Light: Wave or Particle? 9.4

The Nature of Light

Energy can move from one place to another as the energy of moving objects or as the energy of waves. A moving object, whether as small as a subatomic particle such as an electron, or as large as a baseball or a rocket, possesses kinetic energy. In classical Newtonian mechanics, the object has to have both mass and velocity if it is to transfer energy. Energy is conveyed over long distances in waves, even though individual particles do not travel these distances. How, then, does light travel? How does light from a distant source, such as the Sun, bring us energy?

The earliest recorded views on the nature of light come to us from the Greeks. Plato thought that light consisted of "streamers," or filaments, emitted by the eye. Sight was achieved when these streamers came into contact with an object. Euclid agreed with him, arguing, "How else can we explain that we do not see a needle on the floor until our eyes fall on it?" Not all Greeks held this view, however. The Pythagoreans believed that light travelled as a stream of fast-moving particles, while Empedocles taught that light travelled as a wave-like disturbance.

By the seventeenth century, these apparently contradictory views of the nature of light placed scientists into two opposing camps. Isaac Newton was the principal advocate of the particle, or corpuscular, theory. The French mathematician, physicist, and astronomer Pierre Simon de Laplace supported him. One of the principal advocates of the competing wave theory was Christiaan Huygens of Holland, also a mathematician, physicist, and astronomer. Robert Hooke, president of the Royal Society in London, and a vigorous personal opponent of Newton, in turn supported Huygens. The debate continued for more than a hundred years. By the late nineteenth century, there appeared to be overwhelming evidence that the nature of light could be better explained using the wave model. In this section, we will see how appropriate the two theories are for explaining the observed properties of light.

Before beginning this discussion, it is important to recall the two chief functions of a scientific model or theory (the terms can be used interchangeably):

- to explain the known properties of a phenomenon
- to predict new behaviour, or new properties, of a phenomenon

Newton and his supporters used the corpuscular theory to explain known features of light. Newton's arguments are significant historically; moreover they serve as illustrations of the scientific method.

DID YOU KNOW?

Robert Hooke
Robert Hooke (1635–1703), an English scientist, invented the air pump, the balance spring for watches, the first efficient compound microscope, the hygrometer, a wind gauge, a spiral gear, the iris diaphragm, and the refractometer. He also made the first microscopic study of insect anatomy, was the first to use the word "cell" in biology, proposed zero as the freezing point of water, was the first to study crystal structure, explained the nature of colour in thin films, formulated the law of elasticity, surveyed London after the Great Fire, and discovered (but was unable to prove) the inverse square law for gravitation.

Newton's Particle Theory

Building on an earlier theory by French philosopher and mathematician René Descartes, Newton imagined that light consisted of streams of tiny particles, which he called "corpuscles," shooting out like bullets from a light source.

Rectilinear Propagation

Sharp shadows and "rays" from the Sun streaming through clouds show that light travels in straight lines. This is sometimes referred to as the **rectilinear propagation of light**. A ball thrown through space follows a curved path under the influence of gravity. The path of a bullet shot from a gun, on the other hand, curves less because the speed is greater.

rectilinear propagation of light the term used to describe light travelling in straight lines

DID YOU KNOW?

Light Bends

In 1905, as part of his general theory of relativity, Einstein proposed that light bends slightly when it passes through a strong gravitational field such as that near a star or a galaxy. Experimental observation during a solar eclipse verified this in 1919. This bending is so slight that one can say that, for most applications of light, it travels in straight lines.

As with the ball, particles travelling at normal speeds are observed to follow a curved path, due to the effect of gravity. However, faster particles curve less over the same distance. Newton argued that since the path of light has no noticeable curve, light consists of particles whose speed is extremely high. Further, since he was not aware that light exerted any noticeable pressure, he argued that the mass of its particles must be extremely low.

Diffraction

Newton further argued that light does not travel "around a corner," as do waves. In this case he discounted the work of Francesco Grimaldi (an Italian Jesuit mathematician) who had shown that a beam of light passing through two successive narrow slits produced a band of light slightly larger than the width of the slits. Grimaldi believed that the beam had been bent slightly outward at the edges of the second aperature, a phenomenon he named diffraction. Newton maintained that Grimaldi's effect resulted from collisions between the light particles at the edges of the slit rather than from the outward spreading of waves.

Reflection

We know that light falling on a mirror obeys the laws of reflection. How do particles behave under similar conditions? **Figure 1(a)** shows light rays reflected by a mirror (bouncing, Newton would say), and **(b)** shows a series of images of a bouncing steel ball.

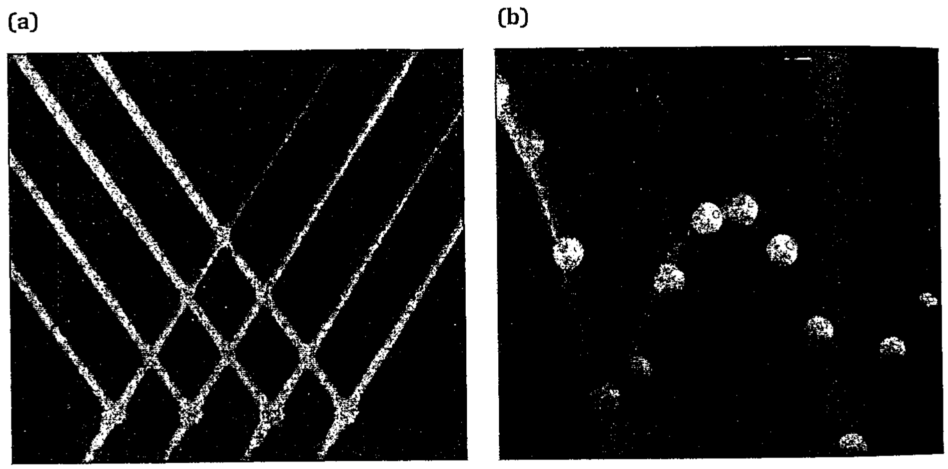

Figure 1
(a) Reflected parallel rays of light
(b) Steel ball bouncing off a hard surface

Newton demonstrated that, under the assumption of perfectly elastic collisions, the laws of reflection follow from the laws of motion. Consider a hard, spherical particle approaching a frictionless, horizontal surface with a velocity whose horizontal and vertical components are v_x and v_y respectively. When the particle is reflected, there is no change in v_x. The vertical velocity component v_y is reversed in direction because of the reactive force of the horizontal surface on the sphere, leaving its magnitude unchanged (**Figure 2**). (Since the collision is perfectly elastic, $\Delta E_K = 0$.) The incident velocity is thus equal in magnitude to the reflected velocity, and $\theta_i = \theta_r$.

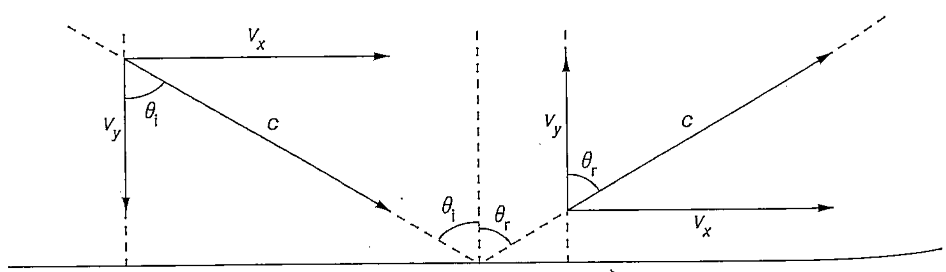

Figure 2
Vector analysis of the bouncing steel ball in a collision assumed to be perfectly elastic. The ball obeys the same law of reflection as a ray of light.

Refraction

Newton was also able to demonstrate the nature of refraction with the particle model: when light passes from air to water, it bends toward the normal (**Figure 3**). Particles, too, will bend toward the normal if their speed increases. For example, if a ball is rolled at a transverse angle down a ramp from a raised horizontal surface to a lower horizontal surface, it will bend, or refract, toward the normal.

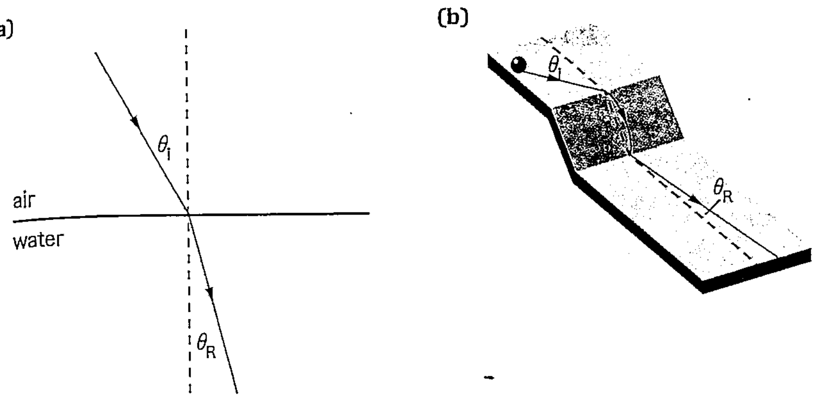

Figure 3
(a) Light travelling obliquely from air into water bends toward the normal.
(b) When the speed of a moving particle increases, it bends toward the normal.

Newton believed that water attracted approaching particles of light in much the same way as gravity attracts a rolling ball on an incline. On the strength of the rolling ball analogy, he conjectured that particles of light accelerate, specifically at the boundary, as they pass from air into a medium with a higher index of refraction, such as glass or water. He therefore predicted that the speed of light in water would be greater than the speed of light in air. At the time, the speed of light in water was not known. It was not until 1850, 123 years after Newton's death, that the French physicist Jean Foucault demonstrated experimentally that the speed of light in water is, in fact, *less* than the speed of light in air—the opposite of what Newton's particle theory predicted.

DID YOU KNOW?

Jean Foucault
Jean Foucault (1819–1868) and another French physicist, Armand Fizeau (1819–1896), measured the speed of light with a system of rotating mirrors and a spinning, toothed wheel. In 1853, they showed that the speed of light was lower in water than in air, providing strong support for the wave theory of light. Foucault is remembered today not only for contributions for optics but also for the "Foucault pendulum," a demonstration of Earth's rotation.

Partial Reflection–Partial Refraction

When light refracts, some of the light is reflected. Newton had difficulty explaining this phenomenon in his corpuscular framework. He did, however, propose a so-called "theory of fits": particles of light arrive at the surface sometimes in a "fit" of easy reflection, sometimes in a "fit" of easy refraction. However, Newton recognized that this explanation was weak.

Dispersion

When white light passes through a glass prism, different wavelengths are refracted through different angles, generating a display of spectral colours (**Figure 4**). This phenomenon, called *dispersion*, has been known since at least the time of the ancient Egyptians. In 1666, however, Newton became the first physicist to investigate the phenomenon systematically.

To explain dispersion in his corpuscular theory, Newton hypothesized that each particle in the spectrum had a different mass. Since the violet-light particles are refracted more than the blue, Newton argued that the violet-light particles must have a lower mass than blue-light particles. (The lower masses, having less momentum, would be diverted more easily.) Similarly, the blue-light particles must be lower in mass than the still less deflection-prone green-light particles. Red-light particles must have the highest masses of all the species of light in the visible spectrum.

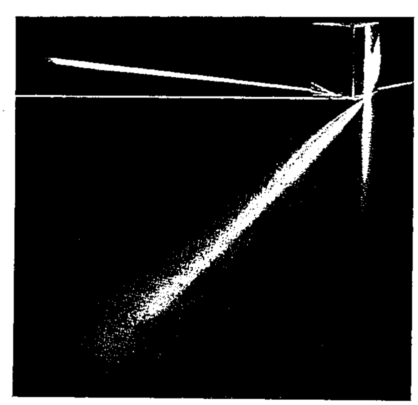

Figure 4
Dispersion occurs when white light is refracted in a prism, producing the spectrum.

Newton's corpuscular theory provided, at the time, a satisfactory explanation for four properties of light: straight-line transmission, reflection, refraction, and dispersion. It was weak in its explanation of diffraction and partial reflection–partial refraction. Considering the evidence available to Newton, his hypothesis was valid. It was, in its day, superior to the competing wave theory of light because it used the laws of mechanics, which had been proven to be valid in other areas of physics. When new evidence became available that could not be explained using Newton's corpuscular theory, this was bound to give stronger support to the wave theory. However, Newton's stature and authority were so compelling that the corpuscular theory of light dominated for more than a century. In fact, his successors adhered to the corpuscular view of light more strongly than Newton ever did himself.

Newton recognized that the experimental evidence was not exclusively strong enough for either particles or waves. Although he preferred the particle theory, he was not dogmatic about it. He considered both theories to be hypotheses, theories that required further testing.

The lesson to be learned from Newton's example is that the theories—in fact, any pronouncements—of esteemed, famous people should be evaluated on the basis of supporting evidence. A theory should not be accepted simply because it is put forward by an eminent person.

DID YOU KNOW?

Christiaan Huygens

Christiaan Huygens (1629–1695) did most of his work in astronomy and physics. He discovered a new and better method for grinding lenses and, using his improved telescope, discovered Titan (the largest satellite of Saturn), the rings of Saturn, and the "markings" on the planet Mars. Although it was first proposed by Galileo, it was Huygens who improved the pendulum clock so that it kept accurate time. Today he is remembered primarily because of the wave theory of light.

Huygens' Wave Model

Robert Hooke proposed the wave theory of light in 1665. Twenty years later, Huygens developed the theory further, introducing *Huygens' principle* (still used today as a diagram-drawing aid) for predicting the position of a wave front:

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. The surface envelope, tangent to all the wavelets, constitutes the new wave front.

As an illustration of the use of Huygens' principle, consider **Figure 5**, in which the wave front AB is travelling away from the source at some instant. The points on the wave

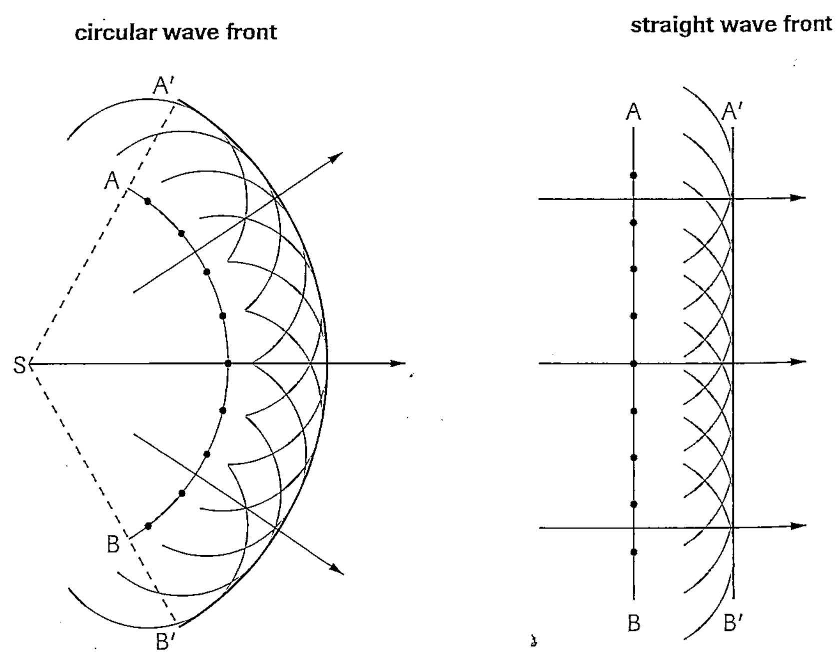

Figure 5
Every point on a wave front can be considered as a point source of tiny secondary wavelets that spread out in front of the wave at the same speed as the wave itself. The surface envelope, tangent to all the wavelets, constitutes the new wave front.

front represent the centres of the new wavelets, drawn as a series of small arcs of circles. The common tangent to all these wavelets, A′B′, is the new position of the wave front a short time later.

Huygens and his supporters were able to use the wave theory to explain some of the properties of light, including reflection, refraction, partial reflection–partial refraction, dispersion, and diffraction. However, they encountered difficulties when trying to explain rectilinear propagation, since waves as encountered in a ripple tank tend to spread out from a source. (This was the primary reason for Newton's rejection of the wave theory.)

Reflection

As **Figure 6** shows, waves obey the laws of reflection from optics. In each case, the angle of incidence equals the angle of reflection for both straight and curved reflectors.

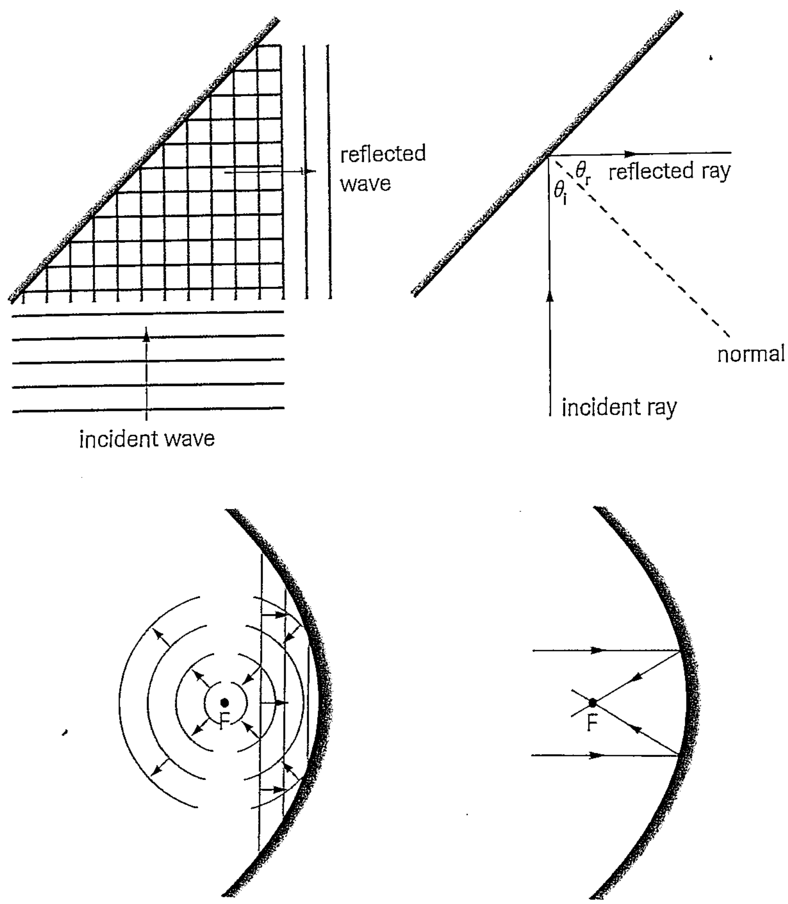

Figure 6
Waves, like light, obey the laws of reflection when reflected by a plane or curved surface.

Refraction

Huygens, using his wavelet model, predicted that light would bend toward the normal as it passes into an optically denser medium such as glass because its speed is slower in the second medium ($v_2 < v_1$). In a given interval Δt, the wavelet whose source is point A in **Figure 7** travels a shorter distance ($v_2\Delta t$) than does the wavelet whose source is B ($v_1\Delta t$). The new wave front, tangent to these wavelets, is CD (consistent with Snell's law). We have seen that Newton's corpuscular theory predicted the reverse, that is, $v_2 > v_1$. By 1850, when a technique was available for measuring the speed of light in a material other than a vacuum, the wave theory had already prevailed, for reasons which we shall examine shortly.

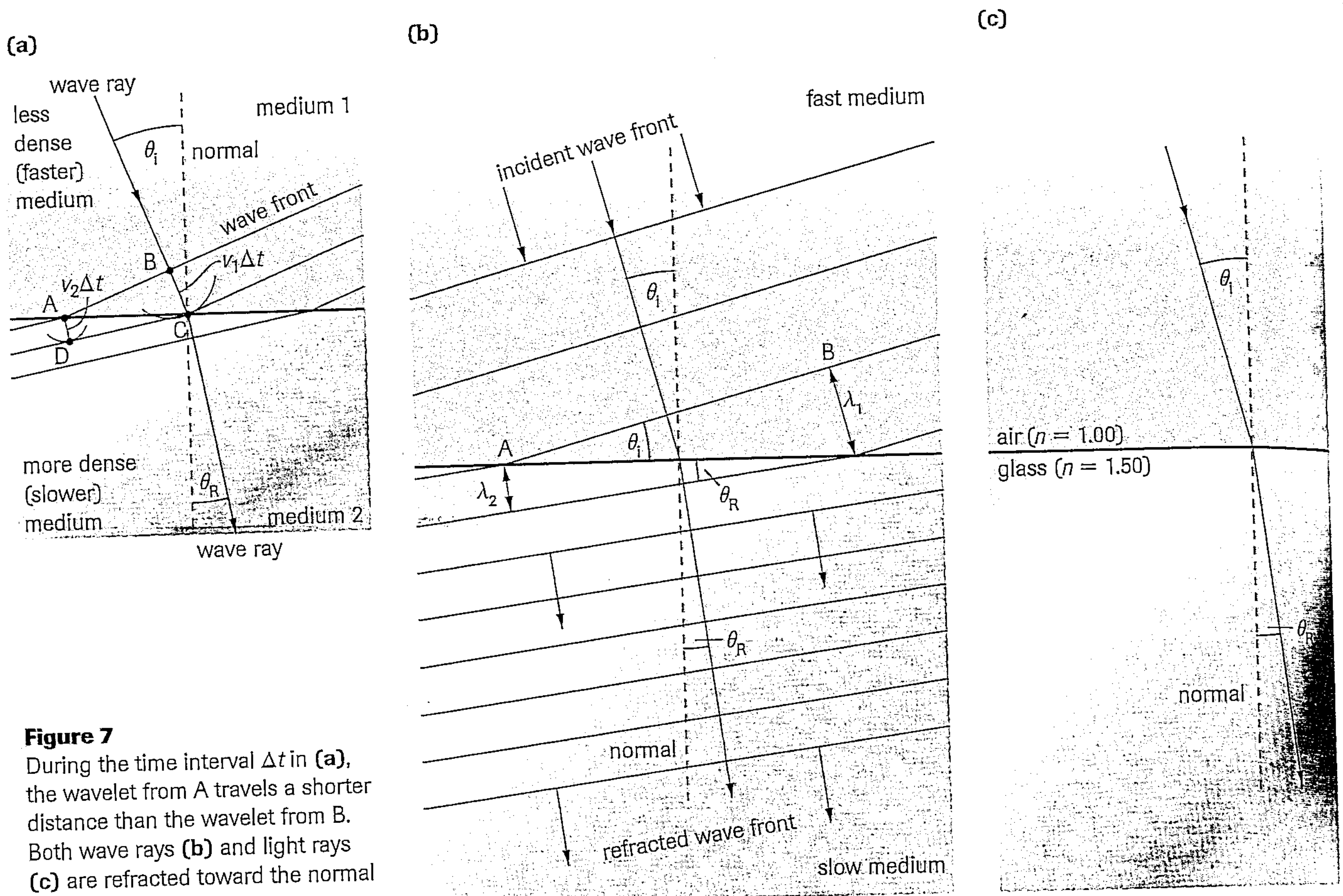

Figure 7
During the time interval Δt in **(a)**, the wavelet from A travels a shorter distance than the wavelet from B. Both wave rays **(b)** and light rays **(c)** are refracted toward the normal when the speed decreases.

Partial Reflection–Partial Refraction

We have already seen from the ripple tank that waves partially reflect and partially refract whenever there is a change in speed, that the amount of partial reflection varies with the angle of incidence, that the reflection becomes total for angles of incidence greater than a critical angle, and that all these phenomena have parallels in optics. Recall that total internal reflection only occurs for waves travelling from a slow to a fast medium, as is the case for light (**Figure 8**).

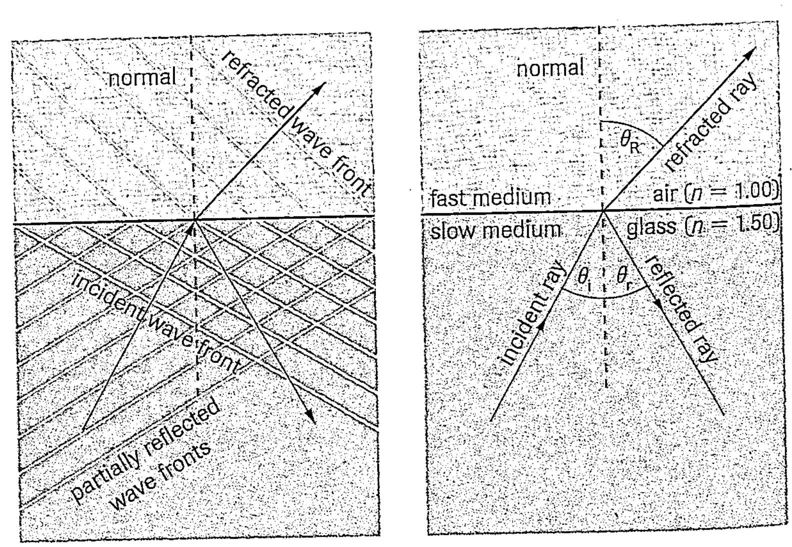

Figure 8
For waves and light refracted away from the normal when the speed increases, partial reflection also occurs.

Diffraction

Grimaldi had observed the diffraction of light when a ray was directed through two successive narrow slits. Newton had said that if light were a wave, then light waves should bend much more than was observed by Grimaldi. We saw in the previous section that diffraction only becomes easy to detect when the aperture is of approximately the same order of magnitude as the wavelength. If the wavelength is extremely small, diffraction will be minimal unless the aperature is extremely small, too.

Huygens' principle is consistent with diffraction around the edge of an obstacle, through a large aperture, and through an aperture whose size is on the same order of magnitude as the wavelength of the wave (**Figure 9**). Neither Newton nor Huygens had been able to determine what is now known, that the wavelengths of visible light are so incredibly small that diffraction effects must be very small as well. Both theories explained the diffraction phenomena known in their day. Once the minuteness of the wavelength of light was known, the wave theory was acknowledged to be superior.

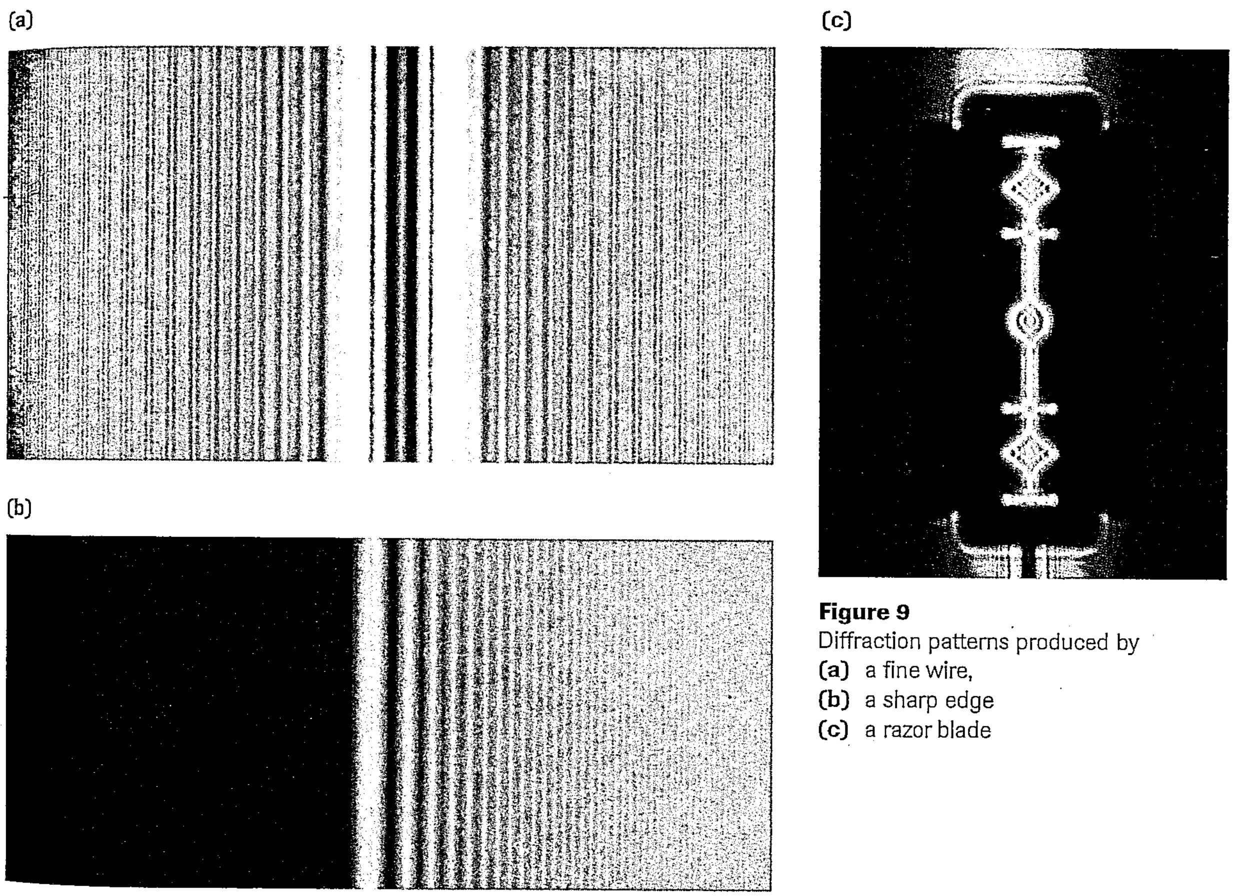

Figure 9
Diffraction patterns produced by
(a) a fine wire,
(b) a sharp edge
(c) a razor blade

Dispersion

Recall from Section 9.1 that long-wavelength waves were refracted a slightly different amount than short-wavelength waves when passing from one medium to another with a lower speed. Wave theory supporters used this fact to explain dispersion. They argued that white light is made up of the colours of the spectrum, each with a different wavelength. When white light passes through a prism, the violet wavelengths, for example, are refracted more than the red because they have different wavelengths. We will see later that the explanation is more complex, but with the knowledge available at the time, this wave explanation was satisfactory.

Rectilinear Propagation

The wave theory treats light as a series of wave fronts perpendicular to the paths of the light rays. Huygens thought of the rays as simply representing the direction of motion of a wave front. Newton felt that this did not adequately explain rectilinear propagation of light, since waves emitted from a point source spread out in all directions rather than travel in a straight line. At the time, Newton's corpuscular theory explained this property better than the wave theory.

In summary, Huygens' wave theory explained many of the properties of light, including reflection, refraction, partial reflection–partial refraction, diffraction, dispersion, and rectilinear propagation. The wave theory was more valid at that time than Newton's corpuscular theory, but because of Newton's reputation in other areas of physics, the corpuscular theory would dominate for 100 years, until Thomas Young provided new and definitive evidence in 1807.

DID YOU KNOW?

Newton As a Cult Figure

Newton, like Einstein in the 20th century, was so revered and his work so well accepted that he became to the general population what we would call today a cult figure. There were Newton jokes and even comedic plays performed where Newton was portrayed as an absented-minded, eccentric figure.

SUMMARY *Light: Wave or Particle?*

- Newton's particle theory provided a satisfactory explanation for four properties of light: rectilinear propagation, reflection, refraction, and dispersion. The theory was weak in its explanations of diffraction and partial reflection–partial refraction.
- Huygens' wave theory considered every point on a wave front as a point source of tiny secondary wavelets, spreading out in front of the wave at the same speed as the wave itself. The surface envelope, tangent to all the wavelets, constitutes the new wave front.
- Huygens' version of the wave theory explained many of the properties of light, including reflection, refraction, partial reflection–partial refraction, diffraction, and rectilinear propagation.

Section 9.4 Questions

Understanding Concepts

1. In what ways does light behave like a wave? Draw diagrams to illustrate your answer.
2. When a real-life approximation to a particle, such as a steel ball, strikes a hard surface, its speed is slightly reduced. Explain how you know that the speed of light does not change when it is reflected.
3. Does Huygens' principle apply to sound waves? to water waves?
4. What experimental evidence suggests that light is a wave?
5. The index of refraction of one type of glass is 1.50. What, according to the particle theory of light, is the speed of light in glass? Explain your answer.

Applying Inquiry Skills

6. Newton hypothesized in his corpuscular theory that particles of light have very low masses. Design an experiment to show that if there are indeed particles of light possessing a low mass, then their mass cannot be high.