9.4 Light: Wave or Particle?

The period from 1650 to about 1710 was significant in the development of theories of light. By the end of the seventeenth century two opposing camps of physicists had emerged—one group followed the wave theory of light, and the other group followed the particle theory of light. The debate continued for over three hundred years.

In 1665, Francesco Grimaldi, who was the first scientist to use the term *diffraction*, suggested that observable diffraction took place when light passed through a narrow slit, creating rays of coloured light, thus showing that light was wave-like in nature.

Also in 1665, Robert Hooke developed his wave theory of light. Christiaan Huygens, in his *Treatise on Light* (1678), further developed Hooke's theory that light behaved as a wave. Huygens formulated the wave principle, called Huygens' principle. **Huygens' principle** states that all points on a wave front can be thought of as new sources of spherical waves. Huygens also claimed that light required an invisible medium in which to travel called the *ether*. Huygens' theory helped explain the concepts of reflection, refraction, and diffraction using wave concepts for light. However, a major objection to Huygens' ideas about light was that waves spread out in all directions.

Huygens' principle every point on a wave front can be considered as a point source of tiny secondary wavelets that spread out in front of the wave at the same speed as the wave itself

Isaac Newton, in contrast, thought of light as travelling in particles that he called corpuscles ("little particles"). The particles travel in straight lines with maximum velocity, and have kinetic energy. Newton's corpuscular, or particle, theory does not need a medium for light to travel in. This theory accounted for the **rectilinear propagation** of light, which means that light travels in a straight line. It also explained some other properties of light, such as reflection, and had some similarities with the much later theory of light. By 1700, Newton's theory still prevailed. It would be many years before direct experimental evidence countered Newton's views.

rectilinear propagation light travelling in straight lines

In the early nineteenth century, Thomas Young seemed to disprove Newton's theory. First, he used a ripple tank to demonstrate the idea of interference of water waves. Then, he recreated Grimaldi's experiment, demonstrating the interference of light using a double-slit experiment. (You experimented with this at the beginning of this chapter, and in Section 9.5 it is described in more detail.) Young described how he placed a narrow card with a single slit in a beam of light and saw fringes of colour in the shadow and to the sides of the card. When he put another card before or after the narrow card to stop the beam of light from striking one of the edges of the card, the fringes disappeared. This result supported the theory that light is composed of waves, results that Newton's theory could not explain.

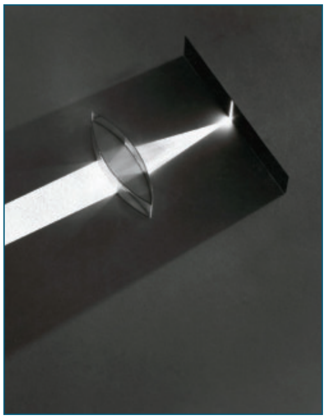
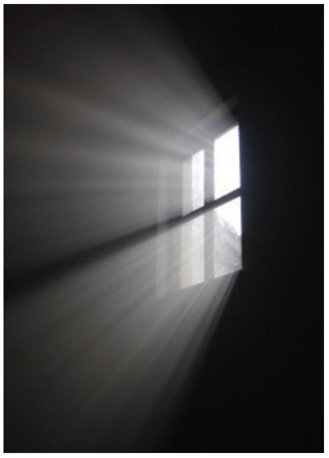
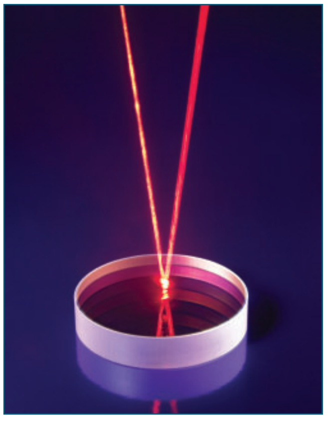
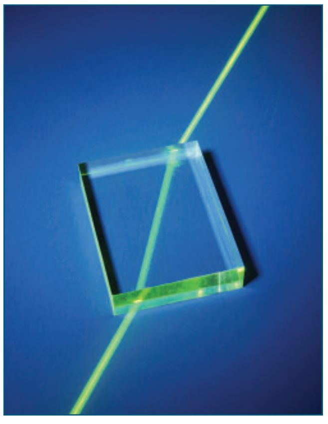
So, is light a wave or a particle? In some instances, light behaves as a wave, such as during interference. Other times, light behaves as a particle, such as light shining on metal. In Chapter 12, you will learn more about light behaving as a particle when shone on metal.

Newton's Particle Theory of Light

Newton's fascination with the ability of prisms to produce colours from white light led to his development of the particle theory of light. He stated that light corpuscles (little particles) travel in straight lines (rectilinear propagation) with a maximum velocity and therefore have kinetic energy. Newton's theory does not require a medium for the light to travel in. Furthermore, he was able to explain the properties of reflection and refraction using his theory. However, his explanation of diffraction showed the shortcomings of his theory.

Table 1, on the next page, summarizes Newton's explanations for these properties.

Table 1 Newton's Particle Theory Applied to Properties of Light

Phenomenon	Explanation	Example
rectilinear propagation	Newton argued that since light does not appear to curve, but travels in a straight line, light must consist of particles with extremely high speeds. In addition, since he did not notice any pressure from light, the mass of the particles must be quite low.	
diffraction	Newton argued that light cannot travel around corners as waves do. He argued that Grimaldi's observations were a result of collisions between light particles at the edges of the slit, rather than from light waves spreading out.	
reflection	Newton showed that, if light particles undergo perfectly elastic collisions, the law of reflection follows from the laws of motion. Horizontal velocity does not change, but vertical velocity is reversed, causing the particles to bounce. The magnitude of the velocity does not change.	
refraction	Newton claimed that particles will bend toward the normal if their speed increases. Particles accelerate at the boundary as they pass from one medium to another and the speed in the medium is greater than in air. This is the opposite of what actually happens.	

Huygens' Principle and the Wave Theory of Light

Huygens' principle leads to a geometric construction that determines the position of a new wave front based on knowledge of the previous wave front.

In **Figure 1(a)**, the straight wave front AB is moving toward the right. The straight wave front AB in Figure 1(a) corresponds to the circular wave front AB in **Figure 1(b)**. Huygens' viewpoint is that all the dots on the straight wave front can be considered as new sources of spherical waves. On the circular wave front AB, the dots represent the centres of the new wavelets—the small arcs of circles in Figure 1(b). The wave front A′B′ is the new position of the wave front a short time later. Notice how A′B′ is the tangent common to all the wavelets.

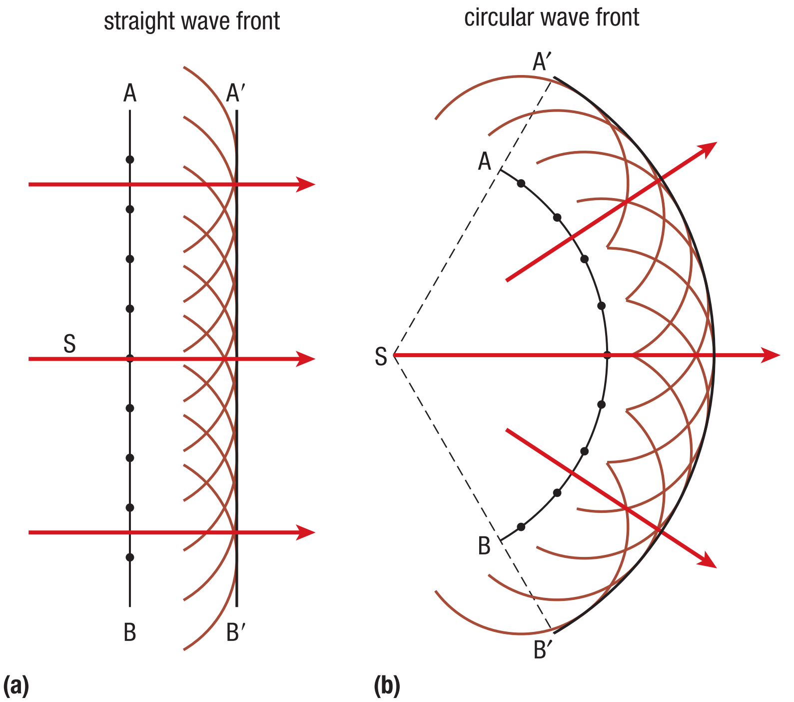


Figure 1 (a) In Huygens' construction of a straight wave front, the wave front is a straight line even though it is defined by circular waves. (b) In Huygens' construction of a spherical wave, the new wave front is drawn tangent to the circular wavelets radiating from the point sources on the original wave front.

Huygens' Principle and Reflection

Huygens' principle shows the derivation of the laws of reflection and refraction. **Figure 2** shows simplified wave fronts striking a surface. At the point where each wave front contacts the reflecting surface, a wave reflects. **Figure 3**, on the next page, simplifies reflection even further by showing one incident ray and one reflected ray, obeying the law of reflection.

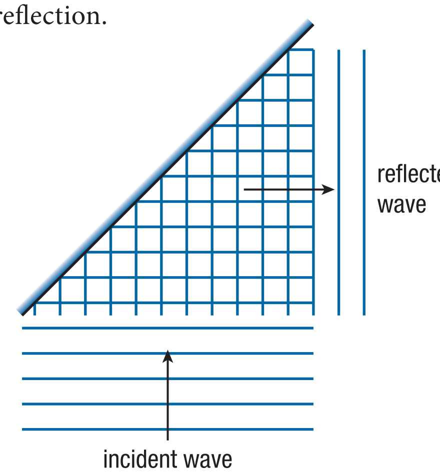


Figure 2 At the points where each wave touches the surface, the wave reflects.

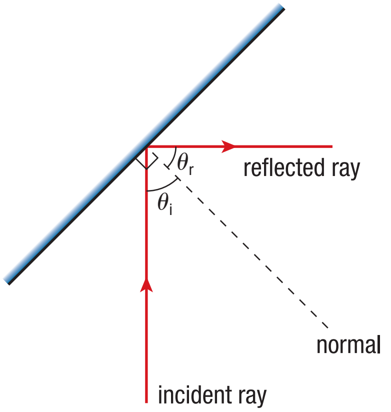


Figure 3 A single ray strikes the surface and reflects according to the law of reflection.

Huygens' Principle and Refraction

Huygens' principle can also be used to derive Snell's law of refraction, as illustrated in **Figure 4**. In time Δt, the portion of a wave front moving in the first medium covers a distance $v_1\Delta t$. The portion moving in the second medium covers a distance $v_2\Delta t$. If the second medium is a slower medium, the portion of the wave front in the second medium moves a shorter distance. As a result, the wave front and the ray deviate from the original path in medium 1. Since the waves in medium 2 do not travel as quickly, it will take longer to move away from the normal line. As a result, the refracted light ray is closer to the normal. This difference in path length results in the law of refraction. Applying trigonometric relations to Figure 4 to take account of the difference in path lengths results in a derivation of the law of refraction.

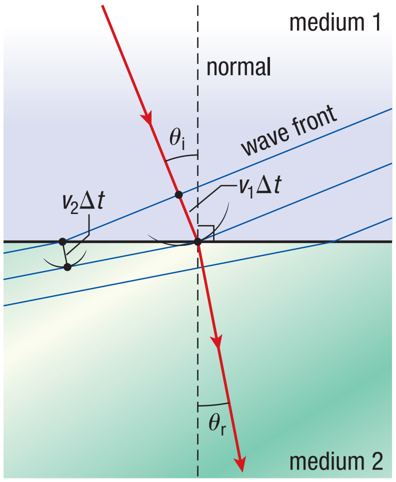


Figure 4 In Huygens' explanation of the law of refraction, the wave fronts bend due to differences in the speed of light in the two media. In this figure, the wave front is travelling faster in medium 1 than in medium 2.

Table 2, on the next page, summarizes the application of Huygens' principle to the properties of light.

Table 2 Huygens' Principle Applied to Properties of Light

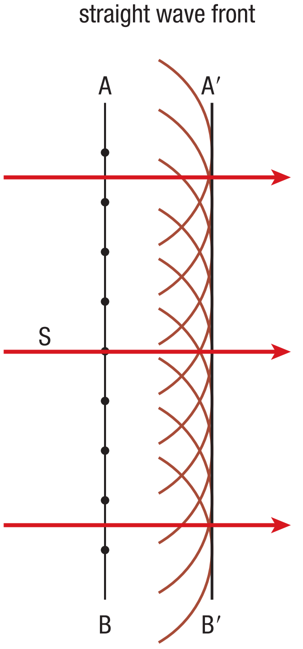
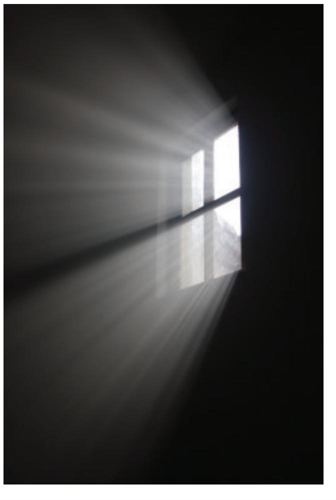
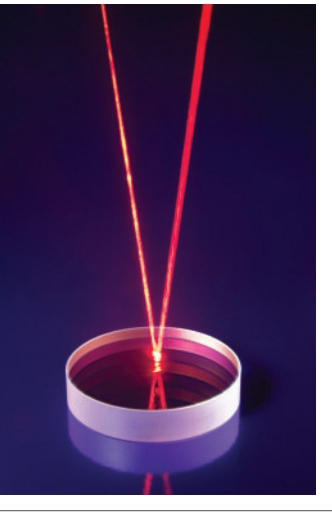
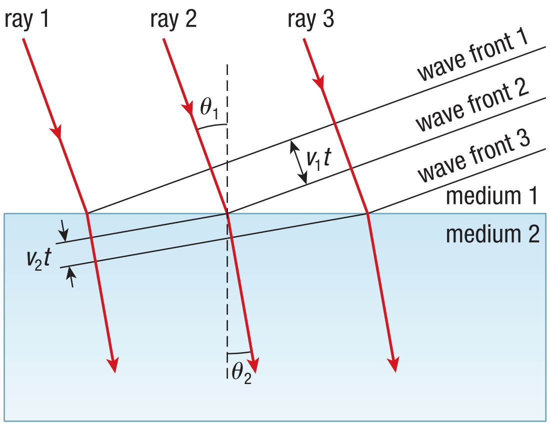
Phenomenon	Explanation	Example
rectilinear propagation	Each point on the wave front acts as a point source for a new spherical wavelet, and the wave propagates away from the source.	
diffraction	Each point passing through an opening acts as a point source for new spherical wavelets. Huygens' principle is consistent with large slit widths, edges of obstacles, and slits of the same magnitude as the wavelength.	
reflection	The incident rays hit points on the reflecting surfaces, which then act as point sources for spherical wavelets.	

Table 2 Huygens' Principle Applied to Properties of Light (*Continued*)

Phenomenon	Explanation	Example
refraction	The difference in the speed of wave fronts travelling in the two media causes the waves to bend toward or away from the normal. When the speed of the wave front decreases, the waves refract toward the normal.	

Huygens' wave theory explained many of the properties of light, including reflection, refraction, partial reflection, partial refraction, diffraction, dispersion, and rectilinear propagation. Although the wave theory made a strong case, Newton's particle theory dominated for much of the following century. This dominance was due largely to Newton's undoubted successes in other scientific areas, including studies of gravity, which gave him immense prestige within the scientific community. Newton's theory went into decline after Young's double-slit experiment demonstrated interference of light waves, which you will read about in Section 9.5.

Research This

Very Long Baseline Interferometry

Skills: Researching, Observing, Communicating

SKILLS HANDBOOK A4.1

Very Long Baseline Interferometry (VLBI) is a technique used by radio astronomers that allows them to combine observations of the same object made at the same time by many telescopes. The technique measures the time differences between the arrivals of radio waves at separate receivers and is best known for producing images of distant cosmic radio sources, tracking spacecraft, and making measurements of astronomical distances. Studying Earth's rotation and accurately mapping movements of tectonic plates are other uses of VLBI.

1. Research VLBI and answer the following questions.

A. Which radio observatory in Canada uses this technique? T/I

B. How are the data recorded at each of the telescopes? T/I

C. How is the signal from the antenna sampled? T/I

D. How are the data sent in VLBI? T/I

E. When the data are played back, how are the data from the different telescopes synchronized? T/I

F. How do the wave-like properties of radio waves enable the compilation of images? T/I

WEB LINK

UNIT TASK BOOKMARK

You can apply what you have learned about the properties of light to the Unit Task on page 556.

9.4 Review

Summary

- Newton proposed the particle theory of light to explain reflection, refraction, and the rectilinear propagation of light. However, Newton's theory could not adequately explain diffraction.
- Huygens' principle states that every point on a wave front acts as a point source for secondary wavelets, which then spread out in front of the initial wave at the same speed as the initial wave. The new wave front appears as a line tangent to all the wavelets.
- The wave theory proposed by Huygens and embodied in Huygens' principle explains reflection, refraction, and diffraction.

Questions

1. Draw diagrams to show how light behaves like a wave in the following situations. K/U T/I C
   (a) rectilinear propagation of light
   (b) reflection
   (c) refraction
2. Which model of light, a wave model or a particle model, best explains known information about light? Explain. K/U C
3. State one piece of experimental evidence that light is a wave. K/U
4. Explain how you know that the speed of light does not change when it is reflected. K/U A
5. Why did Newton think that the mass of a light particle is very low? K/U
6. Why was Newton's theory of light the dominant theory for so long? K/U
7. Does Huygens' principle apply to water and sound waves? K/U
8. Determine whether a wave model or a particle model is best to use in each of the following situations. K/U T/I
   (a) light travelling from the Sun to Earth
   (b) energy travelling for TV, radio, X-rays, and so on
9. You shine laser light through an open window. The window is like a slit, but the laser light does not diffract at all as it passes through the window. Instead, it travels in a straight line. K/U T/I
   (a) What does your observation imply about the relative magnitude of the laser's wavelength and the width of the window?
   (b) How must you change this experiment so that the electromagnetic radiation (light) does diffract through the window?
10. Thomas Young showed that light passing through two parallel narrow slits produces a pattern of light and dark fringes. Did this support or contradict Newton's corpuscular theory of light? Explain your answer. K/U C
11. When light strikes a metal surface, waves of electrons travel along the surface. Researchers call these waves surface plasmon polaritons (SPPs), or surface plasmons for short (**Figure 5**). Research SPPs, and summarize answers to the following in a brief report. T/I C

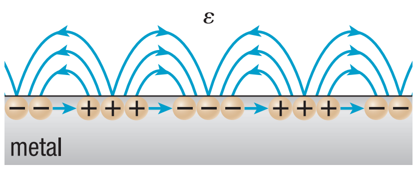


Figure 5

   (a) How do SPPs make use of the wave nature of light?
   (b) What applications do SPPs have for technology and society?
12. Research Newton's contributions to light theory. How else did Newton contribute to the study of light? In what way did Grimaldi's work influence Newton? Organize your findings in a format of your choice. T/I C
13. In 1665, Robert Hooke proposed that light travels as a wave. Research Hooke and his wave theory, and find out how he described this phenomenon. T/I C

WEB LINK