Unit 15 · Refraction at Plane Surfaces

ANSWER KEY · FOR TEACHERS

Full marks 36

Give the marks for the points in the marking scheme; an answer in other words that says the same is right.

1 Key words

1. refraction
2. refractive index
3. optically denser
4. apparent depth
5. lateral shift
6. critical angle
7. total internal reflection
8. optical fiber

K · 4

Each carries 0.5 mark.

2 Label the diagram

1. cool air higher up: denser
2. hot air: rarer
3. hot road
4. image seen: upside down

U · 2

Each carries 0.5 mark.

3 Multiple choice

i. **c.** bends away from the normal — U · 1

Water is optically rarer than glass, so light going from glass into water speeds up and bends away from the normal.

ii. **b.** light travels more slowly in it — U · 1

Optical density is about the speed of light, not mass per volume: kerosene's refractive index (1.44) is larger than water's (1.33).

iii. **b.** 0.67 — A · 1

By the principle of reversibility, ${}_a\mu_g \times {}_g\mu_a = 1$, so ${}_g\mu_a = 1/1.5 = 0.67$.

iv. **c.** goes from a denser towards a rarer medium at more than the critical angle — K · 1

Both conditions are needed: from denser towards rarer, and an angle of incidence greater than the critical angle.

v. **c.** 1.5 cm — A · 1

$d = t(1 - 1/\mu) = 4.5 \times (1 - 1/1.5) = 4.5 \times 1/3 = 1.5$ cm.

4 Very short answers

a. MARKING SCHEME — K · 1

✓ μ = speed of light in vacuum ÷ speed of light in the medium.

b. MARKING SCHEME — K · 1

✓ A reversed ray retraces the same path in the opposite direction.

c. MARKING SCHEME — U · 1

✓ It approaches the thickness of the slab ($L \to t$).

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5 Short answers

a. MARKING SCHEME U · 2

- ✓ Any one, e.g. it reflects all the light, while a silvered mirror absorbs some.
- ✓ Any second, e.g. it gives a single image (a glass mirror gives a faint extra image from its front surface), or it has no silvering to tarnish or peel.

b. MARKING SCHEME U · 2

- ✓ From a into b: ${}_a\mu_b = \sin i/\sin r$; reversed, from b into a at angle r it leaves at i: ${}_b\mu_a = \sin r/\sin i$.
- ✓ Multiplying, ${}_a\mu_b \times {}_b\mu_a = 1$, so ${}_a\mu_b = 1/{}_b\mu_a$.

c. MARKING SCHEME U · 2

- ✓ Light from the part under water bends away from the normal as it leaves the water, so each point of it is seen raised.
- ✓ The deeper points are raised more, so the part under water seems bent up at the surface.

6 Long answer

ANSWER U · 4

The ray AO meets the slab at O, travels along OB inside it and leaves along BC, parallel to AO. Produce AO beyond O and draw BM perpendicular to it: BM = L. The ray turns at O through ∠BOM = i − r, so in the right-angled triangle OMB, BM = OB sin(i − r). In the right-angled triangle ON_2B (N_2 the foot of the normal on the far face), ON_2 = t and the angle at O is r, so OB = t/cos r. Putting this in, L = t sin(i − r)/cos r.

MARKING SCHEME

- ✓ A labelled diagram: the incident ray produced, the refracted ray, the emergent ray parallel to it, and the perpendicular BM = L.
- ✓ ∠BOM = i − r, so BM = OB sin(i − r).
- ✓ From the triangle with the slab's thickness, OB = t/cos r.
- ✓ L = t sin(i − r)/cos r.

7 Numerical problems

a. ANSWER A · 3

Air to water: sin r = sin 50° ÷ 1.33 = 0.766 ÷ 1.33 = 0.576, so r = **35.2**°.
Water to glass: $\mu_w \sin r = \mu_g \sin r'$, and $\mu_w \sin r = \sin 50°$, so sin r′ = 0.766 ÷ 1.52 = 0.504, r′ = **30.3**°.
(The water layer doesn't change the angle in the glass.)

MARKING SCHEME

- ✓ sin r = sin 50°/1.33, r = 35.2°.
- ✓ $\mu_w \sin r = \mu_g \sin r'$ written (or $\mu \sin \theta$ the same at every face).
- ✓ r′ = 30.3°.

b. ANSWER A · 3

sin r = sin 60° ÷ 1.52 = 0.866 ÷ 1.52 = 0.570, so r = 34.7°.
L = t sin(i − r)/cos r = 5.0 × sin 25.3° ÷ cos 34.7° = 5.0 × 0.427 ÷ 0.822 = **2.6 cm**.

MARKING SCHEME

- ✓ r = 34.7°.
- ✓ L = t sin(i − r)/cos r with values put in.
- ✓ L = 2.6 cm.

c. ANSWER A · 4

i. $\mu = 1/\sin C = 1/\sin 40° = 1/0.643 =$ **1.56**.
ii. $v = c/\mu = 3 \times 10^8 \div 1.556 =$ **1.93×10^8 m/s**.
iii. Glass to water: $\sin C' = \mu_w/\mu_g = 1.33 \div 1.556 = 0.855$, so C′ = **58.7**°.

MARKING SCHEME

- ✓ $\mu = 1/\sin 40° = 1.56$.
- ✓ $v = c/\mu = 1.93 \times 10^8$ m/s.
- ✓ $\sin C' = \mu_w/\mu_g$ (the refractive index of glass with respect to water).
- ✓ C′ = 58.7°.

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8 Think

ANSWER HA · 2

Higher. Light from the bird bends towards the normal as it enters the water, so, traced back, it seems to come from a point higher up: for an object in the rarer medium seen from the denser one, apparent height = $\mu \times$ real height.

MARKING SCHEME

- ✓ The bird looks higher (farther away) than it is.
- ✓ Light bends towards the normal entering the water, so produced back it seems to come from higher up (apparent height = $\mu \times$ real height).

9 Activity: The refractive index of water

(not marked)

WHAT STUDENTS SHOULD FIND

The coin always looks raised, to about three quarters of the real depth, and R ÷ a comes out close to 1.33 at every depth (within about 0.1, since judging the level is rough). Looking at a slant makes the coin look higher still, so it must be done straight down.

See it at Science Playground

Exhibits and plants at the center, Bhaktapur, that go with this unit. Book a class visit at science-playground.com/booking.

- **Rays of Light** (exhibit): Slant the block in a laser beam and read the angles on the scale: it bends towards the normal going in, away from it coming out.
- **The Ecosystem Pond** (exhibit): Look straight down at the pebbles on the pond's bottom: they seem nearer than they are, at the real depth divided by water's refractive index.
- **Total Internal Reflection** (exhibit): Inside each fiber the light meets the wall at more than the critical angle and is totally reflected, so it escapes only at the tip.
- **The Periscope** (exhibit): This periscope turns the light with two mirrors at 45°; one with totally reflecting prisms instead loses almost no light at the turns.

Marks by level	Knowledge	Understanding	Application	Higher ability	Total
Marks	7	15	12	2	**36**

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