Chapter Twelve

LIGHT AND GEOMETRIC OPTICS

KEY IDEAS

Visible light is part of the electromagnetic spectrum of waves. Electromagnetic waves are transverse and have a constant speed in space. Because light is a periodic wave, it possesses the characteristics and properties of all periodic waves: reflection, refraction, interference, and diffraction, and it exhibits the Doppler effect.

The principal applications of reflected light involve the use of plane and curved mirrors. Lenses, prisms, and fiber-optic bundles are applications of refraction of light.

Diffraction and interference can be demonstrated by passing light through a single- or double-slit arrangement. These devices can be used to measure the wavelength of light. Interference also occurs with the reflected light from thin films and is responsible for the colors seen on soap bubbles and oil slicks.

If monochromatic light is generated so that all of the waves have a constant phase relationship, the light is said to be coherent. Lasers produce intense beams of coherent light.

KEY OBJECTIVES

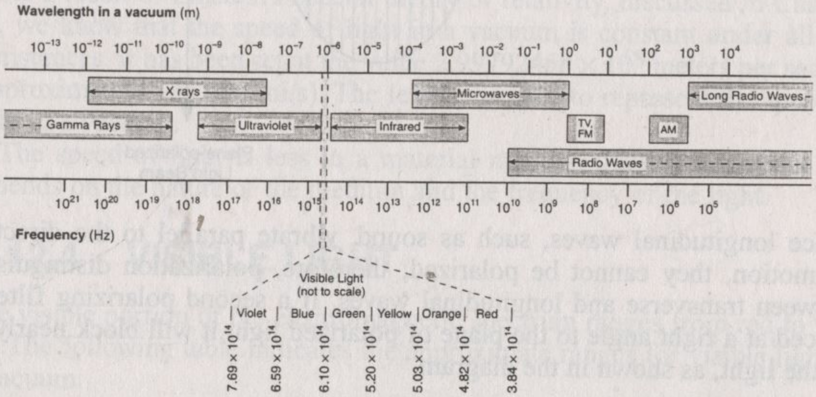
At the conclusion of this chapter you will be able to:

- Define the term *polarization*, and explain why polarization distinguishes between transverse and longitudinal waves.
- Explain how reflection of light produces an image in a plane mirror, and describe the characteristics of such an image.
- Explain how light refracts as it passes from one medium to another.
- Define the term *absolute index of refraction*, and solve problems using this concept.
- State Snell's law in terms of absolute indices of refraction, and solve problems using this equation.
- Define the terms *critical angle* and *total internal reflection,* and relate them to Snell's law.
- Define the term *dispersion*.
- Describe the patterns produced when monochromatic light passes through a double-slit arrangement, and explain how these patterns are formed.

- Explain the difference between the pattern produced by a double-slit arrangement and that produced by a single-slit arrangement.
- Define the term *laser*, and explain how laser light differs from ordinary light.

12.1 INTRODUCTION

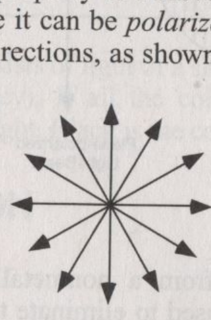
Light is an electromagnetic wave. The different forms of light constitute the *electromagnetic spectrum*, diagramed below, of which visible light is only a very small part.



Electromagnetic waves differ in their frequency and in the sources used to produce them.

12.2 POLARIZATION OF LIGHT

Polarization is the separation of a beam of light so that the vibrations are in one plane. It is an exclusive property of transverse waves. We know that light is a transverse wave because it can be *polarized.* When a light wave is produced, it vibrates in many directions, as shown below.



Unpolarized Light Beam

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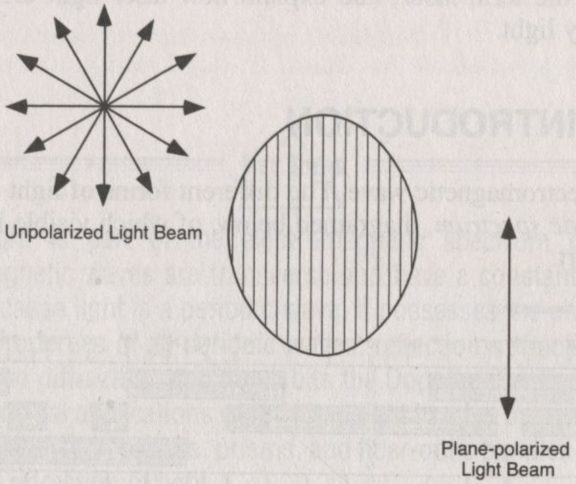
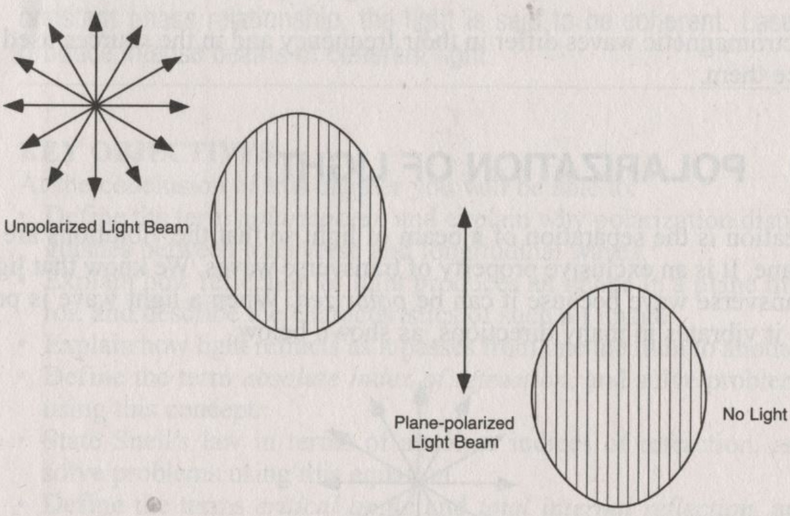
If, however, a beam of light passes through a polarizing filter, the beam that emerges will vibrate in one plane only and is said to be *plane polarized*.



Since longitudinal waves, such as sound, vibrate parallel to the direction of motion, they cannot be polarized; therefore, polarization distinguishes between transverse and longitudinal waves. If a second polarizing filter is placed at a right angle to the plane of polarized light it will block nearly all of the light, as shown in the diagram.



When light is reflected from a nonmetallic surface, it is polarized. Polarized sunglasses can be used to eliminate the glare associated with this type of reflection.

✱ 12.3 SPEED OF LIGHT

Anyone who has observed lightning or fireworks from a distance knows that the flash of light appears nearly instantaneously, while the explosion is heard somewhat later. We know that sound travels in air at approximately 330 meters per second (about 750 mi/h), but how fast does light travel?

This question was first answered in 1675 when the Dutch astronomer Olaus Roemer used his observations of Jupiter and the eclipse of one of its moons to measure the speed of light. In the nineteenth century the American physicist Albert Michaelson used sunlight and rotating mirrors to obtain more precise measurements.

As a result of Einstein's special theory of relativity, discussed in Chapter 15, we know that the speed of light in a vacuum is constant under all circumstances. It has been set at the value 2.99792458×10^8 meters per second (approximately 186,000 mi/s). The letter c is used to represent the speed of light in a vacuum.

The speed of light is less in a material medium than in a vacuum and depends on the nature of the medium and the frequency of the light.

✱ 12.4 VISIBLE LIGHT

The visible portion of the electromagnetic spectrum ranges from red to violet. The following table indicates the approximate ranges for visible light in a vacuum.

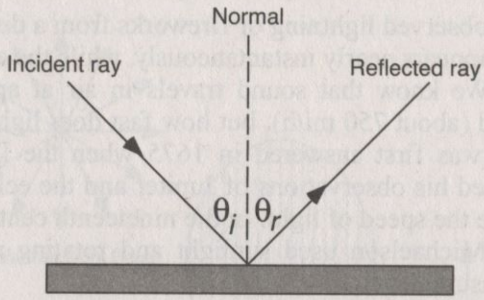
Wavelengths of Light in a Vacuum	
Violet	$4.0 - 4.2 \times 10^{-7}$ m
Blue	$4.2 - 4.9 \times 10^{-7}$ m
Green	$4.9 - 5.7 \times 10^{-7}$ m
Yellow	$5.7 - 5.9 \times 10^{-7}$ m
Orange	$5.9 - 6.5 \times 10^{-7}$ m
Red	$6.5 - 7.0 \times 10^{-7}$ m

Monochromatic light consists of light of a single color, that is, light of a single wavelength (or frequency). If all the colors of visible light are mixed together, the result is white light. Black is the complete absence of visible light.

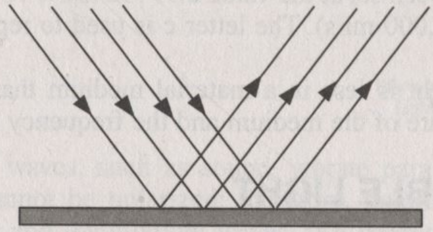
12.5 REFLECTION

✱ Law of Reflection

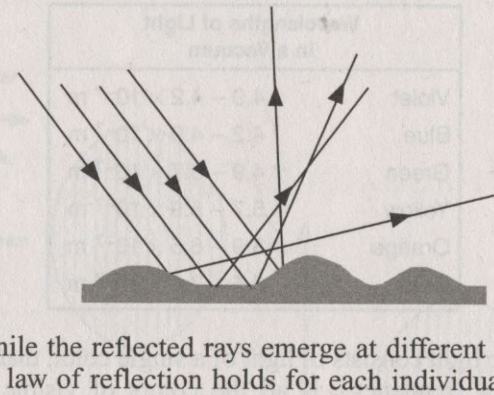
When light is reflected from a surface, the angle that the incident ray makes with the normal to the surface is equal to the angle that the reflected ray makes with the normal to the surface. This statement is known as the *law of reflection*.



Polished surfaces such as plane mirrors produce *regular* reflection.



An irregular surface such as a windblown water surface or the paper on which this book is printed produces *diffuse* reflection.



We note that, while the reflected rays emerge at different angles in the diagram above, the law of reflection holds for each individual pair of incident and reflected rays.

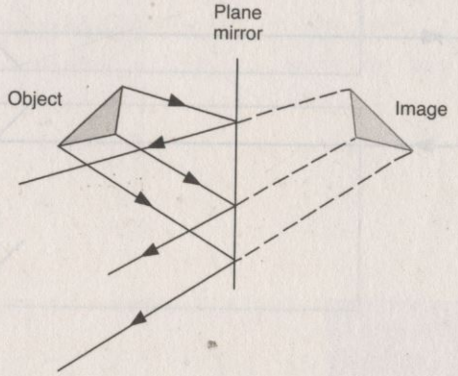
Mirrors

One primary application of reflected light is the image formed by a mirror. Mirrors may be plane or curved.

PLANE MIRRORS

When an object is viewed in a plane mirror, the image that is formed is erect (upright), left-right reversed, and the same size as the object. The object and image distances from the mirror are equal. These relationships can be proved by using the law of reflection and simple geometry.

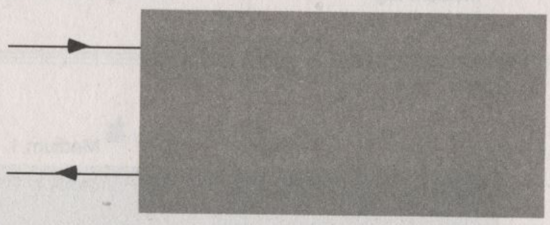
The image produced by a plane mirror is *virtual* because light does not actually pass through the mirror to form the image; it only appears to be located inside the mirror.



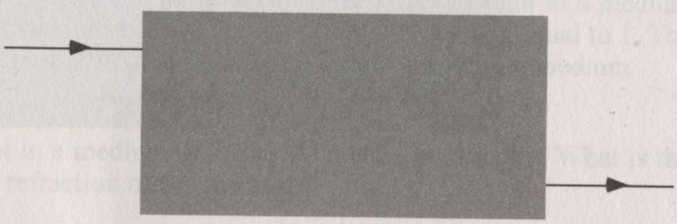
This phenomenon occurs because light appears to travel in straight lines, and a device such as a human eye searches for the apparent origin of the light.

PROBLEM

A beam of light enters and exits a hollow rectangular box. How could plane mirrors be placed in the box to produce the following patterns?



(a)



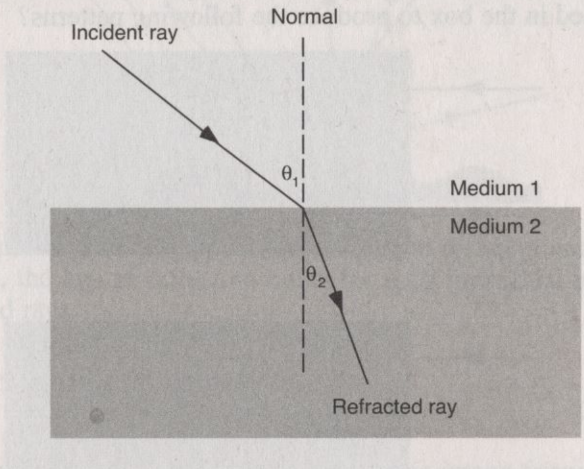
(b)

SOLUTION

(b)

12.6 REFRACTION

 When monochromatic light travels between two media, there is a change in the speed of the light wave. If the light enters at an oblique angle, it will change direction as it passes into the second medium.



PHYSICS CONCEPTS

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{v_1}{v_2}$$

A result of the relationship expressed in this equation (Snell's law) is that the slower the speed, the smaller the angle.

PROBLEM
Monochromatic light passes between two media. If the angle in medium 1 is 45° and the angle in medium 2 is 30.°, calculate the ratio of the light speeds between media 1 and 2.

Absolute Index of Refraction

To simplify refraction problems, a quantity known as the **absolute index of refraction** is defined as follows:

PHYSICS CONCEPTS

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

The equation states that the absolute index of refraction of a medium (n) is the ratio of the speed of light in a vacuum (c) to the speed of light in a medium (v). The absolute index of refraction is always greater than or equal to 1. The larger the index of refraction, the slower the speed of light in a medium.

PROBLEM
The speed of light in a medium is 2.4×10^8 meters per second. What is the absolute index of refraction of the medium?

The table below lists the indices of refraction for some common materials.

Absolute Indices of Refraction ($\lambda = 5.9 \times 10^{-7}$ m)	
Air	1.00
Alcohol (Ethyl)	1.36
Benzene	1.50
Canada Balsam	1.53
Carbon Tetrachloride	1.46
Corn Oil	1.47
Diamond	2.42
Glass, Crown	1.52
Glass, Flint	1.66
Glycerol	1.47
Lucite	1.50
Quartz, Fused	1.46
Sodium Chloride	1.54
Water	1.33
Zircon	1.92

Snell's Law

In terms of the index of refraction, the relationship

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{v_1}{v_2}$$

becomes

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

We write this as follows:

PHYSICS CONCEPTS

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

This relationship is an alternate form of Snell's law.

From the equations above, and the proportional relationship between the velocity of each wave and its wavelength, we can also write an equation to express the relationship between the speed of light and index of refraction in two mediums.

PHYSICS CONCEPTS

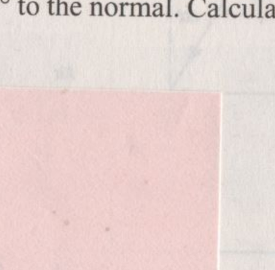
$$\frac{n_2}{n_1} = \frac{v_1}{v_2} = \frac{\lambda_1}{\lambda_2}$$

PROBLEM

A monochromatic light ray is incident on a surface boundary between air and corn oil at an angle of 60.° to the normal. Calculate the refracted angle of the ray in the corn oil.

PROBLEM

A ray of monochromatic light in air is incident on a transparent block of material whose absolute index of refraction is 1.50, as shown in the diagram below.



If the angle of incidence is 30°, trace the path of the light ray through the block and back into the air.

SOLUTION

We begin the solution by apply[illegible] Snell's law in order to calculate the angle of refraction:

$$n_{air} \sin \theta_{air} = n_{block} \sin \theta_{bl}\text{[illegible]}$$

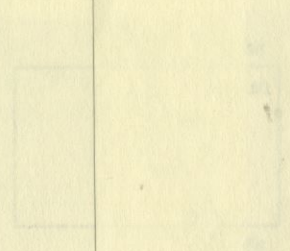
$$(1.00)(\sin 30°) = (1.50)(\sin \theta_{b}\text{[illegible]}$$

$$\sin \theta_{block} = 0.333$$

$$\theta_{block} = 19.5°$$

We now extend the ray into th[illegible] 19.5°. Using geometry (alternate interior angles), we find that th[illegible] the second surface at an angle of 19.5°.

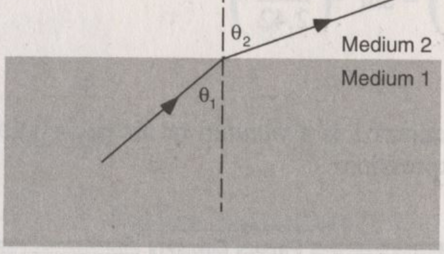
If we applied Snell's law ag[illegible] would conclude that the ray would emerge in air at the original ang[illegible] as illustrated below.



The tendency of light to emerge[illegible] air at the same angle to the normal as it entered into the medi[illegible] example above is referred to as parallelism of light and occurs [illegible] light passes from air into a more dense medium with parallel sid[illegible] back out into air.

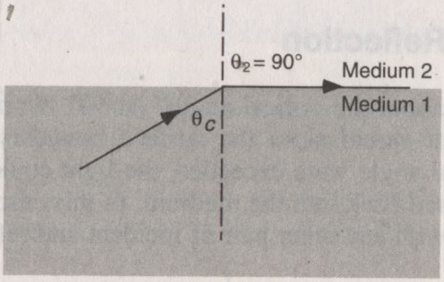
Critical Angle

If monochromatic light passes from medium 1 in which its speed is slower to medium 2 in which its speed is faster, we can draw a ray diagram as follows:



As angle θ_1 is made larger, angle θ_2 also becomes larger ($n_1 \sin \theta_1 = n_2 \sin \theta_2$).

There is one unique angle in medium 1 that will produce an angle of 90° in medium 2, as illustrated.



This unique angle is called the **critical angle** (θ_c). We can derive an equation for the critical angle using Snell's law:

$$n_1 \sin \theta_c = n_2 \sin 90°$$

Then, since $\sin 90° = 1$,

$$n_1 \sin \theta_c = n_2$$

PHYSICS CONCEPTS

$$\sin \theta_c = \frac{n_2}{n_1}$$

PROBLEM

Calculate the critical angle between diamond and Lucite.

SOLUTION

$$\sin \theta_c = \frac{n_2}{n_1}$$

$$\theta_c = \sin^{-1}\left(\frac{n_2}{n_1}\right) = \sin^{-1}\left(\frac{1.50}{2.42}\right)$$

$$= 38°$$

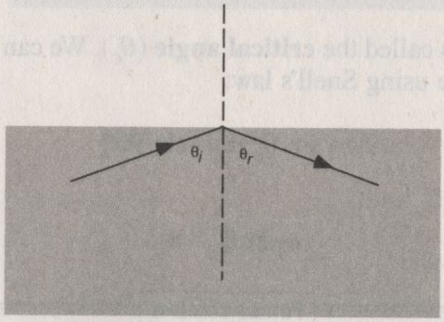
In the event that medium 2 is a vacuum or air ($n_2 = 1$), the above equation simplifies to this expression:

PHYSICS CONCEPTS

$$\sin \theta_c = \frac{1}{n_1}$$

Total Internal Reflection

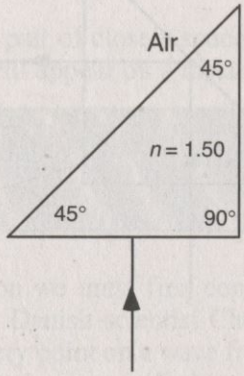
What is so special about the critical angle? At 90° the maximum refracted angle possible, light would skim the surface boundary between the two media. If the critical angle were exceeded, the light could no longer escape but would be reflected back into the medium. In this case, the law of reflection would hold as with any other pair of incident and reflected rays.



We note that the equation $\sin \theta_c = 1/n_1$, given above, implies that larger values of n yield smaller critical angles. A material such as diamond ($n = 2.42$) has a critical angle of only 24°. Because of this small value, much of the light inside a diamond is totally internally reflected. This **total internal reflection** is responsible for much of the diamond's sparkle.

PROBLEM

A monochromatic ray of light in air enters a triangular prism whose absolute index of refraction is 1.50. The prism is in the shape of an isosceles right triangle, and the incident ray is perpendicular to the surface as shown in the diagram.



Complete the path of the light ray as it enters the prism.

SOLUTION

We begin by noting that the angle of [illegible] 0°; consequently the angle of refraction will also be 0°. The ray will [illegible] prism without bending and will make an angle of 45° as it strikes the [illegible] face (hypotenuse) of the prism.

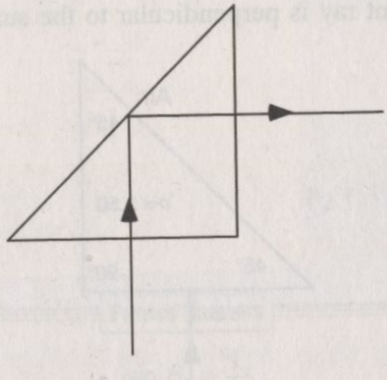
We now must ask: Will the critica[illegible] block-air combination be exceeded?

$$\sin \theta_c = \frac{n_{air}}{n_{block}}$$

$$= \frac{1.00}{1.50} = 0.667$$

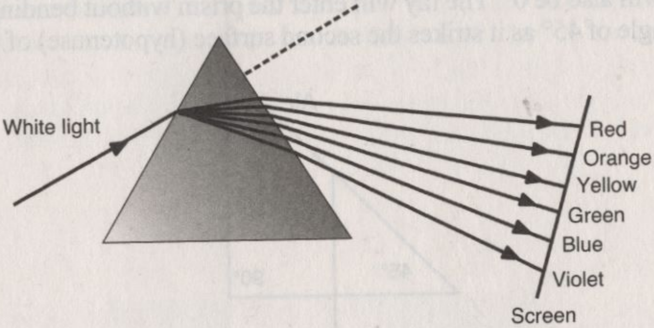
$$\theta_c = 41.8°$$

Since the angle of the ray is 45°, the critical angle is exceeded and total internal reflection results. The ray continues through the prism and exits into the air as shown below.



Dispersion

If white (polychromatic) light is passed through a prism, it is separated into its component colors as shown in the diagram.



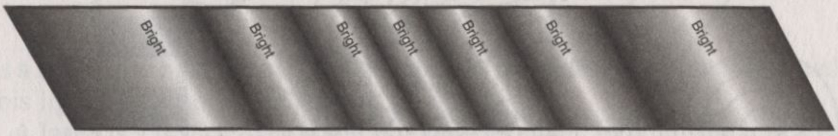
This phenomenon is known as **dispersion**. When water droplets in the air disperse light, rainbows may be produced.

Dispersion occurs because the speed of light inside the prism depends on the color of the light. The index of refraction is different for each component color of the light. From the diagram we can see that red light travels fastest because it has the largest refracted angle (that is, it is bent the least).

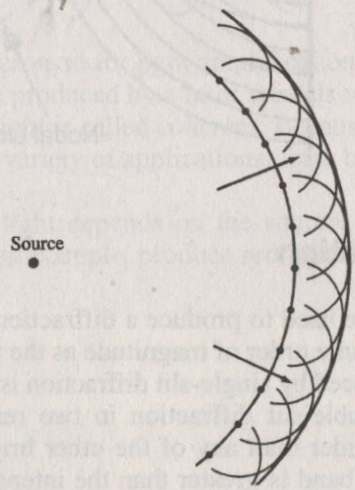
12.7 DIFFRACTION AND INTERFERENCE OF LIGHT

The Double-Slit Experiment

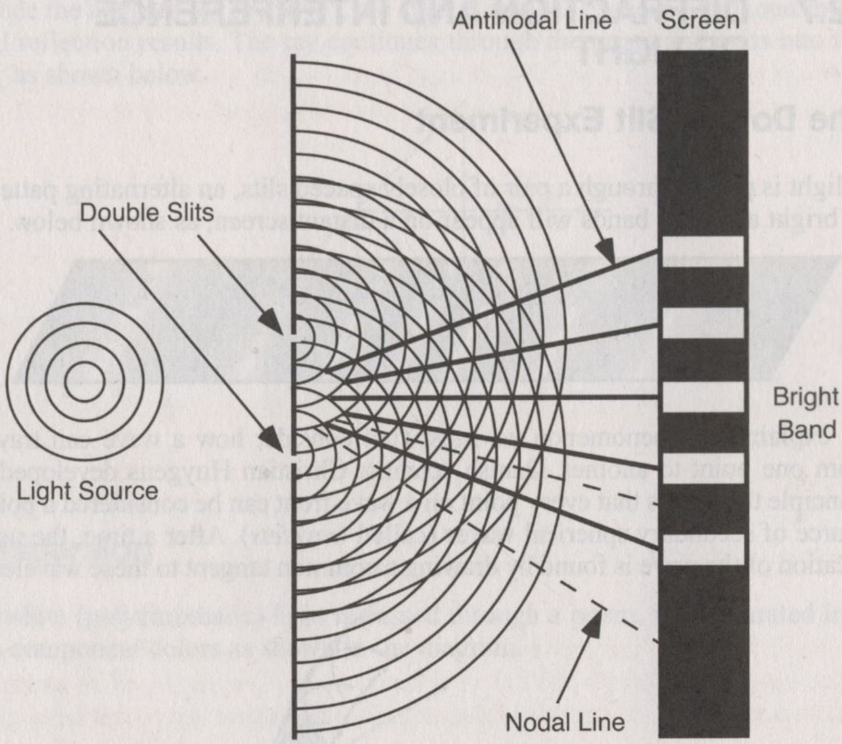
If light is passed through a pair of closely spaced slits, an alternating pattern of bright and dark bands will appear on a distant screen, as shown below.



To explain this phenomenon we must first consider how a wave can travel from one point to another. Danish scientist Christian Huygens developed a principle that states that every point on a wave front can be considered a point source of secondary spherical waves (called *wavelets*). After a time, the new location of the wave is found by drawing a common tangent to these wavelets.

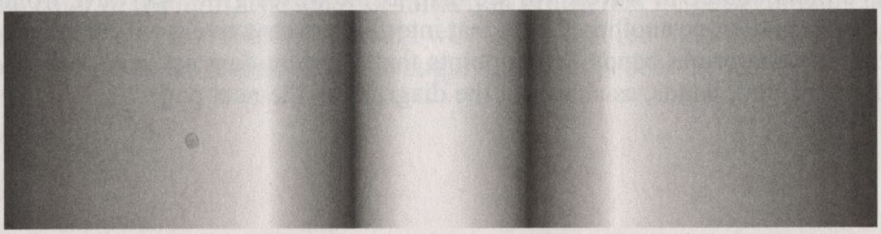


In the double-slit arrangement illustrated on page 362, each slit serves as a point source of waves. We see that, as the waves grow, the wave fronts interfere with one another. Points that interfere constructively will ultimately produce the bright bands, while points that interfere destructively will produce the dark bands, as shown in the diagram on the next page.



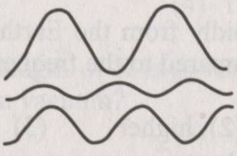
Single-Slit Diffraction

A single slit can also be used to produce a diffraction pattern. The width of the slit must have the same order of magnitude as the wavelength of the light used. The pattern produced by single-slit diffraction is different from the pattern obtained with double-slit diffraction in two respects: (1) the central bright band is much wider than any of the other bright bands, and (2) the intensity of the central band is greater than the intensity of any of the other bright bands.



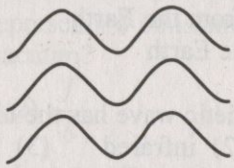
Lasers

When light (even monochromatic light) is emitted by a source, the light waves have no special (phase) relationship with one another.



As a result, the light beam spreads and loses its intensity (brightness) quickly. This light is said to be *incoherent*.

A **laser** is a device that produces monochromatic light in which nearly all of the waves are in phase.



The word *laser* is an acronym for light amplification by stimulated emission of radiation. The beam produced by a laser spreads very little and is extraordinarily intense. This light is called *coherent*. Because of its properties, laser light can be used for a variety of applications, from bar-code scanning to eye surgery.

The color of laser light depends on the sources that produce the light. Helium-neon lasers, for example, produce red light.