Introduction to Diffraction Patterns:

We discussed the fact that light of wavelength comparable to or larger than the width of a slit spreads out in all forward directions upon passing through the slit. We call this phenomenon *diffraction*. This behavior indicates that light, once it has passed through a narrow slit, spreads beyond the narrow path defined by the slit into regions that would be in shadow if light traveled in straight lines. Other waves, such as sound waves and water waves, also have this property of spreading when passing through apertures or by sharp edges.

We might expect that the light passing through a small opening would simply result in a broad region of light on a screen, due to the spreading of the light as it passes through the opening. We find something more interesting, however. A diffraction pattern consisting of light and dark areas is observed, somewhat similar to the interference patterns discussed earlier. For example, when a narrow slit is placed between a distant light source (or a laser beam) and a screen, the light produces a diffraction pattern like that in Figure 38.1.

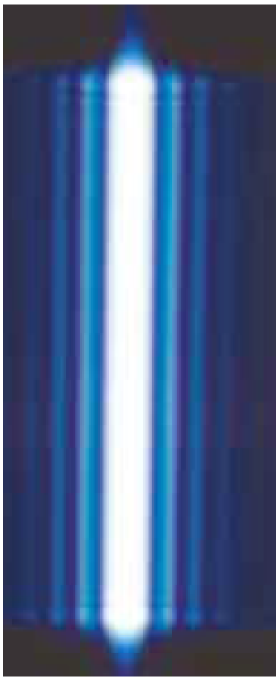

Figure 38.1 The diffraction pattern that appears on a screen when light passes through a narrow vertical slit. The pattern consists of a broad central fringe and a series of less intense and narrower side fringes.

The pattern consists of a broad, intense central band (called the central maximum), flanked by a series of narrower, less intense additional bands (called side maxima or secondary maxima) and a series of intervening dark bands (or minima). Figure 38.2

shows a diffraction pattern associated with light passing by the edge of an object. Again we see bright and dark fringes, which is reminiscent of an interference pattern.

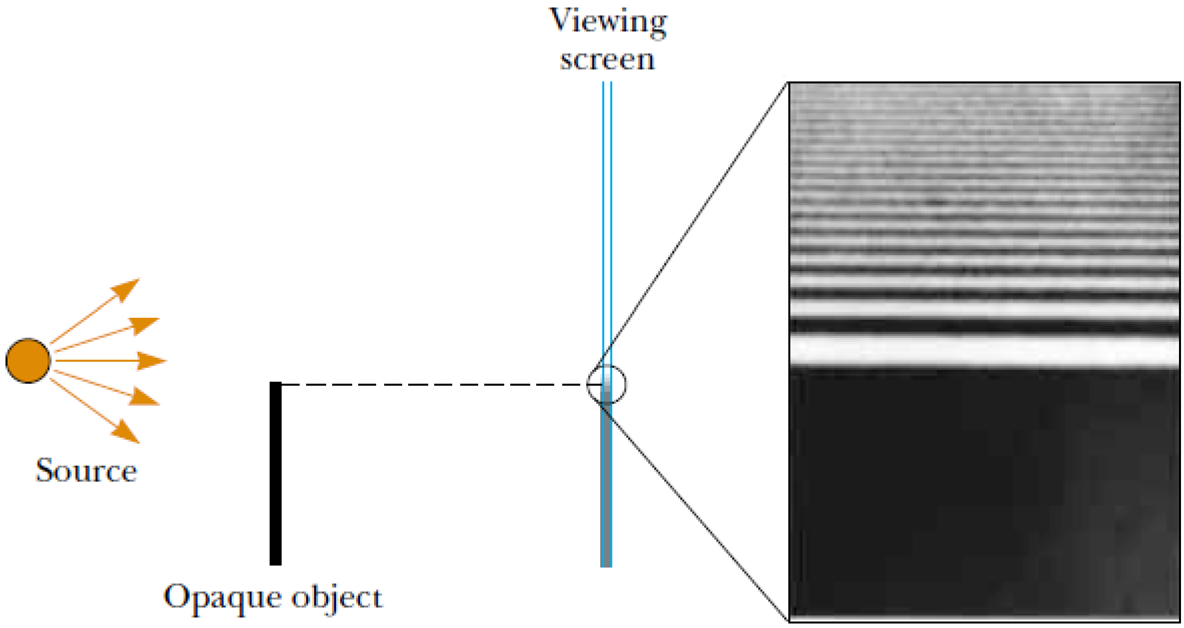

Figure 38.2 Light from a small source passes by the edge of an opaque object and continues on to a screen. A diffraction pattern consisting of bright and dark fringes appears on the screen in the region above the edge of the object.

Figure 38.3 shows a diffraction pattern associated with the shadow of a penny. A bright spot occurs at the center, and circular fringes extend outward from the shadow's edge. We can explain the central bright spot only by using the wave theory of light, which predicts constructive interference at this point. From the viewpoint of geometric optics (in which light is viewed as rays traveling in straight lines), we expect the center of the shadow to be dark because that part of the viewing screen is completely shielded by the penny.

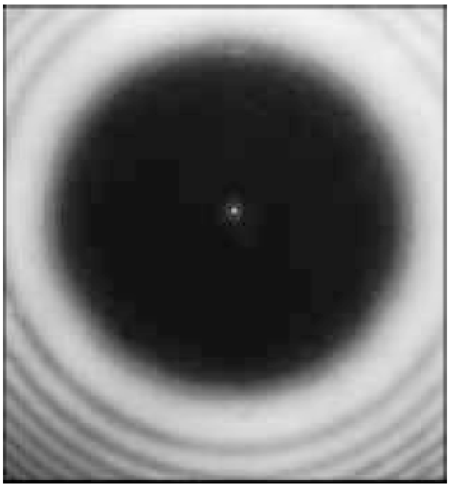

Figure 38.3 Diffraction pattern created by the illumination of a penny, with the penny positioned midway between screen and light source. Note the bright spot at the center.

Fresnel and Fraunhofer Diffraction

Diffraction phenomena are conveniently divided into two general classes, (1) those in which the source of light and the screen on which the pattern is observed are effectively at infinite distances from the aperture causing the diffraction and (2) those in which either the source or the screen, or both, are at finite distances from the aperture. The phenomena coming under class (1) are called, for historical reasons, *Fraunhofer diffraction,* and those coming under class (2) *Fresnel diffraction.* Fraunhofer diffraction is much simpler to treat theoretically. It is easily observed in practice by rendering the light from a source parallel with a lens and focusing it on a screen with another lens placed behind the aperture, an arrangement which effectively removes the source and screen to infinity. In the observation of Fresnel diffraction, on the other hand, no lenses are necessary, but here the wave fronts are divergent instead of plane, and the theoretical treatment is consequently more complex. Only Fraunhofer diffraction will be considered in this chapter.

Diffraction Patterns from Narrow Slits

Let us consider a common situation, that of light passing through a narrow opening modeled as a slit, and projected onto a screen. To simplify our analysis, we assume that the observing screen is far from the slit, so that the rays reaching the screen are approximately parallel. This can also be achieved experimentally by using a converging lens to focus the parallel rays on a nearby screen. In this model, the pattern on the screen is called a ***Fraunhofer diffraction pattern***.

If the screen is brought close to the slit (and no lens is used), the pattern is a Fresnel diffraction pattern. The Fresnel pattern is more difficult to analyze, so we shall restrict our discussion to Fraunhofer diffraction.

Diffraction vs. Diffraction Pattern

Diffraction refers to the general behavior of waves spreading out as they pass through a slit. We used diffraction in explaining the existence of an interference pattern in last Chapter. A diffraction pattern is actually a misnomer but is deeply entrenched in the language of physics. The diffraction pattern seen on a screen when a single slit is illuminated is really another interference pattern. The interference is between parts of the incident light illuminating different regions of the slit.

Figure 38.4a shows light entering a single slit from the left and diffracting as it propagates toward a screen. Figure 38.4b is a photograph of a single-slit Fraunhofer

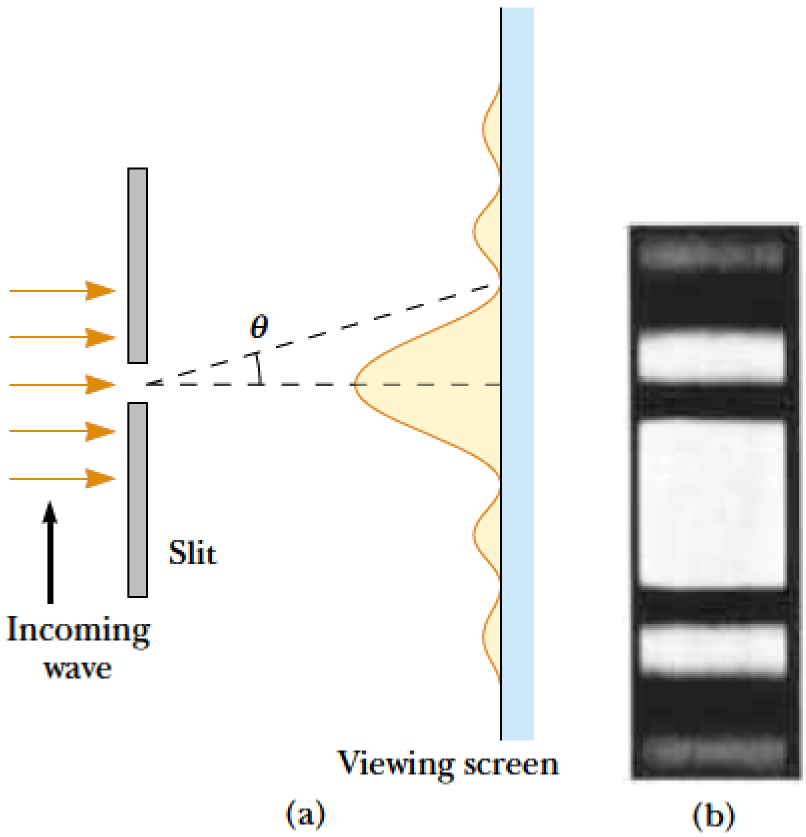

Figure 38.4 (a) Fraunhofer diffraction pattern of a single slit. The pattern consists of a central bright fringe flanked by much weaker maxima alternating with dark fringes. (Drawing not to scale.) (b) Photograph of a single-slit Fraunhofer diffraction pattern.

diffraction pattern. A bright fringe is observed along the axis at $\theta = 0$, with alternating dark and bright fringes on each side of the central bright fringe.

Until now, we have assumed that slits are point sources of light. In this section, we abandon that assumption and see how the finite width of slits is the basis for understanding Fraunhofer diffraction. We can deduce some important features of this phenomenon by examining waves coming from various portions of the slit, as shown in Figure 38.5. According to Huygens's principle, each portion of the slit acts as a source of light waves. Hence, light from one portion of the slit can interfere with light from another portion, and the resultant light intensity on a viewing screen depends on the direction θ. Based on this analysis, we recognize that a diffraction pattern is actually an interference pattern, in which the different sources of light are different portions of the single slit!

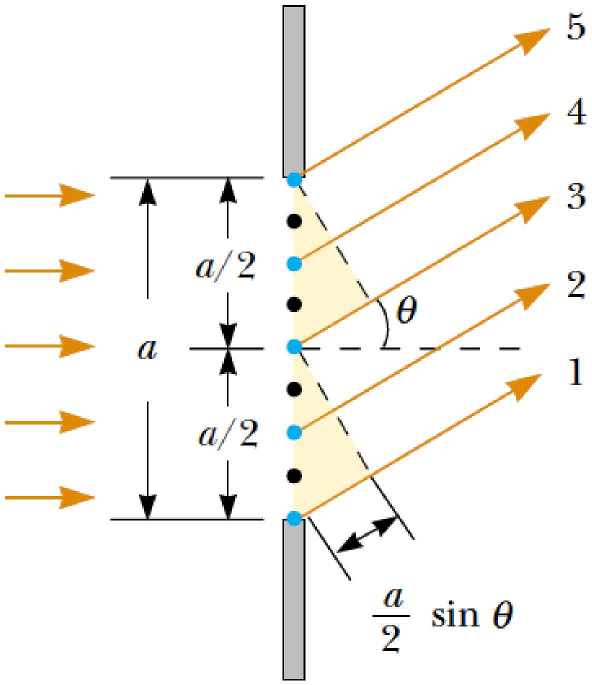

Figure 38.5 Paths of light rays that encounter a narrow slit of width a and diffract toward a screen in the direction described by angle θ. Each portion of the slit acts as a
point source of light waves. The path difference between rays 1 and 3, rays 2 and 4, or rays 3 and 5 is (a/2) sin θ.

To analyze the diffraction pattern, it is convenient to divide the slit into two halves, as shown in Figure 38.5. Keeping in mind that all the waves are in phase as they leave the slit, consider rays 1 and 3. As these two rays travel toward a viewing screen far to the right of the figure, ray 1 travels farther than ray 3 by an amount equal to the path difference $(a/2)\sin\theta$, where a is the width of the slit. Similarly, the path difference between rays 2 and 4 is also $(a/2)\sin\theta$, as is that between rays 3 and 5. If this path difference is exactly half a wavelength (corresponding to a phase difference of 180°), then the two waves cancel each other and destructive interference results. If this is true for two such rays, then it is true for any two rays that originate at points separated by half the slit width because the phase difference between two such points is 180°. Therefore, waves from the upper half of the slit interfere destructively with waves from the lower half when

$$\frac{a}{2}\sin\theta = \pm\frac{\lambda}{2}$$

or when