CHAPTER 1: LIGHT

1.1 INTRODUCTION

Electromagnetic radiation is composed of oscillating electric and magnetic fields emitted by vibrating charged particles. It transports energy and travels through empty space with a constant velocity **c**, where **c** equals the product of wavelength and frequency. The *electromagnetic spectrum* comprises cosmic rays to long wavelength electrical oscillations, as shown in Figure 1.1. *Light* is that very narrow band of the electromagnetic spectrum to which the eye is specifically sensitive.

The study of light falls into two classes of phenomena: **physical optics** and **geometrical optics.** Our interest is in the latter but we will touch briefly on the former.

Physical Optics deals with theories of the nature of light and its interaction with matter. The nature of light has been of fundamental interest to physicists. Two answers to the question, "What is light?" have vied for acceptance. Isaac Newton's **corpuscular theory of light** was initially dominant but was supplanted by the **wave theory** originated by Christian Huygens and developed by Thomas Young and Augustus Fresnel. In this century, Planck showed that radiation is emitted or absorbed in discrete packets or quanta. Einstein extended this idea to explain, where the wave theory was unable to do so, the photoelectric effect. He said that electromagnetic radiation existed as quanta. A *photon* is a quantum of light. Contemporary optics treats photons as having the properties of a particle and a wave.

Geometrical Optics is concerned with how light is propagated, reflected, and refracted, and the formation of images. Light is assumed to consist of *rays*. Rays are merely the paths taken by light. Experimental facts have resulted in some basic postulates of geometrical optics:

1) light is propagated in straight lines in a homogeneous medium,
2) the angle of reflection equals the angle of incidence.
3) the ratio of the sines of the angle of incidence to the angle of refraction is a constant that depends only on the media, and
4) two independent beams of light that intersect each other will in no way affect one another.

1.2 THE ELECTROMAGNETIC SPECTRUM

1.2.1 WAVE MOTION

A pebble dropped into a pond produces ripples that spread out in ever widening circles. These ripples, or waves are disturbances of particles of the water medium. The particles move up and down. The properties of a train of waves are velocity, frequency, wavelength, amplitude and phase. See Figure 1.2. If we observe a fixed point in the wave train, we will find that waves pass it at regular intervals of time. The number of waves that pass per unit time is the *frequency* **f**. The peak-to-peak distance between waves is the *wavelength* λ. More generally, it is the distance between two particles m_1 and m_2 that occupy corresponding positions in two successive waves. Two such particles have the same displacement and are moving in the same direction. They, therefore, are in the same *phase*. The maximum height of the wave is its *amplitude* **a**. The time it takes one wave to pass the observation point is the *period* T. It is the reciprocal of the frequency. The *velocity* of any wave is given by: $\mathbf{v} = \lambda \mathbf{f}$.

Figure 1.1 (a) The total electromagnetic specturm

WAVELENGTH λ			TYPE OF RADIATION	FREQUENCY ν (hz)
10^{-9} µm	=	10^{-6} nm	COSMIC RAYS	$3 X 10^{23}$
10^{-8} µm	=	10^{-5} nm	GAMMA RAYS	
10^{-7} µm	=	10^{-4} nm		
10^{-6} µm	=	10^{-3} nm		$3 X 10^{20}$
10^{-5} µm	=	10^{-2} nm	X-RAYS	
10^{-4} µm	=	10^{-1} nm		
10^{-3} µm	=	1 nm		$3 X 10^{17}$
10^{-2} µm	=	10 nm	ULTRA-VIOLET	
10^{-1} µm	=	100 nm	VISIBLE	
10^{0} µm	=	1 µm	INFRARED	$3 X 10^{14}$
10^{1} µm	=	10 µm		
10^{2} µm	=	100 µm	HEAT	
10^{3} µm	=	1 mm		$3 X 10^{11}$
10^{4} µm	=	10 mm	RADAR	
10^{5} µm	=	100 mm		
10^{6} µm	=	1 meter		$3 X 10^{8}$
10^{7} µm	=	10 meters		
10^{8} µm	=	100 meters	FM RADIO	
10^{9} µm	=	1 km	AM RADIO	$3 X 10^{5}$
10^{10} µm	=	10 km		
10^{11} µm	=	100km		
10^{12} µm	=	1,000 km		$3 X 10^{2}$
10^{13} µm	=	10,000 km	ELECTRICAL	

(b) The visible spectrum

WAVELENGTH λ (nm)	TYPE OF RADIATION	FREQUENCYν (hz)
300	ULTRAVIOLET	
350	VIOLET	$8.5 X 10^{14}$
400	INDIGO	
450	BLUE	
500	GREEN	
550	YELLOW	
600	ORANGE	$5 X 10^{14}$
650	RED	
700		
750	INFRARED	
800		$4 X 10^{14}$

1.2.2 WAVELENGTH AND FREQUENCY RANGE

Electromagnetic radiation ranges from electrical waves with a wavelength of 10^{10} cm, to cosmic rays of wavelength 10^{-13} cm. Energy is transported by all electromagnetic radiation at a constant velocity in vacuum of **c** = 2.998 x 10^{10} cm/sec. Since $\mathbf{c} = \lambda \mathbf{f}$, the frequencies range from 3 Hz to $3 x 10^{23}$ Hz.

The visible spectrum is barely one octave wide. It ranges from 400 nm violet light to 760 nm red light. Beyond red lies the infrared region and below violet is the ultraviolet region of the spectrum.

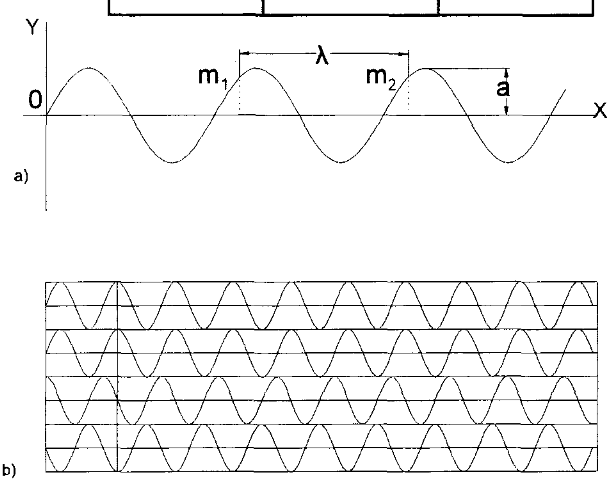

Figure 1.2 Wavelength (λ), amplitude (a) and phase. Points m_1 and m_2 are in phase since they occupy positions of identical amplitude on the wave.

We specify optical wavelengths most commonly in: Angstroms (Å), nanometers (nm), micrometers (µm), millimeters (mm), centimeters (cm), and meters (m). Where:

1 Å = 10^{-10} m, 1 nm = 10^{-9} m, 1 µm = 10^{-6} m, 1 mm = 10^{-3} m, 1 cm = 10^{-2} m.

1.2.3 Measurement of the Velocity of Light

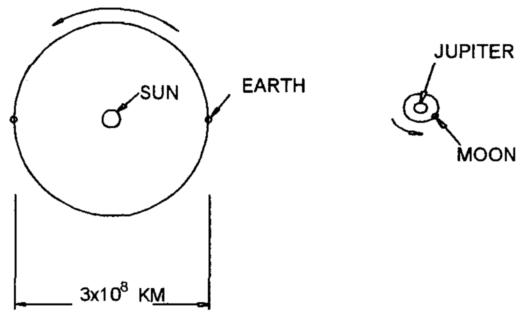

Figure 1.3 Römer's method for inferring the velocity of light.

The first evidence that light travels at a finite speed was provided by the Danish astronomer Römer about 1675. He observed that a moon of Jupiter revolved about Jupiter in an average period of 42.5 hours. In other words every 42.5 hours the moon would disappear (be eclipsed) behind Jupiter. However, the eclipse occurred earlier than predicted as the earth approached Jupiter, and later than predicted as the earth moved away from Jupiter as shown in Figure 1.3. The difference in time was about 1,000 seconds. Römer inferred that the 1,000 seconds were needed for light to travel across Earth's orbit. Subsequently, the diameter of Earth's orbit was found to be 3 x 10^8 km. Huygens in 1678 calculated the velocity of light (c) by dividing this distance by 1000 seconds, thus, c = 300,000 km/sec.

A. A. Michelson, the first American physicist to win the Nobel Prize, did so by measuring the speed of light. Figure 1.4 illustrates his method. A brief flash of light is reflected from side 1 of an octagonal mirror (on Mt. Wilson) to a fixed mirror 35.4 km away (on Mt. San Antonio). The light, on returning to the octagonal mirror, is then reflected by side 7 into the slit and the eye only when the faces of the octagonal mirror are in the positions shown in Figure 1.4a. If the octagonal mirror is rotated slightly as the brief flash of light travels to the distant mirror, the returning light will strike face 7 at a different angle and the reflected light will miss the slit. See Figure 1.4b. The light will enter the slit and be visible only if the mirror rotates exactly 1/8th of a revolution in the time it takes the light to travel from Mt. Wilson to Mt. San Antonio and back. Faces 2 and 8 will then occupy the same positions as faces 1 and 7 did when the light was flashed. Knowing the angular velocity of the octagonal mirror in revolutions per second (rps), and the distance that the light traveled, Michelson could calculate its velocity. He found that the required angular velocity was about 528 rps. The round trip took one-eighth of a revolution or about 0.000236 sec. He found the velocity of light to be 299,853 ±10 km per sec.

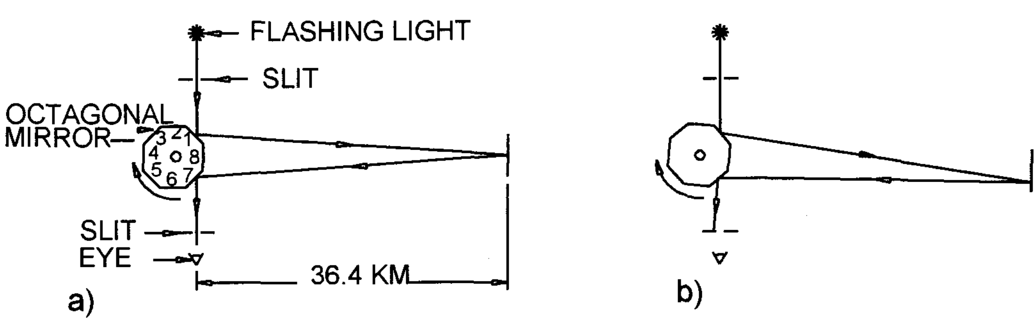

Figure 1.4 Michelson's method for measuring the velocity of light.

1.3 LIGHT SOURCES

1.3.1 SELF-LUMINOUS

1.3.1.1 Incandescent sources

Thermally induced motions of the molecules of solids produce incandescent light. Among incandescent sources are tungsten lamps, candles, and the sun. Incandescent sources emit all visible wavelengths in a continuous spectrum. Special incandescent sources or blackbodies are complete radiators. Figure 1-5 illustrates the spectral radiance of three blackbodies, including the sun at 6000K, at the indicated color temperatures. How much red, yellow, green and blue wavelengths are in the emitted light depends on the temperature of the solids. As the temperature of a solid is increased to incandescence it begins to have a reddish glow, then yellow and at very high temperature it predominantly emits blue light. In other words the wavelength of maximum energy becomes shorter with increasing temperature. The dashed line shows the shift of the peaks of the three radiators toward shorter wavelengths. Of course we may heat objects, such as an iron, below the temperature that produces incandescence. They then principally emit infrared energy.

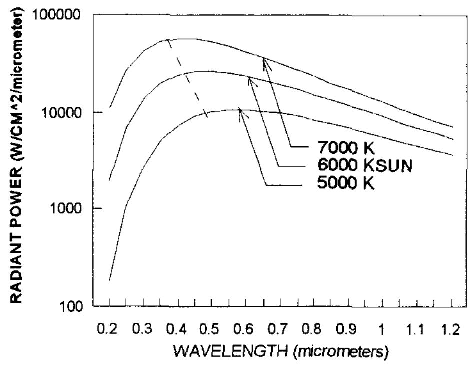

Figure 1.5 Blackbody curves.

1.3.1.2 Electric Arcs and Discharges. Passing an electric current through gases produces a disturbance of the atoms, which then emit light. The emitted light is not a smooth continuous spectrum, but concentrated at wavelengths that are characteristic of the gases. Sodium vapor produces nearly monochromatic light at 589 and 589.6 nm.

1.3.1.3 Fluorescent lamps. The light produced by fluorescent lamps is emitted by the fluorescent powders or phosphors that coat the inside of glass tubes filled with a mercury vapor. When an electric current is passed through the tube, the mercury vapor emits ultraviolet energy. The coating absorbs the UV and reradiates at longer (visible) wavelengths. The color of the light produced by these lamps depends on the mixture of phosphors that coat the tube. Because the phosphors emit at various narrow wavelengths, the spectrum is not smooth.

1.3.1.4 Lasers. Lasers consist of solids, liquids or gases. They emit light because either electrical or radiant energy stimulates their atoms. Laser stands for light amplification by stimulated emission of radiation. The unique properties of lasers are that their light is coherent, i.e., they emit all the waves in phase, and the light has a sharply a defined wavelength and a low beam divergence angle.

1.3.2 LIGHT REFLECTING SOURCES

Substances that reflect light may serve as sources. The moon illuminates the earth by reflecting sunlight. This page reflects light, as does the black print. White surfaces reflect all wavelengths almost equally. Colored surfaces reflect wavelengths selectively. Blue paper efficiently reflects blue light and absorbs longer visible wavelengths.

1.4 OPTICAL MEDIA

1.4.1 TRANSPARENT, COLORED AND TRANSLUCENT MATERIALS

Transparent substances, such as polished glass, transmit about 96% of the light normally incident at each surface. A clear optical glass plate absorbs very little light, consequently, such a plate transmits 0.96^2 or 92% of the light. Transparent optical glass is **homogeneous** and **isotropic**, i.e., has the same optical properties in all directions. Glass and water are isotropic substances. Certain crystals such as calcite and quartz are transparent but anisotropic. They have different optical properties in different directions. Specifically, they polarize light, or they produce double refraction, consequently the source would appear double when viewing it through the crystal.

The addition of various oxides in the manufacture of glass will color it. For example, a red filter glass transmits red or long wavelength light and absorbs blue and green. Other chemicals are used to produce neutral density filters. They absorb light of all colors almost uniformly.

If a glass surface is roughened by sand blasting or acid etching the transmitted light is diffused and the glass is *translucent*.

1.4.2 REFLECTING AND OPAQUE MATERIALS

The polished glass surface that transmits 96% will reflect 4% of the normally incident light. A transparent glass plate will transmit 0.96^2=92% of the light that perpendicularly strikes it. The reflected light is regularly or *specularly* reflected. A white wall may reflect 70% of the light. Since the wall texture is rough, it diffusely reflects the light.

Red paint absorbs most of the short wavelengths and reflects red. The use of green light to illuminate plants is not a very effective way to promote photosynthesis since the plant reflects green. It must absorb light for photosynthesis to occur.

A substance is *opaque* if it only absorbs and reflects light. Ordinary glass is opaque to short ultraviolet light; black glass is opaque to visible light.

In short, light is transmitted, reflected and absorbed. *Transmittance* (t) is the ratio of transmitted to incident light; *reflectance* (r) is the ratio of reflected to incident light; and *absorptance* is the ratio of absorbed to incident light.

EXAMPLE 1:
A two cm thick glass plate reflects 4% of the light at each surface and absorbs 2% per cm thickness. Find the light transmittance of the plate.

The transmittance by each surface is 1-r = 1-0.04 = 0.96. Given *two* surfaces, $t_s = 0.96^2 = 0.9216$. The internal transmittance by one cm of glass is 1-a = 1-0.02 = 0.98. Given two cm of glass, $t_i = 0.98^2 = 0.9604$. Total transmittance $t = (t_s)(t_i) = 0.8851$.

1.5 POINT AND EXTENDED SOURCES

Luminous sources that subtend negligibly small angles are called *point sources.* A distant star and a pinhole are examples of point sources. When the source of light subtends a finite angle, it is an extended source. The big dipper is an extended source as is the sun, the moon, a fluorescent lamp and most objects that we see.

1.6 RECTILINEAR PROPAGATION OF LIGHT

Euclid (300 BC) observed that light travels in straight lines in a homogeneous medium. This is a fundamental postulate of geometrical optics. Rays are drawn as straight lines to represent rectilinear propagation. They do not physically exist, but are merely a useful way to depict light.

1.6.1 PINHOLE CAMERA

The pinhole camera is simply a light-tight box with a pinhole aperture in the center of its front face, as shown in Figure 1.6. It shows that light travels in straight lines. A ray drawn from point M at the lower end of the object through the aperture A will strike the back face of the camera. Rays drawn through the pinhole from all points on the object between M and Q will strike corresponding points at the back end of the box and produce an inverted image. The size of the image is given by

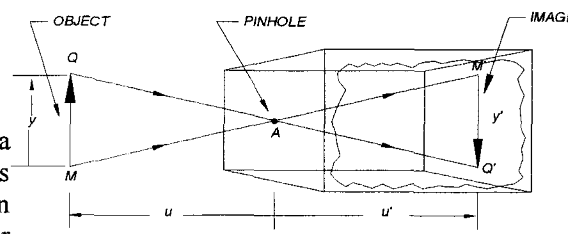

Figure 1.6 The pinhole camera.

$$\frac{y'}{y} = \frac{u'}{u} \qquad 1.1$$

where:
y =MQ = height of the object
u = AM = distance of object from the aperture,
y' = M'Q '= height of the image
u'= AM' = distance of image from the aperture

A pinhole has a finite diameter, and admits a small cone of rays from each point on the object, as illustrated in Figure 1.7. The corresponding "images" are small blurs, and the image of the object will be fuzzy. Attempts to isolate a ray by decreasing the diameter of the pinhole ultimately fail because, although the geometrical blur gets smaller, the blur due to diffraction gets larger. See Chapter 13. Diffraction is best explained with the wave theory, but may be thought of as the bending of light rays as they pass through an aperture. The optimum diameter of a pinhole is that which produces a geometrical blur equal to the diffraction blur.

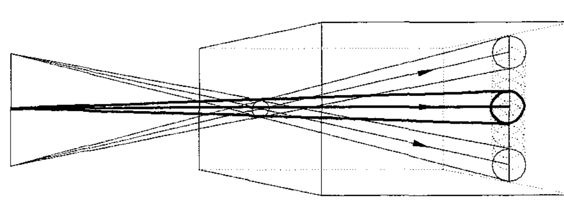

Figure 1.7 Geometric blur produced by a pinhole camera with a large aperture.

1.6.2 PROPAGATION OF LIGHT IN NONHOMOGENEOUS MEDIA

Earth's atmosphere is not homogeneous. Air varies in density with altitude and temperature. Consequently, its refractive index varies. (When light leaves a vacuum and enters a new medium its velocity is reduced. The *refractive index* of the new medium is equal to the ratio of the velocity of light in a vacuum to its velocity in the new medium). The variations in the index of air cause light from the sun and stars, especially when they are at the horizon, to curve on entering the atmosphere. Thus, a star appears higher in the sky than it actually is and is still visible after it is below the horizon. Mirages and looming occur when hot and cool layers of air form over the terrain. See Figure 1.8. (Does the curved path contradict the idea of rectilinear propagation?). In all these phenomena we see images projected along straight lines based on the direction that the rays actually enter the eye.

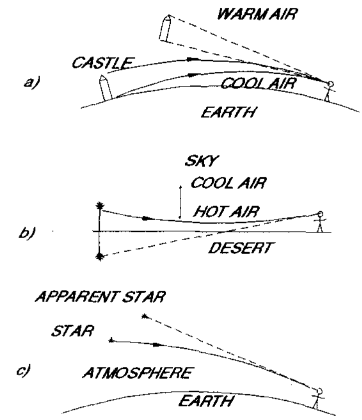

Figure 1.8 a) Looming produces "castles in the air", b) Mirages cause the blue sky to appear as lakes in the desert, c) Earth's atmosphere appears to elevate the position of stars.

1.7 THE CORPUSCULAR AND WAVE THEORY OF LIGHT

Newton considered light to be streams of *corpuscles* spreading out from a point source. The corpuscular theory dominated scientific thinking for decades. According to this theory, light sources emit particles that travel in a straight line because Newton's first law of motion requires this of bodies traveling in a uniform medium, which are not acted on by any forces. That light travels in straight lines would account for the sharp shadows cast by opaque objects. Waves, however, would spread out behind the object and so would not produce sharp shadows. Reflection and refraction were very simply explained by attractive and repulsive forces acting on these particles. The corpuscular theory was less successful in explaining interference, diffraction and polarization.

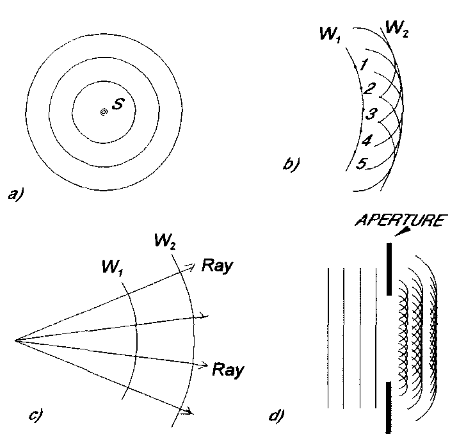

Figure 1.9 Propagation of light according to Huygens' Principle.

These deficiencies led to the wave theory of light.
According to this theory, light is a transverse vibration that travels outward from the source like ripples on the surface of water. The theory could account for reflection and refraction, and easily explained interference, diffraction, and polarization.

For the *wave theory* to gain acceptance, it had to show that light travels in straight lines. Huygens postulated that a point source would produce a wavelike disturbance that would spread out as an ever growing sphere. See Figure 1.9a. At any instant all points on the surface of this sphere would have the same state of excitation or phase and constitute a wavefront. All points on the wavefront then become new sources or centers from which secondary waves or wavelets spread out. These wavelets overlap and interfere with each other. As shown in Figure 1.9b, the envelope of these wavelets from points 1-5 on w_1 is the new wavefront w_2. It corresponds to a surface tangent to each wavelet. The normals to each point of tangency indicate the direction in which the light is traveling. Since the normals to these expanding spherical wavefronts all radiate from a common center, the normals can be thought of as rays. Thus, light travels in straight lines. Figure 1.9c. Close examination revealed that shadows were not perfectly sharp. Light waves, in fact, did spread into the shadow by *diffracting* or bending away from the edge of the aperture. Figure 1.9d. The wave theory dominated optical thinking until the 20th century.

1.8 UMBRA, PENUMBRA and ECLIPSES

The sharp shadows produced by point sources are called **umbras**. Figure 1.10 shows light from point source S being obstructed by an opaque globe **B** and producing a sharply defined shadow that increases in diameter with distance from **B**. The region between u and u' receives no light from any points on the source. When the source **S** is extended, as in Figure 1.11, the sharp boundary between an umbra and the illuminated regions adjoining it will be replaced by a region of partial shadow called a **penumbra**. Between u and p the shadow gradually fades, as increasing numbers of points in the source contribute light to the screen. If **S** is smaller than **B**, the umbra continues to infinity. In Figure 1.12, S is *larger* than **B**. The umbra is a cone that constricts with distance **d** between the opaque object and the screen, becoming zero at $\mathbf{d}_o$. Concomitantly, the penumbra is an expanding annulus. When the screen is moved beyond $\mathbf{d}_o$, the umbra disappears; only penumbra is formed.

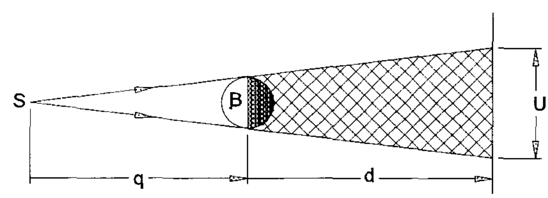

Figure 1.10 Umbra of a sphere formed with a point source.

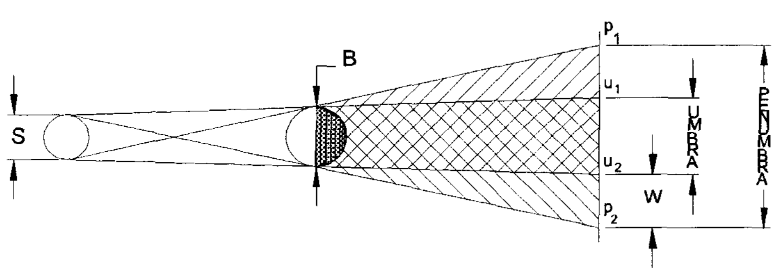

Figure 1.11 Shadows produced by an extended source. p_1p_2 denote the outer diameter (OD) of the penumbra; u_1u_2 denote the outer diameter of the umbra.

A solar eclipse occurs when the moon moves between the sun and the earth. The eclipse is full if we are in the umbra cast by the moon, partial when we are in the penumbra. A lunar eclipse occurs when the moon passes through earth's shadow.

The diameter of the umbra $\mathbf{U} = u_1u_2$ is given by $$U = B + (B - S)\frac{d}{q} \quad 1.2$$

where, S = diameter of the source
B = diameter of an opaque object
q = distance between the source and opaque object
d = distance between the opaque object and the screen

The distance $\mathbf{d_o}$ at which the umbra terminates is found from similar triangles in Figure 1.12, or by setting

U = 0 in Eq. 1.2. $$d_o = \frac{qB}{(S-B)} \quad 1.3$$

A negative value for **U** means $d>d_o$. The width of a penumbra ring **W**, where $W = p_1u_1 = u_2p_2$, is given by

$$W = \frac{dS}{q} \quad 1.4$$

Finally, the outside diameter of the penumbra is given by $\mathbf{D = p_1u_1 + u_1u_2 + u_2p_2 = 2W + U}$. 1.5

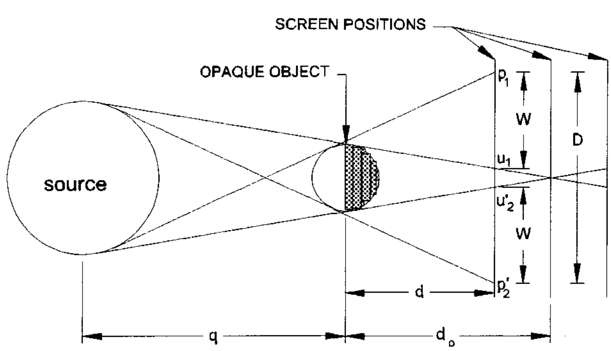

Figure 1.12 Length of shadow (d_0) when the diameter of the source is greater than the diameter of the opaque body.

EXAMPLE 2: A circular source 24 cm in diameter is 2.4 meters from a screen. A coin 2 cm in diameter is held 12 cm from the screen. Find the diameter of the umbra, the width of the penumbra ring and the outside diameter of the penumbra.

Given: S = 24 cm; B = 2 cm; q+d = 240 cm; d = 12 cm. Therefore, q = 228 cm. Substitute in Eq. 1.2 .

$U = \frac{228(2) + (2-24)(12)}{228} = 0.842\ cm$. According to Eq. 1.4, $W = \frac{12(24)}{228} = 1.263\ cm$.

The diameter of the penumbra from Eq.1.5 is: D = 2(1.263) + 0.842 = 3.368 cm.

Find the distance to the end of the umbra. From Eq. 1.3: $d_o = \frac{228\ (2)}{24-2} = 20.727 \quad cm.$

Draw the diagram and use the geometry to solve this example.

1.9 REAL AND VIRTUAL OBJECTS AND IMAGES

One light ray reaching the eye will tell us the direction of the point source from which it originated. However, to locate a point source two rays are necessary. The intersection of the two rays will locate the source or its image if the rays travel through a homogeneous and isotropic medium. See Figure 1.13.

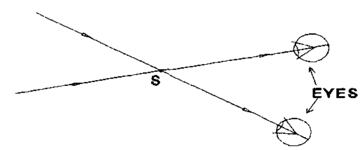

Figure 1.13 Two intersecting rays are necessary for locating point S. Two eyes indicate position.

Objects and images are *real* if the rays coming from the object or going to the image actually intersect. If the rays intersect when extended backwards or forward the image and object, so formed, are *virtual*. Figures 1.14 and 1.15.

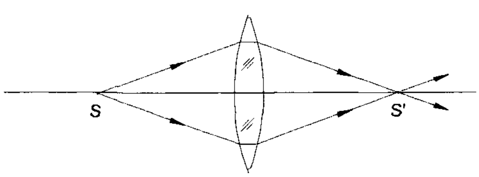

Figure 1.14 A real image is formed when two rays actually intersect.

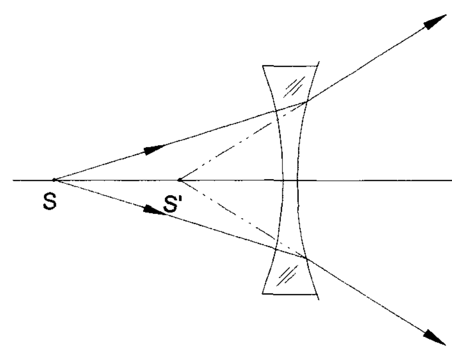

Figure 1.15 A virtual image is produced when two rays from source S must be projected back in order to intersect at S'.

1.10 STOPS

1.10.1 FIELD STOP. The field of view presented to an eye looking through a window depends on the size of the window and the position of the eye. The window acts as a field stop. It limits the extent of the landscape beyond the window that is visible. See Figure 1.16.

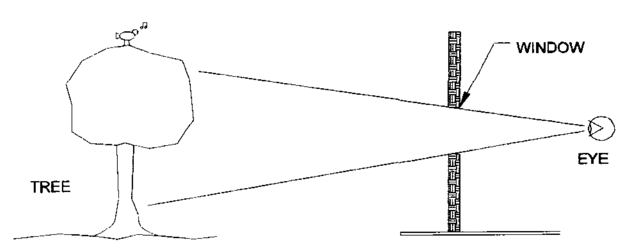

Figure 1.16 The field stop (window) prevents the bird from being seen.

1.10.2 APERTURE STOP. Each point on the landscape emits light in all directions. The pupil of the eye, however, can only admit a small solid angle of light from each point. The iris diaphragm of the eye acts as an aperture stop.

1.10.3 Baffles. Baffles are diaphragms within an optical system that block stray light from reaching the image. In Figure 1.17 a), the detector receives stray light from rays reflected by the inside walls of the camera. b). Baffles block the stray light.

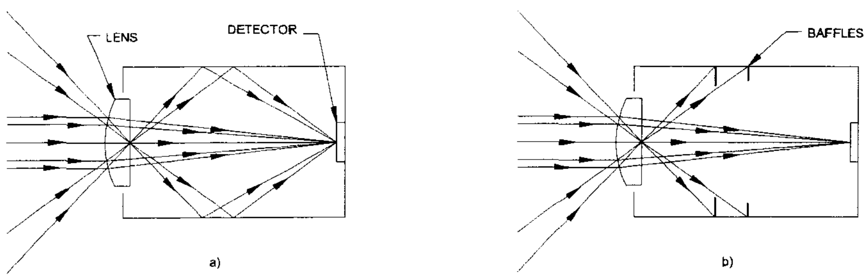

Figure 1.17 Baffles block stray light from reaching the detector.

1.11 OPTICAL SYSTEM

Generally, an optical system consists of a series of spherical reflecting and refracting surfaces that are rotationally symmetrical about an optical axis. Only a few rays from a point object enter an optical system, the rest of the rays are *vignetted.* Before entering the system, they are object rays. Upon leaving the system, they become image rays. In *paraxial optics,* all rays from an object point meet at an image point. An *astigmatic* system will result in image rays that meet to form a line focus.

1.11.1 Vergence and Diopters. If all object rays from a point meet in an image point, the image is perfect or ideal, and the image point is *conjugate* to the object point. Rays from a real object *diverge or have negative vergence.* To form a real image the optical system must produce *positive vergence or converge* the image rays. See Figure 1.18. Vergence is specified in *diopters* as the reciprocal of the distance of the object or image in meters. For example, light from a point source 0.5 meters away has a vergence of -2.00 diopters.

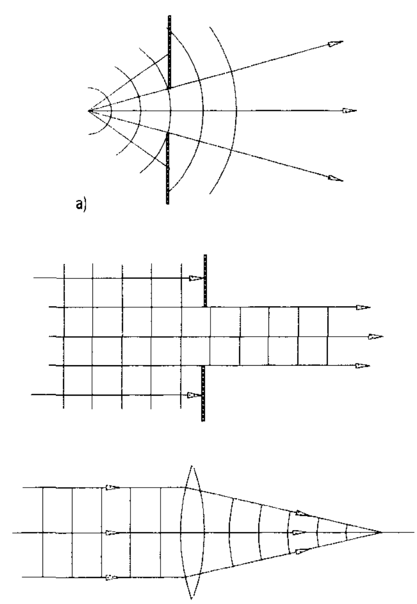

Figure 1.18 a) divergent, b) parallel or collimated, and c) convergent pencils of rays.

1.12 PENCILS AND BEAMS OF LIGHT

1.12.1 Point Source. A point source at a finite distance emits *divergent* light in all directions. When very distant, the light from a point source is *collimated*, i.e., the rays are parallel. A sufficiently strong positive lens will focus the rays to an image point, in which case the light is *convergent*. A section through a bundle of rays that contain the *chief* ray is called a *pencil* of rays. The chief or central ray of each pencil goes through the center of the aperture stop of a system.

1.12.2 Extended Source. An extended source produces overlapping pencils of rays called beams. One postulate of geometrical optics is that intersecting independent bundles and beams of light do not affect one another when they intersect. Figure 1.19.

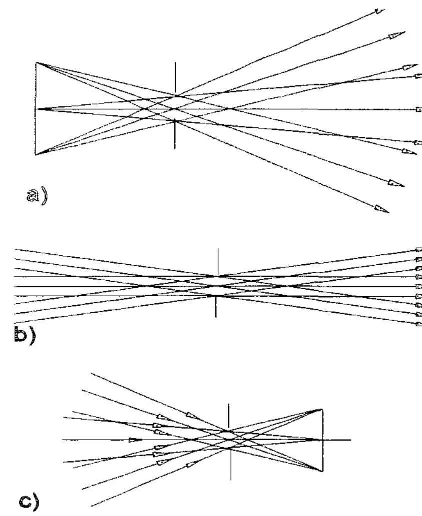

Figure 1.19 Beams of light produced by: a) Near real extended object; b) Distant extended object; c) virtual extended object.

1.13 VISUAL ANGLE

Objects subtend *visual angles* at the eye. The tangent of the visual angle is the *apparent size* of the object. Given a tree with a height **h**, at a distance **d** from the eye, the apparent size = **tan h/d**. Figure 1.20. Another tree, half as tall and at half the distance will have the same apparent size.

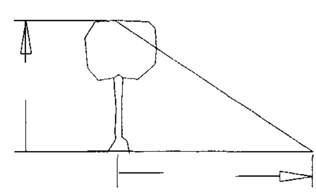

Figure 1.20 Apparent size or visual angle = h/d.

REVIEW QUESTIONS

1. What are the postulates of Geometrical Optics?
2. Define: ray, wavelength, frequency, velocity of light.
3. What is the wavelength range of visible light?
4. What is the difference between a fluorescent and an incandescent source?
5. Explain why light may take a curved path through the atmosphere. Does this violate the postulate of rectilinear propagation?
6. Describe a method for showing that light travels in straight lines.
7. What is the difference between an aperture stop and a field stop?
8. A star is a point source. The sun is a star, is it a point source?
9. Where must an object be to produce collimated light?
10. How are rays accommodated by the wave theory of light?
11. What is meant by conjugacy of object and image?
12. An astigmatic image of a point is a line. What does a stigmatic image look like?
13. Distinguish between a ray, a pencil and a beam.

PROBLEMS

1. Convert a) infrared light of 1.5 μm wavelength to nm, b) 10,000 Å to mm; c) 508 nm to inches.
Ans.: a) 1,500 nm; b) 0.001 mm; c) $2x10^{-5}$ in.

2. Yellow light has a wavelength of 590 nm. If the speed of light is $3x10^8$ m/sec what is the frequency of the light?
Ans.: $5.08x10^{14}$ Hz.

3. The sun is 93 million miles away. How long does it take sunlight to reach the earth? There are 1.609 km/mile.
Ans.: 8.31 minutes.

4. Assume in Michelson's experiment that the octagonal mirror had to make 530 rps before light was seen through the slit. What is the velocity of the light?
Ans.: 300,192 km/sec.

5. a) Light is successively transmitted through two glass plates, each 2 cm thick. The glass absorbs 2% of the light per cm of thickness, and reflects 4% per surface. What percent of the light will be transmitted? b) Repeat this problem for 10% reflection per surface and 10% absorption per cm.
Ans.: a) 78.34%; b) 43.05%

6. A pinhole camera is used to photograph a 10 ft. tall statue, located 20 ft. away. The image is 6 inches tall. How long is the camera?
Ans.: 1 ft.

7. A circular source 24 cm in diameter is 48 cm from a 12-cm diam. opaque disk. The disk is 48 cm from a screen. Find a) the diameter of the umbra, b) the width of the penumbra ring, c) the outside diameter of the penumbra, and d) the length of the shadow. Draw a scale diagram.
Ans.: a) 0 cm; b) 24 cm; c) 48 cm; d) 48 cm.

8. Repeat Problem 7 for a 16-cm diameter disk.
Ans.: a) 8 cm; b) 24 cm; c) 56 cm; d) 96 cm.

9. Repeat Problem 7 for a 24-cm diameter disk.
Ans.: a) 24 cm; b) 24 cm; c) 72 cm; d) ∞.

10. The diameters of the sun, earth and moon are 864,000, 7,927, and 2,160 miles, respectively. The mean distance of the sun from the earth is 93 million miles; the mean distance of the moon is 238,857 miles. a) How long is the earth's shadow? b) what is the diameter of earth's shadow where the moon passes through it? c) what is the corresponding outside diameter of the penumbra?
Ans.: a) 861,154 mi; b) 5728 mi; c) 10,166.4 mi.

11. The apparent size of a 500 ft high tower is 5°. How far away is it?
Ans.: 5715 ft.

12. Find the vergence of the light in diopters (D), a) if a real object is three meters away, b) if the light is collimated, c) if a real image is 25 cm away, d) if virtual object is 100 mm away, e) if a virtual image is 10 inches away.
Ans.: a)-3.0 D., b) zero, c) +4.0 D., d) +10 D., e) -3.94 D.