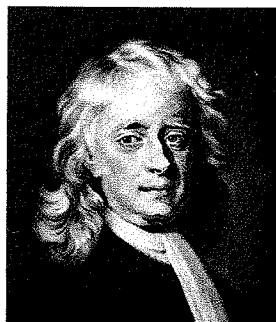

RAY OPTICS

- 1.1 POSTULATES OF RAY OPTICS
- 1.2 SIMPLE OPTICAL COMPONENTS
 - A. Mirrors
 - B. Planar Boundaries
 - C. Spherical Boundaries and Lenses
 - D. Light Guides
- 1.3 GRADED-INDEX OPTICS
 - A. The Ray Equation
 - B. Graded-Index Optical Components
 - *C. The Eikonal Equation
- 1.4 MATRIX OPTICS
 - A. The Ray-Transfer Matrix
 - B. Matrices of Simple Optical Components
 - C. Matrices of Cascaded Optical Components
 - D. Periodic Optical Systems



Sir Isaac Newton (1642–1727) set forth a theory of optics in which light emissions consist of collections of corpuscles that propagate rectilinearly.



Pierre de Fermat (1601–1665) developed the principle that light travels along the path of least time.

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Featuring a logical and applications, c detailed accounts theories of light, inc wave optics, elect and photon optics, teraction of light w theory of semicor and their optical sented at increasi plexity, these se building blocks fo more advanced to ier optics and ho wave and fiber sources and detec and acousto-opti ear optical device munications, and and computing. vital topics as:

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- **Transmission of** cal components and imaging guides, and fibe
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Light is an electromagnetic wave phenomenon described by the same theoretical principles that govern all forms of electromagnetic radiation. Electromagnetic radiation propagates in the form of two mutually coupled *vector* waves, an electric-field wave and a magnetic-field wave. Nevertheless, it is possible to describe many optical phenomena using a *scalar* wave theory in which light is described by a single scalar wavefunction. This approximate way of treating light is called scalar wave optics, or simply **wave optics**.

When light waves propagate through and around objects whose dimensions are much greater than the wavelength, the wave nature of light is not readily discerned, so that its behavior can be adequately described by rays obeying a set of geometrical rules. This model of light is called **ray optics**. Strictly speaking, ray optics is the limit of wave optics when the wavelength is infinitesimally small.

Thus the electromagnetic theory of light (**electromagnetic optics**) encompasses wave optics, which, in turn, encompasses ray optics, as illustrated in Fig. 1.0-1. Ray optics and wave optics provide approximate models of light which derive their validity from their successes in producing results that approximate those based on rigorous electromagnetic theory.

Although electromagnetic optics provides the most complete treatment of light within the confines of **classical optics**, there are certain optical phenomena that are characteristically quantum mechanical in nature and cannot be explained classically. These phenomena are described by a quantum electromagnetic theory known as **quantum electrodynamics**. For optical phenomena, this theory is also referred to as **quantum optics**.

Historically, optical theory developed roughly in the following sequence: (1) ray optics; → (2) wave optics; → (3) electromagnetic optics; → (4) quantum optics. Not

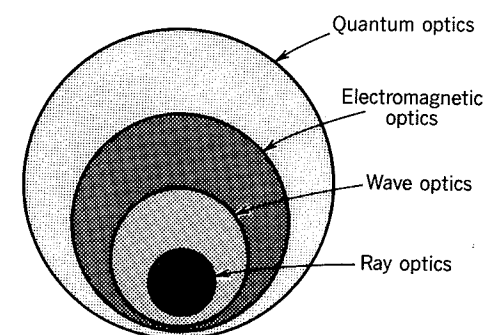


Figure 1.0-1 The theory of quantum optics provides an explanation of virtually all optical phenomena. The electromagnetic theory of light (electromagnetic optics) provides the most complete treatment of light within the confines of classical optics. Wave optics is a scalar approximation of electromagnetic optics. Ray optics is the limit of wave optics when the wavelength is very short.

surprisingly, these models are progressively more difficult and sophisticated, having being developed to provide explanations for the outcomes of successively more complex and precise optical experiments.

For pedagogical reasons, the chapters in this book follow the historical order noted above. Each model of light begins with a set of postulates (provided without proof), from which a large body of results are generated. The postulates of each model are then shown to follow naturally from the next-higher-level model. In this chapter we begin with ray optics.

Ray Optics

Ray optics is the simplest theory of light. Light is described by rays that travel in different optical media in accordance with a set of geometrical rules. Ray optics is therefore also called **geometrical optics**. Ray optics is an approximate theory. Although it adequately describes most of our daily experiences with light, there are many phenomena that ray optics does not adequately describe (as amply attested to by the remaining chapters of this book).

Ray optics is concerned with the *location* and *direction* of light rays. It is therefore useful in studying *image formation*—the collection of rays from each point of an object and their redirection by an optical component onto a corresponding point of an image. Ray optics permits us to determine conditions under which light is guided within a given medium, such as a glass fiber. In isotropic media, optical rays point in the direction of the flow of *optical energy*. Ray bundles can be constructed in which the density of rays is proportional to the density of light energy. When light is generated isotropically from a point source, for example, the energy associated with the rays in a given cone is proportional to the solid angle of the cone. Rays may be traced through an optical system to determine the optical energy crossing a given area.

This chapter begins with a set of postulates from which the simple rules that govern the propagation of light rays through optical media are derived. In Sec. 1.2 these rules are applied to simple optical components such as mirrors and planar or spherical boundaries between different optical media. Ray propagation in inhomogeneous (graded-index) optical media is examined in Sec. 1.3. Graded-index optics is the basis of a technology that has become an important part of modern optics.

Optical components are often centered about an optical axis, around which the rays travel at small inclinations. Such rays are called **paraxial rays**. This assumption is the basis of **paraxial optics**. The change in the position and inclination of a paraxial ray as it travels through an optical system can be efficiently described by the use of a 2×2 -matrix algebra. Section 1.4 is devoted to this algebraic tool, called **matrix optics**.

1.1 POSTULATES OF RAY OPTICS

Postulates of Ray Optics

- Light travels in the form of rays. The rays are emitted by light sources and can be observed when they reach an optical detector.
- An optical medium is characterized by a quantity $n \geq 1$, called the **refractive index**. The refractive index is the ratio of the speed of light in free space c_0 to that in the medium c . Therefore, the time taken by light to travel a distance d equals $d/c = nd/c_0$. It is thus proportional to the product nd , known as the **optical path length**.

In recent years, as communications, computing, and printing, and other self-contained textbook of this rapid engineering

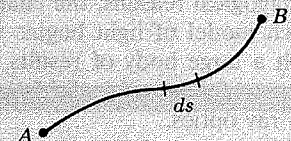
Featuring and applications of wave optics and photonics, and their complexity, the building blocks of more advanced optics, wave and sound, and acoustics, and optical communication and computer topics

- General lasers, luminescent light-emitting diodes
- Transmission of optical signals and image guides, and fiber optics
- Modulation of optical signals electronically
- Amplification of optical signals and interaction of light with matter
- Detection of optical signals and optical conductors

Each chapter highlights and exercises. Examples included to governing interest, and the propagation of linear systems

- In an inhomogeneous medium the refractive index $n(\mathbf{r})$ is a function of the position $\mathbf{r} = (x, y, z)$. The optical path length along a given path between two points A and B is therefore

$$\text{Optical path length} = \int_A^B n(\mathbf{r}) ds,$$



where ds is the differential element of length along the path. The time taken by light to travel from A to B is proportional to the optical path length.

- **Fermat's Principle.** Optical rays traveling between two points, A and B , follow a path such that the time of travel (or the optical path length) between the two points is an extremum relative to neighboring paths. An extremum means that the rate of change is zero, i.e.,

$$\delta \int_A^B n(\mathbf{r}) ds = 0.$$

The extremum may be a minimum, a maximum, or a point of inflection. It is, however, usually a minimum, in which case

light rays travel along the path of least time.

Sometimes the minimum time is shared by more than one path, which are then all followed simultaneously by the rays.

In this chapter we use the postulates of ray optics to determine the rules governing the propagation of light rays, their reflection and refraction at the boundaries between different media, and their transmission through various optical components. A wealth of results applicable to numerous optical systems are obtained without the need for any other assumptions or rules regarding the nature of light.

Propagation in a Homogeneous Medium

In a homogeneous medium the refractive index is the same everywhere, and so is the speed of light. The path of minimum time, required by Fermat's principle, is therefore also the path of minimum distance. The principle of the *path of minimum distance* is known as **Hero's principle**. The path of minimum distance between two points is a straight line so that *in a homogeneous medium, light rays travel in straight lines* (Fig. 1.1-1).

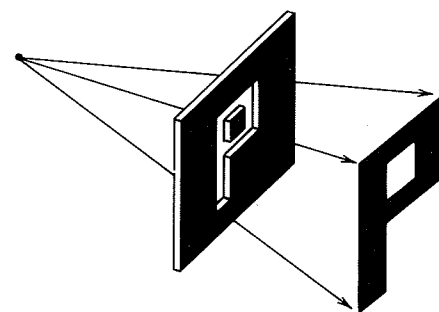


Figure 1.1-1 Light rays travel in straight lines. Shadows are perfect projections of stops.

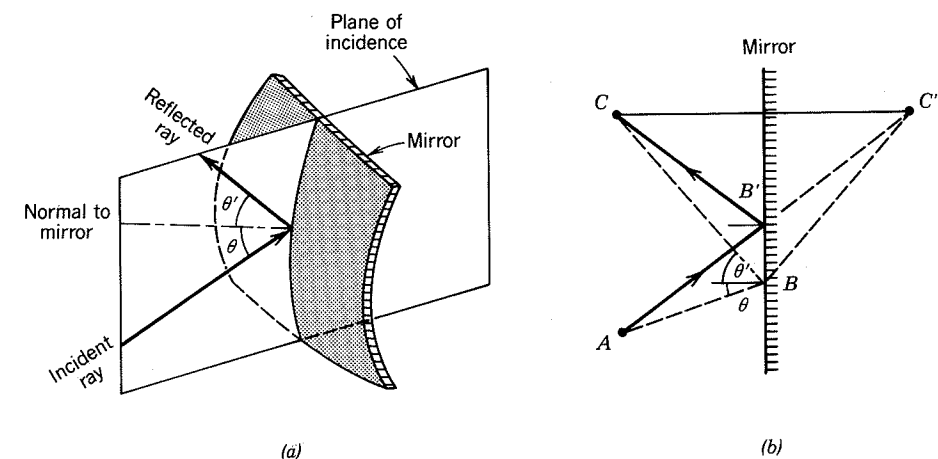


Figure 1.1-2 (a) Reflection from the surface of a curved mirror. (b) Geometrical construction to prove the law of reflection.

Reflection from a Mirror

Mirrors are made of certain highly polished metallic surfaces, or metallic or dielectric films deposited on a substrate such as glass. Light reflects from mirrors in accordance with the law of reflection:

*The reflected ray lies in the plane of incidence;
the angle of reflection equals the angle of incidence.*

The plane of incidence is the plane formed by the incident ray and the normal to the mirror at the point of incidence. The angles of incidence and reflection, θ and θ' , are defined in Fig. 1.1-2(a). To prove the law of reflection we simply use Hero's principle. Examine a ray that travels from point A to point C after reflection from the planar mirror in Fig. 1.1-2(b). According to Hero's principle the distance $\overline{AB} + \overline{BC}$ must be minimum. If C' is a mirror image of C , then $\overline{BC} = \overline{BC'}$, so that $\overline{AB} + \overline{BC'}$ must be a minimum. This occurs when $\overline{ABC'}$ is a straight line, i.e., when B coincides with B' and $\theta = \theta'$.

Reflection and Refraction at the Boundary Between Two Media

At the boundary between two media of refractive indices n_1 and n_2 an incident ray is split into two—a reflected ray and a refracted (or transmitted) ray (Fig. 1.1-3). The

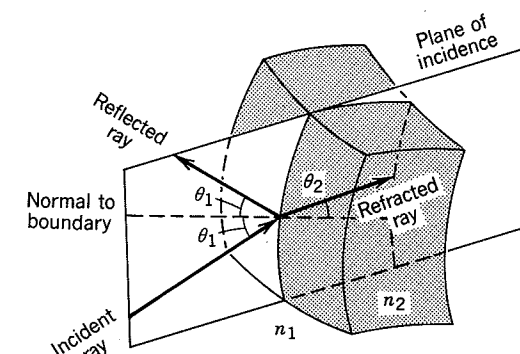


Figure 1.1-3 Reflection and refraction at the boundary between two media.

In recent years, the increasing applications of optics in communication, computing, printing, and energy. *Fundamentals of Photonics* is a self-contained textbook to offer a comprehensive treatment of this rapidly expanding engineering and applied science.

Featuring a logical and detailed account of the theories of light, in wave optics, electrodynamics, and photon optics, the interaction of light with matter, the theory of semiconductors, and their optical properties, presented at increasing complexity, these serve as building blocks for more advanced topics in fiber optics and holography, wave and fiber optics, laser sources and detectors, and acousto-optic and electro-optic devices, optical communications, and optical computing. Other vital topics are:

- Generation of lasers, and in luminescence light-emitting diodes.
- Transmission of optical components and imaging guides, and fiber optics.
- Modulation, switching, and processing of light, electrically, optically, and acoustically controlled.
- Amplification and conversion of light, interactions in nonlinear media.
- Detection of light, and conductor photonic devices.

Each chapter contains highlighted equations and exercises, and lists. Examples are included to emphasize governing applications, and appendices provide the properties of dimensional formulas, linear systems, and linear systems.

reflected ray obeys the law of reflection. The refracted ray obeys the law of refraction:

The refracted ray lies in the plane of incidence; the angle of refraction θ_2 is related to the angle of incidence θ_1 by Snell's law,

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

(1.1-1)
Snell's Law

EXERCISE 1.1-1

Proof of Snell's Law. The proof of Snell's law is an exercise in the application of Fermat's principle. Referring to Fig. 1.1-4, we seek to minimize the optical path length $n_1 \overline{AB} + n_2 \overline{BC}$ between points A and C . We therefore have the following optimization problem: Find θ_1 and θ_2 that minimize $n_1 d_1 \sec \theta_1 + n_2 d_2 \sec \theta_2$, subject to the condition $d_1 \tan \theta_1 + d_2 \tan \theta_2 = d$. Show that the solution of this constrained minimization problem yields Snell's law.

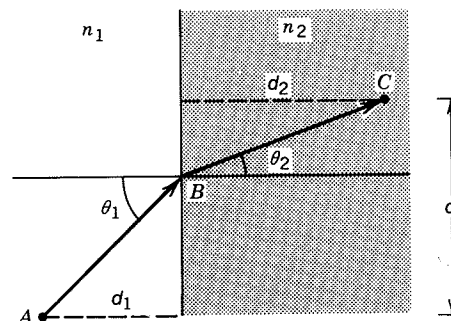


Figure 1.1-4 Construction to prove Snell's law.

The three simple rules—propagation in straight lines and the laws of reflection and refraction—are applied in Sec. 1.2 to several geometrical configurations of mirrors and transparent optical components, without further recourse to Fermat's principle.

1.2 SIMPLE OPTICAL COMPONENTS

A. Mirrors

Planar Mirrors

A planar mirror reflects the rays originating from a point P_1 such that the reflected rays appear to originate from a point P_2 behind the mirror, called the image (Fig. 1.2-1).

Paraboloidal Mirrors

The surface of a paraboloidal mirror is a paraboloid of revolution. It has the useful property of focusing all incident rays parallel to its axis to a single point called the focus. The distance $PF = f$ defined in Fig. 1.2-2 is called the focal length. Paraboloidal

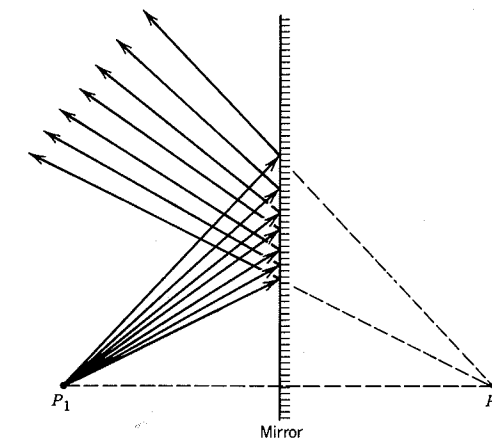


Figure 1.2-1 Reflection from a planar mirror.

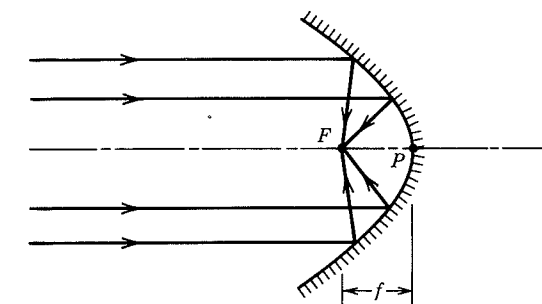


Figure 1.2-2 Focusing of light by a paraboloidal mirror.

mirrors are often used as light-collecting elements in telescopes. They are also used for making parallel beams of light from point sources such as in flashlights.

Elliptical Mirrors

An elliptical mirror reflects all the rays emitted from one of its two foci, e.g., P_1 , and images them onto the other focus, P_2 (Fig. 1.2-3). The distances traveled by the light from P_1 to P_2 along any of the paths are all equal, in accordance with Hero's principle.

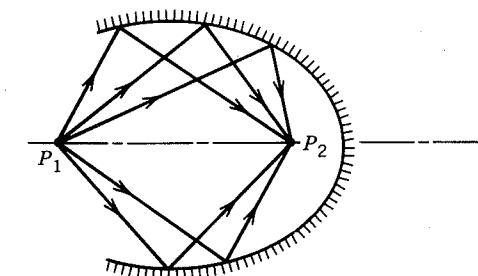


Figure 1.2-3 Reflection from an elliptical mirror.

In recent years, increasing applications as communications, computing, printing, and engineering and a self-contained textbook to offer of this rapidly engineering and a

Featuring a lot of applications and application theories of light wave optics, and photon optics and interaction of light theory of sensors and their applications, presented at increasing complexity, these building blocks more advanced optics and wave and sources and and acousto-optical devices, and communications, and computer vital topics a

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- **Transmissive** cal components and imaging guides, and
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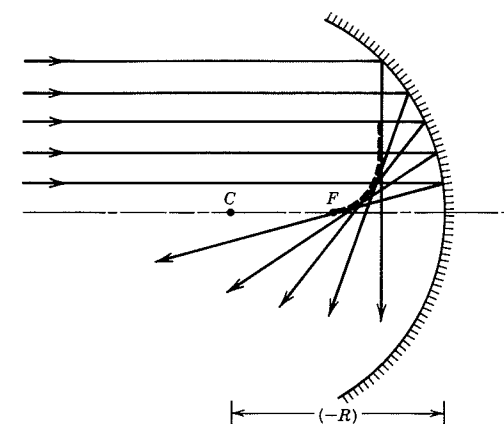


Figure 1.2-4 Reflection of parallel rays from a concave spherical mirror.

Spherical Mirrors

A spherical mirror is easier to fabricate than a paraboloidal or an elliptical mirror. However, it has neither the focusing property of the paraboloidal mirror nor the imaging property of the elliptical mirror. As illustrated in Fig. 1.2-4, parallel rays meet the axis at different points; their envelope (the dashed curve) is called the caustic curve. Nevertheless, parallel rays close to the axis are approximately focused onto a single point F at distance $(-R)/2$ from the mirror center C . By convention, R is negative for concave mirrors and positive for convex mirrors.

Paraxial Rays Reflected from Spherical Mirrors

Rays that make small angles (such that $\sin \theta \approx \theta$) with the mirror's axis are called **paraxial rays**. In the **paraxial approximation**, where only paraxial rays are considered, a spherical mirror has a focusing property like that of the paraboloidal mirror and an imaging property like that of the elliptical mirror. The body of rules that results from this approximation forms **paraxial optics**, also called first-order optics or Gaussian optics.

A spherical mirror of radius R therefore acts like a paraboloidal mirror of focal length $f = R/2$. This is in fact plausible since at points near the axis, a parabola can be approximated by a circle with radius equal to the parabola's radius of curvature (Fig. 1.2-5).

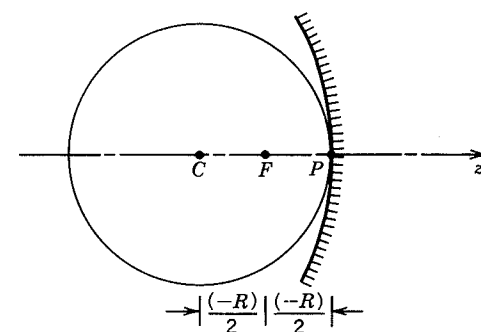


Figure 1.2-5 A spherical mirror approximates a paraboloidal mirror for paraxial rays.

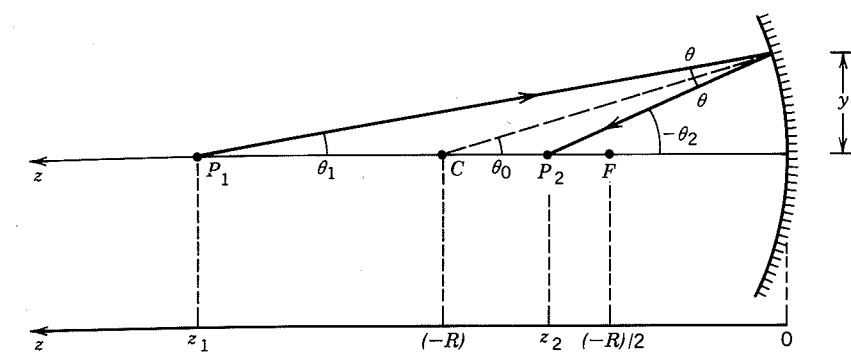


Figure 1.2-6 Reflection of paraxial rays from a concave spherical mirror of radius $R < 0$.

All paraxial rays originating from each point on the axis of a spherical mirror are reflected and focused onto a single corresponding point on the axis. This can be seen (Fig. 1.2-6) by examining a ray emitted at an angle θ_1 from a point P_1 at a distance z_1 away from a concave mirror of radius R , and reflecting at angle $(-\theta_2)$ to meet the axis at a point P_2 a distance z_2 away from the mirror. The angle θ_2 is negative since the ray is traveling downward. Since $\theta_1 = \theta_0 - \theta$ and $(-\theta_2) = \theta_0 + \theta$, it follows that $(-\theta_2) + \theta_1 = 2\theta_0$. If θ_0 is sufficiently small, the approximation $\tan \theta_0 \approx \theta_0$ may be used, so that $\theta_0 \approx y/(-R)$, from which

$$(-\theta_2) + \theta_1 \approx \frac{2y}{-R}, \quad (1.2-1)$$

where y is the height of the point at which the reflection occurs. Recall that R is negative since the mirror is concave. Similarly, if θ_1 and θ_2 are small, $\theta_1 \approx y/z_1$, $(-\theta_2) \approx y/z_2$, and (1.2-1) yields $y/z_1 + y/z_2 \approx 2y/(-R)$, from which

$$\frac{1}{z_1} + \frac{1}{z_2} \approx \frac{2}{-R}. \quad (1.2-2)$$

This relation holds regardless of y (i.e., regardless of θ_1) as long as the approximation is valid. This means that all paraxial rays originating at point P_1 arrive at P_2 . The distances z_1 and z_2 are measured in a coordinate system in which the z axis points to the left. Points of negative z therefore lie to the right of the mirror.

According to (1.2-2), rays that are emitted from a point very far out on the z axis ($z_1 = \infty$) are focused to a point F at a distance $z_2 = (-R)/2$. This means that within the paraxial approximation, all rays coming from infinity (parallel to the mirror's axis) are focused to a point at a distance

$$f = \frac{-R}{2}, \quad (1.2-3)$$

Focal Length of a Spherical Mirror

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which is called the mirror's focal length. Equation (1.2-2) is usually written in the form

$$\frac{1}{z_1} + \frac{1}{z_2} = \frac{1}{f}, \quad (1.2-4)$$

Imaging Equation
(Paraxial Rays)

known as the imaging equation. Both the incident and the reflected rays must be paraxial for this equation to be valid.

EXERCISE 1.2-1

Image Formation by a Spherical Mirror. Show that within the paraxial approximation, rays originating from a point $P_1 = (y_1, z_1)$ are reflected to a point $P_2 = (y_2, z_2)$, where z_1 and z_2 satisfy (1.2-4) and $y_2 = -y_1 z_2 / z_1$ (Fig. 1.2-7). This means that rays from each point in the plane $z = z_1$ meet at a single corresponding point in the plane $z = z_2$, so that the mirror acts as an image-forming system with magnification $-z_2/z_1$. Negative magnification means that the image is inverted.

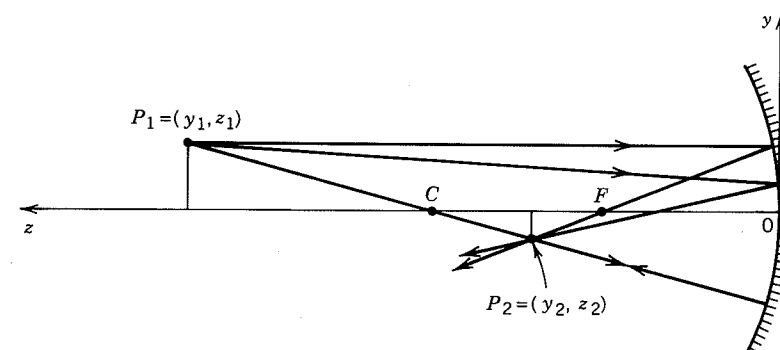


Figure 1.2-7 Image formation by a spherical mirror.

B. Planar Boundaries

The relation between the angles of refraction and incidence, θ_2 and θ_1 , at a planar boundary between two media of refractive indices n_1 and n_2 is governed by Snell's law (1.1-1). This relation is plotted in Fig. 1.2-8 for two cases:

- **External Refraction** ($n_1 < n_2$). When the ray is incident from the medium of smaller refractive index, $\theta_2 < \theta_1$ and the refracted ray bends away from the boundary.
- **Internal Refraction** ($n_1 > n_2$). If the incident ray is in a medium of higher refractive index, $\theta_2 > \theta_1$ and the refracted ray bends toward the boundary.

In both cases, when the angles are small (i.e., the rays are paraxial), the relation between θ_2 and θ_1 is approximately linear, $n_1 \theta_1 \approx n_2 \theta_2$, or $\theta_2 \approx (n_1/n_2) \theta_1$.

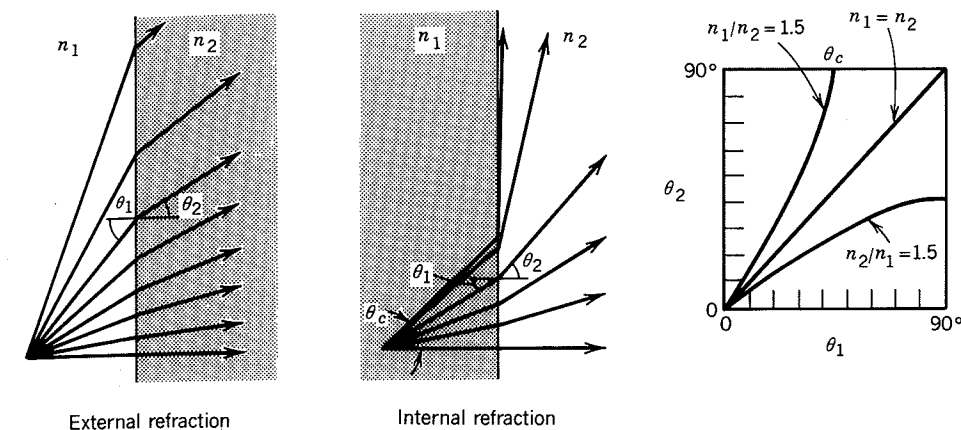


Figure 1.2-8 Relation between the angles of refraction and incidence.

Total Internal Reflection

For internal refraction ($n_1 > n_2$), the angle of refraction is greater than the angle of incidence, $\theta_2 > \theta_1$, so that as θ_1 increases, θ_2 reaches 90° first (see Fig. 1.2-8). This occurs when $\theta_1 = \theta_c$ (the **critical angle**), with $n_1 \sin \theta_c = n_2$, so that

$$\theta_c = \sin^{-1} \frac{n_2}{n_1}. \quad (1.2-5)$$

Critical Angle

When $\theta_1 > \theta_c$, Snell's law (1.1-1) cannot be satisfied and refraction does not occur. The incident ray is totally reflected as if the surface were a perfect mirror [Fig. 1.2-9(a)]. The phenomenon of total internal reflection is the basis of many optical devices and systems, such as reflecting prisms [see Fig. 1.2-9(b)] and optical fibers (see Sec. 1.2D).

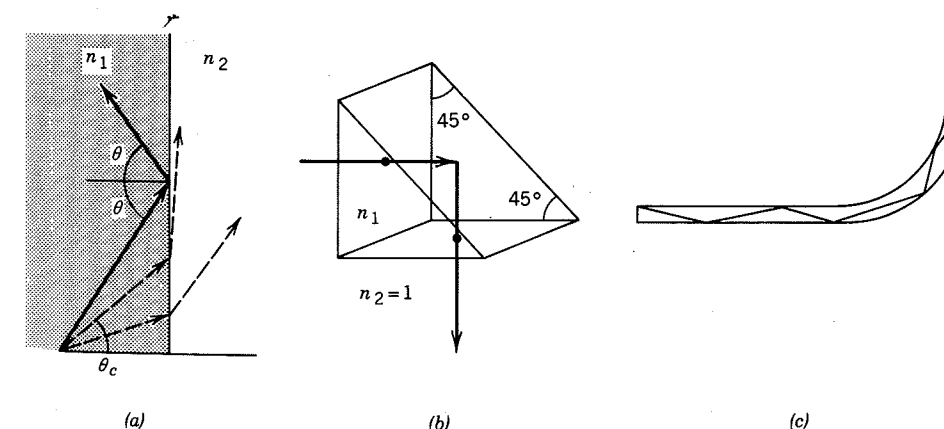


Figure 1.2-9 (a) Total internal reflection at a planar boundary. (b) The reflecting prism. If $n_1 > \sqrt{2}$ and $n_2 = 1$ (air), then $\theta_c < 45^\circ$; since $\theta_1 = 45^\circ$, the ray is totally reflected. (c) Rays are guided by total internal reflection from the internal surface of an optical fiber.

In recent years, as communications, computing, and printing, and other fundamental self-contained textbooks of this rapidly changing engineering and applied science have become more complex, the building blocks of more advanced optics, wave and sources and acoustics, and optical communication and computer topics.

- **Generators** of lasers, light-emitting diodes, and luminescent materials.
- **Transmitters** of optical signals, including optical fibers, waveguides, and integrated optics.
- **Modulators** of light, including electro-optical, acousto-optical, and magneto-optical devices.
- **Amplifiers** of optical signals, including optical fibers, waveguides, and integrated optics.
- **Detectors** of optical signals, including photodiodes, phototubes, and CCDs.

Each chapter highlights key concepts and exercises. Examples are included to illustrate the governing principles, and the proper use of linear systems analysis is emphasized.

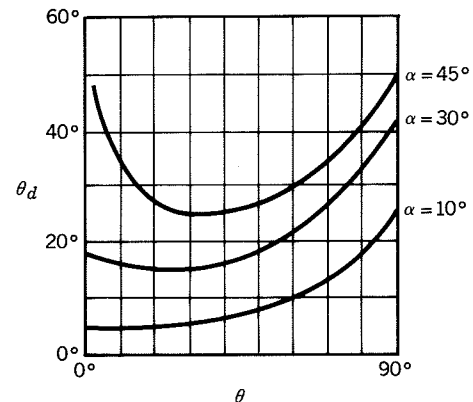
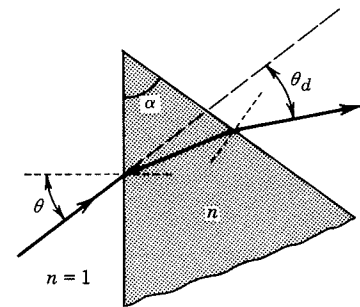


Figure 1.2-10 Ray deflection by a prism. The angle of deflection θ_d as a function of the angle of incidence θ for different apex angles α when $n = 1.5$. When both α and θ are small $\theta_d \approx (n - 1)\alpha$, which is approximately independent of θ . When $\alpha = 45^\circ$ and $\theta = 0^\circ$, total internal reflection occurs, as illustrated in Fig. 1.2-9(b).

Prisms

A prism of apex angle α and refractive index n (Fig. 1.2-10) deflects a ray incident at an angle θ by an angle

$$\theta_d = \theta - \alpha + \sin^{-1}[(n^2 - \sin^2 \theta)^{1/2} \sin \alpha - \sin \theta \cos \alpha]. \quad (1.2-6)$$

This may be shown by using Snell's law twice at the two refracting surfaces of the prism. When α is very small (thin prism) and θ is also very small (paraxial approximation), (1.2-6) is approximated by

$$\theta_d \approx (n - 1)\alpha. \quad (1.2-7)$$

Beamsplitters

The beamsplitter is an optical component that splits the incident light beam into a reflected beam and a transmitted beam, as illustrated in Fig. 1.2-11. Beamsplitters are also frequently used to combine two light beams into one [Fig. 1.2-11(c)]. Beamsplitters are often constructed by depositing a thin semitransparent metallic or dielectric film on a glass substrate. A thin glass plate or a prism can also serve as a beamsplitter.

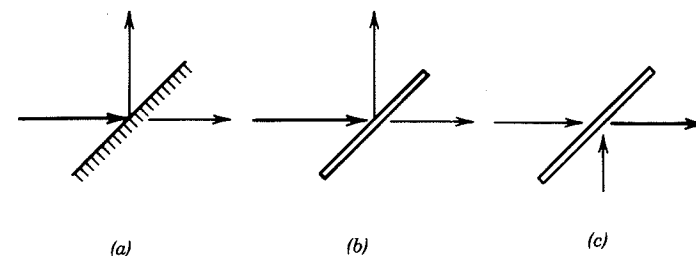


Figure 1.2-11 Beamsplitters and combiners: (a) partially reflective mirror; (b) thin glass plate; (c) beam combiner.

C. Spherical Boundaries and Lenses

We now examine the refraction of rays from a spherical boundary of radius R between two media of refractive indices n_1 and n_2 . By convention, R is positive for a convex boundary and negative for a concave boundary. By using Snell's law, and considering only paraxial rays making small angles with the axis of the system so that $\tan \theta \approx \theta$, the following properties may be shown to hold:

- A ray making an angle θ_1 with the z axis and meeting the boundary at a point of height y [see Fig. 1.2-12(a)] refracts and changes direction so that the refracted ray makes an angle θ_2 with the z axis,

$$\theta_2 \approx \frac{n_1}{n_2} \theta_1 - \frac{n_2 - n_1}{n_2 R} y. \quad (1.2-8)$$

- All paraxial rays originating from a point $P_1 = (y_1, z_1)$ in the $z = z_1$ plane meet at a point $P_2 = (y_2, z_2)$ in the $z = z_2$ plane, where

$$\frac{n_1}{z_1} + \frac{n_2}{z_2} \approx \frac{n_2 - n_1}{R} \quad (1.2-9)$$

and

$$y_2 = -\frac{n_1 z_2}{n_2 z_1} y_1. \quad (1.2-10)$$

The $z = z_1$ and $z = z_2$ planes are said to be conjugate planes. Every point in the first plane has a corresponding point (image) in the second with magnification

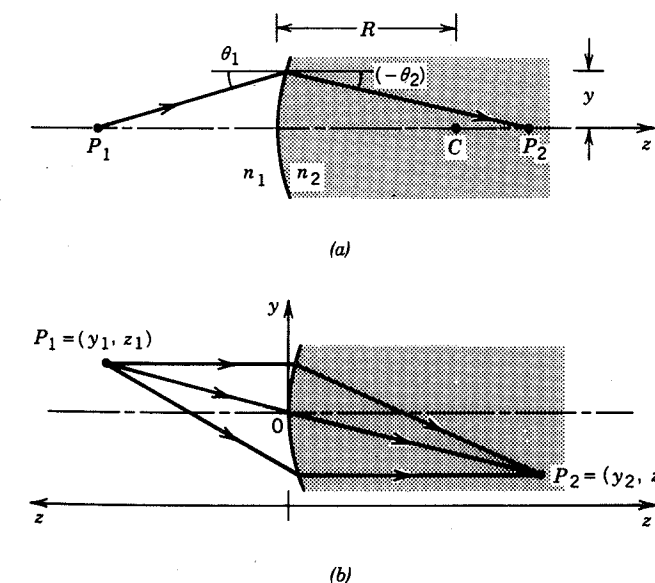


Figure 1.2-12 Refraction at a convex spherical boundary ($R > 0$).

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Featuring and applications of detailed theories of wave optics and photonics, and their interaction with complexity, building to more advanced optics wave and sources and acoustics, optical communication and computer vital topic

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Each chapter highlights and exercises. Examples included governing interest, and the proper dimensions, linear systems, linear systems

$-(n_1/n_2)(z_2/z_1)$. Again, negative magnification means that the image is inverted. By convention P_1 is measured in a coordinate system pointing to the left and P_2 in a coordinate system pointing to the right (e.g., if P_2 lies to the left of the boundary, then z_2 would be negative).

The similarities between these properties and those of the spherical mirror are evident. It is important to remember that the image formation properties described above are approximate. They hold only for paraxial rays. Rays of large angles do not obey these paraxial laws; the deviation results in image distortion called **aberration**.

EXERCISE 1.2-2

Image Formation. Derive (1.2-8). Prove that paraxial rays originating from P_1 pass through P_2 when (1.2-9) and (1.2-10) are satisfied.

EXERCISE 1.2-3

Aberration-Free Imaging Surface. Determine the equation of a convex aspherical (nonspherical) surface between media of refractive indices n_1 and n_2 such that all rays (not necessarily paraxial) from an axial point P_1 at a distance z_1 to the left of the surface are imaged onto an axial point P_2 at a distance z_2 to the right of the surface [Fig. 1.2-12(a)].
Hint: In accordance with Fermat's principle the optical path lengths between the two points must be equal for all paths.

Lenses

A spherical lens is bounded by two spherical surfaces. It is, therefore, defined completely by the radii R_1 and R_2 of its two surfaces, its thickness Δ , and the refractive index n of the material (Fig. 1.2-13). A glass lens in air can be regarded as a combination of two spherical boundaries, air-to-glass and glass-to-air.

A ray crossing the first surface at height y and angle θ_1 with the z axis [Fig. 1.2-14(a)] is traced by applying (1.2-8) at the first surface to obtain the inclination angle θ of the refracted ray, which we extend until it meets the second surface. We then use (1.2-8) once more with θ replacing θ_1 to obtain the inclination angle θ_2 of the ray after refraction from the second surface. The results are in general complicated. When the lens is thin, however, it can be assumed that the incident ray emerges from the lens at

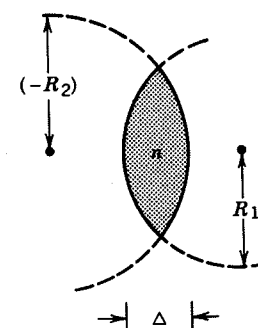


Figure 1.2-13 A biconvex spherical lens.

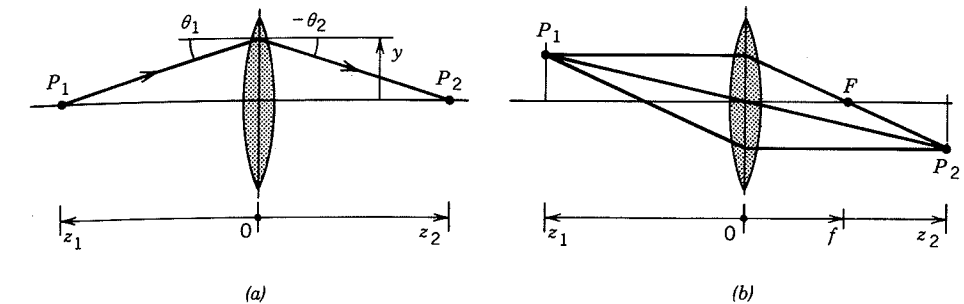


Figure 1.2-14 (a) Ray bending by a thin lens. (b) Image formation by a thin lens.

about the same height y at which it enters. Under this assumption, the following relations follow:

- The angles of the refracted and incident rays are related by

$$\theta_2 = \theta_1 - \frac{y}{f}, \quad (1.2-11)$$

where f , called the **focal length**, is given by

$$\frac{1}{f} = (n - 1) \left(\frac{1}{R_1} - \frac{1}{R_2} \right). \quad (1.2-12)$$

Focal Length of a Thin Spherical Lens

- All rays originating from a point $P_1 = (y_1, z_1)$ meet at a point $P_2 = (y_2, z_2)$ [Fig. 1.2-14(b)], where

$$\frac{1}{z_1} + \frac{1}{z_2} = \frac{1}{f} \quad (1.2-13)$$

Imaging Equation

and

$$y_2 = -\frac{z_2}{z_1} y_1. \quad (1.2-14)$$

Magnification

This means that each point in the $z = z_1$ plane is imaged onto a corresponding point in the $z = z_2$ plane with the magnification factor $-z_2/z_1$. The focal length f of a lens therefore completely determines its effect on paraxial rays.

As indicated earlier, P_1 and P_2 are measured in coordinate systems pointing to the left and right, respectively, and the radii of curvatures R_1 and R_2 are positive for convex surfaces and negative for concave surfaces. For the biconvex lens shown in Fig. 1.2-13, R_1 is positive and R_2 is negative, so that the two terms of (1.2-12) add and provide a positive f .

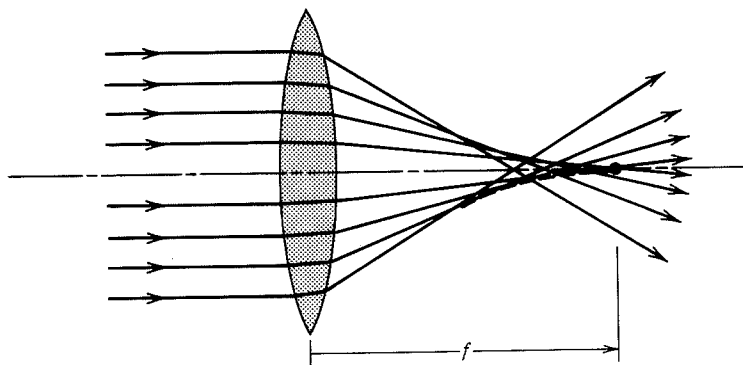


Figure 1.2-15 Nonparaxial rays do not meet at the paraxial focus. The dashed envelope of the refracted rays is called the caustic curve.

EXERCISE 1.2-4

Proof of the Thin Lens Formulas. Using (1.2-8), prove (1.2-11), (1.2-12), and (1.2-13).

It is emphasized once more that the foregoing relations hold only for paraxial rays. The deviations of nonparaxial rays from these relations result in aberrations, as illustrated in Fig. 1.2-15.

D. Light Guides

Light may be guided from one location to another by use of a set of lenses or mirrors, as illustrated schematically in Fig. 1.2-16. Since refractive elements (such as lenses) are usually partially reflective and since mirrors are partially absorptive, the cumulative loss of optical power will be significant when the number of guiding elements is large. Components in which these effects are minimized can be fabricated (e.g., antireflection coated lenses), but the system is generally cumbersome and costly.

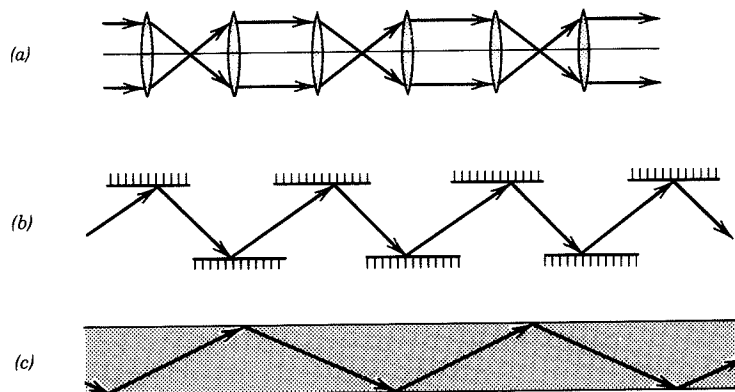


Figure 1.2-16 Guiding light: (a) lenses; (b) mirrors; (c) total internal reflection.