Physics Units 1 & 2

Chapter 12 — Options: light, sound and electricity in the body and the home

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Contents

Scope. This option is set out in the *VCE Physics Study Design*, Unit 2, Area of Study 2, Option 2.8 — *The physics of human vision*. The key knowledge is quoted verbatim below.

- "describe image formation using pinhole cameras and convex and concave lenses"
- "calculate image positions for thin lenses using either accurate ray tracing scale diagrams and/or the thin lens equation: 1/f = 1/U + 1/V"
- "calculate image sizes in pinhole and simple lens cameras: M = −V/U"
- "explain the operation of simple two-lens telescopes and microscopes"
- "model and explain human vision as refraction at a spherical surface with an adjusting lens and explain accommodation in the human eye including the effects of ageing"
- "distinguish between short-sightedness and long-sightedness, and explain their correction by concave and convex lenses, respectively"
- "apply the power of a lens: P = 1/f to eye glasses"
- "investigate sunglasses including the function of polarised lenses, photochromatic lenses and the benefits and possible damaging effects of tinted lenses"

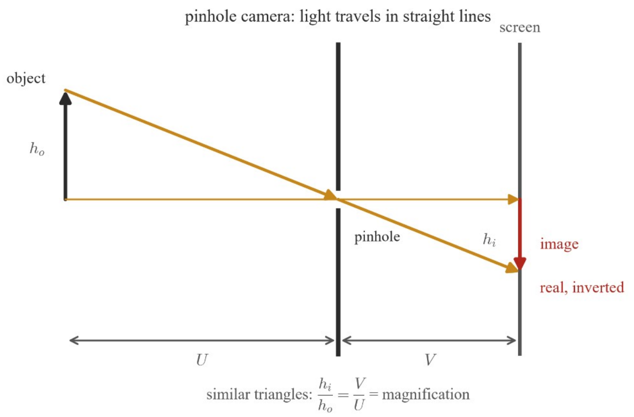
This section also supports the shared *Communicating physics* dot points (owned by Sections 10A and 10B) through the Option task at the end.

Theory

Why vision needs enhancing. The human eye forms a clear image only of objects between its **near point** — the closest distance at which the eye can focus, about 25 cm for a young adult — and its **far point**, which for a healthy eye is very distant. Anything smaller than what the eye can resolve, farther than it can focus, or dimmer than it can detect is beyond unaided vision. Lenses extend vision in three ways: they can correct a focus fault in the eye itself (eye glasses), magnify something small and close (a microscope or magnifier), or collect light from something far away (a telescope). All of these devices rely on the same physics: **refraction**, the bending of light as it crosses a boundary between media of different refractive index (Section 1C).

Image formation with a pinhole camera

The simplest image-forming device has no lens at all. A **pinhole camera** is a light-proof box with a tiny hole in one side and a screen (or film) on the other. Light from each point on an object spreads out in all directions, but only the single narrow ray aimed at the pinhole passes through it and reaches the screen. Because light travels in straight lines, the ray from the *top* of the object lands at the *bottom* of the screen, and the ray from the *bottom* lands at the top. The result is an image that is **real** (formed by light actually arriving at the screen), **inverted** (upside down), and can be captured on the screen.



The size of the image follows from similar triangles. If the object of height h_o is a distance U from the pinhole and the screen is a distance V behind it, then the image height h_i satisfies

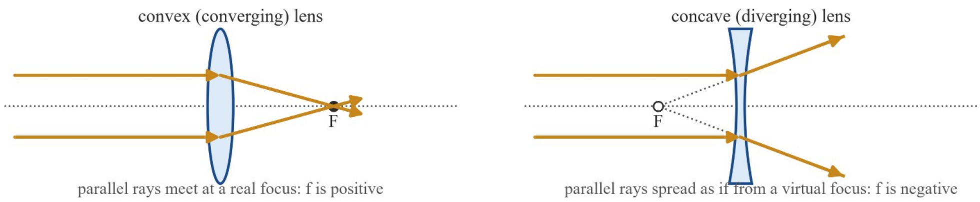
$$\frac{h_i}{h_o} = \frac{V}{U}.$$

The ratio V / U is the **magnification**. A pinhole image is sharp because each point on the object maps to one small patch on the screen, but it is dim because very little light gets through one small hole. Making the hole larger lets in more light (a brighter image) but each object point then maps to a larger patch (a blurrier image). This **brightness–sharpness trade-off** is the central limitation of the pinhole camera, and it is the problem that lenses solve.

Convex and concave lenses

A **lens** is a transparent block, usually glass or plastic, with at least one curved surface. Refraction at the two surfaces bends rays that pass through. Lenses come in two basic shapes.

- A **convex lens** is thicker in the middle than at the edges. It is a **converging lens**: rays parallel to the **principal axis** (the line through the centre of the lens, perpendicular to it) are bent inward so that they meet at a single point on the axis called the **principal focus**, F. The distance from the centre of the lens to F is the **focal length**, f. A convex lens has a *positive* focal length.
- A **concave lens** is thinner in the middle than at the edges. It is a **diverging lens**: rays parallel to the principal axis are bent outward so that they *appear* to spread from a point on the same side as the incoming light. That point is the principal focus of a concave lens, and the focal length is taken as *negative*.



Two terms describe where an image is formed:

- A **real image** is formed where the refracted rays actually meet. It can be projected onto a screen. A convex lens forms a real image when the object is *outside* the focal length ($U > f$).
- A **virtual image** is formed where the rays only *appear* to come from; the rays themselves do not meet there, so it cannot be projected onto a screen. It is seen by looking through the lens. A convex lens forms a virtual image when the object is *inside* the focal length ($U < f$), and a concave lens always forms a virtual image.

Ray tracing for thin lenses

For a **thin lens** (one whose thickness is small compared with f), the image of a point can be located by drawing any two of three standard rays from the top of the object:

1. A ray parallel to the principal axis, which after the lens passes through the principal focus F (for a convex lens) or appears to come from F (for a concave lens).
2. A ray that passes through the centre of the lens, which continues in a straight line without bending.
3. A ray that passes through the focus on the object side (for a convex lens), which after the lens emerges parallel to the principal axis.

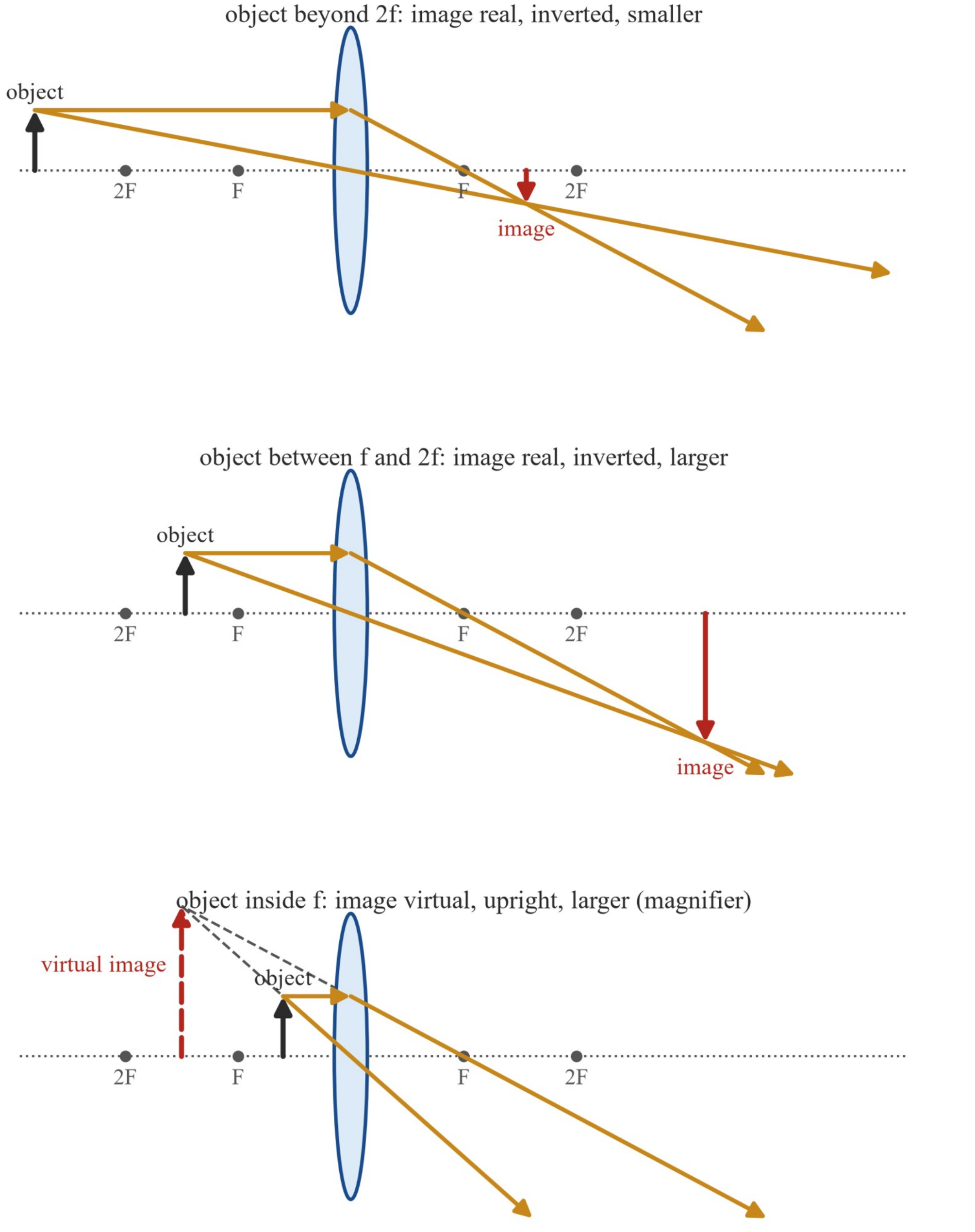
Where the two refracted rays meet (or appear to meet) is the image of the top of the object. Drawing these rays to scale on paper is one of the two ways the study design allows image positions to be found; the other is the thin lens equation below.

For a convex lens, three cases matter:

Object position	Image	Used in
Beyond $2f$	real, inverted, smaller	camera, eye

Object position	Image	Used in
Between f and $2f$	real, inverted, larger	projector, microscope objective
Inside f	virtual, upright, larger	magnifying glass

For a concave lens the image is always **virtual, upright and smaller** than the object, no matter where the object is placed.



two rays from the object tip — parallel then through F, and straight through the centre — locate the image

The thin lens equation and magnification

The exact link between the object distance U, the image distance V and the focal length f is the **thin lens equation**:

$$\frac{1}{f} = \frac{1}{U} + \frac{1}{V}.$$

The sign convention used throughout this option is:

- U is positive for a real object in front of the lens.
- V is positive for a **real** image (formed on the far side of the lens) and negative for a **virtual** image (formed on the same side as the object).
- f is positive for a convex lens and negative for a concave lens.

The **magnification** M is the ratio of the image size to the object size:

$$M = \frac{h_i}{h_o} = -\frac{V}{U}.$$

The sign of M tells you the orientation: a negative M means the image is inverted, a positive M means it is upright. The size of $|M|$ tells you whether the image is enlarged ($|M| > 1$) or reduced ($|M| < 1$). The same formula applies to a pinhole camera, where it reduces to the similar triangles result $M = -V/U$ with the image inverted.

Two-lens instruments: telescopes and microscopes

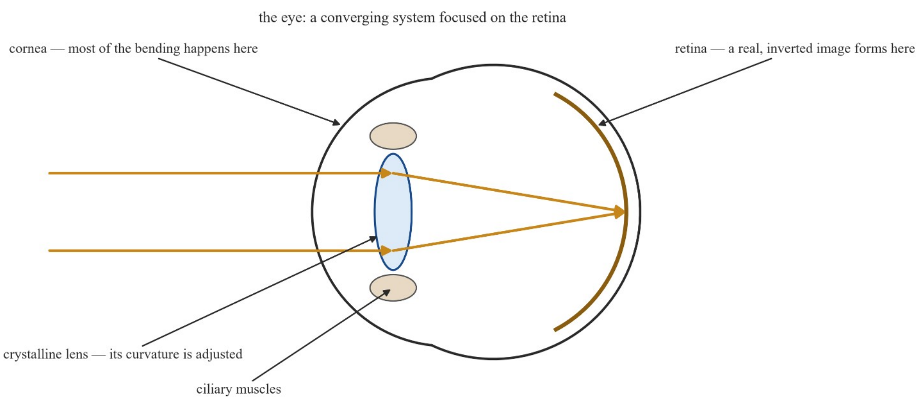
Both instruments use two convex lenses in sequence: an **objective** that forms a real image, and an **eyepiece** that acts as a magnifying glass to view that real image.

- A **telescope** looks at a very distant object. The objective has a *long* focal length, so rays from the far object are almost parallel and are brought to a real, inverted, diminished image at (or just inside) its focal plane. The eyepiece, with a *short* focal length, is placed so this real image lies just inside the eyepiece's focal length; the eyepiece then produces a magnified virtual image. The angular magnification is roughly the ratio $f_{\text{objective}} / f_{\text{eyepiece}}$: a long objective focal length and a short eyepiece focal length give a larger magnification.
- A **microscope** looks at a very small, close object. The objective has a *short* focal length and the object is placed just *outside* its focal length, so the objective forms a real, inverted, *magnified* image inside the tube. The eyepiece magnifies that real image again, exactly as in the telescope. The total magnification is the product of the magnifications of the two lenses.

The two instruments are therefore built the same way but "pointed" differently. Both make an object look larger by making it appear to span a wider angle at the eye: a telescope does this for a distant object, and a microscope does it for a tiny close object.

The human eye as an optical instrument

The eye can be modelled as refraction at a spherical surface with an adjusting lens. Light first crosses the curved front surface of the **cornea**, the transparent window at the front of the eye. Most of the bending happens here, because the change in refractive index from air to the cornea is large. The light then passes through the **crystalline lens**, a flexible transparent lens whose shape — and so whose focal length — can be adjusted. Together the cornea and lens form a **real, inverted image** on the **retina**, the light-sensitive layer at the back of the eye. The brain interprets the inverted image as the right way up.



Accommodation is the process by which the eye changes focus. The **ciliary muscles** around the lens change the lens's curvature:

- To view a **distant** object, the ciliary muscles relax, the lens is pulled thin and flat, and its focal length is *longer*. Parallel rays from the far object are focused on the retina.
- To view a **near** object, the ciliary muscles contract, the lens becomes thicker and more curved, and its focal length is *shorter*. The more strongly converging lens brings the diverging rays from the near object to a focus on the same retina.

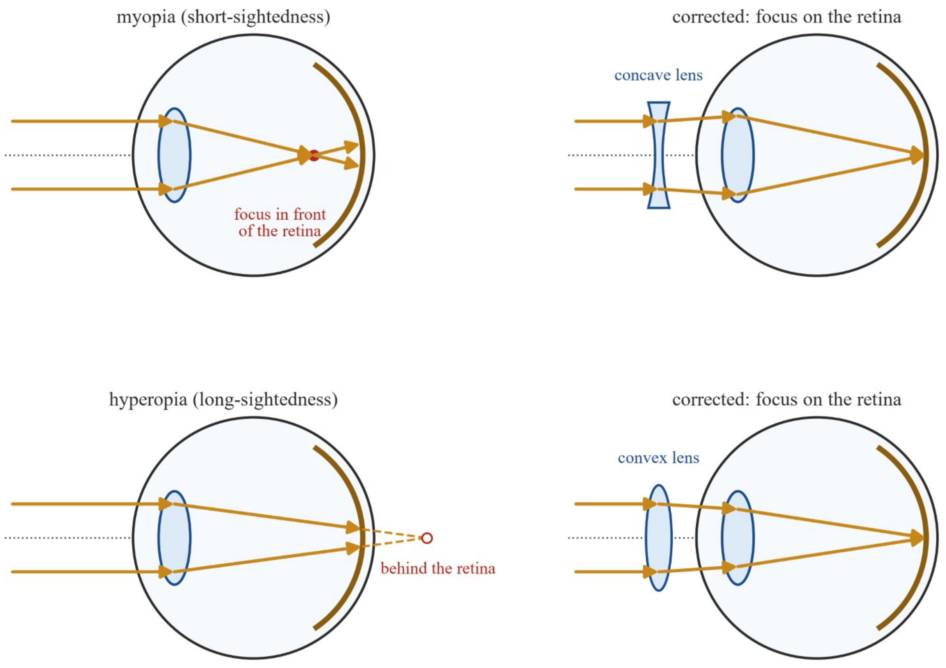
The image distance (lens to retina) is fixed at about 2 cm, so the eye focuses by changing f, not by moving the lens — the opposite of a camera, which usually focuses by changing the lens-to-film distance.

Effects of ageing. With age the lens gradually loses its flexibility and the ciliary muscles weaken, so the lens can no longer become as curved. The eye's near point moves farther away, and close objects such as a book can no longer be brought to a sharp focus on the retina. This age-related loss of accommodation is called **presbyopia**, and it is why many people over about 45 need reading glasses — convex lenses that add the converging power the stiffened lens can no longer supply.

Short-sightedness and long-sightedness

Two common focus faults are due to the shape of the eye rather than its age.

- **Short-sightedness (myopia).** The eyeball is too long, or the cornea and lens are too strongly converging. Rays from a *distant* object are brought to a focus *in front of* the retina, so the image on the retina is blurred. Near objects can still be focused. Myopia is corrected with a **concave (diverging) lens**, which spreads the rays slightly before they enter the eye so that the eye's own lens brings them to a focus exactly on the retina.
- **Long-sightedness (hyperopia).** The eyeball is too short, or the cornea and lens are too weakly converging. Rays from a *near* object would come to a focus *behind* the retina, so the near image is blurred, while distant objects can usually still be focused (the eye can accommodate a little to compensate). Hyperopia is corrected with a **convex (converging) lens**, which adds converging power so the focus moves forward onto the retina.



In both cases the spectacle lens forms an image of the object at the point where the unaided eye *can* focus, so the eye sees that image clearly.

The power of a lens

Optometrists do not usually quote a lens's focal length; they quote its **power**,

$$P = \frac{1}{f},$$

where f is the focal length **in metres**. The unit of power is the **dioptre** (D), equal to m^{-1}. A lens that bends light more strongly has a shorter focal length and a larger power. Because of the sign convention, a convex (converging) lens has a **positive** power and a concave (diverging) lens has a **negative** power — so a prescription of $+2.0\,\mathrm{D}$ is a convex lens for a long-sighted person, and $-2.0\,\mathrm{D}$ is a concave lens for a short-sighted person.

Sunglasses: tinted, polarised and photochromatic lenses

Sunglasses modify the light reaching the eye in different ways, and the physics of each type is different.

Tinted lenses absorb a roughly equal fraction of all visible wavelengths, so they reduce the overall brightness without strongly changing colours. The **benefit** is comfort and reduced glare in bright conditions. The **possible damaging effect** concerns ultraviolet (UV) radiation, which is invisible but can harm the cornea, lens and retina. Behind a dark tint the pupil opens wider to let in more light; if the lens does not also block UV, that wider pupil lets *more* UV into the eye than if no sunglasses were worn at all. A dark tint with poor UV blocking can therefore do more harm than good. Good sunglasses block nearly all UV regardless of how dark the tint is.

Polarised lenses target glare specifically. Light reflected from a flat horizontal surface such as water, snow or a road is partly **plane polarised** — its electric field oscillates preferentially in one direction, parallel to the surface. Light is a transverse wave (Section 1B), so it can be polarised. A polarising filter transmits light oscillating in one chosen direction and absorbs the rest. Polarised sunglasses have their **transmission axis vertical**, so they block the horizontally polarised glare from roads and water while still passing most of the useful, randomly polarised light from the scene. The result is less glare and better contrast than a plain tint of the same darkness could give.

Photochromatic lenses change their tint automatically. They contain molecules that change shape when they absorb UV, darkening the lens in bright sunlight and clearing it again indoors or in low light. Their benefit is convenience: one pair of glasses adapts to changing conditions. A limitation is that they respond to UV, so they may not darken fully behind a car windscreen that already filters UV, and they take a little time to clear again when you go inside.

Worked examples

Example 1 — scaffolded

A camera has a convex lens of focal length $50\,\mathrm{mm}$. It photographs a person standing $2.0\,\mathrm{m}$ from the lens. Calculate the image distance and the magnification, and state the nature of the image formed on the sensor.

Working	Comment
$f=+0.050\,\mathrm{m}$ (convex), $U=2.0\,\mathrm{m}$.	List the data; use metres to match the focal length.
$\frac{1}{V}=\frac{1}{f}-\frac{1}{U}=\frac{1}{0.050}-\frac{1}{2.0}=20-0.5=19.5$.	Rearrange $\frac{1}{f}=\frac{1}{U}+\frac{1}{V}$ for $\frac{1}{V}$ before substituting.
$V=\frac{1}{19.5}=0.0513\,\mathrm{m}=51\,\mathrm{mm}$.	Positive V means the image is real, formed just beyond the focal point.
$M=-\frac{V}{U}=-\frac{0.0513}{2.0}=-0.026$.	Apply $M=-V/U$.
M is negative and $\lvert M\rvert<1$.	The image is **real, inverted and much smaller** than the person.

Example 2 — scaffolded

A concave lens of focal length $15\,\mathrm{cm}$ is placed $30\,\mathrm{cm}$ from a small object. Calculate the image position and magnification, and state the nature of the image.

Working	Comment
$f=-15\,\mathrm{cm}$ (concave is negative), $U=30\,\mathrm{cm}$.	Sign convention: concave lens has negative f.
$\frac{1}{V}=\frac{1}{f}-\frac{1}{U}=\frac{1}{-15}-\frac{1}{30}=-0.0667-0.0333=-0.100$	Rearrange the thin lens equation.

Working	Comment
.	
$V=\dfrac{1}{-0.100}=-10\,\text{cm}$.	Negative V means a **virtual** image, on the same side of the lens as the object.
$M=-\dfrac{V}{U}=-\dfrac{(-10)}{30}=+0.33$.	The double negative gives a positive M.
M is positive and $\lvert M\rvert<1$.	The image is **virtual, upright and smaller** than the object — the standard concave-lens result.

Example 3 — unscaffolded

A person $1.6\,\text{m}$ tall stands $3.0\,\text{m}$ in front of a pinhole camera whose box is $15\,\text{cm}$ deep. Calculate the height of the image on the screen and state its orientation. Explain what happens to the image if the person walks closer to the camera.

The pinhole camera has no lens, so the image size follows from similar triangles, or equivalently from $M=-V/U$, where U is the distance from the object to the pinhole and V is the depth of the box:

$$M=-\frac{V}{U}=-\frac{0.15}{3.0}=-0.050\,.$$

The image height is therefore

$$h_i=M\,h_o=(-0.050)(1.6)=-0.080\,\text{m}=-8.0\,\text{cm}\,.$$

The negative sign shows the image is **inverted**, and its height is $8.0\,\text{cm}$.

∴ the image is $8.0\,\text{cm}$ tall and inverted.

If the person walks closer, U becomes smaller while V (the box depth) is fixed, so $\lvert M\rvert=V/U$ becomes larger and the image grows **taller**. Because the image is formed by straight-line rays, the closer object simply spans a wider angle at the pinhole.

Example 4 — unscaffolded

A long-sighted person has a near point of $1.0\,\text{m}$ — they cannot focus on anything closer than $1.0\,\text{m}$. They want to read a book held at $25\,\text{cm}$. Calculate the power of the reading-glasses lens they need and state whether it is convex or concave.

The glasses must take an object at the comfortable reading distance $U=25\,\text{cm}=0.25\,\text{m}$ and form an image at the person's own near point, where their eye *can* focus. That image must be on the same side of the lens as the object (so the eye looks through the lens at it), so it is virtual and $V=-1.0\,\text{m}$:

$$\frac{1}{f}=\frac{1}{U}+\frac{1}{V}=\frac{1}{0.25}+\frac{1}{(-1.0)}=4.0-1.0=3.0\,\text{m}^{-1}.$$

But $P=1/f$, so the required power is directly

$$P=+3.0\,\text{D}\,.$$

∴ the reading glasses need a power of $+3.0\,\text{D}$. The power is positive, so the lens is **convex** (converging), as expected for correcting long-sightedness: the eye's own lens is too weakly converging, and the convex spectacle lens adds the missing converging power.

Practice questions

Question 1 *(scaffolded)* A pinhole camera has a box $20\,\text{cm}$ deep. It is used to photograph an object $1.5\,\text{m}$ tall standing $2.0\,\text{m}$ from the pinhole. (a) Calculate the magnification of the image. (b) Calculate the height of the image on the screen. (c) State whether the image is upright or inverted, and explain why.

Question 2 *(scaffolded)* A convex lens of focal length $20\,\text{cm}$ is placed $60\,\text{cm}$ from a bright object. (a) Calculate the image distance V. (b) Calculate the magnification. (c) State the nature of the image (real or virtual, upright or inverted, enlarged or reduced).

Question 3 *(scaffolded)* A concave lens of focal length $15\,\text{cm}$ is placed $30\,\text{cm}$ from an object. (a) Calculate the image distance V, including its sign. (b) Calculate the magnification. (c) State the nature of the image.

Question 4 *(scaffolded)* A pair of glasses has lenses of focal length $-0.50\,\text{m}$. (a) Calculate the power of the lenses in dioptres. (b) State whether the wearer is short-sighted or long-sighted, giving a reason. (c) Calculate the focal length of a different lens whose power is $+2.0\,\text{D}$.

Question 5 *(scaffolded)* The eye focuses by changing the shape of its lens. (a) Name the structure where most of the refraction of light occurs as it enters the eye. (b) State what happens to the focal length of the lens when the eye switches from viewing a distant object to viewing a near object. (c) Name the muscles responsible for this change.

Question 6 *(scaffolded)* A simple telescope uses an objective lens of focal length $60\,\text{cm}$ and an eyepiece of focal length $5\,\text{cm}$. (a) State the kind of image (real or virtual) that the objective forms of a distant object. (b) Calculate the approximate angular magnification of the telescope. (c) State the role of the eyepiece.

Question 7 A convex lens of focal length $12\,\text{cm}$ is placed $18\,\text{cm}$ from an object. Calculate the image distance and the magnification, and state the full nature of the image.

Question 8 A camera with a convex lens of focal length $50\,\text{mm}$ photographs a person $2.0\,\text{m}$ tall. The image of the person on the sensor is $12\,\text{mm}$ tall. Calculate the distance between the person and the camera lens.

Question 9 A short-sighted person has a far point $2.0\,\text{m}$ from their eye; they cannot see distant objects clearly. Calculate the power of the spectacle lens that corrects their vision, and state whether it is convex or concave.

Question 10 The objective lens of a microscope has a focal length of $8\,\text{mm}$. A tiny specimen is placed $9\,\text{mm}$ from this lens. Calculate the position of the image formed by the objective and its magnification, and state the nature of this image.

Question 11 A magnifying glass is a convex lens of focal length $10\,\text{cm}$. It is held $6\,\text{cm}$ above a stamp. Calculate the image position and the magnification, and state the nature of the image seen by the eye.

Question 12 A pinhole camera has a box $10\,\text{cm}$ deep. A student wants to form an image $6.0\,\text{cm}$ tall of a person $1.8\,\text{m}$ tall. Calculate how far the person must stand from the pinhole.

Question 13 Explain why a pinhole camera produces an inverted image, and explain the brightness–sharpness trade-off that limits its usefulness.

Question 14 Describe how the eye accommodates to focus on near and distant objects, and explain why many people need reading glasses as they get older.

Question 15 Distinguish between short-sightedness and long-sightedness, stating for each where the image of a distant or near object comes to a focus and which type of lens corrects it.

Question 16 Light reflected from a wet road is partly plane polarised. Explain how polarised sunglasses reduce this glare, and justify why they can give better contrast than a plain tinted lens of the same darkness.

Question 17 State one benefit and one possible damaging effect of wearing tinted sunglasses, and explain the damaging effect in terms of the pupil and ultraviolet radiation.

Question 18 Compare the roles of the objective and eyepiece lenses in a simple two-lens telescope and in a compound microscope. In each instrument, state whether the objective's focal length is long or short and why.

Answers

Question 1 (a) -0.10; (b) $0.15\,\mathrm{m}$ ($15\,\mathrm{cm}$); (c) inverted — light travels in straight lines through the pinhole. **Question 2** (a) $30\,\mathrm{cm}$; (b) -0.50; (c) real, inverted, reduced. **Question 3** (a) $-10\,\mathrm{cm}$; (b) $+0.33$; (c) virtual, upright, reduced. **Question 4** (a) $-2.0\,\mathrm{D}$; (b) short-sighted — the lens is concave (negative power); (c) $+0.50\,\mathrm{m}$. **Question 5** (a) cornea; (b) focal length decreases (lens becomes more curved); (c) ciliary muscles. **Question 6** (a) real; (b) $12\times$; (c) it magnifies the real image formed by the objective, acting as a magnifying glass. **Question 7** $V=36\,\mathrm{cm}$, $M=-2$; real, inverted, enlarged. **Question 8** about $8.4\,\mathrm{m}$. **Question 9** $-0.50\,\mathrm{D}$; concave. **Question 10** $V=72\,\mathrm{mm}$, $M=-8$; real, inverted, enlarged. **Question 11** $V=-15\,\mathrm{cm}$, $M=+2.5$; virtual, upright, enlarged. **Question 12** $3.0\,\mathrm{m}$. **Question 13** See solution. **Question 14** See solution. **Question 15** See solution. **Question 16** See solution. **Question 17** See solution. **Question 18** See solution.

Fully-worked solutions

Question 1 $U=2.0\,\mathrm{m}$, $V=0.20\,\mathrm{m}$. (a) $M=-\frac{V}{U}=-\frac{0.20}{2.0}=-0.10$. (b) $h_i=M\,h_o=(-0.10)(1.5)=-0.15\,\mathrm{m}$, so the image is $15\,\mathrm{cm}$ tall. (c) The image is **inverted**. Light from the top of the object passes through the pinhole and continues in a straight line to the bottom of the screen, and light from the bottom reaches the top, so the image is upside down.

Question 2 $f=20\,\mathrm{cm}$, $U=60\,\mathrm{cm}$. (a) $\frac{1}{V}=\frac{1}{f}-\frac{1}{U}=\frac{1}{20}-\frac{1}{60}=\frac{3}{60}-\frac{1}{60}=\frac{2}{60}$, so $V=30\,\mathrm{cm}$. (b) $M=-\frac{V}{U}=-\frac{30}{60}=-0.50$. (c) V is positive, so the image is **real**; M is negative, so it is **inverted**; and $|M|<1$, so it is **reduced**.

Question 3 $f=-15\,\mathrm{cm}$, $U=30\,\mathrm{cm}$. (a) $\frac{1}{V}=\frac{1}{-15}-\frac{1}{30}=-0.0667-0.0333=-0.100$, so $V=-10\,\mathrm{cm}$. (b) $M=-\frac{V}{U}=-\frac{(-10)}{30}=+0.33$. (c) V is negative, so the image is **virtual**; M is positive, so it is **upright**; and $|M|<1$, so it is **reduced**.

Question 4 $f=-0.50\,\mathrm{m}$. (a) $P=\frac{1}{f}=\frac{1}{-0.50}=-2.0\,\mathrm{D}$. (b) The wearer is **short-sighted**. The negative power means a concave (diverging) lens, which is used to correct short-sightedness by spreading the rays before they enter the eye. (c) $f=\frac{1}{P}=\frac{1}{+2.0}=+0.50\,\mathrm{m}$.

Question 5 (a) The **cornea**, where light crosses from air into the eye and the change in refractive index is largest. (b) The focal length **decreases**: the lens becomes thicker and more curved so it converges the diverging rays from a near object onto the retina. (c) The **ciliary muscles**.

Question 6 (a) The objective forms a **real** image of the distant object at (or just inside) its focal plane. (b) Angular magnification $\approx\frac{f_{\text{objective}}}{f_{\text{eyepiece}}}=\frac{60}{5}=12$, so $12\times$. (c) The eyepiece acts as a **magnifying glass**, producing a magnified virtual image of the real image formed by the objective.

Question 7 $f=12\,\mathrm{cm}$, $U=18\,\mathrm{cm}$. $\frac{1}{V}=\frac{1}{f}-\frac{1}{U}=\frac{1}{12}-\frac{1}{18}=\frac{3}{36}-\frac{2}{36}=\frac{1}{36}$, so $V=36\,\mathrm{cm}$. $M=-\frac{V}{U}=-\frac{36}{18}=-2$. V is positive, so the image is **real**; M is negative, so it is **inverted**; and $|M|=2>1$, so it is **enlarged** (twice the object size).

$\therefore$ $V=36\,\mathrm{cm}$, $M=-2$; the image is real, inverted and enlarged.

Question 8 $f=50\,\mathrm{mm}$, object height $h_o=2.0\,\mathrm{m}=2000\,\mathrm{mm}$, image height $h_i=12\,\mathrm{mm}$. The magnification is

$$M=\frac{h_i}{h_o}=\frac{12}{2000}=0.0060.$$

The image is real and so inverted, meaning $M=-V/U=-0.0060$, hence $V=0.0060\,U$. Substitute into the thin lens equation:

$$\frac{1}{f}=\frac{1}{U}+\frac{1}{V}=\frac{1}{U}+\frac{1}{0.0060\,U}=\frac{1+1/0.0060}{U}.$$

With $f=50\,\text{mm}$, solving gives $V\approx 50.3\,\text{mm}$ and

$$U=\frac{V}{0.0060}=\frac{50.3}{0.0060}\approx 8400\,\text{mm}=8.4\,\text{m}.$$

∴ the person is about $8.4\,\text{m}$ from the camera.

Question 9 The spectacle lens must take parallel rays from a distant object ($U=\infty$) and form an image at the person's far point, where their eye can focus. The image is on the same side as the incoming light, so it is virtual: $V=-2.0\,\text{m}$.

$$P=\frac{1}{f}=\frac{1}{U}+\frac{1}{V}=0+\frac{1}{(-2.0)}=-0.50\,\text{D}.$$

∴ the correcting lens has power $-0.50\,\text{D}$ and is **concave** (diverging), as required for short-sightedness.

Question 10 $f=8\,\text{mm}$, $U=9\,\text{mm}$. $\frac{1}{V}=\frac{1}{f}-\frac{1}{U}=\frac{1}{8}-\frac{1}{9}=\frac{9}{72}-\frac{8}{72}=\frac{1}{72}$, so $V=72\,\text{mm}$. $M=-\frac{V}{U}=-\frac{72}{9}=-8$. V is positive, so the image is **real**; M is negative, so it is **inverted**; and $|M|=8>1$, so it is **enlarged**. This real, magnified image is then viewed through the eyepiece.

∴ the objective forms a real, inverted image $72\,\text{mm}$ behind it, magnified 8 ×.

Question 11 $f=10\,\text{cm}$, $U=6\,\text{cm}$ (the object is *inside* the focal length). $\frac{1}{V}=\frac{1}{f}-\frac{1}{U}=\frac{1}{10}-\frac{1}{6}=\frac{3}{30}-\frac{5}{30}=-\frac{2}{30}$, so $V=-15\,\text{cm}$. $M=-\frac{V}{U}=-\frac{(-15)}{6}=+2.5$. V is negative, so the image is **virtual**; M is positive, so it is **upright**; and $|M|=2.5$, so it is **enlarged**.

∴ the image is virtual, upright and $2.5\times$ larger, appearing $15\,\text{cm}$ from the lens on the same side as the stamp.

Question 12 $V=10\,\text{cm}=0.10\,\text{m}$, $h_o=1.8\,\text{m}$, $h_i=6.0\,\text{cm}=0.060\,\text{m}$. The magnification magnitude is

$$|M|=\frac{h_i}{h_o}=\frac{0.060}{1.8}=\frac{1}{30}.$$

Since $|M|=V/U$,

$$U=\frac{V}{|M|}=\frac{0.10}{1/30}=3.0\,\text{m}.$$

∴ the person must stand $3.0\,\text{m}$ from the pinhole.

Question 13 Model answer points:

- Light travels in straight lines. A ray from the top of the object passes through the pinhole and continues to the bottom of the screen, while a ray from the bottom reaches the top, so the image is inverted.
- Each point on the object maps to one small patch on the screen, giving a sharp image, because only one narrow ray from each point passes through a tiny hole.
- The trade-off: a *smaller* hole gives a sharper image but lets in less light (dimmer); a *larger* hole lets in more light (brighter) but each object point then maps to a larger patch, so the image blurs. This brightness–

sharpness trade-off limits the pinhole camera, which is why a lens — able to gather much more light and still bring it to one focus — is preferred.

Question 14 Model answer points:

- The image distance (lens to retina) is fixed, so the eye focuses by changing the focal length of its lens, a process called accommodation.
- For a *distant* object the ciliary muscles relax and the lens is thin and flat, with a longer focal length, bringing nearly parallel rays to a focus on the retina.
- For a *near* object the ciliary muscles contract, the lens becomes thicker and more curved, and its focal length shortens, so the diverging rays from the near object are focused on the same retina.
- With age the lens loses flexibility and the ciliary muscles weaken, so the lens cannot become as curved; the near point moves farther away (presbyopia). Convex reading glasses add the converging power the stiffened lens can no longer supply, bringing close objects back into focus.

Question 15 Model answer points:

- **Short-sightedness (myopia):** the eyeball is too long or the lens/cornea too strongly converging, so rays from a *distant* object focus *in front of* the retina and distant objects are blurred while near objects are clear. It is corrected by a **concave (diverging)** lens.
- **Long-sightedness (hyperopia):** the eyeball is too short or the lens/cornea too weakly converging, so rays from a *near* object would focus *behind* the retina and near objects are blurred while distant objects can usually be focused. It is corrected by a **convex (converging)** lens.
- In both cases the spectacle lens forms an image at the point where the unaided eye can focus, so the eye sees clearly.

Question 16 Model answer points:

- Light reflected from a flat horizontal surface such as a wet road is partly plane polarised, with its electric field oscillating parallel to (horizontal along) the surface.
- Light is a transverse wave, so it can be polarised. A polarising filter transmits only the component of light oscillating along its transmission axis and absorbs the rest.
- Polarised sunglasses have a vertical transmission axis, so they absorb the horizontally polarised glare from the road while passing most of the useful, randomly polarised light from the rest of the scene.
- A plain tinted lens of the same darkness simply reduces *all* light equally, including the useful light, so it cuts the glare less selectively. The polarised lens removes the glare specifically, giving better contrast and less eye strain for the same overall darkness.

Question 17 Model answer points:

- **Benefit:** tinted lenses reduce the overall brightness and glare in strong sunlight, improving comfort.
- **Damaging effect:** behind a dark tint the pupil opens wider to let in more light. If the lens does not also block ultraviolet (UV) radiation, that wider pupil lets more UV into the eye than if no sunglasses were worn, potentially increasing damage to the cornea, lens and retina.
- A dark tint with poor UV blocking can therefore be worse than no sunglasses at all; good sunglasses block nearly all UV regardless of how dark the tint appears.

Question 18 Model answer points:

- In **both** instruments the objective forms a real image and the eyepiece acts as a magnifying glass to view that real image.
- **Telescope:** the object is very distant, so incoming rays are nearly parallel. The objective has a *long* focal length so it brings these rays to a real image a useful distance behind it; the short- focal-length eyepiece then magnifies that image. Angular magnification is roughly $f_{\text{objective}} / f_{\text{eyepiece}}$.

- **Microscope:** the object is tiny and very close, placed just outside the objective's focal length. The objective has a *short* focal length so it forms a real, inverted, *magnified* image inside the tube; the eyepiece magnifies that image again. Total magnification is the product of the two.
- So the objective focal length is long in a telescope (to collect nearly parallel rays from far away) but short in a microscope (to strongly magnify a close, tiny object).

Option task — Evaluating sunglasses for a purpose

Task type. A comparison and evaluation of two solutions to a problem, in the form of a written response to a contemporary issue (a Unit 2 Outcome 2 task type). Total **30 marks** — house convention only; the study design fixes no marks for Units 1 & 2, and all Units 1 & 2 assessment is school-based.

The task. Choose one specific purpose — for example driving, fishing, snow sports, cycling or general beach use — and **compare and evaluate two pairs of sunglasses** suited to that purpose. One pair should use polarised lenses and the other either tinted or photochromatic lenses. In your response you must:

- describe how each lens type forms or modifies the light reaching the eye, using the physics of polarisation, absorption and refraction from this section;
- evaluate the quality of the evidence for any claims made about the sunglasses (for example advertising or manufacturer claims), naming and judging your sources;
- apply correct physics terminology, definitions and representations (such as ray or polarisation diagrams) throughout;
- discuss at least one sociocultural, economic, legal or political factor relevant to the choice (for example cost, fashion, workplace safety rules, or consumer standards for UV protection);
- use your physics understanding to justify a clear recommendation about which pair is the better choice for your stated purpose.

Suggested length is 800–1200 words, or an equivalent infographic or short presentation. Your reasoning, not your final recommendation, is what is assessed: two students reaching opposite recommendations can both receive full marks if both reason well from defined terms and stated evidence.

Marking rubric

The rubric is keyed to the shared *Communicating physics* key knowledge (Sections 10A and 10B).

Criterion	Key knowledge addressed	Marks
Validity of sources	"evaluate validity of sources of information"	6
Physics concepts and terminology	"apply physics concepts specific to the investigation: definitions of key terms; and use of appropriate scientific terminology, conventions and representations"	6
Models and their limitations	"apply the use of data representations, models and theories in organising and explaining observed phenomena and physics concepts, and discuss the limitations of the explanations"	6
Societal factors	"discuss the influence of sociocultural, economic, legal and political factors relevant to the selected issue or application"	6

Criterion	Key knowledge addressed	Marks
Justified stance	"apply physics understanding to justify a stance, opinion or solution to the selected issue or application"	6
Total		**30**

Criterion descriptors (6 marks each).

- **Validity of sources.** 5–6 marks: several relevant sources are named and their reliability is explicitly judged (for example by expertise, independence or currency). 3–4 marks: sources are named but only partly evaluated. 1–2 marks: sources are listed or relied on without evaluation. 0 marks: no sources or no attempt.
- **Physics concepts and terminology.** 5–6 marks: polarisation, absorption and refraction are used accurately, key terms are defined, and at least one correct diagram or representation supports the explanation. 3–4 marks: the physics is mostly correct with minor errors or missing definitions. 1–2 marks: the physics is present but largely inaccurate or unsupported. 0 marks: no relevant physics.
- **Models and their limitations.** 5–6 marks: the explanation of how each lens works is clearly organised and at least one limitation of the model or claim is discussed. 3–4 marks: the explanation is organised but limitations are only briefly noted. 1–2 marks: the explanation is unstructured and limitations are not discussed. 0 marks: no organised explanation.
- **Societal factors.** 5–6 marks: at least one sociocultural, economic, legal or political factor is discussed and clearly linked to the choice. 3–4 marks: a factor is named but the link is weak. 1–2 marks: a factor is mentioned only in passing. 0 marks: no societal factor.
- **Justified stance.** 5–6 marks: a clear recommendation is given and justified directly by the physics discussed. 3–4 marks: a recommendation is given but only partly supported by the physics. 1–2 marks: a recommendation is stated with little or no physics support. 0 marks: no stance.

Theory

Photography is applied optics. A photograph is made when light from a scene is admitted into a light-tight box and recorded. Every part of a camera exists to control that light: a lens to form the image, an aperture to control how much light enters, a shutter to control how long it enters for, filters to select which light enters, and a light-sensitive surface — film in a traditional camera, an electronic sensor in a digital one — to record the image. From a pinhole camera built from a shoebox to a smartphone photographing a match at the MCG, the physics is the same. This subtopic applies the image-formation ideas of Section 12A to cameras, and then investigates the controls and recording methods that photographers use.

Image formation in a camera — from Section 12A. The image-forming behaviour used in every camera is developed in Section 12A; this section recalls the results and applies them to photography.

- A **pinhole camera** is a light-tight box with a tiny hole in one side. Because light travels in straight lines, each point on the object sends one narrow bundle of rays through the hole to one point on the opposite side of the box, forming a **real, inverted image** of the scene. A pinhole camera has no focusing adjustment: the image is in focus for objects at all distances. The price is that the hole admits very little light, so the image is dim.
- A **convex (converging) lens** gathers far more light than a pinhole and brings the rays from each point of the object together at a point, forming a **real, inverted image** whenever the object is further from the lens than the focal point. A camera places its recording surface — film or sensor — exactly where that image forms. A **concave (diverging) lens** alone cannot form a real image on a screen; in cameras, concave elements are used only in combination with convex elements (see the two-lens camera below).

The image position V for a thin lens is given by the thin lens equation (Section 12A):

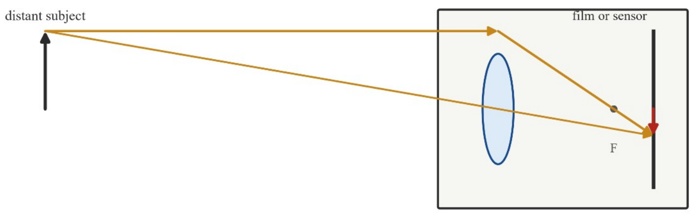
$$\frac{1}{f}=\frac{1}{U}+\frac{1}{V},$$

where f is the focal length and U is the object distance, and the image size is given by the magnification (Section 12A):

$$M=-\frac{V}{U}.$$

A negative M means the image is inverted, and $|M|<1$ means the image is smaller than the object. In ordinary photography the object is far away compared with the focal length, so $|M|$ is much smaller than 1: a camera forms a **real, inverted, diminished** image on the film or sensor.

camera: the convex taking lens forms a real image on the film or sensor



real, inverted, diminished image; for a distant subject V is only a little bigger than f

Focusing a camera. In the thin lens equation, f is fixed for a given lens, so U and V are linked: for the image to be sharp on the film, the equation must hold exactly.

- For a **distant subject**, U is very large, so $1/U\approx 0$ and the equation gives $V\approx f$: the image of a distant subject forms approximately one focal length behind the lens. This is why the focal length is the number printed on a camera lens — a "50 mm lens" forms the image of a distant subject about 50 mm behind the lens.

- For a **nearby subject**, U is smaller, so $1/U$ is larger and V must be larger than f: the lens must sit further from the film. **Focusing** a camera means adjusting the lens-to-film distance until the thin lens equation is satisfied for the subject's distance.

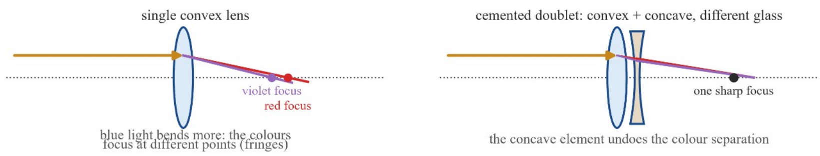
The image size follows the same pattern. Since $|M| = V/U$, and $V \approx f$ for subjects well beyond the focal length, $|M| \approx f/U$: a longer focal length gives a larger image of the same subject (the principle of a telephoto lens), and moving closer to the subject also gives a larger image (the principle of close-up and macro photography).

A simple two-lens camera. A single convex lens forms an image, but not a perfect one. Two defects matter in photography:

- **Chromatic aberration.** Refraction depends on wavelength — the dispersion of white light treated in Section 1D — so a single lens bends blue light more strongly than red light. The colours of one object point come to focus at slightly different distances behind the lens, producing coloured fringes around edges in the image.
- **Blurring and distortion away from the centre.** Rays passing through the edge of a single lens are not brought to exactly the same point as rays passing through its centre, and points near the edge of the picture are imaged less sharply than points in the centre.

A simple two-lens camera corrects these defects by using **two lens elements** arranged on the same axis, often cemented together: typically one convex element and one concave element, made of different types of glass. The convex element does most of the converging and forms the image; the concave element diverges the light slightly, undoing the colour separation and the edge errors introduced by the first element without undoing the overall converging effect. The pair behaves as a single taking lens with one effective focal length, so the thin lens equation and the magnification equation still locate and size the image — but the image is sharper, with far less colour fringing. Almost every camera lens ever made is built this way, from two or more elements, because the corrections are worth the extra glass.

> **A note about the term.** The study design uses the expression *simple two-lens camera* without defining it. Two readings are in common use, and this subtopic uses both, stating which is meant each time: (1) a camera whose taking lens is made of **two lens elements** working together, as described above; and (2) a camera with **two separate lenses**, one to record the image and one to let the photographer view the scene — the arrangement of the twin-lens reflex cameras in which a viewing lens above forms a real image on a screen for composing the picture while the taking lens below forms the image on the film. Every question in this section is answerable on these definitions alone.



the pair behaves as a single taking lens with one effective focal length

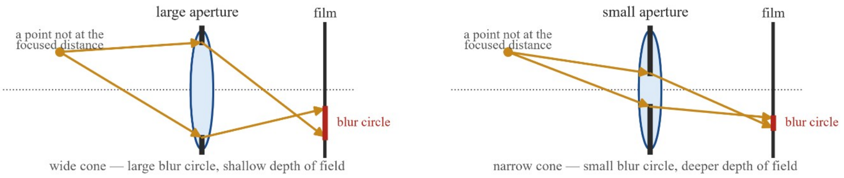
Exposure: aperture and shutter speed. The image must be recorded, and recording needs the right amount of light. The total light energy reaching each part of the film or sensor — the **exposure** — is the rate at which light energy arrives multiplied by the time for which it arrives (the same energy = power × time idea as Section 5A). A camera has two independent controls, one for each factor.

The **aperture** is an adjustable circular opening, the size of the pupil of an eye, placed inside or behind the lens. Its diameter D sets how much light passes through the lens each second: the light admitted is proportional to the area of the opening, $\pi(D/2)^2$. Camera apertures are labelled by the **f-number**,

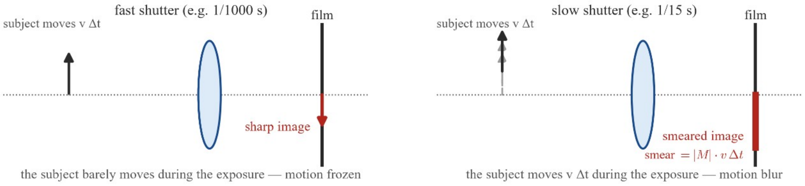
$$N = \frac{f}{D},$$

the ratio of the focal length to the aperture diameter. The standard full-stop scale is f/1.4, f/2, f/2.8, f/4, f/5.6, f/8, f/11, f/16, f/22; from one stop to the next the diameter changes by a factor of about $\sqrt{2}$, so the area — and the light admitted each second — halves or doubles. Note the direction: a **smaller f-number means a larger opening** and more light.

The aperture also affects image formation beyond brightness, through the **depth of field** — the range of subject distances that appear sharp in the image. Only objects at one distance satisfy the thin lens equation exactly for the chosen film position. An object closer or further than that forms a small blur circle on the film instead of a point. A large aperture produces larger blur circles, so only a narrow range of distances looks sharp; a small aperture keeps the blur circles tiny, so a wide range of distances looks sharp — approaching the everything-in-focus behaviour of a pinhole camera. This is a creative control: a large aperture (such as f/2.8) isolates a subject against a blurred background, while a small aperture (such as f/16) keeps a whole landscape sharp.



The **shutter** is a mechanical curtain or electronic switch that exposes the film or sensor for a measured time Δt, the **shutter speed**. The standard scale — 1 s, 1/2, 1/4, 1/8, 1/15, 1/30, 1/60, 1/125, 1/250, 1/500, 1/1000, 1/2000 s — approximately halves the exposure time at each step. Shutter speed controls how motion is recorded. During the exposure, a moving subject moves a distance $v\,\Delta t$ (Section 7C), and its image moves across the film by $|M|$ times that distance. If that image movement is larger than the film or sensor can resolve, the subject is recorded as a blur. A fast shutter (such as 1/1000 s) freezes a sprinter or a bird in flight; a slow shutter (such as 1/15 s) records motion blur — sometimes deliberately, to show speed. At slow shutter speeds the photographer's own hand movement can blur the whole picture, which is why long exposures are taken with the camera on a tripod.



Because exposure is rate × time, the two controls trade against each other: the same exposure can be reached with many combinations, for example f/8 at 1/125 s, f/11 at 1/60 s or f/5.6 at 1/250 s. Choosing between equally exposed combinations is choosing between depth of field (aperture) and frozen motion (shutter speed).

Filters: colour and polarisation. Filters are transparent discs placed in front of the lens that change which light reaches the film or sensor.

- A **colour filter** transmits light of its own colour and absorbs the rest (colour and the spectrum: Section 1B; separation of colours: Section 1D). In black-and-white photography, which records brightness but not colour, a red filter transmits red light from red subjects but absorbs the blue light from a blue sky, so the sky is recorded dark while red subjects stay bright — the contrast of the picture changes. Every filter absorbs some of the light, so the exposure must be increased: if a filter transmits a fraction T of the light falling on it, the exposure time must be multiplied by $1/T$.
- A **polarising filter** transmits only light oscillating in one plane (Section 12A treats polarising lenses in the context of sunglasses). Light reflected from non-metallic surfaces such as water, glass and roads is partially polarised, so a rotated polarising filter can block that reflected glare while passing most of the light from the scene itself. The effect on the image: reflections on water disappear so rocks and fish below the surface become visible, colours look richer, and a bright sky darkens. A polarising filter also absorbs some light overall, so the exposure time must again be increased.

Traditional and digital cameras. Optically, a traditional film camera and a digital camera are the same instrument: each uses a converging lens (in practice a multi-element lens) to form a real, inverted, diminished image, with an aperture, a shutter and a focusing adjustment controlling the light. The difference is entirely in how the image is **recorded**.

- In a **traditional camera**, the recording surface is a **film**: a plastic strip coated with light-sensitive chemicals, silver salts that undergo a chemical change where light falls on them. The energy of the light drives the chemical change. The sensitivity of a given film is fixed when it is manufactured, the exposed film must be chemically processed to reveal the image, and each frame of film can be exposed only once.

- In a **digital camera**, the recording surface is an electronic **sensor** (a CCD or CMOS chip) divided into millions of tiny light-sensitive elements called **pixels**. Each pixel converts the light energy falling on it into electrical charge; the camera's electronics measure the charge at every pixel and store the set of numbers as a digital image file. The sensitivity of the sensor can be changed from shot to shot, the image can be reviewed immediately on a screen, and the sensor is reused for every photograph. Colour images are produced by placing tiny red, green and blue filters over individual pixels so that the camera records the colour content of the light as well as its brightness — the same filter principle as above, applied pixel by pixel.

	Traditional (film) camera	Digital camera
Image formed by	converging lens system	converging lens system
Image at the recording surface	real, inverted, diminished	real, inverted, diminished
Recording surface	light-sensitive film	electronic sensor (pixels)
Energy transformation at recording	light → chemical change	light → electrical signal
Sensitivity	fixed by the film chosen	adjustable between shots
After exposure	chemical processing required	immediate electronic readout
Reuse of recording surface	no — film is consumed	yes — sensor is reused

A smartphone camera is a digital camera in this sense — the same lens-and-sensor physics in a much smaller package, with a tiny lens and sensor.

Investigating photography practically. Several of the ideas above can be investigated in the laboratory, as the study design requires.

1. **Pinhole cameras.** Build a pinhole camera from a box with a small hole at one end and tracing paper as a screen at the other. Measure the height of the image of a chosen object (a window or a lamp works well) for several object distances, and compare each measurement with the prediction $M = V / U$ (Section 12A). Repeat with a second box of different length V to test how the image size depends on the camera length.
2. **Aperture and depth of field.** Using a camera (or a ray box, a convex lens and a card screen), record how the range of object distances that appear sharp changes as the aperture is stopped down from a large opening to a small one.
3. **Filters and exposure.** Measure how the exposure time needed for a given brightness changes when colour filters or a polarising filter are placed in front of the lens, and compare with the factor $1/T$ expected from the transmitted fraction.

Sources of error include judging "sharp" by eye, the finite size of the pinhole, and ambient light reaching the screen. Repeating measurements and averaging improves precision. Record the method, the raw data and any changes to the procedure in your logbook.

Throughout this subtopic, the thin lens equation and the magnification equation are those of Section 12A, motion is treated with the relationships of Chapter 7, and shutter speeds and f-numbers are taken from the standard scales above unless a question states otherwise.

Worked examples

Example 1 — scaffolded

A student builds a simple camera using a converging lens of focal length $50\,\text{mm}$ and uses it to photograph a mural $2.0\,\text{m}$ tall in a Melbourne laneway. The mural is $5.0\,\text{m}$ from the lens. Calculate the distance between the lens and the film needed for a sharp image, and the height of the mural's image on the film.

Working	Comment
$f = 50\,\text{mm} = 0.050\,\text{m}$, $U = 5.0\,\text{m}$, object height $= 2.0\,\text{m}$.	List the data; convert to consistent units.
$\frac{1}{V} = \frac{1}{f} - \frac{1}{U} = \frac{1}{0.050} - \frac{1}{5.0} = 20.0 - 0.20 = 19.8\,\text{m}^{-1}$.	Rearrange the thin lens equation (Section 12A) for the image position.

Working	Comment
$V = \dfrac{1}{19.8} = 0.0505\,\text{m} = 50.5\,\text{mm}$.	The film sits just beyond one focal length, as expected for a subject well beyond f.
$M = -\dfrac{V}{U} = -\dfrac{0.0505}{5.0} = -0.0101$.	The negative sign means the image is inverted.
Image height $= \lvert M \rvert \times 2.0 = 0.0101 \times 2.0 = 0.0202\,\text{m} \approx 20\,\text{mm}$.	The image is diminished: about 1% of the object's height.

Example 2 — scaffolded

A student photographing the Melbourne skyline from the banks of the Yarra River finds that an aperture of f/8 with a shutter speed of $1/125\,\text{s}$ gives a correct exposure. She wants the greater depth of field of f/16. Calculate the shutter speed that gives the same exposure at f/16.

Working	Comment
f/8 → f/16 doubles the f-number, so $D = f/N$ is halved.	The aperture diameter is $D = f/N$.
Light admitted per second $\propto$ area $\propto D^2$, so halving D quarters the light: factor $\left(\dfrac{1}{2}\right)^2 = \dfrac{1}{4}$.	A quarter of the light arrives each second.
Exposure = rate × time, so the time must be multiplied by 4 to compensate.	Same total light energy on the sensor.
$\Delta t = 4 \times \dfrac{1}{125}\,\text{s} = \dfrac{4}{125}\,\text{s} = 0.032\,\text{s} \approx \dfrac{1}{31}\,\text{s}$.	The nearest standard shutter speed is $1/30\,\text{s}$.

Example 3 — unscaffolded

A pinhole camera is made from a box $20\,\text{cm}$ long with a small hole at one end and a translucent screen at the other. It is used to photograph a $2.4\,\text{m}$ tall tram on Swanston Street, $6.0\,\text{m}$ away. Calculate the height of the tram's image on the screen and state the properties of the image. What happens to the image if the box is lengthened to $30\,\text{cm}$ while the tram stays $6.0\,\text{m}$ away?

For a pinhole camera the image size follows from similar triangles, $M = V/U$ (Section 12A), with V the box length:

$$M = \frac{V}{U} = \frac{0.20}{6.0} = 0.0333.$$

The image height is therefore

$$h_{\text{image}} = M \times h_{\text{object}} = 0.0333 \times 2.4 = 0.080\,\text{m} = 8.0\,\text{cm}.$$

The image is real, inverted and diminished, as for every pinhole camera. With the box lengthened to $30\,\text{cm}$,

$$M = \frac{0.30}{6.0} = 0.050,\; h_{\text{image}} = 0.050 \times 2.4 = 0.12\,\text{m} = 12\,\text{cm}.$$

∴ the image is $8.0\,\text{cm}$ tall, real, inverted and diminished; lengthening the box to $30\,\text{cm}$ makes the image larger ($12\,\text{cm}$) but dimmer, because the same light is spread over a larger image.

Example 4 — unscaffolded

A cyclist rides along the Great Ocean Road at a steady $8.0\,\text{m s}^{-1}$ while a photographer takes her picture. The lens forms the image of the cyclist with magnification $\lvert M \rvert = 0.020$. To keep the cyclist sharp, her image must move no more than $0.10\,\text{mm}$ across the sensor during the exposure. Calculate the maximum shutter time, and choose the nearest standard shutter speed that will keep the image sharp.

During an exposure Δt the cyclist moves $v\,\Delta t$ (Section 7C), and her image moves $\lvert M \rvert$ times as far. Setting the image movement equal to the allowed blur:

$$|M|\,v\,\Delta t = 0.10\,\text{mm} = 1.0\times10^{-4}\,\text{m}\,,$$

so the maximum object movement during the exposure is

$$v\,\Delta t = \frac{1.0\times10^{-4}}{0.020} = 5.0\times10^{-3}\,\text{m}\,,$$

and the maximum shutter time is

$$\Delta t = \frac{5.0\times10^{-3}}{8.0} = 6.25\times10^{-4}\,\text{s} \approx 6.3\times10^{-4}\,\text{s}\,.$$

This is about $1/1600\,\text{s}$; the nearest standard shutter speed that is fast enough is $1/2000\,\text{s}$.

∴ the maximum shutter time is $6.3\times10^{-4}\,\text{s}$ (about $1/1600\,\text{s}$); the photographer should use $1/2000\,\text{s}$ to keep the cyclist sharp.

Practice questions

Question 1 A camera has a converging lens of focal length $35\,\text{mm}$. It is used to photograph a sculpture standing $2.8\,\text{m}$ from the lens. (a) Calculate the distance between the lens and the sensor for a sharp image. (b) Calculate the magnification of the image. (c) State three properties of the image formed on the sensor.

Question 2 A student makes a pinhole camera from a box $12\,\text{cm}$ long and photographs a tree $8.0\,\text{m}$ tall standing $20\,\text{m}$ away. (a) Calculate the magnification of the image. (b) Calculate the height of the tree's image on the screen. (c) State two properties of the image, and explain why a pinhole camera needs no focusing adjustment.

Question 3 A camera lens has a focal length of $50\,\text{mm}$. (a) Calculate the aperture diameter when the lens is set to f/8. (b) Calculate the aperture diameter when the lens is set to f/16. (c) Compare the light admitted per second at f/8 and f/16, giving a reason for your answer.

Question 4 A photograph is correctly exposed using an aperture of f/11 and a shutter speed of $1/60\,\text{s}$. (a) Calculate the shutter speed needed for the same exposure at f/5.6, and give the nearest standard shutter speed. (b) Explain how the same exposure can be reached with different combinations of aperture and shutter speed. (c) State which of the two combinations — f/11 at $1/60\,\text{s}$ or f/5.6 at your answer to (a) — is better for freezing a moving subject, and why.

Question 5 A red filter placed in front of a camera lens transmits $20\,\%$ of the light falling on it. The correct exposure without the filter is $1/250\,\text{s}$. (a) State the fraction of the light that the filter absorbs. (b) Calculate the factor by which the exposure time must be multiplied with the filter in place. (c) Calculate the exposure time needed with the filter in place.

Question 6 A traditional film camera and a digital camera are used side by side to photograph the same scene. (a) Name the part of each camera that forms the image. (b) State the physical difference between how the two cameras record the image once it is formed. (c) Give one advantage of each camera type, based on the physics of its recording method.

Question 7 A camera with a $200\,\text{mm}$ focal length lens is first focused on a distant mountain range and then on a landmark $25\,\text{m}$ away. Calculate the image distance in the second case, and hence determine how far, and in which direction, the lens must move between the two photographs.

Question 8 A photographer uses a $50\,\text{mm}$ lens to photograph a person $1.70\,\text{m}$ tall standing $5.0\,\text{m}$ from the camera. Calculate the height of the person's image on the sensor, and state whether the whole image fits on a sensor $24\,\text{mm}$ tall.

Question 9 A kookaburra flies past a photographer at $12\,\text{m s}^{-1}$. The camera lens forms the bird's image with magnification $|M| = 0.015$, and the photographer allows a blur of at most $0.030\,\text{mm}$ on the sensor. Calculate the maximum shutter time that keeps the bird's image within this blur limit.

Question 10 A photographer halves the diameter of her camera's aperture while keeping the same scene. The original shutter speed was $1/500\,\mathrm{s}$. Calculate the shutter speed that now gives the same exposure.

Question 11 A polarising filter transmits $25\,\%$ of the light falling on it. The correct exposure without the filter is $1/250\,\mathrm{s}$. Calculate the exposure time needed with the filter in place, and give the nearest standard shutter speed.

Question 12 A zoom lens is set first to $18\,\mathrm{mm}$ and then to $55\,\mathrm{mm}$ while the camera stays the same distance from a distant subject. Calculate the factor by which the height of the subject's image changes, and explain this in terms of the magnification.

Question 13 The pinhole of a pinhole camera is made smaller. Explain the effect on the sharpness and the brightness of the image, and why there is a trade-off between them.

Question 14 The image formed on the film or sensor of every camera is inverted. Explain why photographs are nevertheless seen the right way up.

Question 15 A photographer at a rock pool on the Mornington Peninsula wants to photograph the fish below the water surface, but the surface acts like a mirror in the bright sun. Explain how a polarising filter in front of the lens solves the problem, making reference to the polarisation of reflected light (Section 12A).

Question 16 In black-and-white photography, a photograph of a blue sky taken through a red filter shows the sky much darker than it would without the filter. Explain why, making reference to what the filter does to the different colours of light.

Question 17 A portrait photographer chooses an aperture of f/2.8, while a landscape photographer of the same scene chooses f/16. Use the idea of blur circles to explain the difference in the images they produce.

Question 18 A student says: "A digital camera doesn't really form an image with a lens — the computer inside makes the picture." Evaluate this claim, making reference to the image formation and recording steps in a digital camera.

Answers

Question 1 (a) $35.4\,\text{mm}$; (b) $M=-0.0127$; (c) real, inverted, diminished. **Question 2** (a) 0.0060; (b) $4.8\,\text{cm}$; (c) real and inverted; a pinhole forms an image by straight-line travel of light, which is in focus at all distances. **Question 3** (a) $6.3\,\text{mm}$; (b) $3.1\,\text{mm}$; (c) f/8 admits 4 times as much light per second — the diameter is doubled, so the area is four times larger. **Question 4** (a) $1/240\,\text{s}$, nearest standard $1/250\,\text{s}$; (b) see solution; (c) f/5.6 at $1/250\,\text{s}$ — the shorter exposure time freezes motion better. **Question 5** (a) $80\,\%$; (b) 5; (c) $0.020\,\text{s}$ ($1/50\,\text{s}$). **Question 6** (a) the converging lens (system); (b) film records by a chemical change, a digital sensor converts light to electrical signals; (c) see solution. **Question 7** $V=201.6\,\text{mm}$; the lens moves about $1.6\,\text{mm}$ away from the sensor. **Question 8** $17\,\text{mm}$; yes, it fits on a $24\,\text{mm}$ tall sensor. **Question 9** $1.7\times10^{-4}\,\text{s}$ (about $1/6000\,\text{s}$). **Question 10** $1/125\,\text{s}$. **Question 11** $1/62.5\,\text{s}$, nearest standard $1/60\,\text{s}$. **Question 12** factor 3.1 larger at $55\,\text{mm}$; for a distant subject $|M|\approx f/U$, so image size is proportional to focal length. **Question 13** See solution (sharper to a point but dimmer; each point of the object is spread over a smaller patch, but less light gets through). **Question 14** See solution (the inverted image is flipped when it is printed, projected or displayed electronically). **Question 15** See solution (glare reflected from the water is partially polarised; the rotated filter blocks it while passing light from below the surface). **Question 16** See solution (the red filter transmits red light but absorbs the blue light from the sky, so the sky exposes the film less and records dark). **Question 17** See solution (f/2.8 gives large blur circles away from one focus distance — isolated subject, blurred background; f/16 keeps blur circles small — a wide depth of field). **Question 18** The claim is false; the lens forms a real optical image on the sensor in a digital camera exactly as in a film camera — electronics record and process an image that has already been formed.

Fully-worked solutions

Question 1 $f=35\,\text{mm}=0.035\,\text{m}$, $U=2.8\,\text{m}$. (a) Rearranging the thin lens equation:

$$\frac{1}{V}=\frac{1}{f}-\frac{1}{U}=\frac{1}{0.035}-\frac{1}{2.8}=28.57-0.357=28.21\,\text{m}^{-1},$$

so $V=1/28.21=0.0354\,\text{m}=35.4\,\text{mm}$. (b) $M=-\dfrac{V}{U}=-\dfrac{0.0354}{2.8}=-0.0127$. (c) The image is **real** (it is formed on the sensor), **inverted** (the negative magnification), and **diminished** ($|M|<1$).

Question 2 $V=12\,\text{cm}=0.12\,\text{m}$, $U=20\,\text{m}$, object height $8.0\,\text{m}$. (a) $M=\dfrac{V}{U}=\dfrac{0.12}{20}=0.0060$. (b) $h_{\text{image}}=M\times h_{\text{object}}=0.0060\times8.0=0.048\,\text{m}=4.8\,\text{cm}$. (c) The image is real and inverted. A pinhole camera needs no focusing because light travels in straight lines from each object point through the hole to one image point: that geometry holds for objects at any distance, so the image is in focus at all distances (though it is dim, because the hole admits little light).

Question 3 $f=50\,\text{mm}$. (a) $D=\dfrac{f}{N}=\dfrac{50}{8}=6.25\,\text{mm}\approx6.3\,\text{mm}$. (b) $D=\dfrac{50}{16}=3.125\,\text{mm}\approx3.1\,\text{mm}$. (c) The light admitted per second is proportional to the aperture area, $\pi\left(D/2\right)^2$. From f/16 to f/8 the diameter doubles ($3.125\rightarrow6.25\,\text{mm}$), so the area, and the light admitted, increase by $2^2=4$: **f/8 admits 4 times as much light per second as f/16**.

Question 4 Original exposure: f/11, $1/60\,\text{s}$. (a) From f/11 to f/5.6 is two stops (f/11 → f/8 → f/5.6), so the aperture admits $2\times2=4$ times as much light each second. The time must be divided by 4 for the same exposure:

$$\Delta t=\frac{1}{60}\div4=\frac{1}{240}\,\text{s}.$$

The nearest standard shutter speed is $1/250\,\text{s}$. (b) Exposure is the product of the rate at which light arrives (set by the aperture area) and the time for which it arrives (set by the shutter). Any change in one factor can be compensated by an opposite change in the other, so many aperture–shutter combinations deliver the same total light energy to the film or sensor. (c) The combination **f/5.6 at** $1/250\,\text{s}$ freezes motion better, because its exposure time ($1/250\,\text{s}$) is shorter than $1/60\,\text{s}$, so a moving subject travels less distance — and its image moves less across the sensor — during the exposure. The price is a smaller depth of field at f/5.6.

Question 5 Transmitted fraction $T=0.20$. (a) The filter absorbs $1-0.20=0.80$, i.e. $80\,\%$, of the light. (b) The exposure time must be multiplied by $\frac{1}{T}=\frac{1}{0.20}=5$. (c) $\Delta t=5\times\frac{1}{250}\,\text{s}=\frac{5}{250}\,\text{s}=0.020\,\text{s}$ (that is, $1/50\,\text{s}$).

Question 6 (a) In each camera the image is formed by a **converging lens** (in practice a lens system of several elements). (b) The film camera records the image by a **chemical change** in light-sensitive silver salts; the digital camera's sensor converts the light at each pixel into an **electrical signal** that is stored as data. (c) For the film camera: no electrical power is needed to store the image once it is exposed. For the digital camera: the sensor's sensitivity can be changed between shots, and the image can be checked immediately and the shot retaken — either is acceptable, with the physics stated.

Question 7 $f=200\,\text{mm}=0.200\,\text{m}$; for the landmark $U=25\,\text{m}$.

$$\frac{1}{V}=\frac{1}{f}-\frac{1}{U}=\frac{1}{0.200}-\frac{1}{25}=5.00-0.040=4.960\,\text{m}^{-1},$$

so $V=1/4.960=0.2016\,\text{m}=201.6\,\text{mm}$. For the distant range $V\approx f=200.0\,\text{mm}$, so the lens must move

$$201.6-200.0=1.6\,\text{mm}$$

away from the sensor (a nearer subject needs a larger image distance).

∴ the image distance is $201.6\,\text{mm}$, and the lens moves $1.6\,\text{mm}$ further from the sensor.

Question 8 $f=50\,\text{mm}=0.050\,\text{m}$, $U=5.0\,\text{m}$, object height $1.70\,\text{m}$.

$$\frac{1}{V}=\frac{1}{0.050}-\frac{1}{5.0}=20.0-0.20=19.8\,\text{m}^{-1}, V=0.0505\,\text{m}.$$

$$|M|=\frac{V}{U}=\frac{0.0505}{5.0}=0.0101, h_{\text{image}}=0.0101\times1.70=0.0172\,\text{m}=17\,\text{mm}.$$

∴ the image is $17\,\text{mm}$ tall, and since $17\,\text{mm}<24\,\text{mm}$ the whole image fits on the sensor.

Question 9 $v=12\,\text{m s}^{-1}$, $|M|=0.015$, allowed blur $0.030\,\text{mm}=3.0\times10^{-5}\,\text{m}$. The maximum object movement during the exposure is

$$v\,\Delta t=\frac{3.0\times10^{-5}}{0.015}=2.0\times10^{-3}\,\text{m},$$

so

$$\Delta t=\frac{2.0\times10^{-3}}{12}=1.67\times10^{-4}\,\text{s}\approx1.7\times10^{-4}\,\text{s}.$$

∴ the maximum shutter time is $1.7\times10^{-4}\,\text{s}$, about $1/6000\,\text{s}$.

Question 10 Halving the aperture diameter quarters the area and hence the light admitted each second. The time must be multiplied by 4 for the same exposure:

$$\Delta t=4\times\frac{1}{500}\,\text{s}=\frac{4}{500}\,\text{s}=\frac{1}{125}\,\text{s}.$$

∴ the required shutter speed is $1/125\,\text{s}$.

Question 11 Transmitted fraction $T=0.25$, so the exposure time is multiplied by $1/T=4$:

$$\Delta t = 4\times\frac{1}{250}\,\mathrm{s} = \frac{4}{250}\,\mathrm{s} = \frac{1}{62.5}\,\mathrm{s}.$$

∴ the exposure time needed is $1/62.5\,\mathrm{s}$; the nearest standard shutter speed is $1/60\,\mathrm{s}$.

Question 12 For a distant subject $V \approx f$, so $|M| = V/U \approx f/U$. With the camera-to-subject distance U unchanged, the image height is proportional to the focal length:

$$\frac{h_{55}}{h_{18}} = \frac{55}{18} = 3.06 \approx 3.1.$$

∴ the image at $55\,\mathrm{mm}$ is about 3.1 times taller than at $18\,\mathrm{mm}$ — this is what the zoom does: a longer focal length gives a larger image of the same subject.

Question 13 Model answer points:

- Each point of the object sends rays in all directions; the pinhole admits one narrow bundle, which lands in a small patch on the screen. Making the hole smaller makes each patch smaller, so the image is sharper.
- But a smaller hole admits less light, so the image is dimmer and needs a longer exposure to record.
- Hence the trade-off: sharpness improves as the hole shrinks, but brightness falls at the same time, and a practical pinhole size balances the two.

Question 14 Model answer points:

- The converging lens crosses the rays from each object point, so the image formed on the film or sensor is inverted.
- The recording itself is therefore upside down, but the image is flipped when it is used: a film negative is printed or projected the right way up, and a digital camera's electronics display and store the image with the orientation corrected.
- The inversion is a property of the image formation, not of the final photograph the viewer sees.

Question 15 Model answer points:

- Light reflected from the water surface is partially polarised (Section 12A), which is why the surface glares like a mirror.
- A polarising filter transmits only light oscillating in one plane; when it is rotated so that this plane is perpendicular to the polarisation of the reflected glare, the glare is blocked.
- Light coming from the fish and rocks below the surface is not polarised in that plane, so it passes through the filter and reaches the sensor — the fish become visible. The trade-off is that the filter absorbs some light overall, so a longer exposure is needed.

Question 16 Model answer points:

- White light reaching the camera is a mixture of colours (Section 1B); the blue sky sends mainly blue light towards the camera.
- A red filter transmits red light and absorbs other colours, so it absorbs most of the blue light from the sky.
- Black-and-white film records brightness only: with less light reaching it from the sky's direction, the sky exposes the film less and is recorded dark, while red subjects, whose light passes the filter, stay bright.

Question 17 Model answer points:

- Only objects at one distance are perfectly focused on the sensor; objects closer or further form small blur circles instead of points.
- At f/2.8 the aperture is large, so those blur circles are large: only a narrow range of distances is sharp, giving the portrait an isolated subject against a blurred background.
- At f/16 the aperture is small, so the blur circles stay tiny over a wide range of distances: the landscape is sharp from near ground to distant hills (the pinhole-camera limit of a very small aperture).

Question 18 Model answer points:

- The claim is **false**.
- In a digital camera, a converging lens forms a real, inverted, diminished image on the sensor by refraction, exactly as a film camera forms one on film: the image exists optically before any electronics act.
- The sensor and computer record and process that already-formed image — converting light to electrical signals, reading them out and correcting the orientation — but they do not create the image from nothing.
- A partial credit point: digital processing can afterwards alter the stored image (adjusting brightness or colour, or combining several exposures), but the starting point of every photograph is still a lens-formed optical image.

Option task — The physics of a photograph (30 marks)

This is the assessed Option task for Option 2.9, one of the seventeen option tasks in this series (Sections 10C–13F). It is school-based assessment for Unit 2, Area of Study 2, in a task format named by the study design itself: **a report of an application of physics concepts to a real-world context**. The 30-mark total and the rubric below are house convention — the study design fixes no mark allocations for Units 1 & 2 — and the task draws on the Communicating physics key knowledge (U2.2.CP.1–.5) taught in Sections 10A and 10B.

Task. Write a report of 800–1200 words, for a reader who has studied Year 11 physics, that uses the physics of this section to investigate **one** of the contexts below. Your report must include at least two worked calculations of your own (for example, image positions and sizes from the thin lens equation and magnification, or exposure changes from aperture, shutter speed and filter factors).

Contexts (from the study design's option statement):

1. camera design to improve image formation;
2. the effect of digital photography on society;
3. the comparison of quality of image formation between traditional and digital cameras;
4. the developments in technology that have led to better imaging by digital cameras and smart phones.

Your report should:

- state the context chosen and the specific question you are addressing;
- define the physics terms you use (for example, focal length, aperture, f-number, exposure, pixel) at first use;
- apply the physics of image formation, light control and recording from this section, with ray diagrams or other representations where they help;
- include the two worked calculations, with the method shown in full;
- evaluate at least two sources of information used, commenting on their validity;
- discuss at least one sociocultural, economic, legal or political factor relevant to your context (for example, who can now take photographs and how often; the cost of film compared with digital; privacy law and photographs of people; the use of images in media and politics);
- state a stance, opinion or solution to the question you posed, and justify it with the physics presented;
- acknowledge all sources using a consistent referencing style.

Record the planning of the report — sources found and evaluated, the draft calculations, and any changes of direction — in your logbook.

Marking rubric (30 marks). The rubric is keyed to the Communicating physics key knowledge of Sections 10A and 10B. Each criterion is marked independently. Marking is on the quality of the reasoning, not on the conclusion reached: two students reaching opposite conclusions can both receive full marks if both reason well from defined terms and stated evidence.

Criterion	Key knowledge	Marks
1. Validity of sources	evaluate validity of sources of	6

Criterion	Key knowledge	Marks
	information (U2.2.CP.1)	
2. Physics concepts and terminology	apply physics concepts specific to the investigation: definitions of key terms; and use of appropriate scientific terminology, conventions and representations (U2.2.CP.2)	6
3. Models, representations and limitations	apply the use of data representations, models and theories in organising and explaining observed phenomena and physics concepts, and discuss the limitations of the explanations (U2.2.CP.3)	6
4. Societal factors	discuss the influence of sociocultural, economic, legal and political factors relevant to the selected issue or application (U2.2.CP.4)	6
5. Stance justified by physics	apply physics understanding to justify a stance, opinion or solution to the selected issue or application (U2.2.CP.5)	6

Criterion descriptors:

- **5–6 marks:** all elements of the criterion are addressed thoroughly and accurately; sources are evaluated with explicit reasoning about their validity (1); every key term is defined at first use and terminology, conventions and representations are used correctly and consistently (2); representations and models are used effectively to organise and explain the physics, with genuine limitations identified (3); the sociocultural, economic, legal or political factors discussed are relevant, specific and connected to the context (4); the stance is stated clearly and the physics of the report is used as evidence for it, with the reasoning shown (5).
- **3–4 marks:** most elements are addressed with minor gaps or inaccuracies; sources are listed with some comment on validity (1); most terms are defined and terminology is mostly correct (2); representations are used but limitations are stated only briefly (3); societal factors are named but the connection to the context is thin (4); a stance is stated but the physics supporting it is incomplete (5).
- **1–2 marks:** elements are addressed partially; sources are listed without evaluation (1); terminology is sparse or often incorrect (2); representations are absent or disconnected from the explanation, with no limitations (3); societal factors are absent or irrelevant (4); the stance is asserted with little or no physics (5).
- **0 marks:** the criterion is not addressed.

Scope — *VCE Physics Study Design, Unit 2, Area of Study 2, Option 2.10: How do instruments make music?* (The physics of sound production and music): "describe sound as the transmission of energy via longitudinal pressure waves and distinguish between sound intensity (W m⁻²) and sound intensity level (dB)" (`U2.2.O10.1`) · "calculate sound intensity at different distances from a source using an inverse square law" (`U2.2.O10.2`) · "explain resonance and identify it as related to the natural frequency of an object, and analyse the unique sound of an instrument as a consequence of multiple resonances created by the instrument and described as timbre" (`U2.2.O10.3`) · "investigate factors that influence natural frequency including shape and material and explain how this relates to instruments" (`U2.2.O10.4`) · "investigate and explain a variety of musical instruments with reference to the similarities and differences of sound production between instrument types (brass, string, woodwind and percussion) and how they compare with the human voice" (`U2.2.O10.5`) · "analyse, for strings and open and closed resonant tubes, the fundamental and subsequent harmonics and apply this analysis to selected musical instruments" (`U2.2.O10.6`).

Theory

What this subtopic is for. When a violin plays the same note as a flute, at the same loudness, you can tell the two apart in an instant — yet the air reaching your ear is, in one important way, doing exactly the same thing in both cases. This subtopic explains what that shared thing is, and what the differences are. You will describe sound as a wave, measure how much energy it carries and how that energy spreads out from the source, and then use the ideas of resonance and standing waves to explain how string, wind and percussion instruments — and the human voice — produce, select and colour the notes they play.

You already hold most of the tools. Waves, and the quantities used to describe them — amplitude, wavelength, period and frequency — were built in 1A, and the wave equation $v = f\lambda$ appears on the formula sheet. Power, the rate of energy transfer, $P = E/t$, was built in 5A. This subtopic applies those ideas to sound; it does not re-teach them. The subtopic closes with the house **Option task**, in which you explain one instrument in full using the physics built here.

Sound is a longitudinal pressure wave. A musical instrument, or any source of sound, has a part that vibrates: a string, a reed, a column of air, a membrane, the player's lips. That vibrating part pushes and pulls on the air beside it. Where it pushes, the air is squeezed together into a region of slightly higher pressure called a **compression**; where it pulls back, the air spreads out into a region of slightly lower pressure called a **rarefaction**. Each compression and rarefaction then disturbs the air beside it, and the pattern travels outward in every direction. The result is a **sound wave**: a longitudinal wave of alternating high- and low-pressure regions moving away from the source.

In a longitudinal wave the particles of the medium oscillate *parallel to* the direction in which the wave travels: an air molecule near a guitar string moves back and forth along the line from the string to your ear, passing the disturbance to its neighbour, rather than travelling to your ear itself. This is the contrast with the transverse waves you met in 1A, such as waves on a rope, where the rope moves up and down while the pattern travels along it. What travels outward from the instrument is **energy**, not air: the energy transferred to the vibrating part by the player (bowing, blowing, striking) is carried away by the wave, through the air, to your ear.

Sound is a mechanical wave, so it needs a medium — a material to carry the pressure pattern. Sound travels through air, through water, and through solids; it cannot travel through a vacuum, because a vacuum contains no particles to compress and rarefy. This is why the classic demonstration of a ringing bell inside an evacuated jar falls silent as the air is pumped out, and it is the sharp difference between sound and the electromagnetic waves of Chapter 1, which do not need a medium (1B).

In dry air at room temperature sound travels at about $340\,\text{m s}^{-1}$ — the value used throughout this subtopic, and the same one used in 1A. The speed is set by the medium (1C): sound travels faster in water (about $1.5 \times 10^3\,\text{m s}^{-1}$) and faster again in most solids, because the particles of liquids and solids interact more stiffly than those of a gas. The frequency of a sound wave is set by the source: a string vibrating 440 times each second sends out a $440\,\text{Hz}$ wave, whatever medium the wave enters. The wavelength then adjusts through $v = f\lambda$.

Pitch, loudness and the audible range. Two wave quantities map onto what you hear:

- **Frequency is heard as pitch.** A higher-frequency sound is heard as a higher note. The note orchestras tune to, A above middle C, has a frequency of $440\,\mathrm{Hz}$.

  Source: International Organization for Standardization, ISO 16:1975 Acoustics — Standard tuning frequency, retrieved 2026-08-18.

- **Amplitude is heard as loudness.** A wave with larger pressure variations — a larger amplitude — carries more energy and is heard as a louder sound.

A healthy young human ear can detect frequencies from about $20\,\mathrm{Hz}$ to about $20\,000\,\mathrm{Hz}$ ($20\,\mathrm{kHz}$). Sound below this range is called **infrasound** and sound above it is called **ultrasound**. Most of the range of instruments used in music, and the entire range of the human voice, sits comfortably inside the audible band: the lowest note of a concert grand piano is $27.5\,\mathrm{Hz}$, and a piccolo can play notes above $4\,\mathrm{kHz}$.

Sound intensity: power spread over an area. To compare sounds quantitatively, physics uses a measure of how much energy the wave delivers each second to each square metre it passes through. The **sound intensity**, I, is the sound power passing through a unit area:

$$I=\frac{P}{A},$$

where P is the sound power in watts (W) and A is the area in square metres (m^2), so intensity is measured in watts per square metre ($\mathrm{W\,m^{-2}}$). Intensity is an objective, measurable quantity: a meter placed in the path of the wave reads the same value whoever is listening.

Most instruments and loudspeakers send sound outward in many directions at once. Model the source as radiating its sound power P uniformly in all directions. At a distance r from the source, that power is spread evenly over the surface of a sphere of radius r, whose area is $A=4\pi r^2$. The intensity at that distance is therefore

$$I=\frac{P}{4\pi r^2}.$$

The inverse square law. Look closely at the expression above: the intensity is proportional to $1/r^2$. This is the **inverse square law** for sound. If you move twice as far from the source, the same power is spread over four times the area, so the intensity falls to one quarter. Move three times as far and it falls to one ninth. In general, between two distances r_1 and r_2 from the same source,

$$\frac{I_2}{I_1}=\left(\frac{r_1}{r_2}\right)^2.$$

The inverse square law holds for a source radiating uniformly into open space. Indoors, reflections from walls, floors and ceilings return some sound energy and soften the fall-off, and real instruments radiate more strongly in some directions than others — the model is an idealisation, and part of the skill in using it is knowing when it applies.

Sound intensity level: the decibel scale. The human ear covers an enormous range of intensities. The quietest sound a healthy ear can detect — the **threshold of hearing** — corresponds to an intensity of about $10^{-12}\,\mathrm{W\,m^{-2}}$; the intensity at which sound begins to cause pain — the **threshold of pain** — is about $1\,\mathrm{W\,m^{-2}}$, one million million (10^{12}) times larger. Writing and comparing numbers across twelve powers of ten is clumsy, so sound is commonly described on a compressed scale: the **sound intensity level**, measured in **decibels** (dB).

The decibel scale is defined by comparison with the threshold of hearing, which is assigned the value $0\,\mathrm{dB}$:

- an intensity of $10^{-12}\,\mathrm{W\,m^{-2}}$ corresponds to an intensity level of $0\,\mathrm{dB}$;
- every time the intensity is multiplied by 10, the intensity level increases by $10\,\mathrm{dB}$.

That rule lets you move along the scale in steps. An intensity of $10^{-6}\,\mathrm{W\,m^{-2}}$ is 10^6 times the reference intensity, so its intensity level is $60\,\mathrm{dB}$.

Intensity ($\mathrm{W\,m^{-2}}$)	Intensity level (dB)	Typical sound
10^{-12}	0	threshold of hearing
10^{-10}	20	a whisper
10^{-8}	40	a quiet library
10^{-6}	60	normal conversation
$\approx 3\times 10^{-4}$	85	sustained exposure limit in workplaces
10^{-2}	100	a loud rock concert
1	120	threshold of pain

The $85\,\mathrm{dB}$ row is worth remembering: in Australian workplaces the model work health and safety regulations set an exposure standard of $85\,\mathrm{dB(A)}$ averaged over an eight-hour day. Musicians, sound engineers and venue workers are routinely exposed to levels above this, which is why purpose-fitted ear protection is common professional practice.

Source: Safe Work Australia, Model Work Health and Safety Regulations (noise exposure standard), retrieved 2026-08-18.

Distinguish the two quantities. The study design asks you to distinguish sound *intensity* from sound *intensity level*, so keep them separate in your mind and in your answers:

	Sound intensity	Sound intensity level
What it is	the sound power passing through each square metre	a comparison of that intensity with the threshold of hearing, expressed on a compressed scale
Unit	$\mathrm{W\,m^{-2}}$	dB
How it changes with distance	falls as $1/r^2$ (inverse square law)	falls by $10\,\mathrm{dB}$ for each factor of 10 the intensity falls by
Kind of quantity	objective physical quantity, measured directly by a meter	a scale built from the intensity

Resonance and natural frequency. Every object that can vibrate has one or more frequencies at which it vibrates particularly easily. These are its **natural frequencies**. Set an object vibrating at one of its natural frequencies and let it go, and it oscillates at that frequency — strike a tuning fork and it rings at one definite pitch, not a jumble of pitches.

If you drive an object with a periodic force — push it repeatedly — the response depends on the driving frequency. Push at the wrong rate and the response stays small. Push at a frequency that matches one of the object's natural frequencies and each small push arrives in step with the motion already there, so energy is added efficiently on every cycle and the amplitude grows large. This large response at a matching frequency is **resonance**. The playground swing is the everyday example: pushes timed to the swing's natural frequency build a large amplitude; pushes at any other rate hardly move it.

Resonance is central to every musical instrument. An instrument is a source of vibration coupled to a **resonator**: the source creates a broad buzz, and the resonator responds strongly only to the frequencies that match its own natural frequencies, amplifying them and transferring their energy efficiently into the air as sound. In a violin the string is the source and the wooden body is the resonator; in a flute the player's air stream is the source and the air column inside the tube is the resonator; in the human voice the vocal folds are the source and the throat and mouth are the resonator. The same idea explains resonance outside music: an opera singer can shatter a wine glass by holding a note matching the glass's natural frequency, because energy builds in the glass with every cycle until the glass flexes beyond its limit.

Timbre: many resonances at once. A tuning fork produces almost a single frequency and sounds pure but thin. Real instruments sound rich because they never vibrate in just one way. When a violin string is bowed, it vibrates as a whole *and* in halves, thirds and quarters at the same time; the air column of a clarinet supports several standing-wave patterns at once; the body of a guitar has many natural frequencies of its own. The sound that reaches your ear is a mixture of the lowest frequency together with a set of higher frequencies, and the resonances of the instrument decide which of those higher frequencies are strong and which are weak.

The study design describes this mixture as **timbre** (pronounced roughly "tam-ber"): the quality of a sound that lets you tell two instruments apart even when they play the same note at the same loudness. In this subtopic *timbre* is used in the study design's own sense — the unique sound of an instrument as a consequence of the multiple resonances the instrument creates. Two instruments playing the same note at the same intensity — say the A above middle C at 440 Hz — produce the same fundamental frequency and the same overall intensity; what differs between them is the mixture of higher frequencies, set by the instrument's shape and material. That mixture is why a piano, a violin and a flute are unmistakable even when they play the one note.

What sets the natural frequency? The natural frequencies of an object are set by its physical properties. This is directly useful, because changing pitch on any instrument means changing a natural frequency, and every technique a player uses is a way of changing one of these properties:

- **Length.** A shorter vibrating object has a higher natural frequency. Shortening the vibrating part of a string or an air column raises the pitch.
- **Tension.** A tighter vibrating object has a higher natural frequency. Tightening a string or a drumhead raises the pitch.
- **Mass and thickness.** A heavier or thicker vibrating object has a lower natural frequency. Thick strings and long, thick bars vibrate more slowly than thin ones.
- **Shape and material.** The shape of a resonator decides *which* frequencies it responds to, and the material affects how strongly and how long it responds. The hollow wooden body of a guitar and the flared bell of a trumpet each impose their own pattern of resonances on the sound, which is part of what gives each instrument its timbre.

Every one of these can be investigated simply. Vary the length of a ruler protruding from a bench and flick it; hang rubber bands of different thicknesses and stretch them to different tensions; fill identical bottles with different volumes of water and blow across their tops. In each case identify the independent variable (the property you change), the dependent variable (the pitch or frequency you measure) and the controlled variables (everything you keep the same) — the variable framework is the one built in 14A.

How the instrument families make music. The study design groups instruments into the families **brass**, **string**, **woodwind** and **percussion**, and asks you to compare them with the human voice.

> **A note on the word "family".** The instrument families are a *stipulated* classification: they are defined by convention, not measured like a wavelength. The study design uses the family names but does not define them, so this subtopic states its frame: instruments are grouped by **what vibrates to produce the sound** — the source of the vibration. On that definition the edge cases settle themselves. A piano is played from a keyboard, but its sound comes from vibrating strings, so it belongs with the strings. A saxophone is made of brass, but its sound comes from a vibrating reed, so it belongs with the woodwind. Every question in this subtopic is answerable on this definition alone.

With that frame, the families compare as follows.

Family	Source of vibration	Resonator	How the pitch is changed	Examples
String	a stretched string, set vibrating by bowing, plucking or striking	the body of the instrument (and the air inside it)	shortening the vibrating length of the string (fingering), or selecting strings of different thickness	violin, guitar, piano

Family	Source of vibration	Resonator	How the pitch is changed	Examples
			and tension	
Woodwind	a vibrating column of air, started by a reed or by air blown across an edge	the air column inside the tube	opening and closing holes to change the effective length of the air column	flute (edge), clarinet (reed), saxophone (reed)
Brass	the player's lips vibrating against a cup-shaped mouthpiece	the air column inside the instrument's tubing	changing the length of tubing (valves or a slide) and selecting which standing-wave pattern the air column supports by changing lip tension	trumpet, trombone
Percussion	a struck membrane or a struck bar	the membrane or bar itself, often coupled to a body or tube	changing the size, thickness or tension of what is struck	snare drum (membrane), xylophone (bars), timpani (tuned membrane)
Human voice	the vocal folds in the larynx, set vibrating by air from the lungs	the throat, mouth and nose	changing the tension and length of the vocal folds, and reshaping the mouth and throat	—

The similarities matter as much as the differences. Every instrument in the table, and the voice, works the same way at the level of physics: a source creates vibrations, a resonator selects and amplifies some frequencies from that vibration, and energy is transferred into the surrounding air as a longitudinal sound wave. What differs between families is *what* vibrates, *how* the player puts energy in (bow, breath, strike, vocal folds), and *which* property the player changes to control the pitch. The voice is closest to a reed woodwind: the vocal folds play the role of the reed, and the mouth and throat play the role of the tube — reshaping the mouth changes the resonances, which is how different vowel sounds are produced from the one pitch.

Percussion adds one twist. A string or an air column vibrates in one dimension, so its natural frequencies form a neat set of whole-number multiples (the harmonics of the next section). A membrane or a bar vibrates in two dimensions, and its natural frequencies do not, in general, fall into such a simple pattern. This is why many percussion instruments — the snare drum, the cymbal — produce sounds of no definite pitch, while tuned percussion such as the xylophone and the timpani are carefully shaped so that their strongest resonances do line up as musical notes.

Standing waves and harmonics on a string. When a string fixed at both ends is set vibrating, waves travel along it and reflect from the fixed ends. The reflected waves combine with incoming waves, and at particular frequencies the string settles into a **standing wave**: a pattern that does not travel, with points that never move — **nodes** — and points that oscillate with maximum amplitude — **antinodes**. Because the ends are fixed, there must be a node at each end. The allowed patterns are the ones that fit that condition.

The lowest-frequency pattern, the **fundamental** or **first harmonic**, is a single loop: nodes at the two ends and one antinode in the middle. One half of a wavelength fits along the string, so $L=\lambda_1/2$, where L is the string length. The wave equation $v=f\lambda$ (1A) then gives the fundamental frequency:

$$f_1=\frac{v}{2L},$$

where v is the speed of waves on the string. Higher patterns fit more half-wavelengths along the same length, giving the **harmonics**: the second harmonic has two loops and frequency $f_2=2f_1$, the third has three loops and $f_3=3f_1$, and in general

$$f_n = n f_1 (n = 1, 2, 3, \ldots).$$

Harmonic	Loops on the string	Wavelength	Frequency
Fundamental (1st)	1	$\lambda_1 = 2L$	f_1
2nd	2	$\lambda_2 = L$	$2f_1$
3rd	3	$\lambda_3 = \frac{2L}{3}$	$3f_1$

When a string is plucked or bowed it vibrates in several of these patterns at once; the mixture of harmonics present is one ingredient of the instrument's timbre. This analysis applies directly to the violin, the guitar and the piano: a fret or a finger shortens L and raises f_1; tuning pegs change the tension, which changes v and hence f_1; and the low-pitched strings are made thicker and heavier so that their natural frequencies are lower.

Standing waves in air columns: open and closed tubes. The same reasoning applies to the air column inside a wind instrument, with pressure standing in place of displacement. At an **open** end of a tube the air is free to oscillate — an antinode. At a **closed** end the air cannot move — a node. Two cases matter for instruments.

Open tube — both ends open (the flute, the recorder, an open organ pipe). Antinodes at both ends, so the fundamental again fits half a wavelength into the tube length, exactly like the string:

$$f_1 = \frac{v}{2L} \text{ and } f_n = n f_1 (n = 1, 2, 3, \ldots),$$

where v is now the speed of sound in air. All harmonics are present.

Closed tube — one end closed, one open (the clarinet behaves approximately this way, as does a stopped organ pipe). A node at the closed end and an antinode at the open end mean the fundamental fits only a *quarter* of a wavelength into the tube:

$$f_1 = \frac{v}{4L}.$$

Only the patterns with a node at the closed end and an antinode at the open end are allowed, which turns out to be the odd-numbered patterns:

$$f_n = n f_1 (n = 1, 3, 5, \ldots).$$

The second and fourth harmonics cannot form in a closed tube. Two consequences follow, and both are audible. First, for the same length L, a closed tube's fundamental is half the frequency of an open tube's — one octave lower — which is why the clarinet reaches notes so much lower than a flute of similar size. Second, the missing even harmonics change the mixture of frequencies the instrument radiates, which is part of why a clarinet and a flute playing the same note are easy to tell apart: their timbres differ because their resonances differ.

In real wind instruments the effective length of the air column is slightly longer than the physical tube, and the bell and tone holes shape the resonances further; the open- and closed-tube models capture the essentials, which is what this analysis needs.

Putting it together: how an instrument plays a note. Trace one note from player to listener. The player puts energy into the source — the bow does work on the string, the breath does work on the reed, the strike does work on the bar. The source vibrates with a mixture of frequencies. The resonator — body, air column, or both — responds strongly at its natural frequencies, selecting and amplifying the harmonics of the note and damping the rest. The vibrating resonator pushes on the surrounding air, launching a longitudinal pressure wave whose frequencies are the harmonics the resonator selected. The wave spreads outward, its intensity falling with the inverse square law, until it reaches the ear, where the eardrum is driven into forced vibration and the note is heard with a pitch set by the fundamental, a loudness set by the intensity, and a timbre set by the mixture of harmonics. Every family in the table above follows this chain; the families differ only in the parts that fill each role.

How this subtopic is assessed. This is an option subtopic, and options sit outside the topic tests and practice examinations of this book, because different students study different options. Its assessment lives here instead: the section closes with the house **Option task**, a 30-mark assessed piece in one of the study design's own Outcome 2 task formats, marked against a rubric keyed to the Communicating physics dot points, `U2.2.CP.1–.5` — the source-evaluation and representation work of 10A, and the societal-context and stance work of 10B. All assessment at Units 1 and 2 is school-based; nothing in this section contributes to a study score (see the front matter).

Worked examples

Example 1 — scaffolded

A trumpet playing a sustained note radiates about $0.40\,\text{W}$ of sound power, approximately uniformly in all directions. (a) Calculate the sound intensity at a distance of $2.0\,\text{m}$ from the trumpet. (b) Calculate the sound intensity at $6.0\,\text{m}$. (c) Find the factor by which the intensity changes between the two positions, and confirm it from the distances alone.

Working	Comment
$P=0.40\,\text{W}$, radiated uniformly, so $I=\dfrac{P}{4\pi r^2}$.	The power spreads over a sphere of area $4\pi r^2$.
(a) $I=\dfrac{0.40}{4\pi\times 2.0^2}=\dfrac{0.40}{50.3}=7.96\times10^{-3}\,\text{W m}^{-2}$	At $r=2.0\,\text{m}$ the sphere has area $4\pi r^2\approx 50.3\,\text{m}^2$.
$I=8.0\times10^{-3}\,\text{W m}^{-2}$ (2 significant figures)	Both given values have 2 significant figures.
(b) $I=\dfrac{0.40}{4\pi\times 6.0^2}=\dfrac{0.40}{452.4}=8.84\times10^{-4}\,\text{W m}^{-2}$	The same power spread over a sphere of area about $452\,\text{m}^2$.
$I=8.8\times10^{-4}\,\text{W m}^{-2}$ (2 significant figures)	
(c) $\dfrac{7.96\times10^{-3}}{8.84\times10^{-4}}=9.0$	The intensity falls by a factor of 9.0.
Check: $\left(\dfrac{r_2}{r_1}\right)^2=\left(\dfrac{6.0}{2.0}\right)^2=9.0$. ✓	Three times the distance means $3^2=9$ times the area and one ninth the intensity — the inverse square law.

Example 2 — scaffolded

The A string of a guitar vibrates along its full length of $0.65\,\text{m}$ with a fundamental frequency of $110\,\text{Hz}$. (a) Calculate the wavelength of the fundamental on the string. (b) Calculate the speed of waves on the string. (c) Calculate the frequency and wavelength of the second harmonic.

Working	Comment
(a) For the fundamental of a string fixed at both ends, $L=\lambda_1/2$.	One half-wavelength fits along the string.
$\lambda_1=2L=2\times0.65=1.3\,\text{m}$	
(b) $v=f_1\lambda_1=110\times1.3=143\,\text{m s}^{-1}$	The wave equation, $v=f\lambda$ (1A).
$v=1.4\times10^2\,\text{m s}^{-1}$ (2 significant figures)	The length $0.65\,\text{m}$ limits the answer to 2 significant figures.
(c) $f_2=2f_1=2\times110=220\,\text{Hz}$	Harmonics of a string are whole-number multiples: $f_n=nf_1$.
$\lambda_2=\lambda_1/2=1.3/2=0.65\,\text{m}$	Two loops fit along the string, each of length $L/2$ — here one loop equals the full length halved, so $\lambda_2=L$.
Check: $v=f_2\lambda_2=220\times0.65=143\,\text{m s}^{-1}$. ✓	The wave speed is set by the string's tension and thickness, not by which harmonic is vibrating.

Example 3 — unscaffolded

A clarinet behaves approximately as a closed resonant tube — closed at the reed end, open at the bell — with an effective length of $0.60\,\mathrm{m}$. The speed of sound in air is $340\,\mathrm{m\,s^{-1}}$. Calculate the fundamental frequency and the next two resonant frequencies of this tube, and explain why a clarinet of this length can play lower notes than a flute of the same length.

A closed tube has a node at its closed end and an antinode at its open end, so its fundamental fits one quarter of a wavelength into the tube length:

$$f_1 = \frac{v}{4L} = \frac{340}{4 \times 0.60} = \frac{340}{2.4} = 141.7\,\mathrm{Hz},$$

which rounds to $1.4 \times 10^2\,\mathrm{Hz}$ (2 significant figures). A closed tube supports only the odd harmonics, so the next two resonant frequencies are

$$f_3 = 3f_1 = 3 \times 141.7 = 425\,\mathrm{Hz} \text{ and } f_5 = 5f_1 = 5 \times 141.7 = 708\,\mathrm{Hz},$$

which round to $4.3 \times 10^2\,\mathrm{Hz}$ and $7.1 \times 10^2\,\mathrm{Hz}$ (2 significant figures).

For comparison, an *open* tube of the same length would have a fundamental of

$$f_1 = \frac{v}{2L} = \frac{340}{1.2} = 283\,\mathrm{Hz},$$

i.e. $2.8 \times 10^2\,\mathrm{Hz}$ (2 significant figures).

The closed tube's fundamental is exactly half the open tube's — one octave lower — because the closed tube fits only a quarter-wavelength into the same length where the open tube fits a half-wavelength. This is why the clarinet, which behaves as a closed tube, reaches much lower notes than the flute, which behaves as an open tube, even when the two instruments are similar in size.

∴ the clarinet's lowest three resonances are $1.4 \times 10^2\,\mathrm{Hz}$, $4.3 \times 10^2\,\mathrm{Hz}$ and $7.1 \times 10^2\,\mathrm{Hz}$, and its closed-tube behaviour gives it a fundamental an octave below an open tube of the same length.

Example 4 — unscaffolded

At an outdoor concert a sound meter placed $10\,\mathrm{m}$ from a loudspeaker reads an intensity level of $90\,\mathrm{dB}$. (a) Determine the sound intensity at the meter. (b) Determine the sound intensity and the intensity level at a position $100\,\mathrm{m}$ from the loudspeaker. (c) Estimate the sound power radiated by the loudspeaker, assuming it radiates uniformly in all directions.

(a) On the decibel scale, $0\,\mathrm{dB}$ corresponds to $10^{-12}\,\mathrm{W\,m^{-2}}$ and each additional $10\,\mathrm{dB}$ represents one more factor of 10. An intensity level of $90\,\mathrm{dB}$ is nine such steps:

$$I = 10^{-12} \times 10^9 = 1.0 \times 10^{-3}\,\mathrm{W\,m^{-2}}.$$

(b) The position at $100\,\mathrm{m}$ is 10 times farther than the position at $10\,\mathrm{m}$. By the inverse square law the intensity falls by $10^2 = 100$:

$$I = \frac{1.0 \times 10^{-3}}{100} = 1.0 \times 10^{-5}\,\mathrm{W\,m^{-2}}.$$

A factor of 100 is two factors of 10, so the intensity level falls by $2 \times 10\,\mathrm{dB} = 20\,\mathrm{dB}$, giving $90\,\mathrm{dB} - 20\,\mathrm{dB} = 70\,\mathrm{dB}$.

(c) Intensity is power per unit area, $I = P/A$ (the power idea is from 5A). At $r = 10\,\mathrm{m}$ the sound power is spread over a sphere of area $A = 4\pi r^2 = 4\pi \times 10^2 = 1.26 \times 10^3\,\mathrm{m^2}$, so the radiated sound power is

$$P = IA = 1.0 \times 10^{-3} \times 1.26 \times 10^3 = 1.26\,\mathrm{W},$$

about 1.3 W (2 significant figures). Even at a very loud concert, only a few watts of sound power reach every listener — a reminder that the ear is exquisitely sensitive, and that the large electrical power of the sound system mostly ends up as thermal energy rather than sound.

∴ the intensity is $1.0 \times 10^{-3}\,\mathrm{W\,m^{-2}}$ at 10 m and $1.0 \times 10^{-5}\,\mathrm{W\,m^{-2}}$ (70 dB) at 100 m, and the loudspeaker radiates about 1.3 W of sound power.

Practice questions

Question 1 A student describes sound as "the air from the instrument travelling to your ear". (a) Explain what is wrong with this description, using the idea of what a wave transfers. (b) Name the two regions of a longitudinal sound wave and say which has the higher pressure. (c) State whether sound can travel through a vacuum, and give the reason.

Question 2 The lowest note of a concert grand piano has a frequency of 27.5 Hz. Sound travels through the air of the concert hall at $340\,\mathrm{m\,s^{-1}}$. (a) Calculate the wavelength of this note in air. (b) Calculate the period of the note.

Question 3 A loudspeaker at an outdoor event radiates 2.0 W of sound power approximately uniformly in all directions. (a) Write down the expression for the sound intensity at a distance r from a source radiating uniformly, and explain where the area term comes from. (b) Calculate the sound intensity at 4.0 m from the loudspeaker. (c) State, with a reason, the sound intensity at 8.0 m.

Question 4 Use the correspondence between intensity and intensity level (each factor of 10 in intensity equals 10 dB). (a) State the intensity level, in dB, of a sound with intensity $1.0 \times 10^{-3}\,\mathrm{W\,m^{-2}}$. (b) A sound's intensity is increased by a factor of 1000. State the change in its intensity level, in dB. (c) State the intensity of a sound whose intensity level is 30 dB.

Question 5 The sound intensity measured 2.0 m from a drummer is $4.5 \times 10^{-3}\,\mathrm{W\,m^{-2}}$. (a) Calculate the intensity at 6.0 m from the drummer. (b) Calculate the intensity at 1.0 m from the drummer. (c) A band member moves from 2.0 m to 20 m from the drummer. Calculate the change in intensity level, in dB.

Question 6 Waves travel along a guitar string at $240\,\mathrm{m\,s^{-1}}$. The vibrating length of the string is 0.60 m. (a) Calculate the fundamental frequency of the string. (b) Copy and complete the table for the first three harmonics of the string.

Harmonic	Frequency (Hz)	Wavelength (m)	Number of loops
1st (fundamental)			
2nd			
3rd			

Question 7 A child on a swing is being pushed by a parent. (a) Identify the natural frequency in this situation. (b) Explain, using the idea of resonance, why pushes timed to the swing's natural frequency build a large amplitude while pushes at a different rate do not. (c) State one other example of resonance and identify the natural frequency involved.

Question 8 An opera singer can shatter a wine glass by singing a sustained note at the right pitch and loudness. Explain how this is possible, using the ideas of natural frequency, resonance and energy transfer. State what would happen if the singer sang the same loudness at a different pitch.

Question 9 Distinguish between sound intensity and sound intensity level. In your answer give the unit of each, and state which one falls with distance according to the inverse square law.

Question 10 The sound intensity 2.0 m from a violin is measured to be $9.0 \times 10^{-4}\,\mathrm{W\,m^{-2}}$. Calculate the distance from the violin at which the intensity is $1.0 \times 10^{-4}\,\mathrm{W\,m^{-2}}$.

Question 11 A sound meter placed 5.0 m from a piano reads a sound intensity of $1.0 \times 10^{-6}\,\mathrm{W\,m^{-2}}$. (a) State the intensity level, in dB, at the meter. (b) Calculate the intensity at a listener 50 m from the piano. (c) State the intensity level, in dB, at 50 m.

Question 12 A guitar has six strings of different thickness, tuning pegs that adjust each string's tension, and a fingerboard that lets the player shorten the vibrating length of a string. Explain how each of these three features allows the instrument to produce a range of pitches, naming the physical property of the string that each feature changes.

Question 13 A student investigates how the pitch of the note produced by blowing across the top of a bottle depends on the volume of water in the bottle, using four identical bottles. (a) Identify the independent variable, the dependent variable and two controlled variables (14A). (b) Predict how the pitch changes as more water is added, and explain your prediction using the idea of the resonating air column. (c) When the bottles are tapped on the side instead of blown across, the trend reverses. Suggest a reason, identifying what vibrates when a bottle is tapped.

Question 14 A flute behaves approximately as an open resonant tube with an effective length of $0.65\,\mathrm{m}$. The speed of sound in air is $340\,\mathrm{m\,s^{-1}}$. (a) Calculate the fundamental frequency of the flute. (b) Calculate the frequencies of the second and third harmonics. (c) The player covers holes and keys to effectively shorten or lengthen the tube. Explain what happens to the fundamental frequency when the effective length is increased.

Question 15 A stopped organ pipe behaves as a closed resonant tube of effective length $0.50\,\mathrm{m}$. The speed of sound in air is $340\,\mathrm{m\,s^{-1}}$. (a) Calculate the fundamental frequency of the pipe. (b) Calculate the next two resonant frequencies above the fundamental. (c) Explain why the second harmonic ($2f_1$) cannot form in this pipe, referring to the node and antinode conditions at the two ends.

Question 16 A violin and a flute play the same note, the A above middle C ($440\,\mathrm{Hz}$), at the same intensity. (a) State the wave quantity that determines the pitch of the note and is therefore the same for the sound of both instruments. (b) State what is different about the two sounds, and give the physical reason for the difference. (c) Name the quality of sound this difference describes.

Question 17 (a) Copy and complete the table for the violin, the flute, the trumpet, a snare drum and the human voice.

	Source of vibration	Resonator	How the pitch is changed
Violin			
Flute			
Trumpet			
Snare drum			
Human voice			

(b) State the one feature of sound production shared by all five rows.

Question 18 A student claims: *"Tightening a guitar string raises the pitch because waves travel faster along a tighter string. Pressing the string against a fret also raises the pitch, but for a different reason: it shortens the wavelength of the fundamental."* Evaluate both halves of this claim using the physics of standing waves on a string. State whether each half is correct and justify your answer.

Answers

Question 1 (a) the air oscillates locally; only energy travels outward; (b) compressions (higher pressure) and rarefactions; (c) no — sound needs a medium. **Question 2** (a) $12\,\text{m}$; (b) $3.6\times10^{-2}\,\text{s}$. **Question 3** (a) $I=P/(4\pi r^2)$ — power spread over a sphere of area $4\pi r^2$; (b) $1.0\times10^{-2}\,\text{W m}^{-2}$; (c) $2.5\times10^{-3}\,\text{W m}^{-2}$ — double the distance gives one quarter the intensity. **Question 4** (a) $90\,\text{dB}$; (b) $+30\,\text{dB}$; (c) $1.0\times10^{-9}\,\text{W m}^{-2}$. **Question 5** (a) $5.0\times10^{-4}\,\text{W m}^{-2}$; (b) $1.8\times10^{-2}\,\text{W m}^{-2}$; (c) a fall of $20\,\text{dB}$. **Question 6** (a) $200\,\text{Hz}$; (b) 1st: $200\,\text{Hz}$, $1.2\,\text{m}$, 1 loop; 2nd: $400\,\text{Hz}$, $0.60\,\text{m}$, 2 loops; 3rd: $600\,\text{Hz}$, $0.40\,\text{m}$, 3 loops. **Question 7** (a) the frequency at which the swing oscillates freely; (b) see solution; (c) any valid example, e.g. a tuning fork driving an air column. **Question 8** see solution — resonance at the glass's natural frequency builds energy in the glass. **Question 9** intensity in W m^{-2} falls as $1/r^2$; intensity level in dB is the comparison scale; see solution. **Question 10** $6.0\,\text{m}$. **Question 11** (a) $60\,\text{dB}$; (b) $1.0\times10^{-8}\,\text{W m}^{-2}$; (c) $40\,\text{dB}$. **Question 12** thickness changes mass per length; pegs change tension; fingerboard changes vibrating length; see solution. **Question 13** (a) water volume; pitch/frequency; e.g. bottle shape and size, blowing technique; (b) higher pitch — shorter air column; (c) tapping makes the bottle and water vibrate — more mass vibrates, lower frequency. **Question 14** (a) $2.6\times10^{2}\,\text{Hz}$; (b) $5.2\times10^{2}\,\text{Hz}$ and $7.8\times10^{2}\,\text{Hz}$; (c) the fundamental falls. **Question 15** (a) $170\,\text{Hz}$; (b) $510\,\text{Hz}$ and $850\,\text{Hz}$; (c) see solution — the closed-end node condition excludes even harmonics. **Question 16** (a) the fundamental frequency, $440\,\text{Hz}$; (b) the mixture of higher harmonics, set by each instrument's resonances; (c) timbre. **Question 17** (a) see solution table; (b) a source drives a resonator, which launches a longitudinal sound wave into the air. **Question 18** both halves correct; see solution.

Fully-worked solutions

Question 1 (a) The air itself does not travel from the instrument to the ear. The particles of air near the instrument oscillate back and forth about fixed positions, passing the disturbance to their neighbours; it is the *energy* of the vibration that travels outward, carried by the wave. (b) The two regions are **compressions**, where the air is squeezed together and the pressure is higher, and **rarefactions**, where the air is spread out and the pressure is lower. The compression is the higher-pressure region. (c) Sound cannot travel through a vacuum. A sound wave is a pressure pattern carried by the particles of a medium, and a vacuum contains no particles to compress and rarefy.

Question 2 $f=27.5\,\text{Hz}$, $v=340\,\text{m s}^{-1}$. (a) $\lambda=\dfrac{v}{f}=\dfrac{340}{27.5}=12.36\ldots\,\text{m}$, which rounds to $12\,\text{m}$ (2 significant figures) — a wavelength longer than most rooms, which is why very low notes seem to fill a hall. (b) $T=\dfrac{1}{f}=\dfrac{1}{27.5}=0.03636\ldots\,\text{s}=3.6\times10^{-2}\,\text{s}$ (2 significant figures).

Question 3 $P=2.0\,\text{W}$. (a) $I=\dfrac{P}{4\pi r^2}$. The source radiates uniformly in all directions, so at distance r its power is spread evenly over a sphere of radius r, whose area is $4\pi r^2$. (b) $I=\dfrac{2.0}{4\pi\times4.0^2}=\dfrac{2.0}{201.1}=9.95\times10^{-3}\,\text{W m}^{-2}$, which rounds to $1.0\times10^{-2}\,\text{W m}^{-2}$ (2 significant figures). (c) At $8.0\,\text{m}$ the distance is doubled, so by the inverse square law the intensity falls by $2^2=4$: $I=\dfrac{9.95\times10^{-3}}{4}=2.5\times10^{-3}\,\text{W m}^{-2}$.

Question 4 Reference: $10^{-12}\,\text{W m}^{-2}$ corresponds to $0\,\text{dB}$, and each factor of 10 in intensity is $10\,\text{dB}$. (a) $1.0\times10^{-3}\,\text{W m}^{-2}$ is 10^9 times the reference intensity, so the level is $9\times10\,\text{dB}=90\,\text{dB}$. (b) $1000=10^3$, three factors of 10, so the intensity level increases by $3\times10\,\text{dB}=30\,\text{dB}$. (c) $30\,\text{dB}$ is three steps of $10\,\text{dB}$, so the intensity is $10^{-12}\times10^3=1.0\times10^{-9}\,\text{W m}^{-2}$.

Question 5 $I_1=4.5\times10^{-3}\,\text{W m}^{-2}$ at $r_1=2.0\,\text{m}$. (a) At $r_2=6.0\,\text{m}$: $\dfrac{I_2}{I_1}=\left(\dfrac{r_1}{r_2}\right)^2=\left(\dfrac{2.0}{6.0}\right)^2=\dfrac{1}{9}$, so $I_2=\dfrac{4.5\times10^{-3}}{9}=5.0\times10^{-4}\,\text{W m}^{-2}$. (b) At $r_2=1.0\,\text{m}$: $\dfrac{I_2}{I_1}=\left(\dfrac{2.0}{1.0}\right)^2=4$, so $I_2=4\times4.5\times10^{-3}=1.8\times10^{-2}\,\text{W m}^{-2}$.

(c) From $2.0\,\text{m}$ to $20\,\text{m}$ the distance increases by a factor of 10, so the intensity falls by $10^2 = 100$. A factor of 100 is two factors of 10, so the intensity level falls by $2 \times 10\,\text{dB} = 20\,\text{dB}$.

Question 6 $v = 240\,\text{m s}^{-1}$, $L = 0.60\,\text{m}$. (a) The fundamental has $L = \lambda_1 / 2$, so $\lambda_1 = 2L = 1.2\,\text{m}$ and $f_1 = \frac{v}{\lambda_1} = \frac{240}{1.2} = 200\,\text{Hz}$. (b) The harmonics are $f_n = n f_1$, with n loops and $\lambda_n = \lambda_1 / n$:

Harmonic	Frequency (Hz)	Wavelength (m)	Number of loops
1st (fundamental)	200	1.2	1
2nd	400	0.60	2
3rd	600	0.40	3

(Check: $v = f\lambda$ in every row, e.g. $600 \times 0.40 = 240\,\text{m s}^{-1}$. ✓)

Question 7 (a) The swing's natural frequency is the frequency at which it oscillates freely when left to itself, set by its length. (b) Each push timed to the swing's natural frequency arrives in step with the swing's motion, so energy is added on every cycle and the amplitude grows — this is resonance. Pushes at any other rate sometimes add energy and sometimes oppose the motion, so little energy accumulates and the amplitude stays small. (c) Any valid example, for example: a tuning fork held over an air column of the right length makes the column ring loudly (the natural frequency of the air column); a singer shattering a wine glass (the natural frequency of the glass); a radio circuit selecting one station (the natural frequency of the circuit).

Question 8 The wine glass has a natural frequency — the frequency at which it rings when tapped. When the singer sustains a note at that frequency, the pressure variations of the sound wave drive the glass in step with its own vibration, so the glass resonates: energy is transferred from the sound wave into the glass efficiently on every cycle, and the amplitude of the glass's vibration grows. If the note is loud enough, the glass flexes beyond its limit and shatters. At a different pitch the driving frequency no longer matches the glass's natural frequency, so there is no resonance: energy is not built up cycle after cycle, and the same loudness produces at most a tiny, harmless vibration.

Question 9 **Sound intensity** is the sound power passing through each square metre of area; it is measured in W m^{-2} and is an objective quantity a meter can read directly. **Sound intensity level** compares that intensity with the threshold of hearing ($10^{-12}\,\text{W m}^{-2}$, defined as $0\,\text{dB}$) and expresses the comparison in dB, with each factor of 10 in intensity equal to $10\,\text{dB}$. Intensity is the physical quantity from which the level is built. It is the **intensity** that falls with distance according to the inverse square law ($I \propto 1/r^2$); the intensity level falls by $10\,\text{dB}$ for each factor of 10 by which the intensity falls.

Question 10 $I_1 = 9.0 \times 10^{-4}\,\text{W m}^{-2}$ at $r_1 = 2.0\,\text{m}$; $I_2 = 1.0 \times 10^{-4}\,\text{W m}^{-2}$. The required intensity is $1/9$ of the measured value, and $1/9$ corresponds to the distance increasing by $\sqrt{9} = 3$ (inverse square law):

$$\frac{I_2}{I_1} = \left(\frac{r_1}{r_2}\right)^2 \Rightarrow \frac{1.0 \times 10^{-4}}{9.0 \times 10^{-4}} = \frac{1}{9} = \left(\frac{2.0}{r_2}\right)^2,$$

so $r_2 = 3 \times 2.0 = 6.0\,\text{m}$.

Question 11 $I = 1.0 \times 10^{-6}\,\text{W m}^{-2}$ at $r_1 = 5.0\,\text{m}$. (a) $10^{-6}\,\text{W m}^{-2}$ is 10^6 times the reference $10^{-12}\,\text{W m}^{-2}$: six steps of $10\,\text{dB}$, so the level is $60\,\text{dB}$. (b) From $5.0\,\text{m}$ to $50\,\text{m}$ the distance increases by a factor of 10, so the intensity falls by $10^2 = 100$: $I = 1.0 \times 10^{-6} / 100 = 1.0 \times 10^{-8}\,\text{W m}^{-2}$. (c) A factor of 100 is two factors of 10, so the level falls by $20\,\text{dB}$: $60\,\text{dB} - 20\,\text{dB} = 40\,\text{dB}$. (Check: $10^{-8}\,\text{W m}^{-2}$ is 10^4 times the reference, i.e. $40\,\text{dB}$. ✓)

Question 12 Each feature changes one physical property that sets the string's natural frequencies ($f_1 = v / 2L$). - **Strings of different thickness** change the mass of the vibrating string. A thicker, heavier string vibrates more slowly, so the thick strings give the low notes and the thin strings the high ones. - **The tuning pegs** change the tension. Tightening a string increases the wave speed v along it, and since the length is unchanged, $f_1 = v / 2L$ rises: the pitch goes up. This is how the guitar is tuned. - **The fingerboard** changes the vibrating length L. Pressing the string against a fret shortens the vibrating part; a shorter L gives a shorter wavelength for the fundamental and a higher frequency, so the pitch rises. This is how different notes are played on the one string.

Question 13 (a) Independent variable: the volume of water in the bottle. Dependent variable: the pitch (frequency) of the note produced. Controlled variables (any two): the size and shape of the bottles (all identical), the way the bottle is blown across (same distance and angle), the temperature of the air, or the person blowing. (b) The pitch rises as more water is added. Blowing across the top sets the air column inside the bottle vibrating; adding water shortens that air column, and a shorter air column has a higher natural frequency, so the resonant note rises. (c) Tapping makes the bottle itself — the glass and the water in it — vibrate, not the air column. More water means more mass in the vibrating system, and a heavier vibrating system has a lower natural frequency, so the pitch falls as more water is added: the opposite trend, because a different object is vibrating.

Question 14 Open tube, $L = 0.65\,\text{m}$, $v = 340\,\text{m s}^{-1}$. (a) $f_1 = \frac{v}{2L} = \frac{340}{2 \times 0.65} = \frac{340}{1.30} = 261.5\,\text{Hz}$, i.e. $2.6 \times 10^2\,\text{Hz}$ (2 significant figures) — very close to the note middle C. (b) All harmonics are present in an open tube; carrying the unrounded fundamental, $f_2 = 2f_1 = 2 \times 261.5 = 523\,\text{Hz}$ and $f_3 = 3f_1 = 3 \times 261.5 = 785\,\text{Hz}$, i.e. $5.2 \times 10^2\,\text{Hz}$ and $7.8 \times 10^2\,\text{Hz}$ (2 significant figures). (c) Increasing the effective length L increases the wavelength of the fundamental ($\lambda_1 = 2L$), and with the wave speed unchanged, $f_1 = v/2L$ falls: the note becomes lower. This is why opening holes — which effectively shortens the tube — raises the pitch.

Question 15 Closed tube, $L = 0.50\,\text{m}$, $v = 340\,\text{m s}^{-1}$. (a) $f_1 = \frac{v}{4L} = \frac{340}{4 \times 0.50} = \frac{340}{2.0} = 170\,\text{Hz}$. (b) A closed tube supports only the odd harmonics: $f_3 = 3f_1 = 510\,\text{Hz}$ and $f_5 = 5f_1 = 850\,\text{Hz}$. (c) The closed end of the tube must be a node (the air cannot move there) and the open end must be an antinode. The fundamental fits one quarter of a wavelength into the tube. The next pattern that satisfies node-at-one-end, antinode-at-the-other adds a half-wavelength at a time, giving three-quarters, then five-quarters of a wavelength — the odd multiples of the fundamental. The second harmonic would require the pattern to fit a half-wavelength into the tube with a node at the closed end, but that places a node at the open end too, where the air must be free to move; the condition cannot be satisfied, so the second harmonic cannot form.

Question 16 (a) The fundamental frequency — $440\,\text{Hz}$ — is the same for both instruments, since pitch is set by frequency, and the two sounds are the same note. (The intensity is also the same, as stated.) (b) The two sounds differ in their mixture of higher frequencies (harmonics). Each instrument vibrates in several modes at once, and the resonances of the instrument — its shape and material — decide which harmonics are strong and which are weak. The violin's bowed string and the flute's air column, set vibrating at the mouth hole, select different mixtures of harmonics, so the two waveforms differ even though their fundamental frequency is the same. (c) This quality is **timbre**: the study design's term for the unique sound of an instrument as a consequence of the multiple resonances the instrument creates.

Question 17

	Source of vibration	Resonator	How the pitch is changed
Violin	a stretched string, set vibrating by the bow	the wooden body of the violin	shortening the vibrating length of the string with the fingers; selecting strings of different thickness
Flute	the air column, set vibrating by the player's air stream at the edge of the mouth hole	the air column inside the tube	opening and closing keys to change the effective length of the air column
Trumpet	the player's lips vibrating against the mouthpiece	the air column inside the tubing and bell	valves adding tubing to change the length, and lip tension selecting which harmonic sounds

	Source of vibration	Resonator	How the pitch is changed
Snare drum	the struck membrane (drumhead)	the membrane and the shell	tension of the drumhead (no definite pitch is produced)
Human voice	the vocal folds, set vibrating by air from the lungs	the throat, mouth and nose	tension and length of the vocal folds set the pitch; the mouth and throat shape the resonances

(b) All five follow the same pattern: a source creates vibrations, a resonator selects and amplifies frequencies matching its natural frequencies, and energy is transferred into the air as a longitudinal sound wave. The differences are what vibrates and which property is changed to control the pitch.

Question 18 Both halves of the claim are correct. *First half — tightening.* For a string fixed at both ends, the fundamental satisfies $f_1 = v/2L$. Tightening the string does not change its length L, but it increases the speed v at which waves travel along the string. With L unchanged and v larger, f_1 is larger: the pitch rises. The student's reasoning is correct. *Second half — fretting.* Pressing the string against a fret shortens the vibrating length L. The wave speed v is unchanged (the tension and thickness of the string have not changed), so the fundamental wavelength $\lambda_1 = 2L$ becomes shorter, and since $f_1 = v/\lambda_1$, the frequency rises: the pitch rises. The student is right that this is a different mechanism — one changes the wave speed, the other changes the wavelength — but both act through the same relationship, $f_1 = v/2L$.

Option task

Option 2.10 assessed task — Explanation of a selected physics device, design or innovation (30 marks; house convention).

This is the house **Option task** for Option 2.10. Each option subtopic closes with one such assessed piece, in one of the study design's own Unit 2 Outcome 2 task formats (*VCE Physics Study Design, Unit 2, Area of Study 2, suitable tasks for assessment*); this task's format is *"an explanation of a selected physics device, design or innovation"*. The marks are house convention: the study design fixes no mark allocations at Units 1 and 2, all assessment is school-based, and nothing here contributes to a study score. Where teachers allow students to choose between tasks they must ensure that the tasks they set are of comparable scope and demand (*VCE Physics Study Design*).

The task. Write an explanation, of roughly 700–1000 words, of how **one** musical instrument makes music. Choose one instrument — from any family (string, woodwind, brass or percussion) — or the human voice. Use the report conventions of 14G: correct terminology, units, significant figures and acknowledgement of references.

What your explanation must show. The task is marked against the shared Communicating physics dot points, taught in 10A and 10B:

1. **Evaluate the validity of the sources** you use (`U2.2.CP.1`). Use at least two sources beyond this book, and for each state what makes it valid or limited — who produced it, what evidence it gives, and whether it is the kind of source that can be checked (10A).
2. **Apply the physics concepts of this option** (`U2.2.CP.2`). Define the key terms your explanation uses — longitudinal wave, sound intensity, sound intensity level, resonance, natural frequency, harmonic, timbre — and use correct terminology, units and representations throughout. Identify your instrument's source of vibration and its resonator, explain how the player changes the pitch and the loudness, and explain the instrument's unique sound as a consequence of its multiple resonances.
3. **Use the models of this option to organise and explain** how the instrument works (`U2.2.CP.3`). Treat the vibrating system as a string or as an open or closed resonant tube, analyse the fundamental and at least two further harmonics, and include at least one calculation of a resonant frequency from $v = f\lambda$. Apply the inverse square law with one calculation comparing the sound intensity at two distances from the instrument, stating any assumptions you make about how the sound spreads. Discuss at least one **limitation** of a model you use

— where the ideal string, ideal tube or uniform-spreading model simplifies, and what that simplification leaves out (10A).

4. **Discuss the relevant societal context** (`U2.2.CP.4`). Give at least one **sociocultural**, one **economic**, one **legal** and one **political** factor relevant to how your instrument is used — for example, who gets to learn music and what role music plays in community life; the cost of instruments and of tuition; the workplace noise-exposure standard that protects musicians' hearing and the noise rules that apply to venues; funding decisions for school and community music programs — and trace each factor's influence rather than listing it (10B).
5. **Justify an evaluated stance** (`U2.2.CP.5`). Use your physics understanding to take and justify a position on one issue connected to your instrument — for example, whether hearing protection should be required in school bands and orchestras, whether the cost of instruments should be subsidised so that more students can play, or how loudly venues should be allowed to amplify music. Marks are awarded for the quality of the reasoning, not the conclusion reached (10B).

Marking rubric (30 marks). Five criteria, keyed to `U2.2.CP.1–.5`, at 6 marks each.

Criterion	6 marks	3 marks	0–1 marks
Validity of sources (`U2.2.CP.1`)	At least two sources evaluated in depth: origin, evidence and checkability each weighed, and the evaluation shapes what the explanation relies on.	Sources named and briefly assessed; the assessment is asserted rather than argued, or applies to only part of the sourcing.	Sources unnamed, or listed without any evaluation.
Application of physics concepts (`U2.2.CP.2`)	Key terms defined at first use; source and resonator correctly identified; pitch, loudness and timbre explained correctly; terminology, units, significant figures and representations correct and consistent throughout.	Most terms defined and used correctly; the source or resonator is unclear; minor slips in units or representations that do not obscure the physics.	Key terms undefined or used incorrectly; the physics of the option is largely absent.
Use and limitation of models (`U2.2.CP.3`)	The standing-wave model (string or tube) and the inverse-square model are applied, each with a correct calculation, and at least one limitation is identified and discussed.	The models are described and applied; a calculation is incomplete, or a limitation is named but not discussed.	No model used, or a model stated without application.
Societal context (`U2.2.CP.4`)	At least one factor from each of the four categories, each traced to its influence on the issue.	Factors from some categories named, with influence traced for some but asserted for others.	Factors listed without influence traced, or fewer than two categories present.
Justified stance (`U2.2.CP.5`)	A clear stance supported by physics understanding; the strongest case on the other side is acknowledged; at least one limitation of the evidence or reasoning is stated.	A stance is stated with some physics support, but the other side or the limits are not engaged.	No stance, or an opinion given without physics support.

Reasoning quality, not the stance reached, is what earns marks: two students reaching opposite conclusions can both receive full marks if both reasoned from defined terms, evaluated sources and acknowledged limits.

Scope — *VCE Physics Study Design, Unit 2, Area of Study 2, Option 2.7: How does the human body use electricity?* (The physics of the use of electricity in the human body): “compare charge carriers in the human body (specifically Na^+, K^+, Ca^{2+}, Mg^{2+}, PO_4^{3-} and Cl^- ions) with those in metals (specifically electrons)” (`U2.2.O7.1`) · “describe the nervous system as the control of the function of the human body through electrical processes of nerve cells (through an action potential) and chemical transfer between nerve cells (through neurotransmitters diffusing across synapses)” (`U2.2.O7.2`) · “model an action potential as a short-lasting electrical event across the cell membrane in response to a stimulus, including reference to the roles of ion channels (leakage and voltage gated) in changing membrane potentials during the processes of depolarisation, repolarisation, hyperpolarisation and return to resting state” (`U2.2.O7.3`) · “explain heart beat with reference to the production of a potential difference and model heart beat with reference to the action of the nodes in atrial and ventricular muscles as the source of the electric signal, the staggering of signals from the atrial and ventricular muscles, and time delay before both muscles can contract again” (`U2.2.O7.4`) · “describe the effects of current through, and potential difference across, the human body” (`U2.2.O7.5`) · “explain why people have different electrical resistances with reference to comparison of the resistances in human bone, fat, muscle, nerves and skin” (`U2.2.O7.6`).

Theory

Your body is an electrical device — though not in the way a torch or a phone is. Every beat of your heart starts as an electrical event. Every movement you make, and every sensation you feel, is carried by electrical signals along your nerves. And when an electric shock harms a person, it usually harms them by interfering with exactly these electrical systems. This option applies the electricity model of Chapter 5 — charge, current, potential difference, resistance, energy and power (5A) — to the human body.

Charge carriers in metals and in the body. You already know the metal case (5A): in a metal wire the charge carriers are **electrons** — negatively charged particles that are free to move through the fixed lattice of metal atoms. When a potential difference is applied across the wire, the electrons drift through it and there is a current. The wire itself does not move, no substance is carried from one end to the other, and the signal that starts the drift travels through the circuit very quickly indeed.

The fluids of the body are different. Body fluids are solutions of dissolved salts, and a dissolved salt separates into charged particles called **ions**. The charge carriers of the body are these ions — specifically **Na^+** (sodium), **K^+** (potassium), **Ca^{2+}** (calcium) and **Mg^{2+}** (magnesium) ions, which carry positive charge, and **Cl^-** (chloride) and **PO_4^{3-}** (phosphate) ions, which carry negative charge. When there is a potential difference across a body fluid, both signs of carrier move: the positive ions drift one way and the negative ions the other. The comparison is worth setting out:

Feature	A metal wire	A body fluid
Charge carrier	electrons only	dissolved ions: Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, PO_4^{3-}
Sign of the carriers	negative only	both positive and negative
What the carriers move through	a fixed solid lattice	a liquid solution
Is matter transported?	no — the wire stays put	yes — the ions themselves travel
Speed of the carriers	the signal travels very fast; the electrons drift slowly	the ions drift far more slowly than a signal in a wire

Two consequences matter for everything else in this option. First, because the carriers in the body are slow, massive particles, electrical signalling in the body is far slower than in a metal wire of the same length. Second, because moving an ion means moving a real piece of matter, the body’s electrical events always involve chemistry as well as charge flow. Every charge, in a wire or in a body, is a whole-number multiple of the elementary charge $e = 1.6 \times 10^{-19}$ C — a Na^+ ion carries $+e$, a Ca^{2+} ion carries $+2e$, a PO_4^{3-} ion carries $-3e$.

The nervous system: electrical within a cell, chemical between cells. The nervous system — the brain, spinal cord and nerves — controls the function of the human body. It does this through nerve cells, or **neurons**. A neuron carries an electrical signal called an **action potential** along its length; the physics of that signal is the next subsection. Between neurons the signal cannot simply continue, because there is a tiny gap, called a **synapse**, between one cell and the next. Instead, the arriving electrical signal causes the first cell to release chemical molecules called **neurotransmitters**, which diffuse — spread out from where they are more concentrated to where they are less concentrated — across the synapse and attach to the next cell, where they trigger a new electrical signal. The message therefore travels as an electrical–chemical–electrical chain. The chemical step is one-way, which is why signals travel in the intended direction, and it is slightly slower than the electrical step, which is one reason the body's signalling is slower than a wire's. Sensation, muscle control, and the ongoing regulation of organs such as the heart all depend on this chain.

The action potential: a short-lasting electrical event across a membrane. Every cell in the body is wrapped in a thin **cell membrane** that separates the fluid inside the cell from the fluid outside. The membrane controls which ions may pass through it, using protein structures called **ion channels**. Because of how those channels are set, the inside of a resting cell sits at a lower electrical potential than the outside: there is a potential difference across the membrane, called the **membrane potential**, of about $-70\,\mathrm{mV}$, the inside relative to the outside. This **resting potential** is maintained by two things: **leakage channels**, which are always open and allow a small steady drift of ions (mainly K^+ leaking out of the cell), and ion pumps, which use the cell's energy supply to keep the ion concentrations different on the two sides — rather like slowly recharging a battery that is always partly running down.

An **action potential** is a brief, all-or-nothing reversal of that membrane potential, triggered when a stimulus is strong enough. The model runs in four stages.

1. **Depolarisation.** A stimulus makes the membrane potential less negative. If it reaches a critical value called the **threshold** (about $-55\,\mathrm{mV}$), **voltage-gated** channels — channels that open only when the membrane potential changes — swing open. Voltage-gated Na^+ channels open first, Na^+ rushes into the cell, and the membrane potential rises rapidly, through zero to about $+30\,\mathrm{mV}$. The membrane is depolarised: its usual separation of charge has briefly broken down.
2. **Repolarisation.** Within about a millisecond the Na^+ channels close again, and voltage-gated K^+ channels open. K^+ rushes out of the cell, and the membrane potential falls back toward the resting value.
3. **Hyperpolarisation.** The K^+ channels are slow to close, so for a moment too much positive charge leaves and the membrane potential dips below the resting value, to about $-80\,\mathrm{mV}$.
4. **Return to resting state.** The leakage channels and the ion pumps restore the resting potential of about $-70\,\mathrm{mV}$ and the original ion distributions, ready for the next stimulus.

The whole event lasts only about two milliseconds. It is all-or-nothing: a stimulus below threshold produces no action potential at all, while any stimulus at or above threshold produces the same full-size event. The event does not fade as it travels — each patch of membrane triggers the next — so an action potential travels along a neuron without shrinking, at speeds from about $1\,\mathrm{m\,s^{-1}}$ in thin fibres to more than $100\,\mathrm{m\,s^{-1}}$ in the fastest. That is fast for a body, but millions of times slower than an electrical signal in a copper wire.

The heart: an electrically driven pump. The heartbeat is the most visible electrical process in the body, and it can be measured from outside the body with an **electrocardiogram (ECG)**. Each beat is driven by a potential difference produced by specialised muscle cells.

- The **sinoatrial (SA) node**, a small region of tissue in the wall of the right atrium, produces potential differences spontaneously and regularly. It is the heart's natural **pacemaker**, setting a resting rate of about 60 –100 beats per minute.
- The signal spreads across the muscle of both atria, and the atria contract, pushing blood into the lower chambers, the ventricles.
- The signal then reaches the **atrioventricular (AV) node**. The AV node is the only electrical pathway between the atrial and ventricular muscle; the tissue between them otherwise acts as an insulator. The AV node delays the signal by about $0.1\,\mathrm{s}$ — long enough for the atria to finish emptying before the ventricles are told to contract.

- The signal spreads through the ventricular muscle and the ventricles contract, pumping blood to the lungs and to the body.

Notice the staggering: atrial signal and contraction first, then, after the built-in delay, ventricular signal and contraction. The two muscle groups never contract at once; the delay is what gives the heart its orderly two-stage pump.

Heart muscle has one more electrical property that matters. After it contracts, it cannot be stimulated to contract again for a comparatively long time — roughly a quarter of a second. This recovery time is the **refractory period**: the time delay before the heart muscles can contract again. It guarantees that the heart relaxes and refills with blood between beats, and it prevents the heart from being driven into a sustained, useless contraction. It also sets a hard upper limit on the heart rate: with a refractory period of $0.25\,\mathrm{s}$, no amount of stimulation can produce more than about $60 \div 0.25 = 240$ beats per minute.

Because body fluids conduct, the heart's electrical activity produces small potential differences — of the order of millivolts — that reach the skin. Electrodes placed on the skin detect a repeating pattern of peaks, one pattern per beat: the peaks correspond to the atria depolarising, the ventricles depolarising, and the ventricles repolarising. Measuring the time between repeating peaks gives the heart rate, and a disrupted pattern is evidence of a disrupted heart rhythm.

Current through the body, and potential difference across it. Because the body's control systems are electrical, an external electrical source can interfere with them. A potential difference applied across the body drives a current through it, according to $I = V / R$ (5A), and it is the current — its size, its path and how long it lasts — that produces the effects. As the current through the body grows, the effects grow in stages:

- very small currents are felt as a tingling sensation;
- larger currents cause muscles to contract. If the current path runs through a hand gripping a conductor, the gripping muscles can lock, so the person cannot let go;
- currents through the chest can interfere with breathing and, most seriously, with the heart's own electrical pattern. The orderly rhythm can collapse into fast, chaotic, uncoordinated activity of the ventricles — **ventricular fibrillation** — in which the heart stops pumping effectively. This is the usual cause of death from electric shock;
- still larger currents heat tissue as energy is transferred ($E = P\,t = V\,I\,t$), causing burns.

The path of the current matters: a hand-to-hand or hand-to-foot path crosses the chest and the heart, while a path confined to one fingertip does not. The exact danger thresholds for current and duration, the causes of shock, the safety devices that protect against it, and first aid treatment are treated in 6E; the physics of *why* the current differs from person to person is below. Australian domestic supply is $230\,\mathrm{V}$, $50\,\mathrm{Hz}$ AC (6B), and this section's physics explains why that supply, common in every home, must be treated with respect.

Why bodies differ: the resistance of human tissues. The body is not a single uniform resistor. Different tissues resist the current very differently, because conduction in the body is carried by dissolved ions: wet, ion-rich tissue conducts well, while dense or dry tissue resists.

- **Skin** — especially its dry outer layer — has by far the largest resistance of any body tissue and dominates the total resistance of the body. Dry skin can resist with tens of thousands of ohms or more; wet skin drops to roughly a thousand ohms; broken skin almost disappears as a barrier.
- **Nerves** and **muscle** are wet, ion-rich tissues with comparatively low resistance; muscle conducts better than fat.
- **Fat** contains little water and conducts poorly, so its resistance is higher.
- **Bone** is dense and dry and has the highest resistance of the internal tissues.

For a current entering one hand and leaving the other, a simple model treats the body as three resistors in series (5D): the skin at the first contact, the internal tissues, and the skin at the second contact:

$$R_{\text{body}} = R_{\text{skin, 1}} + R_{\text{internal}} + R_{\text{skin, 2}}\,.$$

The internal resistance, hand to hand, is only of the order of a few hundred ohms — the skin is what protects you. Typical model values used in this section: dry skin contact about $10\,000\,\Omega$ to well over $100\,000\,\Omega$ per contact; wet skin contact about $1000\,\Omega$ per contact; internal resistance about 300–500 Ω. These are order-of-magnitude values; real values vary widely, which is exactly the point of the last dot point of this option.

People have different electrical resistances because skin differs from person to person and from moment to moment: thickness, moisture, sweat, cuts, scrapes and burns all change the skin resistance, and so do the contact area and how hard the contact is pressed. Once the skin is bypassed, the path through the body depends on which tissues the current crosses — nerve and muscle carry it readily, fat and bone resist it. This is why the same potential difference can drive a harmless current through one person and a dangerous current through another, and why electrical safety is designed for the worst realistic case: wet, broken skin (6E).

How this section is assessed. This option closes with a house **Option task** (30 marks), a school-assessed piece in one of the study design's own Outcome 2 task formats, marked against a rubric keyed to the shared Communicating physics dot points `U2.2.CP.1–.5` taught in 10A and 10B. All assessment at Units 1 and 2 is school-based; nothing in this option contributes to a study score.

Worked examples

Example 1 — scaffolded

At one point on a neuron, the passage of an action potential produces an average current of $1.6\,\mu\text{A}$ lasting $1.0\,\text{ms}$.

(a) Calculate the charge that crosses the membrane at this point during the action potential.
(b) Suppose this charge is carried entirely by Na^+ ions, each of charge $+e = 1.6\times10^{-19}\,\text{C}$. Calculate the number of sodium ions involved.
(c) The action potential travels along a $0.80\,\text{m}$ nerve fibre at $50\,\text{m s}^{-1}$. Calculate the time it takes to travel the fibre's length.

Working	Comment
(a) $I = 1.6\,\mu\text{A} = 1.6\times10^{-6}\,\text{A},\ t = 1.0\,\text{ms} = 1.0\times10^{-3}\,\text{s}$.	Convert to SI units first (5A).
$Q = It = 1.6\times10^{-6}\times1.0\times10^{-3} = 1.6\times10^{-9}\,\text{C}$.	Rearrange the definition of current, $I = Q/t$.
(b) $N = Q/e = \dfrac{1.6\times10^{-9}}{1.6\times10^{-19}} = 1.0\times10^{10}$ ions.	Every Na^+ ion carries exactly $+e$; the total charge is a whole number of ion charges.
(c) $t = \dfrac{d}{v} = \dfrac{0.80}{50} = 0.016\,\text{s} = 16\,\text{ms}$.	Constant-speed motion; notice how long $16\,\text{ms}$ is compared with the $2\,\text{ms}$ of the event itself.

Example 2 — scaffolded

A person with dry hands touches the two terminals of a device. Model the body as two skin resistances of $50\,\text{k}\Omega$ each (one per hand) in series with an internal resistance of $500\,\Omega$.

(a) Calculate the total resistance of this model.
(b) The person first touches the terminals of a $12\,\text{V}$ battery. Calculate the current, and comment on whether it is likely to be felt.
(c) The person's hands are now wet, and each skin resistance falls to $1.0\,\text{k}\Omega$. They touch a $230\,\text{V}$ supply, hand to hand. Calculate the current and comment on its likely effect.

Working	Comment
(a) $R_{body} = 50\,000 + 500 + 50\,000 = 100\,500\,\Omega$.	Series resistances add (5D). The two skin contacts dominate.
(b) $I = \dfrac{V}{R} = \dfrac{12}{100\,500} = 1.2\times10^{-4}\,\text{A} = 0.12\,\text{mA}$.	$I = V/R$ (5A).
This is far below the current at which anything is felt, so a $12\,\text{V}$ battery is harmless through dry skin.	The large dry-skin resistance keeps the current tiny.
(c) $R_{body} = 1000 + 500 + 1000 = 2500\,\Omega$.	Wet skin is roughly fifty times less resistive here.

Working	Comment
$I = \dfrac{230}{2500} = 0.092\text{ A} = 92\text{ mA}$, hand to hand.	A current of this size, on a path across the chest, is well into the range that can disrupt the heart's rhythm; the quantitative danger thresholds are treated in 6E.

Example 3 — unscaffolded

An electrocardiogram (ECG) records a repeating pattern of peaks. For a person at rest, the time between corresponding peaks on successive beats is 0.80 s.

(a) Calculate the heart rate in beats per minute.

(b) During exercise the time between corresponding peaks falls to 0.50 s. Calculate the heart rate during exercise.

(c) Explain the role of the delay produced by the AV node. What would go wrong without it?

(d) The refractory period of heart muscle is about 0.25 s. Calculate the fastest heart rate that stimulation could possibly produce, and explain what this limit protects.

(e) There are 60 s in one minute, so the rate is $60 \div 0.80 = 75$ beats per minute.

(f) During exercise, $60 \div 0.50 = 120$ beats per minute.

(g) The AV node is the only electrical pathway from the atria to the ventricles, and it delays the signal by about 0.1 s. The delay staggers the two contractions: the atria finish emptying blood into the ventricles before the ventricles are told to contract. Without the delay, the atrial and ventricular muscle could contract together, and the ventricles would begin contracting against chambers that had not finished filling — a less effective pump.

(h) Each beat requires at least one refractory period, so the fastest possible rate is $60 \div 0.25 = 240$ beats per minute. The refractory period protects the heart's two-stage action: it guarantees a relaxation and refilling phase between contractions, and it prevents the heart muscle from being driven into a sustained contraction in which it would pump nothing at all.

Example 4 — unscaffolded

A person grips a live 230 V conductor with wet hands, and a current of 92 mA passes hand to hand through the body for 0.20 s before the circuit is broken.

(a) Calculate the energy transferred electrically to the body during this time.

(b) An external defibrillator delivers about 200 J of energy to the chest in about 2.0 ms. Calculate the average power of the shock, and the average current if the potential difference across the chest is about 2000 V.

(c) In ventricular fibrillation the heart's electrical activity is chaotic and the heart stops pumping effectively. Explain, using the physics of this option, why a large, brief current is used to treat it.

(d) Using $E = V I t$:

$$E = 230 \times 0.092 \times 0.20 = 4.2\text{ J}.$$

Notice how little energy this is. A shock can kill through disruption of the heart's rhythm at energies far too small to heat the body significantly; burns require much more energy, or a much longer duration.

(b) Using $P = E / t$:

$$P = \frac{200}{2.0 \times 10^{-3}} = 1.0 \times 10^{5}\text{ W}.$$

The average power is $1.0 \times 10^{5}\text{ W}$ — one hundred kilowatts, briefly. Using $P = V I$, the average current is

$$I = \frac{P}{V} = \frac{1.0 \times 10^{5}}{2000} = 50\text{ A}.$$

(c) The heart's rhythm is set by its own electrical signals: the SA node's regular signal, the AV node's delay, and the wave of contraction it sends through the muscle. In fibrillation the muscle cells are firing independently and chaotically, so no coordinated beat occurs. A large current passed briefly through the chest makes all of the muscle cells reset together; because the current stops after a few milliseconds, the heart's own pacemaker — the SA node, which generates potential differences spontaneously — can re-establish the orderly pattern. The refractory period then does its usual job: it holds the muscle unresponsive while the new rhythm takes over. The shock must be brief, because a sustained current would itself hold the heart in contraction.

Practice questions

Question 1 `U2.2.07.1` compares charge carriers in the human body with those in metals. (a) State the charge carriers in a copper wire and the charge carriers in the fluids of the human body, naming all six body ions required by the study design. (b) Copy the table below and complete it.

Feature	Copper wire	Body fluid
Sign(s) of the charge carriers		
Medium the carriers move through		
Is matter transported by the current?		

(c) State two reasons why electrical signalling in the body is slower than in a metal wire of the same length.

Question 2 At one point on a neuron, each action potential moves a charge of $8.0\times10^{-10}\,\mathrm{C}$ through the membrane in $0.50\,\mathrm{ms}$. (a) Calculate the average current during that time. (b) The neuron carries 200 action potentials each second. Calculate the average current at this point over one second. (c) State what the carriers of this current are, and how they differ from the carriers in a metal wire.

Question 3 The membrane potential of a cell is measured during an action potential, with the results below.

Time (ms)	Membrane potential (mV)
0	−70
0.5	+30
1.5	−70
2.0	−80
3.0	−70

(a) Name the phase of the action potential occurring in each time interval: $0–0.5\,\mathrm{ms}$, $0.5–1.5\,\mathrm{ms}$, $1.5–2.0\,\mathrm{ms}$ and $2.0–3.0\,\mathrm{ms}$.
(b) State which voltage-gated channels are mainly open during depolarisation, and which during repolarisation.
(c) State the role of the leakage channels.

Question 4 A person's heart beats 75 times per minute at rest. (a) Calculate the time between beats. (b) Calculate the number of beats in 10 minutes at this rate. (c) If the refractory period of the heart muscle is $0.30\,\mathrm{s}$, show by calculation that this person's heart cannot beat faster than 200 times per minute, no matter how strongly it is stimulated.

Question 5 A simple model of the body's resistance treats it as two skin resistances in series with an internal resistance. For a particular person, each dry-skin contact has a resistance of $30\,\mathrm{k}\,\Omega$ and the internal resistance is $400\,\Omega$. (a) Calculate the body's total resistance, hand to hand, when the skin is dry. (b) Calculate the current through this person, hand to hand, if they touch a $230\,\mathrm{V}$ supply with dry skin. (c) Moist skin reduces each skin contact resistance to $1.5\,\mathrm{k}\,\Omega$. Calculate the current for the same $230\,\mathrm{V}$ supply, and explain the difference.

Question 6 A Ca^{2+} ion carries charge $+2e$, where $e = 1.6 \times 10^{-19}$ C. (a) Write the charge of the ion in coulombs. (b) The resting membrane potential of a cell is $70\,\text{mV}$. Calculate the energy transferred when one Ca^{2+} ion moves through this potential difference, using $V = E/Q$ rearranged to $E = QV$. (c) During a burst of activity, a total charge of 1.0×10^{-12} C crosses a cell membrane, carried by ions each of charge $+e$. Calculate the number of ions involved.

Question 7 An action potential travels along a $0.90\,\text{m}$ neuron at $40\,\text{m s}^{-1}$. (a) Calculate the time the signal takes to travel the neuron. (b) An electrical signal in a copper wire travels at about $2.0 \times 10^{8}\,\text{m s}^{-1}$. Calculate the time the same $0.90\,\text{m}$ journey would take in the wire. (c) Compare the two times and use the charge-carrier model of `U2.2.07.1` to explain the difference.

Question 8 Between two neurons there is a synapse. Explain why a signal crosses a synapse in one direction only, and why the crossing takes slightly longer than the same distance along a neuron. Refer to the movement of the neurotransmitter molecules.

Question 9 An action potential is all-or-nothing: a stimulus below the threshold of about $-55\,\text{mV}$ produces no action potential, while any stimulus at or above threshold produces the same full-size event. Explain why this makes the body's long-distance signalling reliable, even though the signal is regenerated from place to place rather than travelling like a signal in a wire.

Question 10 During the depolarisation of an action potential, the membrane potential changes from $-70\,\text{mV}$ to $+30\,\text{mV}$. (a) State the total change in membrane potential. (b) The voltage-gated channels are open for $0.50\,\text{ms}$, during which the average current through the membrane is $3.0\,\mu\text{A}$. Calculate the charge that crosses the membrane. (c) If the charge is carried by Na^{+} ions, each of charge $+e = 1.6 \times 10^{-19}$ C, calculate the number of sodium ions involved.

Question 11 Explain the difference between the roles of leakage channels and voltage-gated channels, referring to the resting potential and to the phases of the action potential.

Question 12 Describe one heartbeat as an electrical sequence, referring to the SA node, the spread of the signal through the atrial muscle, the AV node and its delay, and the ventricular muscle. State what the delay achieves.

Question 13 A student claims: *"The faster you stimulate the heart, the more blood it will pump, so there is no upper limit to a useful heart rate."* Evaluate this claim. Refer to the refractory period, the filling of the heart between beats, and what happens when the heart's electrical pattern becomes chaotic.

Question 14 The electrical activity of the heart can be detected by electrodes placed on the skin, some distance from the heart itself. Explain how this is possible, referring to the conducting properties of body fluids and to what the electrodes measure.

Question 15 A person whose total body resistance, hand to hand, is $4.0\,\text{k}\Omega$ touches a $230\,\text{V}$ supply. (a) Calculate the current through the person. (b) As approximate benchmarks: currents of about $1\,\text{mA}$ are felt as tingling, currents above about $10\,\text{mA}$ can lock the muscles of a gripping hand, and currents above about $50\,\text{mA}$ on a path across the chest can disrupt the heart's rhythm (the quantitative danger thresholds for current and duration are treated fully in 6E). State, with your calculation, which effect this current reaches. (c) Explain why the path of the current — hand to hand, rather than between two points on the same hand — matters for the danger.

Question 16 Explain why different people have different electrical resistances, and why the same person's resistance changes from moment to moment. Refer to the comparison of the resistances of skin, nerves, muscle, fat and bone.

Question 17 Explain why a person with wet hands is in far greater danger from the same $230\,\text{V}$ supply than a person with dry hands. Refer to the series model of the body's resistance and to $I = V/R$.

Question 18 An external defibrillator delivers $150\,\text{J}$ of energy to a patient's chest in $3.0\,\text{ms}$. (a) Calculate the average power of the shock. (b) If the potential difference across the chest is $1500\,\text{V}$, calculate the average current. (c) Explain, using the electrical model of the heart from this option, what the shock is intended to achieve and why it is delivered so briefly.

Answers

Question 1 (a) wire: electrons; body: Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, PO_4^{3-} ions; (b) see solution table; (c) the body's carriers are massive ions that drift slowly through a liquid, and charge motion involves moving matter. **Question 2** (a) $1.6\,\mu\text{A}$; (b) $0.16\,\mu\text{A}$; (c) ions, not electrons — both signs move, and matter is transported. **Question 3** (a) depolarisation, repolarisation, hyperpolarisation, return to resting state; (b) Na^+ channels open during depolarisation, K^+ channels during repolarisation; (c) see solution. **Question 4** (a) $0.80\,\text{s}$; (b) 750; (c) $60 \div 0.30 = 200$ beats per minute maximum. **Question 5** (a) $60\,400\,\Omega$; (b) $3.8\,\text{mA}$; (c) $68\,\text{mA}$ — wet skin removes most of the body's resistance. **Question 6** (a) $3.2 \times 10^{-19}\,\text{C}$; (b) $2.2 \times 10^{-20}\,\text{J}$; (c) 6.3×10^{6} ions. **Question 7** (a) $0.023\,\text{s}$; (b) $4.5 \times 10^{-9}\,\text{s}$; (c) the neuron is about five million times slower — see solution. **Question 8** See solution — neurotransmitter diffuses one way across the gap; diffusion is slower than the electrical event along the neuron. **Question 9** See solution — the signal is regenerated at full size at every point, so it neither fades nor varies with stimulus strength. **Question 10** (a) $100\,\text{mV}$; (b) $1.5 \times 10^{-9}\,\text{C}$; (c) 9.4×10^{9} ions. **Question 11** See solution — leakage channels maintain the resting potential; voltage-gated channels produce depolarisation and repolarisation. **Question 12** See solution — SA node fires; atria contract; AV node delays; ventricles contract; the delay lets the atria finish filling the ventricles first. **Question 13** See solution — the claim is wrong: filling time and the refractory period set a limit, and chaotic stimulation causes fibrillation, not more pumping. **Question 14** See solution — body fluids conduct the heart's potential differences to the skin, where electrodes measure a repeating millivolt pattern. **Question 15** (a) $58\,\text{mA}$; (b) above the $50\,\text{mA}$ benchmark for disrupting the heart's rhythm; (c) hand to hand crosses the chest and the heart. **Question 16** See solution — skin dominates and differs between and within people; internal tissues rank nerve and muscle (low), fat (higher), bone (highest). **Question 17** See solution — wet skin cuts the dominant series resistance, so $I = V / R$ gives a far larger current. **Question 18** (a) $5.0 \times 10^{4}\,\text{W}$; (b) $33\,\text{A}$; (c) see solution.

Fully-worked solutions

Question 1 (a) In a copper wire the charge carriers are **electrons**. In the fluids of the human body the carriers are dissolved ions: **Na^+** (sodium), **K^+** (potassium), **Ca^{2+}** (calcium), **Mg^{2+}** (magnesium), **Cl^-** (chloride) and **PO_4^{3-}** (phosphate). (b)

Feature	Copper wire	Body fluid
Sign(s) of the charge carriers	negative only	both positive and negative
Medium the carriers move through	a fixed solid lattice	a liquid solution
Is matter transported by the current?	no	yes — the ions themselves travel

(c) Any two genuine reasons, for example: the body's carriers are ions, which are vastly more massive than electrons and drift slowly through a liquid rather than through a metal lattice; and charge movement in the body requires actual transport of matter (and the chemistry that goes with it), rather than a fast drift response in an already-full conductor.

Question 2 (a) $t = 0.50\,\text{ms} = 5.0 \times 10^{-4}\,\text{s}$:

$$I = \frac{Q}{t} = \frac{8.0 \times 10^{-10}}{5.0 \times 10^{-4}} = 1.6 \times 10^{-6}\,\text{A} = 1.6\,\mu\text{A}.$$

(b) Charge per second: $Q = 200 \times 8.0 \times 10^{-10} = 1.6 \times 10^{-7}\,\text{C}$, so the average current is $1.6 \times 10^{-7}\,\text{A} = 0.16\,\mu\text{A}$.

(c) The carriers are ions in the body fluids (such as Na^+ and K^+). Unlike the electrons in a metal wire, both positive and negative ions move — in opposite directions — and the moving charges are massive particles, so matter itself is transported.

Question 3 (a) 0–$0.5\,\text{ms}$: **depolarisation** (the potential rises from -70 to $+30\,\text{mV}$). 0.5–$1.5\,\text{ms}$: **repolarisation** (the potential falls back to $-70\,\text{mV}$). 1.5–$2.0\,\text{ms}$: **hyperpolarisation** (the potential dips below the resting value to $-80\,\text{mV}$). 2.0–$3.0\,\text{ms}$: **return to resting state** ($-70\,\text{mV}$ is restored and held). (b) During depolarisation the voltage-gated **Na^+** channels are mainly open; during repolarisation the voltage-gated **K^+** channels are mainly open. (c) The leakage channels are always open and allow a small steady drift of ions (mainly K^+ out of the cell). Together with the ion pumps, they establish and maintain the resting potential of about $-70\,\text{mV}$ between action potentials.

Question 4 (a) time between beats $= \frac{60}{75} = 0.80\,\text{s}$. (b) $75 \times 10 = 750$ beats. (c) Each beat requires at least one full refractory period of $0.30\,\text{s}$, because the muscle cannot be made to contract again until the refractory period ends. The fastest possible rate is therefore

$$\frac{60\,\text{s}}{0.30\,\text{s per beat}} = 200\,\text{beats per minute}.$$

No stimulus, however strong, can produce a faster rate.

Question 5 (a) $R_{\text{body}} = 30\,000 + 400 + 30\,000 = 60\,400\,\Omega$. (b)

$$I = \frac{V}{R} = \frac{230}{60\,400} = 3.8 \times 10^{-3}\,\text{A} = 3.8\,\text{mA}.$$

(c) $R_{\text{body}} = 1500 + 400 + 1500 = 3400\,\Omega$, so

$$I = \frac{230}{3400} = 6.8 \times 10^{-2}\,\text{A} = 68\,\text{mA}.$$

The current is about 18 times larger because the wet skin removes most of the body's resistance. In the series model, the skin contacts are the largest resistances; when they collapse, only the small internal resistance is left to limit the current.

Question 6 (a) $Q = +2e = 2 \times 1.6 \times 10^{-19} = 3.2 \times 10^{-19}\,\text{C}$. (b) $V = 70\,\text{mV} = 0.070\,\text{V}$. Rearranging $V = E/Q$:

$$E = QV = 3.2 \times 10^{-19} \times 0.070 = 2.2 \times 10^{-20}\,\text{J}.$$

$$N = \frac{Q}{e} = \frac{1.0 \times 10^{-12}}{1.6 \times 10^{-19}} = 6.3 \times 10^{6}\,\text{ions}.$$

Question 7 (a)

$$t = \frac{d}{v} = \frac{0.90}{40} = 0.023\,\text{s} = 23\,\text{ms}.$$

$$t = \frac{0.90}{2.0 \times 10^{8}} = 4.5 \times 10^{-9}\,\text{s}.$$

(c) The journey takes about five million times longer along the neuron than along the wire. In the wire, the signal is an electrical disturbance travelling through an already-full conductor of light, mobile electrons; in the neuron, the signal is a wave of ion movements through the membrane, rebuilt step by step from place to place, with massive Na^{+} and K^{+} ions physically crossing the membrane at each point. Moving matter is slower than moving a disturbance.

Question 8 Model answer. At a synapse, the arriving electrical signal causes the first neuron to release neurotransmitter molecules from its side of the gap. The molecules then **diffuse** — they spread from the side where they are released (high concentration) toward the far side (low concentration) — and attach to the next neuron, triggering a new electrical signal. The direction is fixed because only the sending side releases the molecules and only the receiving side has the attachment sites for them, so the signal cannot run backward. The crossing is slower than the same distance along a neuron because diffusion of molecules through fluid is a far slower process than the electrical event that travels along the neuron's membrane.

Question 9 Model answer. Because the response is all-or-nothing, the size of the signal does not depend on the strength of the original stimulus: once threshold is reached, the action potential is always the same full-size event. And because each patch of membrane regenerates the full event in the next patch, the signal does not fade with distance. Together these mean that a message arriving at the end of a long neuron is identical in size to the one that started, regardless of small variations in the stimulus or in the path. A wire-like signal, by contrast, would depend on the stimulus strength and would weaken with distance. The regeneration also has a cost — it is slower — but for reliability over long distances in a warm, wet body, an all-or-nothing regenerated signal is a robust design.

Question 10 (a) From $-70\,\mathrm{mV}$ to $+30\,\mathrm{mV}$ is a change of $100\,\mathrm{mV}$. (b) $t=0.50\,\mathrm{ms}=5.0\times10^{-4}\,\mathrm{s}$, $I=3.0\,\mu\mathrm{A}=3.0\times10^{-6}\,\mathrm{A}$:

$$Q=It=3.0\times10^{-6}\times5.0\times10^{-4}=1.5\times10^{-9}\,\mathrm{C}.$$

$$N=\frac{Q}{e}=\frac{1.5\times10^{-9}}{1.6\times10^{-19}}=9.4\times10^{9}\,\text{ions}.$$

Question 11 Model answer. **Leakage channels** are always open. They allow a small, steady drift of ions — mainly K^+ leaking out of the cell — and, together with the ion pumps, they establish and maintain the **resting potential** of about $-70\,\mathrm{mV}$ between events. They set the baseline. **Voltage-gated channels**, by contrast, open only when the membrane potential changes past a certain value. They are responsible for the action potential itself: the voltage-gated Na^+ channels open at threshold and drive **depolarisation**, and the voltage-gated K^+ channels open shortly after and drive **repolarisation**. Their slow closing produces the brief dip of **hyperpolarisation**, after which the leakage channels and pumps return the membrane to its resting state. In short: leakage channels hold the resting state; voltage-gated channels produce the event.

Question 12 Model answer. Each heartbeat begins when the **SA node** — the heart's natural pacemaker, in the wall of the right atrium — spontaneously produces a potential difference. The signal spreads across the muscle of both atria, and the atria contract, pushing blood into the ventricles. The signal reaches the **AV node**, the only electrical pathway between the atrial and ventricular muscle, which delays it by about $0.1\,\mathrm{s}$. The delay staggers the two contractions: it gives the atria time to finish emptying into the ventricles before the ventricles are stimulated. The signal then spreads through the ventricular muscle, the ventricles contract, and blood is pumped to the lungs and the body. After the beat, the refractory period holds the muscle unresponsive long enough for the heart to relax and refill before the SA node's next signal.

Question 13 Model answer. The claim is wrong on two counts. First, each beat only pumps the blood that filled the heart since the last beat. As the rate rises, the time available for filling between beats falls, so each beat pumps less blood; past some rate the heart is beating faster but moving less blood per minute, not more. Second, the heart's refractory period sets a hard ceiling — with a refractory period of about $0.25\,\mathrm{s}$, the muscle physically cannot contract more than about 240 times per minute, however strongly it is stimulated. And stimulation that ignores the heart's own electrical pattern does not speed it up usefully at all: if the muscle cells are triggered independently and chaotically, the result is **ventricular fibrillation** — uncoordinated twitching in which the heart pumps nothing. More stimulation is not more pumping; the heart works only when its electrical sequence stays orderly.

Question 14 Model answer. The heart's electrical activity is not contained inside the heart: the body's fluids are ion-rich solutions and therefore conductors. The potential differences produced by the heart's electrical events spread through these conducting fluids throughout the body, reaching the skin. Electrodes on the skin — for example on the wrists, ankles and chest — measure these small potential differences, of the order of millivolts, which rise and fall in a repeating pattern once per beat. The peaks of the pattern correspond to the atria depolarising, the ventricles depolarising, and the ventricles repolarising, which is why the ECG reveals both the rate and the rhythm of the heart from outside the body.

Question 15 (a)

$$I=\frac{V}{R}=\frac{230}{4000}=5.8\times10^{-2}\,\mathrm{A}=58\,\mathrm{mA}.$$

(b) $58\,\mathrm{mA}$ is above the $50\,\mathrm{mA}$ benchmark given for disrupting the heart's rhythm on a path across the chest, and far above the $10\,\mathrm{mA}$ benchmark for locking the muscles of a gripping hand. A current of this size is life-threatening.

(c) The danger of a current depends on which organs lie on its path. Hand to hand, the current crosses the chest, where it passes through the region of the heart and can disrupt the heart's electrical pattern. Between two points on the one hand, the same current would remain local — it would not reach the heart. The size of the current is not the whole story; the path decides which of the body's electrical systems it can interfere with.

Question 16 Model answer. The body's total resistance is dominated by the **skin**, especially its dry outer layer, and skin differs greatly: in thickness, in moisture, in sweat, and in whether it is cut, scraped or burned. So different people present different skin resistances, and the same person's resistance changes with conditions — a sweaty or wet hand has roughly a hundred times less skin resistance than a dry one. Beneath the skin, the current's path also matters, because the internal tissues differ among themselves: **nerves** and **muscle** are wet and ion-rich and conduct well (low resistance); **fat** contains little water and conducts poorly (higher resistance); and **bone**, dense and dry, has the highest resistance of the internal tissues. Since the current takes the path through whatever tissues lie between the contact points, two people touched by the same potential difference can carry quite different currents.

Question 17 Model answer. In the series model of the body, $R_{\text{body}} = R_{\text{skin, 1}} + R_{\text{internal}} + R_{\text{skin, 2}}$, and the two skin resistances are by far the largest terms — dry skin can be tens of thousands of ohms per contact, while the internal resistance is only a few hundred ohms. Water (especially water with dissolved substances in it) conducts, so wet skin collapses that dominant term to roughly a thousand ohms per contact. The supply's potential difference is the same $230\ \text{V}$ either way, and by $I = V / R$ the current is set by the total resistance: with dry skin the current is a few milliamps, but with wet skin the same supply drives tens of milliamps through the chest — into the range that can lock muscles and disrupt the heart's rhythm. The danger is greater because the body's main protective resistance — the skin — is the first thing water removes.

Question 18 (a)

$$P = \frac{E}{t} = \frac{150}{3.0 \times 10^{-3}} = 5.0 \times 10^{4}\ \text{W}.$$

(b) Using $P = V I$:

$$I = \frac{P}{V} = \frac{5.0 \times 10^{4}}{1500} = 33\ \text{A}.$$

(c) The heart's beat is set by its own electrical sequence: the SA node's signal, the AV node's delay, and the wave of contraction that follows. In ventricular fibrillation this pattern has collapsed into chaotic, independent firing, and the heart stops pumping effectively. The defibrillator passes a large current briefly through the chest, resetting all of the heart's muscle cells together; once the current stops, the SA node — which generates potential differences spontaneously — can re-establish the orderly rhythm. The shock is brief on purpose: the refractory period then holds the muscle still while the natural pacemaker takes over, whereas a sustained current would itself hold the heart in contraction and pump nothing.

Option task

Option 2.7 assessed task — Report of an application of physics concepts to a real-world context (30 marks; house convention).

This is the house **Option task** for Option 2.7. Each option subtopic closes with one such assessed piece, in one of the study design's own Unit 2 Outcome 2 task formats (*VCE Physics Study Design, Unit 2, Area of Study 2, suitable tasks for assessment*); this task's format is *"a report of an application of physics concepts to a real-world context"*. The marks are house convention: the study design fixes no mark allocations at Units 1 and 2, all assessment is school-based, and nothing here contributes to a study score. Where teachers allow students to choose between tasks they must ensure that the tasks they set are of comparable scope and demand (*VCE Physics Study Design*).

The task. Write a report, of roughly 700–1000 words, on **one** application of the physics of electricity in the human body. Choose one:

1. the electrocardiogram (ECG) as a diagnostic tool;
2. the external defibrillator (including the automated external defibrillators found in public places) as an emergency treatment;
3. the artificial pacemaker;
4. nerve conduction studies as used in medicine;

5. the design of electrical safety measures where electricity and water meet (for example, in bathrooms and pools).

Use the report conventions of 14G: correct terminology, units, significant figures and acknowledgement of references.

What the report must show. The task is marked against the shared Communicating physics dot points, taught in 10A and 10B:

1. **Evaluate the validity of the sources** you use (`U2.2.CP.1`). Use at least two sources and state, for each, what makes it valid or limited — who produced it, what evidence it gives, and whether it is the kind of source that can be checked (10A).
2. **Apply the physics concepts of this option** (`U2.2.CP.2`). Define the key terms your report uses — such as charge carrier, membrane potential, action potential, resistance, current — and use correct terminology, units and representations throughout.
3. **Use the models of this option to organise and explain** how the application works (`U2.2.CP.3`): for example, the body as a series-resistance circuit, the action potential as a short-lasting electrical event, or the heart as a signal source with a built-in delay. Discuss at least one **limitation** of a model you use — where the model simplifies, and what that simplification leaves out (10A).
4. **Discuss the relevant societal context** (`U2.2.CP.4`). Give at least one **sociocultural**, one **economic**, one **legal** and one **political** factor relevant to your application, and trace each factor's influence — what it makes more or less likely — rather than listing it (10B).
5. **Justify an evaluated stance** (`U2.2.CP.5`). Use your physics understanding to take and justify a position on your application — for example, whether it should be deployed more widely, how it should be improved, or how it compares with an alternative. Marks are awarded for the quality of the reasoning, not the conclusion reached (10B).

Marking rubric (30 marks). Five criteria, keyed to `U2.2.CP.1–.5`, at 6 marks each.

Criterion	6 marks	3 marks	0–1 marks
Validity of sources (`U2.2.CP.1`)	At least two sources evaluated in depth: origin, evidence and checkability each weighed, and the evaluation shapes what the report relies on.	Sources named and briefly assessed; the assessment is asserted rather than argued, or applies to only part of the sourcing.	Sources unnamed, or listed without any evaluation.
Application of physics concepts (`U2.2.CP.2`)	Key terms defined at first use; terminology, units, significant figures and representations correct and consistent throughout.	Most terms defined and used correctly; minor slips in units or representations that do not obscure the physics.	Key terms undefined or used incorrectly; the physics of the option is largely absent.
Use and limitation of models (`U2.2.CP.3`)	A model from this option is used to organise and explain how the application works, and at least one limitation of the model is identified and discussed.	A model is described and applied; a limitation is named but not discussed.	No model used, or a model stated without application.
Societal context (`U2.2.CP.4`)	At least one factor from each of the four categories, each traced to its influence on the issue.	Factors from some categories named, with influence traced for some but asserted for others.	Factors listed without influence traced, or fewer than two categories present.
Justified stance (`U2.2.CP.5`)	A clear stance supported by physics understanding; the strongest case on the other side is	A stance is stated with some physics support, but the other side or the limits are not engaged.	No stance, or an opinion given without physics support.

Criterion	6 marks	3 marks	0–1 marks
	acknowledged; at least one limitation of the evidence or reasoning is stated.		

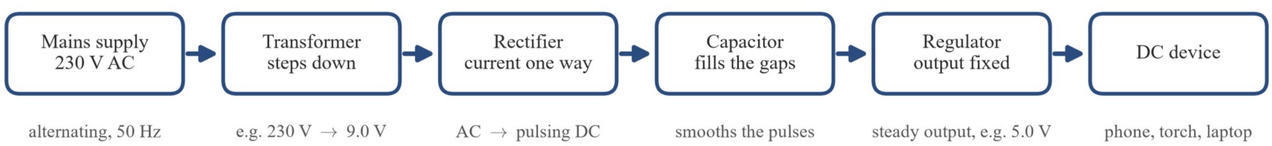
Reasoning quality, not the stance reached, is what earns marks: two students reaching opposite conclusions can both receive full marks if both reasoned from defined terms, evaluated sources and acknowledged limits.

Scope — *VCE Physics Study Design, Unit 2, Area of Study 2, Option 2.12: How can AC electricity charge a DC device?* (The physics of using AC electricity to charge a DC device): "analyse the role of the transformer in the power supply system including the analysis of voltage ratio: $\frac{N_1}{N_2}=\frac{V_1}{V_2}$ (not including induction or its internal workings)" (`U2.2.O12.1`) · "explain the use of diodes in half-wave and full-wave bridge rectification" (`U2.2.O12.2`) · "explain the effect of capacitors with reference to voltage drop and current change when charging and discharging (time constant for charging and discharging, τ = RC) leading to smoothing for DC power supplies" (`U2.2.O12.3`) · "describe the use of voltage regulators including Zener diodes and integrated circuits" (`U2.2.O12.4`) · "apply the use of heat and light sensors such as thermistors and light-dependent resistors (LDRs) to trigger an output device such as lighting or a motor" (`U2.2.O12.5`) · "compare different light sources (bulbs, LEDs, lasers) for their suitability for data transfer" (`U2.2.O12.6`).

Theory

What this subtopic is for. The power point in the wall supplies alternating current at $230\,\text{V}$; the device in your hand — a phone, a torch, a laptop — stores its energy in a battery that only accepts direct current. Somewhere between the two, the AC of the supply system must be turned into the DC the device needs. That conversion is the whole story of this subtopic. You will follow it stage by stage — transformer, rectifier, smoothing capacitor, regulator — and then apply two further ideas from the option: sensors that trigger an output device, and light sources used to carry data. The component physics of diodes, thermistors, LDRs and LEDs was built in 6C; the two-resistor voltage divider was built in 5F; this subtopic applies those ideas and does not re-teach them. The subtopic closes with the house **Option task**, a 30-mark assessed piece in one of the study design's own Outcome 2 formats. As always with electrical work in this book, practical work uses only low-voltage school power supplies (6C): the $230\,\text{V}$ mains is discussed and modelled here, never touched.

The problem: the socket gives AC, the device wants DC. In the Australian supply system the potential difference at a power point is alternating: it completes 50 full cycles of rising, falling and reversing every second ($50\,\text{Hz}$, 6B), and the current in any device connected to it reverses with it. A battery being charged needs the opposite — a current in one steady direction at a low, steady potential difference. Converting one into the other takes four stages, each of which fixes one mismatch between the supply and the device.

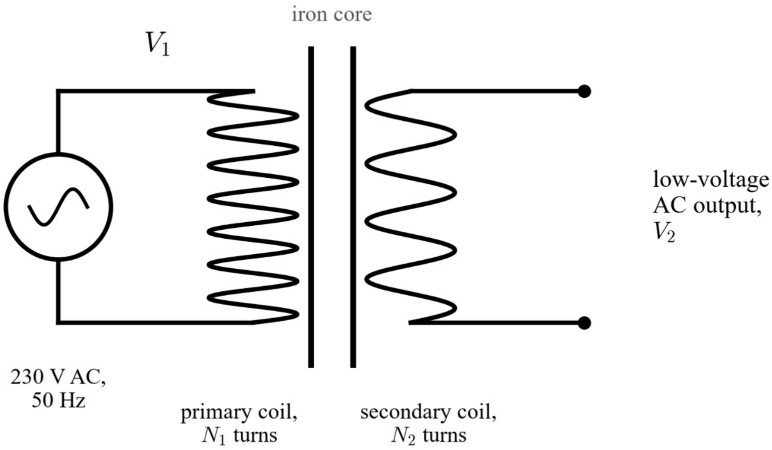


The **transformer** changes the potential difference from the $230\,\text{V}$ of the socket to the few volts a small device needs. The **rectifier** uses diodes to steer the alternating current so that it flows one way only through the device. The **smoothing capacitor** fills the gaps between the rectified pulses so the output stops collapsing to zero a hundred times a second. The **regulator** holds the output at one fixed value even when the supply or the load changes. Each stage is examined in turn.

Stage 1 — the transformer changes the voltage. A transformer is two coils of insulated wire wound around a shared iron core. The coil connected to the supply is the **primary** (N_1 turns, potential difference V_1); the coil connected to the device is the **secondary** (N_2 turns, potential difference V_2). Treated as a black box — the study design's own treatment, which excludes induction and the transformer's internal workings — the rule is that the potential differences are in the same ratio as the turns:

$$\frac{N_1}{N_2} = \frac{V_1}{V_2}.$$

More turns on the secondary than the primary gives a higher output potential difference — a **step-up** transformer; fewer turns gives a lower one — a **step-down** transformer. A transformer only works with a changing current: connected to a steady DC supply, the secondary gives nothing at all. This is why the supply system that relies on transformers is an AC system.



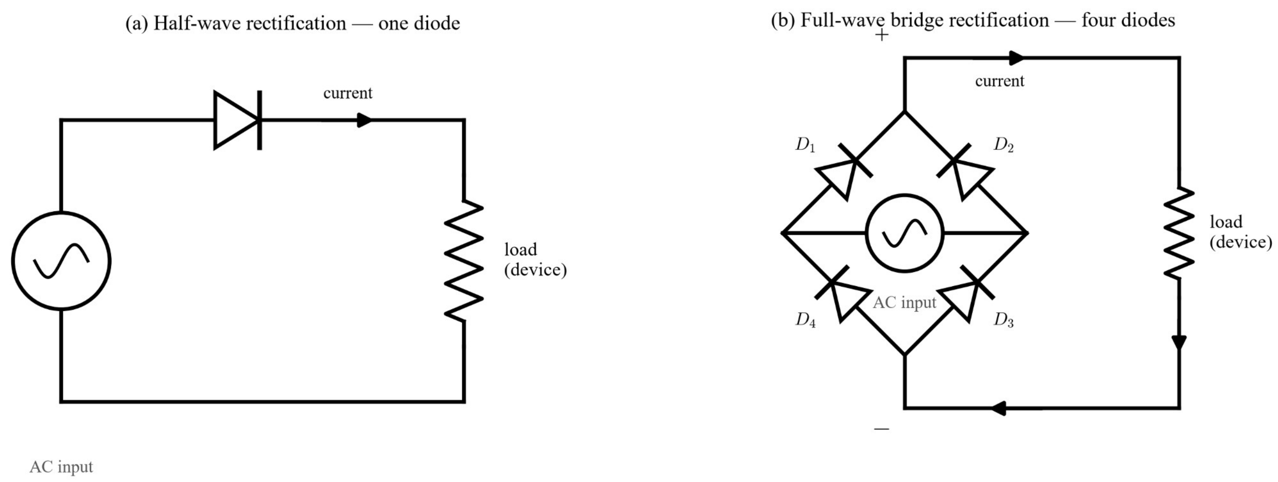
$$\frac{N_1}{N_2} = \frac{V_1}{V_2}$$

The role of the transformer in the power supply system. Energy leaves a power station at a potential difference that is stepped *up* — to values in the hundreds of kilovolts — for the long transmission lines, and stepped *down* again near the user, to $230\,\mathrm{V}$ at the socket, and down once more inside a charger to a few volts. The reason for stepping up is the heating loss in the lines. The power delivered by a supply is $P = V\,I$ (5C), so for a given power a higher potential difference means a smaller current. Substituting $V = I\,R$ (5D) into $P = V\,I$ gives the power dissipated as heat in a line of resistance R as $P_{\text{loss}} = I^2 R$. Ten times the potential difference means a tenth of the current and, since the loss depends on I^2, a hundredth of the heating loss for the same delivered power. High voltage is therefore how the supply system moves large power along thin, light wires without losing it as heat.

An ideal transformer wastes nothing: the power into the primary equals the power out of the secondary, $V_1 I_1 = V_2 I_2$. A transformer that steps the potential difference *down* steps the available current *up* in the same ratio — which is exactly what a charger needs: a small current at $230\,\mathrm{V}$ in, a large current at a few volts out.

Units 3 & 4 preview. The *reason* a changing current in the primary produces a potential difference across the secondary is electromagnetic induction — the core idea of Unit 3. The study design explicitly sets it aside here ("not including induction or its internal workings"), so this section treats the transformer as a black box with a turns rule. Nothing in this preview is assessed in this chapter.

Stage 2 — rectification: diodes steer the current one way. A diode conducts in one direction only: current passes when the diode is connected the conducting way with at least its threshold potential difference across it (about $0.6\,\mathrm{V}$ for silicon), and is blocked when the potential difference tries to push current the other way (6C). Placed in series with a load, a single diode therefore cuts the alternating waveform in half: current flows during the half-cycles the diode allows and is zero during the other half-cycles. This is **half-wave rectification** — simple, but throwing away half of the supply, and leaving long gaps between pulses.



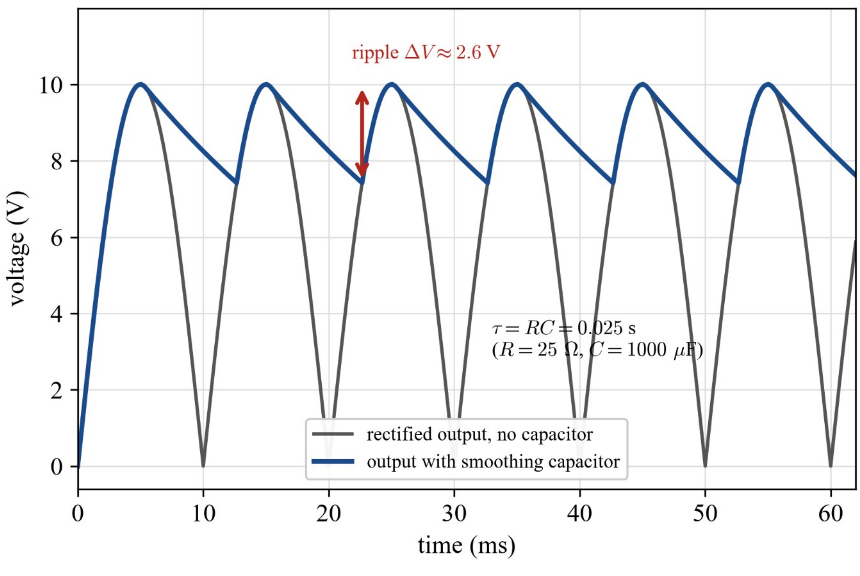
Full-wave bridge rectification wastes nothing. Four diodes are joined in a diamond (the *bridge*), the AC supply connected across one diagonal and the load across the other. When the left corner of the bridge is positive, diodes D_1 and D_3 conduct and current travels through the load from top to bottom; when the supply reverses and the right corner is positive, D_2 and D_4 conduct instead — and the current through the load *still* travels from top to bottom. Whichever half-cycle the supply is in, the bridge steers the current the same way through the load: the output is a run of pulses that never reverses direction, at 100 pulses per second on a $50\,\mathrm{Hz}$ supply because both half-cycles now deliver a pulse. The price is small: at any moment two diodes are in the conducting path, so the output peak is about $2 \times 0.6 = 1.2\,\mathrm{V}$ below the input peak.

Stage 3 — smoothing: the capacitor fills the gaps. The rectified output is direct in direction but far from steady: it is a run of pulses that falls to zero (half-wave) or nearly to zero (full-wave) between peaks. A **capacitor** connected across the load smooths this. A capacitor stores charge, and the potential difference across it grows as it charges. While the rectified potential difference is above the capacitor's, current flows *into* the capacitor and its potential difference rises with the pulse; between pulses the rectified output collapses, and the capacitor becomes the supply instead — current flows *out* of it through the load and its potential difference falls as it discharges. That is the "voltage drop and current change when charging and discharging" of the study design: charging, current in and voltage rising; discharging, current out and voltage falling.

The speed of both processes is set by the **time constant**

$$\tau = RC,$$

the product of the resistance in the capacitor's path and its capacitance. Charging through a resistance, the capacitor reaches about $63\,\%$ of the supply potential difference after one time constant; discharging, it falls to about $37\,\%$ of its starting potential difference after one time constant. A capacitor in farads with a resistance in ohms gives τ in seconds; practical smoothing capacitors are rated in microfarads ($1\,\mu\mathrm{F} = 10^{-6}\,\mathrm{F}$).



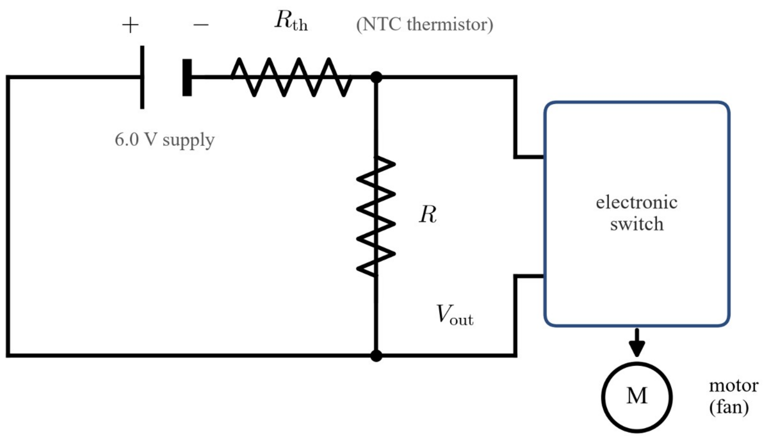
In the figure, a full-wave rectified 10 V peak output (grey) is smoothed by a capacitor with $\tau = RC = 0.025\,\text{s}$ (blue). The capacitor charges to each peak, then discharges through the load until the next pulse overtakes it, so the output never falls below about 7.4 V: the leftover variation, about 2.6 V here, is called the **ripple**. The larger the time constant — a bigger capacitor, or a lighter load — the more slowly the capacitor discharges between pulses and the smaller the ripple. Real supplies choose τ far longer than the 0.010 s between full-wave pulses, so the output is nearly flat DC with only a small ripple riding on it.

Stage 4 — regulation: holding the voltage fixed. Smoothing leaves a small ripple, and the unsmoothed height of the output still follows the mains: a sag at the socket becomes a sag at the capacitor, and drawing more load current deepens the ripple. Most DC devices want none of this — a fixed potential difference such as 5.0 V, steady under all ordinary conditions. A **voltage regulator** is the stage that guarantees it.

One regulator is the **Zener diode**. A Zener is a diode used the reverse way: connected backwards (reverse-biased) it blocks, until the potential difference across it reaches its Zener voltage, at which point it conducts in reverse and holds that potential difference almost exactly constant while the current through it varies. Placed across the output, in series with a resistor that soaks up the surplus potential difference from the supply, the Zener pins the output at its Zener voltage: if the input sags or the load changes, it is the current through the Zener — not the output voltage — that changes. A second kind is the **integrated-circuit regulator**, a three-terminal chip (input, output, common) that behaves as a black box holding its output at a fixed marked value despite ripple on the input and changes in the load, and typically shutting itself down if overloaded. The study design asks you to *describe the use* of both — a Zener for simple, small loads; an integrated circuit where the output must stay exact under a varying load — not to analyse their internal workings.

Sensors that trigger an output device. A thermistor and an LDR are transducers: components whose resistance depends on a physical condition. For the NTC thermistor, heating it makes the resistance fall — from about 10 kΩ at room temperature to hundreds of ohms in boiling water; for the LDR, bright light makes the resistance fall — from about 1 MΩ in the dark to hundreds of ohms in bright light. Both facts, and the idea of a transducer, are 6C's; this option *applies* them, placing the sensor in a circuit so that a change of temperature or light level **triggers an output device** such as lighting or a motor.

The circuit is the two-resistor voltage divider of 5F, with the sensor as one resistor. The supply potential difference divides between the two resistors in proportion to their resistances, so as the sensor's resistance changes, the share across the other resistor changes with it. That share, V_{out}, is fed to an **electronic switch** — a circuit that compares V_{out} with a fixed threshold and closes when the threshold is passed, connecting the output device to the supply.



In the figure the thermistor is the upper resistor and the output is taken across the fixed resistor. When the thermistor is cool its resistance is large, it takes most of the supply, and V_{out} sits below the threshold: the motor is off. As the temperature rises the thermistor's resistance falls, the fixed resistor's share grows, and once V_{out} crosses the threshold the switch closes and the motor runs — a cooling fan that starts by itself when the room gets hot. The same arrangement with an LDR in place of the thermistor switches lighting at dusk; whether V_{out} rises or falls as the condition changes depends on which leg of the divider the sensor sits in (Question 16).

Comparing light sources for data transfer. Light can carry data: switch the source on and off in a pattern and a detector reads the pattern as a signal — the same idea as the pulses of this option, carried by light instead of by wires. Not every light source is equal at it.

	Bulb	LED	Laser
How it can be switched	Slowly — the filament takes time to heat and cool	Very fast — can pulse millions of times per second	Very fast — can pulse millions of times per second
Direction of the light	Spreads in all directions	Fairly directed; couples into a fibre	A narrow, tightly directed beam that couples efficiently into a fibre
Colour	Broad mix of wavelengths	A narrow band of wavelengths	Effectively one wavelength
Suitability for data transfer	Poor — too slow, too much light wasted	Good for short links — a television remote, and short fibre runs to premises (1E)	Best for long links — the fibre backbone that carries the internet (1E)

A bulb's filament is a hot wire: it cannot be switched on and off quickly, and its light leaves in every direction, so almost none of it can be aimed into an optical fibre. An LED (whose action as a transducer is 6C's and 6D's) switches almost instantly and wastes far less light, which is why short data links — a remote control, a short fibre to a home — pulse LEDs. A laser adds a narrow, single-wavelength beam that can be aimed straight down a fibre core with almost no loss, which is why the long-distance fibre links that carry Australia's internet traffic (1E) pulse lasers. For data transfer, the faster and more directional the source, the more data per second it can carry and the farther the signal travels.

Worked examples

Example 1 — scaffolded

A plug pack contains a transformer whose primary has 2300 turns and is connected to the 230 V, 50 Hz mains. The pack is to supply 9.0 V across its output. (a) Calculate the number of turns on the secondary coil. (b) While a device draws 1.5 A from the secondary, calculate the current in the primary, assuming an ideal transformer.

Working	Comment
$N_1 = 2300$, $V_1 = 230\text{ V}$, $V_2 = 9.0\text{ V}$; the voltage ratio is $\frac{N_1}{N_2} = \frac{V_1}{V_2}$.	The study design's transformer rule.
(a) $N_2 = N_1 \times \frac{V_2}{V_1} = 2300 \times \frac{9.0}{230} = 90$ turns	Fewer turns on the secondary than the primary — a step-down transformer, as a charger needs.
(b) Ideal transformer: $V_1 I_1 = V_2 I_2$.	Energy conservation — power in equals power out.
$I_1 = \frac{V_2 I_2}{V_1} = \frac{9.0 \times 1.5}{230} = 0.0587\text{ A}$	
$I_1 \approx 0.059\text{ A} = 59\text{ mA}$ (2 significant figures)	The potential difference was stepped down by about 26, so the current is stepped up by about 26.
Check: $\frac{N_1}{N_2} = \frac{2300}{90} = 25.6$ and $\frac{V_1}{V_2} = \frac{230}{9.0} = 25.6$. ✓	The two ratios agree, as the rule requires.

Example 2 — scaffolded

A smoothing capacitor of $1000\,\mu\text{F}$ is connected across a load of resistance $1.0\text{ k}\Omega$. (a) Calculate the time constant for the capacitor discharging through the load. (b) The capacitor is charged to 12 V and then left to discharge through the load. Calculate its potential difference after one time constant and after two. (c) In a real full-wave supply the capacitor is topped up 100 times per second. Explain why the real output therefore shows only a small ripple, not the large fall calculated in (b).

Working	Comment
$C = 1000\,\mu\text{F} = 1.0 \times 10^{-3}\,\text{F}$; $R = 1.0\,\text{k}\,\Omega = 1.0 \times 10^{3}\,\Omega$.	Convert to base units first.
(a) $\tau = RC = 1.0 \times 10^{3} \times 1.0 \times 10^{-3} = 1.0\,\text{s}$	
(b) After $1\,\tau$: $V \approx 0.37 \times 12 = 4.4\,\text{V}$.	Discharging falls to about $37\,\%$ of the starting value per time constant.
After $2\,\tau$: $V \approx 0.37 \times 4.4 = 1.6\,\text{V}$.	Each further time constant multiplies by the same factor again.
(c) Full-wave pulses arrive every $\frac{1}{100}\,\text{s} = 0.010\,\text{s}$ — one hundredth of τ.	The capacitor is recharged long before it has discharged appreciably.
In $0.010\,\text{s}$ the capacitor loses only a few per cent of its voltage, so the output dips slightly and is topped up again: a small ripple, not a collapse to $4.4\,\text{V}$.	This is exactly the smoothing shown in the figure above: make τ far longer than the gap between pulses and the output is nearly flat.

Example 3 — unscaffolded

A trigger circuit uses the arrangement of the sensor figure: a $6.0\,\text{V}$ supply, an NTC thermistor as the upper resistor and a fixed $2.0\,\text{k}\,\Omega$ resistor below it, with the output taken across the fixed resistor to an electronic switch that closes (starting a fan motor) whenever $V_{\text{out}} \geq 2.0\,\text{V}$. The thermistor's resistance is $10\,\text{k}\,\Omega$ at $25\,°\text{C}$ and $1.0\,\text{k}\,\Omega$ at $80\,°\text{C}$. Calculate V_{out} at each temperature and hence show that the fan is off at $25\,°\text{C}$ and on at $80\,°\text{C}$. Explain, in terms of the thermistor, why the output rises as the temperature rises.

The two resistors form a voltage divider (5F), so the potential difference across the fixed resistor is the supply multiplied by its share of the total resistance. At $25\,°\text{C}$:

$$V_{\text{out}} = 6.0 \times \frac{2.0}{10 + 2.0} = 6.0 \times \frac{2.0}{12} = 1.0\,\text{V},$$

below the $2.0\,\text{V}$ threshold, so the switch is open and the fan is off. At $80\,°\text{C}$:

$$V_{\text{out}} = 6.0 \times \frac{2.0}{1.0 + 2.0} = 6.0 \times \frac{2.0}{3.0} = 4.0\,\text{V},$$

above the threshold, so the switch closes and the fan runs. The reason is the NTC behaviour of the thermistor (6C): as the temperature rises its resistance falls, so it takes a smaller share of the supply and the fixed resistor takes a larger one. The divider turns the thermistor's falling resistance into a rising V_{out}, and the electronic switch turns that rising voltage into an on/off decision — a sensor triggering an output device.

$\therefore V_{\text{out}} = 1.0\,\text{V}$ at $25\,°\text{C}$ (fan off) and $4.0\,\text{V}$ at $80\,°\text{C}$ (fan on): the falling thermistor resistance hands an increasing share of the supply to the fixed resistor until the threshold is crossed.

Example 4 — unscaffolded

A student builds a phone charger from a transformer (stepping $230\,\text{V}$ down to a low AC voltage) and a full-wave bridge rectifier, but leaves out both the smoothing capacitor and the regulator. The phone charges unreliably. Describe what the rectifier's output looks like without the capacitor, and explain — with reference to voltage drop and current change when the capacitor charges and discharges — what the missing capacitor and regulator would each have contributed.

Without the capacitor, the bridge's output is a run of 100 pulses per second (on the $50\,\text{Hz}$ mains), each pulse falling almost to zero before the next. The potential difference across the phone is therefore collapsing a hundred times a second, and the charging current collapses with it — the phone receives current in bursts with gaps between, which is why charging is unreliable.

The capacitor would have filled those gaps. While each pulse rises above the capacitor's potential difference, current flows into the capacitor and its voltage rises with the pulse (charging); between pulses, the rectified output collapses and the capacitor becomes the supply, current flowing out of it through the phone while its voltage falls (discharging). With a time constant $\tau = RC$ far longer than the $0.010\,\mathrm{s}$ between pulses, the capacitor discharges only a little before the next pulse tops it up, so the output becomes nearly steady DC with a small ripple instead of a run of pulses collapsing to zero.

The regulator would have done the final job. Even smoothed, the output still follows the mains — a sag at the socket sags the output — and drawing more current deepens the ripple. A regulator holds the output at the fixed value the phone expects (say $5.0\,\mathrm{V}$) despite both: a Zener diode pinning the output at its Zener voltage with a series resistor soaking up the surplus, or an integrated-circuit regulator holding a fixed marked output under a varying load.

∴ the rectifier alone gives pulsing DC that collapses between pulses; the capacitor smooths the pulses by charging into the peaks and discharging through the gaps ($\tau = RC$ setting how little it falls); the regulator then fixes the smoothed output at one steady value — and without the last two stages the phone sees a pulsing, wandering supply instead of the steady $5\,\mathrm{V}$ DC it needs.

Practice questions

Question 1 A transformer has 500 turns on its primary coil and 2500 turns on its secondary. The primary is connected to the $230\,\mathrm{V}$ mains. (a) State whether this is a step-up or a step-down transformer, with the reason. (b) Calculate the potential difference across the secondary. (c) Name the place in the power supply system where a transformer of this kind is used, and what it achieves there.

Question 2 A model suburban substation uses a transformer to step a distribution voltage of $11.5\,\mathrm{kV}$ down to the $230\,\mathrm{V}$ of the socket. The secondary coil has 300 turns. (a) Calculate the turns ratio N_1 / N_2 from the potential differences. (b) Calculate the number of turns on the primary coil. (c) If the secondary supplies a total current of $65\,\mathrm{A}$ to the street, calculate the primary current, assuming an ideal transformer.

Question 3 Compare half-wave rectification with full-wave bridge rectification. (a) State how many output pulses per second each gives on the $50\,\mathrm{Hz}$ mains. (b) State how many diodes are in the conducting path at any moment in each, and hence the potential difference lost across diodes in each (silicon, about $0.6\,\mathrm{V}$ per diode). (c) Explain why a supply that must make the most of the available energy uses the bridge.

Question 4 A capacitor of $500\,\mu\mathrm{F}$ is connected in series with a resistor of $2.2\,\mathrm{k}\,\Omega$ and a supply. (a) Calculate the time constant of this combination. (b) The capacitor charges from zero toward a supply of $10\,\mathrm{V}$. State its potential difference after one time constant. (c) The charged capacitor is then disconnected and discharged through the resistor. State its potential difference after one time constant of discharging.

Question 5 A simple regulator is built from a Zener diode of Zener voltage $5.1\,\mathrm{V}$ in series with a $390\,\Omega$ resistor, fed from an unregulated $9.0\,\mathrm{V}$ smoothed supply. The output is taken across the Zener. (a) Calculate the potential difference across the series resistor. (b) Calculate the current through the resistor. (c) Calculate the power dissipated in the resistor. (d) Describe how the Zener holds the output at $5.1\,\mathrm{V}$ when the input or the load changes slightly.

Question 6 A dusk-switched lamp uses a divider with an LDR as the lower resistor and a fixed $5.0\,\mathrm{k}\,\Omega$ resistor above it, across a $6.0\,\mathrm{V}$ supply. The switch closes (lamp on) when the potential difference across the LDR exceeds $3.0\,\mathrm{V}$. The LDR's resistance is $500\,\Omega$ in bright daylight and $1.0\,\mathrm{M}\,\Omega$ at night. (a) Calculate the potential difference across the LDR in daylight, and state whether the lamp is on. (b) Calculate it at night (to 2 significant figures), and state whether the lamp is on.

Question 7 A plug pack's transformer has 4600 primary turns and 240 secondary turns, with the primary on the $230\,\mathrm{V}$ mains. While a device is connected, the secondary current is $2.0\,\mathrm{A}$. Assuming an ideal transformer, calculate the secondary potential difference, the primary current and the power delivered to the device.

Question 8 A student proposes powering a charger from a large $12\,\mathrm{V}$ DC battery instead of the mains, connecting the battery straight to the charger's transformer. Explain what the transformer's secondary would give while the battery is connected steadily, and why. Hence explain why a supply system built on transformers distributes AC, and where in such a system the AC-to-DC conversion the title of this option describes must therefore happen.

Question 9 Describe the role of the transformer in the power supply system, from power station to power point to plug pack. Your answer must explain, using $P = V\,I$ and $P_{\text{loss}} = I^2 R$, why transmission uses very high potential differences, and state what the ideal-transformer rule $V_1 I_1 = V_2 I_2$ says about the current on the two sides of a step-up transformer.

Question 10 A model generator delivers $120\,\text{kW}$ into transmission lines of total resistance $4.0\,\Omega$. (a) The generator's output is stepped to $2.0\,\text{kV}$ for transmission. Calculate the line current and the power lost as heat in the lines. (b) The output is instead stepped up to $20\,\text{kV}$. Calculate the line current and the power lost. (c) Comment on the two results, expressing each loss as a percentage of the $120\,\text{kW}$.

Question 11 Using the bridge of the rectifier figure, trace the conducting path when the left corner is positive and when it is negative, naming the two diodes that conduct in each case. Explain why the current through the load has the same direction in both half-cycles, state the pulse rate of the output on the $50\,\text{Hz}$ mains, and state the potential difference lost across the conducting diodes.

Question 12 A smoothed supply uses a $1000\,\mu\text{F}$ capacitor across a load of $220\,\Omega$; the rectified peak is $12\,\text{V}$. (a) Calculate the time constant for the capacitor discharging through the load. (b) If the capacitor were left to discharge for one full time constant from $12\,\text{V}$, state the potential difference it would reach. (c) In the real supply the capacitor is topped up every $0.010\,\text{s}$. Compare this with τ and explain what that comparison says about the size of the ripple.

Question 13 Explain why a DC supply includes a regulator *after* the smoothing capacitor, naming two things the smoothed output still gets wrong that the regulator fixes. Describe the use of a Zener diode and of an integrated-circuit regulator as voltage regulators, and state one advantage of the integrated circuit.

Question 14 A regulator stage is fed from an unregulated $12\,\text{V}$ smoothed supply and uses a Zener diode of Zener voltage $5.1\,\text{V}$ with a series resistor of $470\,\Omega$. (a) Calculate the potential difference across the series resistor. (b) Calculate the current through it. (c) Calculate the power dissipated in it.

Question 15 A cooling-fan trigger uses a $9.0\,\text{V}$ supply with the thermistor as the upper resistor and a fixed $3.0\,\text{k}\,\Omega$ resistor below, the output taken across the fixed resistor. The switch closes (fan on) when $V_{\text{out}} \geq 4.0\,\text{V}$. The thermistor's resistance is $9.0\,\text{k}\,\Omega$ at $20\,°\text{C}$ and $1.0\,\text{k}\,\Omega$ at $100\,°\text{C}$. Calculate V_{out} at both temperatures, state whether the fan runs at each, and explain the trend using the thermistor's NTC behaviour.

Question 16 A lighting controller's electronic switch closes (lamp on) when the potential difference across the *lower* resistor of its divider exceeds $3.0\,\text{V}$. The lamp must come on at dusk. Decide which leg of the divider — upper or lower — the LDR must sit in, and justify your choice by comparing the LDR's resistance and its share of the $6.0\,\text{V}$ supply in daylight and at night.

Question 17 Compare a bulb, an LED and a laser as light sources for data transfer. Address how fast each can be switched, how directional its light is, and its spread of wavelengths, and hence say which source suits (i) a television remote, (ii) a long fibre-optic backbone link, giving a reason in each case.

Question 18 A phone charger takes the $230\,\text{V}$, $50\,\text{Hz}$ mains and delivers a steady $5.0\,\text{V}$ DC. Trace the four stages — transformer, rectifier, smoothing capacitor, regulator — stating for each what mismatch between the supply and the device it fixes and what the charger's output would look like if that one stage were left out.

Answers

Question 1 (a) step-up — $N_2 > N_1$; (b) $1150\ \text{V} \approx 1.2\ \text{kV}$; (c) at the transmission end of the supply system, stepping the voltage up (and the current down) to cut heating loss in the lines. **Question 2** (a) 50; (b) 1.5×10^4 turns; (c) $1.3\ \text{A}$. **Question 3** (a) half-wave 50 per second; bridge 100 per second; (b) half-wave 1 diode, about $0.6\ \text{V}$ lost; bridge 2 diodes, about $1.2\ \text{V}$ lost; (c) see solution. **Question 4** (a) $1.1\ \text{s}$; (b) about $6.3\ \text{V}$; (c) about $3.7\ \text{V}$. **Question 5** (a) $3.9\ \text{V}$; (b) $0.010\ \text{A}$ ($10\ \text{mA}$); (c) $0.039\ \text{W}$; (d) see solution. **Question 6** (a) $0.55\ \text{V}$ — lamp off; (b) $6.0\ \text{V}$ — lamp on. **Question 7** $V_2 = 12\ \text{V}$; $I_1 \approx 0.10\ \text{A}$; $P = 24\ \text{W}$. **Question 8** see solution — a steady DC gives the secondary nothing; the conversion must happen at the device end. **Question 9** see solution. **Question 10** (a) $60\ \text{A}$, $14.4\ \text{kW}$; (b) $6.0\ \text{A}$, $144\ \text{W}$; (c) $12\,\%$ of the power lost at $2.0\ \text{kV}$ versus $0.12\,\%$ at $20\ \text{kV}$ — a hundredfold reduction. **Question 11** see solution — D_1 and D_3, then D_2 and D_4; 100 pulses per second; about $1.2\ \text{V}$ lost. **Question 12** (a) $0.22\ \text{s}$; (b) about $4.4\ \text{V}$; (c) $0.010\ \text{s}$ is about a twenty-second of τ, so the capacitor hardly discharges between top-ups — a small ripple. **Question 13** see solution. **Question 14** (a) $6.9\ \text{V}$; (b) $0.015\ \text{A}$; (c) $0.10\ \text{W}$. **Question 15** $2.25\ \text{V}$ at $20\ °\text{C}$ (fan off); $6.75\ \text{V}$ at $100\ °\text{C}$ (fan on); see solution. **Question 16** the lower leg; see solution. **Question 17** see solution. **Question 18** see solution.

Fully-worked solutions

Question 1 (a) $N_2 = 2500 > N_1 = 500$: more turns on the secondary, so a step-up transformer. (b) From $\frac{N_1}{N_2} = \frac{V_1}{V_2}$, $V_2 = V_1 \times \frac{N_2}{N_1} = 230 \times \frac{2500}{500} = 1150\ \text{V}$, about $1.2\ \text{kV}$ to 2 significant figures. (c) A step-up transformer of this kind is used at the transmission end of the supply system: raising the potential difference lowers the current for the same power ($P = V\,I$), and the heating loss $I^2 R$ in the lines falls with the square of the current.

Question 2 (a) $\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{11500}{230} = 50$. (b) $N_1 = 50 \times N_2 = 50 \times 300 = 1.5 \times 10^4$ turns. (c) Ideal transformer: $I_1 = \frac{V_2 I_2}{V_1} = \frac{230 \times 65}{11500} = 1.3\ \text{A}$. The primary carries a fiftieth of the secondary current, exactly the inverse of the voltage ratio.

Question 3 (a) Half-wave passes one half-cycle in every cycle: 50 pulses per second. The bridge delivers a pulse on *both* half-cycles: 100 per second. (b) Half-wave has one diode in the path, losing about $0.6\ \text{V}$; the bridge always has two conducting diodes in the path, losing about $1.2\ \text{V}$. (c) The bridge uses both half-cycles of the supply instead of throwing one away, so its pulses arrive twice as often (halving the gaps the capacitor must fill) and it extracts energy from the whole waveform. The cost — an extra diode drop of about $0.6\ \text{V}$ — is small compared with the doubling of usable output, which is why real supplies use the bridge.

Question 4 (a) $\tau = R\,C = 2.2 \times 10^3 \times 500 \times 10^{-6} = 1.1\ \text{s}$. (b) Charging reaches about $63\,\%$ of the supply in one time constant: $0.63 \times 10 \approx 6.3\ \text{V}$. (c) Discharging falls to about $37\,\%$ of the starting value in one time constant: $0.37 \times 10 \approx 3.7\ \text{V}$.

Question 5 (a) The resistor takes the surplus: $9.0 - 5.1 = 3.9\ \text{V}$. (b) $I = \frac{V}{R} = \frac{3.9}{390} = 0.010\ \text{A} = 10\ \text{mA}$. (c) $P = V\,I = 3.9 \times 0.010 = 0.039\ \text{W}$. (d) The Zener is reverse-biased and conducts in reverse so as to hold about $5.1\ \text{V}$ across itself. If the input sags or the load draws more, the extra or missing current goes through the Zener rather than into changing the output: the resistor soaks up the surplus potential difference and the output, taken across the Zener, stays at $5.1\ \text{V}$.

Question 6 (a) Daylight: $V_{LDR} = 6.0 \times \frac{0.50}{5.0+0.50} = 6.0 \times \frac{0.50}{5.5} = 0.55\,V$ — below $3.0\,V$, lamp off. (b) Night: $V_{LDR} = 6.0 \times \frac{1000}{5.0+1000} = 6.0 \times \frac{1000}{1005} = 5.97 \approx 6.0\,V$ — above $3.0\,V$, lamp on. In the dark the LDR's huge resistance takes almost the whole supply, crossing the threshold and switching the lamp on at dusk.

Question 7 $V_2 = V_1 \times \frac{N_2}{N_1} = 230 \times \frac{240}{4600} = 12\,V$. Power to the device: $P = V_2 I_2 = 12 \times 2.0 = 24\,W$. Ideal transformer: $I_1 = \frac{P}{V_1} = \frac{24}{230} = 0.104 \approx 0.10\,A$. ∴ the pack delivers $12\,V$ and $24\,W$ while drawing about $0.10\,A$ from the mains.

Question 8 While the battery is connected steadily, the primary current is constant, so the secondary gives nothing at all — a transformer's output depends on a *changing* current, and a steady DC is unchanging. (The mechanism is electromagnetic induction, a Unit 3 idea the study design sets aside for this option; the observed black-box behaviour is simply that transformers do nothing on steady DC.) A supply system built on transformers must therefore distribute AC — only a changing current can be stepped up and down along the way. The AC-to-DC conversion of this option must then happen at the device end of the chain, inside the charger or power supply, after the final step-down transformer.

Question 9 The transformer appears three times. At the power station a step-up transformer raises the potential difference to transmission values; near the user, step-down transformers bring it to $230\,V$ at the socket; inside a charger, a further step-down gives a few volts. The reason for the high-voltage stage is the line loss: for delivered power P, $P = V\,I$ means the current is $I = P/V$, so raising V lowers I; the heat dissipated in a line of resistance R is $P_{loss} = I^2 R$ (from $P = V\,I$ with $V = I\,R$), so a tenth of the current gives a hundredth of the loss for the same power — high voltage is what lets large power travel long distances along practical wires. The ideal-transformer rule $V_1 I_1 = V_2 I_2$ (energy conservation) says that a step-up transformer raises the potential difference in the same ratio that it lowers the available current: the transmission side carries a small current at a large potential difference, and the socket side a large current at a small one.

Question 10 (a) $I = \frac{P}{V} = \frac{120 \times 10^3}{2.0 \times 10^3} = 60\,A$; $P_{loss} = I^2 R = 60^2 \times 4.0 = 1.44 \times 10^4\,W = 14.4\,kW$. (b) $I = \frac{120 \times 10^3}{20 \times 10^3} = 6.0\,A$; $P_{loss} = 6.0^2 \times 4.0 = 144\,W$. (c) As percentages of $120\,kW$: $\frac{14.4}{120} = 12\,\%$ lost at $2.0\,kV$ but $\frac{0.144}{120} = 0.12\,\%$ at $20\,kV$. Ten times the potential difference gives a tenth of the current and a hundredth of the heating loss — the entire argument for stepping up before transmission.

Question 11 When the left corner is positive, current leaves it through D_1 to the top corner, through the load from top to bottom, back through D_3 to the right corner and to the supply: D_1 and D_3 conduct. When the supply reverses, the right corner is positive and current goes through D_2 to the top corner, through the load top to bottom *again*, and back through D_4: D_2 and D_4 conduct. In both half-cycles the load is fed from the top corner and drained at the bottom corner, so the load current never reverses — that is the rectification. Each half-cycle gives one pulse, so the output runs at 100 pulses per second on the $50\,Hz$ mains, and with two conducting diodes always in the path the output peak sits about $2 \times 0.6 = 1.2\,V$ below the input peak.

Question 12 (a) $\tau = RC = 220 \times 1000 \times 10^{-6} = 0.22\,s$. (b) After one time constant of discharging the capacitor holds about $37\,\%$: $0.37 \times 12 \approx 4.4\,V$. (c) The gap between top-ups, $0.010\,s$, is about $\frac{0.010}{0.22} \approx \frac{1}{22}$ of τ — the capacitor is recharged after discharging for only a small fraction of a time constant, so it loses only a few per cent of its voltage between pulses: a small ripple on a nearly flat $12\,V$ output, not the fall to $4.4\,V$ a whole τ would give.

Question 13 The smoothed output is nearly flat but not fixed: it still carries a small ripple, and its height follows the mains (a sag at the socket sags it) and falls when the load draws more current. The regulator fixes both, holding the output at one exact value — say $5.0\,V$ — regardless. A Zener diode regulator reverse-biases the Zener across the output with a series resistor to the supply: the Zener conducts in reverse so as to hold its Zener voltage across the output, the resistor soaking up the surplus, and variations in input or load change the Zener current rather than the output voltage. An integrated-circuit regulator is a three-terminal chip that holds a fixed marked output under ripple and varying load, typically with overload protection built in; that accuracy and robustness under a varying load is its advantage over the simple Zener.

Question 14 (a) $12-5.1=6.9\,\text{V}$. (b) $I=\frac{6.9}{470}=0.0147\approx0.015\,\text{A}\ (15\,\text{mA})$. (c) $P=V\,I=6.9\times0.0147=0.101\approx0.10\,\text{W}$.

Question 15 At $20\,°\text{C}$: $V_{\text{out}}=9.0\times\frac{3.0}{9.0+3.0}=9.0\times\frac{3.0}{12}=2.25\,\text{V}$ — below $4.0\,\text{V}$, fan off. At $100\,°\text{C}$: $V_{\text{out}}=9.0\times\frac{3.0}{1.0+3.0}=9.0\times\frac{3.0}{4.0}=6.75\approx6.8\,\text{V}$ — above $4.0\,\text{V}$, fan on. The trend is the NTC behaviour (6C): heating the thermistor makes its resistance fall, so it takes a smaller share of the supply and the fixed resistor's share — V_{out} — rises until it crosses the switch threshold.

Question 16 The LDR must sit in the **lower** leg. At night the LDR's resistance is huge (about $1\,\text{M}\Omega$ against the fixed $5.0\,\text{k}\Omega$ above it), so as the lower leg it takes almost the whole $6.0\,\text{V}$ supply — about $6.0\,\text{V}$, above the $3.0\,\text{V}$ threshold, and the switch closes the lamp on. In daylight its resistance is small (about $500\,\Omega$), its share is about $0.55\,\text{V}$, below the threshold, and the lamp stays off. Placed in the upper leg instead, the dark-time behaviour inverts: at night the large LDR resistance would sit above, leaving the fixed lower resistor with only a small share (about $0.03\,\text{V}\ldots$ precisely $6.0\times\frac{5.0}{1005}\approx0.030\,\text{V}$), and the lamp would light in daylight and go out at dusk — the opposite of what is required.

Question 17 A bulb is slow to switch — its filament takes time to heat and cool — spreads its light in all directions and emits a broad mix of wavelengths, so it cannot pulse fast and almost none of its light can be aimed into a fibre: unsuited to data. An LED switches millions of times per second, emits a narrow band of wavelengths and is directional enough to couple into a fibre: well suited to short links. A laser also switches very fast and adds a narrow, single-wavelength beam that couples efficiently into a fibre core: best for long links. Hence (i) a television remote uses an LED — a fast, cheap source for a short, undemanding link; (ii) a long fibre backbone uses a laser — its fast, directional, single-wavelength beam carries more data per second over long distances with little loss (1E).

Question 18 **Transformer:** the mismatch is the size of the potential difference — $230\,\text{V}$ against the few volts a device needs. It steps the voltage down (and, ideally, steps the available current up). Without it, the rectifier would receive $230\,\text{V}$ and the output would be far above anything the device can take. **Rectifier:** the mismatch is direction — the supply reverses direction twice in each cycle, 100 times a second at $50\,\text{Hz}$, while a battery charges on one-way current. The bridge steers both half-cycles the same way through the load. Without it, the device would receive alternating current and not charge at all. **Smoothing capacitor:** the mismatch is steadiness — the rectified output is 100 pulses per second collapsing between peaks. The capacitor charges into the peaks and discharges through the gaps ($\tau=R\,C$), filling them. Without it, the device would receive pulsing DC that drops to nearly zero a hundred times a second. **Regulator:** the mismatch is constancy — the smoothed output still carries ripple and follows the mains and the load. The regulator pins the output at the fixed value (here $5.0\,\text{V}$). Without it, the device would see a wandering, rippling supply rather than the steady DC its charging circuit expects. With all four stages in place, $230\,\text{V}$ AC in becomes steady $5.0\,\text{V}$ DC out — AC electricity charging a DC device.

Option task — Should Australia set a minimum-efficiency standard for plug packs? (30 marks)

Task format. "A physics-referenced response to an issue" — one of the task formats listed for Unit 2 Outcome 2 in the *VCE Physics Study Design*. You may present your response as a written report or as a scientific poster; the conventions of reports and posters (terminology, units, significant figures, acknowledgement of references) are 14G's.

The issue. Every plug pack wastes some of the energy it draws as heat — in its transformer's coils, in its rectifier diodes, in its regulator — and even a pack with a full or disconnected device draws a little. Should Australia introduce a mandatory minimum-efficiency standard for plug packs and chargers sold here?

The task. Write a physics-referenced response to the issue. Your response must include all of the following.

1. **The physics of where the waste arises.** Describe a charger with the four-stage model of this option — transformer, rectifier, smoothing capacitor, regulator — and identify where in that chain electrical energy is transformed into heat (`U2.2.O12.1–.4`).
2. **A quantitative comparison.** Use efficiency = useful energy out ÷ energy in (9D) to compare two plug packs delivering the same power to the same device, and express the energy wasted by each over a stated period of typical use in kW h (5C). Base at least one input of this calculation on a value you have sourced and evaluated under point 5 (`U2.2.CP.1`).
3. **A representation.** Include a labelled stage diagram of the charger chain, marking where the losses of point 1 occur (`U2.2.CP.2`).
4. **Models and their limitations.** Discuss the ideal-transformer model ($V_1 I_1 = V_2 I_2$, no losses) used in this option, and state where and why a real transformer departs from it (`U2.2.CP.3`).
5. **Sources.** Use at least two sources of information beyond this book — for example a government energy-regulation publication and a manufacturer's specification — and for each state why you judge it valid: who produced it, for what purpose, and how current it is (`U2.2.CP.1`, 10A).
6. **The societal context.** Trace the influence of at least two factors beyond the physics — for example the economic cost of compliant chargers and of wasted energy across millions of homes, the legal and regulatory question of who sets and enforces a standard, the political question of how it interacts with energy and e-waste policy, or the sociocultural habits of consumers who leave packs plugged in (`U2.2.CP.4`, 10B). Trace each factor to a consequence; do not merely name it.
7. **A reasoned position.** Conclude with your own stance on the issue, justified with the physics and the evidence you have assembled (`U2.2.CP.5`).

All calculations must show working, use SI units, and be rounded using the significant-figure rules of 1A. Record your sourced values and any trial calculations in your logbook.

Conditions. Individual work, completed in class under your teacher's supervision. Marks are house convention (§2.2 of this book's plan): all Units 1 and 2 assessment is school-based, and nothing in this task contributes to a study score.

Marking rubric (30 marks). Marks are keyed to the Communicating physics dot points (`U2.2.CP.1–.5`, owned by 10A and 10B). Marks are awarded for the quality of the reasoning and communication, not for which stance is reached.

Criterion	Dot point	0–2 marks	3–4 marks	5–6 marks
Use of sources	`U2.2.CP.1`	Sources listed with little or no evaluation	Sources named and their validity partly evaluated	Each source evaluated for validity (author, purpose, currency, expertise) and its sourced values used appropriately in the quantitative comparison
Physics concepts and representations	`U2.2.CP.2`	Stage names used loosely; losses located vaguely; calculation incomplete or without units	The four stages described with losses identified; efficiency and kW h calculation complete with units and appropriate significant figures; diagram labelled	The four-stage model described precisely with every loss located; calculation correct, conventional and clearly tied to the diagram; terminology (rectification, smoothing,

Criterion	Dot point	0–2 marks	3–4 marks	5–6 marks
				regulation, time constant) used accurately throughout
Models and their limitations	`U2.2.CP.3`	The ideal transformer used without recognition that it is a model	The ideal model applied correctly; a limitation noted	The ideal-transformer model applied correctly and its limitations discussed (where $V_1 I_1 = V_2 I_2$ holds, where and why a real transformer departs)
Societal context	`U2.2.CP.4`	Factors named without development	Relevant factors identified and their influence partly traced	At least two sociocultural, economic, legal or political factors traced to their consequences for the issue
Physics understanding supporting the position	`U2.2.CP.5`	A stance stated with little physics	The stance uses the physics and evidence correctly in places	The stance is justified coherently, with the four-stage physics, the efficiency comparison and the sourced evidence carrying the argument throughout