Unit 13

Answers: Light

Quick checks

1 b Thinner in the middle means concave, and a concave glass lens in air always diverges light, whichever face the light meets first. With one face flat, it is plano-concave.

2 c The size of the power tells how strongly a lens bends light; the sign tells only which way (+ together, − apart). −8 D has the shortest focal length, 12.5 cm, so it bends light most, spreading it apart.

3 c In the "real is positive" convention, a negative image distance means a virtual image, on the object's side of the lens. A convex lens gives one when the object is closer than F, as in a magnifying glass.

4 b Just beyond F_o, so that the objective makes a real, inverted, magnified image, which the eyepiece then magnifies again. Inside F_o the objective would form a virtual image on the object's side, which the eyepiece couldn't use.

5 b $M = \frac{f_o}{f_e}$: a shorter f_e (or a longer f_o) gives a larger M. Two lenses of equal focal length would give M = 1: no magnification at all.

1 a. **b** Thinner in the middle means concave, and a concave lens diverges light. Plano-convex and concavo-convex lenses are both thicker in the middle.

1 b. **c** Power is $\frac{1}{f}$ with f in meters, so its unit is per meter, given the name diopter (D).

1 c. **b** $f = \frac{1}{P} = \frac{1}{-4} = -0.25$ m $= -25$ cm. The minus sign means a concave lens.

1 d. **b** $\frac{1}{v} = \frac{1}{10} - \frac{1}{20} = \frac{1}{20}$, so $v = 20$ cm and $m = \frac{20}{20} = 1$. The object is at 2F, so the image is at 2F on the other side, real, inverted and the same size.

1 e. **d** Only then do the rays still spread after the lens, so they meet only when traced back, giving a virtual, upright, magnified image (a magnifying glass).

1 f. **b** The object is just beyond the objective's focus (between F and 2F), so its image is real, inverted and magnified. In a telescope the first image is diminished instead, because the object is very far away.

1 g. **b** The first image is at the objective's focus and also at the eyepiece's focus, so the lenses are $f_o + f_e$ apart. $f_o \div f_e$ is the magnifying power.

1 h. **b** P = +3 + (−1) = +2 D, so $f = \frac{1}{2}$ m = +50 cm, a converging combination.

2 a. Rays of light that fall on a convex lens parallel to its principal axis are bent towards the axis and come together (converge) at its principal focus after passing through it. Each part of the lens acts like a small prism bending light towards its thicker middle.

2 b. A concave lens spreads light out, so parallel rays only seem to come from its focus, on the same side as the light comes from: its focus is virtual. In the sign convention its focal length is negative, so its power, $\frac{1}{f}$, is negative too.

2 c. A magnifying glass makes the object look $1 + \frac{D}{f}$ times larger (D = 25 cm). The shorter its focal length f, the larger $\frac{D}{f}$, so the more it magnifies. A lens of long focal length hardly magnifies at all.

2 d. A larger objective collects more light from a distant object, so faint stars and planets look brighter and more of them can be seen; it also shows finer details. Distant objects are faint, so the light-collecting area matters as much as the magnification.

2 e. The objective forms a real, inverted image of the distant object at its focus. The eyepiece acts as a magnifying glass on this image, which magnifies without turning it over again, so the final image stays inverted compared with the object.

2 f. Just beyond the focus, the objective forms a real, inverted, magnified image far behind it, inside the tube, which the eyepiece can magnify again. Inside the focus, the objective would form a virtual image on the object's side, and the eyepiece couldn't magnify it into a large image for the eye.

3 i.

Convex lens	Concave lens
Thicker in the middle than at the edges.	Thinner in the middle than at the edges.
Converges parallel rays to a real focus.	Diverges parallel rays, which seem to come from a virtual focus.
Focal length and power are positive.	Focal length and power are negative.
Forms real or virtual images, depending on where the object is.	Always forms a virtual, upright, diminished image.
Used in magnifying glasses, cameras, and spectacles for long sight.	Used in spectacles for short sight and in door peepholes.

3 ii.

Magnification	Power
How many times the image is taller than the object.	How strongly the lens converges or diverges light.
$m = \frac{h_i}{h_o} = \frac{v}{u}$	$P = \frac{1}{f}$, f in meters
Depends on where the object is placed.	Fixed for a lens: depends only on its focal length.
Positive for a real image, negative for a virtual one.	Positive for a convex lens, negative for a concave one.
Has no unit.	Unit: diopter (D).

3 iii.

Compound microscope	Astronomical telescope
Used to see tiny objects close by.	Used to see distant objects.
Objective of very short focal length and small size.	Objective of long focal length and large size.
The first image is real, inverted and magnified.	The first image is real, inverted and diminished.
The final image is usually at the least distance of distinct vision.	The final image is at infinity in normal adjustment.
$M = m_o \times m_e$	$M = \frac{f_o}{f_e}$

4 a. A lens is a piece of transparent material bounded by two surfaces, at least one of which is curved (part of a sphere), which refracts light so that rays converge or diverge. Convex lenses (thicker in the middle): biconvex, plano-convex and concavo-convex. Concave lenses (thinner in the middle): biconcave, plano-concave and convexo-concave. Their shapes are drawn as in Figure 13.2.

4 b. The power of a lens is the reciprocal of its focal length in meters, $P = \frac{1}{f}$; its SI unit is the diopter (D), the power of a lens of focal length 1 m. A more strongly curved lens bends light more, so it brings parallel rays to a focus nearer to itself: its focal length is shorter and its power greater. A gently curved lens has a long focal length and a small power.

4 c. Lens formula: $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$. Sign convention: all distances from the optical center; distances of real objects and real images positive, of virtual images negative; f positive for a convex lens, negative for a concave one.
Derivation (as in Figure 13.3): object AB at OA = u, image A′B′ at OA′ = v, focus F at OF = f; the ray from B parallel to the axis meets the lens at Q, so OQ = AB.
Triangles ABO and A′B′O are similar: $\frac{A'B'}{AB} = \frac{v}{u}$.
Triangles OQF and A′B′F are similar: $\frac{A'B'}{OQ} = \frac{v-f}{f}$.
Since OQ = AB, $\frac{v}{u} = \frac{v-f}{f}$, so vf = uv − uf, or uv = vf + uf. Dividing by uvf: $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$.

4 d. Function: to see very small objects close by, magnified many times.
Structure: an objective lens of very short focal length and small aperture near the object; an eyepiece of short (but longer) focal length near the eye; a body tube holding them a fixed distance apart; a stage with clips for the slide; a mirror or lamp with a condenser below the stage; coarse and fine adjustment knobs for focusing; arm and base.
Working: the object is placed just beyond the focus of the objective, which forms a real, inverted, magnified image inside the tube. This falls just inside the focus of the eyepiece, which acts as a magnifying glass and forms a virtual, magnified, inverted final image, usually at the least distance of distinct vision. Magnifying power $M = m_o \times m_e$. The ray diagram is as in Figure 13.5 (Practical 21).

4 e. Function: to see distant objects, such as the Moon, planets and stars, magnified.
Structure: an objective lens of long focal length and large aperture facing the object; an eyepiece of short focal length near the eye; a tube, in two sliding parts, holding them on one axis so their distance can be adjusted.
Working: parallel rays from the distant object are brought by the objective to its focus, forming a real, inverted, diminished image there. In normal adjustment this image is at the focus of the eyepiece too, so the rays leave the eyepiece parallel and the final image, inverted, is at infinity, seen with a relaxed eye. The length is $f_o + f_e$ and the magnifying power $M = \frac{f_o}{f_e}$. The ray diagram is as in Figure 13.6 (Practical 22).

4 f. **Microscope:** the 2 cm lens as the objective (very short focal length, close to the object) and the 5 cm lens as the eyepiece. **Telescope:** the 50 cm lens as the objective and the 2 cm lens as the eyepiece, which gives $M = \frac{50}{2} = 25$ in a tube 52 cm long (with the 5 cm eyepiece it would magnify only 10 times). The 50 cm lens would be useless as a microscope objective: the first image would be far away and hardly magnified.

5 a. Convex: $P = \frac{1}{+0.25} = \mathbf{+4\ D}$. Concave: $P = \frac{1}{-0.20} = \mathbf{-5\ D}$.

5 b. $f = \frac{1}{-1.5} = -0.667$ m = **−66.7 cm: concave (diverging) lenses**, for a short-sighted person.

5 c. $\frac{1}{v} = \frac{1}{15} - \frac{1}{30} = \frac{1}{30}$ $\quad v = 30$ $\quad m = \frac{30}{30} = 1$

30 cm behind the lens: real, inverted and the same size (the object is at 2F).

5 d. $\frac{1}{v} = \frac{1}{12} - \frac{1}{8} = \frac{2-3}{24} = -\frac{1}{24}$ $\quad v = -24$

$m = \frac{v}{u} = \frac{-24}{8} = -3$, so the image is $3 \times 3 = 9$ cm tall (the minus sign: virtual and upright).

24 cm from the lens on the object's side: virtual, upright, 9 cm tall.

5 e. $\frac{1}{v} = -\frac{1}{20} - \frac{1}{60} = \frac{-3-1}{60} = -\frac{4}{60}$ $\quad v = -15$ $\quad m = \frac{v}{u} = \frac{-15}{60} = -0.25$

15 cm from the lens on the object's side: virtual, upright, a quarter of the size.

5 f. $\frac{1}{f} = \frac{1}{40} + \frac{1}{40} = \frac{2}{40}$ $\quad f = 20$ $\quad P = \frac{1}{0.20} = +5$

Focal length 20 cm, power +5 D (a convex lens; the bulb is at 2F).

5 g. $f = \frac{1}{2.5}$ m $= 40$ cm, $v = 4u$:

$\frac{1}{40} = \frac{1}{u} + \frac{1}{4u} = \frac{5}{4u}$ $\quad 4u = 200,\ u = 50$ $\quad v = 200$

The object is 50 cm from the lens, the image 2.0 m away on the other side.

5 h. $\frac{1}{12} = \frac{1}{u} - \frac{1}{3u} = \frac{2}{3u}$ $\quad 3u = 24,\ u = 8$

8 cm from the lens (the image is 24 cm away, on the same side).

5 i. $P = \frac{1}{0.25} + \frac{1}{-0.10} = +4 - 10 =$ **-6 D**, $f = \frac{1}{-6} = -0.167$ m = **-16.7 cm: diverging.**

5 j. $m_e = 1 + \frac{25}{5} = 6$, $M = m_o \times m_e = 8 \times 6 =$ **48**.

5 k. Objective: $\frac{1}{v_o} = \frac{1}{2} - \frac{1}{2.5} = \frac{0.5}{5} = \frac{1}{10}$, so $v_o = 10$ cm and $m_o = \frac{10}{2.5} = 4$.
Eyepiece: $\frac{1}{u_e} = \frac{1}{5} + \frac{1}{25} = \frac{6}{25}$, so $u_e = 4.17$ cm and $m_e = \frac{25}{4.17} = 6$.
$M = 4 \times 6 =$ **24**; the lenses are $10 + 4.17 =$ **14.2 cm** apart.

5 l. $M = \frac{120}{4} =$ **30**, $L = 120 + 4 =$ **124 cm**.

5 m. $11 f_e = 55$, so $f_e =$ **5 cm** (+20 D) and $f_o =$ **50 cm** (+2 D).