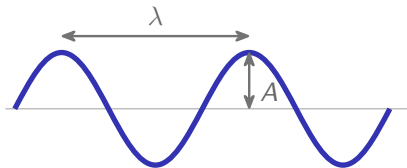


# Waves

AS Physics ■ Topic 7

A-Level Physics



# What we will cover

- 1 Progressive waves 7.1
- 2 Phase and the CRO 7.1.1
- 3 Transverse & longitudinal 7.2
- 4 Doppler effect 7.3
- 5 Electromagnetic spectrum 7.4
- 6 Polarisation 7.5
- 7 Recap





## Sheet 7.1 – what you need to know

### You must be able to:

- describe a **progressive wave** and what it transfers
- use displacement, amplitude, wavelength, period, frequency and speed
- read  $\lambda$ ,  $T$  and  $A$  off graphs against distance and against time
- derive  $v = f\lambda$  and use it with kHz, MHz and ms

### What the exam asks

“State what is meant by a progressive wave.” [1]

“Use the definitions of speed  $v$ , frequency  $f$  and wavelength  $\lambda$  to derive the wave equation  $v = f\lambda$ .” [2]

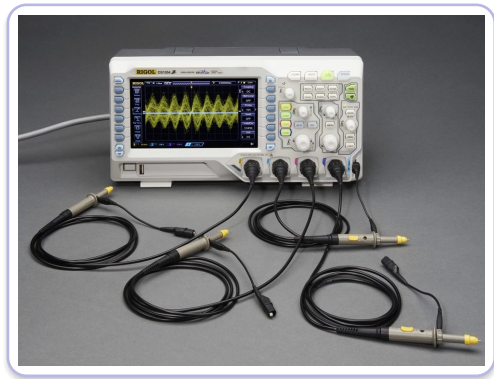
“Calculate the frequency, in GHz, of the microwaves.” [2]

*Practise on exercise sheet 7.1, then try the real exam questions on past-paper sheet 7.1.*

# What a wave is

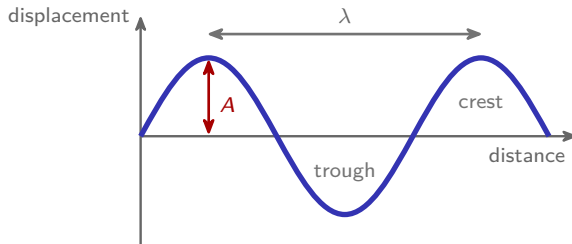
A **progressive wave** carries **energy** without moving matter overall.

- particles of the **medium** **oscillate** about rest positions
- only the disturbance **propagates**



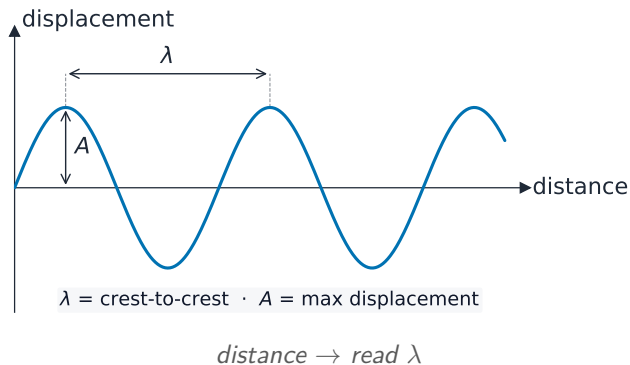
*Oscilloscope*

# Key terms



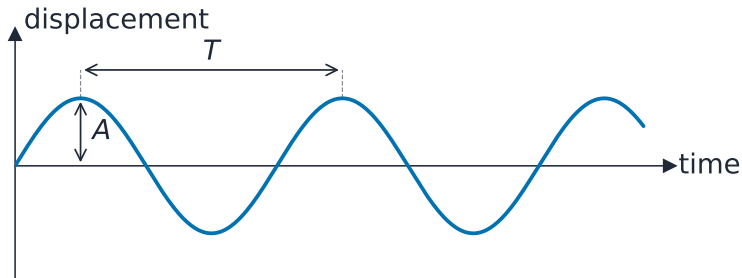
- **displacement**  $y$  – how far a particle has moved from rest *now*; a **vector**
- **amplitude**  $A$  – the largest displacement
- **wavelength**  $\lambda$  – shortest distance between two points **in phase**
- **period**  $T$  and **frequency**  $f = 1/T$ , in **hertz**
- **speed**  $v$  – how fast a **crest** travels
- **phase difference** – the fraction of a cycle between two oscillations, in **radians**

## Displacement against *distance*: read $A$ and $\lambda$



A snapshot of the whole wave at one moment – a **sine curve** for **both** kinds. For a longitudinal wave the axis is the small back-and-forth displacement *along* the direction of travel.

## Displacement against *time*: read $A$ and $T$



amplitude  $A$  = peak displacement · period  $T$  = time  
for one full cycle

One particle followed through time – also a sine curve. This is the graph that gives you  $T$ , and so  $f = 1/T$ .

## Reading the two graphs

- against **distance**: crest to crest is  $\lambda$
- against **time**: crest to crest is  $T$
- on either: the amplitude is from the middle to a crest, **not** crest to trough

**Read off:**  $\lambda = 0.80 \text{ m}$ ,  $T = 0.40 \text{ s}$ ,  $A = 3.0 \text{ cm}$

frequency:  $f = \frac{1}{T} = \frac{1}{0.40 \text{ s}} = 2.5 \text{ Hz}$

speed, the wave equation:

$$v = f\lambda = (2.5 \text{ Hz})(0.80 \text{ m}) = 2.0 \text{ m s}^{-1}$$

6.0 cm crest to trough is **twice** the amplitude.

# The wave equation

In one period the wave moves one wavelength:

$$v = \frac{\text{distance}}{\text{time}} = \frac{\lambda}{T} \xrightarrow{f = 1/T} v = f\lambda$$

$v = f\lambda$  holds for every progressive wave.

# The wave equation with prefixes

## Radio at 97.5 MHz

$$\lambda = \frac{v}{f} = \frac{3.00 \times 10^8 \text{ m s}^{-1}}{97.5 \times 10^6 \text{ Hz}} = 3.08 \text{ m}$$

## Ultrasound: 2.0 MHz in tissue at $1540 \text{ m s}^{-1}$

$$\lambda = \frac{v}{f} = \frac{1540 \text{ m s}^{-1}}{2.0 \times 10^6 \text{ Hz}} = 7.7 \times 10^{-4} \text{ m}$$

## Sound: $T = 5.0 \text{ ms}$ , $\lambda = 1.7 \text{ m}$

$$v = \frac{\lambda}{T} = \frac{1.7 \text{ m}}{5.0 \times 10^{-3} \text{ s}} = 340 \text{ m s}^{-1}$$

Convert the prefix first:  $\text{M} = 10^6$ ,  $\text{k} = 10^3$ ,  $\text{m} = 10^{-3}$ .



## Sheet 7.1.1 – what you need to know

### You must be able to:

- find the **phase difference** of two points or two oscillations
- read the period, frequency and amplitude off an **oscilloscope** trace
- use  $\text{intensity} = \frac{\text{power}}{\text{area}}$ , including a point source
- use  $\text{intensity} \propto \text{amplitude}^2$

### What the exam asks

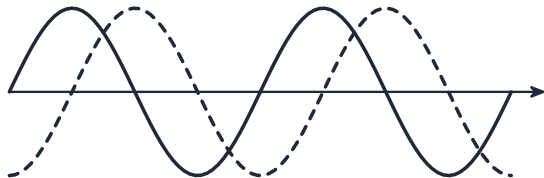
“State the phase difference between the oscillations of points R and T.” [1]

“Determine the time-base setting, in  $\text{s cm}^{-1}$ , of the CRO.” [2]

“Determine, in terms of  $I_0$ , the final intensity of the wave.” [2]

*Practise on exercise sheet 7.1.1, then try the real exam questions on past-paper sheet 7.1.1.*

## Phase, drawn



phase difference

Two points are **in phase** when they move together, and antiphase when one is exactly half a cycle behind.

Two points one wavelength apart are **in phase** (phase difference 0 or  $2\pi$ ); half a wavelength apart they are exactly **out of phase** ( $\pi$ ).

# Phase difference

$$\Delta\phi = \frac{x}{\lambda} \times 360^\circ$$

$$\Delta\phi = \frac{t}{T} \times 360^\circ$$

$360^\circ = 2\pi$  rad. Half a wavelength apart: **antiphase**,  $180^\circ$ .

**A wave with  $\lambda = 0.80$  m and  $T = 0.40$  s**

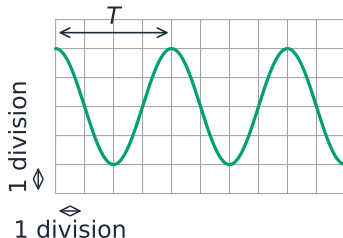
two points 0.30 m apart:

$$\Delta\phi = \frac{x}{\lambda} \times 360^\circ = \frac{0.30 \text{ m}}{0.80 \text{ m}} \times 360^\circ = 135^\circ, \text{ or } \frac{3}{4}\pi \text{ rad}$$

crests 0.10 s apart:

$$\Delta\phi = \frac{t}{T} \times 360^\circ = \frac{0.10 \text{ s}}{0.40 \text{ s}} \times 360^\circ = 90^\circ$$

# Reading a CRO trace



period =  $n \times$  timebase · peak voltage =  $n \times$  Y-gain

- a **cathode-ray oscilloscope** (CRO) plots voltage against time
- **time-base** : seconds per division across  $\rightarrow$  read  $T$
- **y-gain** : volts per division up  $\rightarrow$  read amplitude

5 ms/div, one cycle = 4 div

$$T = (4 \text{ div})(5 \text{ ms div}^{-1}) = 20 \text{ ms}$$

$$f = \frac{1}{T} = \frac{1}{0.020 \text{ s}} = 50 \text{ Hz}$$

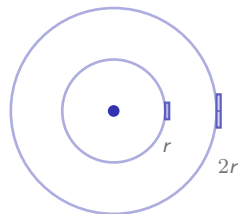
# Intensity

Power through unit area:

$$I = \frac{P}{A}, \quad I \propto (\text{amplitude})^2.$$

A **point source** spreads over a sphere  $4\pi r^2$ :

$$I = \frac{P}{4\pi r^2}, \quad I \propto \frac{1}{r^2}.$$



same power,  
4× the area  
 $\Rightarrow I/4$

**60 W lamp,  $r = 2.0$  m**

$$I = \frac{P}{4\pi r^2} = \frac{60 \text{ W}}{4\pi (2.0 \text{ m})^2} \\ \approx 1.2 \text{ W m}^{-2}$$



## Sheet 7.2 – what you need to know

### You must be able to:

- compare **transverse** and **longitudinal** waves, with examples
- find the compressions and rarefactions of a longitudinal wave
- read both kinds of wave off displacement graphs
- say which way a particle is moving at an instant

### What the exam asks

“By reference to the direction of transfer of energy, state what is meant by a longitudinal wave.”

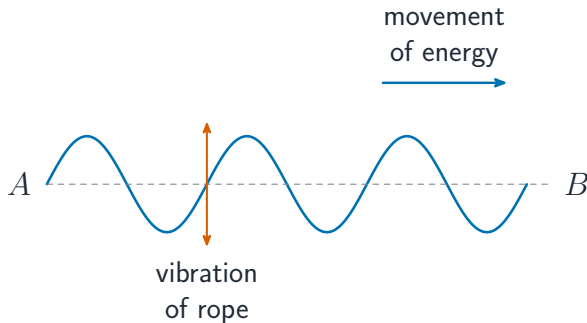
**[1]**

“Draw circles around two particles which are exactly one wavelength apart.” **[1]**

“State the direction of motion of particle Z at time  $t_0 + \frac{T}{4}$ .” **[1]**

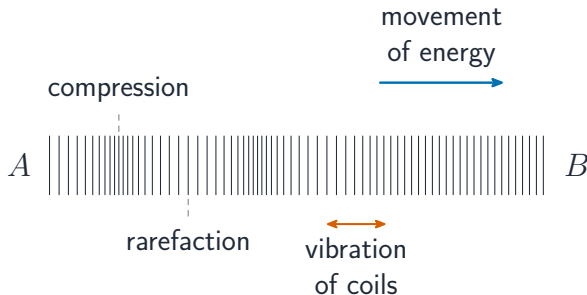
*Practise on exercise sheet 7.2, then try the real exam questions on past-paper sheet 7.2.*

# Transverse waves



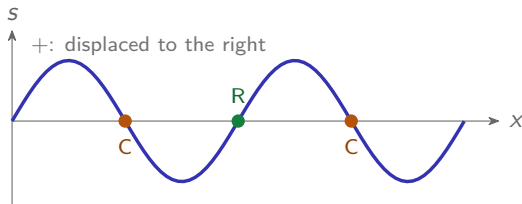
Particles **oscillate** perpendicular to the **energy** flow. Examples: a wave on a rope, all EM waves, S-waves.

# Longitudinal waves



Particles oscillate **parallel** to the energy flow. Made of **compressions** and **rarefactions**.  
Examples: sound, P-waves.

# Compressions on a displacement graph



- **compression** C: the particles on its left move right, those on its right move left; the curve crosses zero going **down**
- **rarefaction** R: they move apart; the curve crosses zero going **up**
- at a crest or a trough the displacement is largest, but the air is at normal pressure



## Sheet 7.3 – what you need to know

### You must be able to:

- explain why a moving source changes the **observed frequency**
- use  $f_o = \frac{f_s v}{v \pm v_s}$  with the right sign
- find the source's speed from the frequencies heard

### What the exam asks

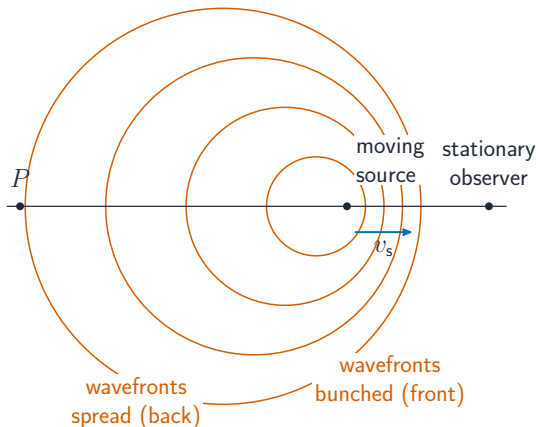
“Explain why the frequency of the sound detected by the observer is sometimes above and sometimes below 1.2 kHz.” [2]

“Determine the frequency, to three significant figures, of the sound heard by the child.” [2]

“Use Fig. 4.2 to determine the speed of the vehicle.” [3]

*Practise on exercise sheet 7.3, then try the real exam questions on past-paper sheet 7.3.*

# Doppler effect



A moving **source** changes the frequency a **stationary observer** hears, because the **wavefronts** ahead are squashed:

$$f_o = \frac{v f_s}{v \pm v_s}.$$

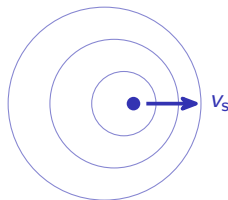
- towards → **minus**, wavefronts squashed,  $f_o$  higher
- away → **plus**, wavefronts spread out,  $f_o$  lower

## Worked example – a car horn

$$f_s = 800 \text{ Hz}, v_s = 30 \text{ m s}^{-1} \text{ towards you, } v = 340 \text{ m s}^{-1}$$

$$f_o = \frac{f_s v}{v - v_s} = \frac{(800 \text{ Hz})(340 \text{ m s}^{-1})}{340 \text{ m s}^{-1} - 30 \text{ m s}^{-1}} \approx 877 \text{ Hz}$$

Higher than 800 Hz – as expected for approach.



bunched ahead



## Sheet 7.4 – what you need to know

### You must be able to:

- state that all EM waves are **transverse** and travel at  $c$
- order the regions from radio waves to  $\gamma$ -rays
- use  $c = f\lambda$ , and recall visible light is 400 to 700 nm

### What the exam asks

“State the name of the principal region of the electromagnetic spectrum for the wave.” [1]

“Calculate the frequency, in THz, of the wave.” [2]

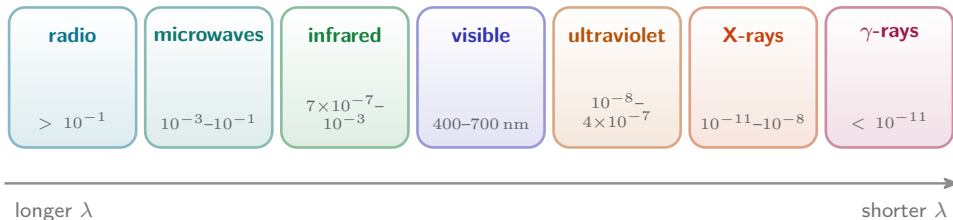
“State whether the frequency of the red light is greater than, less than or the same as the frequency of the original light.” [1]

*Practise on exercise sheet 7.4, then try the real exam questions on past-paper sheet 7.4.*

# The electromagnetic spectrum

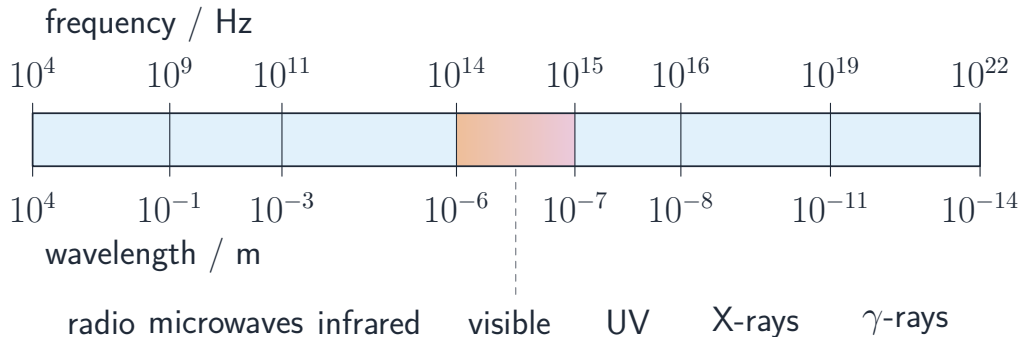
All **electromagnetic waves** are **transverse** and travel in a **vacuum** at  $c = 3.00 \times 10^8 \text{ m s}^{-1}$ .

Use  $c = f\lambda$ .



The boundaries are **not sharp**. Learn the orders of magnitude, not the edges.

# The electromagnetic spectrum, in detail



One family, one speed: only the wavelength changes across it.

## Which region of the spectrum?

**A wave of frequency  $2.5 \times 10^{14}$  Hz**

$$\lambda = \frac{c}{f} = \frac{3.00 \times 10^8 \text{ m s}^{-1}}{2.5 \times 10^{14} \text{ Hz}} = 1.2 \times 10^{-6} \text{ m}$$

just longer than red light: **infrared**

**A wave of wavelength  $8.4 \times 10^{-6}$  m**

$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^8 \text{ m s}^{-1}}{8.4 \times 10^{-6} \text{ m}} = 3.6 \times 10^{13} \text{ Hz} \\ = \text{36 THz, also infrared}$$

Visible light is 400 to 700 nm, about  $4 \times 10^{14}$  to  $7.5 \times 10^{14}$  Hz: work from there.



## Sheet 7.5 – what you need to know

### You must be able to:

- explain why only **transverse** waves can be polarised
- use **Malus's law**  $I = I_0 \cos^2 \theta$ , forwards and backwards
- link the transmitted intensity to the amplitude,  $I \propto A^2$
- apply Malus's law once for each filter

### What the exam asks

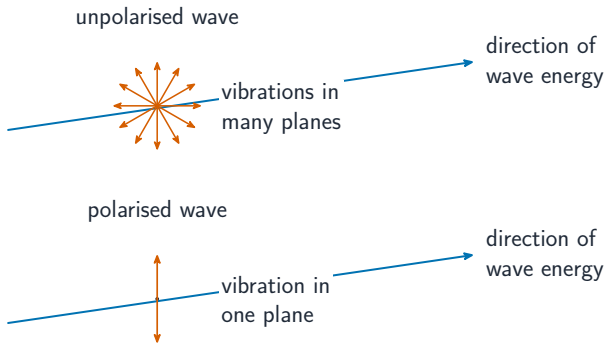
“State the meaning of polarisation.” **[1]**

“State why light waves can be plane polarised but sound waves cannot.” **[1]**

“Calculate the angle of rotation of filter B from its starting position.” **[3]**

*Practise on exercise sheet 7.5, then try the real exam questions on past-paper sheet 7.5.*

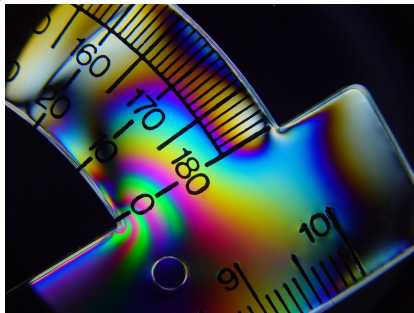
# Polarisation



**Polarisation** : oscillation confined to **one plane**. Light that has been through a **polarising filter** is **plane-polarised** ; the filter passes the part along its **transmission axis** .

Only **transverse** waves polarise. Sound (longitudinal) cannot – a useful test.

## Polarisation put to work



Stressed plastic between crossed polarisers: the plastic rotates the plane of polarisation by an amount that depends on the stress, so the colour fringes map where the material is loaded.

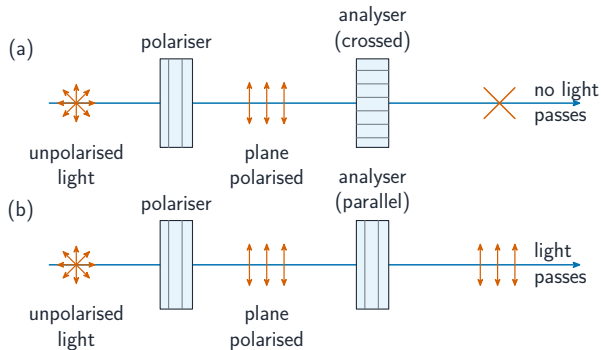
# Malus's law

Through a filter at angle  $\theta$  to the polarisation:

$$I = I_0 \cos^2 \theta.$$

$$I_0 = 12 \text{ W m}^{-2}, \theta = 30^\circ$$

$$\begin{aligned} I &= I_0 \cos^2 \theta \\ &= (12 \text{ W m}^{-2}) \cos^2 30^\circ \\ &= 9.0 \text{ W m}^{-2} \end{aligned}$$



Crossed filters (a) block the light; parallel filters (b) let it pass

## Malus's law backwards, and the amplitude

**For what  $\theta$  is the intensity halved?**

$$\cos^2 \theta = \frac{I}{I_0} = 0.5, \text{ so } \cos \theta = \sqrt{0.5} \text{ and } \theta = 45^\circ$$

**A filter passes  $I = 0.25 I_0$ : the amplitude?**

$$I \propto A^2: \\ A = A_0 \sqrt{\frac{I}{I_0}} = A_0 \sqrt{0.25} = 0.50 A_0$$

**Two filters:  $30^\circ$ , then  $60^\circ$  further**

once per filter, each angle from the axis before it:

$$I_1 = I_0 \cos^2 30^\circ = 0.75 I_0$$

$$I_2 = I_1 \cos^2 60^\circ = 0.75 I_0 \times 0.25 = 0.19 I_0$$

Crossed filters,  $90^\circ$  apart, pass nothing.



## Exam tips

- Define terms precisely (displacement, amplitude, wavelength, period, frequency) and use  $v = f\lambda$ .
- Distinguish **transverse** (vibration perpendicular to travel) from **longitudinal** (parallel); only transverse waves can be **polarised**.
- For the **Doppler effect**, the observed frequency **rises** as the source approaches and falls as it recedes.
- Learn the **electromagnetic spectrum** order; all its waves travel at  $c$  in a vacuum.

## Topic 7 – key takeaways

1

### Wave equation

$$v = f\lambda; \text{ intensity} \propto \text{amplitude}^2, \\ \propto 1/r^2$$

2

### Two types

transverse  $\perp$ , longitudinal  $\parallel$  to  
energy

3

### Doppler

moving source shifts the heard  
frequency

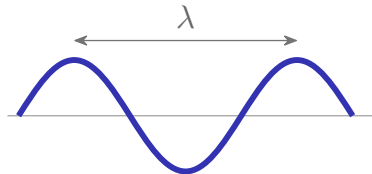
4

### Polarisation

one plane; only transverse;  $I =$   
 $I_0 \cos^2 \theta$

## Check yourself

- 1 A wave has  $f = 50 \text{ Hz}$ ,  $\lambda = 6.0 \text{ m}$  – find  $v$ .
- 2 Can a sound wave be polarised?
- 3 Source moves away – does the pitch rise or fall?
- 4 Light through a filter at  $90^\circ$  – how much passes?



**Answers** 1.  $v = f\lambda = 300 \text{ m s}^{-1}$  2. no (longitudinal) 3. falls  
4. none ( $\cos^2 90^\circ = 0$ )