EM radiations

- **describe light as an electromagnetic wave which is produced by the acceleration of charges, which in turn produces changing electric fields and associated changing magnetic fields.**
- **identify that all electromagnetic waves travel at the same speed, *c*, in a vacuum.**
- **compare the wavelength and frequencies of different regions of the electromagnetic spectrum, including radio, microwave, infrared, visible, ultraviolet, x-ray and gamma, and identify the distinct uses each has in society.**

Polarisation

- **explain polarisation of visible light and its relation to a transverse wave model**

Refraction TIR

- **investigate and analyse theoretically and practically the behaviour of waves including:**

  – refraction using Snell's Law: $n_1\sin(\theta_1) = n_2\sin(\theta_2)$ and $n_1v_1 = n_2v_2$

  – total internal reflection and critical angle including applications:

  $n_1\sin(\theta_c) = n_2\sin(90°)$

Dispersion

- **investigate and explain theoretically and practically colour dispersion in prisms and lenses with reference to refraction of the components of white light as they pass from one medium to another.**

Production of light

- **compare the production of light in lasers, synchrotrons, LEDs and incandescent lights.**

Paper	Multiple choice	Short Answer	Idea	Marks	%	Type
2022	12		n for TIR, given θ	1	51%	Calculation
	16		Polarisation properties	1	80%	Concept
		13a	Refraction concept		49%	Calculation
		13b	Dispersion effects		57%	Explanation
2022 NHT	13		Critical angle	1	NA	Calculation
	14		Perpendicular axes	1	NA	Concept
	18		Laser operation	1	NA	Concept
		14a	$n_1v_1 = n_2v_2$	1	NA	Concept
		14b	Critical angle	3	NA	Calculation
2021	14		EM Spectrum	1	70%	Concept
	15		Dispersion principle	1	67%	Concept
		11	Polarisation perpendicular axes	2	64%	Explanation
		12a	Angle of refraction	2	67%	Calculation
		12b	Critical angle	3	38%	Explanation

2021 NHT	15		Polarisation properties	1	NA	Concept
		13a	Refraction concept	1	NA	Concept
		13b	Critical angle	3	NA	Calculation
2020		14	EM basic concept	3	70%	Concept
2019	9		$n_1v_1 = n_2v_2$	1	73%	Concept
	10		$n_1\sin i = n_2\sin r$	1	75%	Calculation
	17		Incoherent/coherent	1	74%	Concept
		14c	Polarisation definition	2	53%	Explanation
		15a	Dispersion concept	3	54%	Concept
		15b	Refraction of two colours	1	68%	Concept
2019 NHT	10		Refraction concept	1	NA	Concept
	11		Polarisation properties	1	NA	Concept
	12		EM basic concept	1	NA	Concept
	14		EM basic concept	1	NA	Concept
		12a	Refraction concept	1	NA	Concept
		12b	Critical angle	2	NA	Calculation
2018	16		Polarisation properties	1	84%	Concept
		12b	Critical angle	2	73%	Calculation
		12c	$n_1v_1 = n_2v_2$	2	48%	Calculation
2018 NHT	13		Polarisation properties	1	NA	Concept
	14		Speed of EM waves	1	NA	Concept
	15		EM Spectrum	1	NA	Concept
2017		14a	Critical angle	2	81%	Calculation
		14b	Critical angle	2	37%	Concept
		14c	Critical angle	2	56%	Explanation

Light as an EM wave questions can be grouped into the following ideas.

Basic properties and definitions	Worked example 1

Polarisation questions can be grouped into the following ideas.

Properties and definitions	Worked example 2

Refraction and TIR questions can be grouped into the following ideas.

Basic concepts	Worked example 3
Snell's law, $n_1 \sin i = n_2 \sin r$	Worked example 4
Snell's law, $n_1 v_1 = n_2 v_2$	Worked example 5
Critical angle	Worked example 6

Dispersion questions can be grouped into the following ideas.

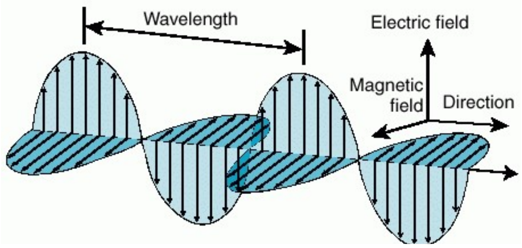
Basic concepts	Worked example 7

Production of light questions can be grouped into the following ideas.

Incoherent/coherent	Worked example 8
Laser	Worked example 9

EM Radiations

Maxwell discovered that light was an EM radiation in the frequency range of 4.3×10^{14} to 7×10^{14} Hz. He understood that light of any kind is energy-carrying waves of electric and magnetic fields that continually regenerate each other and travel at a single fixed speed, the speed of light.



An accelerating charge creates a changing current. Every current is surrounded by a magnetic field, so every changing current is surrounding by a changing magnetic field. We also know that every changing magnetic field will induce an EMF, in other words, generates an electric field. This is electromagnetic induction.

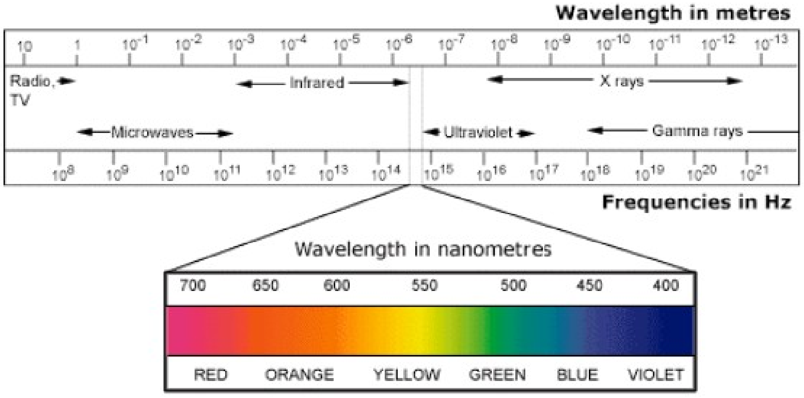
If the magnetic field is oscillating, the electric field that it generates will be oscillating, too. This oscillating electric field induces an oscillating magnetic field. The vibrating electric and magnetic fields regenerate each other to make up an **electromagnetic wave**, which emanates from the vibrating charge.

In summary, light is an energy carrying electromagnetic wave that emanates from vibrating electrons in atoms.

Speed of Light

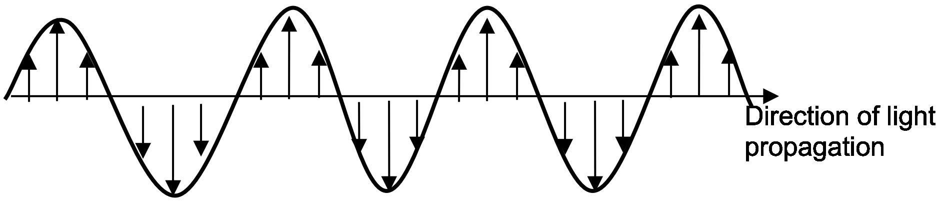
There is only one speed for which the electric and magnetic fields remain in perfect balance, reinforcing each other as they carry energy through space. If light were to slow down, its changing electric field would generate a weaker magnetic field, which in turn, would generate a weaker electric field, and so on, until the wave dies out. This would result in a loss of energy, which is incompatible with the law of conservation of energy. So light can't slow down (or speed up).

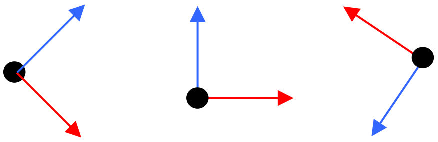
Electromagnetic spectrum



Polarisation

Light is a transverse electromagnetic wave. The diagram below is a snapshot of an electromagnetic wave. As the light propagates to the right, the electric field oscillates up and down as shown. There is a magnetic field oscillating into and out of the page, which is not shown.

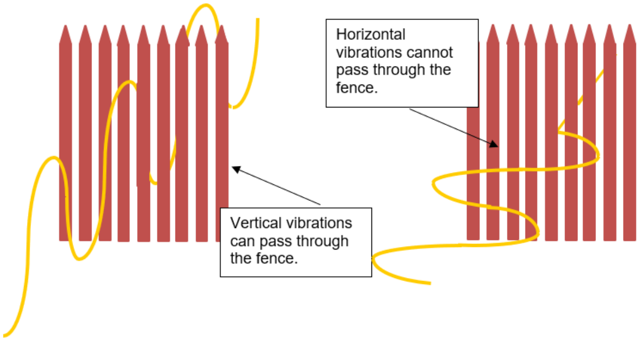




The direction of oscillation of the electric field is called the polarization of the light. In a beam of light from most sources the light is unpolarised, which means that the electric fields of the light are oscillating in many different directions. Consider the diagram on the right. The light is travelling into the page. It is possible for the electric fields (blue arrows) and the magnetic fields (red arrows) to be oscillating in any direction, including the three shown. In unpolarised light, all of these directions are present at the same time.

Polarising Light

Consider a string that is passing through a wire grid. Wave passes are sent along the string in two directions as shown below.



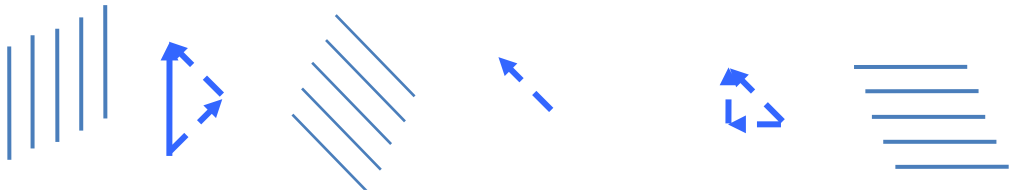
Horizontal vibrations cannot pass through the fence.

Vertical vibrations can pass through the fence.

In a similar way, optical devices called polarisers only allow light with a specific polarisation to pass through them. The plane of polarisation is defined as the plane of the electric field.

How do three polarising filters work?

The first filter only allows the electric field through in one direction. Let us assume that it is vertical.



This electric field can be resolved into two perpendicular components.

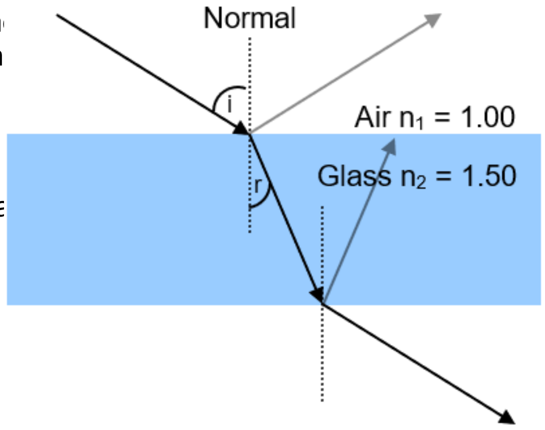
This component of the electric field can pass through the middle polariser.

This electric field can again be resolved into two perpendicular components.

This component of the electric field can pass through the middle polariser.

Hence some light can pass through the three filters, but not through two. You just have to love vectors!

Refraction of Light



A ray of light travels along a straight path within the same m
However, when a ray of light enters one medium from anoth
the point of incidence.

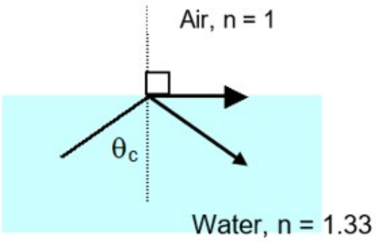
Refraction is the bending of the light path as it passes from one transparent material to another.
The amount of refraction can be determined using Snell's La

$n_1 \sin i = n_2 \sin r$ or $\frac{\sin i}{\sin r} = \frac{n_2}{n_1} = \frac{v_1}{v_2}$

Where v = speed of light in medium 1,
v_2 = speed of light in medium 2,
n_1 = absolute refractive index of medium 1
n_2 = absolute refractive index of medium 2

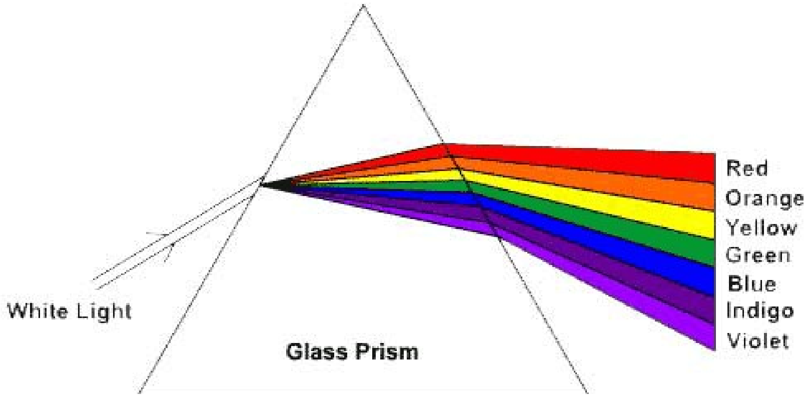
The Critical Angle

The critical angle is the angle at which the refracted way will skim across the surface of the material (the orange ray above). For angles of incidence greater than this critical angle, the ray will be totally internally reflected. The critical angle can be calculated using *Snell's Law*.



$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$
$$1.33 \sin\theta_c = 1 \sin 90$$
$$\sin\theta_c = \frac{1}{1.33}$$
$$\theta_c = 48.8$$

White Light



White light is made up of all of the colours of the visible spectrum. The light can be split into its constituent colours by shining it through a prism. The refractive index of a material depends on the wavelength of light travelling through the material. There is a large difference in speed (depending on wavelength) and therefore a large difference in the angle of refraction. The effect that this has is to separate the colours of white light. Red light (with its long wavelength) travels fastest ($v = f\lambda$) in glass, so it bends less. This process is known as **dispersion**.

My mnemonic for remembering this is r**e**d b**e**nds l**e**ss, The only vowel is **e**.

Coherent light

A beam of photons having the same frequency, phase, and direction – that is, a beam of identical photons – is said to be **coherent**. A beam of coherent light spreads and weakens very little.

Incoherent light

Light emitted by a common lamp is incoherent, that is, photons of many frequencies and in many phases of vibration are emitted. A beam of incoherent light spreads out after a short distance, becoming wider and less intense with increased distance.

Monochromatic light

Even if the beam is filtered so that it is formed with a single frequency waves (monochromatic), it is still incoherent, for the waves are out of phase with each other. The wave spreads and becomes weaker with distance.

Laser

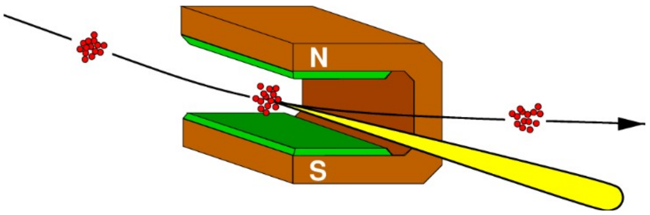
A laser is a device that produces a beam of coherent light. The laser is a converter of energy that takes advantage of the process of stimulated emission to concentrate a certain fraction of its energy (commonly 1%). Electrons are stimulated to rise to a higher energy level. On return to their original level, they release the energy difference as light of a single frequency in a single direction.

Synchrotron Radiation

As a particle accelerates it releases energy in the form of electromagnetic radiation. This reduces the particle's energy, and thus slows the particle down, more energy is then required to accelerate it. In order to get particles up to near the speed of light this acceleration process needs to occur over a long distance. It is more convenient to bend the path around in a circle so that the particles can be accelerated round and round a loop. Because of this most particle accelerators are often circular (synchrotrons). Unfortunately, more radiation is released in this bending process.

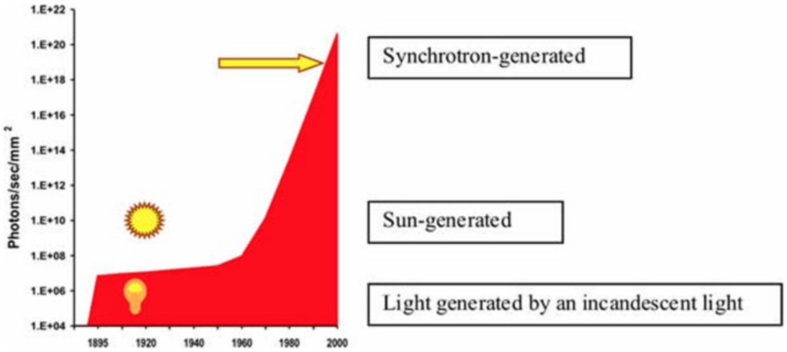
In order to bend the electron beam it is placed in a magnetic field, the black line shows the path of the electron beam, the yellow shows that the electromagnetic radiation is emitted tangentially to the path of the electrons. The right hand slap rule can be used to determine the direction the beam will bend.

Electrons that are accelerated through a circular arc by magnetic fields and release radiation while they are moving in the circular arc.



The radiation that comes off a synchrotron can be manipulated by how tight the bend is, and this radiation can be very useful for different purposes.

Synchrotrons can emit a broad range of electromagnetic radiation, from microwaves to X-rays, with the potential to be tuned to a required frequency. On top of this they have a high intensity or brightness, and the beam is coherent (the light waves are synchronised).



Synchrotron Light

- Is produced in the range of wavelengths (λ) from 10^{-11} (hard X-rays) to10^{-1} m (microwaves). These photons have energies respectively from 10^{5} eV (hard X-rays) down to 10^{-5} eV (microwaves).
- It is of high intensity (brilliance)
- Emitted in short pulses.
- Arrives in parallel rays (collimated)
- Is coherent (all photons are in phase – wave property)
- Highly polarised (limited to a single plane for direction of wave vibration)

Light emitting Diodes

Light Emitting Diodes **(LED's)** are diodes that emit light when a current passes through them at a suitable voltage. Their V-I graphs are like that of an ordinary diode.

How LED's produce light

When an LED is provided with a voltage, electrons are able to jump the band-gap width. The light emitted is from the transition of electrons back from the conduction band to the valence band.

The band gap energy determines the energy and hence, the colour of the light emitted.

Output characteristics of an LED

The amount of output light emitted by the LED is directly proportional to the amount of forward current flowing through the LED.

Incandescent lights

Incandescence is the term used to describe light that is produced as a result of high temperatures. The energy causes the atoms of the filament to gain kinetic energy and some of the energy is absorbed by the atom's electrons. The electrons rise to a higher energy level and as they return to their original energy level, they release the energy difference as light.

The peak frequency of radiant energy is proportional to the absolute temperature of the heated substance. Typically incandescent lights contain an infinite number of frequencies, spread across the spectrum.

Worked example 1: EM radiations: Basic concepts.

1989 Question 27, 2 marks

Which of the following **(A - C)** below is greater for red light travelling through a vacuum, than for blue light travelling through a vacuum?

A. Frequency.

B. Speed of propagation.

C. Wavelength. (One or more answers)

Solution

Both colours will have the same speed in a vacuum, but both the frequency and wavelength will depend on colour. The wavelength of red light is greater than for blue light.

∴ **C (ANS)**

Current study design:

2021 Question 14 (70%)

2020 Question 14 (72%)

2019 NHT Question 12

2019 NHT Question 14

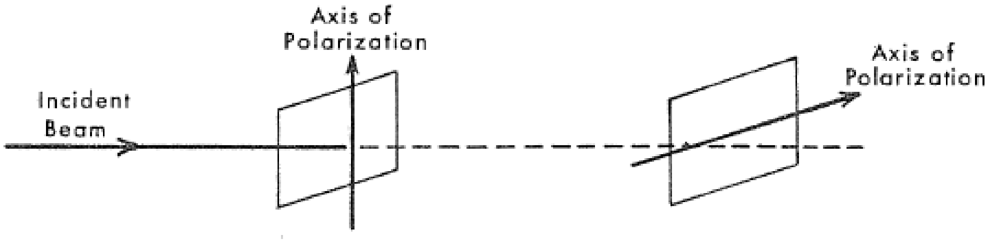
2018 Question 19a (70%)

2018 NHT Question 14

2018 NHT Question 15

Worked example 2: Polarisation: Properties, definitions.

The axes of polarization of two perfect polarizers are perpendicular to each other, as shown in the diagram.



1977 Question 74, 1 mark

Which of the following statements correctly describes the effect of the polarizers on the beam?

A. The transmitted light will be unpolarized.

B. The light transmitted by the first polarizer will be stopped by the second.

C. The light transmitted by the first polarizer will also be transmitted by the second.

D. Light transmitted through the first polarizer will be de-polarized by the second one.

Solution

The components of the electric fields in both vertical and horizontal directions will be blocked.

∴ **B (ANS), (72%)**

Current study design:

2022 Question 16 (80%)

2022 NHT Question 14

2021 Question 11 (64%)

2021 NHT Question 15

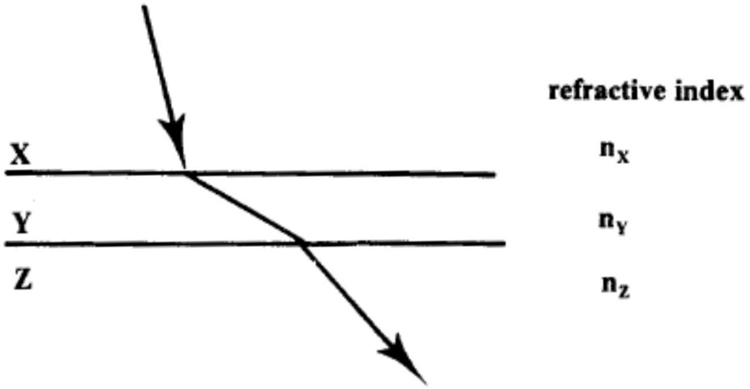
2019 Question 14c (53%)

2019 NHT Question 11

2018 Question 16 (84%)

2018 NHT Question 13

Worked example 3: Refraction: Basic concepts.



A narrow beam of light passes through materials, X, Y and Z,

1982 Question 34, 1 mark

Which of the following statements about the refractive indices is correct?

A. $n_Z > n_Y > n_X$

B. $n_Y > n_X$ and $n_Y > n_Z$

C. $n_X > n_Z > n_Y$

D. $n_Z > n_X > n_Y$

Solution

The light bends away from the normal as it goes from X to Y, therefore, $n_X > n_Y$.
The light bends towards the normal as it goes from Y to Z, therefore, $n_Z > n_Y$.
Comparing the angles in X and Y, the light bends away from the normal, therefore, **$n_X > n_Z$.**

$\therefore n_X > n_Z > n_Y$

$\therefore$ C (ANS), (64%)

Current study design:

2022 NHT Question 14a

2021 NHT Question 13a

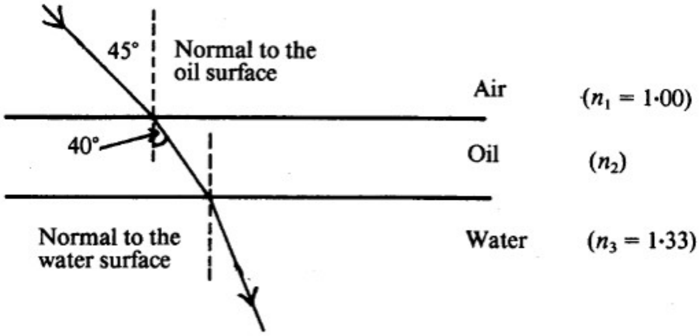
2019 NHT Question 10

2019 NHT Question 12a

2017 Question 14b (37%)

Worked example 4: Refraction: Snell's Law, $n_1 \sin i = n_2 \sin r$.

A ray of monochromatic yellow light passes from air into a layer of oil floating on the water surface as shown in the diagram. The light then emerges from the oil into the water below. The refractive indices for the yellow light are shown on the diagram.



1986 Question 33, 1 mark

Calculate the value of n_2, the absolute index of refraction for the oil.

Solution

Use $n_1 \sin i = n_2 \sin r$

$\therefore 1.0 \times \sin 45 = n_2 \sin 40$

$\therefore n_2 = 1.10$ (ANS)

Current study design:

2022 Question 13a (49%)

2021 Question 12a (67%)

2019 Question 10 (75%)

Worked example 5: Refraction: Snell's Law, $n_1 v_1 = n_2 v_2$.

1986 Question 34, 1 mark

Calculate the value of the ratio: $\dfrac{\text{speed of the yellow light in water}}{\text{speed of the yellow light in air}}$

Solution

Use $n_1 v_1 = n_2 v_2$

$\therefore \dfrac{v_{water}}{v_{air}} = \dfrac{v_{water}}{v_{air}}$

$\therefore \dfrac{1}{1.33} = 0.75$

$\therefore 0.75$ (ANS)

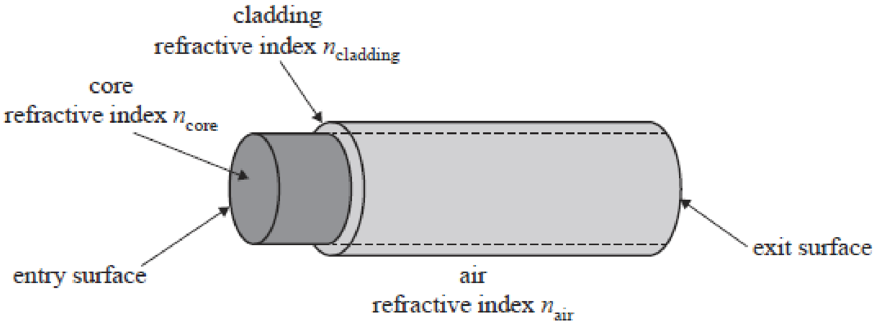
Current study design:

2019 Question 9 (73%)

2018 Question 12c (48%)

Worked example 6: Refraction: Snell's Law, critical angle.

A step-index optical fibre is shown below. Take n_{air} to equal 1.



2016 Question 4, 2 marks

Which of the following combinations gives a critical angle for the core and cladding closest to 83°?

A. $n_{core} = 1.31$, $n_{cladding} = 1.32$

B. $n_{cladding} = 1.71$, $n_{core} = 1.73$

C. $n_{core} = 1.71$, $n_{cladding} = 1.73$

D. $n_{cladding} = 1.31$, $n_{core} = 1.32$

Solution

For a critical angle to exist in the core,

$n_{cladding} < n_{core}$.

Use $n_1 \sin i = n_2 \sin r$

$\therefore 1.73 \sin i_c = 1.71 \times \sin 90$

$\therefore \sin i_c = \frac{1.71}{1.73}$

$\therefore i_c = 81.3°$

or

$\therefore 1.32 \sin i_c = 1.31 \times \sin 90$

$\therefore \sin i_c = \frac{1.31}{1.32}$

$\therefore i_c = 82.9°$

∴ D (ANS), (54%)

Current study design:

2022 Question 12 (51%)

2022 NHT Question 13

2022 NHT Question 14b

2021 Question 12b (38%)

2021 NHT Question 13b

2019 NHT Question 12b

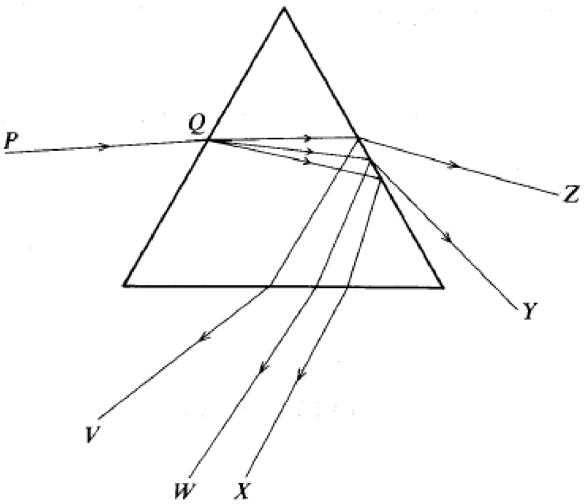
2018 Question 12b (73%)

2017 Question 14a (81%)

2017 Question 14c (56%)

Worked example 7: Dispersion: Basic concepts.

A mixed beam of red and blue light is incident to a glass prism along the path PQ as shown below.



The paths of the emerging beam of red light are marked as W and Y on the diagram.

1985 Question 35, 1 mark

Which of the choices (**A - E**) could represent the path of the blue light emerging from the prism?

A. X

B. W

C. V and Z

D. W and Y

E. V

Solution

The blue light will bend more than red light on entering the prism. Therefore, when it leaves the prism, it will pass through X.

∴ A (ANS), (60%)

Current study design:

2022 Question 13b (57%)

2021 Question 15 (67%)

2019 Question 15a (54%)

2019 Question 15b (68%)

Worked example 8: Production of light: Incoherent/coherent.

2016 Question 1, 2 marks

Which of the following best describes a source and mechanism of wide-spectrum incoherent light emission?

	Source	Mechanism
A.	a star (such as the sun)	stimulated photon emission by electron collisions
B.	an incandescent light	random thermal motion of valence electrons in collisions
C.	a laser	transition of electrons from the valence band
D.	a light-emitting diode (LED)	stimulated emission of photons

Solution

The light emitted by the sun is incoherent but not by stimulated photon emission. Lasers and LED's are not wide spectrum.

∴ B (ANS), (48%)

Current study design:

2022 NHT Question 18

Worked example 9: Production of light: Laser.

2015 Question 3, 2 marks

Which one of the following best describes laser light and its production?

A. Many photons are emitted from different atoms, with the same wavelength but not in phase.

B. Many photons are emitted from one atom, with photons of the same wavelength and in phase.

C. Many photons are emitted from different atoms, with photons of the same wavelength and in phase.

D. Many photons are emitted from different atoms, with photons all with the same direction but not in phase.

Solution

The stimulated emission is from many atoms, but the light is in phase and of a single wavelength.

∴ C (ANS), (71%)

Current study design:

2019 Question 17 (74%)
