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Ray Optics and
Optical Instruments

THE DROWNING CHILD, LIFEGUARD AND SNELL'S LAW

Consider a rectangular swimming pool PQSR; see figure here. A lifeguard sitting at G outside the pool notices a child drowning at a point C. The guard wants to reach the child in the shortest possible time. Let SR be the side of the pool between G and C. Should he/she take a straight line path GAC between G and C or GBC in which the path BC in water would be the shortest, or some other path GXC? The guard knows that his/her running speed v_1 on ground is higher than his/her swimming speed v_2 .

Suppose the guard enters water at X. Let $GX = l_1$ and $XC = l_2$. Then the time taken to reach from G to C would be

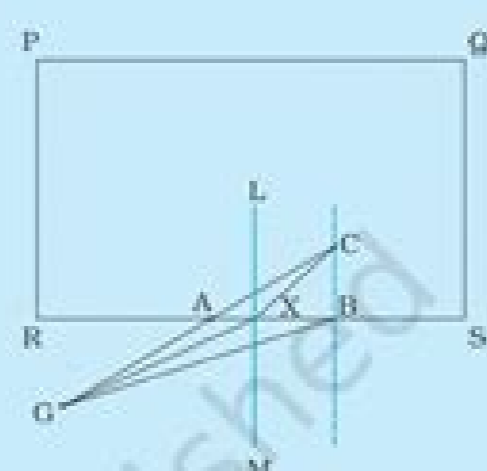
$$t = \frac{l_1}{v_1} + \frac{l_2}{v_2}$$

To make this time minimum, one has to differentiate it (with respect to the coordinate of X) and find the point X when t is a minimum. On doing all this algebra (which we skip here), we find that the guard should enter water at a point where Snell's law is satisfied. To understand this, draw a perpendicular LM to side SR at X. Let $\angle GXM = i$ and $\angle CXL = r$. Then it can be seen that t is minimum when

$$\frac{\sin i}{v_1} = \frac{\sin r}{v_2}$$

In the case of light v_1/v_2 , the ratio of the velocity of light in vacuum to that in the medium, is the refractive index n of the medium.

In short, whether it is a wave or a particle or a human being, whenever two mediums and two velocities are involved, one must follow Snell's law if one wants to take the shortest time.



9.4 TOTAL INTERNAL REFLECTION

When light travels from an optically denser medium to a rarer medium at the interface, it is partly reflected back into the same medium and partly refracted to the second medium. This reflection is called the *internal reflection*.

When a ray of light enters from a denser medium to a rarer medium, it bends away from the normal, for example, the ray AO, B in Fig. 9.12. The incident ray AO, is partially reflected (O, C) and partially transmitted (O, B) or refracted, the angle of refraction (r) being larger than the angle of incidence (i). As the angle of incidence increases, so does the angle of refraction, till for the ray AO₁, the angle of refraction is $\pi/2$. The refracted ray is bent so much away from the normal that it grazes the surface at the interface between the two media. This is shown by the ray AO₁, D in Fig. 9.12. If the angle of incidence is increased still further (e.g., the ray AO₂), refraction is not possible, and the incident ray is totally reflected.

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Dual Nature of Radiation
and Matter

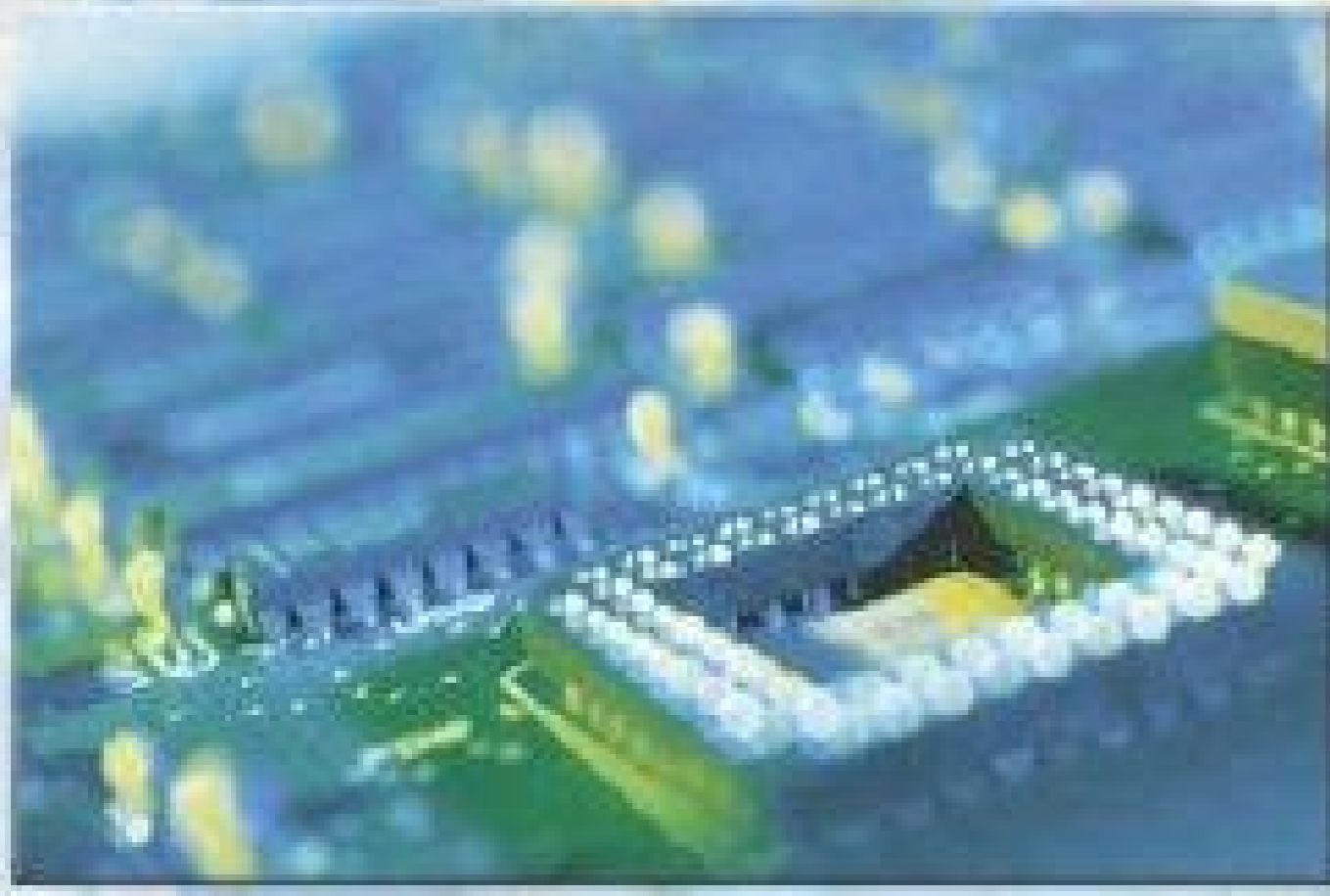
4. Observations on photoelectric effect imply that in the event of matter-light interaction, *absorption of energy takes place in discrete units of $h\nu$* . This is not quite the same as saying that light consists of particles, each of energy $h\nu$.
5. Observations on the stopping potential (its independence of intensity and dependence on frequency) are the crucial discriminator between the wave-picture and photon-picture of photoelectric effect.
6. The wavelength of a matter wave given by $\lambda = \frac{h}{p}$ has physical significance: its phase velocity v_p has no physical significance. However, the group velocity of the matter wave is physically meaningful and equals the velocity of the particle.

EXERCISES

- 11.1 Find the
 - (a) maximum frequency, and
 - (b) minimum wavelength of X-rays produced by 30 kV electrons.
- 11.2 The work function of caesium metal is 2.14 eV. When light of frequency 6×10^{14} Hz is incident on the metal surface, photoemission of electrons occurs. What is the
 - (a) maximum kinetic energy of the emitted electrons,
 - (b) Stopping potential, and
 - (c) maximum speed of the emitted photoelectrons?
- 11.3 The photoelectric cut-off voltage in a certain experiment is 1.5 V. What is the maximum kinetic energy of photoelectrons emitted?
- 11.4 Monochromatic light of wavelength 632.8 nm is produced by a helium-neon laser. The power emitted is 9.42 mW.
 - (a) Find the energy and momentum of each photon in the light beam,
 - (b) How many photons per second, on the average, arrive at a target irradiated by this beam? (Assume the beam to have uniform cross-section which is less than the target area), and
 - (c) How fast does a hydrogen atom have to travel in order to have the same momentum as that of the photon?
- 11.5 The energy flux of sunlight reaching the surface of the earth is 1.388×10^3 W/m². How many photons (nearly) per square metre are incident on the Earth per second? Assume that the photons in the sunlight have an average wavelength of 550 nm.
- 11.6 In an experiment on photoelectric effect, the slope of the cut-off voltage versus frequency of incident light is found to be 4.12×10^{-15} V s. Calculate the value of Planck's constant.
- 11.7 A 100W sodium lamp radiates energy uniformly in all directions. The lamp is located at the centre of a large sphere that absorbs all the sodium light which is incident on it. The wavelength of the sodium light is 589 nm. (a) What is the energy per photon associated

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