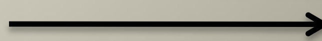
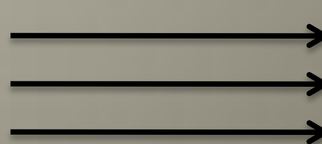
Chapter 2

Ray theory and applications

- A number of optic phenomena (particularly those associated with lenses) are adequately explained by considering that the optical energy in a wave follows narrow paths, called ***rays***.



- Because these rays are used to describe optical effects geometrically, ray theory is called *geometrical optics.*
- Although rays are really geometrical paths, it is often convenient to speak of them as if they actually carried the **beam** energy



Ray theory and applications

- Rays travel at certain speeds and reflected by objects i.e. the energy in the wave is traveling at speed or is reflected by the object. Rays obey simple rules:
- **Rules 1.**
- In a vacuum, rays travel at a velocity of $c = 3 \times 10^8$ m/s.
- In any other medium it travel at slower speed, given by

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

- n is the ***index of refraction*** (*refractive index)* of medium.
- For air and gases, the ray velocity is very close to c, so that $n \cong 1$.

Ray theory and applications

- At optic frequencies, the refractive index of water is 1.33.
- Glass has many compositions, each with a slightly different ray velocity.
- for the silica glasses used in fibers it is 1.5 approx.
- more precise values for these glasses lie between 1.45 and 1.48.
- Table 2-1 lists the refractive index for several materials.
- index varies with a number of parameters (such as temperature and wavelength)

Index of Refraction (Some Materials)

Index of Material	**Refraction**
Air	1.0
Carbon dioxide	1.0
Water	1.33
Ethyl alcohol	1.36
Magnesium fluoride	1.38
Fused silica	1.46
Polymethyl methacry late	1.49
Silica glass	1.5
Sodium chloride	1.54
Polystyrene	1.59
Calcite	1.6
Sapphire	1.8
Lithium niobate	2.25
Zinc sulfide	2.3
Rutile	2.6
Indium phosphide	3.21
Gallium arsenide	3.35
Silicon	3.5
Indium gallium arsenide phosphide	3.51
Aluminum gallium arsenide	3.6
Germanium	4.0

Rules 2.

- Rays travel in **straight paths** unless deflected by some change in the medium.

Rules 3.

- At a plane boundary between two media, a ray is **reflected** at an angle equal to the angle of incidence, as illustrated in Fig. 2-1.
  - Note that the angles are measured with respect to the boundary normal i.e. the direction perpendicular to the surface. This is the conventional notation in optic work.

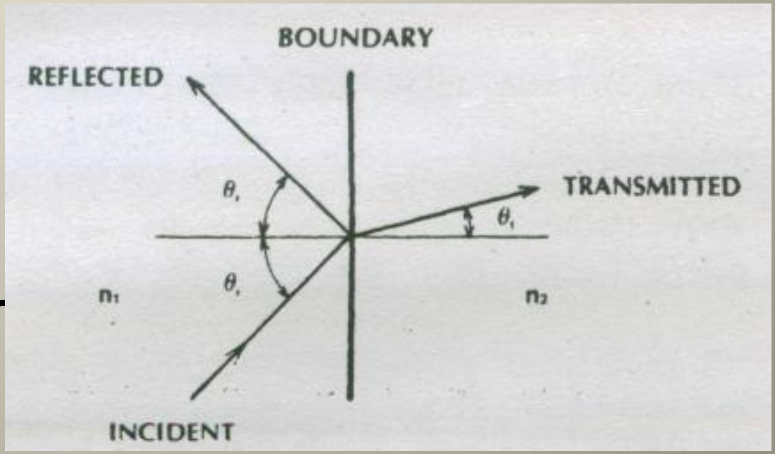


Figure 2-1 Incident, reflected, and transmitted rays at a boundary between two media

it is clear that $\boldsymbol{\theta_r = \theta_i}$ **(2-2)**

where $\boldsymbol{\theta_i}$, is the angle of incidence

$\boldsymbol{\theta_r}$ .is the angle of reflection.

Rules 4. *Snell 's law*

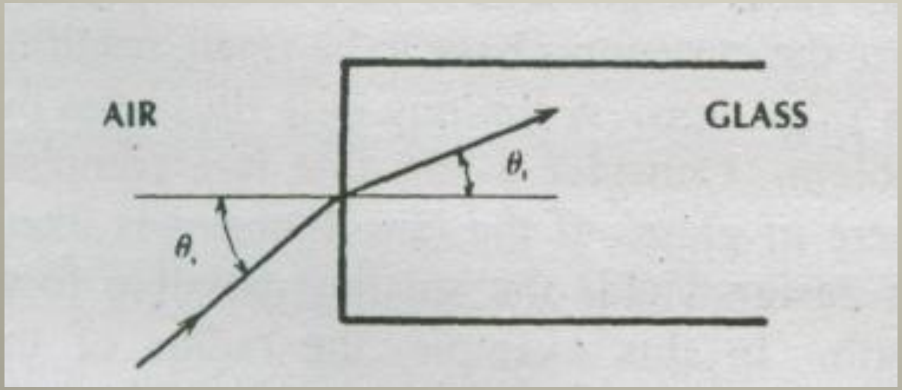
- If ray crosses the boundary, the transmitted ray direction is given by *Snell 's law*

$$\frac{\sin \theta_t}{\sin \theta_i} = \frac{n_1}{n_2}$$

- where θ_t is the angle of transmission and n_1 and n_2 are the refractive indices of the incident and transmission regions.
- The only angles having physical significance are those lying between 0° and 90°. The trigonometric sine function is plotted in Fig. 2-2 over this range.

Snell 's law

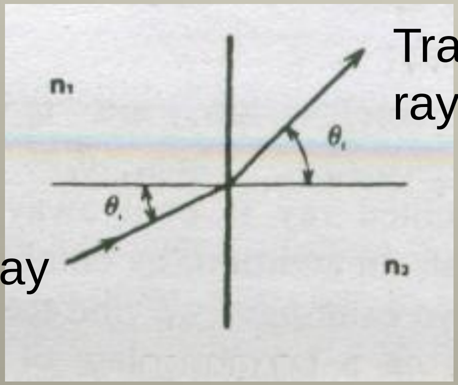
- The transmitted ray is bent toward the normal when traveling from a medium having a low refractive index into a medium with a higher refractive index.
- If $n_i > n_2$ Snell's law yields $\mathbf{\sin \theta_t > \sin \theta_i}$.



Bending of a light ray as it enters a glass fiber

Snell 's law

- The transmitted ray is bent away from the normal when traveling from a medium having a **high** refractive index into a medium with a **lower** refractive index.
- So $\boldsymbol{\theta_t > \theta_i}$, and the ray is bent away from the normal,



When $n_1 > n_2$, the ray is bent **away** from the normal and toward the boundary surface.

A light ray proceeds from air (n_1 = 1) into glass (n_2 = 1.5). Find the transmission angles when θ_i = 0° and when θ_t = 15°

- **Solution:**
- When the incident angle is 0, then sin θ_i = 0°.
- Snell's law yields sin θ_t = 0 and finally θ_t, = 0° itself.
- The ray is undeflected.

- When θ_t= 15°,
- $$\frac{\sin \theta_t}{\sin \theta_i} = \frac{n_1}{n_2}$$
- $$\frac{\sin \theta_t}{\sin 15} = \frac{1}{1.5}$$
- $$\sin \theta_t = \frac{1}{1.5} \times \sin 15$$
- $$\sin \theta_t = \frac{1}{1.5} \times .258$$
- $$\sin \theta_t = .17$$
- $$\theta_t = 9.93$$
- As expected, the ray is redirected toward the normal.

If light is incident upon a piece of glass of refractive index 1.52, at an angle of 45. What is the angle of refraction/transmission.

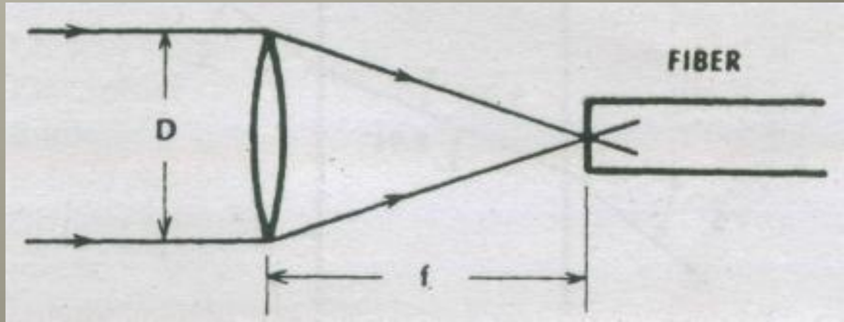
Lenses

- Fibers can be tested by sending visible beams of light through them.
- A continuity check can be made by observing whether any light emerges from the end of the fiber.
- Cracks or in homogeneities in a bare fiber can be located by observing the scattered light they produce.
- Gas lasers are convenient for these tests. Because their output beams have diameters of the order of a millimeter (and fibers are much smaller), a lens is used to focus the light onto the fiber end face.

Thin Lenses

- To simplify we consider only ***thin lenses.*** *A* lens is thin when its thickness is so small that the translation of a ray is negligible.
- i.e. rays enter and leave at the same distance from the lens axis.
- We will assume initially that our lenses are ideal, have no absorption or reflection losses, and produce no aberrations.
- In Fig. a parallel beam of light (called a *collimated beam)* is focused to a point.
- The incident light is made up of a no of **parallel rays**.
- All the rays converge to the position, known as the ***focal point.*** It lies at distance f (called *the focal length)* from the lens.

The plane that passes through the focal point and is perpendicular to the axis of the lens is the ***focal plane.***

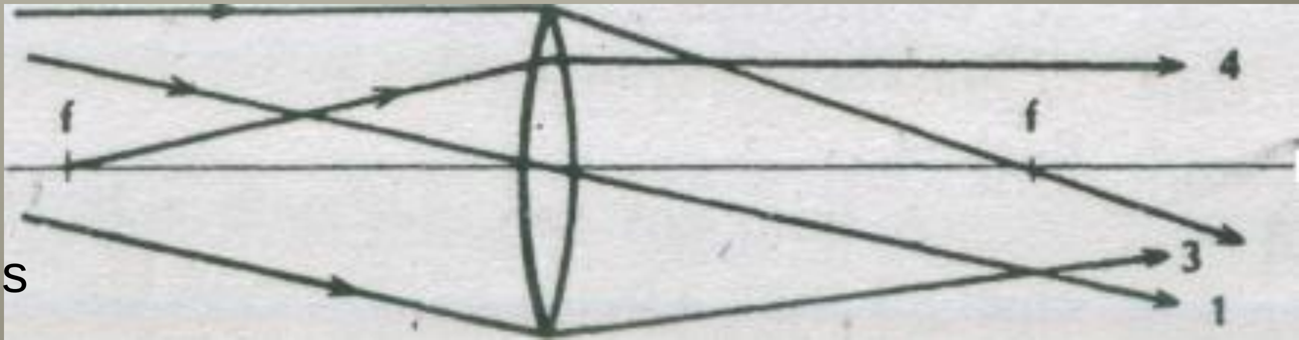


Rules for tracing rays

These rules will enable you to trace rays for focusing, collimating, and imaging by using thin lenses.

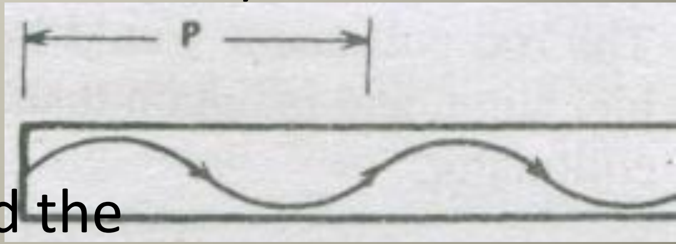
1. Rays traveling through the center of the lens are **un-deviated**.
2. Incident rays traveling parallel to the lens axis pass **through the focal point** after emerging from the lens.
3. An incident ray traveling parallel to a central ray **intersects that ray in the focal plane** after transmission through the lens.
4. An incident ray passing through the focal point travels **parallel to the lens axis** after it emerges from the lens.

The no. refer to the rules

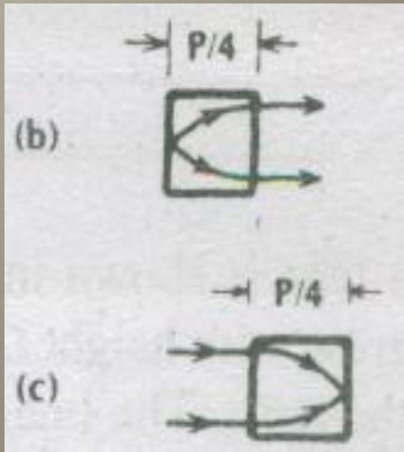


GRIN

- The *graded-index rod lens,(*GRIN) rod lens, is a modern development that has been applied to fiber systems in a no. of ways.
- The GRIN rod has a refractive index that decreases with distance from its axis. This causes light rays to travel in sinusoidal paths .(Section 5-2 for more discussion.)

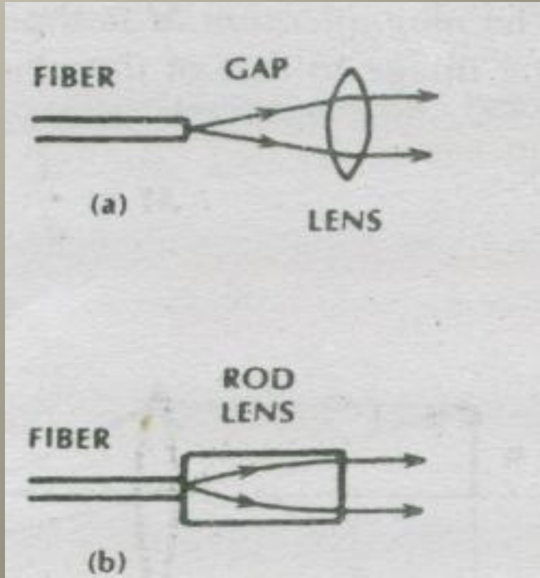


- The length of one complete cycle is called the lens *pitch P.*
- Notice what will happen if a length of rod is cut equal to a *quarter pitch.* The light from a point source located at the center of this rod will be collimated
- Collimated light entering this lens will be focused



GRIN

- Evidently, the GRIN rod has focusing and collimating properties in common with the classical spherical lens.
- The GRIN rod is also useful for imaging. The rod is desirable because small focal lengths can be obtained, permitting construction of short, solid optic structures.
- E.g. the light emitted from the end of a fiber can be collimated by
  - a conventional lens (Fig. 2-16(a) or
  - by a rod lens (Fig. 2-16(b).



GRIN

- When the spherical lens is used, an air gap exists between the fiber and the lens. The rod lens needs no gap.
- The fiber can be cemented to the rod, yielding a continuous and solid mechanical structure.
- The rod collimator would be easier to assemble, align, and maintain than the spherical-lens collimator