Unit 13 · Light

STUDY NOTES

Key terms

Optically denser / rarer: light slower / faster in it (speed, not mass): kerosene floats on water but is optically denser.

Refraction: change in the direction of light passing at a slant from one transparent medium into another, because its speed changes.

Normal: imaginary line at right angles to the surface at the point of incidence; angles measured **from it**.

Angle of incidence i, **angle of refraction** r: between each ray and the normal.

Absolute refractive index: with respect to a vacuum (air taken as the same); **no unit**.

Relative refractive index: medium 2 with respect to medium 1; can be under 1.

Critical angle c: the angle of incidence in the denser medium for which the angle of refraction in the rarer medium is 90°.

Total internal reflection: all light reflected back into the denser medium, at more than c.

Lateral shift: perpendicular distance between the emergent ray and the incident ray produced.

Real depth: surface to where the object is. **Apparent depth**: surface to its image.

Apparent shift (normal shift): real depth − apparent depth.

Formulas

$\mu = \dfrac{\sin i}{\sin r} = \dfrac{c}{v}$	$c = 3 \times 10^8$ m/s **Use:** from air or vacuum
${}_1\mu_2 = \dfrac{\mu_2}{\mu_1} = \dfrac{v_1}{v_2}$	medium 2 w.r.t. 1 **Use:** two media
$\mu_1 \sin i = \mu_2 \sin r$	index beside the sine in it **Use:** any two media
${}_2\mu_1 = \dfrac{1}{{}_1\mu_2}$	reversibility **Use:** the way back
$\sin c = \dfrac{1}{\mu}$	medium in air **Use:** critical angle
$\sin c = \dfrac{\mu_2}{\mu_1}$	μ_1 the denser **Use:** two media
$\mu = \dfrac{\text{real depth}}{\text{apparent depth}}$	looking straight down only **Use:** depth
$\text{shift} = \text{real depth} \times (1 - \frac{1}{\mu})$	apparent shift **Use:** how far raised

- layers: apparent depths add: 12 cm kerosene (1.44) on 20 cm water (4/3): 8.33 + 15 = 23.3 cm
- careful: c is both the critical angle and the speed of light

Refraction

Going	Speed	Bends
rarer → denser	slows	toward the normal, $r < i$
denser → rarer	speeds up	away from it, $r > i$
along the normal	changes	not at all, $i = 0°$

- marching line reaching sand at a slant: one end slows first, the line swings; square on, all slow together
- ray at 30° **to the surface**: $i = 60°$

Laws of refraction:

1. The incident ray, the refracted ray and the normal at the point of incidence all lie in the same plane.
2. **Snell's law:** for a given pair of media and a given color of light, $\sin i / \sin r$ is a constant.

- the **sines** keep a fixed ratio, not the angles: air to glass 30° → 19.5°, 60° → 35.3° (not 39°)

Medium	μ	Speed (m/s)	c in air
air	1.0003 (take 1)	3.0×10^8	
ice	1.31	2.29×10^8	
water	1.33 (4/3)	2.26×10^8	48.8°
kerosene	about 1.44	2.08×10^8	about 44°
glycerine	1.47	2.04×10^8	42.9°
glass	1.5	2.0×10^8	41.8°
diamond	2.42	1.24×10^8	24.4°

- higher μ: slower light, more bending, smaller c
- ${}_w\mu_g = 1.5/1.33 = 1.13$; ${}_g\mu_w = 0.887$
- **reversibility:** a ray sent back along its path retraces it exactly (50° ↔ 30.7°)

Total internal reflection

Conditions:

1. Light going from an optically **denser** into a **rarer** medium.
2. Angle of incidence **greater than** the critical angle.

- $i < c$: refracted out, a little reflected
- $i = c$: $r = 90°$, skims the surface
- $i > c$: all reflected
- change is smooth: near c, less gets out; draw the skimming ray in an exam
- **derivation:** $\mu \sin c = 1 \times \sin 90° = 1 \rightarrow \sin c = 1/\mu$
- glass in water: $\sin c = 1.33/1.5 \rightarrow 62.5°$; glass in air 41.8°
- glass at 45°: $\sin r = 1.06 > 1 \rightarrow$ totally reflected; water at 45°: gets out at 70.1°
- not from air into water: $r < i$, never 90°, no critical angle
- mirror absorbs a few percent, tarnishes; total internal reflection: all light, never tarnishes

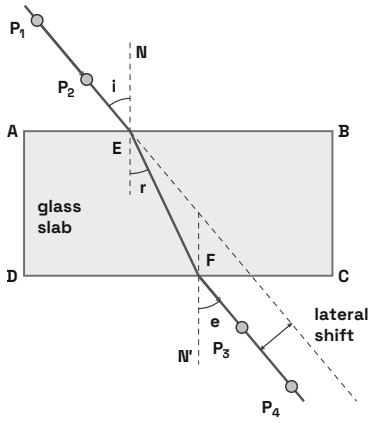
Practical 24:

- tank of water, drops of milk, laser up through the side at the surface
  - flatter beam
  - emerging beam dimmer
  - past about 49° none gets out
- empty test tube at a slant in water: silvery, marble hidden (glass with air behind it); filled with water: shine vanishes, marble seen

Around us:

- **diamond**
  - $c = 24.4°$
  - faces angled, light bounces inside and leaves by the top
  - splits colors strongly ("fire")
  - glass leaks at the back
- **optical fiber**
  - core 1.48, cladding 1.46 ($c = 80.6°$)
  - reflected thousands of times a meter
  - telephone, internet
  - Nepal's through India and, since 12 January 2018, Rasuwagadhi from China
- **endoscope**: bundle of fibers; some carry light in, others, in the same order at both ends, the picture back
- **prism** 90°, 45°, 45°
  - meets long face at 45° > 41.8°
  - turns light 90° or 180°
  - periscopes, binoculars
- **mirage**
  - air near a hot road rarer
  - sky's light bent up
  - looks like water
- **Snell's window**: from under water, whole sky in a circle about 97° across; outside, a mirror

Finding μ of glass (Practical 25)



Pin method: $\mu = \sin i / \sin r$; emergent ray parallel to incident, shifted sideways.

1. Outline ABCD; normal at E on AB; incident ray at 40°; pins P_1, P_2 on it
2. Slab back; through DC, line up P_1 and P_2; pins P_3, P_4 in line with them
3. Remove; P_3P_4 to F on DC; join EF; measure r
4. Repeat at 30°, 50°, 60°; average $\sin i / \sin r \approx 1.5$

- **good result**
  - pins upright, well apart
  - i 30°–60°
  - feet of the pins
  - sharp pencil
- $e = i$: $\frac{\sin i}{\sin r} \times \frac{\sin r}{\sin e} = \mu \times \frac{1}{\mu} = 1$
- shift bigger with
  - thicker slab
  - bigger i
  - higher μ

Real and apparent depth

- light from under water bends away from the normal; the eye traces it straight back, image **higher**
- **proof:** O object, A above it on the surface, B where a ray leaves, I image: $\tan i = AB/AO$, $\tan r = AB/AI$; $\mu = \sin r / \sin i$; straight down, angles small, sine ≈ tangent → $\mu = AO/AI$
- at a slant: shallower still; bottom seems to tilt up
- straight down into water: about ¾ of the real depth. 2.4 m → 1.8 m
- check depth with a stick; fisherman aims **below** the image
- from under water: a person on the edge looks taller, farther up

Traveling microscope:

- readings
  - on the mark (no slab) R_1
  - on the mark through the slab R_2
  - on powder on top R_3
- real = $R_3 - R_1$
- apparent = $R_3 - R_2$
- shift = $R_2 - R_1$
- 2.50, 3.80, 6.40: $3.90 \div 2.60 = 1.5$

COMMON MISTAKES

✗ Angle from the surface.
✓ From the normal.

✗ Denser means heavier.
✓ Light slower: kerosene is optically denser than water.

✗ i/r is constant.
✓ $\sin i / \sin r$.

✗ Refractive index has a unit.
✓ None: a ratio.

✗ Total internal reflection from air into water.
✓ Only denser to rarer.

✗ Apparent depth = real × μ.
✓ Real ÷ μ.

✗ Real ÷ apparent = μ at any angle.
✓ Only straight down.

✗ Emergent ray in line with incident.
✓ Parallel, shifted sideways.