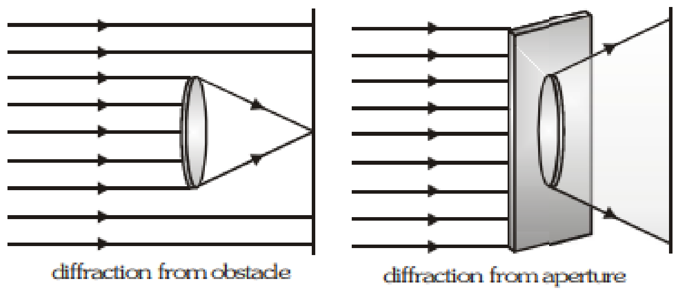
WAVE OPTICS

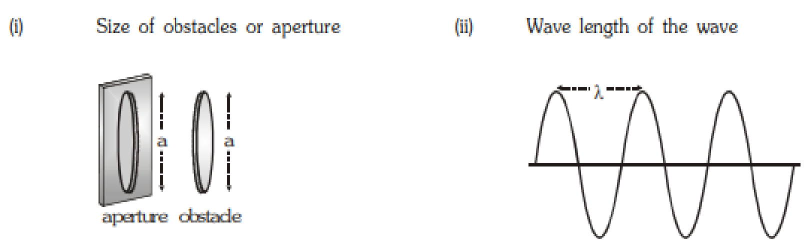
DIFFRACTION

DIFFRACTION OF LIGHT

The phenomenon characterized by the deviation of light rays as they interact with the sharp edges of an opaque obstacle or aperture, causing them to disperse within the geometric shadow region, is formally termed "light diffraction." This encompasses the alteration of light's otherwise straight-line propagation tendency.



- The revelation of diffraction can be credited to Grimaldi's pioneering observations.
- A comprehensive theoretical framework for diffraction was subsequently provided by Fresnel.
- It's essential to recognize that diffraction is a phenomenon applicable to various types of waves, encompassing both mechanical and electromagnetic waves. In essence, it is a universal characteristic of wave behavior.
- The manifestation of diffraction is contingent upon two primary factors.



In the context of diffraction, a critical condition emerges when the dimensions of the obstacle or aperture closely match the wavelength of light, denoted as λ, and are represented as α. mathematically, this condition is expressed as

$\lambda = \alpha$, resulting in $\frac{\alpha}{\lambda} = 1$.

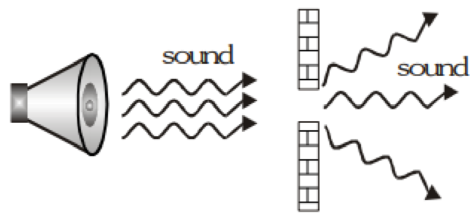
Conversely, when the size of the obstacle significantly surpasses the wavelength of light, diffraction becomes negligible, and light tends to propagate in a straight-line, exhibiting a rectilinear motion.

- Practical observation reveals that when the size of an aperture or obstacle exceeds approximately 50 times the wavelength (λ), diffraction effects become negligible.

- Light waves exhibit a wavelength in the order of 10^-7 meters, making it uncommon to encounter obstacles of this specific wavelength, resulting in light rays appearing to propagate in a straight-line path. In contrast, sound waves have much longer wavelengths, ranging from 16 millimeters to 16 meters, which contributes to their increased tendency to diffract when encountering objects in our daily environment.

- Ultrasonic waves, with a wavelength on the order of about 1 centimeter, do not readily display diffraction, whereas radio waves, featuring considerably longer wavelengths ranging from 2.5 meters to 250 meters, exhibit noticeable diffraction effects.

- Remarkably, X-rays are highly amenable to diffraction by crystals, and this phenomenon was first discovered by Lave.



diffraction of sound from a window

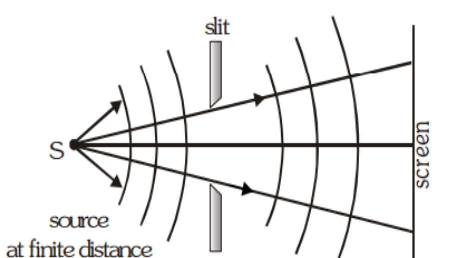
TYPES OF DIFFRACTION

Light diffraction encompasses two fundamental categories:
(a) Fresnel diffraction.
(b) Fraunhofer diffraction.

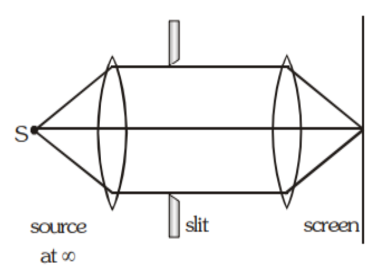
(a) Fresnel diffraction

When either the source of light, the screen, or both are situated at finite distances from the diffracting element, such as an obstacle or aperture, the resulting phenomenon is termed "Fresnel diffraction." In this case, the observed pattern is essentially the shadow of the diffracting element, which is subsequently altered by the effects of diffraction.

For instance, the diffraction occurring at the edge of a straight surface, a small opaque disc, or a narrow wire are illustrative examples of Fresnel diffraction.



Fresnel's diffraction



Fraunhofer's diffraction

(b) Fraunhofer diffraction

Fraunhofer diffraction represents a specific and constrained scenario within the broader category of Fresnel diffraction. In the case of Fraunhofer diffraction, both the source of light and the screen are considered to be positioned at effectively infinite distances from the diffracting apparatus. The resulting pattern observed under Fraunhofer diffraction is essentially the image of the light source, which is then subjected to modifications brought about by diffraction effects.

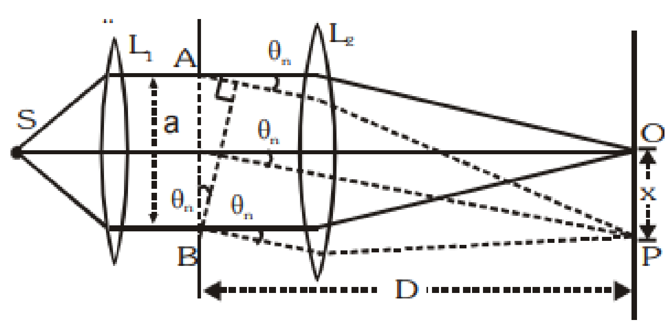
This is prominently exemplified in situations like the diffraction occurring at a single slit, a double slit, or a diffraction grating, all of which serve as instances of Fraunhofer diffraction.

Comparison between Fresnel and Fraunhofer diffraction

	Fresnel Diffraction	Fraunhofer Diffraction
(a)	Source and screen both are at finite distance from the diffractor.	Source and screen both are at infinite distance from the diffractor
(b)	Incident and diffracted wave fronts Are spherical or cylindrical.	Incident and diffracted wave fronts are Plane due to infinite distance from source.
(c)	Mirror or lenses are not used for Obtaining the diffraction pattern.	Lens are used in this diffraction pattern.
(d)	Centre of diffraction pattern is sometime bright and sometime dark depending on size of diffractor and distance of observation point.	Centre of diffraction is always bright.
(e)	Amplitude of wave coming from Different half period zones are different due to difference of obliquity.	Amplitude of waves coming from Different half period zones are same due to same obliquity.

FRAUNHOFER DIFFRACTION DUE TO SINGLE SLIT

AB is single slit of width a, Plane wave front is incident on a slit AB. Secondary wavelets coming from every part of AB reach the axial point P in same phase forming the central maxima. The intensity of central maxima is maximum in this diffraction. Where θn represents direction of nth minima Path difference BB' = a sin θn



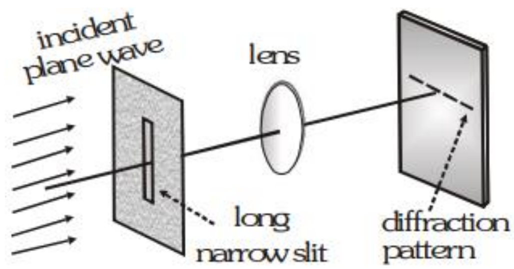
For the nth order minima, the condition is expressed as: a sin $\theta_n = n_\lambda$

(If θn is small)

When considering the disparity in path lengths between secondary wavelets originating from

If the path difference between points A and B measures as n_λ, $2n\left(\frac{\lambda}{2}\right)$, or any other even multiple of these values, it results in the occurrence of minima.

For minima $a\sin\theta_n = 2n\left(\frac{\lambda}{2}\right)$ where n = 1, 2, 3...



When the path discrepancy between the secondary wavelets emanating from

If the path difference between points A and B amounts to $(2n+1)\frac{\lambda}{2}$ or any odd multiple of $\frac{\lambda}{2}$, it leads to the manifestation of maxima.

For maxima $a\sin\theta_n = (2n+1)\frac{\lambda}{2}$ where n = 1, 2, 3...

$n = 1 \rightarrow$ first maxima and $n = 2 \rightarrow$ second maxima

An alternating sequence of minima and maxima is observed on both sides of the central maximum.

RESOLVING POWER (R.P.)

The phenomenon of light diffraction results in the formation of numerous images from a single source. When two sources are positioned in such a way that the central maxima of their respective diffraction patterns do not overlap, their individual images can be distinctly identified and are said to be "resolved." In the context of an optical instrument, the term "resolution power" (R.P.) characterizes its capacity to differentiate and distinguish between two adjacent or neighboring points in an observed scene or object.

Linear R.P. = $d/\lambda D$ here D = Observed distance

Angular R.P. = d/λ d = Distance between two points

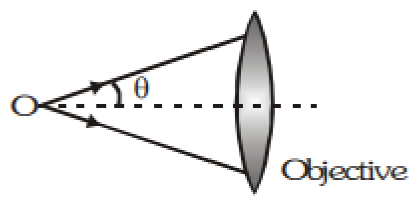
Microscope

Regarding a microscope, the smallest separation between two closely positioned lines, at which they can be perceived as separate entities, is referred to as the "Resolving Limit" (RL). Its inverse is known as the "Resolving Power" (RP).

$$R.L. = \frac{\lambda}{2\mu \sin\theta} \qquad \text{And} \qquad R.P = \frac{2\mu\sin\theta}{\lambda} \qquad \Rightarrow R.P \alpha \frac{1}{\lambda}$$

In the context of optical systems, the following parameters are defined:

- λ represents the wavelength of the light employed to illuminate the object.
- μ signifies the refractive index of the medium situated between the object and the objective lens.
- θ represents the half-angle subtended by the cone of light originating from a point object.
- $\mu \sin\theta$ is referred to as the numerical aperture, which characterizes the light-gathering ability of the optical system.



Telescope

The minutest angular distinctions d_θ between two remote objects, such that their respective images can be distinguished in a telescope, are denoted as the "resolving limit." The formula for the resolving limit is expressed as $d\theta = 1.22\lambda/a$, where λ represents the wavelength of the light used and 'a' signifies the aperture size of the optical system.

Consequently, the "resolving power" (RP) of the telescope, which denotes its capability to discriminate between such closely spaced objects, can be quantified by RP $= \frac{1}{d_\theta}$.

$$(RP) = \frac{1}{d\theta} = \frac{a}{1.22\lambda} \Rightarrow R.P\alpha\frac{1}{\lambda} \text{ Where a = aperture of objective}$$

Example.

When light characterized by a wavelength of 5000 angstroms interacts with a slit of 0.1 millimeters in width, the objective is to ascertain the breadth of the central bright region observed on a screen positioned 2 meters away from the slit.

Solution.

$$w_x = \frac{2f\lambda}{a} = \frac{2\times2\times5\times10^{-7}}{10^{-4}} = 20mm$$