University of Mosul

College of Science

Department of Physics

Third Stage

Lecture 1

Geometric Optics

2024 – 2025

Lecture 1: Reflection and Refraction of light

Preparation

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Light is bent (refracted) as it passes through water, with different wavelengths bending by different amounts, a phenomenon called dispersion. Together with reflection, these physical phenomena lead to the creation of a rainbow when light passes through small, suspended droplets of water.

Reflection and Refraction of Light 22

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Light has a dual nature. In some experiments it acts like a particle, while in others it acts like a wave. In this and the next two chapters, we concentrate on the aspects of light that are best understood through the wave model. First we discuss the reflection of light at the boundary between two media and the refraction (bending) of light as it travels from one medium into another. We use these ideas to study the refraction of light as it passes through lenses and the reflection of light from mirrored surfaces. Finally, we describe how lenses and mirrors can be used to view objects with telescopes and microscopes and how lenses are used in photography. The ability to manipulate light has greatly enhanced our capacity to investigate and understand the nature of the Universe.

22.1 The Nature of Light

Until the beginning of the 19th century, light was modeled as a stream of particles emitted by a source that stimulated the sense of sight on entering the eye. The chief architect of the particle theory of light was Newton. With this theory, he provided simple explanations of some known experimental facts concerning the nature of light, namely, the laws of reflection and refraction.

Most scientists accepted Newton's particle theory of light. During Newton's lifetime, however, another theory was proposed. In 1678 Dutch physicist and astronomer Christian Huygens (1629–1695) showed that a wave theory of light could also explain the laws of reflection and refraction.

The wave theory didn't receive immediate acceptance, for several reasons. First, all the waves known at the time (sound, water, and so on) traveled through some

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Christian Huygens
(1629–1695), Dutch Physicist and Astronomer
Huygens is best known for his contributions to the fields of optics and dynamics. To Huygens, light was a vibratory motion in the ether, spreading out and producing the sensation of light when impinging on the eye. On the basis of this theory, he deduced the laws of reflection and refraction and explained the phenomenon of double refraction.

sort of medium, but light from the Sun could travel to Earth through empty space. Further, it was argued that if light were some form of wave, it would bend around obstacles; hence, we should be able to see around corners. It is now known that light does indeed bend around the edges of objects. This phenomenon, known as *diffraction*, is difficult to observe because light waves have such short wavelengths. Even though experimental evidence for the diffraction of light was discovered by Francesco Grimaldi (1618–1663) around 1660, for more than a century most scientists rejected the wave theory and adhered to Newton's particle theory, probably due to Newton's great reputation as a scientist.

The first clear demonstration of the wave nature of light was provided in 1801 by Thomas Young (1773–1829), who showed that under appropriate conditions, light exhibits interference behavior. Light waves emitted by a single source and traveling along two different paths can arrive at some point and combine and cancel each other by destructive interference. Such behavior couldn't be explained at that time by a particle model because scientists couldn't imagine how two or more particles could come together and cancel one another.

The most important development in the theory of light was the work of Maxwell, who predicted in 1865 that light was a form of high-frequency electromagnetic wave (Chapter 21). His theory also predicted that these waves should have a speed of 3×10^8 m/s, in agreement with the measured value.

Although the classical theory of electricity and magnetism explained most known properties of light, some subsequent experiments couldn't be explained by the assumption that light was a wave. The most striking experiment was the *photoelectric effect* (which we examine more closely in Chapter 27), discovered by Hertz. Hertz found that clean metal surfaces emit charges when exposed to ultraviolet light.

In 1905, Einstein published a paper that formulated the theory of light quanta ("particles") and explained the photoelectric effect. He reached the conclusion that light was composed of corpuscles, or discontinuous quanta of energy. These corpuscles or quanta are now called *photons* to emphasize their particle-like nature. According to Einstein's theory, the energy of a photon is proportional to the frequency of the electromagnetic wave associated with it, or

Energy of a photon ▶

$$E = hf \qquad [22.1]$$

where $h = 6.63 \times 10^{-34}$ J · s is *Planck's constant*. This theory retains some features of both the wave and particle theories of light. As we discuss later, the photoelectric effect is the result of energy transfer from a single photon to an electron in the metal. This means the electron interacts with one photon of light as if the electron had been struck by a particle. Yet the photon has wave-like characteristics, as implied by the fact that a frequency is used in its definition.

In view of these developments, light must be regarded as having a *dual nature*. **In some experiments light acts as a wave and in others it acts as a particle.** Classical electromagnetic wave theory provides adequate explanations of light propagation and of the effects of interference, whereas the photoelectric effect and other experiments involving the interaction of light with matter are best explained by assuming light is a particle.

So in the final analysis, is light a wave or a particle? The answer is neither and both: light has a number of physical properties, some associated with waves and others with particles.

22.2 Reflection and Refraction

When light traveling in one medium encounters a boundary leading into a second medium, the processes of reflection and refraction can occur. In **reflection** part of the light encountering the second medium bounces off that medium. In

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refraction the light passing into the second medium bends through an angle with respect to the normal to the boundary. Often, both processes occur at the same time, with part of the light being reflected and part refracted. To study reflection and refraction we need a way of thinking about beams of light, and this is given by the ray approximation.

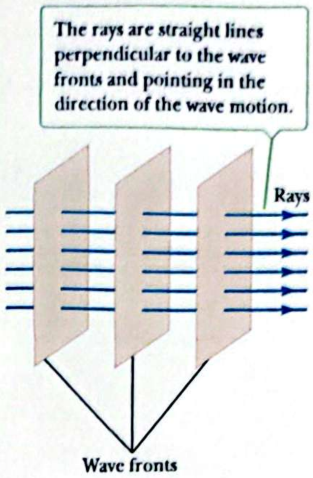

Figure 22.1 A plane wave traveling to the right.

The Ray Approximation in Geometric Optics

An important property of light that can be understood based on common experience is the following: **light travels in a straight-line path in a homogeneous medium, until it encounters a boundary between two different materials.** When light strikes a boundary, it is reflected from that boundary, passes into the material on the other side of the boundary, or partially does both.

The preceding observation leads us to use what is called the **ray approximation** to represent beams of light. As shown in Figure 22.1, a ray of light is an imaginary line drawn along the direction of travel of the light beam. For example, a beam of sunlight passing through a darkened room traces out the path of a light ray. We also make use of the concept of wave fronts of light. A **wave front** is a surface passing through the points of a wave that have the same phase and amplitude. For instance, the wave fronts in Figure 22.1 could be surfaces passing through the crests of waves. The rays, corresponding to the direction of wave motion, are straight lines perpendicular to the wave fronts. When light rays travel in parallel paths, the wave fronts are planes perpendicular to the rays.

Reflection of Light

When a light ray traveling in a transparent medium encounters a boundary leading into a second medium, part of the incident ray is reflected back into the first medium. Figure 22.2a shows several rays of a beam of light incident on a smooth, mirror-like reflecting surface. The reflected rays are parallel to one another, as indicated in the figure. The reflection of light from such a smooth surface is called **specular reflection.** On the other hand, if the reflecting surface is rough, as in Figure 22.2b, the surface reflects the rays in a variety of directions. Reflection from any rough surface is known as **diffuse reflection.** A surface behaves as a smooth surface as long as its variations are small compared with the wavelength of the incident light. Figures 22.2c and 22.2d are photographs of specular and diffuse reflection of laser light, respectively.

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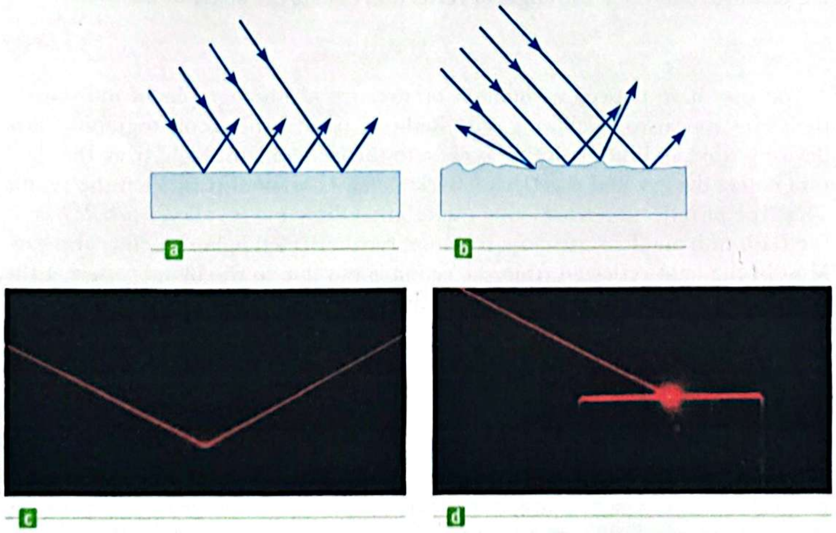

Photographs Courtesy of Henry Leap and Jim Lehman

Figure 22.2 A schematic representation of (a) specular reflection, where the reflected rays are all parallel to one another, and (b) diffuse reflection, where the reflected rays travel in random directions. (c, d) Photographs of specular and diffuse reflection, made with laser light.

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APPLICATION
Seeing the Road on a Rainy Night

As an example, consider the two types of reflection from a road surface that a driver might observe while driving at night. When the road is dry, light from oncoming vehicles is scattered off the road in different directions (diffuse reflection) and the road is clearly visible. On a rainy night when the road is wet, the road's irregularities are filled with water. Because the wet surface is smooth, the light undergoes specular reflection. This means that the light is reflected straight ahead, and the driver of a car sees only what is directly in front of him. Light from the side never reaches the driver's eye. In this book we concern ourselves only with specular reflection, and we use the term *reflection* to mean specular reflection.

Quick Quiz

22.1 Which part of Figure 22.3, (a) or (b), better shows specular reflection of light from the roadway?

Figure 22.3 (Quick Quiz 22.1)

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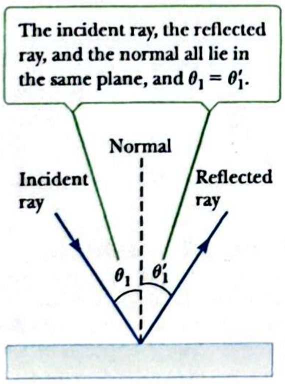

Active Figure 22.4
The wave under reflection model.

Consider a light ray traveling in air and incident at some angle on a flat, smooth surface, as in Active Figure 22.4. The incident and reflected rays make angles θ_1 and θ_1', respectively, **with a line perpendicular to the surface** at the point where the incident ray strikes the surface. We call this line the *normal* to the surface. Experiments show that **the angle of reflection equals the angle of incidence:**

$$\theta_1' = \theta_1 \qquad [22.2]$$

BIO APPLICATION
Red Eyes in Flash Photographs

You may have noticed a common occurrence in photographs of individuals: their eyes appear to be glowing red. "Red-eye" occurs when a photographic flash device is used and the flash unit is close to the camera lens. Light from the flash unit enters the eye and is reflected back along its original path from the retina. This type of reflection back along the original direction is called *retroreflection*. If the flash unit and lens are close together, retroreflected light can enter the lens. Most of the light reflected from the retina is red due to the blood vessels at the back of the eye, giving the red-eye effect in the photograph.

APPLYING PHYSICS 22.1 The Colors of Water Ripples at Sunset

An observer on the west-facing beach of a large lake is watching the beginning of a sunset. The water is very smooth except for some areas with small ripples. The observer notices that some areas of the water are blue and some are pink. Why does the water appear to be different colors in different areas?

EXPLANATION The different colors arise from specular and diffuse reflection. The smooth areas of the water will specularly reflect the light from the west, which is the pink light from the sunset. The areas with small ripples will reflect the light diffusely, so light from all parts of the sky will be reflected into the observer's eyes. Because most of the sky is still blue at the beginning of the sunset, these areas will appear to be blue. ■

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APPLYING PHYSICS 22.2 Double Images

When standing outside in the Sun close to a single-pane window looking to the darker interior of a building, why can you often see two images of yourself, one superposed on the other?

EXPLANATION Reflection occurs whenever there is an interface between two different media. For the glass in the window, there are two such surfaces, the window surface facing outdoors and the window surface facing indoors. Each of these interfaces results in an image. You will notice that one image is slightly smaller than the other, because the reflecting surface is farther away. ■

EXAMPLE 22.1 The Double-Reflecting Light Ray

GOAL Calculate a resultant angle from two reflections.

PROBLEM Two mirrors make an angle of 120° with each other, as in Figure 22.5. A ray is incident on mirror M_1 at an angle of 65° to the normal. Find the angle the ray makes with the normal to M_2 after it is reflected from both mirrors.

STRATEGY Apply the law of reflection twice. Given the incident ray at angle θ_{inc}, find the final resultant angle, β_{ref}.

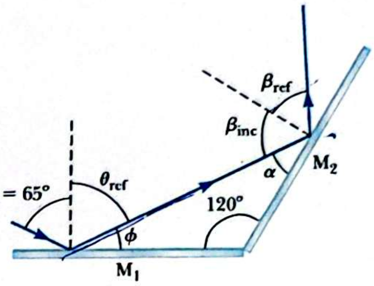

Figure 22.5 (Example 22.1) Mirrors M_1 and M_2 make an angle of 120° with each other.

SOLUTION

Apply the law of reflection to M_1 to find the angle of reflection, θ_{ref}:

$$\theta_{ref} = \theta_{inc} = 65°$$

Find the angle ϕ that is the complement of the angle θ_{ref}:

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$$\phi = 90° - \theta_{ref} = 90° - 65° = 25°$$

Find the unknown angle α in the triangle of M_1, M_2, and the ray traveling from M_1 to M_2, using the fact that the three angles sum to 180°:

$$180° = 25° + 120° + \alpha \quad \rightarrow \quad \alpha = 35°$$

The angle α is complementary to the angle of incidence, β_{inc}, for M_2:

$$\alpha + \beta_{inc} = 90° \quad \rightarrow \quad \beta_{inc} = 90° - 35° = 55°$$

Apply the law of reflection a second time, obtaining β_{ref}:

$$\beta_{ref} = \beta_{inc} = 55°$$

REMARKS Notice the heavy reliance on elementary geometry and trigonometry in these reflection problems.

QUESTION 22.1 In general, what is the relationship between the incident angle θ_{inc} and the final reflected angle β_{ref} when the angle between the mirrors is 90.0°? (a) $\theta_{inc} + \beta_{ref} = 90.0°$ (b) $\theta_{inc} - \beta_{ref} = 90.0°$ (c) $\theta_{inc} + \beta_{ref} = 180°$

EXERCISE 22.1 Repeat the problem if the angle of incidence is 55° and the second mirror makes an angle of 100° with the first mirror.

ANSWER 45°

Refraction of Light

When a ray of light traveling through a transparent medium encounters a boundary leading into another transparent medium, as in Active Figure 22.6a (page 766), part of the ray is reflected and part enters the second medium. The ray that enters the second medium is bent at the boundary and is said to be *refracted*. The incident ray, the reflected ray, the refracted ray, and the normal at the point of incidence all lie in the same plane. **The angle of refraction, θ_2,** in Active Figure 22.6a depends

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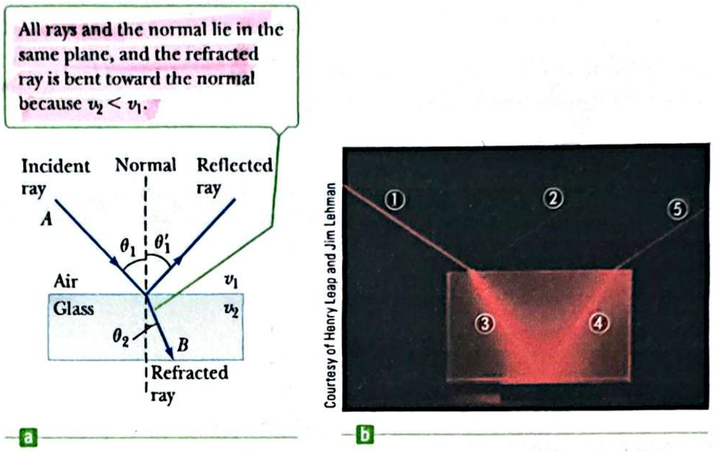

Active Figure 22.6
(a) The wave under refraction model. (b) Light incident on the Lucite block refracts both when it enters the block and when it leaves the block.

on the properties of the two media and on the angle of incidence, through the relationship

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1} = \text{constant} \qquad \textbf{[22.3]}$$

where v_1 is the speed of light in medium 1 and v_2 is the speed of light in medium 2. Note that the angle of refraction is also measured with respect to the normal. In Section 22.7 we derive the laws of reflection and refraction using Huygens' principle.

Experiment shows that **the path of a light ray through a refracting surface is reversible.** For example, the ray in Active Figure 22.6a travels from point A to point B. If the ray originated at B, it would follow the same path to reach point A, but the reflected ray would be in the glass.

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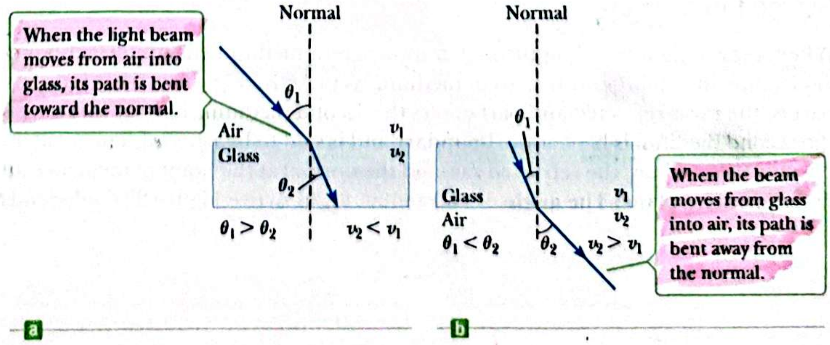
Quick Quiz

22.2 If beam 1 is the incoming beam in Active Figure 22.6b, which of the other four beams are due to reflection? Which are due to refraction?

When light moves from a material in which its speed is high to a material in which its speed is lower, the angle of refraction θ_2 is less than the angle of incidence. The refracted ray therefore bends toward the normal, as shown in Active Figure 22.7a. If the ray moves from a material in which it travels slowly to a material in which it travels more rapidly, θ_2 is greater than θ_1, so the ray bends away from the normal, as shown in Active Figure 22.7b.



Active Figure 22.7
The refraction of light as it (a) moves from air into glass and (b) moves from glass into air.

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