UNIT 6 LIGHT AND OPTICS

PHYS:1200 LECTURE 29 — LIGHT AND OPTICS (1)

Maxwell and Hertz established the existence of electromagnetic waves. Electromagnetic waves cover all wavelengths and frequencies and propagate in vacuum at the speed of light $c = 299{,}792{,}458\ m/s \approx 3\times10^8\ m/s$. The wavelength λ and frequency f obey the relation $\lambda f = c$. Visible light or simply *light,* is that portion of the electromagnetic spectrum that human eyes are sensitive to, and covers the wavelength range of approximately 400 nm to 700 nm (1 nm = 10^{-9} m).

Example 29-1: What is the frequency range of visible light?

Solution: Use $\lambda f = c$ in the form $f = \frac{c}{\lambda}$ to compute the frequencies corresponding to

$\lambda = 400\,nm\ and\ \lambda = 700\,nm$.

$$\lambda = 400\ nm = 400\times10^{-9}\,m = 4\times10^{-7}\,m \Rightarrow f = \frac{c}{\lambda} = \frac{3\times10^8\ m/s}{4\times10^{-7}\,m} = 7.5\times10^{15}\ Hz$$

$$\lambda = 700\ nm = 700\times10^{-9}\,m = 7\times10^{-7}\,m \Rightarrow f = \frac{c}{\lambda} = \frac{3\times10^8\ m/s}{7\times10^{-7}\,m} = 4.3\times10^{15}\ Hz$$

The frequency range of visible light is 4.3 x 10^{15} Hz t0 7.5 x 10^{15} Hz.

29-1. Measurement of the Speed of Light.—In 1638, Galileo is often credited with being the first scientist to try to measure the speed of light. His method was quite simple. He and an assistant each had lamps which could be covered and uncovered at will, and they got as far away from each other as possible. Galileo would uncover his lamp, and as soon as his assistant saw the light he would uncover his. By measuring the elapsed time until Galileo saw his assistant's light and knowing how far apart the lamps were, Galileo reasoned he should be able to determine the speed of the light. His conclusion: "If not instantaneous, it is extraordinarily rapid". Most likely he used a water clock, where the amount of water that empties from a container represents the amount of time that has passed. If the distance between Galileo and his assistant was L, the light traveled a total distance of 2 L, and the speed of light is then c = 2L/T. Suppose L = 15 km = 15,000 m; then the time delay from sending to receiving the light beam would be T = 2L/c = (2x15,000 m) / (3x10^8 m/s) =10^{-4} s. Galileo had no chance of measuring this small of a time interval. He concluded that the speed of light was at least ten times faster than the speed of sound (it is actually about a million times faster). We will measure the speed of light in class using modern equipment that is capable of measuring time intervals down to 1 nanosecond (10^{-9} s). Instead of reflecting the light from a distant mirror, we will send a light pulse down a 20 m long fiber optic cable and measure the time it takes for the light to travel along the full length of the fiber optic cable.

29-2. The Speed of Light in a Medium - Index of Refraction.—The speed of light in *vacuum* is $c \approx 3\times10^8\ m/s$. In a medium, light travels at a *lower* speed v_{medium} which is computed using

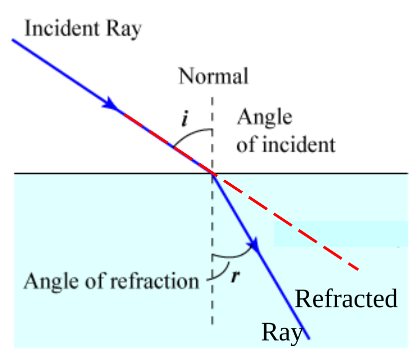
Speed of light in a medium	$v_{medium} = \dfrac{c}{n},$	[1]

Where n is a *number* greater than 1 that is a characteristic of the medium and is known as the **index of refraction**. Since $n \geq 1,\ v_{medium} \leq c.$ For example, in glass having an index of refraction $n_{glass} \cong 1.5,\ so\ \ v_{glass} = \left(3\times10^8\ m/s\right)/1.5 = 2\times10^8\ \ m/s$. A table of values of n for various media is given on slide 7. For vacuum, n = 1, for air $n_{air} = 1.000293 \cong 1,$ so $v_{air} \approx c.$ (We will consider air as vacuum in all calculations.)

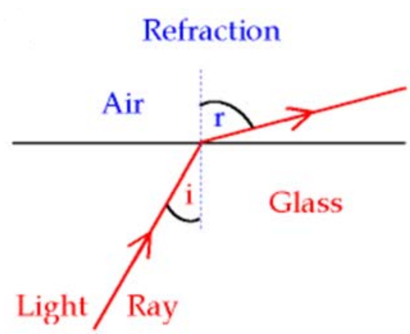
Example 29-2: What is the speed of light in a medium having n = 2?

Solution- $v_{medium} = c/n = \left(3\times10^8\ m/s\right)/2 = 1.5\times10^8\ m/s$

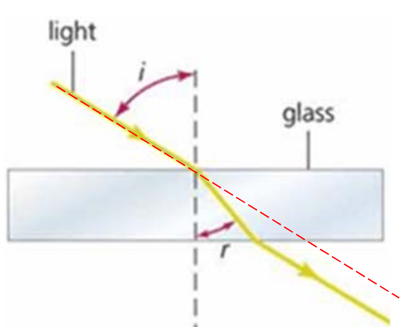
29-3. Refraction.—A consequence of the fact that light travels more slowly in a medium than in air, is that a light ray that is incident on the plane surface of another medium at an angle of incidence other than zero is **bent** as it enters the medium. Refraction of light entering water is illustrated in the diagram on the right. The angle of incidence, ***i*** is measured



with respect to the so-called normal line (the black dashed vertical line) (here *normal* means perpendicular to the interface). The blue line represents a light ray, and it is refracted (bent) as it travels from air into water. Refraction means in effect that the ray does not follow its path in the air (the red dashed line) but deviates from that path toward the normal. The angle of refraction, ***r*** is the angle which the refracted ray makes with the normal. Notice that $r < i,$ which is typical when light enters a medium that has a higher index of refraction. The index of refraction of the medium determines the amount of bending that occurs. The larger the n value, the more bending that occurs. Slide 15 illustrates refraction with water and glass. For the same angle of incidence, light rays are bent more in glass than in water, because the index of refraction of glass is larger than the index of refraction of water. The case of normal incidence (angle of incidence = 0 degrees) is illustrated on slide 16. No bending of the light ray occurs in this case, but because the speed of light in the medium is lower, the wavelength of the light in the medium is shorter to accommodate a lower speed.

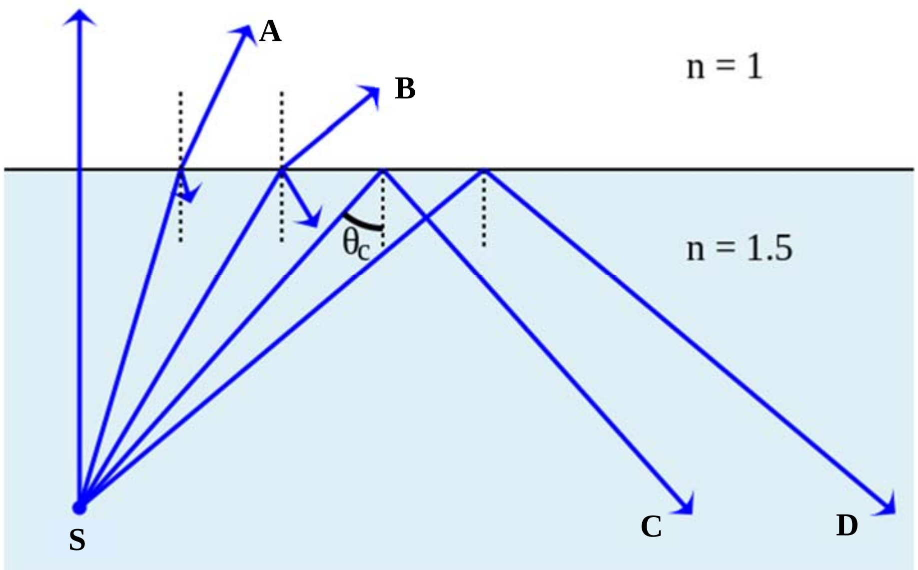


It is possible to have the light beam originate in the medium and for the light beam to pass into air as illustrated on the right. In this case, the ray that exists the glass into the air is bent away from the normal line, and $r > i$. This occurs when light passes through a plane slab of glass as shown on the left side. In this case the exiting light ray will be parallel to the incoming light ray but displaced by an amount that depends on the thickness of the glass. For an ordinary window pane, this displacement is not noticeable.

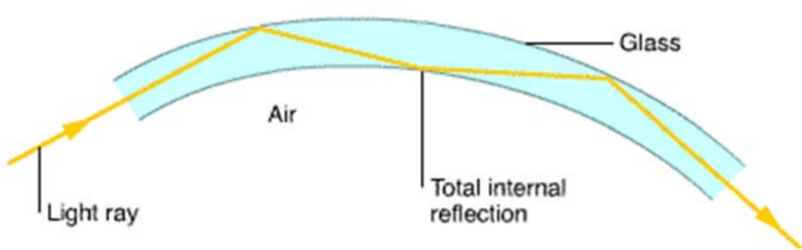


An interesting consequence of the refraction of light is shown on **slide 20**.

29-4. Total Internal Reflection.—When light is incident from a medium of high n value on a boundary with a medium of low n, an interesting phenomenon, total internal reflection, may occur. This is illustrated in the diagram below. Several beams are emitted by a light source **S**, that is located in a medium of n = 1. Beams A, B, C, and D travel through the medium at various angles and arrive at the interface with air, at increasingly larger angles of incidence. If the angle of incidence is less than a critical value (for glass 42 degrees) the incident rays are refracted and pass through the interface. This occurs with rays A and B. Rays C and D have an angle of incidence larger than the critical angle and do not emerge from the glass, but are reflected back into the glass. This is total internal reflection. An observer in the air looking toward the source would not see rays C and D.



Total internal reflection is the process used **in fiber optic communications**. Light is sent down



very fine stands of flexible glass fibers and total internal reflection keeps reflecting the beam inside the fiber as shown below. Typically bundles of several thousands of glass fibers having diameters less than a human hair are used. Electronic signals are converted to digital light pulses which are guided over very long distances along the fiber bundles. Fiber optics can carry significantly more information over longer distances than copper wires and with less distortion. (see **slide 23**).