General Physics - E&M (PHY 1308) Lecture Notes

Lecture 023: Reflection and Refraction

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no tags

Goals of this Lecture

- Introduce the ideas behind optics - reflection and refraction

Optics - the behavior of light

Optics is simple the study of the behavior of light. While Maxwell showed that light is an electromagnetic wave - and, in fact, all of optics can be described using Maxwell's Equations - in fact it is enough for our purposes that we treat light as follows:

Light can be treated as RAYS - straight lines that point from the origin of the light to the destination.

The language of *light rays* can be easily used to describe the behavior of light when traveling through empty space, or air, or reflecting off glass or a mirror, or traveling from one medium - air, for instance - into another - water, for instance.

Reflection

Let us begin our description of the behavior of light by considering *reflection*. Reflection is when a ray of light strikes a surface and bounces off the surface. There may be some transmission into the material, but we are interested in the light ray that then leaves the material.

The geometry that we use to describe reflection can be easily motivated by considering a laser beam reflecting off of a surface (see the slides). This simple experiment demonstrates a powerful fact:

If we draw the surface, the incident ray, the outgoing ray, and the normal to the surface in the same plane, then we find that a light ray with an incident angle θ_1 (in medium 1) with respect to the normal to the surface will make the same angle $\theta_1' = \theta_1$ with respect to the normal when it is outgoing.

There are two kinds of reflection: specular reflection, when parallel light rays reflect off of a smooth surface and the entire beam is reflected without distortion; and diffuse reflection, when a parallel beam is scattered by a rough surface and the beam spreads out. The law of reflection - that the incident and outgoing angles to the normal are equal - is still true for each light ray on the surface it strikes; but the net effect is to spread out the beam.

White paper is a *diffuse reflector*. The aluminum coating of a mirror is a *specular reflector.*

Reflection all takes place in one medium. By medium, I mean a material through which light moves.

The corner reflector

Use the corner reflector (Example 30.1) to illustrate the application of reflection.

Refraction

Illustrate refraction with laser light passing through mineral oil and then air (see slides). Demonstrate that when light goes from one medium to another, its angle of travel also changes. Different media lead to different changes in angle.

This is because light travels at different speeds in different media. Light travels in vacuum (free space) at $c = 3.00 \times 10^8 \mathrm{m/s}$, but in air it travels slightly more slowly and in glass it travels even more slowly than in air.

The change in the speed of light from one material to another is called the *index of refraction*, and is given by the ratio of the speed of light in free space ("the vacuum") to speed of light in the material:

$$n = \frac{c}{v}$$

Typical indices of refraction:

- Air: 1.000293
- Carbon dioxide: 1.00045
- Water: 1.333
- Glass: 1.5-1.9
- Diamond: 2.419

Light is fundamentally an electromagnetic wave. It's standard to think about the oscillating electric field in the wave, since the electric and magnetic fields oscillate at the same time. If we draw the oscillating electric field traveling in medium 1 and then it reaches medium 2, the wave must be continuous across the boundary and the frequency (the rate at which crests of the wave pass a point) of the wave can't change between media. Thus if the speed changes from medium 1 to medium 2, the WAVELENGTH of the light wave must be changing:

$$v_1 = \lambda_1 f$$

$$v_2 = \lambda_2 f$$

using $n = c/v$:

$$\lambda_1 = (c/n_1) f$$

$$\lambda_2 = (c/n_2) f$$

Using the image in the slides, we can relate the wavelengths to the angles of refraction - the angles of the light rays with respect to the normal to the interface. Since the two waves share the common hypotenuse (h) of the right-triangles shown in the picture in the slides, we know that:

$$h = \frac{\lambda_1}{\sin\theta_1} = \frac{\lambda_2}{\sin\theta_2}$$

Substituting the equations above for the frequencies:

$$\frac{cf}{n_1 \sin\theta_1} = \frac{cf}{n_2 \sin\theta_2}$$

canceling out the cf on both sides and rearranging we find:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2$$

This equation is known as "Snell's Law," first developed geometrically in 1621 by van Roijen Snell of the Netherlands and described analytically by Rene Descartes in France. It allows us to predict what light will do when it travels from one medium to another.

Total Internal Reflection

When the source of light is in a medium with a HIGHER index of refraction than the medium into which the light travels, we see that light is bent not toward the normal but AWAY from the normal. If we think of light rays traveling from a source point P in medium 1, where $n_1 > n_2$, then we see that when the angle of incidence to the normal is INCREASED inside medium 1, the ray in medium 2 bends further and further away. At some point, the angle of the ray in medium 2 will be 90-degrees with respect to the normal. That is, $\sin\theta_2 = \sin(\pi/2) = 1$. This corresponds to an angle θ_1 which is called *the critical angle*. θ_c. We can solve for the critical angle using Snell's Law:

$$\sin\theta_c = n_2/n_1$$

It depends only on the ratios of the indices of refraction of the two materials (which also happens to be the same as the ratios of the speeds of light in the two materials). Once you exceed the critical angle in material 1, all light is reflected internally in the medium.

Total internal reflection in a fish tank

Consider the laser beam in the water in the fish tank. It strikes the glass-water interface. What is the critical angle?

$$\sin\theta_c = 1.000293/1.333 = 0.750 \longrightarrow \theta_c = 0.849\mathrm{rad.} = 48.6 degrees$$

or just about 45-degrees.