An Introduction to Optics

Hitesh Yalamanchili

May 22, 2015

1 Introduction

Optics is the study of visible light, and how light can be manipulated to produce visual images. In this lecture, we will look at three main branches of optics: classical optics, optical instruments, and wave optics.

2 Classical Optics

Classical optics refers to the study of optics using the particle model of light, in contrast to wave optics, which makes use of the wavelike light model. Using this field of optics, we will examine and account for some of the more commonplace optical phenomena, especially those involving mirrors and lenses.

2.1 Reflection

Specular reflection is a phenomenon that occurs when a light ray strikes a smooth reflective surface. In general, when an incident light ray strikes a totally reflective surface, the reflected ray bounces back in a related manner to the path of the incident ray. The angle of incidence measured from the incident ray to the normal of the surface is equal to the angle of reflection measured from the reflected ray to the normal.

$$\theta_{\text{incident}} = \theta_{\text{reflected}} \tag{1}$$

On the other hand, when the surface is rough, diffuse reflection occurs when the surface is not uniform, resulting in a non-uniform distribution of the reflected beams of light.

2.2 Refraction and Total Internal Reflection

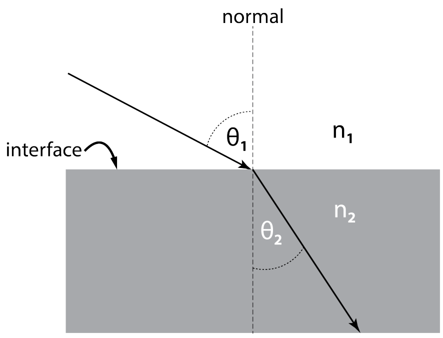


Figure 1: An Example of Refraction

Refraction is a phenomenon that bends a light ray due to a change in the medium it is traveling in. If we consider a single beam of laser light, we can observe it as it passes from one medium into another. A quantitative analysis of refraction can be understood using the *angle of incidence*, θ_i, at which the beam approaches the new medium from the normal, and the *angle of refraction*, θ_r, which the beam forms in the new medium. In addition, the *index of refraction* $n = \frac{c}{v}$ is a measure of the way the light ray refracts in a certain medium. These properties are all related by **Snell's law of refraction**.

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 \tag{2}$$

At some incident angles, this equation may sometimes lead to a value for $\sin \theta_2$ that is greater than 1 or less than -1. There is a critical angle $\theta_c = \arcsin \frac{n_2}{n_1}$ for the angle of incidence at which the refracted ray bends almost parallel to the surface between the two media. This leads to **total internal reflection**, when the refraction no longer occurs and the incident light ray is completely reflected back according to the law of reflection in equation 1.

3 Optical Instruments

So far, we have dealt with flat surfaces and mirrors, which allowed for simple laws of reflection and refraction. Now, we will understand the following optical instruments: plane mirrors, convex and concave mirrors, convex and concave lenses.

3.1 Image Characteristics

There are several key image characteristics that we will analyze for the various mirrors and lenses we look at in this section

- **Virtual vs. Real**
  Virtual images are images that are formed in locations where light does not actually reach. Real images are those that are formed on the same side of the mirror as the object and light passes through the actual image location. It is important to note that virtual images for lenses are located on the same side of the lenses as the original objects.
- **Upright vs. Inverted**
- **Object Distance and Image Distance**
- **Image Magnification**
  The magnification of an image is measured as the ratio of the image dimensions to the object dimensions.

3.2 Ray Tracing

Ray tracing is a useful technique to determine the various characteristics of an image as mentioned previously and to determine how the lens or mirror will create the image. To do this, we must draw various lines of sight and use the law of reflection to determine the various properties of the image. We will look at this technique in detail for the various lenses and mirrors later on.

3.3 Plane Mirrors

Plane mirrors are the most common type of mirrors, and are the most straightforward in terms of the optics as well. Since plane mirrors are flat, they follow the law of reflection, as a person sees the image of an object due to the reflection of the light ray emanated by the object. If the reflected light ray is extended backward behind the mirror for several viewers, we can see that they all intersect at a special point, the image location of the object, from which all the reflected light seems to diverge from.

3.4 Key Terms for Mirrors and Lenses

- **Principal Axis:** Line passing through the center of the spherical shape of the mirror and the mirror
- **Focal Point:** Point midway between the center of curvature and the vertex

- **Center of Curvature:** Point in the center of the spherical shape of the mirror
- **Radius of Curvature:** Distance from the vertex to the center of curvature
- **Vertex:** Point on the mirror's surface where the principal axis meets the mirror
- **Focal Length:** Distance from the focal point to the mirror

3.5 Concave Mirrors

Rules for Ray Tracing:

1. Any incident ray traveling parallel to the principal axis will pass through the focal point upon reflection.
2. Any incident ray passing through the focal point will travel parallel to the principal axis upon reflection.

Images for Various Object Locations:

1. Object located beyond center of curvature: Real, reduced, inverted image is between the center of curvature and the focal point
2. Object located at center of curvature: Real, same-sized, inverted image is at the center of curvature
3. Object located between center of curvature and focal point: Real, larger, inverted image is located beyond the center of curvature
4. Object located at focal point: No image is formed
5. Object located in front of the focal point: Virtual, magnified, upright image is formed behind the mirror

3.6 Convex Mirrors

Rules for Ray Tracing:

1. Any incident ray traveling parallel to the principal axis will reflect in such a manner that its extension will pass through the focal point.
2. Any incident ray traveling towards a convex mirror such that its extension passes through the focal point will reflect and travel parallel to the principal axis.

The image for any object is virtual, reduced, and upright.

3.7 Double Convex (Converging) Lenses

Rules for Ray Tracing:

1. Any incident ray traveling parallel to the principal axis will refract through the lens and travel through the focal point on the opposite side.
2. Any incident ray traveling through the focal point will refract through the lens and travel parallel to the principal axis.
3. An incident ray that passes through the center of the lens will continue in the same direction.

Images for Various Object Locations:

1. Object located beyond $2F$: Real, reduced, inverted image between F and 2F
2. Object located at 2F: Real, same-sized, inverted image at 2F
3. Object located between 2F and F: Real, larger, inverted beyond 2F
4. Object located at F: No image is formed
5. Object located in front of the focal point: Virtual, magnified, upright image before lens

3.8 Double Concave (Diverging) Lenses

Rules for Ray Tracing:

1. Any incident ray traveling parallel to the principal axis will refract and travel in line with the focal point.
2. Any incident ray traveling towards the focal point will refract and travel parallel to the principal axis.
3. An incident ray passing through the center of the lens will continue in the same direction.

The image for any object is virtual, reduced, upright.

3.9 The Mirror/Lens and Magnification Equations

The Mirror/Lens Equation is an equation that relates the object, image, and focal distances.

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f} \tag{3}$$

The Magnification Equation is an equation that relates the height of the image to the height of the object as well as the ratio of the object and image distances.

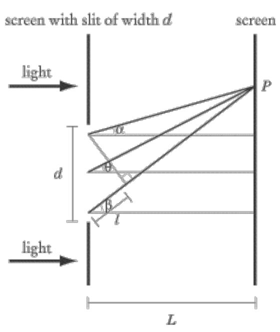
$$M = \frac{h_i}{h_o} = -\frac{d_i}{d_o} \tag{4}$$

4 Wave Optics

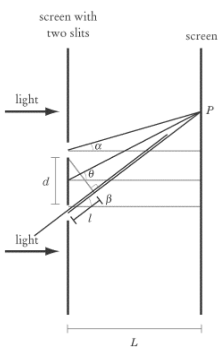
So far, we have used a classical approach to optics. The wavelike model of light rose to fame in the late 1700s and the early 1800s. Now, we will use this model to describe some phenomena.

4.1 Diffraction and Interference

Diffraction is a phenomenon that occurs when a light wave bends around obstacles or goes through a small opening. A diffraction grating is a screen with a bunch of parallel slits, each spaced a distance d apart. When the wave passes through one of these slits, an interference pattern results. For a single-slit experiment, there will be a front screen containing the slit and a back screen which will display the interference pattern of the light beams after they enter through the slit.



(a) Single-Slit Diffraction



(b) Young's Double-Slit Experiment

Figure 2: Diffraction and Interference Patterns

For any point P on the back screen, the diffraction pattern at that point is caused by an infinite number of waves entering the slit. The interference caused by the waves results in various maxima and minima throughout the back screen. Constructive interference occurs when waves add onto each other and are in phase, resulting in a bright maximum of light at the center of the back screen. The other instances of constructive interference are much less visible. When destructive interference occurs when the interacting waves are out of phase, we see a dark band in the back screen. Thus, the pattern on the back screen will be a series of alternating bright and dark bands, although the center band will be the brightest and most visible band.

In 1801, Thomas Young conducted a double-slit diffraction interference experiment, as shown in Figure 2(b). This experiment works in a similar way to the single-slit experiment, except that the bright bands are much more visible and clearly alternating with the dark bands.

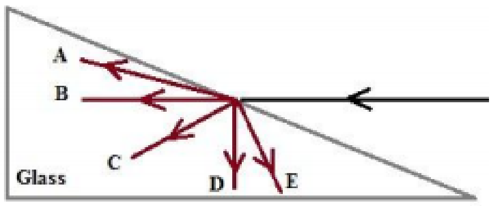
4.2 Polarization

Polarization is another phenomenon that can affect light waves. Naturally light is a transverse wave, oscillating in a direction perpendicular to the direction in which it is traveling. There are certain crystals that have the property of polarizing light, forcing the light to oscillate in only the direction of the crystals' alignment.

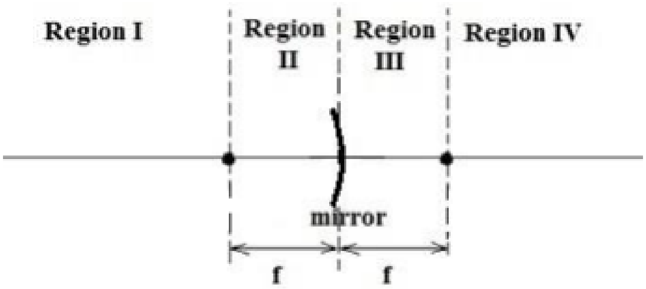
To the naked eye, the difference between unpolarized light and polarized light cannot be observed. However, if two filters are used with different polarizations, the light that gets through will be dimmed, as not all of the light will be able to pass through.

5 Problems

1. Where is the image of an object placed 7 centimeters away from a 5 centimeter focal length convex lens? Concave mirror? Are the images real or virtual in each case? [Easy]
2. Light of wavelength 600 nm is transmitted from air (n = 1) into a piece of glass (n = 1.5). Which one of the labeled arrows best indicates the path of the light ray after it enters the glass? [Easy]



3. A concave mirror with focal length f is shown in the figure. A real object is now placed to the left of the mirror. In theory, in which regions is it impossible for an image to form from the mirror, regardless of where the object is placed to the left of the mirror? [Medium]



4. Why does a plane mirror only reflect from left to right? [Tricky]