Unit 10

Nature and Propagation of Light

This unit online, with its interactives:
science-playground.com/s/12f10

Stand at a window in Bhaktapur on a winter morning. Sunlight crosses 150 million kilometers of empty space in about eight minutes, slips through the glass, bends a little as it goes in and out, and throws a sharp-edged patch on the floor. What *is* it that made that journey? For three hundred years the best scientists in the world argued over two answers: a stream of tiny particles, fired like bullets, or a wave, spreading like the rings on a pond.

This unit is about the wave answer and the simple rule behind it. In 1678 the Dutch scientist Christiaan Huygens imagined that every point a wave reaches becomes a new little source of waves. From that one idea you will build any wavefront's next position with a compass and a ruler, and prove the laws of reflection and refraction, which Unit 15 of Grade 11 could only state. The next units use the same wavelets to explain how light adds up and cancels (Unit 11) and how it bends round edges.

A STORY FROM SCIENCE

The man who measured time and imagined waves

Christiaan Huygens (1629–1695) was born in The Hague, in the Netherlands, into a family of poets and diplomats. He became one of the leading scientists of the 1600s, in physics, astronomy and mathematics alike. Grinding his own lenses, he built better telescopes than anyone before him, discovered Titan, Saturn's largest moon, in 1655, and was the first to see that Saturn's strange "ears" were a thin, flat ring around the planet. He invented the **pendulum clock** (1656), which kept time to within about a minute a day instead of a quarter of an hour, and worked out the laws of colliding bodies and of motion in a circle well before Newton's *Principia*.

In 1678 he read his theory of light to the French Academy of Sciences in Paris, and published it in 1690 as *Traité de la lumière* (Treatise on Light). In it light is a disturbance spreading through an all-filling medium, and every point it reaches sends out its own small waves. With them he explained reflection, refraction, and even the strange double refraction of the crystal called Iceland spar. Newton's particle theory was far better known for a hundred years; Huygens' idea came back when Young and Fresnel showed that light really does behave as a wave.



Figure 10.1 *Christiaan Huygens (1629–1695), painted by Caspar Netscher in 1671.*
Photo: Caspar Netscher, Public domain

10.1 Introduction

Light is an **electromagnetic wave**: an electric field and a magnetic field, at right angles to each other and to the direction it travels, oscillating together. It needs no medium, and crosses a vacuum at about 3×10^8 m/s. Like every wave, it has a **wavelength**, a **frequency** and an **amplitude**: visible light has wavelengths from about 400 nm (violet) to 700 nm (red).

Yet light also behaves like a stream of particles. Look at what it does:

- It makes plants grow, and it also runs a solar calculator: it hands over its energy in little lumps, like particles.
- It casts sharp shadows, yet it also bends a little round the edges of obstacles, like a wave.
- It reflects from mirrors, refracts in water, and paints the colors in a soap bubble, which only waves can do.

So we study light not only as particles, as Newton believed, but also as waves, starting with **Huygens' principle**: every point on a wavefront acts as a source of secondary wavelets, and the new wavefront is the surface that touches (the **envelope** of) all these wavelets. This one principle accounts for the way light travels, and for reflection, refraction, interference and diffraction.

10.2 Nature and propagation of light

The nature of light is **dual**. It shows wave properties (interference, diffraction, polarization) and particle properties (photons). It travels in straight lines in a uniform medium, and changes direction by reflection, refraction and diffraction when it meets other materials. How it spreads and forms patterns is the heart of optics and of modern physics.

Newton's corpuscular theory (1704, in his book *Opticks*) said that light is a stream of tiny, very light particles, **corpuscles**, shot out by a luminous body at enormous speed. In a uniform medium they travel in straight lines. They bounce off a mirror as a perfectly elastic ball bounces off a wall, which gives the law of reflection. At the surface of water or glass they are pulled towards it, which turns them towards the normal: refraction. The theory explained reflection, refraction and straight-line travel, but it could not explain interference and diffraction, the typical wave behaviors. And it made a prediction that turned out wrong: to bend towards the normal, the corpuscles had to go **faster** in the denser medium.

Huygens' wave theory (1678) said that light is a wave, spreading through an all-filling medium he and his followers called the **ether**. He brought in two new ideas, **wavefronts** and **secondary wavelets**, and with them explained reflection and refraction, with light going **slower** in the denser medium. A century later, Thomas Young and Augustin Fresnel joined his wavelets to the idea of interference, and the same wavelets then explained interference and diffraction too.

The story went on. **Young's double-slit experiment** (early 1800s) and **Fresnel's** mathematics of diffraction (1818) established that light is a wave. **Maxwell's electromagnetic theory** (1865) showed it is an electromagnetic wave, needing no ether at all. Then **Planck's quantum theory** (1900) and **Einstein's explanation of the photoelectric effect** (1905) showed that light's energy comes in packets, photons. The **quantum theory of light** now unites both pictures, and it is the base of modern physics.

16. Huygens' principle involves wavelets that appear to travel backwards, which raises questions about their physical meaning.
    a. What are backward wavelets in Huygens' principle?
    b. Why are backward wavelets not observed in practice?
    c. What theoretical assumption removes the effect of the backward wavefronts?

17. Huygens' principle explains not only the propagation of light but also other waves such as sound, and effects such as refraction.
    a. How can Huygens' principle be applied to explain the propagation of sound waves?
    b. Use Huygens' principle to explain the refraction of light.
    c. How is the new position of a wavefront found using secondary wavelets?
    d. Why is it physically impossible for two wavefronts to cross?

A companion to your textbook, not a replacement for it: study from the book your school uses, and where the two differ, follow your teacher. Found a mistake? Please tell us.

Check 12

8. Which statement about Huygens' principle is correct?

a Every point on a wavefront acts as a source of new wavelets.
b Light particles are emitted from a luminous body.
c Light travels faster in a denser medium.
d Light consists of discrete packets of energy.

Check 13

9. The idea of wavefronts in Huygens' theory is used to explain:

a polarization
b diffraction and interference
c the emission of light particles
d only the straight-line motion of light

Check 14

10. What is the fundamental difference between Newton's and Huygens' theories of light?

a Newton explained light as waves, while Huygens considered it particles.
b Newton described light as particles, while Huygens considered it waves.
c Both described light as waves but differed in their explanations of color.
d Both described light as particles but differed in explaining its speed in a medium.

13. Huygens' principle is essential in understanding how light waves propagate and interact with obstacles.
    a. Describe the construction of a new wavefront according to Huygens' principle.
    b. Explain how Huygens' principle helps to describe the nature and propagation of light.
    c. State two limitations of Huygens' wave theory of light.

14. When studying waves, the idea of phase helps to explain how different points on a wave relate to each other as it propagates.
    a. What is meant by phase in a wave?
    b. What is the phase relationship of all points on a wavefront? Explain.
    c. How does a phase difference affect the propagation of light waves?

15. Understanding how wavefronts advance helps to explain the propagation of waves in different media.
    a. What principle is used to determine the new position of a wavefront?
    b. Explain how the new position of a wavefront is constructed using Huygens' principle.
    c. What shape of wavefront is formed by a point source in a homogeneous medium?

	Newton's corpuscular theory	Huygens' wave theory
Light is	a stream of tiny particles	a wave in a medium (the ether)
Straight-line travel	easily explained	explained only roughly, with a puzzle about the backward wavelets
Reflection, refraction	explained	explained
Speed of light in water or glass	**faster** than in air	**slower** than in air (correct)
Interference, diffraction	not explained	explained, once Young and Fresnel added interference
Photoelectric effect	(not known then)	not explained (needs photons)

Check 1

Which measurement settled the argument between Newton's and Huygens' explanations of refraction?

a that light reflects at equal angles from a mirror
b that light travels slower in water than in air
c that light travels in straight lines
d that light carries energy

10.3 Wave theory of light

The **wave theory of light** says that light behaves as a wave, not as a stream of particles. Huygens first proposed it in the 17th century, through his principle: every point on a wavefront sends out secondary waves, which spread and form the new wavefront. Wavelets spreading out from the edge of an opening also explain why light bends round obstacles (**diffraction**) and spreads out after passing through small openings.

One of the strongest pieces of evidence came from **Thomas Young**. Between 1801 and 1803 he showed the Royal Society that two beams of light from one source can cancel each other, and in his lectures of 1807 he described the form of the experiment now named after him: light through **two closely spaced slits** makes a pattern of bright and dark bands on a screen. (Exam answers usually give the year as 1801.) Only waves can do this: where the waves from the two slits arrive in step, they reinforce each other (**constructive interference**); where one arrives a crest when the other brings a trough, they cancel (**destructive interference**). The bands were a major confirmation that light has wave properties.

Two more effects point the same way. **Polarization** shows that light's vibrations are across its direction of travel and can be confined to one direction, which you can show by passing light through two polarizing filters and turning one of them. **Diffraction**, the bending of light round edges and through narrow slits, is a wave effect too. Interference, polarization and diffraction together strongly suggest that light is a wave, and Huygens' principle is the framework that explains them in classical physics.

Wavefront and wavelet

Phase

To say what a wavefront is, you need **phase**. As a wave passes, each particle of the medium (for light, the electric field at each point) vibrates. Its **phase** is the stage it has reached in its vibration: where it is and which way it is going, written as an angle. In $y = a\sin(\omega t - kx)$ the phase is $\omega t - kx$. One whole vibration is a change of phase of 2π (360°). Two points whose vibrations are exactly in step are **in phase**; two points half a cycle apart, one at a crest while the other is at a trough, are **out of phase** by π (180°).

Along the direction the wave travels, the phase falls behind by 2π for every wavelength. So two points a distance x apart along the wave differ in phase by

$$\phi = \frac{2\pi}{\lambda} x$$

This **phase difference** decides what happens when two waves meet: in phase they add up, out of phase they cancel. Unit 11 is built on it.

Wavefront

A **wavefront** is an imaginary surface joining all the points of a wave that are **in the same phase**, vibrating in the same way at the same time: all on a crest, say. A wave's crests are a set of wavefronts, one wavelength apart. In a uniform medium the wave travels at right angles to its wavefronts: the lines along which the wave travels, the **rays**, are always **perpendicular to the wavefronts**. The shape of the wavefronts depends on the source and on how the wave spreads (Figure 10.2).

1. **Spherical wavefront.** A point source, such as a small bulb, sends light out equally in all directions; at any instant the points in the same phase are all at the same distance from the source, so the wavefronts are spheres centered on it, and the rays spread out along the radii. A spherical wavefront can be **diverging** (spreading out from a point, as here) or **converging** (shrinking towards a point, as after a convex lens, towards its focus).
2. **Plane wavefront.** Far from a source, a small piece of a huge sphere is practically flat. Sunlight reaching Earth, or the beam of a laser, has flat, parallel wavefronts, and its rays are parallel.
3. **Cylindrical wavefront.** A long, narrow source, such as a lit slit or a long tube light, sends out wavefronts that are cylinders around it, with the source along their axis.

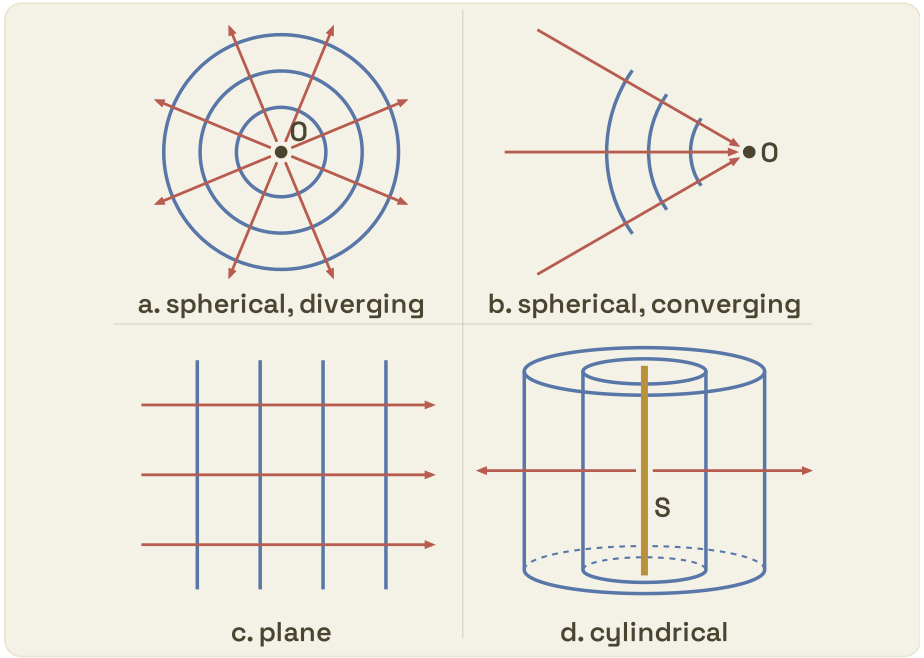


Figure 10.2 *Wavefronts (crests, all in the same phase) and rays. a. A point source O: spherical wavefronts spreading out. b. Spherical wavefronts converging to a point O, as after a convex lens. c. Plane wavefronts, far from a source: parallel rays. d. A line source, such as a lit slit S: cylindrical wavefronts around it. In every case the rays are perpendicular to the wavefronts.*

Exercise

Choose the correct option

Check 5

1. Which of the following phenomena cannot be explained by Newton's corpuscular theory of light?

a reflection
b refraction
c diffraction
d rectilinear propagation

Check 6

2. According to Huygens' principle, light propagates as:

a particles
b waves
c pulses of particles
d rays only

Check 7

3. According to Newton's corpuscular theory, light travels faster in:

a air
b water only
c glass only
d denser media

Check 8

4. Which phenomenon observed in Young's double-slit experiment supports Huygens' wave theory?

a refraction
b reflection
c interference
d dispersion

Check 9

5. Why does Huygens' wave theory, on its own, fail to explain the rectilinear propagation of light completely?

a it assumes light travels as particles
b it does not account for diffraction effects
c it predicts that light should spread in all directions from the secondary wavelets
d it cannot explain reflection

Check 10

6. According to Huygens' wave theory, why does light bend around obstacles (diffraction)?

a light behaves as particles
b secondary wavelets spread into the shadow region
c the speed of light increases in the obstacle region
d light cannot penetrate obstacles

Check 11

7. Which of the following observations disproved Newton's corpuscular theory?

a light travels in straight lines
b the speed of light decreases in denser media
c reflection occurs at smooth surfaces
d light refracts at the interface between two media

Answer these questions

11. While studying how light travels through different media, it is important to understand wavefronts and their role in describing light's propagation.
    a. What is a wavefront?
    b. Describe the different types of wavefronts, with suitable examples.

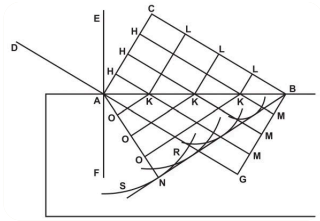


Figure 10.8 *Huygens' own figure of refraction, from his Treatise on Light (1690). The wave AC arrives at the surface AB, end A first. While C travels to B, the wavelet from A, the arc SNR, grows only two-thirds of that distance (AG would be the whole of it) in the glass below, and BN, the line touching all the wavelets from the points K, is the refracted wave. The ray DA goes on along AN, bent towards the normal EF.*

Photo: Christiaan Huygens, Public domain

IN SHORT

- Light is an electromagnetic wave, but it also gives up its energy in packets, photons: its nature is dual.
- Newton's corpuscular theory explains reflection, refraction and straight-line travel, but not interference or diffraction, and it needs light to be faster in water. Huygens' wave theory explains refraction with light slower in water (correct).
- A **wavefront** joins points in the same phase; rays are perpendicular to it. Point source: spherical fronts; line source: cylindrical; far away: plane.
- **Huygens' principle**: every point on a wavefront is a source of secondary wavelets at the wave's speed; the new wavefront is their forward envelope. The backward wave doesn't exist (the obliquity factor is zero backwards).
- Huygens' construction proves $i = r$ for reflection and $\sin i / \sin r = c/v = \mu$ for refraction.
- Phase difference $= \dfrac{2\pi}{\lambda} \times$ path difference.

Check 2

Light from a distant star reaches a telescope on Earth. Its wavefronts there are:

a spherical, diverging, because the star is a point source

b cylindrical

c practically plane

d spherical, converging

Wavelet

A **wavelet** is a small, secondary wave sent out from a point on a wavefront. In Huygens' picture every point a wavefront reaches starts vibrating, and so becomes a new source sending out its own small waves, in the same medium and at the same speed as the original wave. As time goes on, these wavelets spread out and together build the new wavefront. Wavelets spreading from the edges of an opening explain how waves spread out beyond it (diffraction), and where wavelets from different places overlap they can add up or cancel, making interference patterns.

10.4 Huygens' principle

Huygens' principle gives the position of a wavefront at any later time, if you know where it is now. It has two parts:

1. Every point on a wavefront (the **primary** wavefront) acts as a source of **secondary wavelets**, which spread out in all directions with the speed of the wave in that medium.
2. The new wavefront at any later time is the **envelope** of these secondary wavelets: the surface that touches all of them, in the forward direction.

The construction (Figure 10.3). A point source S sends out a spherical wavefront; AB is a part of it at time $t = 0$. To find where it is a short time Δt later:

1. Mark many points on AB: a, b, c, d, e.
2. Around each one, draw a sphere (in the drawing, a circle) of radius $c\Delta t$, the distance the wave travels in Δt, where c is its speed.
3. Draw the surface that touches all these spheres on the far side from S. This is the new wavefront A′B′ at $t = \Delta t$, a sphere centered on S, larger by $c\Delta t$.
4. A second surface also touches the spheres, on the side towards the source: A″B″. It would be a wave running backwards, towards S. No such wave exists, and Huygens simply discarded it.

The same construction moves a **plane** wavefront: wavelets of equal radius drawn from points on a flat front all touch a flat surface $c\Delta t$ ahead of it (Figure 10.4). So a plane wave stays plane, and travels straight on, at right angles to its fronts.

Why light travels in straight lines

The plane construction is Huygens' explanation of the **rectilinear propagation** of light: a wide wavefront rebuilds itself, flat and parallel, step after step, so the light goes straight on along its rays. Now let it pass a wide opening. The wavelets from the edges of the opening spread sideways into the shadow too. Taken alone, they would blur every shadow, and that was the strongest objection to the wave theory. The answer, worked out by Fresnel in 1818, is interference: in the shadow region the wavelets from different parts of the front arrive with all sorts of phases and very nearly cancel, except within a few wavelengths of the shadow's edge. Since light's wavelength is under a thousandth of a millimeter, the blurred band at the edge of an ordinary shadow is far too thin to notice, and light seems to travel in straight lines. Sound, with wavelengths of about a meter, bends easily round a doorway; light, with wavelengths a million times shorter, hardly bends at all.

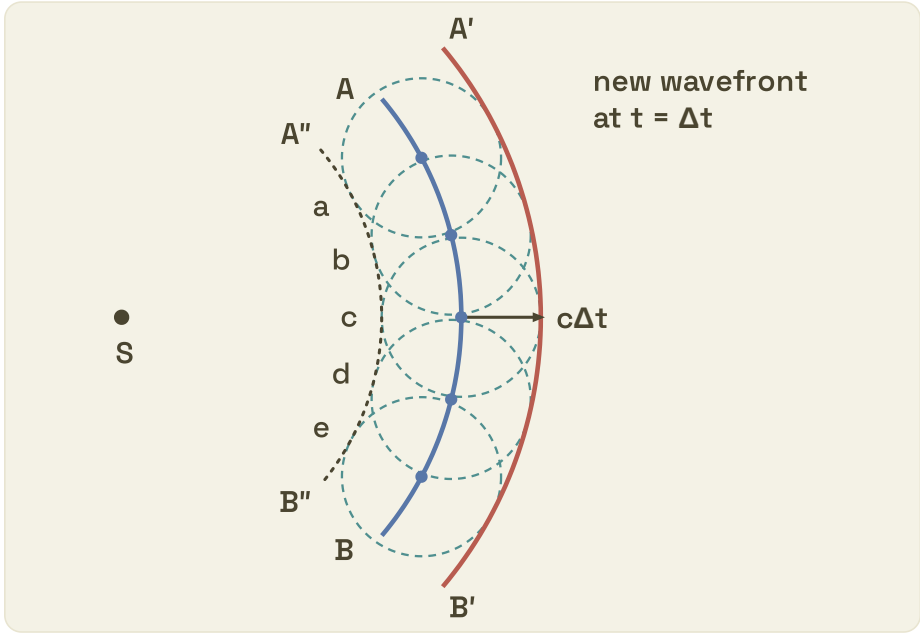


Figure 10.3 *Huygens' construction for a spherical wavefront from a point source S. Each point a–e of the wavefront AB at $t = 0$ sends out a wavelet of radius $c\Delta t$. The surface touching them all on the far side, A′B′, is the new wavefront at $t = \Delta t$. The surface on the near side, A″B″ (dotted), would be a backward wave, which is not there.*

The backward wavelets

Why is there no backward wave A″B″? Huygens had no reason; he just left it out, and this was a weakness of his theory. The answer came from the mathematics of Fresnel and of Gustav Kirchhoff (1882): a secondary wavelet is **not equally strong in all directions**. Its amplitude falls off with the angle θ from the forward direction, in proportion to the **obliquity** (or **inclination**) **factor**

$$K(\theta) = \tfrac{1}{2}\,(1 + \cos\theta)$$

which is 1 straight ahead ($\theta = 0$) and **zero straight back** ($\theta = 180°$). So the backward wave has no energy, and there is none to see. The wavelets are best thought of as a way of working out where the wave goes, not as real little waves running off backwards.

Check 4

Light passes from air into water ($\mu = 1.33$). According to the wave theory, its speed in water is:

a 4.0×10^8 m/s
b 3.0×10^8 m/s
c 2.26×10^8 m/s
d 1.33×10^8 m/s

WORKED EXAMPLE

Example 10.1: a wavelet in glass

A plane wavefront meets a glass surface ($\mu = 1.5$) at an angle of incidence of 45°. The point A of the front reaches the surface first; the other end, B, reaches it at B′, 6.0 cm from A, a time t later. How far has the wavelet from A grown into the glass by then, and what is the angle of refraction?

Answer

In triangle ABB′, $BB' = AB' \sin i = 6.0 \times \sin 45° = 4.24$ cm. That is ct.

In the same time, the wavelet in glass grows $AA' = vt = \dfrac{ct}{\mu} = \dfrac{4.24}{1.5} = \mathbf{2.83\ cm}$.

Then $\sin r = \dfrac{AA'}{AB'} = \dfrac{2.83}{6.0} = 0.471$, so $r = \mathbf{28.1°}$.

(Check: $\sin 45° / \sin 28.1° = 0.707/0.471 = 1.50 = \mu$.)

YOUR TURN

The speed in diamond

Light of frequency 5.0×10^{14} Hz enters diamond ($\mu = 2.42$) from air. Find its speed and its wavelength in diamond, and its wavelength in air. Which of the three quantities (speed, frequency, wavelength) does not change?

Answer

$v = c/\mu = 3.0 \times 10^8 / 2.42 = \mathbf{1.24 \times 10^8\ m/s}$.

In diamond, $\lambda = v/f = 1.24 \times 10^8 / 5.0 \times 10^{14} = 2.48 \times 10^{-7}$ m = **248 nm**.

In air, $\lambda = c/f = 3.0 \times 10^8 / 5.0 \times 10^{14} = 6.0 \times 10^{-7}$ m = **600 nm**.

The **frequency** doesn't change: it is set by the source, and each wavelet vibrates in step with the wave that started it. Speed and wavelength both fall by the factor μ.

DID YOU KNOW?

Huygens' own drawing

Huygens drew his wavelets for refraction in 1690, almost exactly as in Figure 10.7: a front AC meets the surface at A, and while C travels to B the wavelet from A grows only two-thirds as far in the glass. He took the ratio of the speeds to be the ratio of the sines, as here: light slower in glass. Newton's *Opticks*, fourteen years later, said the opposite, and Newton's fame meant most scientists believed him for over a century.

$$\sin r = \frac{AA'}{AB'} = \frac{vt}{AB'} \qquad (10.2)$$

Dividing (10.1) by (10.2),

$$\frac{\sin i}{\sin r} = \frac{c}{v} \qquad (10.3)$$

The ratio c/v, the speed of light in the first medium divided by its speed in the second, is a constant for a given pair of media: it is the refractive index of the second medium with respect to the first, μ. So

$$\boxed{\frac{\sin i}{\sin r} = \mu}$$

which is Snell's law, the first law of refraction. And since the incident front AB, the refracted front A′B′ and the boundary XY are all perpendicular to the plane of the paper, the incident ray, the normal and the refracted ray all lie in that plane: the second law.

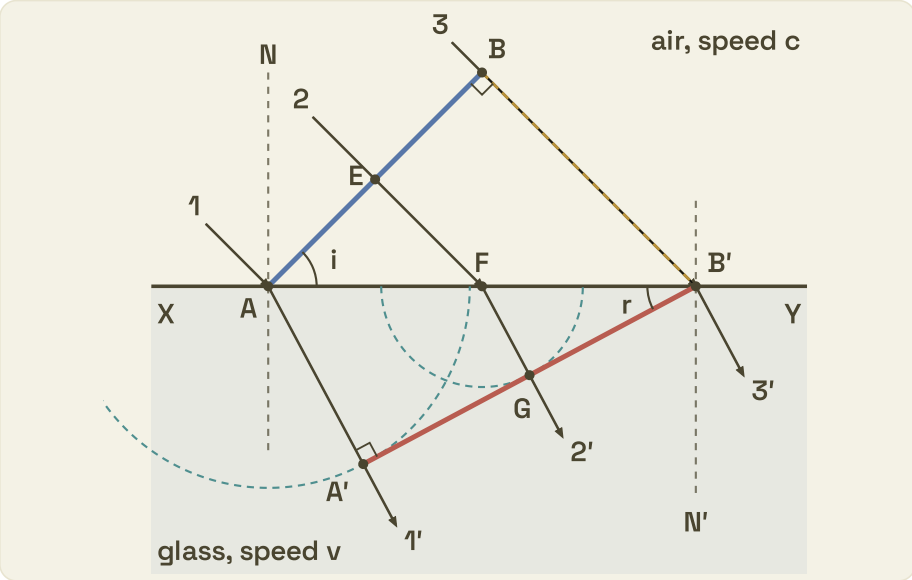


Figure 10.7 *Refraction of a plane wavefront by Huygens' construction, from air into glass (μ = 1.5). While B travels BB′ = ct in air, the wavelet from A grows only AA′ = vt in the glass. The tangent A′B′ is the refracted front, turned towards the boundary: the ray bends towards the normal. sin i = BB′/AB′ and sin r = AA′/AB′, so sin i / sin r = c/v.*

The proof shows *why* light bends: the end of the front that enters the glass first slows down first, and the front swings round, as a line of marching students turns when the ones at one end step onto mud. It also shows that $\mu = c/v$: the refractive index of glass, 1.5, means light goes 1.5 times slower in glass than in air. This is the prediction Foucault confirmed in 1850. It also explains **total internal reflection**: going from glass into air, the wavelet from A grows in air at c, *faster* than B travels to the boundary in glass (BB′ = vt, while AA′ = ct). If $\sin i > v/c$, the wavelet from A is already wider than AB′ by the time B arrives, no tangent can be drawn from B′ to it, and there is no refracted wavefront: all the light is reflected. And because light of different colors travels at slightly different speeds in glass, each color has its own c/v and its own angle of refraction: **dispersion**.

Build both constructions yourself:

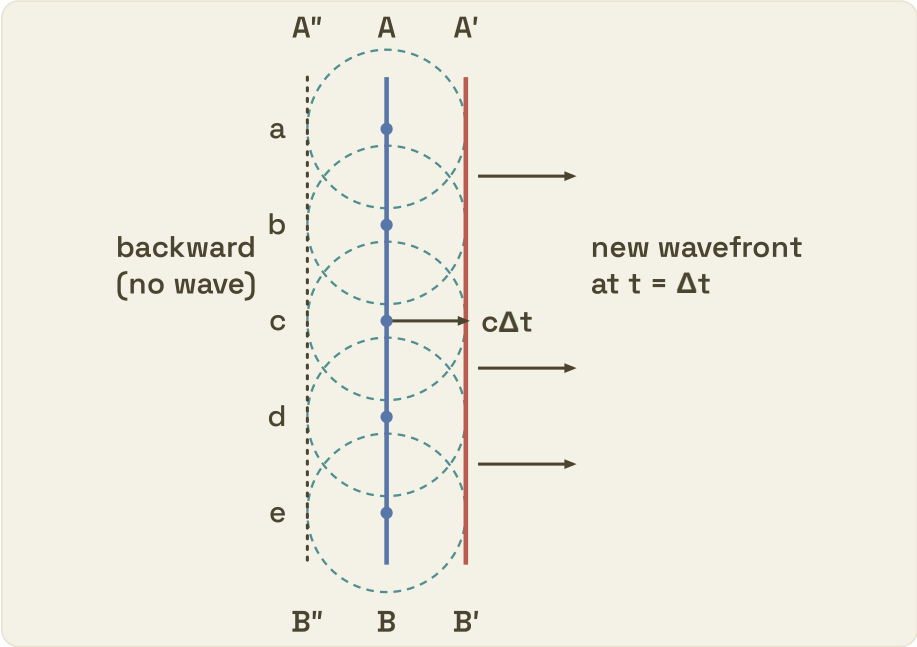


Figure 10.4 *The same construction for a plane wavefront AB: the forward envelope A′B′ is another plane, cΔt ahead. A plane wave stays plane and goes straight on.*

CAREFUL

Two wavefronts never cross

Two wavefronts of the **same wave** can never cross each other. Each is a surface of one phase, and the wave travels at right angles to it. Where two of them met, a point would have two different phases at the same instant, and the wave there would be traveling in two directions at once, which is impossible. (Two *different* waves can pass through one another, as ripples from two stones do; where they overlap they simply add up to one disturbance, by superposition.)

Limitations of Huygens' theory

As Huygens left it, the theory had real gaps:

- It had no reason for leaving out the **backward wavelets** (put right by the obliquity factor, above).
- It needed a medium, the **ether**, to carry light through empty space. No ether was ever found; Maxwell showed that light is an electromagnetic wave that needs no medium, and in 1887 Michelson and Morley's experiment found no sign of one.
- Huygens' waves were a series of pulses with no wavelength, so on their own they did not explain **interference**, **diffraction** or **colors**; that needed Young's and Fresnel's periodic waves.
- He took light to be a longitudinal disturbance, like sound, which can't explain **polarization**; light's waves are transverse.
- No wave theory explains the **photoelectric effect**, black-body radiation or the line spectra of atoms, which need light's energy to come in packets, photons.

Check 3

In Huygens' construction, the new wavefront is:

a the wavelet drawn from the middle of the old wavefront

b the surface that touches all the secondary wavelets, in the forward direction

c the surface joining the centers of the wavelets

d the surface that touches all the wavelets on both sides

10.4.1 Applications of Huygens' principle

Huygens' principle applies to every kind of wave: light, sound, ripples on water. For **sound**, each layer of air that a compression reaches pushes on the next, so it acts as a source of sound wavelets in turn; the envelope gives the next wavefront, and sound spreads from a speaker as spheres. Because sound's wavelengths are large (34 cm at 1000 Hz), its wavelets spread well beyond the edges of a doorway, and you hear a radio round a corner. On a clear night, the air near the ground is cooler than the air above it, and sound travels faster in warmer air: the upper part of each wavefront runs ahead, the front tilts downwards, and a distant bus or temple bell sounds unusually clear. Huygens' construction gives each of these.

For light, the principle proves the two laws you have so far only been told: the laws of reflection and of refraction.

1. Reflection of light

When a wavefront meets a mirror, each point it reaches becomes a source of wavelets that go back into the first medium. Their envelope is the reflected wavefront. There are two laws of reflection:

1. The incident ray, the normal at the point of incidence and the reflected ray all lie in the same plane.
2. The angle of incidence equals the angle of reflection.

Proof of the laws of reflection (Figure 10.6). Let XY be a plane reflecting surface, and AB a plane wavefront meeting it at an angle. Rays 1, 2 and 3, perpendicular to AB, are the incident rays.

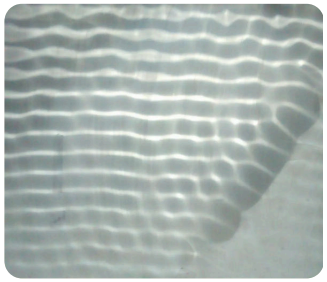


Figure 10.5 *Straight waves in a ripple tank, reflected by a straight barrier.*
Photo: Psgs123xyz, CC0

1. At $t = 0$, the end A of the wavefront touches the surface. The other end B is still a distance BB′ from the surface; it reaches the surface at B′ a time t later, so $BB' = ct$, where c is the speed of light.
2. Meanwhile A, struck at $t = 0$, has been sending out a wavelet back into the same medium, at the same speed c. By time t it is a hemisphere of radius $AA' = ct$.
3. Each point between them, such as D (whose ray strikes the surface at P), sends out a wavelet from P as soon as the front reaches it; by time t that wavelet is smaller, since it started later. All of them touch one plane through B′: draw the tangent from B′ to the wavelet from A, touching it at A′. **A′B′ is the reflected wavefront**, and the wavelet from P touches it at D′.
4. The reflected rays 1′, 2′ and 3′ are perpendicular to A′B′.

The angle between a wavefront and the surface equals the angle between its ray and the normal (each is the other turned through 90°). So the angle of incidence is $i = \angle BAB'$, between the incident wavefront and the surface, and the angle of reflection is $r = \angle A'B'A$, between the reflected wavefront and the surface.

Compare the right-angled triangles ABB' and $B'A'A$:

- $\angle ABB' = \angle B'A'A = 90°$ (a ray is perpendicular to its wavefront, and AA′ is the ray from A);
- the hypotenuse AB' is common to both;
- $BB' = AA' = ct$.

So the triangles are congruent (right angle, hypotenuse, side), and their corresponding angles are equal: $\angle BAB' = \angle A'B'A$, that is,

$$i = r$$

The angle of incidence equals the angle of reflection. Also, the incident wavefront AB, the reflected wavefront A′B′ and the surface XY are all perpendicular to the plane of the paper, so the incident ray, the normal and the reflected ray all lie in the plane of the paper: the first law.

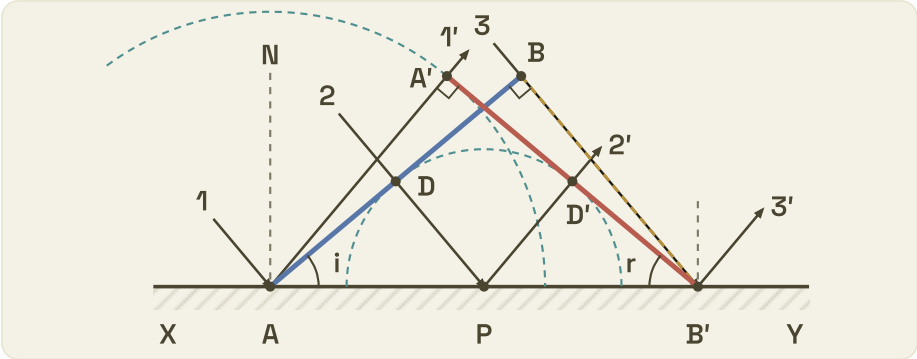


Figure 10.6 *Reflection of a plane wavefront by Huygens' construction. The front AB reaches A first; while B travels to B′ (BB′ = ct), the wavelet from A grows to radius AA′ = ct. The tangent A′B′ from B′ is the reflected front. Right triangles ABB′ and B′A′A share the hypotenuse AB′ and have BB′ = AA′, so i = r. The point D's ray strikes the surface at P, and its wavelet reaches the new front at D′.*

2. Refraction of light

Refraction is the change in the direction of light as it passes at a slant from one medium into another, because its speed changes. (At normal incidence the speed still changes, but the direction does not.) The laws of refraction:

1. The ratio of the sine of the angle of incidence to the sine of the angle of refraction is a constant for a given pair of media (**Snell's law**), $\sin i / \sin r = \mu$, where the constant μ is the refractive index of the second medium with respect to the first.
2. The incident ray, the normal at the point of incidence and the refracted ray all lie in the same plane.

Proof of the laws of refraction (Figure 10.7). Let XY be the boundary between two media: medium 1 above (rarer, light's speed c) and medium 2 below (denser, speed v, with $v < c$). AB is a plane wavefront in medium 1, and rays 1, 2, 3, perpendicular to it, are the incident rays. NA is the normal at A.

1. At $t = 0$, A touches the boundary. B reaches the boundary at B′ a time t later: $BB' = ct$.
2. In that time the wavelet from A grows in medium 2, where it travels at v: its radius is $AA' = vt$, smaller than BB′.
3. A point E on AB reaches the boundary at F, and its wavelet in medium 2 reaches G by time t. Draw the tangent from B′ to the wavelet from A, touching it at A′: the wavelet from F touches the same plane at G. **A′B′ is the refracted wavefront**, and the refracted rays 1′, 2′, 3′ are perpendicular to it.
4. Draw the normal N′B′ at B′. The angle of incidence is $i = \angle BAB'$ (between the incident front and the boundary), and the angle of refraction is $r = \angle AB'A'$ (between the refracted front and the boundary).

In the right-angled triangle ABB' (right angle at B),

$$\sin i = \frac{BB'}{AB'} = \frac{ct}{AB'} \qquad (10.1)$$

In the right-angled triangle $AA'B'$ (right angle at A′),