Physics 30 Unit C diploma pack: Electromagnetic radiation

This pack gets you ready for the Unit C questions on the Physics 30 diploma exam. You can work through it on your own, at your own speed.

1. Do the start check.
2. Tick the checklist.
3. Do each card you need: read the steps, follow the worked example, then answer the questions.
4. Hand in each card check.
5. When your Part 1 cards are done, ask for Quiz 1. When your Part 2 cards are done, ask for Quiz 2.
6. Do the practice unit check and the exam-style question sets at the end. Then ask for the unit final.

1. Start check

Do these questions first, one for each card. If you get a question right, you may skip that card. If you get it wrong, or you guessed, do that card.

Start check 1 (card 1)

An FM radio station sends out waves with a frequency of 1.00×10^{8} Hz. The wavelength of these waves is

A. 3.00 m
B. 0.333 m
C. 3.00×10^{16} m
D. 1.00 m

Start check 2 (card 2)

In a rotating-mirror experiment with an eight-sided mirror, the light travels to a far mirror and back. The observer first sees the light when, in that time, the mirror has made

A. one whole turn
B. one quarter of a turn
C. one half of a turn
D. one eighth of a turn

Start check 3 (card 3)

An object is 30.0 cm in front of a concave mirror with a focal length of 10.0 cm. The image is

A. 15.0 cm from the mirror and real
B. 15.0 cm from the mirror and virtual
C. 7.5 cm from the mirror and real
D. 20.0 cm from the mirror and virtual

Start check 4 (card 4)

An object is placed closer to a converging lens than its focal point. The image is

A. real and inverted
B. real and erect
C. virtual and erect
D. virtual and inverted

Start check 5 (card 5)

A ray of light in air meets water (n = 1.33) at an angle of incidence of 30.0°. The angle of refraction is

A. 41.7°
B. 22.1°
C. 30.0°
D. 22.6°

Start check 6 (card 6)

Total internal reflection can happen when light travels

A. from air into glass
B. from air into water
C. from water into glass
D. from glass into air

Start check 7 (card 7)

Which observation shows that light is a transverse wave?

A. Light reflects from a mirror
B. Light can be polarized
C. Light travels in straight lines
D. Light travels through a vacuum

Start check 8 (card 8)

A diffraction grating has 2.00×10^{5} lines per metre. The distance d between its lines is

A. 2.00×10^{5} m
B. 2.00×10^{-5} m
C. 5.00×10^{-6} m
D. 5.00×10^{-5} m

Start check 9 (card 9)

Light has a frequency of 6.00×10^{14} Hz. Use $h = 4.14 \times 10^{-15}$ eV·s. The energy of one photon of this light is

A. 2.48 eV
B. 1.45 eV
C. 6.90 eV
D. 3.98 eV

Start check 10 (card 10)

Light frees electrons from a metal. The light is made brighter, and its frequency stays the same. Each electron now leaves with

A. more kinetic energy
B. less kinetic energy
C. no kinetic energy
D. the same maximum kinetic energy

Start check 11 (card 11)

Photons with an energy of 5.00 eV shine on a metal with a work function of 3.20 eV. The maximum kinetic energy of the electrons is

A. 8.20 eV
B. 1.80 eV
C. 3.20 eV
D. 5.00 eV

Start check 12 (card 12)

On a graph of maximum kinetic energy against frequency for the photoelectric effect, the slope of the line is

A. the work function
B. the threshold frequency
C. Planck’s constant
D. the stopping voltage

Start check 13 (card 13)

The momentum of a photon is found with

A. $p = mv$
B. $p = h \div \lambda$
C. $p = hf$
D. $p = mc^2$

Answers for the start check

Start check 1 (card 1): A. $\lambda = c \div f = (3.00 \times 10^8 \text{ m/s}) \div (1.00 \times 10^8 \text{ Hz}) = 3.00 \text{ m}$. Wrong or unsure? Do card 1.

Start check 2 (card 2): D. The next side must turn into the place of the first side. For eight sides that is 1/8 of a turn. Wrong or unsure? Do card 2.

Start check 3 (card 3): A. $1/d_i = 1/10.0 - 1/30.0$, so $d_i = +15.0$ cm. A positive image distance means a real image. Wrong or unsure? Do card 3.

Start check 4 (card 4): C. Inside the focal point, a converging lens works as a magnifying glass. The image is virtual, erect and larger. Wrong or unsure? Do card 4.

Start check 5 (card 5): B. $\sin \theta_2 = (1.00)(\sin 30.0°) \div 1.33 = 0.376$, so $\theta_2 = 22.1°$. Wrong or unsure? Do card 5.

Start check 6 (card 6): D. It happens only when light goes from a larger index of refraction toward a smaller one, and the angle of incidence is larger than the critical angle. Wrong or unsure? Do card 6.

Start check 7 (card 7): B. Only a transverse wave can be polarized. Wrong or unsure? Do card 7.

Start check 8 (card 8): C. $d = 1 \div (2.00 \times 10^5 \text{ lines per metre}) = 5.00 \times 10^{-6}$ m. Wrong or unsure? Do card 8.

Start check 9 (card 9): A. $E = hf = (4.14 \times 10^{-15})(6.00 \times 10^{14}) = 2.48$ eV. Wrong or unsure? Do card 9.

Start check 10 (card 10): D. Brighter light has more photons, so more electrons leave. Each photon has the same energy, so the maximum kinetic energy is the same. Wrong or unsure? Do card 10.

Start check 11 (card 11): B. Ek max = photon energy − work function = 5.00 − 3.20 = 1.80 eV. Wrong or unsure? Do card 11.

Start check 12 (card 12): C. Ek max = hf − W is a straight line with a slope of h. Wrong or unsure? Do card 12.

Start check 13 (card 13): B. A photon has no mass, so p = mv does not work. The data sheet gives $p = h \div \lambda$. Wrong or unsure? Do card 13.

2. Checklist

Tick one box for each line. Come back and change it as you finish cards.

Card	I can …	Can do	Not yet
1	say how EMR is made and how it travels, put the spectrum in order, and use $c = f\lambda$	☐	☐
2	explain how the speed of light is measured, and find it from a rotating-mirror experiment	☐	☐
3	read a ray diagram for a curved mirror, and use the mirror equation and magnification	☐	☐
4	read a ray diagram for a thin lens, and use the lens equation and magnification	☐	☐
5	use Snell’s law, the index of refraction, and the change in speed and wavelength	☐	☐
6	find a critical angle and say when total internal reflection happens	☐	☐
7	explain diffraction, interference and polarization, and what Young’s experiment shows	☐	☐
8	solve a double-slit or diffraction grating question	☐	☐
9	find the energy of a photon, in joules and in electron volts, and rank the spectrum by photon energy	☐	☐
10	explain the photoelectric effect: what intensity, frequency and the metal each change, and why the wave model fails	☐	☐
11	solve a photoelectric question: work function, threshold frequency, maximum kinetic energy and stopping voltage	☐	☐
12	read a photoelectric graph: Planck’s constant from the slope, the work function from the intercept	☐	☐
13	solve a Compton question, find the momentum of a photon, and say what wave-particle duality means	☐	☐

3. Terms

These are the words the diploma exam uses for this part of the unit. Each one has a plain meaning.

Part 1

electromagnetic radiation (EMR)
Energy that travels as a wave of an electric field and a magnetic field. Light, radio waves and X-rays are all EMR. The exam writes EMR for short.

electromagnetic spectrum
All the types of EMR, in order of wavelength or frequency: radio waves, microwaves, infrared, visible light, ultraviolet, X-rays, gamma rays.

accelerating charge
A charge that speeds up, slows down or changes direction. An accelerating charge makes EMR.

antenna
A metal rod or wire. Electrons that move back and forth along it send out radio waves.

frequency (f)
The number of complete waves each second. The unit is the hertz (Hz).

wavelength (λ)
The length of one complete wave. The unit is the metre.

period (T)
The time for one complete wave, or for one complete turn. $T = 1 \div f$.

speed of light (c)
The speed of all EMR in a vacuum: 3.00×10^8 m/s. It is on the data sheet. Use it for air as well.

transverse wave
A wave that vibrates at right angles to the direction it travels. EMR is a transverse wave.

longitudinal wave
A wave that vibrates along the direction it travels. Sound is a longitudinal wave.

medium
The material a wave travels through. EMR needs no medium: it can travel through a vacuum.

vacuum
Space with no matter in it.

ray
A straight line with an arrow that shows the path of light.

normal
A line drawn at 90° to a surface, at the point where a ray meets the surface. Angles are measured from the normal.

angle of incidence
The angle between the ray that arrives and the normal.

angle of reflection
The angle between the reflected ray and the normal.

law of reflection
The angle of reflection equals the angle of incidence.

plane mirror
A flat mirror.

concave mirror
A mirror that curves inward, like the inside of a spoon. It brings parallel rays together. Its focal length is positive.

convex mirror
A mirror that bulges outward, like the back of a spoon. It spreads parallel rays apart. Its focal length is negative.

principal axis
The straight line through the centre of a mirror or lens, at 90° to it.

focal point (F)
The point where rays parallel to the principal axis meet after a concave mirror or a converging lens. For a convex mirror or a diverging lens, it is the point the rays seem to come from.

focal length (f)
The distance from the mirror or lens to its focal point.

centre of curvature (C)
The centre of the ball that a curved mirror is a piece of. It is twice as far from the mirror as the focal point.

vertex
The centre point of a curved mirror, where the principal axis meets it.

real image
An image made where light rays really meet. It can be caught on a screen. Its image distance is positive. It is always inverted.

virtual image
An image at a place the rays only seem to come from. It cannot be caught on a screen. Its image distance is negative. It is always erect.

erect
Upright: the same way up as the object. The image height is positive.

inverted
Upside down compared with the object. The image height is negative.

magnification (m)
How many times as tall the image is as the object. A negative magnification means the image is inverted.

converging lens
A lens that brings parallel rays together at a focal point. It is thicker in the middle. Its focal length is positive.

diverging lens
A lens that spreads parallel rays apart. It is thinner in the middle. Its focal length is negative.

optics bench
A long rail with a scale. A light source, a lens or mirror and a screen slide along it so that distances can be measured.

screen
A flat white surface that a real image can be seen on.

refraction
The bending of light when it passes at an angle from one material into another, because its speed changes.

index of refraction (n)
A number that tells how much a material slows light. A larger index means slower light. Air has n = 1.00.

Snell's law
The rule that links the angles and the indexes of refraction: $n_2/n_1 = \sin \theta_1/\sin \theta_2$.

angle of refraction
The angle between the refracted ray and the normal.

critical angle
The angle of incidence that makes the angle of refraction exactly 90°.

total internal reflection
All the light reflects back into the material and none refracts out. It happens when light heads from a larger index toward a smaller index at more than the critical angle.

optical fibre
A thin glass thread. Light stays inside it by total internal reflection.

dispersion
The spreading of white light into colours by refraction, as in a prism.

prism
A block of glass with flat sides, often a triangle.

diffraction
The spreading out of a wave after it passes through a gap or around an edge.

interference
What happens when two waves overlap: they add in some places and cancel in others.

constructive interference
Two waves arrive in step and add. For light, this makes a bright spot.

destructive interference
Two waves arrive half a wavelength out of step and cancel. For light, this makes a dark spot.

antinode
A bright spot in an interference pattern. Also called a bright fringe or a maximum. The middle one is the central antinode, n = 0.

node
A dark spot in an interference pattern. Also called a dark fringe or a minimum.

path difference
How much farther a point is from one slit than from the other slit.

double slit
Two narrow slits close together. Light through them makes an interference pattern.

diffraction grating
A piece of glass or plastic with thousands of slits (lines), all the same distance apart.

monochromatic light
Light of one colour, so one wavelength. Laser light is monochromatic.

polarization
Making a transverse wave vibrate in one direction only.

polarizing filter
A sheet that lets through light that vibrates in one direction and blocks the rest.

Part 2

quantum
One packet of energy. The plural is quanta.

photon
One packet (quantum) of EMR. Its energy is E = hf.

Planck's constant (h)
The number that links the energy of a photon to its frequency. On the data sheet: 6.63×10^{-34} J·s, or 4.14×10^{-15} eV·s.

electron volt (eV)
A small unit of energy. 1 eV = 1.60×10^{-19} J.

blackbody
An object that gives off EMR because it is hot. Planck's idea of quanta explained the light from hot objects.

photoelectric effect
Light that shines on a metal frees electrons from the metal.

photoelectron
An electron freed from a metal by light.

intensity
How bright the light is. More intense light has more photons each second.

threshold frequency (f_o)
The lowest frequency of light that can free electrons from a metal.

work function (W)
The least energy needed to free an electron from a metal. $W = hf_o$.

maximum kinetic energy (Ek max)
The most kinetic energy an electron can have as it leaves the metal: the photon energy minus the work function.

stopping voltage (Vstop)
The voltage that just stops the fastest electrons. $E_{k\,max} = q_e V_{stop}$.

photocell
A glass tube with a metal plate and a collector. Light on the plate makes a current.

classical
From physics before quantum ideas. The classical model of light is the wave model.

Compton effect
An X-ray photon collides with an electron. The photon leaves with a longer wavelength.

scattering
A change in the direction of a photon or a particle after a collision.

momentum of a photon (p)
$p = h \div \lambda$. A photon has momentum even though it has no mass.

wave-particle duality
Light and matter each act as a wave in some experiments and as a particle in others.

matter wave

The wave that goes with a moving particle such as an electron.

4. Concept pages

Each page is one idea the diploma exam tests.

Concept 1: How diploma questions are answered

The diploma exam has 50 questions on a computer. Every question is marked by the computer. Fewer than half need a calculation.

Some questions are multiple choice. Some ask you to pick more than one answer, to finish a statement, to match items, or to put items in order.

Some questions ask you to type a number. This pack calls these numerical response. Read how the question tells you to record the answer. The table shows each way.

In this unit, some questions ask you to measure an angle or a length on a diagram. The exam gives you a ruler tool and a protractor tool on the screen. Measure angles from the normal.

Use the constants from the data sheet, with three digits. Do not use a constant stored in your calculator.

The question says	Your answer	What you record	Why
Record your three-digit answer.	2.88 N	2 . 8 8	Type the number as it is, with its decimal point.
Write your answer as a.bc × 10^{w} N/C. Record the four digits a, b, c and w.	2.16 × 10^{5} N/C	2 1 6 5	a = 2, b = 1, c = 6 and w = 5. Do not type the "× 10".
Write your answer as a.b × 10^{-cd} C. Record the four digits a, b, c and d.	9.6 × 10^{-19} C	9 6 1 9	a = 9, b = 6, c = 1 and d = 9. The minus sign is already in the question.
Record your three-digit answer.	0.601 N	0 . 6 0	For an answer below 1, the zero in front counts as one of the three digits. So 0.60 is a three-digit answer.
Record the number of the direction.	down and to the right	4	Use the direction picture on this page. Pick the direction closest to yours.
Record the four numbers in order.	step 2, then 4, then 1, then 3	2 4 1 3	Type the step numbers in the order the steps happen.
Record the numbers of the two principles.	principles 0 and 1	0 1	Either order is marked right.

Concept 2: Naming the physics principles

The data sheet lists ten physics principles, numbered 0 to 9. Some questions ask which two principles you need to solve a problem.

Part 1 of this unit uses the two principles in the table. Part 2 adds conservation of momentum and conservation of energy.

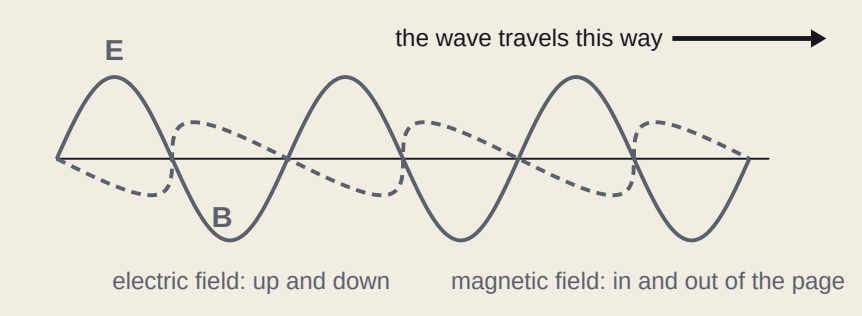
Number	Principle	When you use it in this unit
0	Uniform motion (the net force is zero)	Light travels at a constant speed in one material. Use speed = distance ÷ time, as in the rotating-mirror experiment.
9	Wave-particle duality	Light acts as a wave when it diffracts, interferes or is polarized. Part 2 shows that light also acts as a particle.

Concept 3: An EMR wave

Electromagnetic radiation (EMR) is made when a charge accelerates. Electrons moving back and forth in an antenna make radio waves.

The wave has two parts: an electric field and a magnetic field. They are at right angles to each other and to the direction the wave travels. So EMR is a transverse wave.

EMR needs no medium. In a vacuum, all EMR travels at 3.00×10^8 m/s.

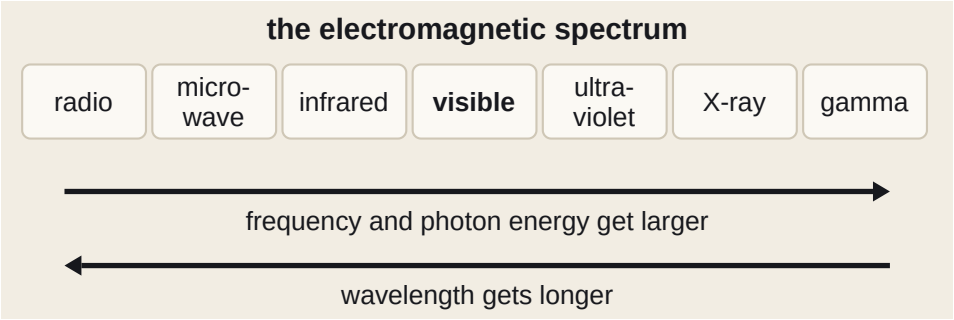


Concept 4: The spectrum

All EMR is the same kind of wave. The types differ in wavelength and frequency.

From radio waves to gamma rays, the wavelength gets shorter and the frequency gets larger. The speed in a vacuum is the same for all of them.

Visible light is a small part of the spectrum. Red light has the longest wavelength you can see, about 700 nm. Violet has the shortest, about 400 nm.



Concept 5: A model is tested: light as a wave

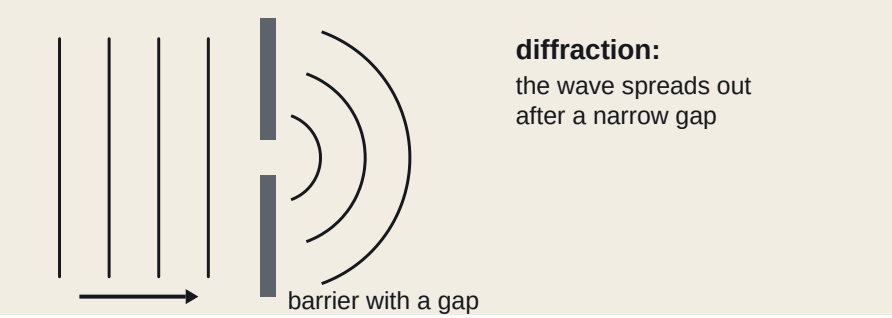
A model is kept only as long as it explains what we see. The wave model of light explains three things.

Refraction. Light slows down when it enters glass or water, so it bends toward the normal. Its wavelength gets shorter and its frequency stays the same.

Diffraction. Light spreads out after a very narrow slit, as water waves do after a gap.

Interference. Light from two slits makes bright and dark bands. Only waves can cancel each other. Young's experiment made scientists accept the wave model.

Part 2 shows an experiment the wave model cannot explain.



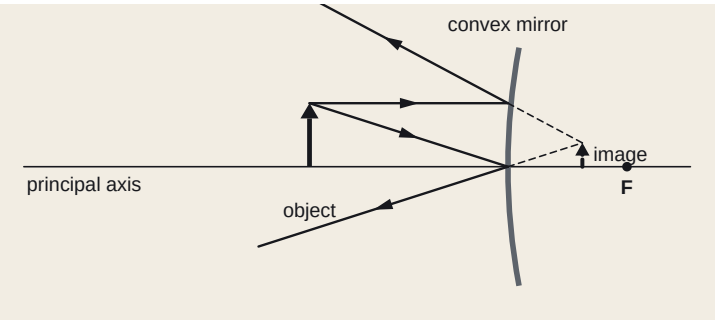
Concept 6: Mirrors and lenses: the rays and the words

To find an image on a diagram, follow two rays from the top of the object. Ray 1 goes parallel to the principal axis, then through the focal point (or away from it). Ray 2 goes to the centre of the mirror or lens.

Where the two rays meet, the image is real. If they spread apart, trace them back with dashed lines: where the dashed lines meet, the image is virtual.

The exam names a mirror by its shape: concave or convex. It names a lens by what it does: converging or diverging.

One pair of equations does all four: $1/f = 1/d_o + 1/d_i$ and $m = h_i/h_o = -d_i/d_o$. The table gives the signs.



Quantity	Positive	Negative
focal length f	concave mirror, converging lens	convex mirror, diverging lens
image distance d_i	real image	virtual image
image height h_i and magnification m	erect image	inverted image

Concept 7: A model fails: the photoelectric effect

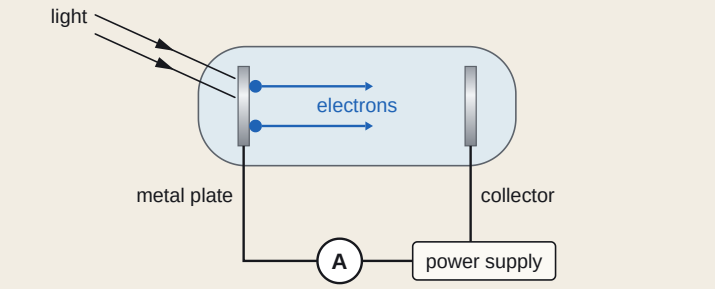
Light that shines on a metal can free electrons. The wave model of light made three predictions. All three were wrong.

Wave model: any light will free electrons if it is bright enough. **Seen:** below a threshold frequency, no electrons leave, however bright the light.

Wave model: in dim light there is a delay while energy builds up. **Seen:** electrons leave at once.

Wave model: brighter light gives each electron more kinetic energy. **Seen:** the kinetic energy depends on the frequency, not on the brightness.

Einstein explained all three with photons. Light arrives in packets of energy hf. One photon gives all its energy to one electron.



The supply can push the electrons back: the stopping voltage.

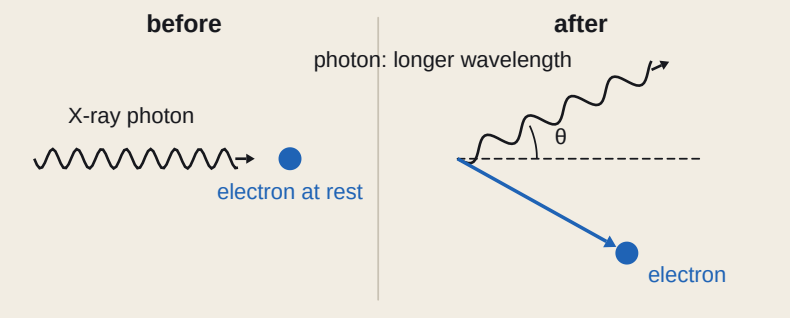
Concept 8: Wave-particle duality

Diffraction, interference and polarization show light acting as a wave. The photoelectric effect and the Compton effect show light acting as a particle.

Neither model is enough alone. Light has both natures. Which one you see depends on the experiment.

Matter is the same. Electrons are particles, but a beam of electrons through two slits makes an interference pattern, as waves do.

This is physics principle 9 on the data sheet: wave-particle duality.



Concept 9: Where these ideas are used

Optical fibres carry phone and internet signals as light that stays inside by total internal reflection.

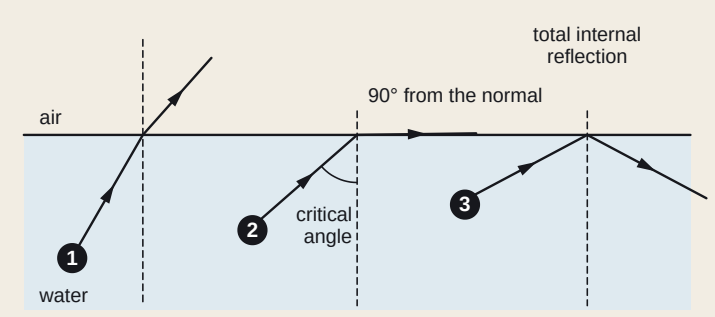
Cameras and telescopes use lenses and curved mirrors to make real images.

Polarizing sunglasses block light that vibrates in one direction, which cuts glare.

Automatic doors, light meters and solar cells use the photoelectric effect: light frees electrons and makes a current.

X-ray pictures use high-energy photons that pass through soft tissue but not through bone.

The picture shows total internal reflection, the idea behind an optical fibre.



5. Data sheet card

You get the Physics 30 data sheet in the exam. This card says where to look for what this unit needs. Use the constants as they are printed, with three digits.

What you need	Where it is on the data sheet	How to use it
Speed of light, c	Constants	3.00×10^{8} m/s. Use it for EMR in a vacuum and in air.
Index of refraction of air	Constants	n = 1.00.
Prefixes: n, μ, m, c, k, M, G	Prefixes table	1 nm = 10^{-9} m. 1 mm = 10^{-3} m. 1 cm = 10^{-2} m. 1 MHz = 10^{6} Hz. Change the units before you calculate.
$v = f\lambda$	Equations: Waves	For EMR in air or a vacuum, v = c.
$T = 1/f$	Equations: Waves	The time for one wave or one turn. You need it for a rotating mirror.
$1/f = 1/d_o + 1/d_i$	Equations: Waves	One equation for curved mirrors and thin lenses. Here f is the focal length, not the frequency.
$m = h_i/h_o = -d_i/d_o$	Equations: Waves	Magnification. Keep the minus sign.
$n_2/n_1 = \sin\theta_1/\sin\theta_2$	Equations: Waves	Snell's law, for angles. Measure the angles from the normal.
$n_2/n_1 = v_1/v_2 = \lambda_1/\lambda_2$	Equations: Waves	For the speed and the wavelength in a new material. The frequency does not change.
$\lambda = d \sin\theta/n$	Equations: Waves	For a double slit or a grating when an angle is given. Here n is the number of the antinode, not an index of refraction.
$\lambda = xd/(nl)$	Equations: Waves	For a double slit when a distance on the screen is given. Small angles only.
Planck's constant, h	Constants	Two values: 6.63×10^{-34} J·s for joules, 4.14×10^{-15} eV·s for electron volts.
Electron volt	Constants	1 eV = 1.60×10^{-19} J.
Mass and charge of an electron	Constants	9.11×10^{-31} kg and 1.60×10^{-19} C (the elementary charge).
$E = hf = hc/\lambda$	Equations: Atomic physics	The energy of one photon.
$W = hf_o$	Equations: Atomic physics	The work function from the threshold frequency.
$E_{k\,max} = q_eV_{stop}$	Equations: Atomic physics	The maximum kinetic energy from the stopping voltage.

$p = h/\lambda$ and $E = pc$	Equations: Quantum mechanics and nuclear physics	The momentum and the energy of a photon.
$\Delta\lambda = (h/mc)(1 - \cos\theta)$	Equations: Quantum mechanics and nuclear physics	The Compton effect. m is the mass of the electron.
Not on the data sheet: the order of the spectrum		Learn it: radio, microwave, infrared, visible, ultraviolet, X-ray, gamma. If a question needs wavelength limits, it gives them.
Not on the data sheet: d for a grating		d = 1 ÷ (lines per metre).
Not on the data sheet: the critical angle equation		Use Snell's law with $\theta_2 = 90°$: $\sin\theta_1 = n_2 \div n_1$.
Not on the data sheet: the sign rules for mirrors and lenses		Learn the table on the concept page "Mirrors and lenses".
Not on the data sheet: the rotating-mirror equation		Build it: the light travels 2d in the time for 1/N of a turn.
Not on the data sheet: Ek max = hf − W		Build it from conservation of energy: photon energy = work function + maximum kinetic energy.
Not on the data sheet: the wavelength of a moving particle		If a question needs it, the question gives the relation.

Card 1: I can say how EMR is made and how it travels, put the spectrum in order, and use c = fλ

Part 1

What the question looks like

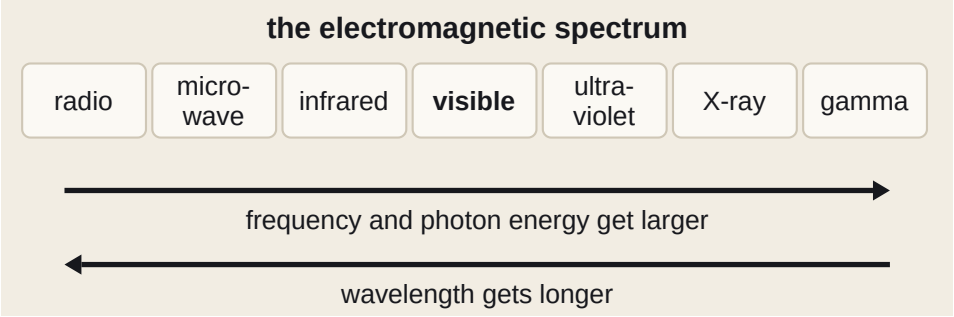
The question names a type of electromagnetic radiation (EMR), such as radio waves, light or X-rays. It gives a frequency or a wavelength and asks for the other one. Or it asks how EMR is made, how its two fields point, or where a type sits in the spectrum. Words to look for: “frequency”, “wavelength”, “MHz”, “nm”, “antenna”.

Steps: Find a wavelength or a frequency with v = fλ

1. **List what you know.** Change the units: 1 MHz = 10^{6} Hz, 1 nm = 10^{-9} m.
2. **Write v = fλ from the data sheet.** For EMR in air or in a vacuum, v is the speed of light: c = 3.00 × 10^{8} m/s.
3. **Rearrange and solve.** λ = c ÷ f, or f = c ÷ λ.
4. **Name the type of EMR, if the question asks.** Use the wavelength table the question gives.

Check: A larger frequency must give a smaller wavelength, because f × λ is always 3.00 × 10^{8} m/s.

Worked example



A radio station sends out radio waves with a frequency of 98.5 MHz.

Question: What is the wavelength of these radio waves?

Step 1 f = 98.5 MHz = 98.5 × 10^{6} Hz = 9.85 × 10^{7} Hz. c = 3.00 × 10^{8} m/s.

Step 2 v = fλ, with v = c.

Step 3 λ = c ÷ f = (3.00 × 10^{8} m/s) ÷ (9.85 × 10^{7} Hz) = 3.05 m.

Step 4 The question does not ask for the type. (It is a radio wave: the wavelength is longer than 0.1 m.)

The common mistake

> Leaving the units as MHz or nm. **Change to Hz and to metres before you divide.** A second mistake: mixing up the order of the spectrum. From longest wavelength to shortest: radio, microwave, infrared, visible, ultraviolet, X-ray, gamma.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 1.1

Electromagnetic radiation is produced by a charged particle that is

A. at rest
B. moving at a constant velocity
C. accelerating
D. neutral

Question 1.2

In an electromagnetic wave, the electric field and the magnetic field are

A. parallel to each other and to the direction the wave travels
B. perpendicular to each other and to the direction the wave travels
C. parallel to each other and perpendicular to the direction the wave travels
D. perpendicular to each other, with one of them along the direction the wave travels

Question 1.3

Green laser light has a wavelength of 532 nm in air. The frequency of this light is

Numerical response. Write your answer as a.b × 10^{cd} Hz. Record the four digits a, b, c and d.

☐☐☐☐

Question 1.4

Four types of EMR are numbered: **1** infrared; **2** X-rays; **3** ultraviolet; **4** radio waves. Put them in order from the longest wavelength to the shortest wavelength.

Put in order. Record the four numbers in order. ☐☐☐☐

Question 1.5

Type of EMR	Wavelength
radio waves	longer than 0.1 m
microwaves	1 mm to 0.1 m
infrared	700 nm to 1 mm
visible light	400 nm to 700 nm
ultraviolet	10 nm to 400 nm
X-rays and gamma rays	shorter than 10 nm

An antenna sends out EMR best when the antenna is half as long as the wavelength. An antenna is 1.50 m long. Use the table. The EMR this antenna sends out best is

A. a radio wave
B. a microwave
C. infrared
D. visible light

Challenge question

A microwave oven makes EMR with a wavelength of 12.2 cm. In one second, how many complete waves does the oven make? (This is the frequency.)

Numerical response. Write your answer as a.bc × 10^{w} Hz. Record the four digits a, b, c and w.

□□□□

Hint: The number of complete waves in one second is the frequency. Change 12.2 cm to metres first.

Card 1 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 1.1

Which list puts three types of EMR in order from the lowest frequency to the highest frequency?

A. gamma rays, visible light, microwaves
B. visible light, microwaves, gamma rays
C. microwaves, gamma rays, visible light
D. microwaves, visible light, gamma rays

Check 1.2

Microwaves have a wavelength of 3.00 cm in air. The frequency of these microwaves is

Numerical response. Write your answer as a.b × 10^{cd} Hz. Record the four digits a, b, c and d.

☐☐☐☐

Check 1.3

Red light has a wavelength of 650 nm in air. The frequency of this light is

Numerical response. Write your answer as a.b × 10^{cd} Hz. Record the four digits a, b, c and d.

☐☐☐☐

Need more? Read the steps and the worked example on this card again. Then ask for the short lesson on this card.

Answers for card 1

Question 1.1: C. EMR is made when a charge accelerates: it speeds up, slows down or changes direction. Electrons that move up and down in an antenna accelerate all the time, so the antenna sends out radio waves. A charge that moves in a circle is also accelerating, so it also gives off EMR.

Question 1.2: B. The two fields are at right angles to each other, and both are at right angles to the direction of travel. That makes EMR a transverse wave.

Question 1.3: Record 5614. λ = 532 nm = 5.32 × 10^{-7} m. f = c ÷ λ = (3.00 × 10^{8}) ÷ (5.32 × 10^{-7}) = 5.64 × 10^{14} Hz. Written as a.b × 10^{cd}, that is 5.6 × 10^{14} Hz.

Question 1.4: Record 4132. From longest wavelength to shortest: radio (4), infrared (1), ultraviolet (3), X-rays (2). The order is 4, 1, 3, 2.

Question 1.5: A. The wavelength is 2 × 1.50 m = 3.00 m. That is longer than 0.1 m, so it is a radio wave. Its frequency is c ÷ λ = (3.00 × 10^{8}) ÷ 3.00 = 1.00 × 10^{8} Hz.

Challenge: Record 2469. λ = 12.2 cm = 0.122 m. f = c ÷ λ = (3.00 × 10^{8}) ÷ 0.122 = 2.46 × 10^{9} Hz. The frequency is the number of complete waves in one second.

Card 2: I can explain how the speed of light is measured, and find it from a rotating-mirror experiment

Part 1

What the question looks like

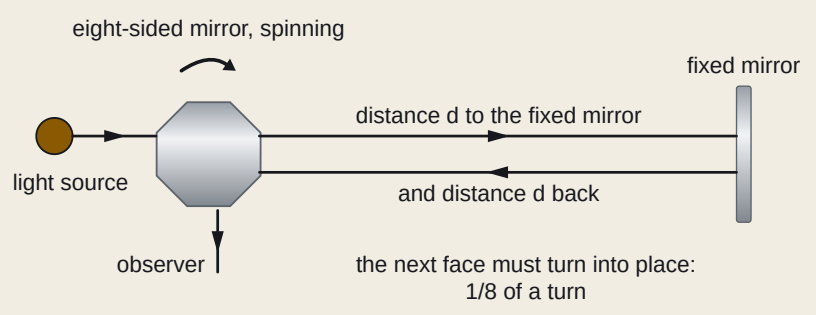
The question describes a spinning mirror with several flat sides, a far mirror and an observer. It gives a distance and a frequency of rotation. It asks for the speed of light, the frequency or the distance. Or it asks why an experiment worked or failed. Words to look for: “rotating mirror”, “eight-sided”, “minimum frequency”.

Steps: Find the speed of light from a rotating mirror

1. **Find the distance the light travels.** It goes to the far mirror and back: 2 × d.
2. **Find the time for the next side to turn into place.** A mirror with N sides must make 1/N of a turn. One turn takes T = 1 ÷ f. So t = 1 ÷ (N × f).
3. **Use speed = distance ÷ time.** c = 2d ÷ t.
4. **Round once, at the end.** Keep three significant digits.

Check: The answer must be close to 3.00 × 10^8 m/s. If it is far off, check that you used 2d and 1/N of a turn.

Worked example



An eight-sided mirror spins. Light reflects from one side, travels 35.0 km to a fixed mirror and comes back. The observer first sees the light when the mirror spins at 535 Hz (535 turns each second).

Question: What speed of light does this experiment give?

Step 1 Distance = 2 × 35.0 km = 70.0 km = 7.00 × 10^4 m.

Step 2 t = 1 ÷ (8 × 535 Hz) = 2.336 × 10^{-4} s. This is the time for 1/8 of a turn.

Step 3 c = (7.00 × 10^4 m) ÷ (2.336 × 10^{-4} s) = 3.00 × 10^8 m/s.

Step 4 To three significant digits: 3.00 × 10^8 m/s.

The common mistake

> Using the distance d one way. **The light goes there and back: use 2d.** A second mistake: using the time for a whole turn. An eight-sided mirror needs only 1/8 of a turn.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 2.1

Galileo tried to measure the speed of light with two people who uncovered lanterns on hills about 1 km apart. The experiment failed because

A. light does not travel through air
B. the time for light to travel 1 km is far shorter than a person's reaction time
C. the lanterns were not bright enough to see
D. light travels at an infinite speed

Question 2.2

Light travels 35.0 km to a mirror and 35.0 km back. The time for the whole trip is

Numerical response. Write your answer as $a.bc \times 10^{-w}$ s. Record the four digits a, b, c and w.

□□□□

Question 2.3

An eight-sided mirror spins. The fixed mirror is 30.0 km away. The lowest frequency of rotation at which the observer sees the light, in Hz, is

Numerical response. Record your three-digit answer. □□□□

Question 2.4

The eight-sided mirror is replaced with a six-sided mirror. The observer first sees the light when the mirror has turned through what fraction of a turn while the light was away?

A. 1/6 of a turn
B. 1/8 of a turn
C. 1/3 of a turn
D. 1/12 of a turn

Question 2.5

A group measures the speed of light with a rotating mirror and gets 2.80×10^{8} m/s. Which change would do the most to improve the result?

A. Use a dimmer light source
B. Use a mirror with fewer sides and a shorter distance
C. Move the fixed mirror closer
D. Move the fixed mirror much farther away

Challenge question

An eight-sided mirror spins at 480 Hz. This is the lowest frequency at which the observer sees the light. The distance from the spinning mirror to the fixed mirror is

Numerical response. Write your answer as a.bc × 10ʷ m. Record the four digits a, b, c and w.



Hint: Find the time for 1/8 of a turn. Find how far light goes in that time. That distance is there and back.

Card 2 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 2.1

In the rotating-mirror experiment with an eight-sided mirror, the observer first sees the light when the travel time of the light equals the time for the mirror to make

A. one whole turn
B. half a turn
C. one eighth of a turn
D. eight turns

Check 2.2

An eight-sided mirror first shows the light at 500 Hz. The fixed mirror is 37.5 km away. The speed of light from this experiment is

Numerical response. Write your answer as a.bc × 10ʷ m/s. Record the four digits a, b, c and w.



Check 2.3

The observer first sees the light when the eight-sided mirror spins at a frequency f. The observer will also see the light when the mirror spins at

A. ½ f
B. 2 f
C. 1.5 f
D. ¼ f

Need more? Read the steps and the worked example on this card again. Then ask for the short lesson on this card.

Answers for card 2

Question 2.1: B. Light crosses 1 km in about 3 millionths of a second. A person needs about 0.2 s to react. The reaction time hides the travel time. A good experiment needs a very long distance or a very

fast timer.

Question 2.2: Record 2334. t = distance ÷ speed = (7.00 × 10^{4} m) ÷ (3.00 × 10^{8} m/s) = 2.33 × 10^{-4} s.

Question 2.3: Record 625. Time for the trip: t = 2d ÷ c = (6.00 × 10^{4}) ÷ (3.00 × 10^{8}) = 2.00 × 10^{-4} s. In that time the mirror makes 1/8 of a turn, so one turn takes T = 8t = 1.60 × 10^{-3} s. f = 1 ÷ T = 625 Hz.

Question 2.4: A. The next side must move into the place of the first side. With six sides, that is 1/6 of a turn.

Question 2.5: D. A longer distance gives a longer travel time. A longer time is easier to measure well, so the error is a smaller part of the result.

Challenge: Record 3914. t = 1 ÷ (8 × 480) = 2.604 × 10^{-4} s. The light travels 2d = c × t = (3.00 × 10^{8}) (2.604 × 10^{-4}) = 7.81 × 10^{4} m. So d = 3.91 × 10^{4} m.

Card 3: I can read a ray diagram for a curved mirror, and use the mirror equation and magnification

Part 1

What the question looks like

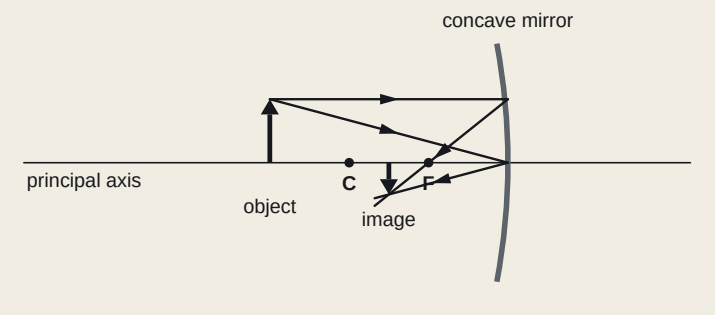
The question shows or describes a curved mirror and an object. It gives two of: the focal length, the object distance, the image distance. It asks for the third, for the height of the image, or for what the image is like. Words to look for: “concave”, “convex”, “focal length”, “real”, “virtual”, “erect”, “inverted”.

Steps: Find an image made by a curved mirror

1. **List what you know, with signs.** The focal length f is positive for a concave mirror and negative for a convex mirror. The object distance d_o is positive.
2. **Use $1/f = 1/d_o + 1/d_i$ from the data sheet.** Solve for the one you do not know.
3. **Use $m = h_i/h_o = -d_i/d_o$ for the size.** Keep the minus sign in the equation.
4. **Read the signs of your answers.** d_i positive: a real image, in front of the mirror. d_i negative: a virtual image, behind the mirror. h_i negative: inverted. h_i positive: erect (upright).

Check: A real image is always inverted. A virtual image is always erect. A convex mirror always gives a virtual, erect, smaller image.

Worked example



An object 8.0 cm tall stands 30.0 cm in front of a concave mirror. The focal length of the mirror is 10.0 cm.

Question: Where is the image, how tall is it, and what is it like?

Step 1 f = +10.0 cm (concave). d_o = +30.0 cm. h_o = 8.0 cm.

Step 2 $1/d_i = 1/f - 1/d_o = 1/10.0 - 1/30.0 = 0.0667$ per cm. d_i = +15.0 cm.

Step 3 $m = -d_i/d_o = -15.0 \div 30.0 = -0.500$. $h_i = m \times h_o = (-0.500)(8.0\text{ cm}) = -4.0$ cm.

Step 4 d_i is positive: the image is real, 15.0 cm in front of the mirror. h_i is negative: it is inverted. It is 4.0 cm tall, so it is smaller than the object.

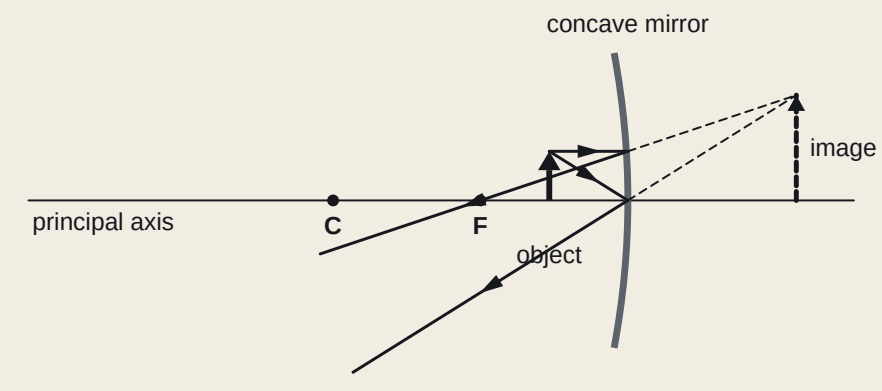
The common mistake

> Dropping the signs. **A convex mirror has a negative focal length.** A negative image distance is not an error: it tells you the image is virtual and behind the mirror. A negative magnification tells you the image is inverted.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 3.1



The ray diagram shows an object in front of a concave mirror. The object is closer to the mirror than the focal point F. The image is

A. real, inverted and larger than the object
B. real, erect and smaller than the object
C. virtual, erect and larger than the object
D. virtual, inverted and smaller than the object

Question 3.2

An object is 18.0 cm in front of a concave mirror with a focal length of 12.0 cm. The distance from the mirror to the image, in cm, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Question 3.3

A convex mirror always gives an image that is

A. virtual, erect and smaller than the object
B. virtual, inverted and larger than the object
C. real, erect and smaller than the object
D. real, inverted and larger than the object

Question 3.4

An object is 30.0 cm in front of a convex mirror. The focal length of the mirror is 15.0 cm in size. The image is behind the mirror. The distance from the mirror to the image, in cm, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Question 3.5

A student finds that the magnification of an image is −2.0. This means that the image is

A. erect and half as tall as the object
B. erect and twice as tall as the object
C. inverted and half as tall as the object
D. inverted and twice as tall as the object

Challenge question

A concave mirror makes a real image that is 3.00 times as tall as the object. The object is 20.0 cm from the mirror. The focal length of the mirror, in cm, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Hint: A real image is inverted, so the magnification is −3.00. Use it to find the image distance first.

Card 3 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 3.1

An object is 60.0 cm in front of a concave mirror with a focal length of 20.0 cm. The distance from the mirror to the image, in cm, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Check 3.2

For a curved mirror, a student calculates an image distance of −12 cm. The image is

A. real and in front of the mirror
B. virtual and behind the mirror
C. real and behind the mirror
D. virtual and in front of the mirror

Check 3.3

An object 6.0 cm tall is 30.0 cm from a concave mirror. Its image is 15.0 cm from the mirror, in front of it. The height of the image, in cm, is (record the size, without a sign)

Numerical response. Record your three-digit answer. ☐☐☐☐

Need more? Read the steps and the worked example on this card again. Then ask for the short lesson on this card.

Answers for card 3

Question 3.1: C. The reflected rays spread apart, so they never meet in front of the mirror. Traced back (the dashed lines), they meet behind the mirror. So the image is virtual. It is erect and larger than the object.

Question 3.2: Record 36.0. $1/d_i = 1/12.0 - 1/18.0 = 0.02778$ per cm. $d_i = +36.0$ cm. It is positive, so the image is real.

Question 3.3: A. A convex mirror spreads the rays apart. They only seem to come from a point behind the mirror. The image is always virtual, erect and smaller. Store security mirrors are convex.

Question 3.4: Record 10.0. Convex, so $f = -15.0$ cm. $1/d_i = 1/(-15.0) - 1/30.0 = -0.1000$ per cm. $d_i = -10.0$ cm. The minus sign means the image is virtual, behind the mirror. The distance is 10.0 cm.

Question 3.5: D. The minus sign means inverted. The 2.0 means the image is 2.0 times as tall as the object.

Challenge: Record 15.0. A real image is inverted, so $m = -3.00$. $m = -d_i/d_o$ gives $d_i = 3.00 \times 20.0 = +60.0$ cm. $1/f = 1/20.0 + 1/60.0 = 0.0667$ per cm. $f = 15.0$ cm.

Card 4: I can read a ray diagram for a thin lens, and use the lens equation and magnification

Part 1

What the question looks like

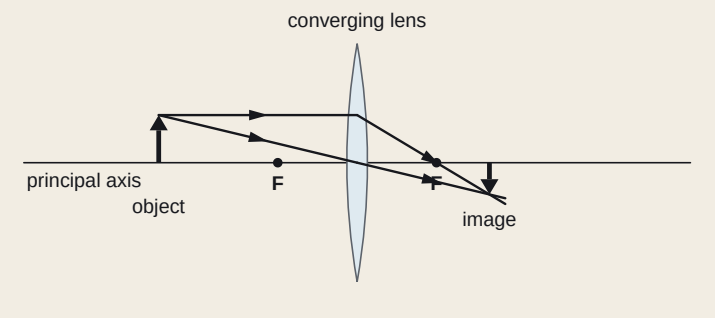
The question shows or describes a lens and an object. It gives two of: the focal length, the object distance, the image distance. It asks for the third, for the height of the image, or for what the image is like. Or it asks where to put a lens, a candle and a screen. Words to look for: “converging”, “diverging”, “thin lens”, “screen”, “optics bench”.

Steps: Find an image made by a thin lens

1. **List what you know, with signs.** The focal length f is positive for a converging lens and negative for a diverging lens. The object distance d_o is positive.
2. **Use $1/f = 1/d_o + 1/d_i$ from the data sheet.** It is the same equation as for a mirror.
3. **Use $m = h_i/h_o = -d_i/d_o$ for the size.** Keep the minus sign in the equation.
4. **Read the signs of your answers.** d_i positive: a real image, on the far side of the lens. It can be caught on a screen. d_i negative: a virtual image, on the same side as the object. h_i negative: inverted.

Check: Only a real image can be caught on a screen. A diverging lens always gives a virtual, erect, smaller image.

Worked example



A candle flame 6.0 cm tall is 25.0 cm from a converging lens. The focal length of the lens is 10.0 cm.

Question: Where is the image, how tall is it, and what is it like?

Step 1 f = +10.0 cm (converging). d_o = +25.0 cm. h_o = 6.0 cm.

Step 2 $1/d_i = 1/f - 1/d_o = 1/10.0 - 1/25.0 = 0.0600$ per cm. d_i = +16.7 cm.

Step 3 $m = -d_i/d_o = -16.7 \div 25.0 = -0.667$. $h_i = (-0.667)(6.0\text{ cm}) = -4.0$ cm.

Step 4 d_i is positive: the image is real, 16.7 cm from the lens on the far side. h_i is negative: it is inverted. It is 4.0 cm tall, so it is smaller than the object.

The common mistake

> Naming a lens by its shape. **The exam names a lens by what it does: converging or diverging.** (It names a mirror by its shape: concave or convex.) A second mistake: a positive focal length for a diverging lens. It is negative.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 4.1

Rays of light that are parallel to the principal axis pass through a lens. After the lens, the rays all pass through one point. The lens is

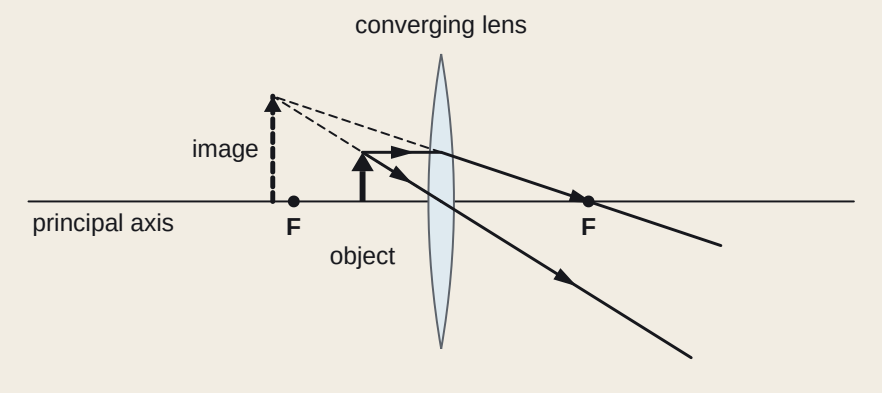
A. a diverging lens, and the point is the focal point
B. a diverging lens, and the point is the centre of the lens
C. a converging lens, and the point is the centre of the lens
D. a converging lens, and the point is the focal point

Question 4.2

An object is 45.0 cm from a converging lens with a focal length of 15.0 cm. The distance from the lens to the image, in cm, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Question 4.3



The ray diagram shows an object that is closer to a converging lens than the focal point F. The image is

A. real and inverted, so it can be caught on a screen
B. virtual and erect, so it cannot be caught on a screen
C. real and erect, so it can be caught on a screen
D. virtual and inverted, so it cannot be caught on a screen

Question 4.4

An object is 24.0 cm from a diverging lens. The focal length of the lens is 12.0 cm in size. The distance from the lens to the image, in cm, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Question 4.5

Students have an optics bench, a candle, a screen and a converging lens with a focal length of 10 cm. They want a sharp image of the candle on the screen. Which set-up works?

A. The candle 25 cm from the lens, and the screen on the other side of the lens
B. The candle 5 cm from the lens, and the screen on the other side of the lens
C. The candle 25 cm from the lens, and the screen on the same side as the candle
D. The candle 5 cm from the lens, and the screen on the same side as the candle

Challenge question

A candle and a screen are 90.0 cm apart on an optics bench. A converging lens is placed between them, 30.0 cm from the candle. A sharp image forms on the screen. The focal length of the lens, in cm, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Hint: The image is on the screen. Find how far the screen is from the lens. That is the image distance.

Card 4 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 4.1

An object is 30.0 cm from a converging lens with a focal length of 20.0 cm. The distance from the lens to the image, in cm, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Check 4.2

A diverging lens always gives an image that is

A. real, inverted and smaller than the object
B. real, erect and larger than the object
C. virtual, erect and smaller than the object
D. virtual, inverted and larger than the object

Check 4.3

An object is 30.0 cm from a converging lens. Its real image is 60.0 cm from the lens. The image is how many times as tall as the object?

Numerical response. Record your three-digit answer. ☐☐☐☐

Need more? Read the steps and the worked example on this card again. Then ask for the short lesson on this card.

Answers for card 4

Question 4.1: D. A converging lens brings parallel rays together at its focal point. A diverging lens spreads parallel rays apart.

Question 4.2: Record 22.5. $1/d_i = 1/15.0 - 1/45.0 = 0.0444$ per cm. $d_i = +22.5$ cm. It is positive, so the image is real and on the far side of the lens.

Question 4.3: B. After the lens the rays spread apart, so they never meet on the far side. Traced back (the dashed lines), they meet on the same side as the object. The image is virtual, erect and larger. This is how a magnifying glass works. No light reaches a virtual image, so a screen shows nothing.

Question 4.4: Record 8.00. Diverging, so $f = -12.0$ cm. $1/d_i = 1/(-12.0) - 1/24.0 = -0.125$ per cm. $d_i = -8.00$ cm. The minus sign means a virtual image, on the same side as the object. The distance is 8.00 cm.

Question 4.5: A. A screen catches only a real image. A converging lens makes a real image when the object is farther from the lens than the focal point. The real image forms on the far side of the lens. The students then slide the screen until the image is sharp.

Challenge: Record 20.0. $d_o = 30.0$ cm. The screen is $90.0 - 30.0 = 60.0$ cm from the lens, so $d_i = +60.0$ cm. $1/f = 1/30.0 + 1/60.0 = 0.0500$ per cm. $f = 20.0$ cm.

Card 5: I can use Snell’s law, the index of refraction, and the change in speed and wavelength

Part 1

What the question looks like

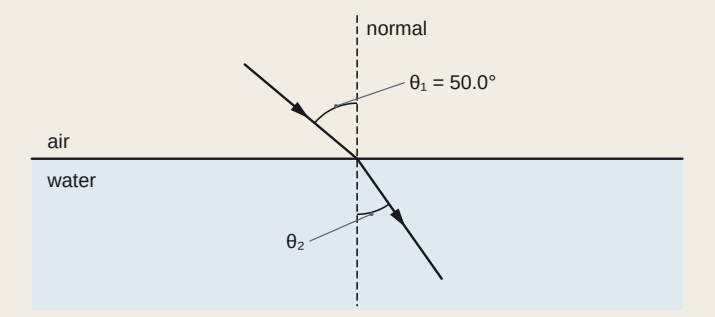
The question shows a ray of light that crosses from one clear material into another and bends. It gives angles, or an index of refraction, and asks for the missing one. Or it asks for the speed or the wavelength of the light in the new material. Words to look for: “refracts”, “index of refraction”, “normal”, “angle of incidence”.

Steps: Find an angle with Snell’s law

1. **Draw or find the normal.** The normal is the line at 90° to the boundary. Measure every angle from the normal, not from the surface.
2. **List n_1, θ_1, n_2 and θ_2.** Material 1 is where the light comes from. The index of refraction of air is 1.00 (data sheet).
3. **Use $n_2/n_1 = \sin\theta_1/\sin\theta_2$ from the data sheet.** Rearrange for the one you do not know.
4. **Check the bend.** Into a larger index: the ray bends toward the normal. Into a smaller index: it bends away from the normal.

Check: The larger index of refraction always has the smaller angle.

Worked example



A ray of light in air meets a water surface. The angle of incidence is 50.0°. The index of refraction of water is 1.33.

Question: What is the angle of refraction in the water?

Step 1 The angles are measured from the normal.

Step 2 $n_1 = 1.00$ (air). $\theta_1 = 50.0°$. $n_2 = 1.33$ (water).

Step 3 $\sin\theta_2 = n_1 \sin\theta_1 \div n_2 = (1.00)(\sin 50.0°) \div 1.33 = 0.576$. $\theta_2 = 35.2°$.

Step 4 Water has the larger index, so the ray bends toward the normal: 35.2° is smaller than 50.0°.

Steps: Find the speed or the wavelength in a new material

1. **List what you know in each material.** In air: $n_1 = 1.00$, $v_1 = 3.00 \times 10^8$ m/s.
2. **Use $n_2/n_1 = v_1/v_2 = \lambda_1/\lambda_2$ from the data sheet.** Use the pair that has your unknown.

3. **Solve.** A larger index means a smaller speed and a shorter wavelength.
4. **Remember what does not change.** The frequency stays the same when light enters a new material.

Check: In glass or water the speed and the wavelength must both come out smaller than in air.

Worked example

Yellow light has a wavelength of 589 nm in air. It enters glass with an index of refraction of 1.50.

Question: What are the speed and the wavelength of the light in the glass?

Step 1 $n_1 = 1.00$, $v_1 = 3.00 \times 10^8$ m/s, $\lambda_1 = 589$ nm. $n_2 = 1.50$.

Step 2 $n_2/n_1 = v_1/v_2$ and $n_2/n_1 = \lambda_1/\lambda_2$.

Step 3 $v_2 = v_1 \times n_1 \div n_2 = (3.00 \times 10^8) \div 1.50 = 2.00 \times 10^8$ m/s. $\lambda_2 = 589$ nm $\div 1.50 = 393$ nm.

Step 4 The frequency in the glass is the same as in air.

The common mistake

> Measuring the angle from the surface. **Every angle is measured from the normal.** A second mistake: saying the frequency changes. The speed and the wavelength change. The frequency does not.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 5.1

A ray of light passes from air into glass at an angle. In the glass, the light

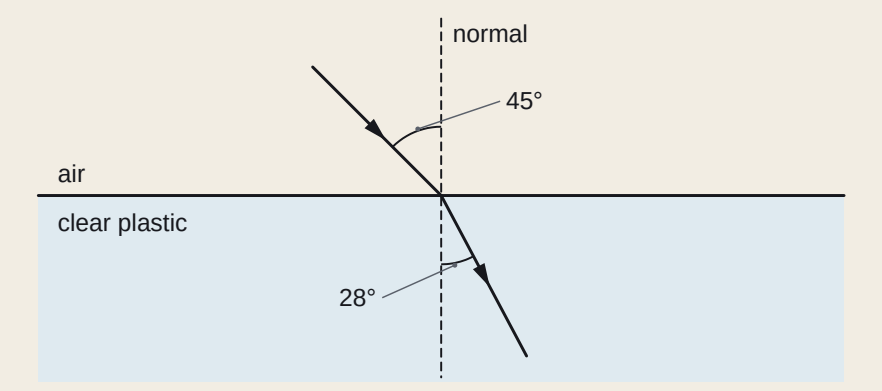
A. speeds up and bends toward the normal
B. speeds up and bends away from the normal
C. slows down and bends toward the normal
D. slows down and bends away from the normal

Question 5.2

A ray of light in air meets a glass block. The angle of incidence is 40.0°. The index of refraction of the glass is 1.50. The angle of refraction, in degrees, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Question 5.3



The diagram shows a ray of light that passes from air into a clear plastic. The angles are marked on the diagram. The index of refraction of the plastic is

Numerical response. Record your three-digit answer. ☐☐☐☐

Question 5.4

Light passes from air into water. Which property of the light stays the same?

A. Its speed
B. Its frequency
C. Its wavelength
D. Its direction

Question 5.5

The index of refraction of diamond is 2.42. The speed of light in diamond is

Numerical response. Write your answer as a.bc × 10^{w} m/s. Record the four digits a, b, c and w.
☐☐☐☐

Question 5.6

A ray of light passes through three clear layers, A, then B, then C. Measured from the normal, the ray is at 40° in layer A, at 25° in layer B and at 55° in layer C. Which list puts the layers in order from the largest index of refraction to the smallest?

A. C, A, B
B. A, B, C
C. B, C, A
D. B, A, C

Challenge question

A ray of light travels in water (n = 1.33) and meets a flat piece of glass (n = 1.52). The angle of incidence is 60.0°. The angle of refraction in the glass, in degrees, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Hint: Material 1 is water, not air. Use $n_1 = 1.33$ and $n_2 = 1.52$ in $n_2/n_1 = \sin\theta_1/\sin\theta_2$.

Card 5 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 5.1

A ray of light passes from glass into air at an angle. In the air, the light

A. speeds up and bends away from the normal
B. speeds up and bends toward the normal
C. slows down and bends away from the normal
D. slows down and bends toward the normal

Check 5.2

A ray of light in air meets a liquid with an index of refraction of 1.40. The angle of incidence is 30.0°. The angle of refraction, in degrees, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Check 5.3

Red light has a wavelength of 650 nm in air. Its wavelength in water (n = 1.33), in nm, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Need more? Read the steps and the worked example on this card again. Then ask for the short lesson on this card.

Answers for card 5

Question 5.1: C. Glass has a larger index of refraction than air, so light is slower in glass. A ray that slows down bends toward the normal.

Question 5.2: Record 25.4. $\sin\theta_2 = (1.00)(\sin 40.0°) \div 1.50 = 0.4285$. $\theta_2 = 25.4°$.

Question 5.3: Record 1.51. $n_2/n_1 = \sin\theta_1/\sin\theta_2$. $n_2 = (1.00)(\sin 45°) \div (\sin 28°) = 0.7071 \div 0.4695 = 1.51$. Both angles are measured from the normal.

Question 5.4: B. The frequency is set by the source and does not change. The speed and the wavelength both get smaller in water. The direction changes unless the ray is along the normal.

Question 5.5: Record 1248. $n_2/n_1 = v_1/v_2$. $v_2 = (3.00 \times 10^8)(1.00) \div 2.42 = 1.24 \times 10^8$ m/s.

Question 5.6: D. The larger the index of refraction, the closer the ray is to the normal. The smallest angle is in B (25°), then A (40°), then C (55°). So B has the largest index, then A, then C.

Challenge: Record 49.3. Neither material is air. $n_1 = 1.33$, $n_2 = 1.52$. $\sin \theta_2 = n_1 \sin \theta_1 \div n_2 = (1.33)(\sin 60.0°) \div 1.52 = 0.7578$. $\theta_2 = 49.3°$. Glass has the larger index, so the angle is smaller.

Card 6: I can find a critical angle and say when total internal reflection happens

Part 1

What the question looks like

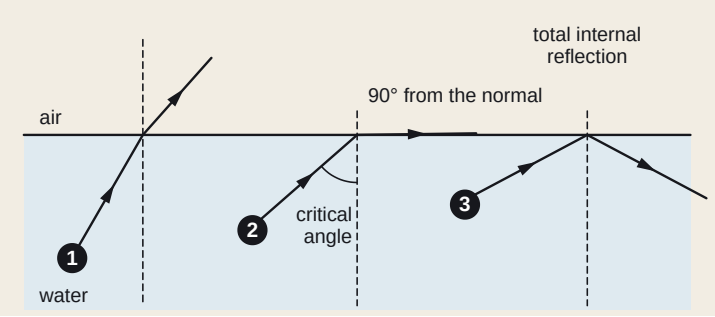
The question has light inside glass, water, diamond or an optical fibre, heading for a boundary with air or another material. It asks for the critical angle, or whether the light gets out. Words to look for: “critical angle”, “total internal reflection”, “optical fibre”, “does not leave”.

Steps: Find a critical angle

1. **Check the direction.** Total internal reflection can happen only when light goes from a larger index of refraction toward a smaller one.
2. **Set the angle of refraction to 90°.** At the critical angle, the refracted ray runs along the boundary.
3. **Use $n_2/n_1 = \sin\theta_1/\sin\theta_2$ with $\theta_2 = 90°$.** $\sin 90° = 1$, so $\sin\theta_1 = n_2 \div n_1$. This θ_1 is the critical angle.
4. **Compare.** Angle of incidence larger than the critical angle: all the light reflects. Smaller: some light refracts out.

Check: $n_2 \div n_1$ must be less than 1. If it is more than 1, you have the two materials the wrong way round.

Worked example



Light travels in water toward the surface. Above the water is air. The index of refraction of water is 1.33.

Question: What is the critical angle for light going from water to air?

Step 1 The light goes from water (1.33) toward air (1.00): from larger to smaller. Total internal reflection can happen.

Step 2 $\theta_2 = 90°$.

Step 3 $\sin\theta_1 = n_2 \div n_1 = 1.00 \div 1.33 = 0.752$. $\theta_1 = 48.8°$. This is the critical angle.

Step 4 Light that meets the surface at more than 48.8° from the normal reflects back into the water.

The common mistake

> Trying to find a critical angle for light going from air into glass or water. **There is none.** Total internal reflection happens only on the way from a larger index to a smaller index.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 6.1

Total internal reflection of light happens when the light travels

A. from a smaller index of refraction toward a larger one, at an angle of incidence larger than the critical angle
B. from a larger index of refraction toward a smaller one, at an angle of incidence larger than the critical angle
C. from a larger index of refraction toward a smaller one, at an angle of incidence smaller than the critical angle
D. from a smaller index of refraction toward a larger one, at an angle of incidence smaller than the critical angle

Question 6.2

Light travels in glass with an index of refraction of 1.50 toward a boundary with air. The critical angle, in degrees, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Question 6.3

A ray of light in air meets a water surface at an angle of incidence of 80°. Which statement is correct?

A. Some light refracts into the water, because light going into a larger index always has a refracted ray
B. All the light reflects, because 80° is larger than the critical angle of water
C. All the light reflects, because water has a larger index than air
D. No light reflects, because the angle is less than 90°

Question 6.4

The index of refraction of diamond is 2.42. The critical angle for light going from diamond to air, in degrees, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Question 6.5

An optical fibre has a glass core with a coating around it. Light stays inside the core because the core has

A. the same index of refraction as the coating
B. a mirror painted on its inside
C. a smaller index of refraction than the coating, so the light refracts back in
D. a larger index of refraction than the coating, so the light is totally internally reflected

Challenge question

Light travels in glass (n = 1.52) toward a boundary with water (n = 1.33). The critical angle, in degrees, is

Numerical response. Record your three-digit answer. ☐☐☐

Hint: Use $\sin \theta_1 = n_2 \div n_1$. Here n_2 is 1.33, not 1.00.

Card 6 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 6.1

Light in glass meets a boundary with air at exactly the critical angle. The angle of refraction is

A. 0°
B. 45°
C. 90°
D. 180°

Check 6.2

Light travels in a plastic with an index of refraction of 1.60 toward a boundary with air. The critical angle, in degrees, is

Numerical response. Record your three-digit answer. ☐☐☐

Check 6.3

The critical angle for a glass-to-air boundary is 42°. A ray inside the glass meets the boundary at an angle of incidence of 50°. The ray

A. refracts into the air at 90°
B. is totally reflected back into the glass
C. refracts into the air at 50°
D. stops at the boundary

Need more? Read the steps and the worked example on this card again. Then ask for the short lesson on this card.

Answers for card 6

Question 6.1: B. Two conditions. The light must be in the material with the larger index. The angle of incidence must be larger than the critical angle.

Question 6.2: Record 41.8. $\sin \theta_1 = n_2 \div n_1 = 1.00 \div 1.50 = 0.667$. $\theta_1 = 41.8°$.

Question 6.3: A. Total internal reflection cannot happen here. The light is going from the smaller index (air) into the larger index (water). Some light refracts into the water and some reflects.

Question 6.4: Record 24.4. $\sin \theta_1 = 1.00 \div 2.42 = 0.413$. $\theta_1 = 24.4°$. The small critical angle keeps light inside a diamond for many reflections. That is why a diamond sparkles.

Question 6.5: D. The core has the larger index. Light meets the edge of the core at more than the critical angle, so all of it reflects back in, again and again, along the fibre.

Challenge: Record 61.0. The second material is water, not air. $\sin \theta_1 = n_2 \div n_1 = 1.33 \div 1.52 = 0.875$. $\theta_1 = 61.0°$.

Card 7: I can explain diffraction, interference and polarization, and what Young’s experiment shows

Part 1

What the question looks like

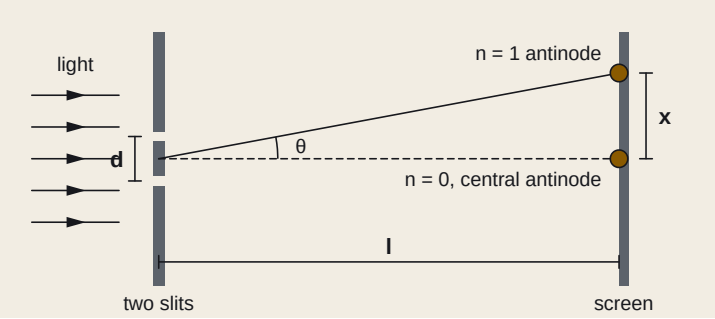
The question describes light that spreads out after a narrow slit, makes a pattern of bright and dark spots, is blocked by filters, or is split into colours. It asks you to name what happened or to say what it shows about light. Words to look for: “diffraction”, “interference”, “antinode”, “polarizing filter”, “spectrum”, “wave model”.

Steps: Say what a light observation shows

1. **Name what happened.** Light spreads out after a narrow gap: diffraction. Light from two or more slits makes bright and dark spots: interference. A filter blocks light that got through another filter: polarization.
2. **Explain the bright and dark spots.** Bright spot (antinode): the waves arrive in step and add. Dark spot (node): the waves arrive half a wavelength out of step and cancel.
3. **Say what it shows about light.** Diffraction and interference: light acts as a wave. Polarization: light is a transverse wave.
4. **For colours, name the cause.** A diffraction grating spreads colours by interference: red, the longest wavelength, is spread the most. A prism spreads colours by refraction: violet bends the most.

Check: Diffraction is the spreading. Interference is the adding and cancelling. A double-slit pattern needs both.

Worked example



Young sent light of one colour through two narrow slits. On a screen he saw a row of bright and dark bands.

Question: What does this pattern show about light?

Step 1 Light from the two slits overlaps and makes bright and dark bands. This is interference.

Step 2 Bright bands: the two waves arrive in step. Dark bands: they arrive half a wavelength out of step.

Step 3 Only waves can cancel each other. So the pattern shows that light acts as a wave.

Step 4 One colour was used, so there is no spreading of colours to explain.

The common mistake

> Mixing up diffraction and interference. **Diffraction is a wave spreading out after a gap or an edge. Interference is two waves adding or cancelling where they overlap.**

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 7.1

Young's double-slit experiment gave strong evidence that light

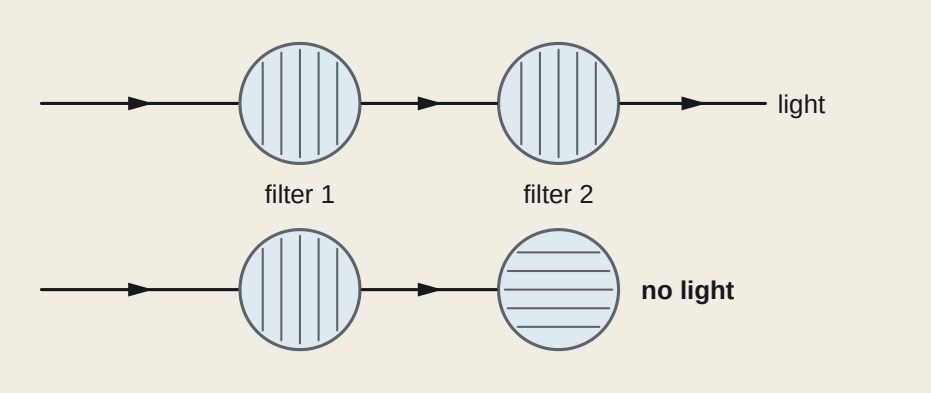
A. is made of particles
B. travels at 3.00×10^8 m/s
C. acts as a wave
D. needs a medium to travel through

Question 7.2

Light can be polarized. This shows that light is

A. a transverse wave
B. a longitudinal wave
C. a stream of particles
D. a wave that needs a medium

Question 7.3



Light passes through two polarizing filters. Three set-ups are numbered by the angle between the lines of the two filters: **1** 90°; **2** 0°; **3** 45°. Put the set-ups in order from the brightest light that gets through to the dimmest.

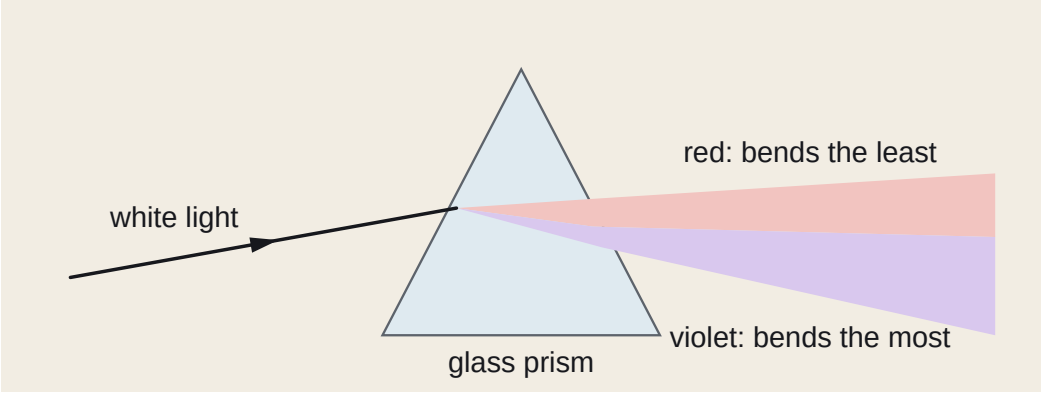
Put in order. Record the three numbers in order. ☐☐☐

Question 7.4

Diffraction of a wave through a gap is easiest to see when the width of the gap is

A. much larger than the wavelength
B. about the same as the wavelength, or smaller
C. exactly twice the wavelength
D. larger than the screen

Question 7.5



White light passes through a glass prism and spreads into colours. Violet light bends more than red light because, in the glass, violet light

A. has a longer wavelength than red light
B. has a smaller frequency than red light
C. travels faster than red light
D. travels slower than red light

Question 7.6

White light makes a spectrum with a diffraction grating and with a prism. Which row names the colour that is turned through the largest angle by each one?

A. Grating: violet. Prism: violet.
B. Grating: red. Prism: red.
C. Grating: red. Prism: violet.
D. Grating: violet. Prism: red.

Challenge question

In a double-slit pattern, a point on the screen is 1.5 wavelengths farther from one slit than from the other slit. At this point there is

A. a bright spot (antinode), because the waves arrive in step
B. a dark spot (node), because the waves arrive half a wavelength out of step
C. a bright spot (antinode), because the path is longer
D. a dark spot (node), because no light reaches this point

Hint: Ask whether the two waves arrive in step. A whole number of wavelengths: in step. A half left over: out of step.

Card 7 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 7.1

Water waves pass through a narrow gap in a wall and spread out on the other side. This spreading is called

A. refraction
B. interference
C. polarization
D. diffraction

Check 7.2

Two polarizing filters are held so that their lines are at 90° to each other. A light shines at them. Through both filters, a person sees

A. no light
B. light twice as bright
C. light of a new colour
D. the same brightness as with no filters

Check 7.3

In a double-slit pattern, a bright spot (antinode) forms where the two waves

A. have different frequencies
B. cancel each other
C. arrive in step and add
D. arrive at different speeds

Need more? Read the steps and the worked example on this card again. Then ask for the short lesson on this card.

Answers for card 7

Question 7.1: C. The pattern of bright and dark bands is interference. Particles cannot cancel each other, but waves can. So the experiment supports the wave model of light.

Question 7.2: A. Only a transverse wave can be polarized. A polarizing filter lets through the vibrations in one direction and blocks the rest. A longitudinal wave, such as sound, cannot be polarized.

Question 7.3: Record 231. At 0° the filters are lined up, so the most light gets through (2). At 45° some light gets through (3). At 90° the filters are crossed and no light gets through (1). The order is 2, 3, 1.

Question 7.4: B. A wave spreads out the most when the gap is about as wide as its wavelength, or narrower. Light has a very short wavelength, so the slits must be very narrow.

Question 7.5: D. Glass has a slightly larger index of refraction for violet light than for red light. So violet light slows down more and bends more. This spreading of colours by refraction is called dispersion.

Question 7.6: C. A grating works by interference: $\lambda = d \sin \theta \div n$, so the longest wavelength, red, has the largest angle. A prism works by refraction: violet slows down the most, so violet bends the most.

Challenge: B. A difference of 1.5 wavelengths leaves the two waves half a wavelength out of step: a crest meets a trough. They cancel, so the point is dark. Light does reach the point: two waves arrive and cancel.

Card 8: I can solve a double-slit or diffraction grating question

Part 1

What the question looks like

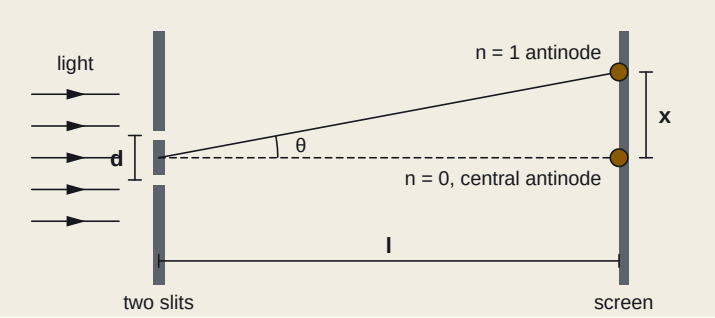
The question gives the distance between two slits, or the number of lines in a diffraction grating. It gives a distance on a screen or an angle to a bright spot, and asks for the wavelength. Or it gives the wavelength and asks for one of the others. Words to look for: “double slit”, “diffraction grating”, “lines per metre”, “antinode”, “bright fringe”, “screen”.

Steps: Find a wavelength from an interference pattern

1. **List what you know, in metres.** d is the distance between slits. For a grating, d = 1 ÷ (the number of lines per metre). n is the number of the antinode: the central one is n = 0.
2. **Pick the equation from the data sheet.** An angle is given: $\lambda = d \sin\theta \div n$. A distance x on the screen and the distance l to the screen are given: $\lambda = xd \div (nl)$.
3. **Solve.** x is measured from the central antinode to antinode n.
4. **Check the size.** Visible light is between about 400 nm and 700 nm: 4×10^{-7} m to 7×10^{-7} m.

Check: $\lambda = xd \div (nl)$ works only when the angle is small (the screen is far away). If the angle is large, as with most gratings, use $\lambda = d \sin\theta \div n$.

Worked example



Light of one colour passes through two slits that are 0.150 mm apart. A screen is 3.00 m from the slits. The second antinode (n = 2) is 2.36 cm from the central antinode.

Question: What is the wavelength of the light?

Step 1 d = 0.150 mm = 1.50×10^{-4} m. l = 3.00 m. x = 2.36 cm = 0.0236 m. n = 2.

Step 2 x and l are given, so use $\lambda = xd \div (nl)$.

Step 3 $\lambda = (0.0236\text{ m})(1.50 \times 10^{-4}\text{ m}) \div [(2)(3.00\text{ m})] = 5.90 \times 10^{-7}$ m.

Step 4 5.90×10^{-7} m is 590 nm. That is visible light, so the size makes sense.

The common mistake

> Using the number of lines as d. **For a grating, d = 1 ÷ (lines per metre).** A second mistake: leaving mm or cm in the equation. Change every length to metres.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 8.1

Light passes through two slits that are 2.00×10^{-4} m apart. A screen is 2.50 m away. The first antinode (n = 1) is 7.50 mm from the central antinode. The wavelength of the light is

Numerical response. Write your answer as $a.bc \times 10^{-w}$ m. Record the four digits a, b, c and w.

□□□□

Question 8.2

A diffraction grating has 5.00×10^{5} lines per metre. Light of one colour passes through it. The first antinode (n = 1) is at an angle of 17.5° from the centre. The wavelength of the light is

Numerical response. Write your answer as $a.bc \times 10^{-w}$ m. Record the four digits a, b, c and w.

□□□□

Question 8.3

A bright spot from a diffraction grating is at an angle of 25° from the centre. To find the wavelength, a student should use

A. $\lambda = xd \div (nl)$, because it has more measurements in it
B. $\lambda = xd \div (nl)$, because gratings do not have an angle
C. $\lambda = d \sin\theta \div n$, because $\lambda = xd \div (nl)$ works only for small angles
D. either equation, because they always give the same answer

Question 8.4

Green light makes a double-slit pattern on a screen. The green light is replaced with red light, and nothing else changes. The bright spots on the screen are now

A. closer together, because red light has a longer wavelength
B. closer together, because red light has a shorter wavelength
C. farther apart, because red light has a shorter wavelength
D. farther apart, because red light has a longer wavelength

Question 8.5

Blue light with a wavelength of 450 nm passes through two slits that are 1.00×10^{-4} m apart. A screen is 2.00 m away. The distance on the screen from the central antinode to the third antinode (n = 3) is

Numerical response. Write your answer as $a.bc \times 10^{-w}$ m. Record the four digits a, b, c and w.

□□□□

Challenge question

Red laser light with a wavelength of 633 nm passes through a diffraction grating with 3.00×10^5 lines per metre. The angle from the centre to the second antinode (n = 2), in degrees, is

Numerical response. Record your three-digit answer. ☐☐☐

Hint: Find d from the lines per metre. Then rearrange $\lambda = d \sin\theta \div n$ for $\sin\theta$.

Card 8 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 8.1

A diffraction grating has 4.00×10^5 lines per metre. The distance d between its lines is

Numerical response. Write your answer as $a.bc \times 10^{-w}$ m. Record the four digits a, b, c and w.

☐☐☐☐

Check 8.2

Light passes through two slits that are 1.20×10^{-4} m apart. A screen is 2.20 m away. The first antinode (n = 1) is 0.990 cm from the central antinode. The wavelength of the light is

Numerical response. Write your answer as $a.bc \times 10^{-w}$ m. Record the four digits a, b, c and w.

☐☐☐☐

Check 8.3

In a double-slit experiment, the two slits are moved closer together, and nothing else changes. The bright spots on the screen

A. move closer together
B. move farther apart
C. stay in the same places
D. disappear

Need more? Read the steps and the worked example on this card again. Then ask for the short lesson on this card.

Answers for card 8

Question 8.1: Record 6007. $x = 7.50 \times 10^{-3}$ m. $\lambda = xd \div (nl) = (7.50 \times 10^{-3})(2.00 \times 10^{-4}) \div [(1)(2.50)] = 6.00 \times 10^{-7}$ m.

Question 8.2: Record 6017. $d = 1 \div (5.00 \times 10^5) = 2.00 \times 10^{-6}$ m. $\lambda = d \sin\theta \div n = (2.00 \times 10^{-6})(\sin 17.5°) \div 1 = 6.01 \times 10^{-7}$ m.

Question 8.3: C. $\lambda = xd \div (nl)$ comes from treating $\sin\theta$ as $x \div l$. That is close only when the angle is small. At 25° it is not, so use $\lambda = d \sin\theta \div n$.

Question 8.4: D. Rearrange $\lambda = xd \div (nl)$ to $x = n\lambda l \div d$. A longer wavelength gives a larger x. Red light has a longer wavelength than green light.

Question 8.5: Record 2702. $\lambda = 4.50 \times 10^{-7}$ m. Rearrange $\lambda = xd \div (nl)$: $x = n\lambda l \div d = (3)(4.50 \times 10^{-7})(2.00) \div (1.00 \times 10^{-4}) = 2.70 \times 10^{-2}$ m.

Challenge: Record 22.3. $d = 1 \div (3.00 \times 10^{5}) = 3.33 \times 10^{-6}$ m. $\lambda = 6.33 \times 10^{-7}$ m. Rearrange $\lambda = d \sin\theta \div n$: $\sin\theta = n\lambda \div d = (2)(6.33 \times 10^{-7}) \div (3.33 \times 10^{-6}) = 0.380$. $\theta = 22.3°$.

Card 9: I can find the energy of a photon, in joules and in electron volts, and rank the spectrum by photon energy

Part 2

What the question looks like

The question gives the frequency or the wavelength of light or other EMR and asks for the energy of one photon. Or it asks which type of EMR has photons with the most energy. Words to look for: “photon”, “quantum”, “energy of one photon”, “eV”, “Planck’s constant”.

Steps: Find the energy of one photon

1. **List what you know, in Hz or in metres.** 1 nm = 10^{-9} m.
2. **Pick the equation from the data sheet.** A frequency is given: E = hf. A wavelength is given: E = hc ÷ λ.
3. **Pick the value of h.** For an answer in joules: h = 6.63 × 10^{-34} J·s. For an answer in electron volts: h = 4.14 × 10^{-15} eV·s.
4. **Change the unit if you need to.** 1 eV = 1.60 × 10^{-19} J. To go from J to eV, divide by 1.60 × 10^{-19}.

Check: One photon of visible light has about 2 eV to 3 eV, which is about 3 × 10^{-19} J to 5 × 10^{-19} J. A larger frequency always means more energy.

Worked example

Green light has a wavelength of 500 nm.

Question: What is the energy of one photon of this light, in joules and in electron volts?

Step 1 λ = 500 nm = 5.00 × 10^{-7} m.

Step 2 A wavelength is given, so E = hc ÷ λ.

Step 3 E = (6.63 × 10^{-34} J·s)(3.00 × 10^{8} m/s) ÷ (5.00 × 10^{-7} m) = 3.98 × 10^{-19} J.

Step 4 E = (3.98 × 10^{-19} J) ÷ (1.60 × 10^{-19} J/eV) = 2.49 eV.

The common mistake

> Mixing the two values of h. **6.63 × 10^{-34} gives joules. 4.14 × 10^{-15} gives electron volts.** Decide which unit the question wants before you start.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 9.1

Planck explained the light from hot objects with a new idea. His idea was that energy is given off

A. in any amount at all
B. only in small packets, each with an energy of hf
C. only as waves with no energy
D. only by objects that are cold

Question 9.2

Violet light has a frequency of 7.50×10^{14} Hz. The energy of one photon of this light is

Numerical response. Write your answer as $a.b \times 10^{-cd}$ J. Record the four digits a, b, c and d.

□□□□

Question 9.3

Ultraviolet radiation has a frequency of 1.20×10^{15} Hz. The energy of one photon, in electron volts, is

Numerical response. Record your three-digit answer. □□□□

Question 9.4

Four types of EMR are numbered: **1** red light; **2** X-rays; **3** microwaves; **4** ultraviolet. Put them in order from the lowest photon energy to the highest photon energy.

Put in order. Record the four numbers in order. □□□□

Question 9.5

Photon X has twice the wavelength of photon Y. Compared with the energy of photon Y, the energy of photon X is

A. half as large
B. the same
C. twice as large
D. four times as large

Challenge question

A laser gives off 5.00×10^{-3} J of light energy each second. The light has a wavelength of 633 nm. The number of photons the laser gives off each second is

Numerical response. Write your answer as $a.b \times 10^{cd}$ photons. Record the four digits a, b, c and d.

□□□□

Hint: Find the energy of one photon in joules. Then divide the total energy by the energy of one photon.

Card 9 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 9.1

Which type of EMR has photons with the most energy?

A. Radio waves
B. Infrared
C. Visible light
D. Gamma rays

Check 9.2

Ultraviolet radiation has a wavelength of 250 nm. The energy of one photon is

Numerical response. Write your answer as a.b × 10^{-cd} J. Record the four digits a, b, c and d.
☐☐☐☐

Check 9.3

Orange light has a frequency of 5.00 × 10^{14} Hz. The energy of one photon, in electron volts, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Need more? Read the steps and the worked example on this card again. Then ask for the short lesson on this card.

Answers for card 9

Question 9.1: B. Planck said energy is given off in packets, called quanta. One packet has an energy of E = hf. He changed the model to fit the measurements. A packet of light is called a photon.

Question 9.2: Record 5019. E = hf = (6.63 × 10^{-34})(7.50 × 10^{14}) = 4.97 × 10^{-19} J. Written as a.b × 10^{-cd}, that is 5.0 × 10^{-19} J.

Question 9.3: Record 4.97. The answer is in eV, so use h = 4.14 × 10^{-15} eV·s. E = hf = (4.14 × 10^{-15})(1.20 × 10^{15}) = 4.97 eV.

Question 9.4: Record 3142. E = hf, so photon energy goes up with frequency: microwaves (3), red light (1), ultraviolet (4), X-rays (2). The order is 3, 1, 4, 2.

Question 9.5: A. E = hc ÷ λ. The energy is inversely proportional to the wavelength. Twice the wavelength gives half the energy.

Challenge: Record 1616. One photon: E = hc ÷ λ = (6.63 × 10^{-34})(3.00 × 10^{8}) ÷ (6.33 × 10^{-7}) = 3.14 × 10^{-19} J. Number each second = (5.00 × 10^{-3} J) ÷ (3.14 × 10^{-19} J) = 1.59 × 10^{16}. As a.b × 10^{cd}: 1.6 × 10^{16} photons.

Card 10: I can explain the photoelectric effect: what intensity, frequency and the metal each change, and why the wave model fails

Part 2

What the question looks like

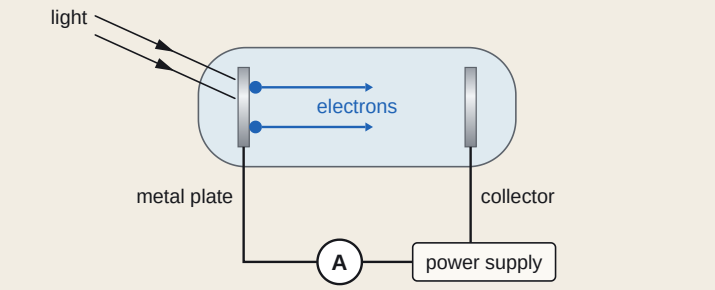
The question has light shining on a metal plate and electrons leaving the plate. It changes the brightness (intensity), the colour (frequency) or the metal, and asks what happens. Or it asks what this shows about light. Words to look for: “photoelectric”, “photoelectrons”, “intensity”, “threshold frequency”, “work function”.

Steps: Predict what a change does in the photoelectric effect

1. **Compare the photon energy with the work function.** The work function W is the least energy needed to free an electron from that metal. If hf is less than W, no electrons leave, however bright the light is.
2. **If the frequency goes up:** each photon has more energy, so each electron leaves with more kinetic energy. The stopping voltage goes up.
3. **If the intensity goes up:** more photons arrive each second, so more electrons leave each second. The current goes up. The kinetic energy of each electron does not change.
4. **If the metal changes:** the work function changes, so the threshold frequency changes.

Check: One photon gives all its energy to one electron. Photons do not team up.

Worked example



The supply can push the electrons back: the stopping voltage.

Dim violet light frees electrons from a metal plate. Very bright red light frees no electrons from the same plate.

Question: Why does the bright red light free no electrons?

Step 1 A photon of red light has a low frequency, so its energy hf is less than the work function of the metal.

Step 2 The frequency was not raised: red photons stay too small.

Step 3 Bright light means more photons each second. But each red photon is still too small, and photons do not team up.

Step 4 The metal is the same. Violet photons have more energy than the work function, so even dim violet light frees electrons.

The common mistake

> Saying that brighter light gives the electrons more energy. **Brighter light gives more electrons, not faster ones.** Only a higher frequency gives each electron more kinetic energy.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 10.1

Light above the threshold frequency shines on a metal plate, and electrons leave the plate. The intensity of the light is doubled, and its frequency stays the same. Which row describes what happens?

A. More electrons leave each second. Each has the same maximum kinetic energy.
B. More electrons leave each second. Each has more maximum kinetic energy.
C. The same number leave each second. Each has more maximum kinetic energy.
D. The same number leave each second. Each has the same maximum kinetic energy.

Question 10.2

Light frees electrons from a metal plate. The light is changed to a higher frequency with the same intensity. The maximum kinetic energy of the electrons

A. goes down
B. stays the same
C. goes up
D. becomes zero

Question 10.3

The wave model of light made predictions about the photoelectric effect. Which prediction of the wave model does **not** match what is seen?

A. Light carries energy to the metal.
B. Brighter light carries more energy each second.
C. Light can free electrons from a metal.
D. Bright light of any frequency will free electrons if it shines long enough.

Question 10.4

Four things are seen in a photoelectric experiment:
1 There is a threshold frequency. Below it, no electrons leave.
2 Brighter light gives a larger current.
3 Electrons leave at once, even in very dim light.
4 Light gives energy to the metal.
Which two can be explained by the photon model but **not** by the wave model?

Pick two. Record the two numbers. ☐☐

Question 10.5

Hertz and Planck both helped start quantum physics. Which row describes what each one did?

A. Hertz proposed that energy comes in packets. Planck measured the charge of the electron.
B. Hertz saw in an experiment that light on a metal helped a spark to jump. Planck proposed that energy comes in packets.
C. Hertz measured the speed of light. Planck showed that light is a transverse wave.
D. Hertz proposed that energy comes in packets. Planck saw that light on a metal helped a spark to jump.

Challenge question

Light with a frequency just below the threshold frequency shines on a metal plate. No electrons leave. The intensity of the light is made 100 times larger. Now

A. no electrons leave, because each photon still has less energy than the work function
B. a few electrons leave, because 100 photons can add their energy
C. many electrons leave, because the light carries 100 times the energy
D. electrons leave after a delay, because energy builds up in the metal

Hint: Ask what one photon can do to one electron. Has the energy of one photon changed?

Card 10 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 10.1

The work function of a metal is the

A. energy of the light that shines on it
B. least energy needed to free an electron from the metal
C. kinetic energy of an electron after it leaves
D. voltage that stops the electrons

Check 10.2

In the photoelectric effect, the number of electrons that leave the metal each second depends on the

A. frequency of the light only
B. colour of the metal
C. intensity of the light
D. stopping voltage

Check 10.3

The photoelectric effect is strong evidence that light

A. acts as a particle
B. acts only as a wave
C. is a longitudinal wave
D. travels slower in a metal

Need more? Read the steps and the worked example on this card again. Then ask for the short lesson on this card.

Answers for card 10

Question 10.1: A. Double the intensity means twice as many photons each second, so twice as many electrons. Each photon has the same energy hf as before, so the maximum kinetic energy is the same.

Question 10.2: C. Each photon now has more energy. The work function is the same, so more energy is left over as kinetic energy.

Question 10.3: D. In the wave model, energy arrives steadily, so any bright light should free electrons in the end. In fact, light below the threshold frequency never frees electrons. The photon model explains this: each photon is too small.

Question 10.4: Record 13. The wave model has no threshold frequency (1): any wave would add up enough energy in time. The wave model needs a delay in dim light (3): a photon gives its energy to one electron all at once. Both models explain 2 and 4. Record 13. The order does not matter, so 31 is also right.

Question 10.5: B. Hertz noticed the effect in an experiment: light shining on metal made a spark jump more easily. Planck changed the model: energy is given off in packets of hf. Einstein used Planck's idea to explain what Hertz saw.

Challenge: A. One photon gives its energy to one electron. Each photon is still too small to free an electron. More photons do not help.

Card 11: I can solve a photoelectric question: work function, threshold frequency, maximum kinetic energy and stopping voltage

Part 2

What the question looks like

The question gives the frequency or wavelength of the light and something about the metal: its work function or its threshold frequency. It asks for the maximum kinetic energy of the electrons, the stopping voltage, or the missing fact about the metal. Words to look for: “work function”, “threshold frequency”, “stopping voltage”, “maximum kinetic energy”.

Steps: Solve a photoelectric question

1. **Find the energy of one photon.** $E = hf$ or $E = hc \div \lambda$. Working in eV is quicker: use $h = 4.14 \times 10^{-15}$ eV·s.
2. **Find the work function, in the same unit.** It is given, or use $W = hf_o$, where f_o is the threshold frequency.
3. **Use conservation of energy.** photon energy = work function + maximum kinetic energy. So $E_{k\,max} = hf - W$.
4. **Find the stopping voltage, if asked.** $E_{k\,max} = q_e V_{stop}$. An electron with 1.5 eV of kinetic energy is stopped by 1.5 V.

Check: If $hf - W$ comes out negative, the photon is too small: no electrons leave. At the threshold frequency, $E_{k\,max}$ is zero.

Worked example

Light with a wavelength of 410 nm shines on a metal with a work function of 2.28 eV.

Question: What is the maximum kinetic energy of the electrons, and what is the stopping voltage?

Step 1 $E = hc \div \lambda = (4.14 \times 10^{-15}\ \text{eV·s})(3.00 \times 10^{8}\ \text{m/s}) \div (4.10 \times 10^{-7}\ \text{m}) = 3.03$ eV.

Step 2 $W = 2.28$ eV. It is given.

Step 3 $E_{k\,max} = hf - W = 3.03\ \text{eV} - 2.28\ \text{eV} = 0.749$ eV.

Step 4 Each electron has a charge of one elementary charge, so $V_{stop} = 0.749$ V.

The common mistake

> Mixing joules and electron volts in one subtraction. **Put the photon energy and the work function in the same unit first.** A second mistake: forgetting to subtract the work function at all.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 11.1

The threshold frequency of a metal is 5.50×10^{14} Hz. The work function of the metal, in electron volts, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Question 11.2

Photons with an energy of 4.50 eV shine on a metal with a work function of 2.90 eV. The maximum kinetic energy of the electrons, in electron volts, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Question 11.3

A metal has a work function of 2.50 eV. The longest wavelength of light that can free electrons from this metal is

Numerical response. Write your answer as $a.bc \times 10^{-w}$ m. Record the four digits a, b, c and w.
☐☐☐☐

Question 11.4

Students combine $E_{k\,max} = q_e V_{stop}$ with conservation of energy. Which equation gives the stopping voltage?

A. $V_{stop} = (hf + W) \div q_e$
B. $V_{stop} = q_e(hf - W)$
C. $V_{stop} = hf \div (W\, q_e)$
D. $V_{stop} = (hf - W) \div q_e$

Question 11.5

Light with a frequency of 1.00×10^{15} Hz shines on a metal with a work function of 2.30 eV. The stopping voltage, in volts, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Challenge question

Electrons leave a metal with a maximum kinetic energy of 1.84 eV. The maximum speed of these electrons is

Numerical response. Write your answer as $a.bc \times 10^{w}$ m/s. Record the four digits a, b, c and w.
☐☐☐☐

Hint: $E_k = \frac{1}{2}mv^2$ needs joules and kilograms. Change the energy from eV to J first.

Card 11 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 11.1

A metal has a work function of 4.00 eV. The threshold frequency of the metal is

Numerical response. Write your answer as a.b × 10^{cd} Hz. Record the four digits a, b, c and d.

☐☐☐☐

Check 11.2

Light at exactly the threshold frequency shines on a metal. The maximum kinetic energy of the electrons that leave is

A. equal to the work function
B. zero
C. equal to the photon energy
D. twice the work function

Check 11.3

Photons with an energy of 6.00 × 10^{-19} J shine on a metal with a work function of 3.50 × 10^{-19} J. The maximum kinetic energy of the electrons is

Numerical response. Write your answer as a.b × 10^{-cd} J. Record the four digits a, b, c and d.

☐☐☐☐

Need more? Read the steps and the worked example on this card again. Then ask for the short lesson on this card.

Answers for card 11

Question 11.1: Record 2.28. $W = hf_o = (4.14 \times 10^{-15}\ \text{eV·s})(5.50 \times 10^{14}\ \text{Hz}) = 2.28$ eV.

Question 11.2: Record 1.60. $E_{k\,max} = hf - W = 4.50\ \text{eV} - 2.90\ \text{eV} = 1.60$ eV.

Question 11.3: Record 4977. The longest wavelength has the smallest photon energy that still works: $E = W = 2.50$ eV. $\lambda = hc \div E = (4.14 \times 10^{-15})(3.00 \times 10^{8}) \div 2.50 = 4.97 \times 10^{-7}$ m. Any longer wavelength has photons that are too small.

Question 11.4: D. $E_{k\,max} = hf - W$ and $E_{k\,max} = q_eV_{stop}$. So $q_eV_{stop} = hf - W$, and $V_{stop} = (hf - W) \div q_e$.

Question 11.5: Record 1.84. $E = hf = (4.14 \times 10^{-15})(1.00 \times 10^{15}) = 4.14$ eV. $E_{k\,max} = 4.14 - 2.30 = 1.84$ eV. So $V_{stop} = 1.84$ V.

Challenge: Record 8045. Change to joules: $E_k = (1.84\ \text{eV})(1.60 \times 10^{-19}\ \text{J/eV}) = 2.944 \times 10^{-19}$ J. $E_k = \frac{1}{2}mv^2$, so $v = \sqrt{(2E_k \div m)} = \sqrt{[2(2.944 \times 10^{-19}) \div (9.11 \times 10^{-31})]} = 8.04 \times 10^{5}$ m/s. The mass of an electron is on the data sheet.

Card 12: I can read a photoelectric graph: Planck’s constant from the slope, the work function from the intercept

Part 2

What the question looks like

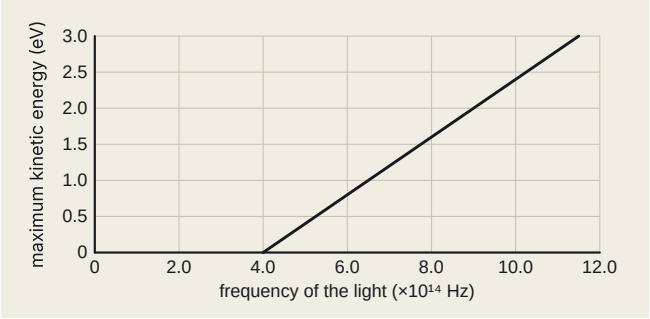
The question shows a graph of the maximum kinetic energy of the electrons (or the stopping voltage) against the frequency of the light. It asks for the threshold frequency, Planck’s constant or the work function. Or it asks how to do the experiment. Words to look for: “graph”, “slope”, “intercept”, “line of best fit”, “LED”.

Steps: Read a graph of maximum kinetic energy against frequency

1. **Find where the line meets the frequency axis.** That frequency is the threshold frequency f_o. There, Ek max = 0.
2. **Find the slope with two points on the line.** slope = rise ÷ run. Ek max = hf − W is a straight line, y = mx + b. The slope is Planck’s constant h.
3. **Find the work function.** W = hf_o. On the graph it is also where the line, drawn back, would meet the energy axis: at −W.
4. **Read the units on each axis.** The frequency axis is often in units of 10^{14} Hz. If the energy is in eV, the slope is in eV·s.

Check: Your slope should be close to 4.14 × 10^{-15} eV·s (or 6.63 × 10^{-34} J·s). A measured value is rarely exact.

Worked example



The graph shows the results of a photoelectric experiment.

Question: What are the threshold frequency and the value of Planck’s constant from this graph?

Step 1 The line meets the frequency axis at 4.0 × 10^{14} Hz. That is the threshold frequency.

Step 2 Two points on the line: (4.0 × 10^{14} Hz, 0 eV) and (9.0 × 10^{14} Hz, 2.0 eV). slope = (2.0 − 0) ÷ (9.0 × 10^{14} − 4.0 × 10^{14}) = 4.0 × 10^{-15} eV·s.

Step 3 W = hf_o = (4.0 × 10^{-15} eV·s)(4.0 × 10^{14} Hz) = 1.6 eV.

Step 4 The frequency axis is in units of 10^{14} Hz. The energy axis is in eV.

The common mistake

> Reading the frequency axis as 4.0 Hz. **The axis label says × 10^{14} Hz.** A second mistake: using a measured dot that is not on the line. Use two points on the line of best fit.

Your turn

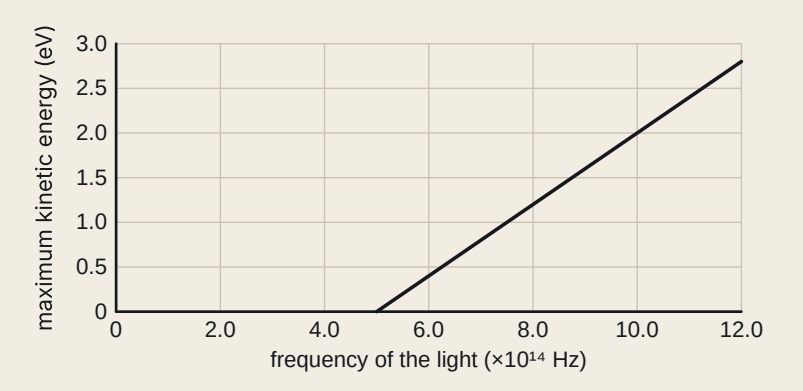
The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 12.1

On a graph of maximum kinetic energy against frequency for the photoelectric effect, the slope of the line is

A. the work function
B. the threshold frequency
C. Planck's constant
D. the charge of the electron

Question 12.2

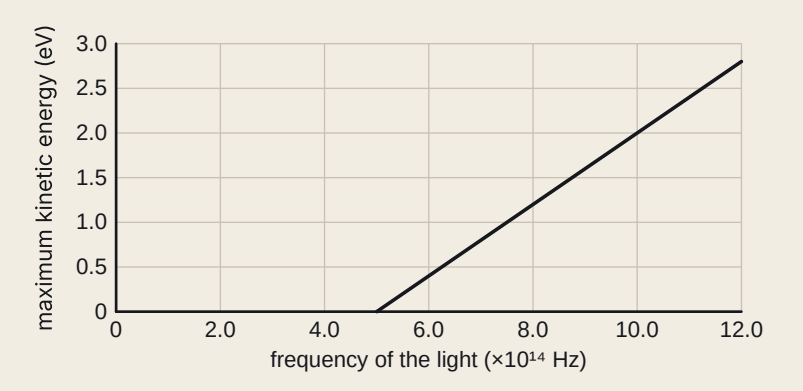


Use the graph. The value of Planck's constant from this graph is

Numerical response. Write your answer as a.b × 10^{-cd} eV·s. Record the four digits a, b, c and d.

☐☐☐☐

Question 12.3

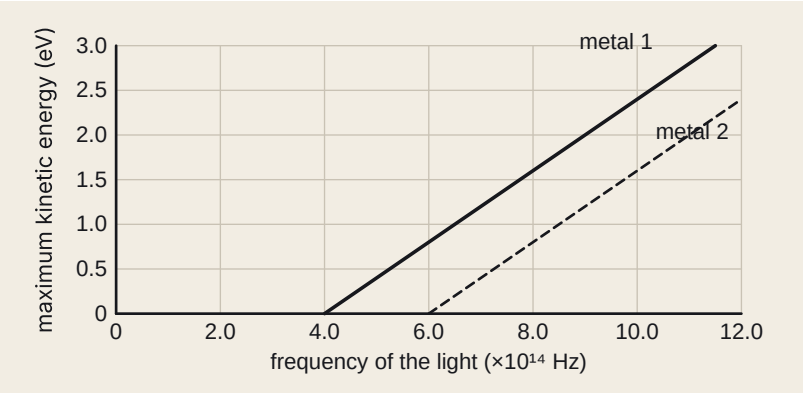


Use the same graph as the last question. The threshold frequency of the metal is

Numerical response. Write your answer as a.b × 10^{cd} Hz. Record the four digits a, b, c and d.

☐☐☐☐

Question 12.4



The graph shows results for two metals. Compared with metal 1, metal 2 has

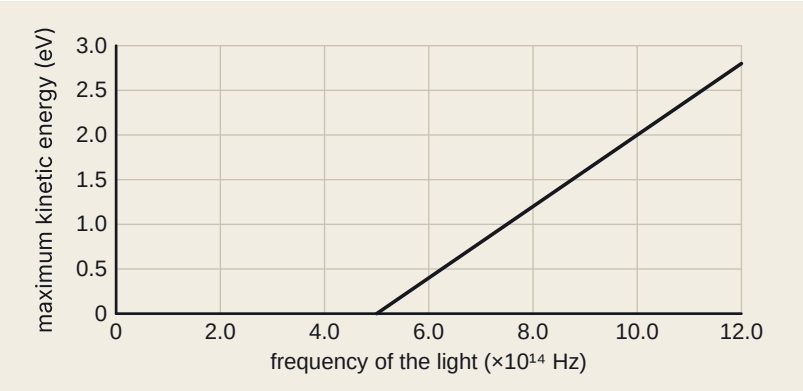
A. a larger work function, and its line has a steeper slope
B. a smaller work function, and its line has the same slope
C. a smaller work function, and its line has a steeper slope
D. a larger work function, and its line has the same slope

Question 12.5

Students want to measure Planck's constant with a photocell. They shine light of several different frequencies on it. For each frequency they should measure the

A. stopping voltage, because it gives the maximum kinetic energy of the electrons
B. brightness of the light, because it gives the energy of each photon
C. distance from the light to the photocell
D. time the light is on

Challenge question



Use the graph from question 2. The work function of the metal, in electron volts, is

Numerical response. Record your three-digit answer. ☐☐☐

Hint: $W = hf_o$. Use your slope for h and the frequency where the line meets the axis for f_o.

Card 12 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 12.1

On a graph of maximum kinetic energy against frequency, the point where the line meets the frequency axis gives the

A. work function
B. threshold frequency
C. stopping voltage
D. value of Planck's constant

Check 12.2

The line on a graph of maximum kinetic energy against frequency is drawn back until it meets the energy axis. It meets the axis at −2.3 eV. The work function of the metal is

A. 0 eV
B. 4.14 eV
C. 2.3 eV
D. −2.3 eV with no meaning

Check 12.3

A line of best fit passes through (6.0 × 10^{14} Hz, 0.50 eV) and (11.0 × 10^{14} Hz, 2.55 eV). The value of Planck's constant from this line is

Numerical response. Write your answer as a.b × 10^{-cd} eV·s. Record the four digits a, b, c and d.



Need more? Read the steps and the worked example on this card again. Then ask for the short lesson on this card.

Answers for card 12

Question 12.1: C. Ek max = hf − W has the form y = mx + b, with y = Ek max and x = f. The slope m is h.

Question 12.2: Record 4015. Two points on the line: (5.0 × 10^{14} Hz, 0 eV) and (10.0 × 10^{14} Hz, 2.0 eV). slope = 2.0 ÷ (5.0 × 10^{14}) = 4.0 × 10^{-15} eV·s.

Question 12.3: Record 5014. The line meets the frequency axis at 5.0 on an axis in units of 10^{14} Hz. The threshold frequency is 5.0 × 10^{14} Hz.

Question 12.4: D. The slope is Planck's constant, which is the same for every metal, so the lines are parallel. The line for metal 2 starts at a higher threshold frequency, and W = hf_o, so metal 2 has the larger work function.

Question 12.5: A. The frequency is the variable they change. The stopping voltage is the variable they measure: Ek max = q_eVstop. A graph of Ek max against frequency has a slope of h.

Challenge: Record 2.00. W = hf_o. Use the slope from the graph for h: W = (4.0 × 10^{-15} eV·s)(5.0 × 10^{14} Hz) = 2.00 eV.

Card 13: I can solve a Compton question, find the momentum of a photon, and say what wave-particle duality means

Part 2

What the question looks like

The question has an X-ray photon that hits an electron and bounces off, or it asks for the momentum of a photon. Or it describes electrons that make an interference pattern. Words to look for: “Compton”, “scattered”, “momentum of a photon”, “change in wavelength”, “wave-particle duality”.

Steps: Find the momentum of a photon

1. **List the wavelength in metres.** 1 nm = 10^{-9} m.
2. **Use p = h ÷ λ from the data sheet.** Use h = 6.63 × 10^{-34} J·s. The unit of the answer is kg·m/s.
3. **Solve.** A shorter wavelength gives a larger momentum.
4. **For the energy, use E = pc.** This is the same energy as E = hc ÷ λ.

Check: A photon has no mass, but it has momentum. Do not use p = mv for a photon.

Worked example

An X-ray photon has a wavelength of 0.0500 nm.

Question: What is the momentum of the photon?

Step 1 λ = 0.0500 nm = 5.00 × 10^{-11} m.

Step 2 p = h ÷ λ.

Step 3 p = (6.63 × 10^{-34} J·s) ÷ (5.00 × 10^{-11} m) = 1.33 × 10^{-23} kg·m/s.

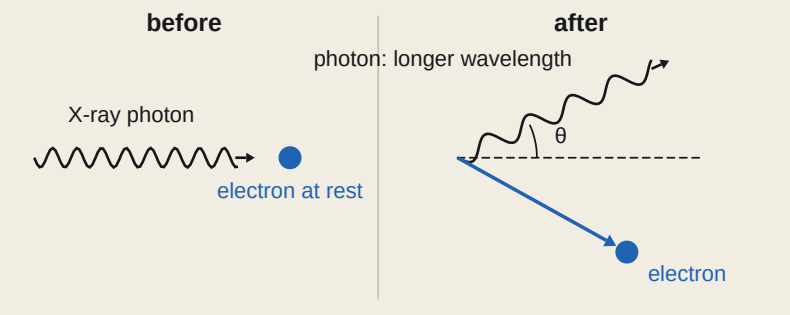
Step 4 The question does not ask for the energy.

Steps: Find the change in wavelength in a Compton collision

1. **Find the angle θ.** θ is the angle between the first direction of the photon and its direction after the collision.
2. **Use Δλ = (h ÷ mc)(1 − cos θ) from the data sheet.** m is the mass of the electron: 9.11 × 10^{-31} kg.
3. **Solve for Δλ.** This is how much longer the wavelength gets.
4. **Add, if the question asks for the new wavelength.** new wavelength = first wavelength + Δλ.

Check: The photon gives some energy to the electron. So after the collision the photon has less energy and a longer wavelength, never a shorter one.

Worked example



An X-ray photon with a wavelength of 5.00×10^{-11} m hits an electron at rest. The photon is scattered at 90° from its first direction.

Question: What is the wavelength of the photon after the collision?

Step 1 $\theta = 90°$, so $\cos\theta = 0$.

Step 2 $\Delta\lambda = (h \div mc)(1 - \cos\theta)$.

Step 3 $\Delta\lambda = (6.63 \times 10^{-34}) \div [(9.11 \times 10^{-31})(3.00 \times 10^{8})] \times (1 - 0) = 2.43 \times 10^{-12}$ m.

Step 4 New wavelength = 5.00×10^{-11} m + 0.243×10^{-11} m = 5.24×10^{-11} m.

The common mistake

> Using $p = mv$ for a photon. **A photon has no mass: use $p = h \div \lambda$.** A second mistake: making the wavelength shorter after a Compton collision. It always gets longer.

Your turn

The questions go from easy to exam level. Use your data sheet. Do each one on paper, then check your answer.

Question 13.1

In the Compton effect, an X-ray photon collides with an electron and both move away. This effect is evidence that photons

A. have mass and charge
B. travel slower than light
C. have momentum, as particles do
D. are longitudinal waves

Question 13.2

An X-ray photon has a wavelength of 0.0250 nm. The momentum of the photon is

Numerical response. Write your answer as $a.b \times 10^{-cd}$ kg·m/s. Record the four digits a, b, c and d.

☐☐☐☐

Question 13.3

An X-ray photon is scattered by an electron at an angle of 60° from its first direction. The change in the wavelength of the photon is

Numerical response. Write your answer as a.b × 10^{-cd} m. Record the four digits a, b, c and d.



Question 13.4

Compared with the X-ray photon before a Compton collision, the scattered photon has

A. a longer wavelength and less energy
B. a longer wavelength and more energy
C. a shorter wavelength and less energy
D. a shorter wavelength and more energy

Question 13.5

Number	Physics principle
3	Work-energy theorem
4	Conservation of momentum
5	Conservation of energy
7	Conservation of charge

A full analysis of a Compton collision uses two physics principles. Use the table. The two principles are

A. 3 and 7
B. 4 and 7
C. 3 and 5
D. 4 and 5

Question 13.6

A beam of electrons passes through two very narrow slits. On a screen behind the slits, the electrons build up a pattern of many bands. This shows that electrons

A. are not particles
B. can act as waves
C. have no charge
D. travel at the speed of light

Challenge question

A moving particle has a wavelength given by $\lambda = h \div p$, where $p = mv$ is its momentum. An electron moves at 2.00×10^{6} m/s. The wavelength of the electron is

Numerical response. Write your answer as $a.b \times 10^{-cd}$ m. Record the four digits a, b, c and d.



Hint: The question gives you the relation. Find the momentum of the electron with $p = mv$ first.

Card 13 check: hand this in

Three questions. No answers are given here. Your teacher uses them to see what to go over with you.

Check 13.1

Which two effects show that EMR can act as a particle?

A. Diffraction and interference
B. Refraction and reflection
C. The photoelectric effect and the Compton effect
D. Polarization and dispersion

Check 13.2

A photon has a momentum of 2.00×10^{-23} kg·m/s. The energy of the photon is

Numerical response. Write your answer as $a.b \times 10^{-cd}$ J. Record the four digits a, b, c and d.



Check 13.3

In a Compton collision, the change in the wavelength of the photon is largest when the photon is scattered at an angle of

A. 0°
B. 180°
C. 45°
D. 90°

Need more? Read the steps and the worked example on this card again. Then ask for the short lesson on this card.

Answers for card 13

Question 13.1: C. The collision follows conservation of momentum and conservation of energy, like a collision of two balls. So a photon carries momentum. Like the photoelectric effect, this shows EMR acting as a particle.

Question 13.2: Record 2723. $\lambda = 2.50 \times 10^{-11}$ m. $p = h \div \lambda = (6.63 \times 10^{-34}) \div (2.50 \times 10^{-11}) = 2.65 \times 10^{-23}$ kg·m/s. As $a.b \times 10^{-cd}$: 2.7×10^{-23} kg·m/s.

Question 13.3: Record 1212. $\cos 60° = 0.500$. $\Delta\lambda = (h \div mc)(1 - \cos\theta) = (6.63 \times 10^{-34}) \div [(9.11 \times 10^{-31})(3.00 \times 10^{8})] \times (1 - 0.500) = 1.21 \times 10^{-12}$ m. As $a.b \times 10^{-cd}$: 1.2×10^{-12} m.

Question 13.4: A. The photon gives some of its energy to the electron. Less energy means a lower frequency and a longer wavelength.

Question 13.5: D. The photon and the electron are an isolated system, so momentum is conserved (4) and energy is conserved (5). A diploma question asks you to use one of them, not both in full.

Question 13.6: B. A pattern of bands is an interference pattern, and only waves interfere. So matter, such as electrons, can act as a wave. Light acts as a wave and as a particle; so does matter. This is wave-particle duality.

Challenge: Record 3610. $p = mv = (9.11 \times 10^{-31}\text{ kg})(2.00 \times 10^{6}\text{ m/s}) = 1.822 \times 10^{-24}$ kg·m/s. $\lambda = h \div p = (6.63 \times 10^{-34}) \div (1.822 \times 10^{-24}) = 3.64 \times 10^{-10}$ m. As $a.b \times 10^{-cd}$: 3.6×10^{-10} m.

Practice unit check

Do this when your cards are done. It mixes the whole unit, like the unit final. Give yourself about 30 minutes, with your data sheet. Then check your answers. Each answer names the card to go back to.

Unit check 1

A wireless router sends out EMR with a frequency of 2.45×10^{9} Hz. The wavelength of this EMR is

Numerical response. Write your answer as $a.bc \times 10^{-w}$ m. Record the four digits a, b, c and w.

☐☐☐☐

Unit check 2

A mirror with 12 sides spins. Light travels 24.0 km to a fixed mirror and back. The observer first sees the light when the mirror spins at 520 Hz. The speed of light from this experiment is

Numerical response. Write your answer as $a.bc \times 10^{w}$ m/s. Record the four digits a, b, c and w.

☐☐☐☐

Unit check 3

An object is 48.0 cm in front of a concave mirror with a focal length of 16.0 cm. The distance from the mirror to the image, in cm, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Unit check 4

An object is 20.0 cm from a diverging lens with a focal length of 20.0 cm in size. Which row describes the image?

A. 10.0 cm from the lens, virtual and erect
B. 10.0 cm from the lens, real and inverted
C. 40.0 cm from the lens, virtual and erect
D. There is no image

Unit check 5

A ray of light in air meets a clear oil with an index of refraction of 1.47. The angle of incidence is 35.0°. The angle of refraction, in degrees, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Unit check 6

Light travels in the same oil (n = 1.47) toward a boundary with air. The critical angle, in degrees, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Unit check 7

Which row matches each observation with what it shows about light?

A. Interference: light is a particle. Polarization: light is a longitudinal wave.
B. Interference: light is a wave. Polarization: light is a longitudinal wave.
C. Interference: light is a particle. Polarization: light is a transverse wave.
D. Interference: light is a wave. Polarization: light is a transverse wave.

Unit check 8

A diffraction grating has lines that are 1.80×10^{-6} m apart. The first antinode (n = 1) of a laser beam is at 20.0° from the centre. The wavelength of the laser light is

Numerical response. Write your answer as $a.bc \times 10^{-w}$ m. Record the four digits a, b, c and w.

☐☐☐☐

Unit check 9

Violet light has a wavelength of 420 nm. The energy of one photon, in electron volts, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Unit check 10

Light frees electrons from a metal plate. Which change makes each electron leave with more kinetic energy?

A. Using brighter light of the same colour
B. Using light of a higher frequency
C. Moving the light closer
D. Shining the light for a longer time

Unit check 11

Light with a frequency of 9.00×10^{14} Hz shines on a metal with a work function of 2.50 eV. The maximum kinetic energy of the electrons, in electron volts, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Unit check 12

Two different metals are tested in a photoelectric experiment. On one graph of maximum kinetic energy against frequency, the two lines

A. cross each other at the threshold frequency
B. are the same line
C. are parallel, and meet the frequency axis at different places
D. have different slopes, and meet the frequency axis at the same place

Unit check 13

An X-ray photon is scattered straight back by an electron, at 180° from its first direction. The change in the wavelength of the photon is

Numerical response. Write your answer as $a.b \times 10^{-cd}$ m. Record the four digits a, b, c and d.

□□□□

Answers for the practice unit check

Unit check 1: Record 1221. $\lambda = c \div f = (3.00 \times 10^{8}) \div (2.45 \times 10^{9}) = 1.22 \times 10^{-1}$ m. *Wrong? Go back to card 1.*

Unit check 2: Record 3008. The light travels 2 × 24.0 km = 4.80×10^{4} m. The mirror makes 1/12 of a turn: $t = 1 \div (12 \times 520) = 1.603 \times 10^{-4}$ s. $c = (4.80 \times 10^{4}) \div (1.603 \times 10^{-4}) = 3.00 \times 10^{8}$ m/s. *Wrong? Go back to card 2.*

Unit check 3: Record 24.0. $1/d_i = 1/16.0 - 1/48.0 = 0.04167$ per cm. $d_i = +24.0$ cm. The image is real. *Wrong? Go back to card 3.*

Unit check 4: A. $f = -20.0$ cm. $1/d_i = 1/(-20.0) - 1/20.0 = -0.100$ per cm, so $d_i = -10.0$ cm. The minus sign means a virtual image. A diverging lens always gives a virtual, erect image. *Wrong? Go back to card 4.*

Unit check 5: Record 23.0. $\sin \theta_2 = (1.00)(\sin 35.0°) \div 1.47 = 0.3902$. $\theta_2 = 23.0°$. *Wrong? Go back to card 5.*

Unit check 6: Record 42.9. $\sin \theta_1 = n_2 \div n_1 = 1.00 \div 1.47 = 0.680$. $\theta_1 = 42.9°$. *Wrong? Go back to card 6.*

Unit check 7: D. Only waves interfere, so an interference pattern shows a wave. Only a transverse wave can be polarized. *Wrong? Go back to card 7.*

Unit check 8: Record 6167. $\lambda = d \sin \theta \div n = (1.80 \times 10^{-6})(\sin 20.0°) \div 1 = 6.16 \times 10^{-7}$ m. *Wrong? Go back to card 8.*

Unit check 9: Record 2.96. $E = hc \div \lambda = (4.14 \times 10^{-15}$ eV·s$)(3.00 \times 10^{8}) \div (4.20 \times 10^{-7}) = 2.96$ eV. *Wrong? Go back to card 9.*

Unit check 10: B. The kinetic energy depends on the energy of each photon, hf. Only a higher frequency raises it. The other three change how many photons arrive, not how big each one is. *Wrong? Go back to card 10.*

Unit check 11: Record 1.23. $E = hf = (4.14 \times 10^{-15})(9.00 \times 10^{14}) = 3.726$ eV. Ek max = 3.726 − 2.50 = 1.23 eV. *Wrong? Go back to card 11.*

Unit check 12: C. The slope of each line is Planck's constant, so the lines are parallel. Each metal has its own work function, so each has its own threshold frequency. *Wrong? Go back to card 12.*

Unit check 13: Record 4912. $\cos 180° = -1$, so $(1 - \cos \theta) = 2$. $\Delta\lambda = (h \div mc)(2) = 2(6.63 \times 10^{-34}) \div [(9.11 \times 10^{-31})(3.00 \times 10^{8})] = 4.85 \times 10^{-12}$ m. As $a.b \times 10^{-cd}$: 4.9×10^{-12} m. *Wrong? Go back to card 13.*

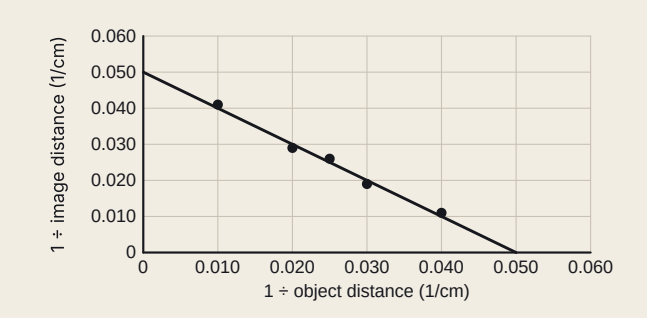
Exam-style question sets

The diploma exam often gives one situation and then asks several questions about it. The questions can come from different cards. Read the box first. Then answer each question in the set. Each answer names the card to go back to.

Set 1: An optics bench

Use the following information to answer the questions in set 1.

Students have an optics bench, a candle, a converging lens and a screen. They put the candle at several distances from the lens. Each time they slide the screen until the image is sharp, and they measure the object distance d_o and the image distance d_i. They graph $1 \div d_i$ against $1 \div d_o$ and draw the line of best fit.



Set 1, question 1

In which order must the three items sit along the optics bench?

A. candle, screen, lens
B. lens, candle, screen
C. candle, lens, screen
D. screen, candle, lens

Set 1, question 2

The sharp image that the students see on the screen is

A. real and inverted
B. real and erect
C. virtual and inverted
D. virtual and erect

Set 1, question 3

The line of best fit meets the vertical axis at 0.050 per cm. The focal length of the lens, in cm, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Set 1, question 4

The slope of the line of best fit is −1. This is expected because

A. the image is inverted
B. $1/d_i = 1/f - 1/d_o$, which is a straight line with a slope of −1
C. the lens has a negative focal length
D. the magnification is always −1

Set 1, question 5

The candle is placed 30.0 cm from this lens. The distance from the lens to the sharp image, in cm, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Answers for set 1

Set 1, question 1: C. A converging lens makes a real image on the far side of the lens from the object. The screen must be there to catch it. So the lens is between the candle and the screen. *Wrong? Go back to card 4.*

Set 1, question 2: A. Only a real image can be caught on a screen. A real image made by one lens is always inverted. *Wrong? Go back to card 4.*

Set 1, question 3: Record 20.0. $1/f = 1/d_o + 1/d_i$. On the vertical axis, $1/d_o = 0$, so $1/d_i = 1/f$. So $1/f = 0.050$ per cm, and $f = 1 \div 0.050 = 20.0$ cm. The line meets the other axis at the same value, for the same reason. *Wrong? Go back to card 4.*

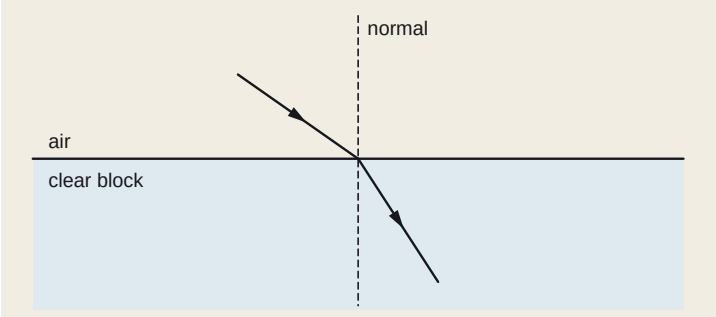
Set 1, question 4: B. Rearrange the lens equation: $1/d_i = -(1/d_o) + 1/f$. Compare with $y = mx + b$. The slope m is −1 and the intercept b is 1/f. *Wrong? Go back to card 4.*

Set 1, question 5: Record 60.0. $1/d_i = 1/f - 1/d_o = 1/20.0 - 1/30.0 = 0.01667$ per cm. $d_i = 60.0$ cm. *Wrong? Go back to card 4.*

Set 2: A ray drawn to scale

Use the following information to answer the questions in set 2.

> The diagram shows a ray of light that passes from air into a clear block. The diagram is drawn to scale. On the exam, you measure angles with the protractor tool. Here, measure the two angles with a protractor on the printed page. If you cannot measure, use these values: the ray in air is 55° from the normal, and the ray in the block is 33° from the normal.



Set 2, question 1

The angle of incidence is the angle between the ray in air and the

A. surface of the block
B. ray in the block
C. edge of the page
D. normal

Set 2, question 2

The index of refraction of the block is

Numerical response. Record your three-digit answer. ☐☐☐☐

Set 2, question 3

Use an index of refraction of 1.50 for the block. The speed of the light in the block is

Numerical response. Write your answer as a.bc × 10ʷ m/s. Record the four digits a, b, c and w.
☐☐☐☐

Set 2, question 4

The light has a wavelength of 600 nm in air. Use an index of refraction of 1.50. The wavelength of the light in the block, in nm, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Set 2, question 5

Light inside the block travels toward a side that touches air. Use an index of refraction of 1.50. The critical angle, in degrees, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Answers for set 2

Set 2, question 1: D. Every angle in Snell's law is measured from the normal, the dashed line at 90° to the surface. *Wrong? Go back to card 5.*

Set 2, question 2: Record 1.50. $n_2/n_1 = \sin\theta_1/\sin\theta_2$. $n_2 = (1.00)(\sin 55°) \div (\sin 33°) = 0.8192 \div 0.5446 = 1.50$. A measurement that is 1° off changes the last digit a little. *Wrong? Go back to card 5.*

Set 2, question 3: Record 2008. $n_2/n_1 = v_1/v_2$. $v_2 = (3.00 \times 10^8)(1.00) \div 1.50 = 2.00 \times 10^8$ m/s. *Wrong? Go back to card 5.*

Set 2, question 4: Record 400. $n_2/n_1 = \lambda_1/\lambda_2$. $\lambda_2 = 600$ nm $\div$ 1.50 = 400 nm. The frequency does not change. *Wrong? Go back to card 5.*

Set 2, question 5: Record 41.8. $\sin\theta_1 = n_2 \div n_1 = 1.00 \div 1.50 = 0.667$. $\theta_1 = 41.8°$. *Wrong? Go back to card 6.*

Set 3: Three layers and a prism

Use the following information to answer the questions in set 3.

> **Part 1.** A ray of red light passes from air into layer X, then from layer X into layer Y. Measured from the normal, the ray is at 50° in air, at 30° in layer X and at 38° in layer Y.
> **Part 2.** A narrow beam of white light enters a glass prism. The light that leaves the prism is spread into colours.

Set 3, question 1

In Part 1, which list puts the three materials in order from the largest index of refraction to the smallest?

A. X, Y, air
B. air, Y, X
C. Y, X, air
D. X, air, Y

Set 3, question 2

In Part 1, the index of refraction of layer X is

Numerical response. Record your three-digit answer. ☐☐☐☐

Set 3, question 3

In Part 1, the ray is made to meet each boundary at a larger and larger angle. Total internal reflection can happen at

A. the boundary from air into X only
B. both boundaries
C. the boundary from X into Y only
D. neither boundary

Set 3, question 4

In Part 2, why does the prism spread white light into colours?

A. Each colour has a new frequency after it enters the glass.
B. The colours interfere with each other in the glass.
C. Red light is absorbed by the glass and violet light is not.
D. Each colour travels at a different speed in the glass, so each bends by a different amount.

Set 3, question 5

In Part 2, the colour that is bent the least by the prism is

A. violet
B. red
C. green
D. blue

Answers for set 3

Set 3, question 1: A. The larger the index of refraction, the smaller the angle from the normal. The angles are 30° (X), 38° (Y) and 50° (air). So X is largest, then Y, then air. *Wrong? Go back to card 5.*

Set 3, question 2: Record 1.53. From air into X: n_2 = (1.00)(sin 50°) ÷ (sin 30°) = 0.7660 ÷ 0.500 = 1.53. *Wrong? Go back to card 5.*

Set 3, question 3: C. Total internal reflection needs light going from a larger index toward a smaller one. From X into Y the index goes down, so it can happen there. From air into X the index goes up, so it cannot. *Wrong? Go back to card 6.*

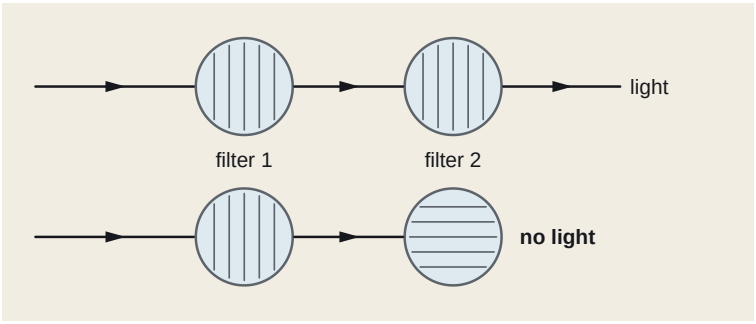
Set 3, question 4: D. Glass has a slightly different index of refraction for each colour. So each colour slows down by a different amount and refracts by a different amount. This is dispersion. *Wrong? Go back to card 7.*

Set 3, question 5: B. Red light slows down the least in glass, so it bends the least. Violet bends the most. *Wrong? Go back to card 7.*

Set 4: A radio station

Use the following information to answer the questions in set 4.

> **Part 1.** A radio station sends out radio waves with a frequency of 92.5 MHz. Its antenna is a vertical metal rod. An antenna works best when its length is one half of the wavelength.
> **Part 2.** In class, students model polarized waves with light and two polarizing filters. They try three set-ups, numbered by the angle between the lines of the two filters: **1** 30°; **2** 90°; **3** 0°.



Set 4, question 1

In Part 1, the radio waves are made by electrons in the antenna that

A. sit at rest on the rod
B. move along the rod at a constant velocity
C. move back and forth along the rod, so they accelerate
D. leave the rod as a beam

Set 4, question 2

In Part 1, the wavelength of the radio waves, in metres, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Set 4, question 3

In Part 1, the best length for the antenna, in metres, is

Numerical response. Record your three-digit answer. ☐☐☐☐

Set 4, question 4

In Part 1, the radio waves from the vertical rod are polarized. A second rod picks up the strongest signal when it is held vertical, and almost none when it is held level. This shows that radio waves are

A. transverse waves
B. longitudinal waves
C. not electromagnetic
D. slower than light

Set 4, question 5

In Part 2, put the three set-ups in order from the brightest light that gets through to the dimmest.

Put in order. Record the three numbers in order. ☐☐☐

Answers for set 4

Set 4, question 1: C. EMR is made by accelerating charges. Electrons that move back and forth along the rod are always speeding up, slowing down and turning round. *Wrong? Go back to card 1.*

Set 4, question 2: Record 3.24. f = 92.5 MHz = 9.25×10^7 Hz. $\lambda = c \div f = (3.00 \times 10^8) \div (9.25 \times 10^7)$ = 3.24 m. *Wrong? Go back to card 1.*

Set 4, question 3: Record 1.62. Half of the wavelength: 3.24 m ÷ 2 = 1.62 m. Halve the unrounded wavelength, then round once. *Wrong? Go back to card 1.*

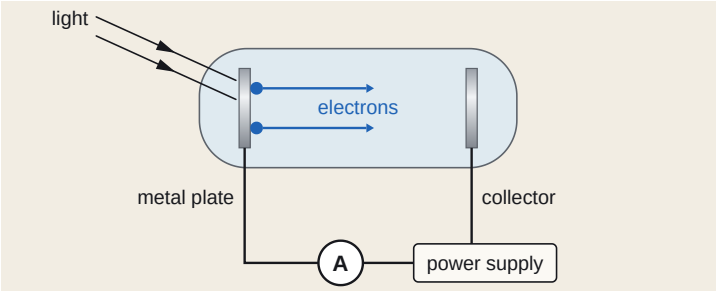
Set 4, question 4: A. Only a transverse wave can be polarized. The electric field of these waves goes up and down, so it moves electrons best in a rod that is also up and down. *Wrong? Go back to card 7.*

Set 4, question 5: Record 312. At 0° the filters are lined up: the most light (3). At 30° some light is blocked (1). At 90° the filters are crossed: no light (2). The order is 3, 1, 2. *Wrong? Go back to card 7.*

Set 5: A photocell experiment

Use the following information to answer the questions in set 5.

Students shine light from LEDs of different colours on the metal plate of a photocell. The metal has a work function of 2.10 eV. For each LED they turn up the voltage of the power supply until the ammeter reads zero. That voltage is the stopping voltage.



The supply can push the electrons back: the stopping voltage.

Set 5, question 1

Which row names the variable the students change and the variable they measure?

A. They change the stopping voltage. They measure the frequency of the light.
B. They change the frequency of the light. They measure the stopping voltage.
C. They change the work function. They measure the current.
D. They change the brightness of the light. They measure the work function.

Set 5, question 2

The longest wavelength of light that frees electrons from this metal is

Numerical response. Write your answer as a.bc × 10^{-w} m. Record the four digits a, b, c and w.

☐☐☐☐

Set 5, question 3

The students want the frequency of an LED from its stopping voltage. Which equation gives the frequency?

A. $f = (q_e V_{stop} - W) \div h$
B. $f = h \div (q_e V_{stop} + W)$
C. $f = hW \div (q_e V_{stop})$
D. $f = (q_e V_{stop} + W) \div h$

Set 5, question 4

Four statements are numbered:
1 A brighter LED gives each electron more kinetic energy.
2 An LED below the threshold frequency frees no electrons, however bright it is.
3 With a very dim LED, electrons leave only after a delay.
4 Electrons leave as soon as the light is turned on.
Which two statements are what the photon model predicts and what the students see?

Pick two. Record the two numbers. ☐☐

Set 5, question 5

The students graph the stopping voltage against the frequency. Their line of best fit passes through (6.0×10^{14} Hz, 0.40 V) and (10.0×10^{14} Hz, 2.08 V). An electron stopped by 1 V had 1 eV of kinetic energy. The value of Planck's constant from their line is

Numerical response. Write your answer as $a.b \times 10^{-cd}$ eV·s. Record the four digits a, b, c and d.
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Answers for set 5

Set 5, question 1: B. Each LED has its own frequency: that is the variable they change. For each one they find the stopping voltage: that is the variable they measure. The metal, so the work function, stays the same. *Wrong? Go back to card 12.*

Set 5, question 2: Record 5917. The longest wavelength has photons with an energy equal to the work function. $\lambda = hc \div W = (4.14 \times 10^{-15}\ \text{eV·s})(3.00 \times 10^{8}\ \text{m/s}) \div (2.10\ \text{eV}) = 5.91 \times 10^{-7}$ m. *Wrong? Go back to card 11.*

Set 5, question 3: D. Conservation of energy: $hf = W + E_{k\,max}$, and $E_{k\,max} = q_e V_{stop}$. So $hf = W + q_e V_{stop}$, and $f = (q_e V_{stop} + W) \div h$. *Wrong? Go back to card 11.*

Set 5, question 4: Record 24. Statements 1 and 3 are predictions of the classical wave model, and they are not seen. Statements 2 and 4 are what the photon model predicts: one photon gives its energy to one electron, all at once. Record 24. The order does not matter, so 42 is also right. *Wrong? Go back to card 10.*

Set 5, question 5: Record 4215. In eV, the kinetic energies are 0.40 eV and 2.08 eV. slope = $(2.08 - 0.40) \div (10.0 \times 10^{14} - 6.0 \times 10^{14}) = 1.68 \div (4.0 \times 10^{14}) = 4.2 \times 10^{-15}$ eV·s. *Wrong? Go back to card 12.*

Set 6: Electrons and photons

Use the following information to answer the questions in set 6.

> This set mixes Unit C with Unit A (momentum) and Unit B (electric potential difference).
> **Part 1.** An electron starts from rest and is sped up through a potential difference of 150 V. A beam of these electrons then passes through two very narrow slits and builds up a pattern of bands on a screen.
> **Part 2.** An X-ray photon with a wavelength of 1.00×10^{-10} m moves to the right. It hits an electron at rest and bounces straight back to the left. After the collision, the momentum of the photon is 6.50×10^{-24} kg·m/s to the left.

Set 6, question 1

In Part 1, the speed of the electron after it is sped up is

Numerical response. Write your answer as $a.bc \times 10^{w}$ m/s. Record the four digits a, b, c and w.



Set 6, question 2

The wavelength of a moving particle is $\lambda = h \div p$, where $p = mv$. Use your speed from the last question. In Part 1, the wavelength of the electron is

Numerical response. Write your answer as $a.b \times 10^{-cd}$ m. Record the four digits a, b, c and d.



Set 6, question 3

In Part 1, the pattern of bands on the screen shows that electrons

A. are stopped by the slits
B. can act as waves
C. are photons
D. have no mass

Set 6, question 4

In Part 2, the momentum of the photon before the collision is

Numerical response. Write your answer as $a.b \times 10^{-cd}$ kg·m/s. Record the four digits a, b, c and d.



Set 6, question 5

In Part 2, the momentum of the electron after the collision is

Numerical response. Write your answer as $a.b \times 10^{-cd}$ kg·m/s. Record the four digits a, b, c and d.



Set 6, question 6

Number	Physics principle
0	Uniform motion
3	Work-energy theorem
4	Conservation of momentum
5	Conservation of energy
9	Wave-particle duality

Use the table. Which two physics principles are used in a full analysis of the collision in Part 2?

Pick two. Record the two numbers. ☐☐

Answers for set 6

Set 6, question 1: Record 7266. The electric potential energy lost becomes kinetic energy: $q\Delta V = \frac{1}{2}mv^2$. $v = \sqrt{(2q\Delta V \div m)} = \sqrt{[2(1.60 \times 10^{-19})(150) \div (9.11 \times 10^{-31})]} = 7.26 \times 10^{6}$ m/s. This is a Unit B method. *Wrong? Go back to card 13.*

Set 6, question 2: Record 1010. $p = mv = (9.11 \times 10^{-31})(7.26 \times 10^{6}) = 6.61 \times 10^{-24}$ kg·m/s. $\lambda = h \div p = (6.63 \times 10^{-34}) \div (6.61 \times 10^{-24}) = 1.00 \times 10^{-10}$ m. As a.b × 10^{-cd}: 1.0×10^{-10} m. *Wrong? Go back to card 13.*

Set 6, question 3: B. A pattern of bands is an interference pattern. Only waves interfere. So a beam of electrons can act as a wave: wave-particle duality. *Wrong? Go back to card 13.*

Set 6, question 4: Record 6624. $p = h \div \lambda = (6.63 \times 10^{-34}) \div (1.00 \times 10^{-10}) = 6.63 \times 10^{-24}$ kg·m/s, to the right. As a.b × 10^{-cd}: 6.6×10^{-24} kg·m/s. *Wrong? Go back to card 13.*

Set 6, question 5: Record 1323. Momentum is conserved. Take right as positive. Before: $+6.63 \times 10^{-24}$ (photon) + 0 (electron). After: -6.50×10^{-24} (photon) + p. So $p = 6.63 \times 10^{-24} + 6.50 \times 10^{-24} = 1.31 \times 10^{-23}$ kg·m/s, to the right. As a.b × 10^{-cd}: 1.3×10^{-23} kg·m/s. This is a Unit A method. *Wrong? Go back to card 13.*

Set 6, question 6: Record 45. The photon and the electron are an isolated system. Momentum is conserved (4) and energy is conserved (5). Record 45. The order does not matter, so 54 is also right. *Wrong? Go back to card 13.*