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Geometrical light

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فيزياء٢ (ضوء+ حرارة+صوت)

لطلاب الفرقة الاولى علوم جيولوجيا

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The Nature of Light

Before the beginning of the nineteenth century, light was considered to be a stream of particles that either was emitted by the object being viewed or emanated from the eyes of the viewer. Newton, the chief architect of the particle theory of light, held that particles were emitted from a light source and that these particles stimulated the sense of sight upon entering the eye. Using this idea, he was able to explain reflection and refraction.


Sir Isaac Newton (1642-1727)

Most scientists accepted Newton's particle theory. During his lifetime, however, another theory was proposed—one that argued that light might be some sort of wave motion. In 1678, the Dutch physicist and astronomer Christian Huygens showed that a wave theory of light could also explain reflection and refraction.


Christaan Huygens (1629-1695)

In 1801, Thomas Young (1773–1829) provided the first clear demonstration of the wave nature of light. Young showed that, under appropriate conditions, light rays interfere with each other. Such behaviour could not be explained at that time by a particle theory because there was no conceivable way in which two or more particles could come together and cancel one another.


Thomas Young (1773-1829)

Additional developments during the nineteenth century led to the general acceptance of the wave theory of light, the most important resulting from the work of Maxwell, who in 1873 asserted that light was a form of high-frequency electromagnetic


James Clerk Maxwell (1831-1879)

wave. As discussed, Hertz provided experimental confirmation of Maxwell's theory in 1887 by producing and detecting electromagnetic waves.

Although the wave model and the classical theory of electricity and magnetism were able to explain most known properties of light, they could not explain some subsequent experiments. The most striking of these is the photoelectric effect, also discovered by Hertz: when light strikes a metal surface, electrons are sometimes ejected from the surface. As one example of the difficulties that arose, experiments showed that the kinetic energy of an ejected electron is independent of the light intensity. This finding contradicted the wave theory, which held that a more intense beam of light should add more energy to the electron.

Heinrich Rudolph Hertz
(1857-1894)

An explanation of the photoelectric effect was proposed by Einstein in 1905 in a theory that used the concept of quantization developed by Max Planck (1858–1947) in 1900. The quantization model assumes that the energy of a light wave is present in particles called photons; hence, the energy is said to be quantized. According to Einstein's theory, the energy of a photon is proportional to the frequency of the electromagnetic wave:

Albert Einstein
(1879-1955)

$$E=h\nu$$

where the constant of proportionality $h = 6.63 \times 10^{-34}$ J.s is Planck's constant.

Max Planck
(1858-1947)

In view of these developments, light must be regarded as having a dual nature: **Light exhibits the characteristics of a wave in some situations and the characteristics of a particle in other situations.**

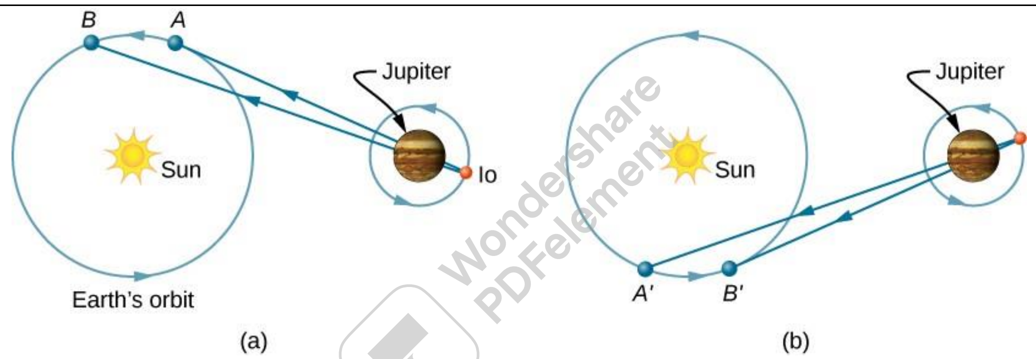
Light is light, to be sure. However, the question —Is light a wave or a particle? is inappropriate. Sometimes light acts like a wave, and at other times it acts like a particle.

The speed of light : early measurements

Ole Christensen Roemer (1644-1710)

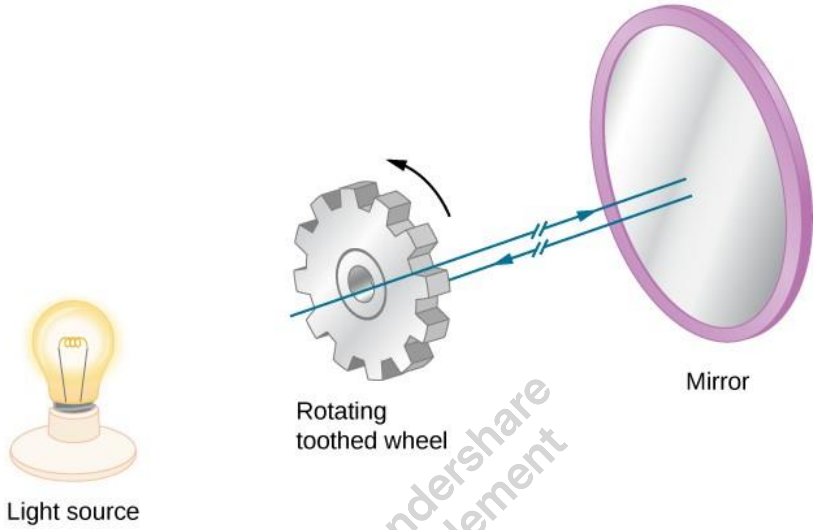
The first measurement of the speed of light was made by the Danish astronomer Ole Roemer (1644–1710) in 1675. He studied the orbit of Io, one of the four large moons of Jupiter, and found that it had a period of revolution of 42.5 h around Jupiter. He also discovered that this value fluctuated by a few seconds, depending on the position of Earth in its orbit around the Sun. Roemer realized that this fluctuation was due to the finite speed of light and could be used to determine *c*.

Roemer found the period of revolution of Io by measuring the time interval between successive eclipses by Jupiter. Figure 1a shows the planetary configurations when such a measurement is made from Earth in the part of its orbit where it is receding from Jupiter. When Earth is at point *A*, Earth, Jupiter, and Io are aligned. The next time this alignment occurs, Earth is at point *B*, and the light carrying that information to Earth must travel to that point. Since *B* is farther from Jupiter than *A*, light takes more time to reach Earth when Earth is at *B*. Now imagine it is about 6 months later, and the planets are arranged. The measurement of Io's period begins with Earth at point A' and Io eclipsed by Jupiter. The next eclipse then occurs when Earth is at point B', to which the light carrying the information of this eclipse must travel. Since B' is closer to Jupiter than A', light takes less time to reach Earth when it is at B'. This time interval between the successive eclipses of Io seen at A' and B' is therefore less than the time interval between the eclipses seen at *A* and *B*. By measuring the difference in these time intervals and with appropriate knowledge of the distance between Jupiter and Earth, Roemer calculated that the speed of light was 2.0×10^{8} m/s, which is only 33% below the value accepted today.



Roemer's method for measuring the speed of light. In the time interval during which the Earth travels 90° around the Sun (three months), Jupiter travels only about 7.5° (drawing not to scale).

The first successful terrestrial measurement of the speed of light was made by Armand Fizeau (1819–1896) in 1849. He placed a toothed wheel that could be rotated very rapidly on one hilltop and a mirror on a second hilltop 8 km away. An intense light source was placed behind the wheel, so that when the wheel rotated, it chopped the light beam into a succession of pulses. The speed of the wheel was then adjusted until no light returned to the observer located behind the wheel. This could only happen if the wheel rotated through an angle corresponding to a displacement of (n+½) teeth, while the pulses travelled down to the mirror and back. Knowing the rotational speed of the wheel, the number of teeth on the wheel, and the distance to the mirror, Fizeau determined the speed of light to be 3.15×10^{8} m/s, which is only 5% too high.



Fizeau's method for measuring the speed of light using a rotating toothed wheel. The light source is considered to be at the location of the wheel; thus, the distance d is known.

Example 1 **Measuring the Speed of Light with Fizeau's Wheel**

Assume that Fizeau's wheel has 360 teeth and is rotating at 27.5 rev/s when a pulse of light passing through opening *A* in Figure 2 is blocked by tooth *B* on its return. If the distance to the mirror is 7500 m, what is the speed of light?

Solution The wheel has 360 teeth, and so it must have 360 openings. Therefore, because the light passes through opening *A* but is blocked by the tooth immediately adjacent to *A*, the wheel must rotate through an angular displacement of (1/720) rev in the time interval during which the light pulse makes its round trip. From the definition of angular speed, that time interval is

$$\Delta t = \frac{\Delta\theta}{\omega} = \frac{(1/720)\ \text{rev}}{27.5\ \text{rev/s}} = 5.05 \times 10^{-5}\ \text{s}$$

Hence, the speed of light calculated from this data is:

$$c = \frac{2d}{\Delta t} = \frac{2(7\,500\ \text{m})}{5.05 \times 10^{-5}\ \text{s}} = 2.97 \times 10^{8}\ \text{m/s}$$

The French physicist Jean Bernard Léon Foucault (1819–1868) modified Fizeau's apparatus by replacing the toothed wheel with a rotating mirror. In 1862, he measured the speed of light to be 2.98×10^{8}m/s, which is within 0.6% of the presently accepted value.


Jean-Bernard-Leon Foucault (1819-1868)

Albert Michelson (1852–1931) also used Foucault's method on several occasions to measure the speed of light. His first experiments were performed in 1878; by 1926, he had refined the technique so well that he found c to be $(2.99796 \pm 4) \times10^{8}$ m/s.


Albert Abraham Michelson (1852-1931)

Today, the speed of light is known to great precision. In fact, the speed of light in a vacuum c is so important that it is accepted as one of the basic physical quantities and has the value

$$c = 2.99792458\times10^{8}\text{m/s} \equiv 3.00\times10^{8}\text{m/s}$$

where the approximate value of 3.00×10^{8}m/s is used whenever three-digit accuracy is sufficient.

Speed of light in matter

The speed of light through matter is less than it is in a vacuum, because light interacts with atoms in a material. The speed of light depends strongly on the type of material, since its interaction varies with different atoms, crystal lattices, and other substructures. We can define a constant of a material that describes the speed of light in it, called the index of refraction *n*:

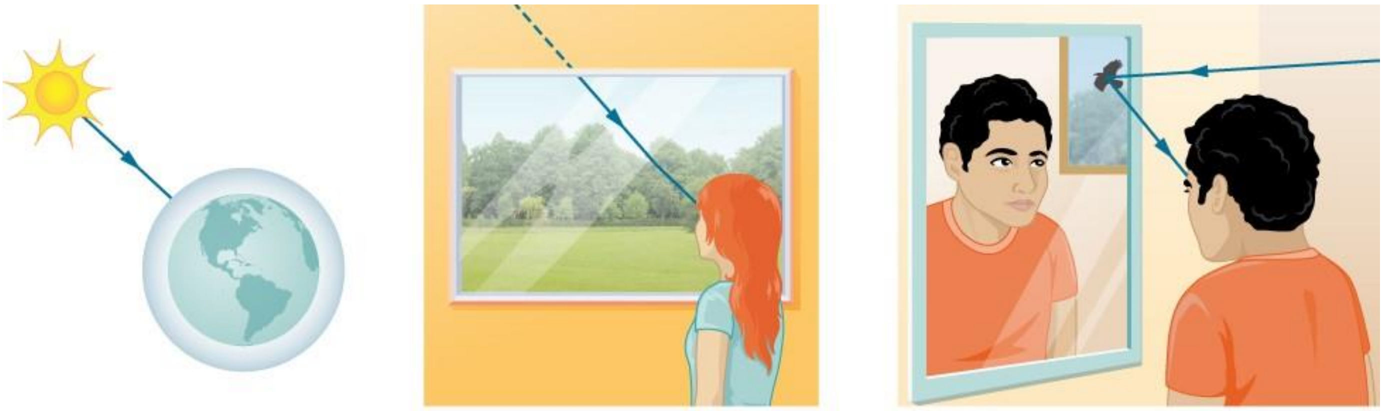
$$n = c/v$$

where v is the observed speed of light in the material.

Since the speed of light is always less than *c* in matter and equals *c* only in a vacuum, the index of refraction is always greater than or equal to one; that is, $n \geq 1$. This can have important effects, such as colours separated by a prism, as we will see in dispersion. Note that for gases, *n* is close to 1.0. This seems reasonable, since atoms in gases are widely separated, and light travels at *c* in the vacuum between atoms. It is common to take n = 1 for gases unless great precision is needed. Although the speed of light *v* in a medium varies considerably from its value *c* in a vacuum, it is still a large speed.

The ray model of light

There are three ways in which light can travel from a source to another location. It can come directly from the source through empty space, such as from the Sun to Earth. Or light can travel through various media, such as air and glass, to the observer. Light can also arrive after being reflected, such as by a mirror. In all of these cases, we can model the path of light as a straight line called a ray.



(a) (b) (c)

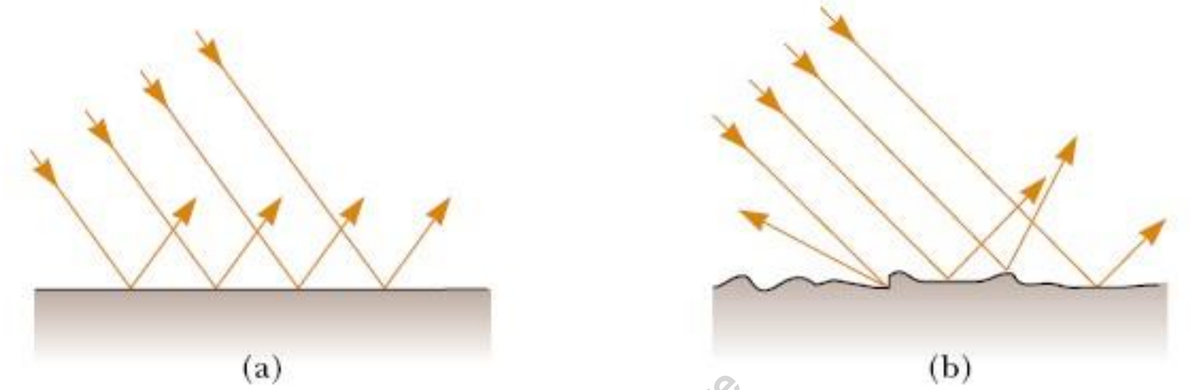
Experiments show that when light interacts with an object several times larger than its wavelength, it travels in straight lines and acts like a ray. Its wave characteristics are not pronounced in such situations. Since the wavelength of visible light is less than a micron (a thousandth of a millimetre), it acts like a ray in the many common situations in which it encounters objects larger than a micron. For example, when visible light encounters anything large enough that we can observe it with unaided eyes, such as a coin, it acts like a ray, with generally negligible wave characteristics.

Properties of light

Reflection, refraction, dispersion and velocity are the important properties of light. We briefly discuss about them here.

Reflection of light

when light travelling in a medium encounters a boundary leading to a second medium, part of the incident light is returned to the first medium from which it came. This phenomenon is called reflection. Reflection of light from a smooth surface is called regular or specular reflection see figure 1a. If the reflecting surface is rough, as shown in Figure 1b, the surface reflects the rays not as a parallel set but in various directions. Reflection from any rough surface is known as diffuse reflection. A surface behaves as a smooth surface as long as the surface variations are much smaller than the wavelength of the incident light. the difference between diffuse and specular reflection is a matter of surface roughness. In the study of optics, the term reflection is used to mean specular reflection.



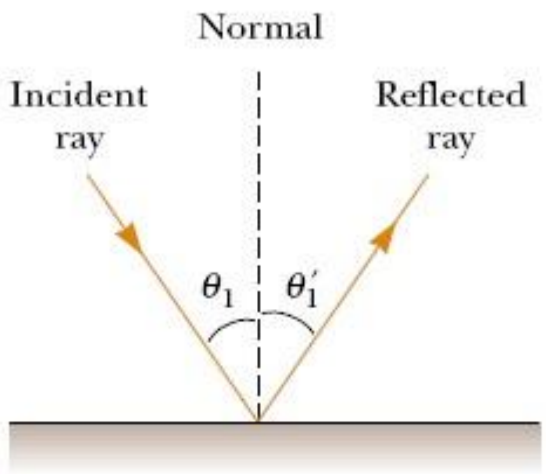
Schematic representation of (a) specular reflection, where the reflected rays are all parallel to each other, and (b) diffuse reflection, where the reflected rays travel in random directions.

Laws of reflection

First law: The incident ray, the reflected ray and the normal at the of point incidence are in the same plane. This plane is called plane of incidence.

Second law: The angle of reflection equals the angle of incidence.

$$\theta_1 = \theta_1'$$



According to the law of reflection, $\theta_1 = \theta_1'$*. The incident ray, the reflected ray, and the normal all lie in the same plane.*

Refraction of light

When a ray of light traveling through a transparent medium encounters a boundary leading into another transparent medium, as shown in Figure 3, part of the energy 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.

Laws of refraction

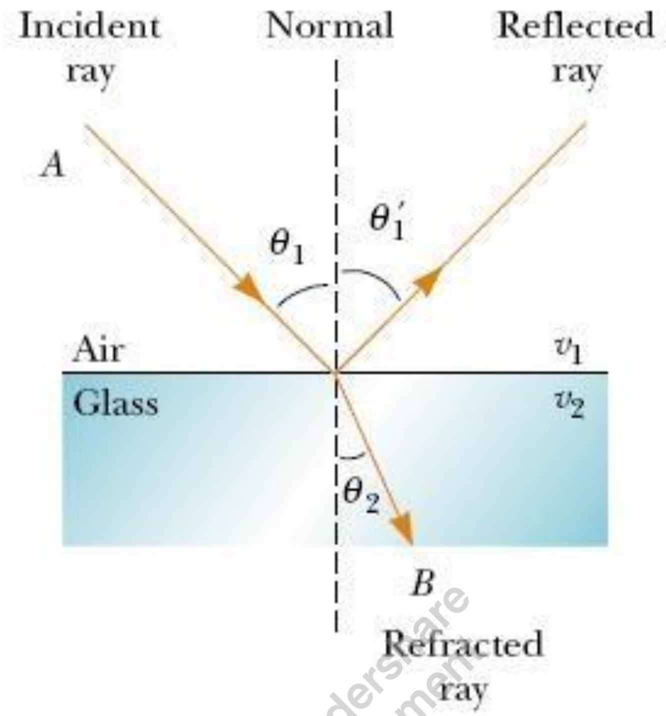
First law: The incident ray, the refracted ray and the normal at the of point incidence lie in the same plane. This plane is called plane of incidence.

Second law: The ratio of the sine of the angle of incidence to the sine of the angle of refraction for any two given media is constant.

$$\frac{\sin\theta_2}{\sin\theta_1} = \frac{v_2}{v_1} = \text{constant} \qquad (3)$$

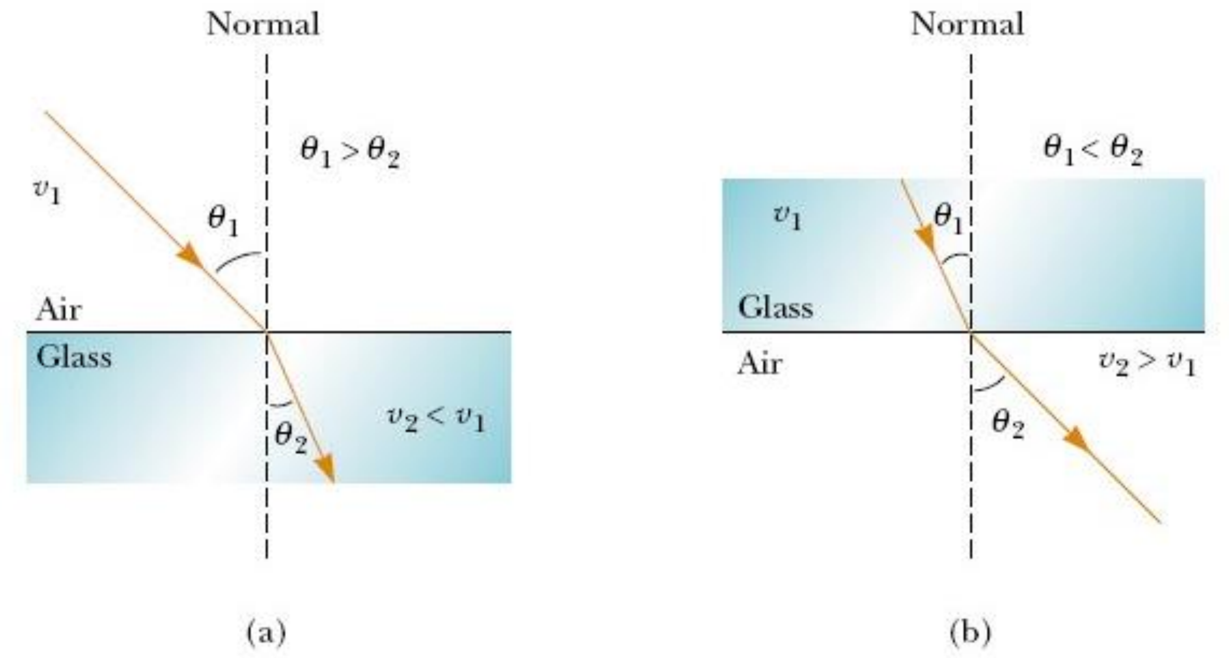
where v_1 is the speed of light in the first medium and v_2 is the speed of light in the second medium.

The angle of refraction depends on the properties of the two media and on the angle of incidence.



A ray obliquely incident on an air–glass interface. The refracted ray is bent toward the normal because $v_2 < v_1$. All rays and the normal lie in the same plane.

From Equation 3, we can infer that when light moves from a material in which its speed is high to a material in which its speed is lower, as shown in Figure 4a, the angle of refraction θ_2 is less than the angle of incidence θ_1, and the ray is bent toward the normal. If the ray moves from a material in which light moves slowly to a material in which it moves more rapidly, as illustrated in Figure 4b, θ_2 is greater than θ_1, and the ray is bent away from the normal.



(a) When the light beam moves from air into glass, the light slows down on entering the glass and its path is bent toward the normal. (b) When the beam moves from glass into air, the light speeds up on entering the air and its path is bent away from the normal.

Index of Refraction

The refraction index of a medium is defined as the ratio of velocity of light in a vacuum to the velocity of light in the medium index. Refraction index defined as above is called as absolute refraction index.

Thus,

$$n = \frac{c}{v} \qquad (4)$$

From this definition, we see that the index of refraction is a dimensionless number greater than unity because v is always less than c.

Furthermore, n is equal to unity for vacuum.

As light travels from one medium to another, its frequency does not change but its wavelength does.

$$v_1 = f\lambda_1 \quad \text{and} \quad v_2 = f\lambda_2 \qquad (5)$$

Because $v_1 \neq v_2$, it follows that $\lambda_1 \neq \lambda_2$.

We can obtain a relationship between index of refraction and wavelength by dividing the first Equation 5 by the second and then using Equation 4:

$$\frac{\lambda_1}{\lambda_2} = \frac{v_1}{v_2} = \frac{c/n_1}{c/n_2} = \frac{n_1}{n_2}$$

This gives

$$n_1\lambda_1 = n_2\lambda_2$$

If medium 1 is vacuum, or for all practical purposes air, then $n_1 = 1$. Hence, it follows from Equation 6 that the index of refraction of any medium can be expressed as the ratio

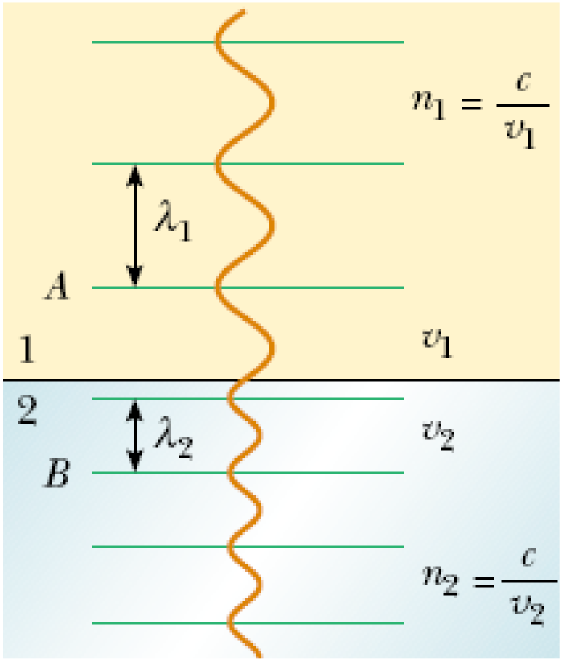
$$n = \frac{\lambda}{\lambda_n} \qquad (7)$$

where λ is the wavelength of light in vacuum and λn is the wavelength of light in the medium whose index of refraction is n.

We are now in a position to express Equation 3 in an alternative form. If we replace the v_2/v_1 term in Equation 3 with n_1/n_2 from Equation 6, we obtain

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \qquad (8)$$

The experimental discovery of this relationship is usually credited to Willebrord Snell (1591–1627) and is therefore known as Snell's law of refraction.



As a wave moves from medium 1 to medium 2, its wavelength changes but its frequency remains constant.

Indices of Refraction[a]

Substance	Index of Refraction	Substance	Index of Refraction
Solids at 20°C		*Liquids at 20°C*	
Cubic zirconia	2.20	Benzene	1.501
Diamond (C)	2.419	Carbon disulfide	1.628
Fluorite (CaF_2)	1.434	Carbon tetrachloride	1.461
Fused quartz (SiO_2)	1.458	Ethyl alcohol	1.361
Gallium phosphide	3.50	Glycerin	1.473
Glass, crown	1.52	Water	1.333
Glass, flint	1.66		
Ice (H_2O)	1.309	*Gases at 0°C, 1 atm*	
Polystyrene	1.49	Air	1.000 293
Sodium chloride (NaCl)	1.544	Carbon dioxide	1.000 45

Example 2 **An Index of Refraction Measurement**

A beam of light of wavelength 550 nm traveling in air is incident on a slab of transparent material. The incident beam makes an angle of 40.0° with the normal, and the refracted beam makes an angle of 26.0° with the normal. Find the index of refraction of the material.

Solution Using Snell's law of refraction with these data, and taking $n_1 = 1.00$ for air, we have $n_1 \sin \theta_1 = n_2 \sin \theta_2$

$$n_2 = \frac{n_1 \sin \theta_1}{\sin \theta_2} = (1.00)\frac{\sin 40.0°}{\sin 26.0°}$$

$$= \frac{0.643}{0.438} = 1.47$$

Example 3 **Angle of Refraction for Glass**

A light ray of wavelength 589 nm traveling through air is incident on a smooth, flat slab of crown glass at an angle of 30.0° to the normal, as sketched in Figure 14. Find the angle of refraction.

Solution We rearrange Snell's law of refraction to obtain:

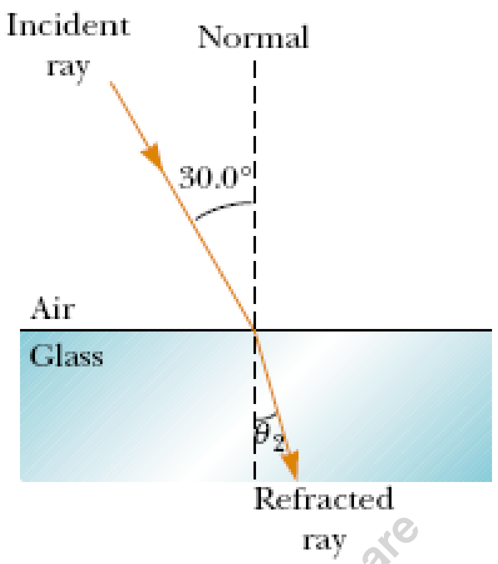
$$\sin \theta_2 = \frac{n_1}{n_2} \sin \theta_1$$

From the refractive index table, we find that $n_1 = 1.00$ for air and $n_2 = 1.52$ for crown glass. Therefore,

$$\sin \theta_2 = \left(\frac{1.00}{1.52}\right) \sin 30.0° = 0.329$$

$$\theta_2 = \sin^{-1}(0.329) = 19.2°$$

Because this is less than the incident angle of 30°, the refracted ray is bent toward the normal, as expected. Its change in direction is called the *angle of deviation* and is given by $\delta = |\theta_1 - \theta_2| = 30.0° - 19.2° = 10.8°$.



(Example 4) Refraction of light by glass.

Example 4 **Laser Light in a Compact Disc**

A laser in a compact disc player generates light that has a wavelength of 780 nm in air.

(A) Find the speed of this light once it enters the plastic of a compact disc (n =1.55).

Solution We expect to find a value less than 3.00×10^8 m/s because $n > 1$. We can obtain the speed of light in the plastic

$$v = \frac{c}{n} = \frac{3.00 \times 10^8 \text{ m/s}}{1.55} \qquad v = 1.94 \times 10^8 \text{ m/s}$$

(B) What is the wavelength of this light in the plastic?

Solution We calculate the wavelength in plastic, noting that we are given the wavelength in air to be λ= 780 nm:

$$\lambda_n = \frac{\lambda}{n} = \frac{780\text{ nm}}{1.55} = 503\text{ nm}$$

Example 5 **Light Passing Through a Slab**

A light beam passes from medium 1 to medium 2, with the latter medium being a thick slab of material whose index of refraction is n_2. Show that the emerging beam is parallel to the incident beam.

Solution First, let us apply Snell's law of refraction to the upper surface:

$$(1) \qquad \sin\theta_2 = \frac{n_1}{n_2}\sin\theta_1$$

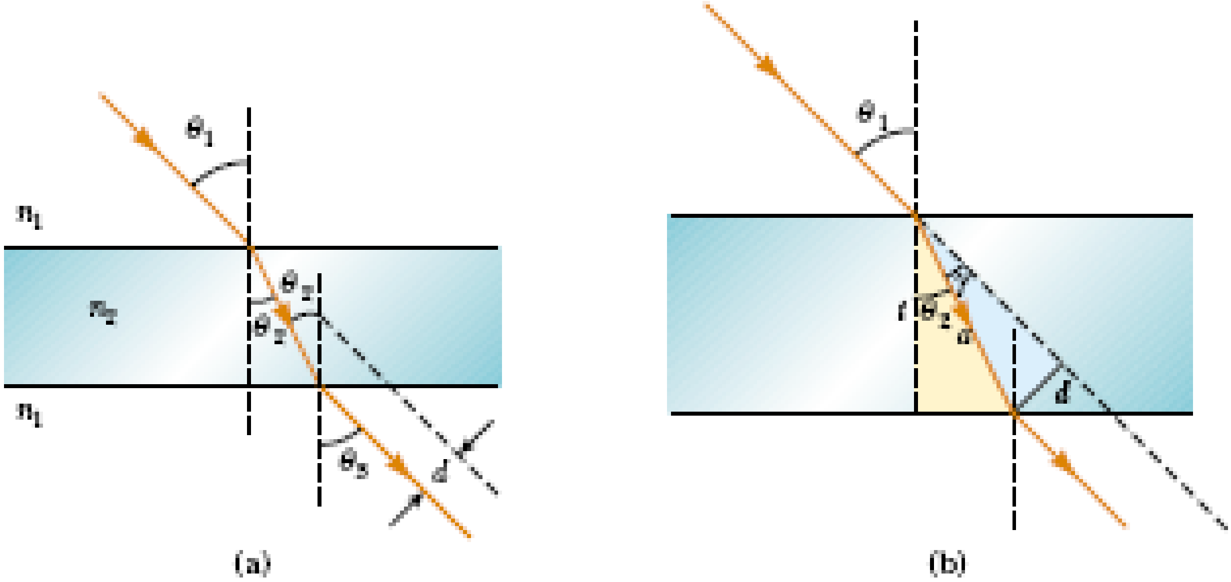
Applying this law to the lower surface gives

$$(2) \qquad \sin\theta_3 = \frac{n_2}{n_1}\sin\theta_2$$

Substituting Equation (1) into Equation (2) gives

$$\sin\theta_3 = \frac{n_2}{n_1}\left(\frac{n_1}{n_2}\sin\theta_1\right) = \sin\theta_1$$

Therefore, $\theta_3 = \theta_1$, and the slab does not alter the direction of the beam. It does, however, offset the beam parallel to itself by the distance *d*.

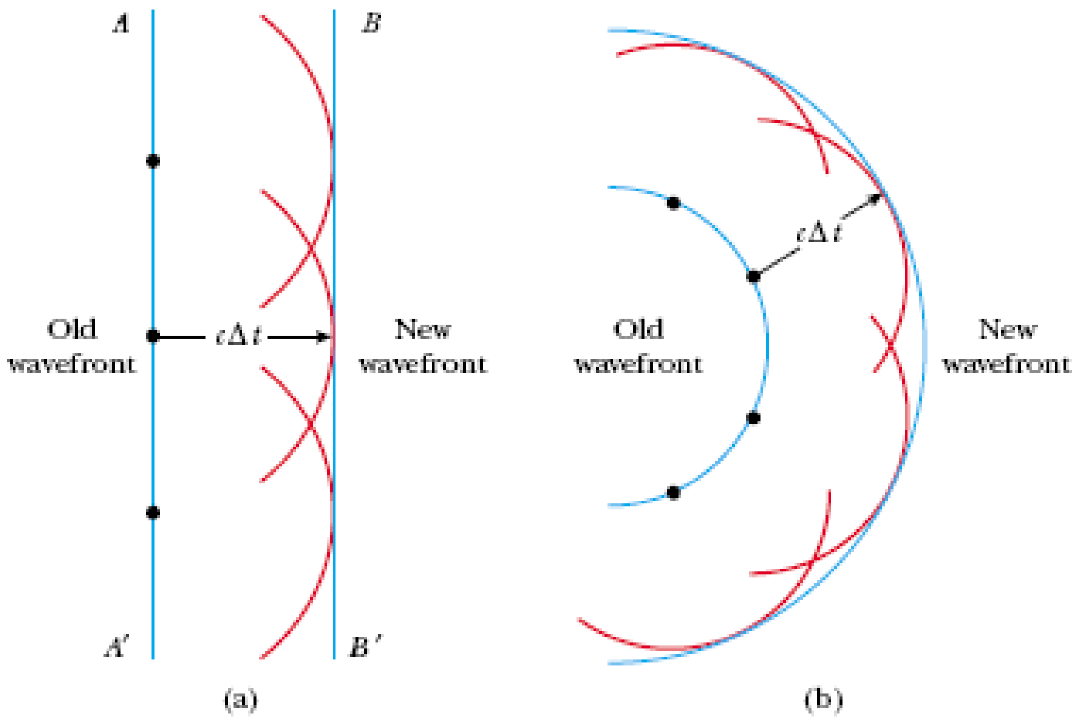


(Example 6) (a) When light passes through a flat slab of material, the emerging beam is parallel to the incident beam, and therefore $\theta_3 = \theta_1$. The dashed line drawn parallel to the ray coming out the bottom of the slab represents the path the light would take if the slab were not there. (b) A magnification of the area of the light path inside the slab.

Huygens's Principle

In this section, we develop the laws of reflection and refraction by using a geometric method proposed by Huygens in 1678. Huygens's principle is a geometric construction for using knowledge of an earlier wave front to determine the position of a new wave front at some instant. In Huygens's construction,

all points on a given wave front are taken as point sources for the production of spherical secondary waves, called wavelets, which propagate outward through a medium with speeds characteristic of waves in that medium. After some time interval has passed, the new position of the wave front is the surface tangent to the wavelets.



Huygens's construction for (a) a plane wave propagating to the right and (b) a spherical wave propagating to the right.

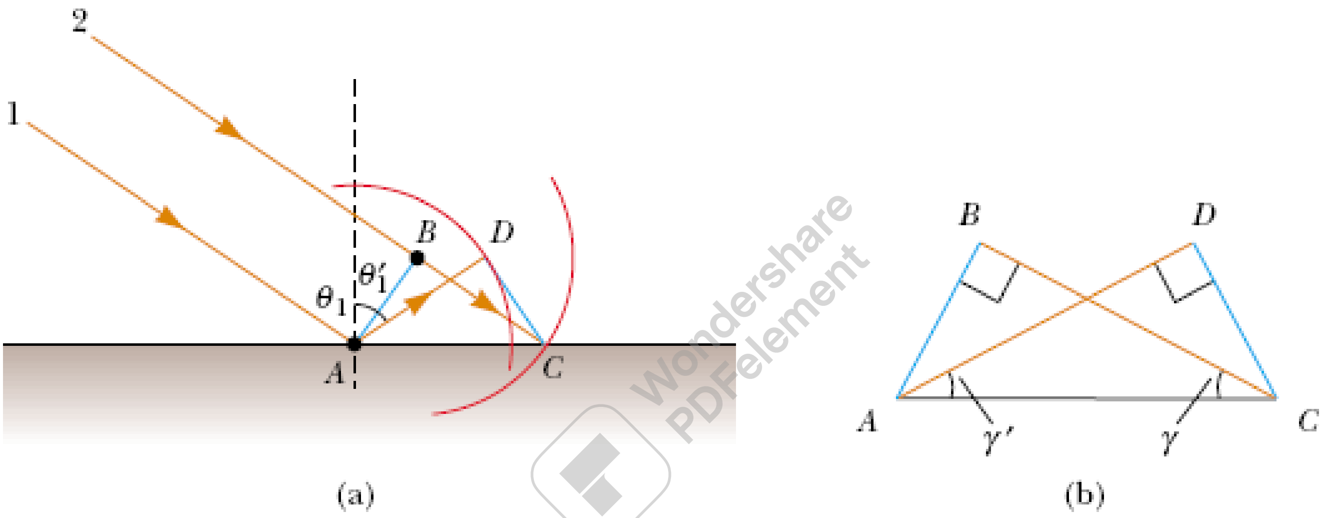
First, consider a plane wave moving through free space, as shown in the figure. At $t = 0$, the wave front is indicated by the plane labeled *AA*\`. In Huygens's construction, each point on this wave front is considered a point source. For clarity, only three points on *AA*\` are shown. With these points as sources for the wavelets, we draw circles, each of radius $c\ \Delta t$, where c is the speed of light in vacuum and Δt is some time interval during which the wave propagates. The surface drawn tangent to these wavelets is the plane *BB*\`, which is the wave front at a later time, and is parallel to *AA*\`. In a similar manner, Figure b shows Huygens's construction for a spherical wave.

Huygens's Principle Applied to Reflection and Refraction

The laws of reflection and refraction were stated earlier in this chapter without proof. We now derive these laws, using Huygens's principle.

For the law of reflection

The line *AB* represents a wave front of the incident light just as ray 1 strikes the surface. At this instant, the wave at *A* sends out a Huygens wavelet (the circular arc centered on *A*) toward *D*. At the same time, the wave at *B* emits a Huygens wavelet (the circular arc centered on *B*) toward *C*. Figure a show these wavelets after a time interval Δt, after which ray 2 strikes the surface. Because both rays 1 and 2 move with the same speed, we must have $AD = BC = c\,\Delta t$.



(a) Huygens's construction for proving the law of reflection. At the instant that ray 1 strikes the surface, it sends out a Huygens wavelet from A and ray 2 sends out a Huygens wavelet from B. We choose a radius of the wavelet to be cΔt, where Δt is the time interval for ray 2 to travel from B to C. (b) Triangle ADC is congruent to triangle ABC.

The remainder of our analysis depends on geometry, as summarized in Figure b, in which we isolate the triangles *ABC* and *ADC*. Note that these two triangles are congruent because they have the same hypotenuse *AC* and because $AD = BC$. From Figure b, we have

$$\cos\gamma = \frac{BC}{AC} \qquad \text{and} \qquad \cos\gamma' = \frac{AD}{AC}$$

where, comparing Figures 17a and 17b, we see that . $\gamma = 90° - \theta_1$ and $\gamma` = 90° - \theta`_1$. Because *AD* ! *BC*, we have cos γ = cos γ`

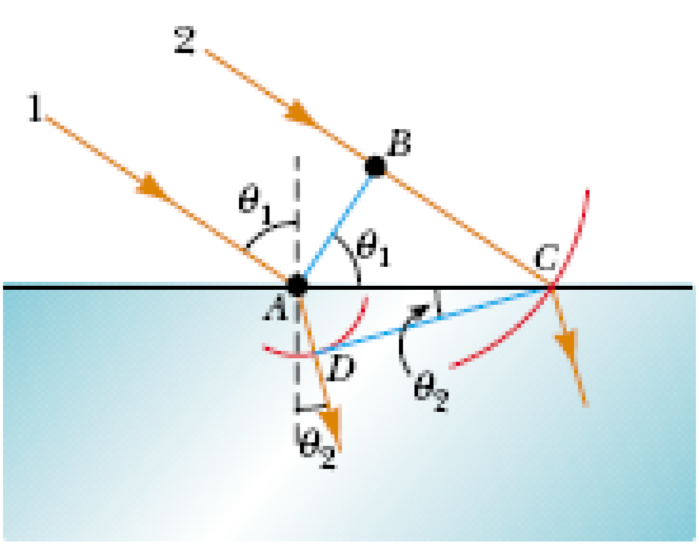
Therefore,

$$\gamma = \gamma` \;››\; 90° - \theta_1 = 90° - \theta`_1 \;››\; \theta_1 = \theta`_1$$

which is the law of reflection.

Snell's law of refraction

We focus our attention on the instant ray 1 strikes the surface and the subsequent time interval until ray 2 strikes the surface. During this time interval, the wave at *A* sends out a Huygens wavelet (the arc centered on *A*) toward *D*. In the same time interval, the wave at *B* sends out a Huygens wavelet (the arc centered on *B*) toward *C*. Because these two wavelets travel through different media, the radii of the wavelets are different. The radius of the wavelet from *A* is $AD = v_2\,\Delta t$, where v_2 is the wave speed in the second medium. The radius of the wavelet from *B* is $BC = v_1\,\Delta t$, where v_1 is then wave speed in the original medium.



Huygens's construction for proving Snell's law of refraction. At the instant that ray 1 strikes the surface, it sends out a Huygens wavelet from A and ray 2 sends out a Huygens wavelet from B. The two wavelets have different radii because they travel in different media.

From triangles *ABC* and *ADC*, we find that

$$\sin\theta_1 = \frac{BC}{AC} = \frac{v_1\,\Delta t}{AC} \qquad \text{and} \qquad \sin\theta_2 = \frac{AD}{AC} = \frac{v_2\,\Delta t}{AC}$$

If we divide the first equation by the second, we obtain

$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{v_1}{v_2}$$

But we know that $v_1 = c/n_1$ and $v_2 = c/n_2$. Therefore,

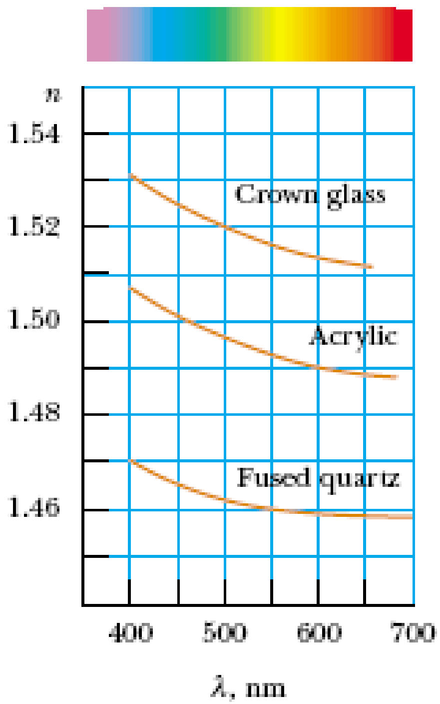
$$\frac{\sin\theta_1}{\sin\theta_2} = \frac{c/n_1}{c/n_2} = \frac{n_2}{n_1}$$

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

which is Snell's law of refraction.

Dispersion and Prisms

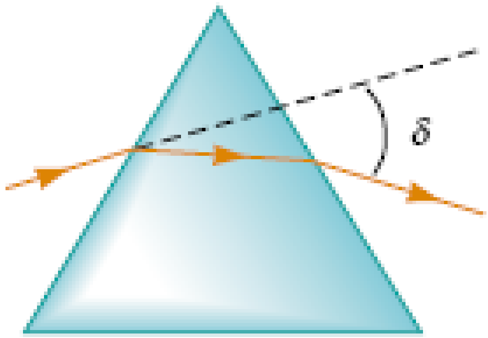
An important property of the index of refraction *n* is that, for a given material, the index varies with the wavelength of the light passing through the material. This behavior is called **dispersion**. Because *n* is a function of wavelength, Snell's law of refraction indicates that light of different wavelengths is bent at different angles when incident on a refracting material.



Variation of index of refraction with vacuum wavelength for three materials.

As we see the index of refraction generally decreases with increasing wavelength. This means that violet light bends more than red light does when passing into a refracting material. To understand the effects that dispersion can have on light, consider what happens when light strikes a prism. A ray of single-wavelength light incident on the prism from the left emerges refracted from its original direction of travel by an angle δ, called the **angle of deviation**.

Now suppose that a beam of *white light* (a combination of all visible wavelengths) is incident on a prism, as illustrated in Figure 21. The rays that emerge spread out in a series of colors known as the visible spectrum. These colors, in order of decreasing wavelength, are red, orange, yellow, green, blue, and violet. Clearly, the angle of deviation δ depends on wavelength. Violet light deviates the most, red the least, and the remaining colors in the visible spectrum fall between these extremes. Newton showed that each color has a particular angle of deviation and that the colors can be recombined to form the original white light.

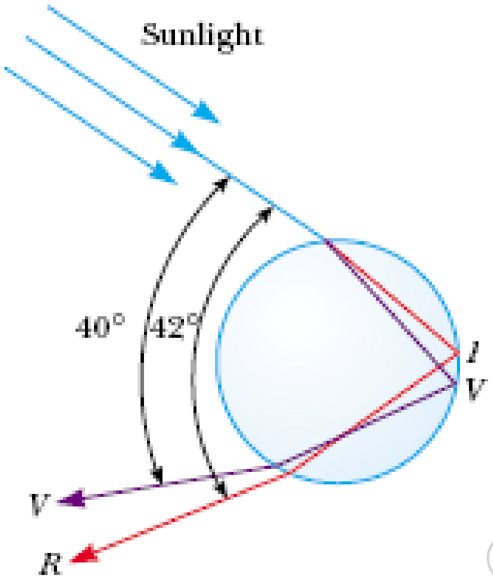


A prism refracts a single-wavelength light ray through an angle δ.

The dispersion of light into a spectrum is demonstrated most vividly in nature by the formation of a rainbow, which is often seen by an observer positioned between the Sun and a rain shower. To understand how a rainbow is formed, consider a ray of sunlight (which is white light) passing overhead strikes a drop of water in the atmosphere and is refracted and reflected as follows: It is first refracted at the front surface of the drop, with the violet light deviating the most and the red light the least.

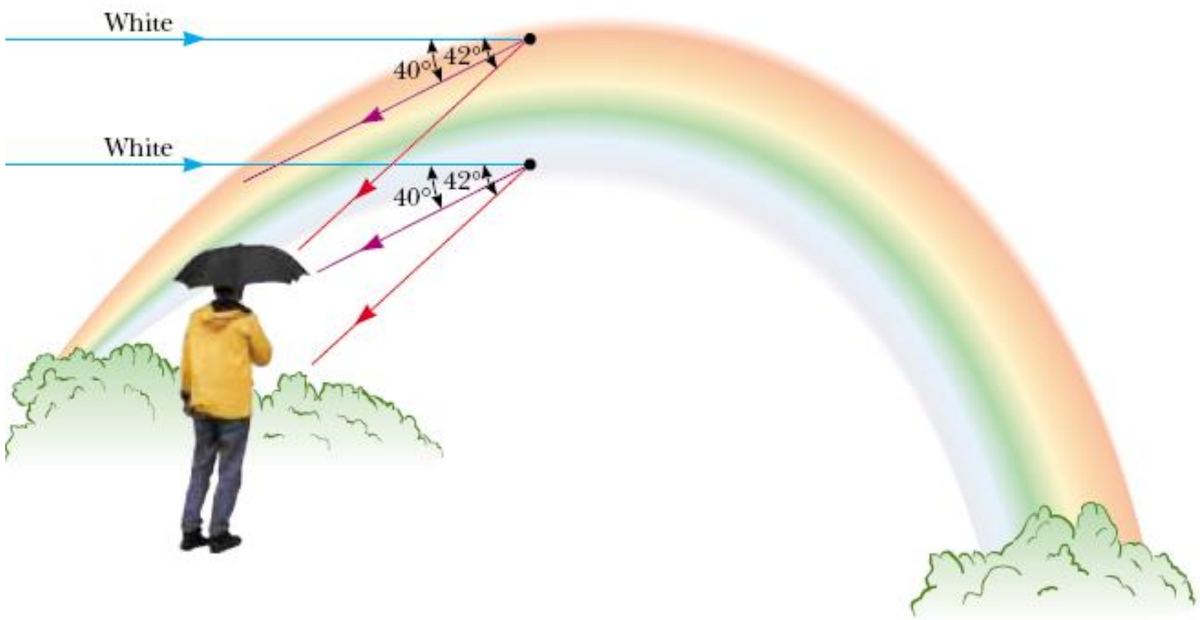
White light enters a glass prism at the upper left. A reflected beam of light comes out of the prism just below the incoming beam. The beam moving toward the lower right shows distinct colors. Different colors are refracted at different angles because the index of refraction of the glass depends on wavelength. Violet light deviates the most; red light deviates the least.

At the back surface of the drop, the light is reflected and returns to the front surface, where it again undergoes refraction as it moves from water into air. The rays leave the drop such that the angle between the incident white light and the most intense returning violet ray is 40° and the angle between the white light and the most intense returning red ray is 42°. This small angular difference between the returning rays causes us to see a colored bow.



Path of sunlight through a spherical raindrop. Light following this path contributes to the visible rainbow.

Now suppose that an observer is viewing a rainbow, as shown in the figure. If a raindrop high in the sky is being observed, the most intense red light returning from the drop can reach the observer because it is deviated the most, but the most intense violet light passes over the observer because it is deviated the least. Hence, the observer sees this drop as being red.

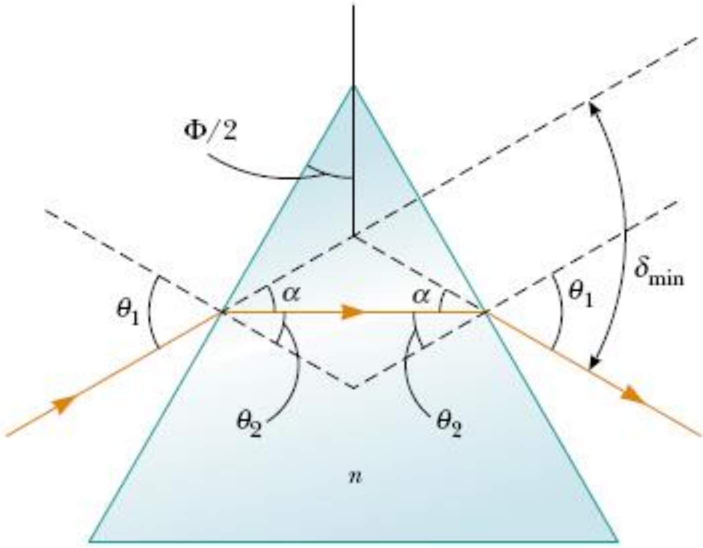


The formation of a rainbow seen by an observer standing with the Sun behind his back.

Similarly, a drop lower in the sky would direct the most intense violet light toward the observer and appears to be violet. (The most intense red light from this drop would pass below the eye of the observer and not be seen.) The most intense light from other colors of the spectrum would reach the observer from raindrops lying between these two extreme positions.

Example 6 **Measuring n Using a Prism**

Although we do not prove it here, the minimum angle of deviation δ_{min} for a prism occurs when the angle of incidence θ_1 is such that the refracted ray inside the prism makes the same angle with the normal to the two prism faces,1 as shown in the figure. Obtain an expression for the index of refraction of the prism material.



(Example 7) A light ray passing through a prism at the minimum angle of deviation δ_{min}.

Solution Using the geometry shown in the figure, we find that $\theta_2 = \phi/2$, where ϕ is the apex angle and

$$\theta_1 = \theta_2 + \alpha = \frac{\Phi}{2} + \frac{\delta_{\min}}{2} = \frac{\Phi + \delta_{\min}}{2}$$

From Snell's law of refraction, with $n_1 = 1$ because medium 1 is air, we have

$$\sin\theta_1 = n\sin\theta_2$$

$$\sin\left(\frac{\Phi + \delta_{\min}}{2}\right) = n\sin(\Phi/2)$$

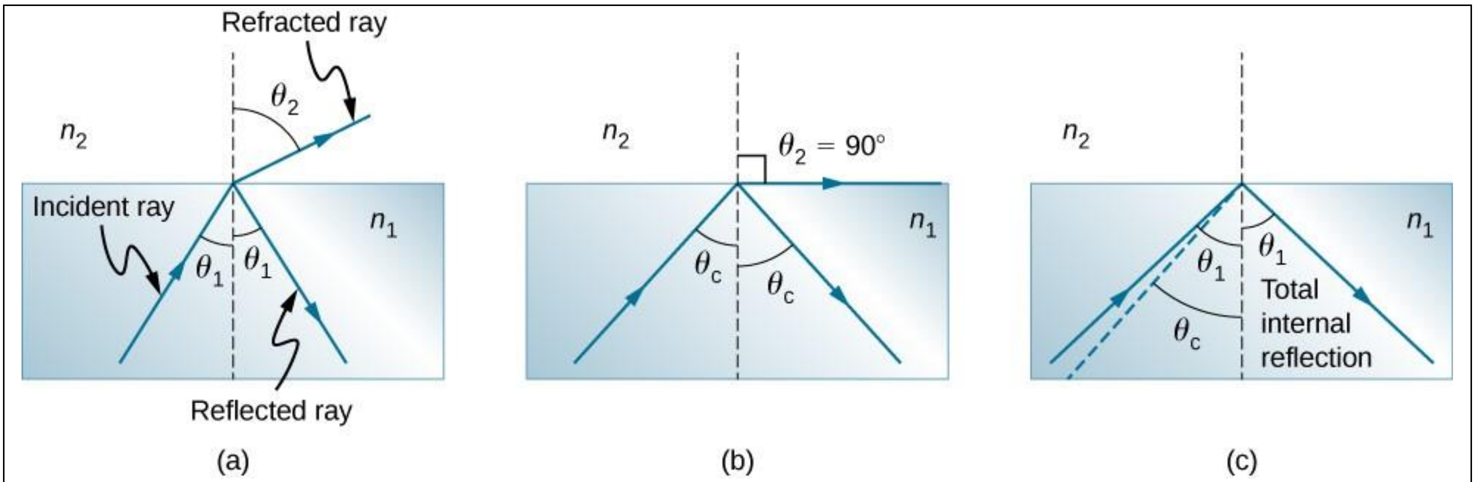
$$n = \frac{\sin\left(\frac{\Phi + \delta_{\min}}{2}\right)}{\sin(\Phi/2)}$$

Hence, knowing the apex angle ϕ of the prism and measuring δ_{min}, we can calculate the index of refraction of the prism material. Furthermore, we can use a hollow prism to determine the values of *n* for various liquids filling the prism.

Total internal reflection

A good-quality mirror may reflect more than 90% of the light that falls on it, absorbing the rest. But it would be useful to have a mirror that reflects all of the light that falls on it. Interestingly, we can produce total reflection using an aspect of refraction.

Consider what happens when a ray of light strikes the surface between two materials. Part of the light crosses the boundary and is refracted; the rest is reflected. If, as shown in the figure, the index of refraction for the second medium is less than for the first, the ray bends away from the perpendicular. (Since $n_1 > n_2$, the angle of refraction is greater than the angle of incidence—that is, $\theta_1 > \theta_2$.) Now imagine what happens as the incident angle increases. This causes θ2 to increase also. The largest the angle of refraction θ2 can be is 90°.



(a) A ray of light crosses a boundary where the index of refraction decreases. That is, $n_2 < n_1$. The ray bends away from the perpendicular. (b) The critical angle θ_c is the angle of incidence for which the angle of refraction is 90°. (c)

Total internal reflection occurs when the incident angle is greater than the critical angle.

The critical angle θ_c for a combination of materials is defined to be **the incident angle θ_1 that produces an angle of refraction of 90°.**

That is, θ_c is the incident angle for which $\theta_2 = 90°$. If the incident angle θ_1 is greater than the critical angle, then all of the light is reflected back into medium 1, a condition called **total internal reflection**. The reflected rays obey the law of reflection so that the angle of reflection is equal to the angle of incidence in all three cases.) Snell's law states the relationship between angles and indices of refraction. It is given by

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

When the incident angle equals the critical angle ($\theta_1 = \theta_c$), the angle of refraction is 90° ($\theta_2 = 90°$). Noting that sin90° = 1, Snell's law in this case becomes

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

The critical angle θ_c for a given combination of materials is thus

$$\theta c = \sin^{-1}(n_2/n_1) \qquad \text{for } n_1 > n_2$$

Total internal reflection occurs for any incident angle greater than the critical angle θ_c, and it can only occur when the second medium has an index of refraction less than the first. Note that this equation is written for a light ray that travels in medium 1 and reflects from medium 2.

Example 6:

What is the critical angle for light traveling in a polystyrene (a type of plastic) pipe surrounded by air? The index of refraction for polystyrene is 1.49.

Solution

The index of refraction of air can be taken to be 1.00, as before. Thus, the condition that the second medium (air) has an index of refraction less than the first (plastic) is satisfied, and we can use the equation:

$$\theta c = \sin^{-1}(n_2/n_1)$$

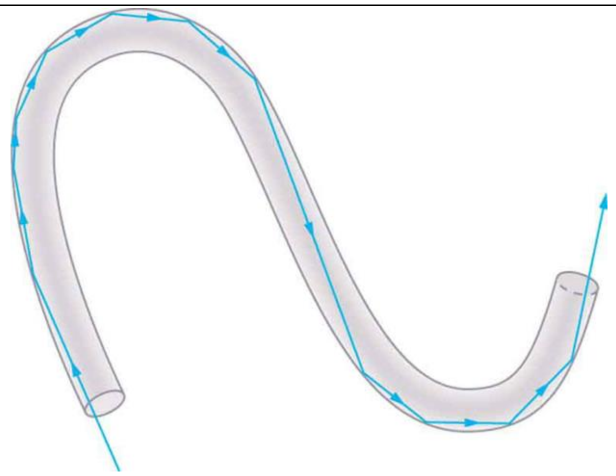
$$\theta c = \sin^{-1}(1.00/1.49)$$

$$\theta c = \sin^{-1}(0.671)$$

$$\theta c = 42.2°$$

Fiber Optics: Endoscopes to Telephones

Fiber optics is one application of total internal reflection that is in wide use. In communications, it is used to transmit telephone, internet, and cable TV signals. *Fiber optics* employs the transmission of light down fibers of plastic or glass. Because the fibers are thin, light entering one is likely to strike the inside surface at an angle greater than the critical angle and, thus, be totally reflected.



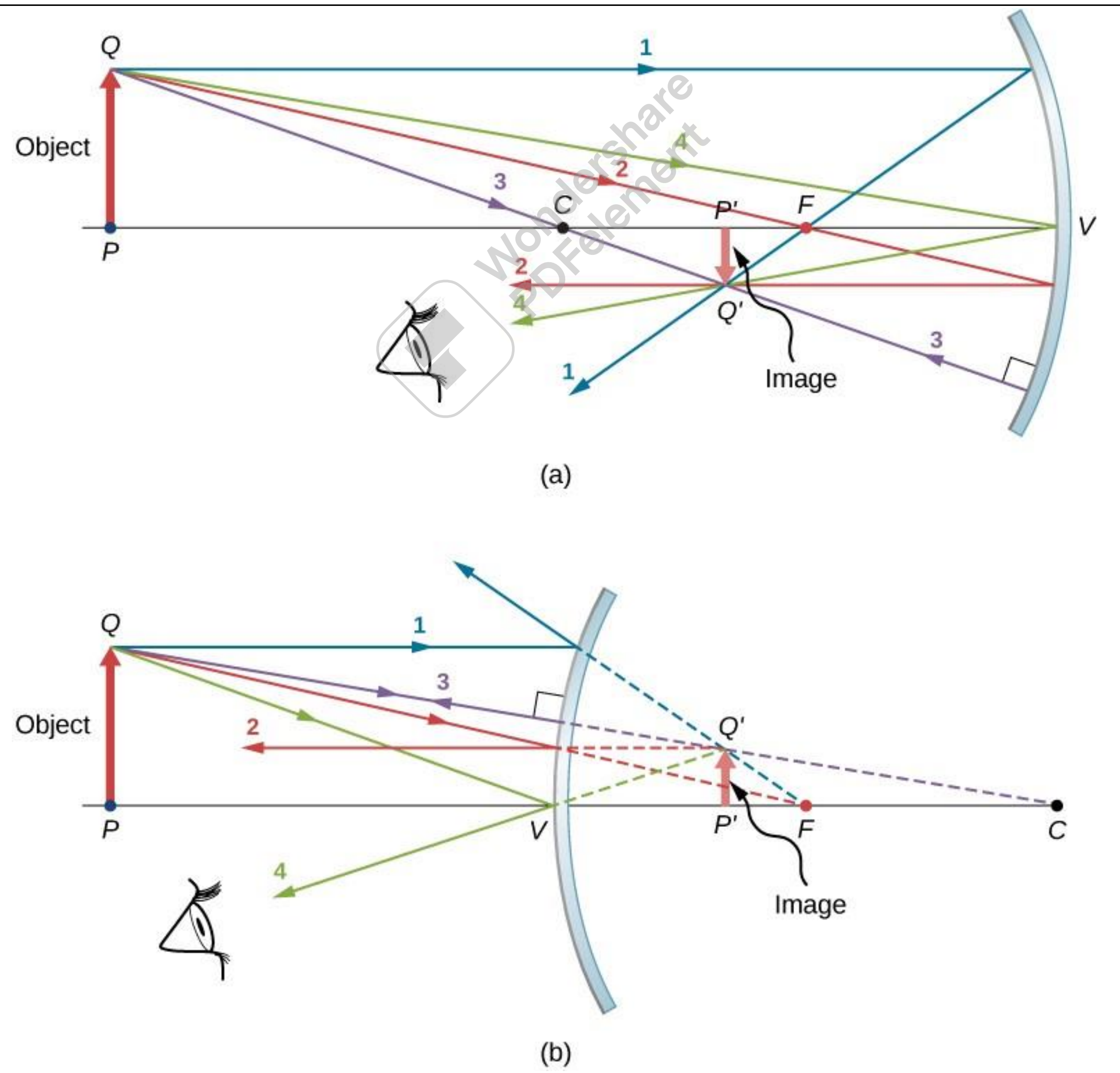
Light entering a thin fiber may strike the inside surface at large or grazing angles and is completely reflected if these angles exceed the critical angle.

convex mirror, the backward extension of the reflection of principal ray 1 goes through the focal point (i.e., a virtual focus).

Principal ray 2 travels first on the line going through the focal point and then is reflected back along a line parallel to the optical axis.

Principal ray 3 travels toward the centre of curvature of the mirror, so it strikes the mirror at normal incidence and is reflected back along the line from which it came.

Principal ray 4 strikes the vertex of the mirror and is reflected symmetrically about the optical axis.



The four principal rays shown for both (a) a concave mirror and (b) a convex mirror. The image forms where the rays intersect (for real images) or where their backward extensions intersect (for virtual images).

The four principal rays intersect at point Q', which is where the image of point Q is located. To locate point Q', drawing any two of these principle rays would suffice.

Ray tracing rules

Ray tracing is very useful for mirrors. The rules for ray tracing are summarized here for reference:

- A ray traveling parallel to the optical axis of a spherical mirror is reflected along a line that goes through the focal point of the mirror (ray 1).
- A ray traveling along a line that goes through the focal point of a spherical mirror is reflected along a line parallel to the optical axis of the mirror (ray 2).
- A ray traveling along a line that goes through the centre of curvature of a spherical mirror is reflected back along the same line (ray 3).
- A ray that strikes the vertex of a spherical mirror is reflected symmetrically about the optical axis of the mirror (ray 4).

Image formation by reflection – the mirror equation

For a plane mirror, we showed that the image formed has the same height and orientation as the object, and it is located at the same distance behind the mirror as the object is in front of the mirror. Although the situation is a bit more complicated for curved mirrors, using geometry leads to simple formulas relating the object and image distances to the focal lengths of concave and convex mirrors.

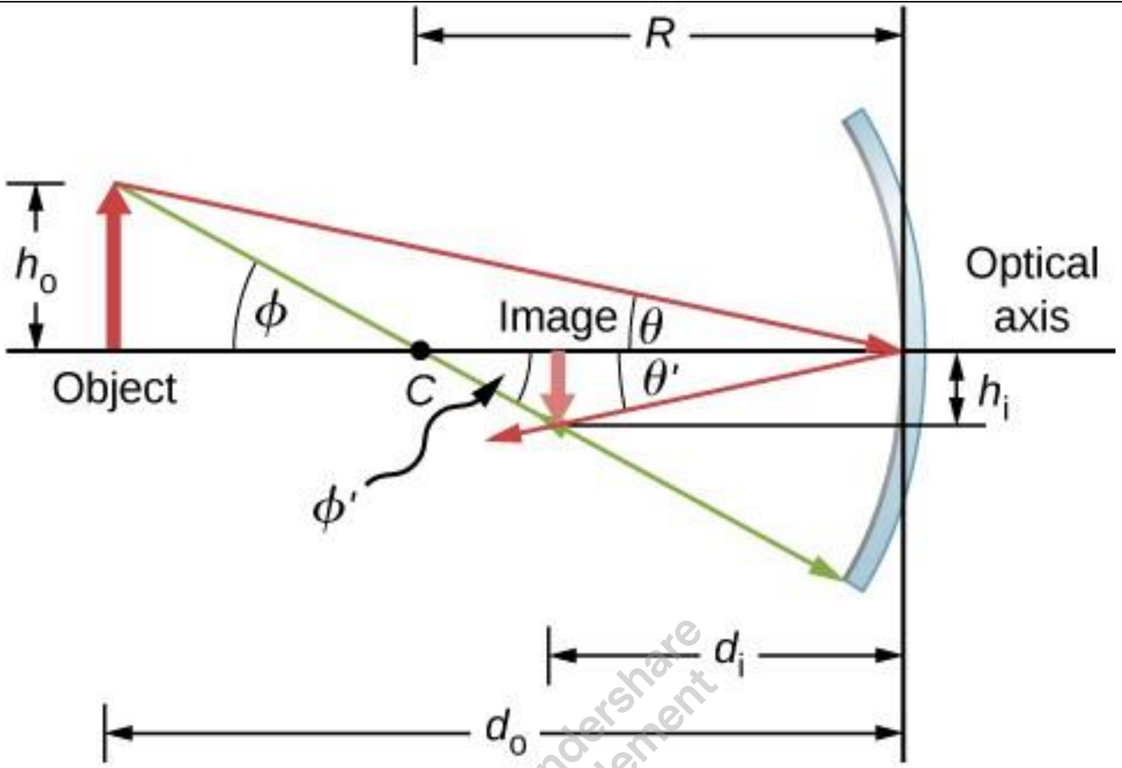


Image formed by a concave mirror.

Consider the object OP. The centre of curvature of the mirror is labelled C and is a distance R from the vertex of the mirror, as marked in the figure. The object and image distances are labelled do and di, and the object and image heights are labelled ho and hi, respectively. Because the angles ϕ and ϕ' are alternate interior angles, we know that they have the same magnitude. However, they must differ in sign if we measure angles from the optical axis, so ϕ = −ϕ'. An analogous scenario holds for the angles θ and θ'. The law of reflection tells us that they have the same magnitude, but their signs must differ if we measure angles from the optical axis. Thus, θ = θ'. Taking the tangent of the angles θ and θ', and using the property that tan(−θ) = −tan θ, gives us tan θ = ho

$$\left.\begin{aligned} \tan\theta &= \frac{h_o}{d_o} \\ \tan\theta' = -\tan\theta &= \frac{h_i}{d_i} \end{aligned}\right\} = \frac{h_o}{d_o} = -\frac{h_i}{d_i}$$

Or

$$-\frac{h_o}{h_i} = \frac{d_o}{d_i}.$$

Similarly, taking the tangent of ϕ and ϕ' gives

$$\left.\begin{aligned} \tan\phi &= \frac{h_o}{d_o - R} \\ \tan\phi' = -\tan\phi &= \frac{h_i}{R - d_i} \end{aligned}\right\} = \frac{h_o}{d_o - R} = -\frac{h_i}{R - d_i}$$

Or

$$-\frac{h_o}{h_i} = \frac{d_o - R}{R - d_i}$$

Combining the two equations gives:

$$\frac{d_o}{d_i} = \frac{d_o - R}{R - d_i}$$

After a little algebra, this becomes:

$$\frac{1}{d_o} + \frac{1}{d_i} = \frac{2}{R}$$

No approximation is required for this result, so it is exact. However, as discussed above, in the small-angle approximation, the focal length of a spherical mirror is one-half the radius of curvature of the mirror, or f=R/2. Inserting this into the equation gives the mirror equation:

$$\underbrace{\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}}_{\text{mirror equation}}.$$

The mirror equation relates the image and object distances to the focal distance and is valid only in the small-angle approximation. Although it was derived for a concave mirror, it also holds for convex mirrors. We can extend the mirror equation to the case of a plane mirror by noting that a plane mirror has an infinite radius of curvature. This means the focal point is at infinity, so the mirror equation simplifies to

$$d_o = -d_i$$

which is the same equation obtained earlier.

Notice that we have been very careful with the signs in deriving the mirror equation. For a plane mirror, the image distance has the opposite sign of the object distance. Also, the real image formed by the concave mirror is on the opposite side of the optical axis with respect to the object. In this case, the image height should have the opposite sign of the object height. To keep track of the signs of the various quantities in the mirror equation, we now introduce a sign convention.

Sign convention for spherical mirrors

Using a consistent sign convention is very important in geometric optics. It assigns positive or negative values for the quantities that characterize an optical system. Understanding the sign convention allows you to describe an image without constructing a ray diagram.

This text uses the following sign convention:

- The focal length f is positive for concave mirrors and negative for convex mirrors.
- The image distance d_i is positive for real images and negative for virtual images.

Notice that rule 1 means that the radius of curvature of a spherical mirror can be positive or negative. What does it mean to have a negative radius of curvature? This means simply that the radius of curvature for a convex mirror is defined to be negative.

Image Magnification

Let's use the sign convention to further interpret the derivation of the mirror equation. In deriving this equation, we found that the object and image heights are related by:

$$-\frac{h_o}{h_i} = \frac{d_o}{d_i}$$

Both the object and the image formed by the mirror are real, so the object and image distances are both positive. The highest point of the object is above the optical axis, so the object height is positive. The image, however, is below the optical axis, so the image height is negative. Thus, this sign convention is consistent with our derivation of the mirror equation.

We thus define the dimensionless magnification m as follows:

$$\underbrace{m = \frac{h_i}{h_o}}_{\text{linear magnification}}$$

If m is positive, the image is upright, and if m is negative, the image is inverted. If |m|>1, the image is larger than the object, and if |m|<1, the image is smaller than the object. With this definition of magnification, we get the following relation between the vertical and horizontal object and image distances:

$$m = \frac{h_i}{h_o} = -\frac{d_o}{d_i}$$

This is a very useful relation because it lets you obtain the magnification of the image from the object and image distances, which you can obtain from the mirror equation.

Example:

An image is located at exactly the same position as it's object for a mirror of focal length 6 cm. What is the object distance?

Solution:

Use the formula $$\frac{1}{d_0} + \frac{1}{d_i} = \frac{1}{f}$$

with d_i and d_o equal to get $$\frac{2}{d_0} = \frac{1}{f}$$

d_o = 12 cm

b.) If the height of the object is 4.5 mm, what is the height of the image?

Solution:

Use $$\frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

to see that the image height equals the object height.

hi = - 4.5 mm (inverted)

Example:

A convex mirror has an object 14 cm from the mirror, and the image appears to be 7 cm behind the mirror. What is the focal length of the mirror?

Solution:

Use the formula $$\frac{1}{d_0} + \frac{1}{d_i} = \frac{1}{f}$$

with the image distance negative.

f = -14 cm

b.) If the object height is 8.0 mm, what is the height of the image?

Solution:

Use the formula $$\frac{h_i}{h_o} = -\frac{d_i}{d_o}$$

with the image distance negative.

hi = 4.0 cm (upright)

Example:

Suppose one wishes to use a mirror as a projector, to illuminate a small object of height 1.0 cm, and display the image on a screen at a size of 1.0 m where the distance to the screen is 4.0 m.

a.) What kind of mirror should one use? (concave or convex)

concave

b.) What should the focal length of the mirror be?

Solution:

First calculate the object distance via the magnification formula. One obtains do = 4.0 cm. Next, calculate the focal length via

$$\frac{1}{f}=\frac{1}{d_o}+\frac{1}{d_i}$$

Since di is large compared to do, the focal length will be approximately equal to do.

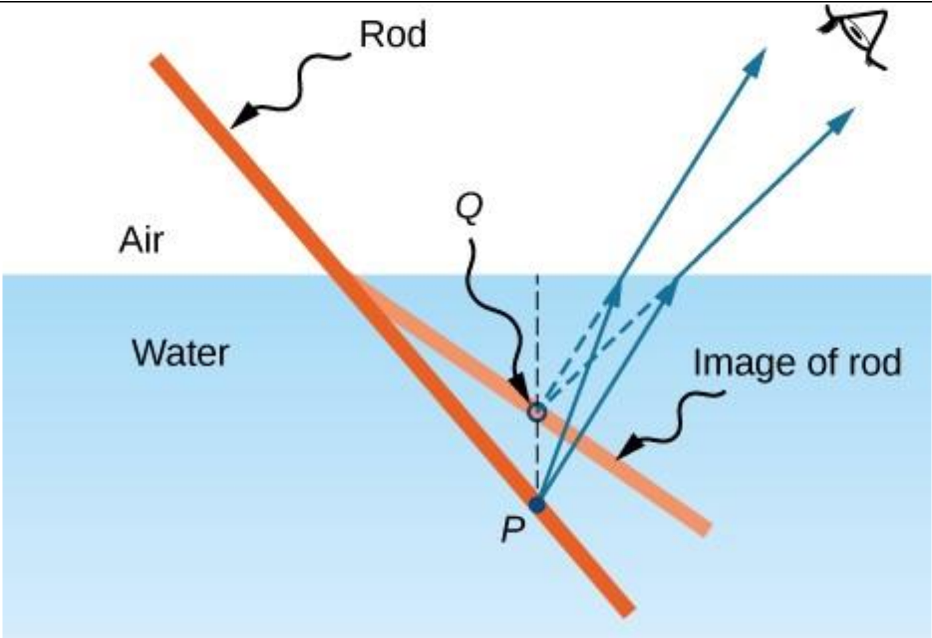
f = 4.0 cm

Images formed by refraction

When rays of light propagate from one medium to another, these rays undergo refraction, which is when light waves are bent at the interface between two media. The refracting surface can form an image in a similar fashion to a reflecting surface, except that the law of refraction (Snell's law) is at the heart of the process instead of the law of reflection.

Refraction at a plane interface – apparent depth

If you look at a straight rod partially submerged in water, it appears to bend at the surface. The reason behind this curious effect is that the image of the rod inside the water forms a little closer to the surface than the actual position of the rod, so it does not line up with the part of the rod that is above the water. The same phenomenon explains why a fish in water appears to be closer to the surface than it actually is.



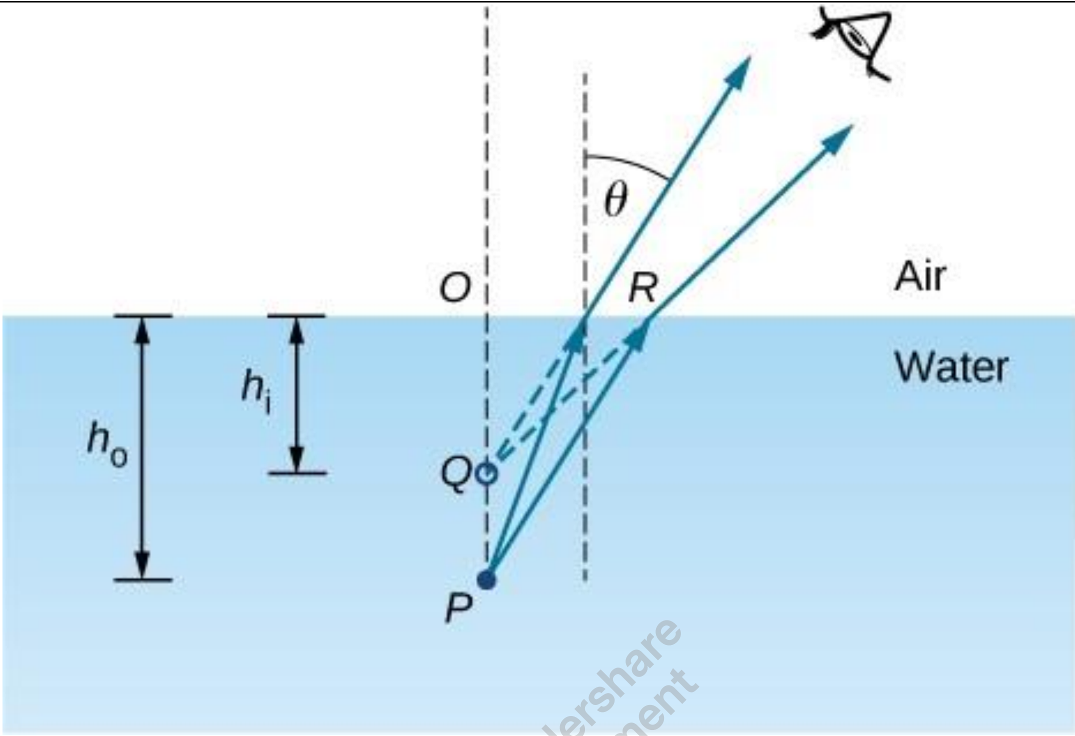
Bending of a rod at a water-air interface. Point P on the rod appears to be at point Q, which is where the image of point P forms due to refraction at the air-water interface.

To study image formation as a result of refraction, consider the following questions:

1- What happens to the rays of light when they enter or pass through a different medium?

2- Do the refracted rays originating from a single point meet at some point or diverge away from each other?

To be concrete, we consider a simple system consisting of two media separated by a plane interface. The object is in one medium and the observer is in the other. For instance, when you look at a fish from above the water surface, the fish is in medium 1 (the water) with refractive index 1.33, and your eye is in medium 2 (the air) with refractive index 1.00, and the surface of the water is the interface. The depth that you "see" is the image height hi and is called the apparent depth. The actual depth of the fish is the object height ho.



Apparent depth due to refraction. The real object at point P creates an image at point Q. The image is not at the same depth as the object, so the observer sees the image at an "apparent depth."

The apparent depth hi depends on the angle at which you view the image. For a view from above (the so-called "normal" view), we can approximate the refraction angle θ to be small and replace sinθ in Snell's law by tanθ. With this approximation, you can use the triangles ΔOPR and ΔOQR to show that the apparent depth is given by:

$$h_i = \left(\frac{n_2}{n_1}\right) h_o$$

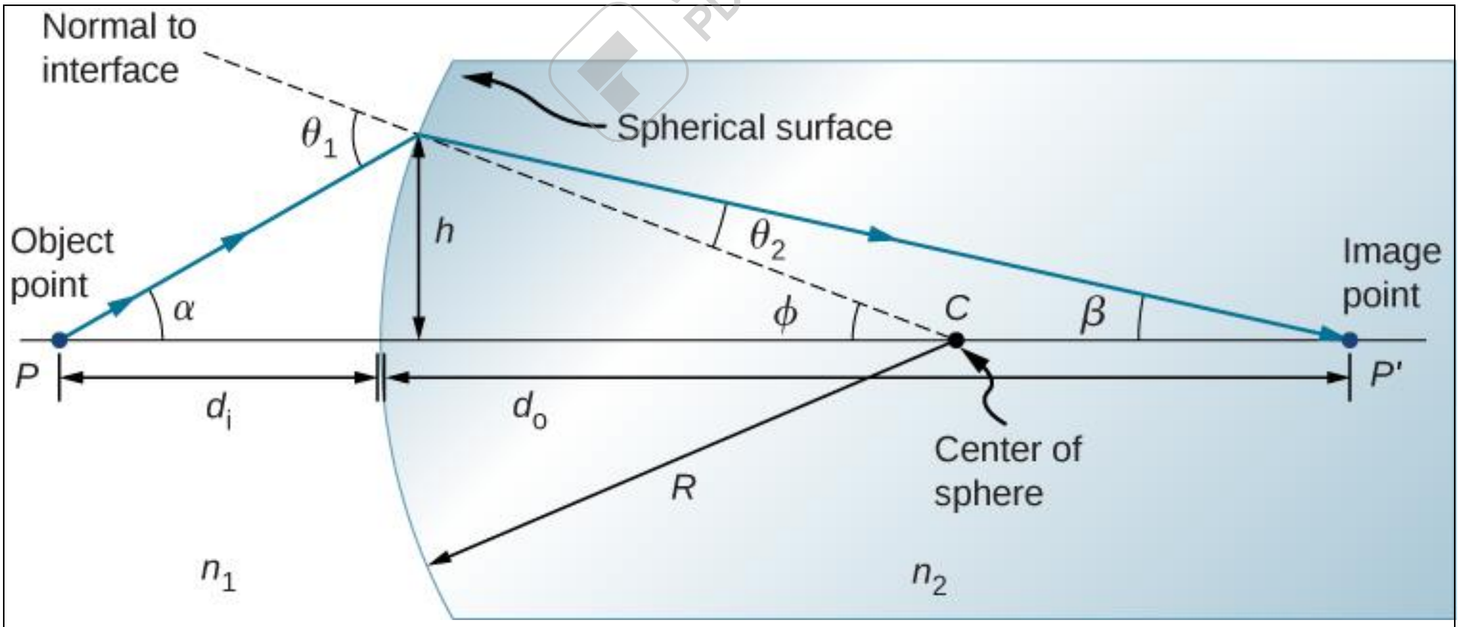
The derivation of this result is left as an exercise. Thus, a fish appears at 3/4 of the real depth when viewed from above.

Refraction at a Spherical Interface

Spherical shapes play an important role in optics primarily because high-quality spherical shapes are far easier to manufacture than other curved surfaces. To study refraction at a single spherical surface, we assume that the medium with the spherical surface at one end continues indefinitely (a "semi-infinite" medium).

Refraction at a Convex Surface

Consider a point source of light at point *P* in front of a convex surface made of glass. Let R be the radius of curvature, n1 be the refractive index of the medium in which object point *P* is located, and n2 be the refractive index of the medium with the spherical surface. We want to know what happens as a result of refraction at this interface.



Refraction at a convex surface (n2>n1).

Because of the symmetry involved, it is sufficient to examine rays in only one plane. The figure shows a ray of light that starts at the object point P, refracts at the interface, and goes through the image point P'. We derive a formula relating the object distance do, the image distance di, and the radius of curvature R

Applying Snell's law to the ray emanating from point P gives:

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

Within the small-angle approximation

$$\sin\theta \approx \theta,$$

Snell's law then takes the form:

$$n_1\theta_1 \approx n_2\theta_2$$

From the geometry, we see that:

$$\theta_1 = \alpha + \phi,$$

$$\theta_2 = \phi - \beta.$$

Inserting both expressions into the equation gives:

$$n_1(\alpha + \phi) \approx n_2(\phi - \beta)$$

Using the figure, we calculate the tangent of the angles α, β, and ϕ:

$$\tan\alpha \approx \frac{h}{d_o} \qquad \alpha \approx \frac{h}{d_o}$$

But $\tan\theta \approx \theta$

$$\tan\beta \approx \frac{h}{d_i} \qquad \beta \approx \frac{h}{d_i}$$

$$\tan\phi \approx \frac{h}{R} \qquad \phi \approx \frac{h}{R}$$

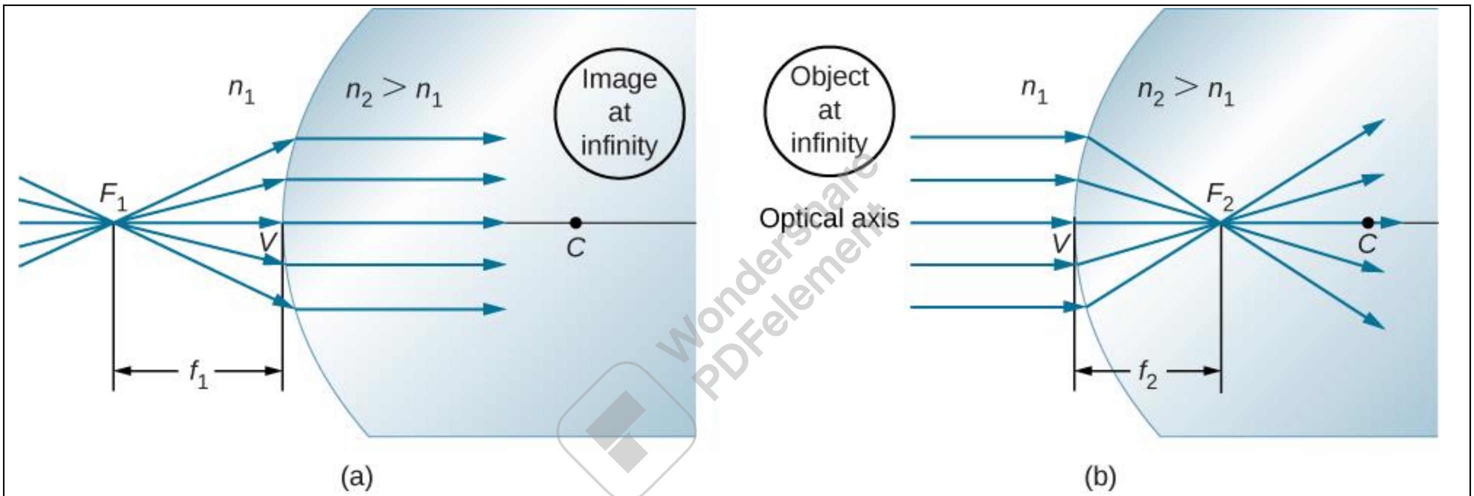
Putting these angles into the equation gives:

$$n_1\left(\frac{h}{d_o}+\frac{h}{R}\right)=n_2\left(\frac{h}{R}-\frac{h}{d_i}\right)$$

We can write this more conveniently as:

$$\frac{n_1}{d_o}+\frac{n_2}{d_i}=\frac{n_2-n_1}{R}$$

If the object is placed at a special point called the first focus, or the object focus F1, then the image is formed at infinity, as shown in Figure a.



(a) First focus (called the "object focus") for refraction at a convex surface. (b) Second focus (called "image focus") for refraction at a convex surface.

We can find the location f1 of the first focus F1 by setting di=∞ in the equation.

$$\frac{n_1}{f_1}+\frac{n_2}{\infty}=\frac{n_2-n_1}{R}$$

$$f_1=\frac{n_1 R}{n_2-n_1}$$

Similarly, we can define a second focus or image focus F2 where the image is formed for an object that is far away (Figure b). The location of the second focus F2 is obtained from Equation 2.3.9 by setting d0=∞

$$\frac{n_1}{\infty} + \frac{n_2}{f_2} = \frac{n_2 - n_1}{R}$$

$$f_2 = \frac{n_2 R}{n_2 - n_1}$$

Note that the object focus is at a different distance from the vertex than the image focus because n1≠n2.

Sign convention for single refracting surfaces

Although we derived this equation for refraction at a convex surface, the same expression holds for a concave surface, provided we use the following sign convention:

1- R>0 if surface is convex toward object; otherwise, R<0
2- di>0 if image is real and on opposite side from the object; otherwise, di<0.

The human eye as an optical refracting system

Interesting facts about eyes that you probably didn't know

- Your eyes are about 2.5 cm across and weigh about 7.087381 gm.
- The human eye can differentiate approximately 10 million different colors.
- Our eyes remain the same size throughout life, whereas our nose and ears never stop growing.
- The human eye blinks an average of 4,200,000 times a year.

- Eyes are made up of over 2 million working parts.
- Each individual eye contains 107 million cells, and all are light sensitive.
- Your eye is the fastest muscle in your body. Hence, the phrase: "In the blink of an eye."
- The world's most common eye color is brown.
- Brown eyes are blue eyes underneath. Consequently, a person can receive surgery in order to make their brown eyes blue.

The eye is an optical instrument that can

- Focus automatically on objects over a wide range of distances
- Adjust automatically to a wide range of light intensities
- Sensitive to a continuous range of electromagnetic waves from less than 400 nm to about 650 nm in wavelength.

The structure the human eye

1. Tear Layer

The Tear Layer (The Lacrimal System) is the first layer of the eye that light strikes. It is clear, moist, and salty. Its purpose is to keep the eye smooth and moist.

2. Cornea

The Cornea is the second structure that light strikes. It is the clear, transparent front part of the eye that covers the iris, pupil and anterior chamber and provides most of an eye's optical power. It needs to be smooth, round, clear, and tough. It is like a protective window.

The function of the cornea is to let light rays enter the eye and converge the light rays.

3. Anterior Chamber

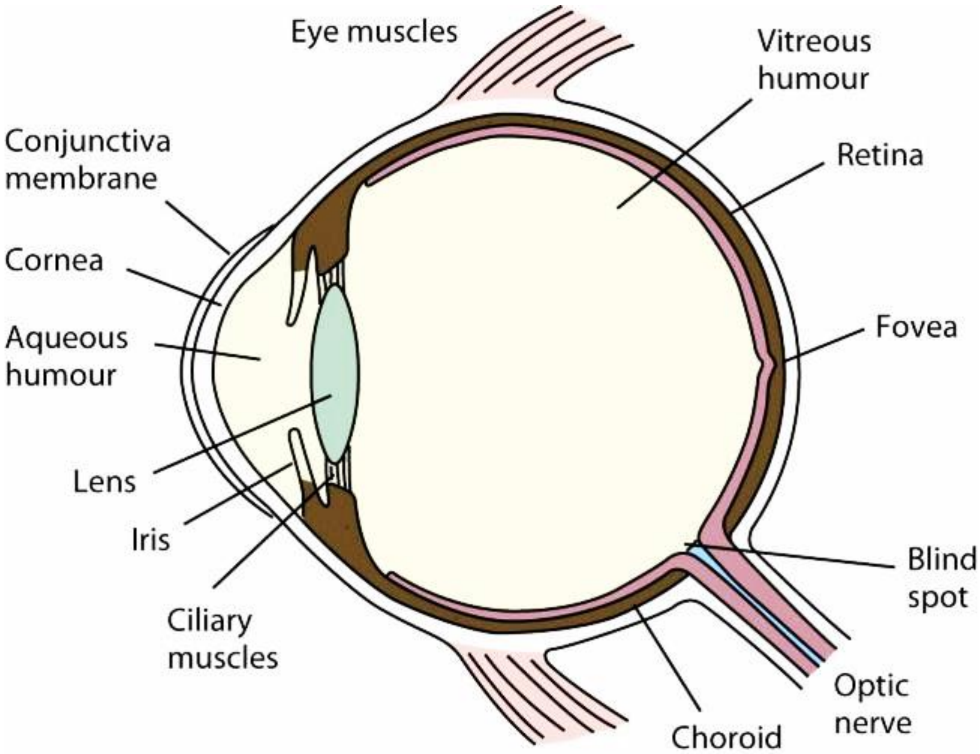
The Anterior Chamber is filled with **Aqueous Humor**. Aqueous Humour is a clear, watery fluid that fills the space between the back surface of the cornea and the front surface of the vitreous, bathing the lens. The eye receives oxygen through the aqueous. **Its function is to feed the cornea, iris, and lens by carrying nutrients. It removes waste products excreted from the lens, and maintain intraocular pressure and thus maintains the shape of the eye.**

4. Iris

The iris is the pigmented tissue lying behind the cornea that gives color to the eye and controls the amount of light entering the eye by varying the size of the papillary opening.

It functions like a camera. The color of the iris affects how much light gets in.

The iris controls light constantly, adapts to lighting changes, and is responsible for near point reading (to see close, pupils must constrict)



Pupil

It is a variable-sized black circular opening in the center of the iris that regulates the amount of light that enters the eye. The pupil needs to be round in order to constrict.

A constricted pupil occurs when the pupil size is reduced to constriction of the iris or relaxation of the iris dilator muscle. The iris constricts with bright illumination, with certain drugs, and can be a consequence of ocular inflammation.

A dilated pupil is an enlarged pupil, resulting from contraction of the dilator muscle or relaxation of the iris sphincter. It occurs normally in dim illumination or may be produced by certain drugs (mydriatics) or result from blunt trauma.

5. Lens

The lens is the natural lens of the eye (crystalline lens). Transparent, biconvex intraocular tissue that helps bring rays of light to focus on the retina (It bends light, but not as much as the cornea).

Ciliary Body. The circumferential tissue (a ring of tissue between the end of the choroids and the beginning of the iris) inside the eye composed of the ciliary muscle (involved in lens accommodation and control of intraocular pressure and thus the shape of the lens) and 70 ciliary processes that produce aqueous fluid.

6. Vitreous Humour (Chamber)

Vitreous Humour (Chamber) is the transparent, colorless gelatinous mass that fills rear two-thirds of the eyeball, between the lens and the retina. It has to be clear so light can pass through it and it has to be there, or eye would collapse.

7. Retina

The retina is the **light sensitive nerve tissue** in the eye that converts images from the eye's optical system into electrical impulses that are sent along the optic nerve to the brain, to interpret as vision.

- **Cones** The cones are the light-sensitive retinal receptor cell that **provides the sharp visual acuity** (**detail vision**) and color discrimination; most numerous in macular area. Function under bright lighting.
- **Rods** The light-sensitive, specialized retinal receptor cell that works **at low light levels** (**night vision**). The rods function with movement and provide **light/dark contrast**. It makes up peripheral vision.
- **Macula** It is the "**yellow spot**" in the small (3 °) central area of the retina surrounding the fovea. It is the area of acute central vision **(used for**

reading and discriminating fine detail and color). Within this area is the **largest concentration of cones.**

- **Fovea** The fovea is the central pit in the macula that produces the **sharpest vision**. **It contains a high concentration of cones** within the macula and no retinal blood vessels.

8. Choroid

The vascular (major blood vessel), central layer of the eye lying between the retina and sclera. Its function is to provide food to the outer layers of the retina through blood vessels. It is part of the uveal tract.

9. Sclera

The sclera is the opaque, fibrous, tough, protective outer layer of the eye ("**white of the eye**") that is directly continuous with the cornea in front and with the sheath covering the optic nerve behind. **The sclera provides protection.**

10. Optic Nerve

The Optic Nerve is the largest sensory nerve of the eye. It carries impulses for sight from the retina to the brain. Composed of retinal nerve fibers that exit the eyeball through the optic disc, traverse the orbit, pass through the optic foramen into the cranial cavity, where they meet fibers from the other optic nerve at the optic chiasm.

11. Extraocular Muscles

- There are six extraocular muscles in each eye:
- **Rectus Muscles.** There are four Rectus muscles that are responsible for straight movements: **Superior** (upward), **Inferior** (lower), **Lateral**

(toward the outside, or away from the nose), and **Medial** (toward the inside, or toward the nose).

- **Oblique Muscles.** There are two Oblique muscles that are responsible for angled movements. The **superior oblique** muscles control angled movements **upward toward the right or left**. **Inferior oblique** muscles control angled movements **downward toward the right or left**.

Mechanism of generating visual signals

- ➢ Light rays
- ➢ cornea and lens
- ➢ retina generates impulses in rods and cones opsin and retinol of photo pigment dissociates
- ➢ result in change in opsin structure
- ➢ cause membrane permeability changes
- ➢ it results p.ds. generated in photoreceptor cells
- ➢ action potential in ganglion cells through bipolar cells
- ➢ optic nerve
- ➢ visual cortex area of brain
- ➢ image recognized based on earlier memory and experience.

<u>Sensitivity of the eye</u>

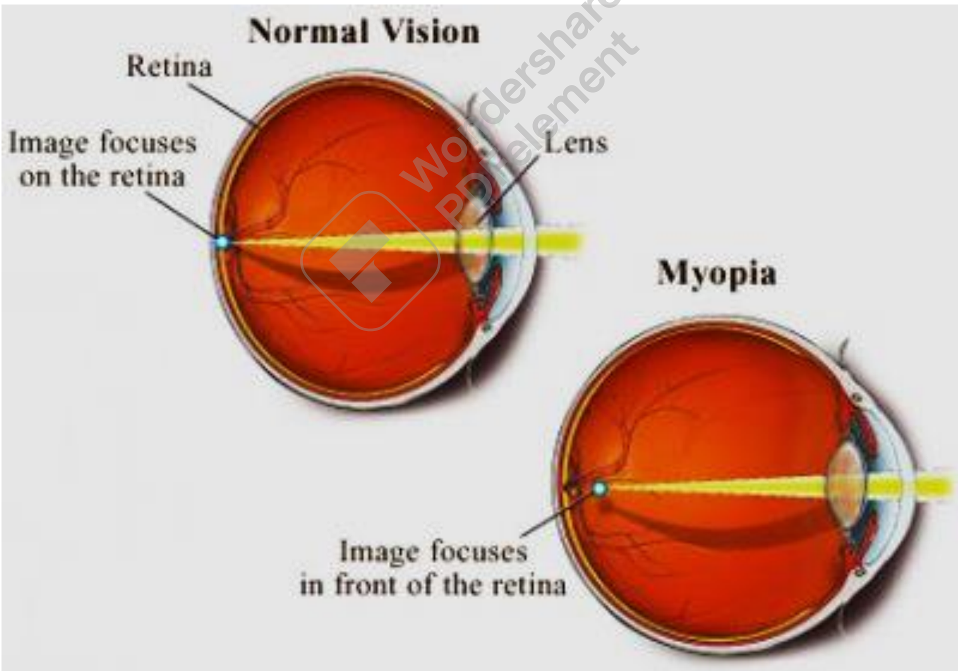
- ➢ Rods are sensitive to low levels of light intensity but cannot distinguish between colors.
- ➢ Cones are of three types, each sensitive to a different range of wavelengths.

Vision defects

Myopia or short sight

occurs when an eye cannot focus on distant objects. The uncorrected far point of the defective eye is nearer than infinity. This is because the eye muscles cannot make the eye lens thin enough to focus an image on the retina of an object at infinity. The eye can focus nearby objects hence the defect is referred to as 'short-sight'.

- The cause of myopia is that light, after passing through the eye lens, converges in front of the retina.
- This happens if the eye lens cannot become thin enough to focus light onto the retina or if the eyeball is too long.

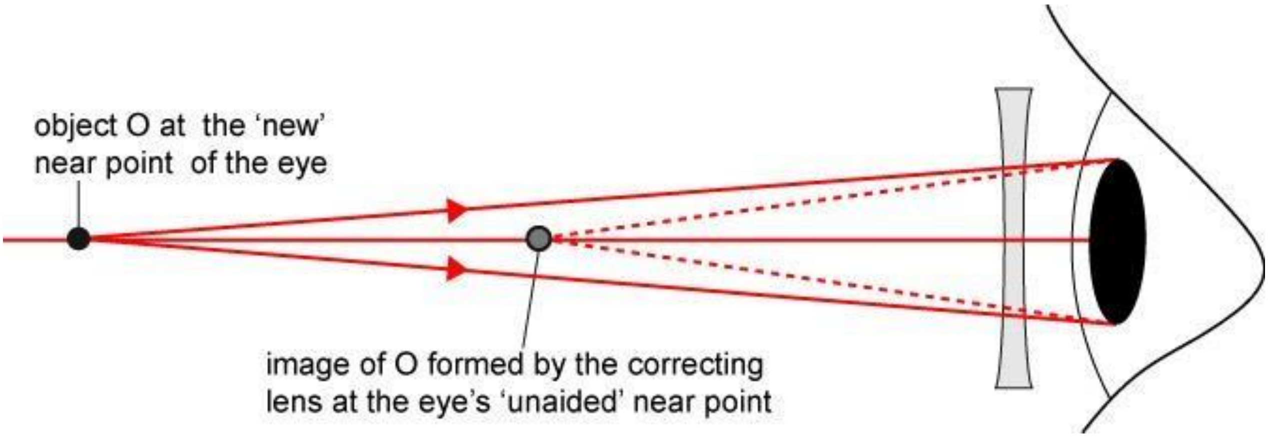


Correction

To correct myopia using a lens, a diverging lens of a suitable focal length must be placed in front of the. The correcting lens makes parallel rays from a distant object diverge so they appear to come from the uncorrected far point. Therefore, the correcting lens for myopia must:

- Be a diverging lens

- Have a focal length equal to the distance from the eye to the uncorrected far point.



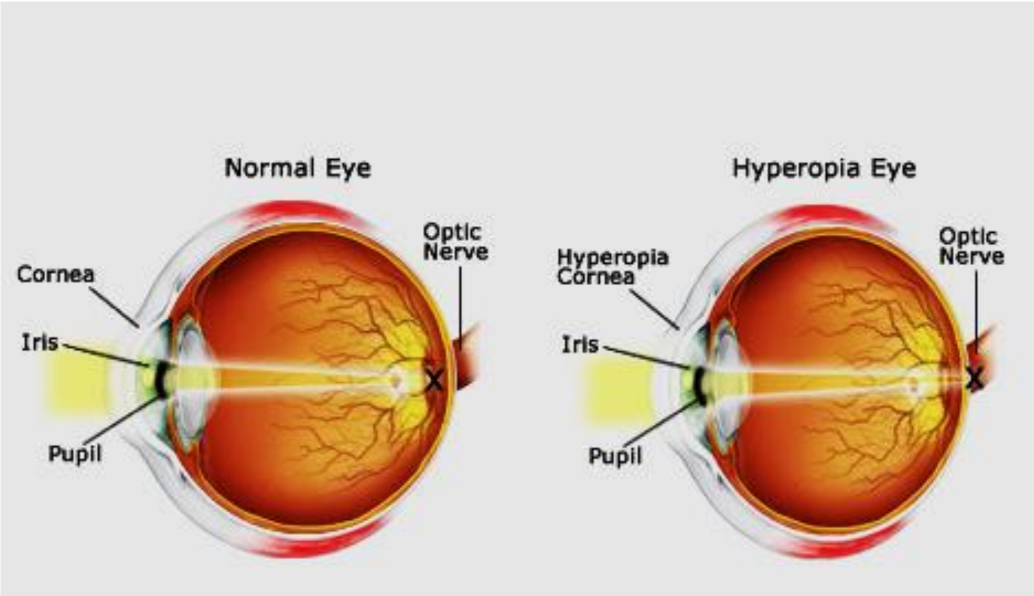
<u>The figure shows that:</u>

- the correcting lens forms a virtual image of the distant point object at the uncorrected far point
- the cornea and eye lens see the object as if it was at the uncorrected far point and form a real image of the object on the retina.

Hypermetropia or long-sight

occurs when an eye cannot focus on nearby objects. The uncorrected near point of the defective eye is further away than 25 cm. This is because the eye muscles cannot make the eye lens thick enough to focus an image on the retina of an object 25 cm away. The eye can focus distant objects hence the defect is referred to as 'long-sight'.

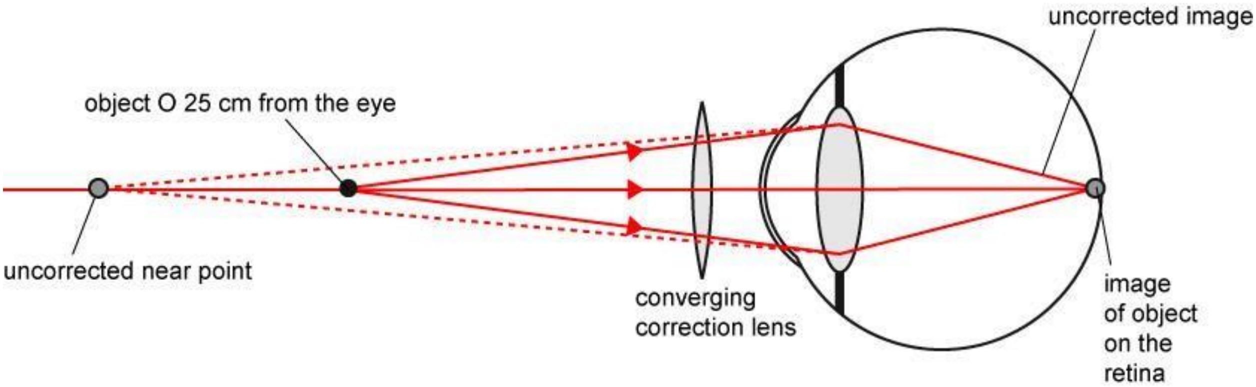
- The cause of hypermetropia is that light, after passing through the eye lens, does not converge enough to form an image on the retina.
- This happens if the eye lens cannot become thick enough to focus light onto the retina or if the eyeball is too short.



Correction

To correct hypermetropia using a lens, a converging lens of a suitable focal length must be placed in front of the eye. The correcting lens makes the rays from an object 25 cm away diverge less so they appear to come from the uncorrected near point. Therefore, the correcting lens for hypermetropia must:

- Be a converging lens
- Have a focal length which makes an object placed 25 cm from the eye appear as if it is at the uncorrected near point.



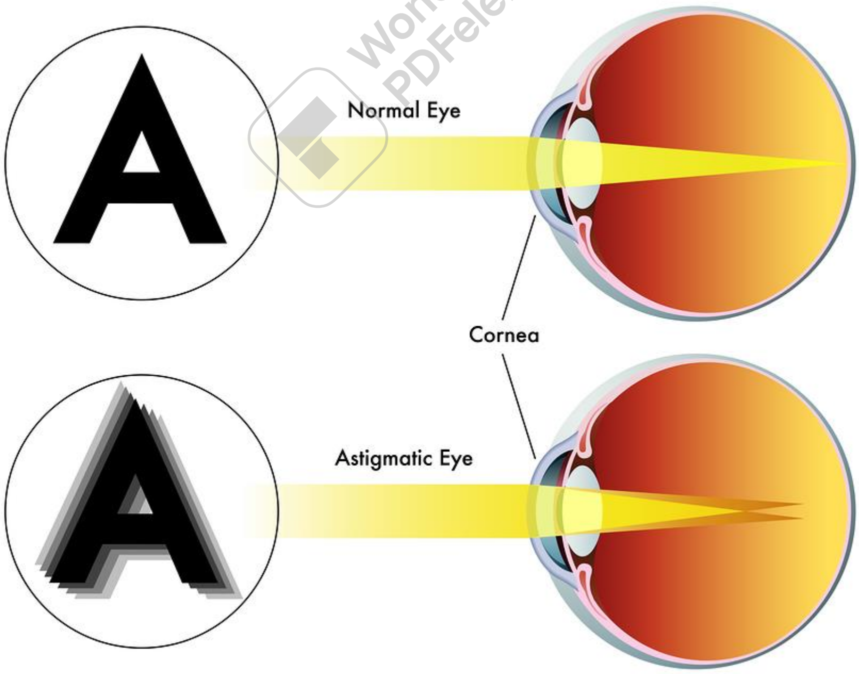
The figure shows that:

➢ the correcting lens forms a virtual image of the point object at the uncorrected near point

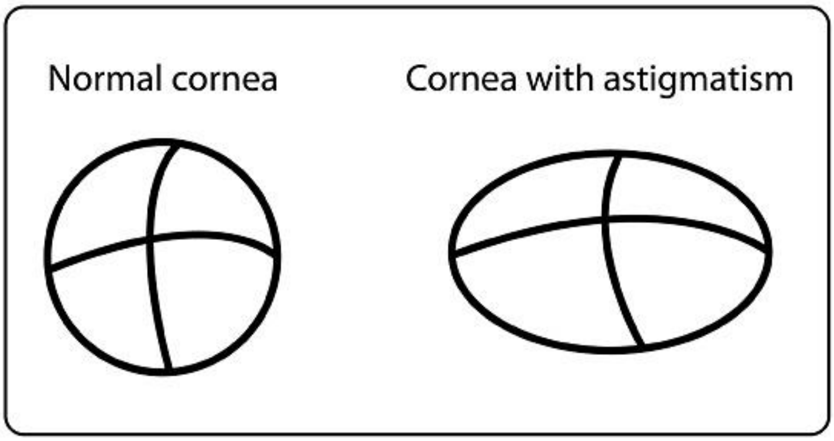
➢ the cornea and eye lens see the object as if it was at the uncorrected near point and form a real image of the object on the retina.

Astigmatism

Astigmatism is a sight defect in which objects are seen to be sharper in focus in one direction than in other directions. It is most noticeable when observing parallel lines in perpendicular directions. A simple test for astigmatism is to observe two sets of parallel lines on a card that are perpendicular to each other. If one set of lines stands out more than the other set at a certain orientation (e.g. vertical), the eye is astigmatic. When the card is rotated, the other set of lines stand out more as they reach the same orientation as the first set of lines were in when they were more prominent.



The cause of astigmatism is uneven curvature of the cornea. If the curvature is different in different directions, straight lines at different orientations cannot be focused on the retina at the same time. The more prominent line(s) will be in focus on the retina; the other lines will be out of focus.



Correction

<u>The correction of astigmatism</u> requires a lens with a cylindrical-shaped surface orientated so that it compensates for the uneven curvature of the cornea. An optician's prescription for astigmatism will state:

- the curvature of the cylindrical-shaped surface

the orientation of the axis of the cylindrical surface.

Chapter one

1-What is the Heat

Particles of matter are in movement. For example, in gases, molecules in all directions move irregularly and irregularly, and the speed and direction of a molecule changes when that part collides with another. In solids, the motion of their molecules is a fluctuating motion around its equilibrium position.

In the liquid state, the movement of molecules is a compromise between the movement of molecules in gaseous and solid matter. In all cases, the molecules are in motion. This means that each molecule has kinetic energy.

$$KE = \frac{1}{2} m v^2$$

"It should be noted that we mean the motion of the molecule is the kinetic energy of the molecules of the substance.

Each body has kinetic energy of the molecules of the substance and this is equivalent to what it contains of the amount of heat It means that the heat is only the energy of the of the molecules motion of the material

Heat is the energy that causes the transition sensation of heat or cold.

2-Thermal effects

- **Physiological effects**: such as feeling warm and alerting blood circulation and burns.
- **Chemical effects:** such as chemical reactions caused by heating, for example, the sulfur union with iron by heating and produces iron sulfate.
- **Physical effects:** expansion - changing the state from hardness (solid) to liquidity and from liquid to gaseous - increasing electrical resistance - increasing water vapor pressure - generating electric power when heating point of contact of two different metals (Copper and Iron for example

3- Temperature

If we touch a hot object, we feel that we have feelings with a certain feeling. We assume that we divided this body into parts and touched its parts individually. We feel the same feeling as in the first case.

It has because that the sense of touch does not indicate the amount of heat in the body, but it shows us a fixed characteristic of the characteristics of the temperature, which does not change when the division of any body into small parts this property will know it as the temperature.

What does not change in the body when it is divided into parts is clearly the energy of the movement of its molecules. Therefore,

Temperature is a standard or a measure of this medium kinetic energy of the molecules of matter.

4-Temperature Scale

When the state of the crystalline material changes from solidity to fluidity or from liquid to gaseous, this change occurs at constant temperatures - which can be considered as fixed points in temperature

The most important of these points are : the freezing point (or freezing point) and the boiling point of distilled water under pressure 76 cm / Hg (or the boiling point of water under pressure 76 cm / Hg)

Let us assume that the value of the physical property measured at freezing point is x_0 and x_{100} at boiling point. n = the number of equal sections in between the two fixed points.

The change in the physical property of each section is:

$$\frac{X_{100} - X_0}{n}$$

Assuming that the value of the physical property x_t is at t temperature, then the change in the physical property corresponding to 1 ° C is:

$$\frac{x_t - x_0}{t} = \frac{x_{100} - x_0}{100}$$

$$x_t = x_0 + \left(\frac{x_{100} - x_0}{100}\right)t$$

$$= x_0\left(1 + \left(\frac{x_{100} - x_0}{100x_0}\right)t\right)$$

$$= x_0(1 + \alpha t)$$

$$\alpha = \frac{x_{100} - x_0}{100x_0}$$

α is the coefficient of increasing in the physical property by high temperature, ie for example, increasing the length, size or resistance. The temperature obtained by this method may vary depending on the quantity this variation is undesirable and therefore we need to have a calibration process for correction and it is agreed to make the thermometer the fixed-size hydrogen gas a standard thermometer. The most common temperature scales are summarized below:

a- Celsius Scale

The Celsius scale was invented in 1742 by the Swedish astronomer, Anders Celsius. This scale divides the range of temperature between the freezing and boiling temperatures of water into 100 equal parts. You will sometimes find this scale identified as the centigrade scale. Temperatures on the Celsius scale are known as degree Celsius (ºC).

b- Fahrenheit Scale

The Fahrenheit scale was established by the German-Dutch physicist, Gabriel Daniel Fahrenheit, in 1724. While many countries now use the Celsius scale, the Fahrenheit scale is widely used in the United States. It divides the difference between the melting and boiling points of water into 180 equal intervals. Temperatures on the Fahrenheit scale are known as degree Fahrenheit (ºF)

c- Kelvin Scale

The Kelvin scale is named after William Thompson Kelvin, a British physicist who devised it in 1848. It extends the Celsius scale down to absolute zero, a hypothetical temperature characterized by a complete absence of heat energy. Temperatures on this scale are called Kelvins (K)

Converting Temperatures It is sometimes necessary to convert temperature from one scale to another. Here is how to do this**.**

Temperature Conversion Formulas		
Example	Formula	Conversion
21°C = 294 K	K = C + 273	Celsius to Kelvin
313 K = 40 °C	C = K - 273	Kelvin to Celsius
89 °F = 31.7 °C	C = (F - 32) x 5/9	Fahrenheit to Celsius
50 °C = 122 °F	F = (C x 9/5) + 32	Celsius to Fahrenheit

Comparison of Temperature Scales			
Kelvin	Celsius	Fahrenheit	Set Points
373	100	212	water boils
310	37	98.6	body temperature
273	0	32	water freezes
0	-273	-460	absolute zero

5- Thermometers

What is the principle on which thermometers are made? There are many physical properties that are regularly altered by temperature changes, such as the volume of a certain amount of liquid, the pressure of a certain amount of stationary gas, the electric force at the point of contact of two different metals in a closed circuit.

Note some of the other physical properties that can change regularly by changing the temperature. If we choose one of these qualities those changes regularly by changing the temperature we can measure the temperature by the number that measures this variable.

A thermometer is a device that measures temperature or temperature gradient, using a variety of different principles. The word thermometer is derived from two smaller word fragments: *thermo* from the Greek for heat and *meter* from Greek, meaning to measure. A thermometer has two important elements, the temperature sensor (e.g. the bulb on a mercury thermometer) in which some physical change occurs with temperature, plus some means of converting this physical change into a value (e.g. the scale on a mercury thermometer). Industrial thermometers commonly use electronic means to provide a digital display or input to a computer.

6 Types of Thermometers

a- The Liquid in Glass Thermometer

The Liquid in Glass thermometer utilizes the variation in volume of a liquid in temperature. They use the fact that most fluids expand on heating. The fluid is contained in a glass bulb, and its expansion is measured using a scale etched in the stem of the thermometer Liquid in Glass thermometers have been used in science, medicine, metrology and industry for almost 300 years. Liquids commonly used include Mercury and Alcohol.

Structure:

Two basic parts:

a. The bulb: Acting as a reservoir holding the liquid whose volume changes with temperature. The bulb also acts as a sensor or gauge which is inserted in the body whose temperature is to be measured.

b. **The Stem**: containing the scale that is measuring the temperature and a capillary through which the liquid can accordingly expand and contract

General Properties

Advantages:

1. They are cheap to manufacture
2. Easy to carry and handle.

Disadvantages:

1. They tend to have high heat capacities. They are not sensitive enough, that is they cannot measure rapid temperature changes

General Equation for Temperature calculation using a liquid in glass thermometer:

$$t = \left(\frac{L_t - L_0}{L_{100} - -L_0} \right) \times 100$$

b- The resistance thermometer

It use of the change of resistance in a metal wire with temperature. As electrons move through a metal, they are impeded by the thermal vibrations of the atoms in the crystal lattice. The higher the temperature the greater the impediment to flow thus the higher the resistance. This effect is very marked in pure metals, and for a well-behaved material enables measurements of temperature to be made to better than 0.001 °C.

Usually platinum wire is used in the construction of the thermometer, since it is a noble metal which is un-reactive over a wide range of temperatures. But copper, nickel and rhodium alloy may also be used in various temperature ranges. Usually a coil of the pure wire is wound onto an alumina former or placed in the bores of an alumina tube, and this assembly is mounted in a steel tube.

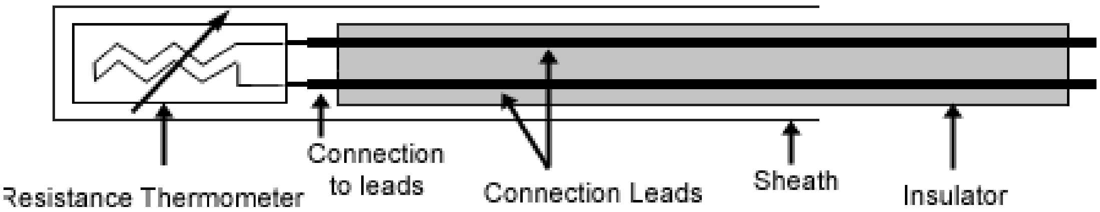
Resistance thermometers are slowly replacing thermocouples in many lower temperature industrial applications (below 600°C). Resistance thermometers come in a number of construction forms and offer greater stability, accuracy and repeatability. The resistance tends to be almost linear with temperature. A small power source is required.

No special extension cables or cold junction compensations are required. The resistance of a conductor is related to its temperature. Platinum is usually used due to its stability with temperature. The Platinum detecting wire needs to be kept free of contamination to remain stable. A Platinum wire or film is created and supported on a former in such a way that it gets minimal differential expansion or other strains from its former, yet is reasonably resistant to vibration.

Resistance thermometers require a small current to be passed through in order to determine the resistance. This can cause self heating and manufacturer’s limits should always be followed along with heat path considerations in design.

Care should also be taken to avoid any strains on the resistance thermometer in its application.

Resistance thermometers elements are available in a number of forms. The most common are: Wire Wound in a ceramic insulator - High temperatures to 850 °C Wires encapsulated in glass - Resists the highest vibration and offers most protection to the Pt Thin film with Pt film on a ceramic substrate - Inexpensive mass production



Advantages

1. Depending on the metal being used resistance, thermometers are able to cover extensive temperature ranges. Maximum values are generally related to the melting points of the metal used.
2. Variation of resistance with temperature is stable over an extensive temperature range.
3. Very accurate

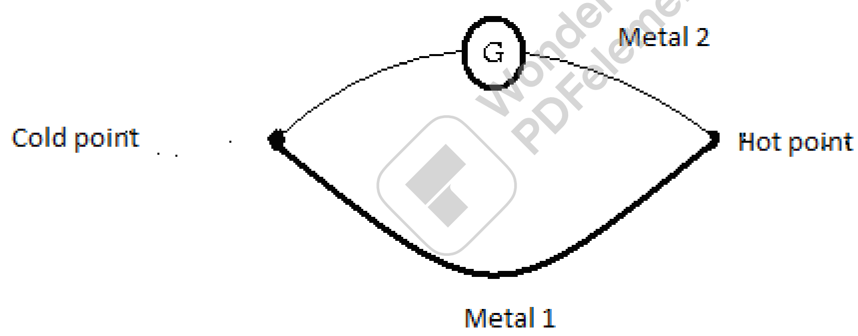
Disadvantages

1. Compared to liquid in glass thermometers, they tend to be expensive.
2. Require other equipment to measure temperature.
3. They exhibit high heat capacities thus they are not sensitive to temperature change meaning that they can not be used to measure rapid temperature changes.

$$t = \left(\frac{R_t - R_0}{R_{100} - R_0} \right) \times 100$$

C- Thermocouples

As a Thermometric, property thermocouples utilize the variation of EMF generated at a bimetallic junction with temperature. In1821, the German-Estonian physicist Thomas Johann Seebeck discovered that when any conductor (such as a metal) is subjected to a thermal gradient, it would generate a voltage. This is now known as the thermoelectric effect or Seebck effect



Unknown temperature is found according to the relation:

$$t = \left(\frac{E_t - E_0}{E_{100} - E_0} \right) \times 100$$

Many different thermocouple combinations have been used, but only 8 are standardized. These include 3 noble metal thermocouples using platinum and platinum-rhodium alloys, widely used for temperature measurement up to 1600 °C. The remaining 5 mainly use nickel-based alloys, which are cheaper and more suitable for industrial use up to about 1200 °C. Other refractory alloys can be used up to and beyond 2000 °C.

Advantages:

1. Cheap to manufacture.
2. The simplicity, ruggedness, low cost, small size and wide temperature range of thermocouples make them the most common type of temperature sensor in industrial use.
3. Low heat capacities making it capable of measuring rapid temperature changes.

Disadvantages:

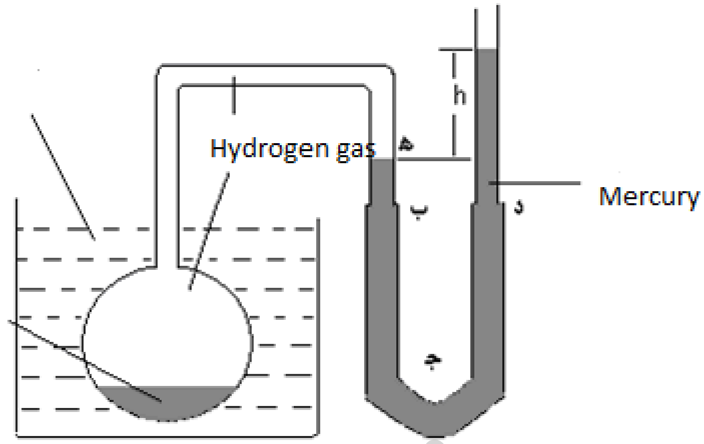
1. Sensitivity reduces accuracy

C -The Constant Volume Gas Thermometer

As a thermometric property it uses the variation of pressure of a gas with temperature. Usually air is used as a gas. For better accuracy other gases like helium that tend to have very low melting points close to absolute zero are used.

Advantages:

1. It is very accurate. In fact its accuracy allows it to be utilized to calibrate other thermometers.



Disadvantages:

1. It is not easy to handle and read.
2. It tends to be highly sensitive to temperature change, and mechanical vibrations. In fact to give a reading it usually entails a lot of time.
3. Expensive to manufacture and keep

Unknown temperature is found according to the relation:

$$t = \left(\frac{p_t - p_0}{p_{100} - p_0} \right) \times 100$$

EX 1 Calculate the temperature of an object where its value is measured by a Fahrenheit temperature equal to twice its value measured by a centigrade, then calculate the temperature at which the readings are equal

Solution:

$$C = (F - 32)5/9$$

And F=2C, then

$C=160^0$ c

And F=C

F= -40 f

Ex2 Platinum thermometer Its resistance at the ice melting point is 6.5 ohm and at boiling water point of water 11.5 ohm Find the temperature when the resistance is 14 ohm and then calculate the resistance of the thermometer at 60 ° C

Solution:

$$t = \left(\frac{R_t - R_0}{R_{100} - R_0} \right) \times 100$$

$$= \left(\frac{14-6.5}{11.5-6.5}\right).\times 100$$
$$= 150$$

$$60 = \left(\frac{R_t - 6.5}{11.5-6.5}\right)\times 100$$

$$R_t = 9.5 \quad \text{ohm}$$

Ex3 Using the thermometer gas thermometer for the measurement of the temperature of the chamber, the gas pressures were 80cm, 109.3cm at temperature 0 C ^{0}, 100C ^{0} ,respectively. If the pressure is 83cm at room temperature and 100cm in hot water. Find a hot degree both from the room and hot water

Solution

$$t = \left(\frac{p_t - p_0}{p_{100} - p_0}\right)\times 100$$

$$= \left(\frac{83-80}{109.3-80}\right)\times 100$$
$$= 10.239\,\text{C}$$

$$= \left(\frac{100-80}{109.3-80}\right)\times 100$$
$$68.26\,\text{C}$$

Ex

1- if the length of the mercury column in the thermometer's leg at freezing and boiling point, respectively is 15 and 25 cm, calculate the temperature at which the length of the column is equal to 22 cm.

2. Platinum thermometer resistances at 0 ° C and water boiling point respectively are 200 and 400 ohm Calculate the temperature that makes it resist 300 ohm

Chapter 1
Wave motion

Types of motion

Wave motion transfers energy from one point to another, usually without permanent displacement of the particles of the medium.

wave :A moving disturbance in the energy level of a field.

Periodic Motion

motion of the hands of a clock, motion of the wheels of a car and motion of a planet around the sun? They all are repetitive in nature, that is, they repeat their motion after equal intervals of time. A motion which repeats itself in equal intervals of time is periodic.

A body starts from its equilibrium position (at rest) and completes a set of movements after which it will return to its equilibrium position. This set of movements repeats itself in equal intervals of time to perform the periodic motion.

Circular motion is an example of periodic motion. Very often the equilibrium position of the body is in the path itself. When the body is at this position, no external force is acting on it. Therefore, if it is left at rest, it remains at rest.

We know that motion which repeats itself after equal intervals of time is periodic motion. The time interval after which the motion repeats itself is called time period (T) of periodic motion. Its S.I. unit is second.

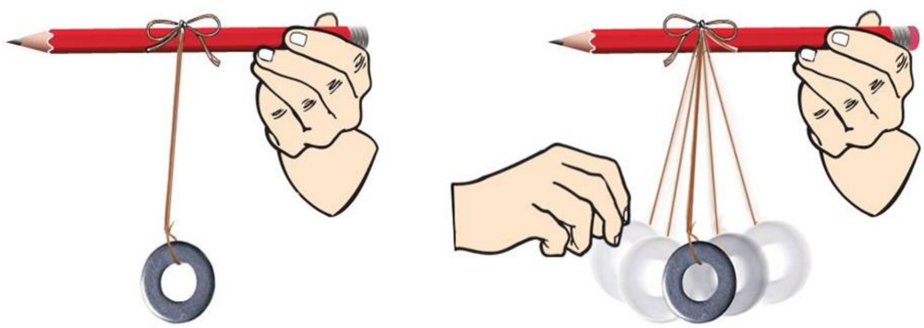
The reciprocal of T gives the number of repetitions per unit time. This quantity is the frequency of periodic motion. The symbol υ represents frequency. Therefore, the relation between υ and T is

$$\upsilon = 1/T$$

Thus, the unit of υ is s^{-1} or hertz(after the scientist Heinrich Rudolf Hertz). Its abbreviation is Hz. Thus, 1 hertz = 1 Hz = 1 oscillation per second = 1 s-1 The frequency of periodic motion may not be an integer. It can be a fraction.

Oscillatory Motion

Everybody at rest is in its equilibrium position. At this position, no external force is acting on it. Therefore, the net force acting on the body is zero. Now, if this body is displaced a little from its equilibrium position, a force acts on the body which tries to bring back the body to its equilibrium position. This force is the restoring force and it gives rise to oscillations or vibrations.



For example, consider a ball that is placed in a bowl. It will be in its equilibrium position. If displaced a little from this position, it will perform oscillations in the bowl. Therefore, every oscillatory motion is periodic, but all periodic motions are not oscillatory. Circular motion is a periodic motion but

not oscillatory motion.
There is no significant difference between oscillations and vibrations. When the frequency is low, we call it oscillatory motion and when the frequency is high, we call it vibrations. Simple harmonic motion is the simplest form of oscillatory motion. This motion takes place when the restoring force acting on the body is directly proportional to its displacement from its equilibrium position.
In practice, Oscillatory motion eventually comes to rest due to damping or frictional forces. However, we can force them by means of some external forces. A number of oscillatory motions together form waves like electromagnetic waves.

Displacement in Oscillatory Motion

Displacement of a particle is a change in its position vector. In an oscillatory motion, it simply displacement means a change in any physical property with time.
Consider a block attaches to a spring, which in turn is fixed to a rigid wall. We measure the displacement of the block from its equilibrium position. In an oscillatory motion, we can represent the displacement by a mathematical function of time. One of the simplest periodic functions is given by,

$$f(t) = A\cos\omega t$$

If the argument, ωt, is increased by an integral multiple of 2π radians, the value of the function remains the same. Therefore, it is periodic in nature and its period T is given by,

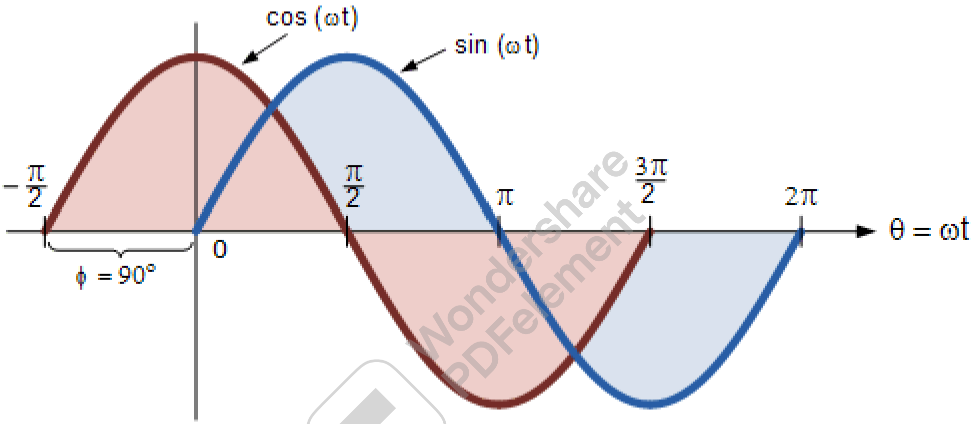
$$T = 2\pi/\omega$$

Thus, the function f(t) is periodic with period T.

$$\therefore f(t) = f(t + T).$$

Now, if we consider a sine function, the result will be the same. Further, taking a linear combination of sine and cosine functions is also a periodic function with period T.

$$f(t) = A\sin\omega t + B\cos\omega t$$



Taking

A = DcosØ and B = DsinØ equation V becomes,

$$f(t) = D\sin(\omega t + \emptyset)$$

In this equation D and Ø are constant and they are given by,

$$D = \sqrt{}A^2 + B^2 \text{ and } \emptyset = \tan^{-2}(B/A)$$

Therefore, we can express any periodic function as a superposition of sine and cosine functions of different time periods with suitable coefficients. The period of the function is 2π/ω.

Quiz

- Calculate the frequency and angular frequency of:
  - A pendulum of period 4s
  - A water wave of period 12s
  - Mains electricity of period 0.02s
  - Laser light with period 1.5 fs

Difference Between Periodic and Oscillatory Motion

The main difference is that oscillatory motion is always periodic, but a periodic motion may or may not be oscillatory motion. For example, the motion of a pendulum is both oscillatory motion and periodic motion but the motion of the wheels of a car is only periodic because the wheels rotate in a circular motion. Circular motion is only periodic motion and not oscillatory motion. The wheels do not move to and fro about a mean position.

Quiz

In periodic motion, the displacement is.

a) directly proportional to the restoring force.

b) inversely proportional to the restoring force.

c) independent of restoring force.

d) none of them.

Solution:

a) directly proportional to the restoring force. The displacement of the body from its equilibrium is directly proportional to the restoring force. Therefore, higher the displacement, higher is the restoring force.

Simple Harmonic Motion

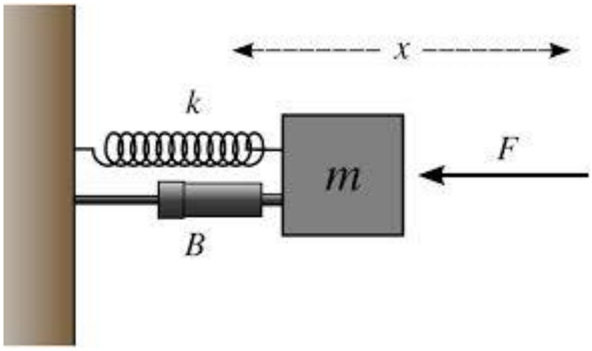
We see different kinds of motion every day. The motion of the hands of a clock, motion of the wheels of a car, etc. Did you ever notice that these types of motion keep repeating themselves? Such motions are periodic in nature. One such type of periodic motion is simple harmonic motion (S.H.M.). But what is S.H.M.? Let's find out.

Simple Harmonic Motion (S.H.M.)

When an object moves to and fro along a line, the motion is called simple harmonic motion. Have you seen a pendulum? When we swing it, it moves to and fro along the same line. These are called oscillations. Oscillations of a pendulum are an example of simple harmonic motion.

Now, consider there is a spring that is fixed at one end. When there is no force applied to it, it is at its equilibrium position. Now,

- If we pull it outwards, there is a force exerted by the string that is directed towards the equilibrium position.
- If we push the spring inwards, there is a force exerted by the string towards the equilibrium position.



In each case, we can see that the force exerted by the spring is towards the equilibrium position. This force is called the restoring force. Let the force be F and the displacement of the string from the equilibrium position be x.

Therefore, the restoring force is given by, F= – kx (the negative sign indicates that the force is in opposite direction). Here, k is the constant called the force constant. Its unit is N/m in S.I. system and dynes/cm in C.G.S. system.

Linear Simple Harmonic Motion

Linear simple harmonic motion is defined as the linear periodic motion of a body in which the restoring force is always directed towards the equilibrium position or mean position and its magnitude is directly proportional to the displacement from the equilibrium position. All simple harmonic motions are periodic in nature, but all periodic motions are not simple harmonic motions.

Now, take the previous example of the string. Let its mass be m. The acceleration of the body is given by,

$$a = F/m = -kx/m = -\omega^2 x$$

Here, $k/m = \omega^2$ (ω is the angular frequency of the body)

Concepts of Simple Harmonic Motion (S.H.M)

- **Amplitude**: The maximum displacement of a particle from its equilibrium position or mean position is its amplitude. Its S.I. unit is the metre. The dimensions are $[L^1M^0 T^0]$. Its direction is always away from the mean or equilibrium position.
- **Period**: The time taken by a particle to complete one oscillation is its period. Therefore, period if S.H.M. is the least time after which the motion will repeat itself. Thus, the motion will repeat itself after nT. where n is an integer.
- **Frequency**: Frequency of S.H.M. is the number of oscillations that a particle performs per unit time. S.I. unit of frequency is hertz or r.p.s (rotations per second). Its dimensions are $[L^0M^0T^{-1}]$.
- **Phase**: Phase of S.H.M. is its state of oscillation. Magnitude and direction of displacement of particle represent the phase.

Note: The period of simple harmonic motion *does not* depend on amplitude or energy or the phase constant.

Difference between Periodic and Simple Harmonic Motion

Periodic Motion	**Simple Harmonic Motion**
In the periodic motion, the	In the simple harmonic motion,

displacement of the object may or may not be in the direction of the restoring force.	the displacement of the object is always in the opposite direction of the restoring force.
The periodic motion may or may not be oscillatory.	Simple harmonic motion is always oscillatory.
Examples are the motion of the hands of a clock, the motion of the wheels of a car, etc.	Examples are the motion of a pendulum, motion of a spring, etc.

Velocity and Acceleration in Simple Harmonic Motion

A motion is said to be accelerated when its velocity keeps changing. But in simple harmonic motion, the particle performs the same motion again and again over a period of time. Do you think it is accelerated? Let’s find out and learn how to calculate the acceleration and velocity of SHM.

Acceleration in SHM

We know what acceleration is. It is velocity per unit time. We can calculate the acceleration of a particle performing S.H.M. Lets learn how. The differential equation of linear S.H.M. is $d^2x/dt^2 + (k/m)x = 0$ where d^2x/dt^2 is the acceleration of the particle, x is the displacement of the particle, m is the mass of the particle and k is the force constant. We know that $k/m = \omega^2$ where ω is the angular frequency.

Therefore, $d^2x/dt^2 + \omega^2 x = 0$

Hence, acceleration of S.H.M. = $d^2x/dt^2 = -\omega^2 x$

The negative sign indicated that acceleration and displacement are in opposite direction of each other. Equation I is the expression of acceleration of S.H.M. Practically, the motion of a particle performing S.H.M. is accelerated because its velocity keeps changing either by a constant number or varied number.

Take a simple pendulum for example. When we swing a pendulum, it moves to and fro about its mean position. But after some time, it eventually stops and returns to its mean position. This type of simple harmonic motion in which velocity or amplitude keeps changing is damped simple harmonic motion.

Velocity in SHM

Velocity is distance per unit time. We can obtain the expression for velocity using the expression for acceleration. Let's see how. Acceleration $d^2x/dt^2 = dv/dt = dv/dx \times dx/dt$.

But dx/dt = velocity 'v'

Therefore, acceleration = $v(dv/dx)$

When we substitute equation II in equation I, we get, $v(dv/dx) = -\omega^2 x$.

$$\therefore vdv = -\omega^2 xdx$$

After integrating both sides, we get,

$$\int v dv = \int -\omega^2 x dx = -\omega^2 \int x dx$$

Hence, $v^2/2 = -\omega^2 x^2/2 + C$ where C is the constant of integration. Now, to find the vaue of C, lets consider boundary value condition. When a particle performing SHM is at the extreme position, displacement of the particle is maximum and velocity is zero. (a is the amplitude of SHM)

Therefore, At $x = \pm a$, $v = 0$

And $0 = -\omega^2 a^2/2 + C$

Hence, $C = \omega^2 a^2/2$

Let's substitute this value of C in equation $v^2/2 = -\omega^2 x^2/2 + C$

$$\therefore v^2/2 = -\omega^2 x^2/2 + \omega^2 a^2/2$$

$$\therefore v^2 = \omega^2 (a^2 - x^2)$$

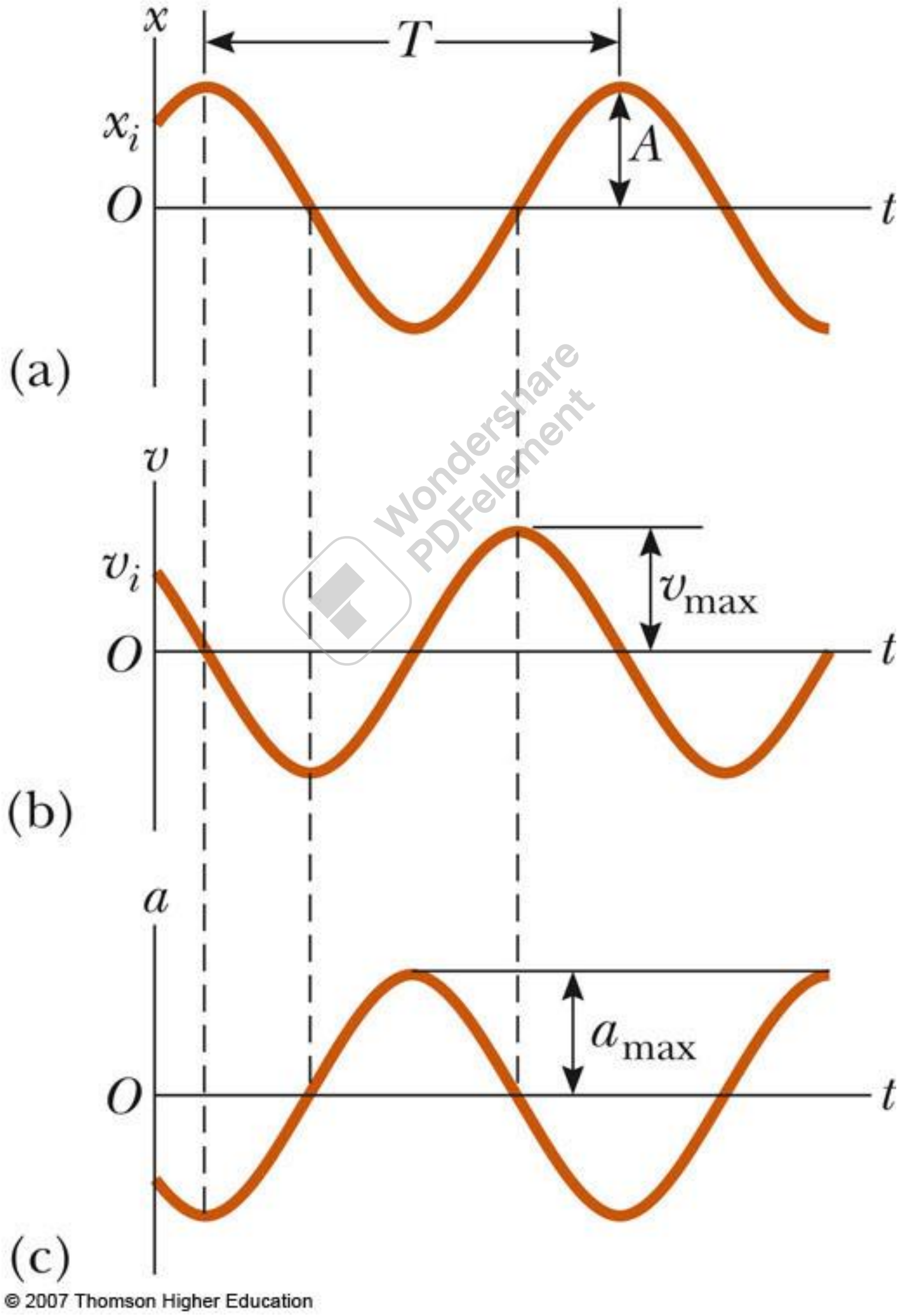
Taking square root on both sides, we get,

$$v = \pm \omega \sqrt{(a^2 - x^2)}$$

This equation is the expression of the velocity of S.H.M. The double sign indicates that when a particle passes through a given point in the positive direction of *x*, v is positive, and when it passes through the same point in opposite direction of *x*, v is negative.

Maximum and Minimum velocity

We know the velocity of a particle performing S.H.M. is given by, $v = \pm \omega \sqrt{a^2 - x^2}$. At mean position, $x = 0$. Therefore, $v = \pm \omega \sqrt{a^2 - 0^2} = \pm \omega \sqrt{a^2} = \pm a\omega$. Therefore, at mean position, velocity of the particle performing S.H.M. is maximum which is $V_{max} = \pm a\omega$. At extreme position, $x = \pm a$ Therefore, $v = \pm \omega \sqrt{a^2 - a^2} = \omega \times 0 = 0$. Therefore, at extreme position, velocity of the particle performing S.H.M. is minimum which is $V_{min} = 0$



Solved Examples For You

Q: What is the value of acceleration at the mean position?

Solution: At mean position, x =0

∴ acceleration = $-\omega^2 x = -\omega^2 \times 0 = 0$. Therefore, the value of acceleration at the mean position is minimum and it is zero.

Quiz

- A body oscillates with shm decribed by:
  - x=1.6cos3πt
- What are the amplitude and period of the motion
- At t=1.5s, calculate the displacement, velocity and acceleration.

- The needle of a sewing machine moves up and down with shm. If the total vertical motion of the needle is 12mm and it makes 30 stitches in 7.0s calculate:
  - The period,
  - The amplitude,
  - The maximum speed of the needle tip
  - The maximum acceleration of the needle tip.

Energy in Simple Harmonic Motion

Each and every object possesses energy, either while moving or at rest. In the simple harmonic motion, the object moves to and fro along the same path. Do you think an object possesses energy while travelling the same path again and again? Yes, it is energy in simple harmonic motion. Let's learn how to calculate this energy and understand its properties.

Energy in Simple Harmonic Motion

The total energy that a particle possesses while performing simple harmonic motion is energy in simple harmonic motion. Take a pendulum for example. When it is at its mean position, it is at rest. When it moves towards its extreme position, it is in motion and as soon as it reaches its extreme position, it comes to rest again. Therefore, in order to calculate the energy in simple harmonic motion, we need to calculate the kinetic and potential energy that the particle possesses.

Kinetic Energy (K.E.) in S.H.M

Kinetic energy is the energy possessed by an object when it is in motion. Let's learn how to calculate the kinetic energy of an object. Consider a particle with mass *m* performing simple harmonic motion along a path AB. Let O be its mean position. Therefore, OA = OB = a.

The instantaneous velocity of the particle performing S.H.M. at a distance x from the mean position is given by

$$v = \pm\omega \sqrt{a^2 - x^2}$$

$$\therefore\ v^2 = \omega^2 (a^2 - x^2)$$

$\therefore$ Kinetic energy= $1/2\ mv^2 = 1/2\ m\,\omega^2 (a^2 - x^2)$

$$\text{As, } k/m = \omega^2$$

$$\therefore k = m\,\omega^2$$

Kinetic energy= 1/2 k ($a^2 - x^2$) . The equations Ia and Ib can both be used for calculating the kinetic energy of the particle.

Potential Energy (P.E.) of Particle Performing S.H.M.

Potential energy is the energy possessed by the particle when it is at rest. Let's learn how to calculate the potential energy of a particle performing S.H.M. Consider a particle of mass *m* performing simple harmonic motion at a distance x from its mean position. You know the restoring force acting on the particle is F= -kx where k is the force constant.

Now, the particle is given further infinitesimal displacement dx against the restoring force F. Let the work done to displace the particle be dw. Therefore, the work done dw during the displacement is

$$dw = -\,fdx = -\,(-\,kx)dx = kxdx$$

Therefore, the total work done to displace the particle now from 0 to x is

$$\int dw = \int kxdx = k \int x\,dx$$

Hence Total work done = 1/2 K x^2 = 1/2 m $\omega^2 x^2$

The total work done here is stored in the form of potential energy.

Therefore, Potential energy = 1/2 kx^2 = 1/2 m $\omega^2 x^2$

Equations IIa and IIb are equations of potential energy of the particle. Thus, potential energy is directly proportional to the square of the displacement, that is P.E. α x^2.

Total Energy in Simple Harmonic Motion (T.E.)

The total energy in simple harmonic motion is the sum of its potential energy and kinetic energy.

Thus,

$$T.E. = K.E. + P.E. = 1/2\ k\,(a^2 - x^2) + 1/2\ K\,x^2 = 1/2\ k\,a^2$$

Hence, $T.E. = E = 1/2\ m\,\omega^2 a^2$

Equation III is the equation of total energy in a simple harmonic motion of a particle performing the simple harmonic motion. As ω^2, a^2 are constants, the total energy in the simple harmonic motion of a particle performing simple harmonic motion remains constant. Therefore, it is independent of displacement x.

$$\text{As } \omega = 2\pi f,\ E = 1/2\ m\,(2\pi f)^2 a^2$$

$$\therefore E = 2m\pi^2 f^2 a^2$$

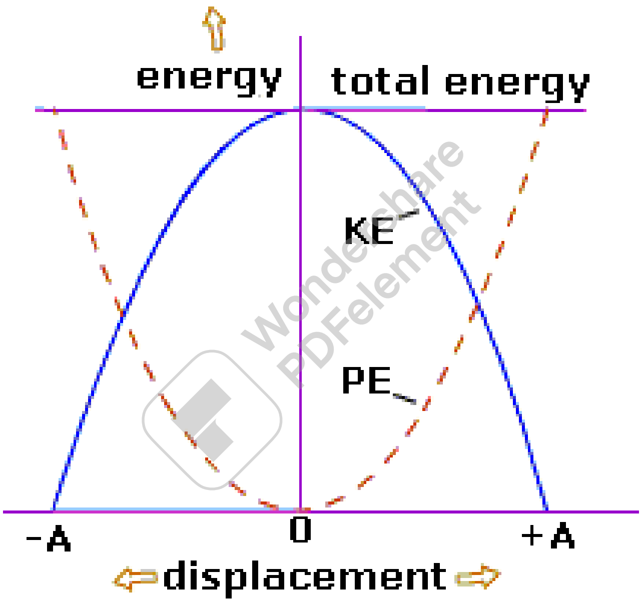
As 2 and π^2 constants, we have T.E. $\sim$ m, T.E. $\sim$ f^2, and T.E. $\sim$ a^2

Thus, the total energy in the simple harmonic motion of a particle is:

- Directly proportional to its mass
- Directly proportional to the square of the frequency of oscillations and

- Directly proportional to the square of the amplitude of oscillation.

The law of conservation of energy states that energy can neither be created nor destroyed. Therefore, the total energy in simple harmonic motion will always be constant. However, kinetic energy and potential energy are interchangeable. Given below is the graph of kinetic and potential energy vs instantaneous displacement.



In the graph, we can see that,

- At the mean position, the total energy in simple harmonic motion is purely kinetic and at the extreme position, the total energy in simple harmonic motion is purely potential energy.
- At other positions, kinetic and potential energies are interconvertible, and their sum is equal to 1/2 k a^2.
- The nature of the graph is parabolic.

Here's a Solved Question for You

Q: At the mean position, the total energy in simple harmonic motion is _________

a) purely kinetic b) purely potential c) zero d) None of the above

Answer: a) purely kinetic. At the mean position, the velocity of the particle in S.H.M. is maximum and displacement is minimum, that is, x=0. Therefore, P.E. $=1/2\ K\ x^2 = 0$ and K.E. $= 1/2\ k\ (a^2 - x^2) = 1/2\ k\ (a^2 - o^2) = 1/2\ ka^2$. Thus, the total energy in simple harmonic motion is purely kinetic.

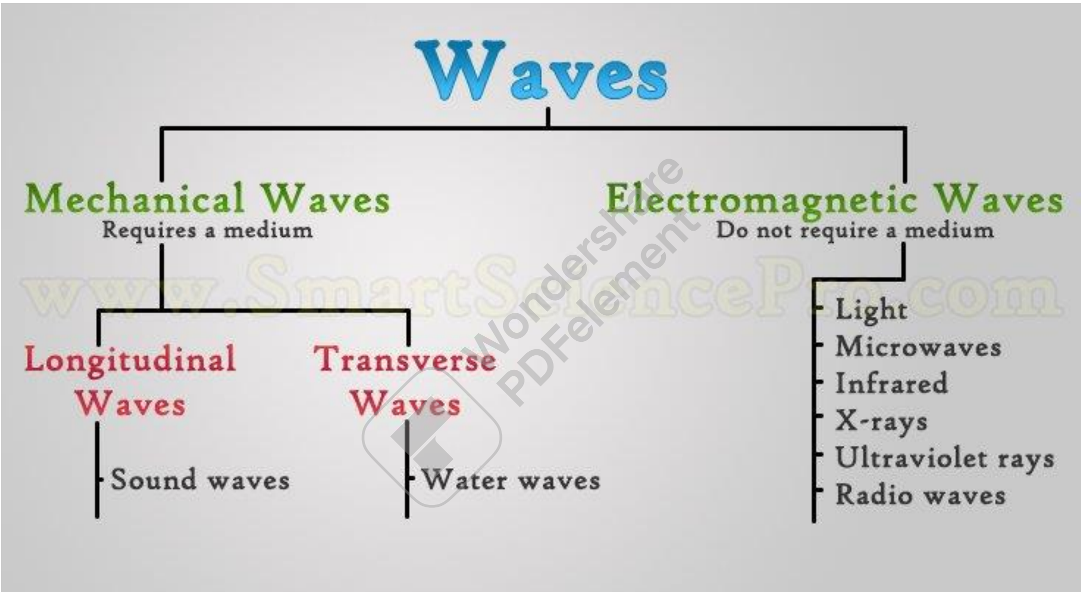
Quiz

- A pendulum of mass 250g is released from its maximum displacement and swings with shm. If the period is 4s and the amplitude of the swing is 30cm, calculate:
  - The frequency of the pendulum
  - The maximum speed of the pendulum
  - The total energy of the pendulum
  - The maximum height of the pendulum bob.
  - The energies of the pendulum at t=0.2s.

Types of Waves

Have you ever observed water in a lake or pond? The pattern of waves that generate after a disturbance occurs in the water body, what do you call it? In this case, water waves are in the visible form; however, there are sound waves, radio waves etc., which aren't visible, but they exist! Yes, waves are always around us and are present in a variety of forms. Hence, in order to understand the importance and the types of waves, the following content is quite resourceful. Let us scroll down.

There is two main types of waves mechanical waves and electromagnetic waves.



1- Mechanical waves such as sound waves required medium in order to transport their energy from one location to another. Because mechanical waves rely on particle interaction in order to transport their energy, they cannot travel through regions of space, which are void of particles.

<u>There are two types of mechanical waves:</u>

- ✓Transverse Wave
- ✓Longitudinal Wave

Transverse wave, which is a series of disturbances traveling through a medium in which particles of the medium vibrate in paths that are **perpendicular** to the direction of motion of the disturbances of the wave.

Transverse waves are made up of **crests** and **troughs**.
The crest is the portion of a transverse wave that lies above the horizontal time axis. The axis line is referred to as the rest or equilibrium point.
The trough is the portion that lies below the axis line.

A wavelength in a transverse wave is the distance from the beginning of the crest to the end of an adjacent trough. It also described as the distance from the point of maximum displacement in one crest to the point of maximum displacement in the next closest crest. **λ** is the symbol for wavelength.

Longitudinal wave, which is a series of disturbances traveling through a medium in which the particles vibrate in paths **parallel** to the directions the disturbances of the wave are traveling. Longitudinal waves are waves in which the motion of the medium is in the same direction as the motion of the wave.

A longitudinal wave consists of **compression** and **rarefaction**.
Compression is the part of the longitudinal wave where the particles of the medium are pushed closer together.

Rarefaction is that part of the longitudinal wave where the particles of the wave are spread apart.

The wavelength (λ) in a longitudinal wave is the distance between two consecutive points that are in phase.

2- Electromagnetic Waves

Under electromagnetic waves, the presence of medium isn't actually necessary for propagation. In this type of waves, the periodic changes occur in electric and magnetic fields; therefore, it is termed as Electromagnetic Wave.

Properties of Electromagnetic Waves:

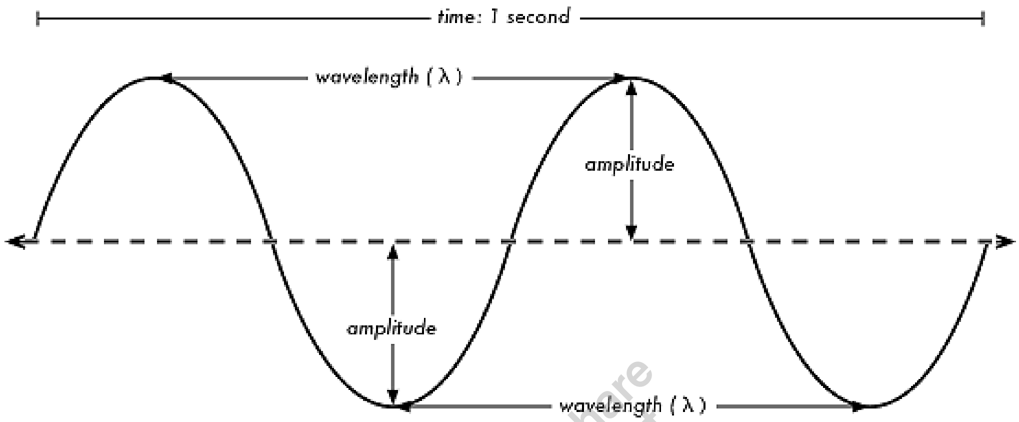
- ✓In a vacuum, electromagnetic waves travel with the speed of light.
- ✓These waves can be polarized.
- ✓They tend to have a transverse nature.
- ✓There is no need for a medium to propagate E.M waves.
- ✓Momentum is present in E.M waves.

Examples: Light waves, Radio waves, thermal radiation etc.

The main properties of waves

- **Amplitude:** the height of the wave, measured in meters.
- **Wavelength:** the distance between two consecutive points that are in phase, measured in meters.
- **Period:** the time it takes for one complete wave to pass a given point, measured in seconds.

- **Frequency:** the number of complete waves that pass a point in one second, measured in inverse seconds, or Hertz (Hz).
- **Speed:** the horizontal speed of a point on a wave as it propagates, measured in meters / second.

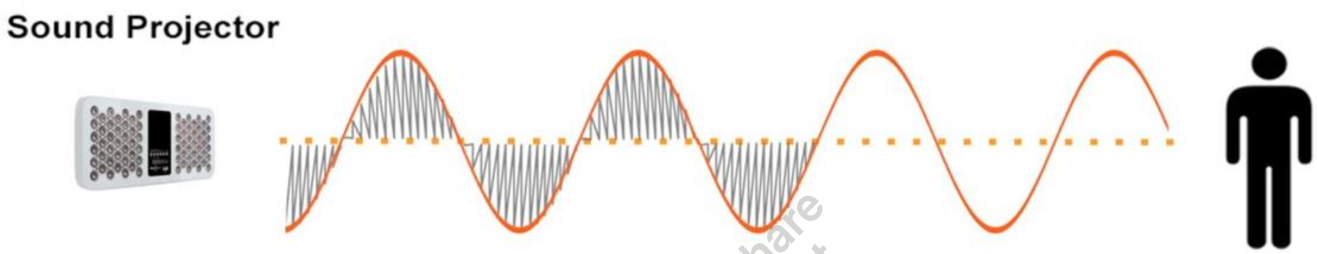


Chapter 2
Sound waves

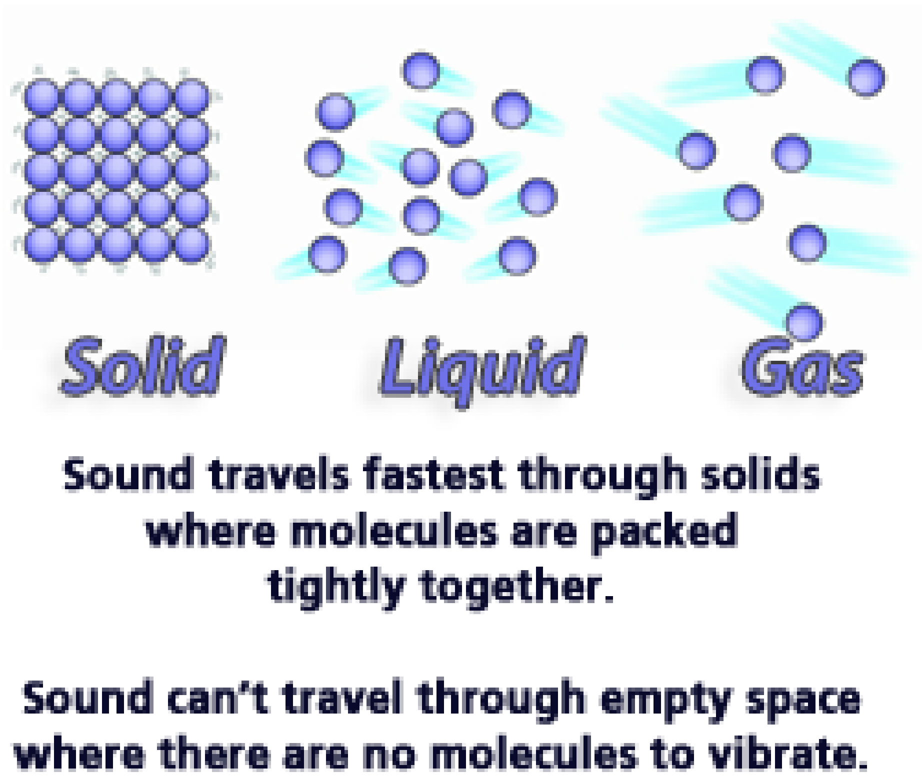
What is Sound?

Definitions

1- **Sound is a form of energy**. It can be generated, moved, can do work, can dissipate over time and distance, and can carry tremendous amounts of energy. Sound will continue only as long as there is energy in the system to keep it going.



2- Sound is defined as **something that can be heard**. It is a wave that is a series of vibrations traveling through a medium, especially those within the range of frequencies that can be perceived by the human ear. Sound can travel through many types of mediums, for example: **gasses**, **liquids** and **solids**. The compressions and rarefactions that move through the atmosphere are compressing and stretching the molecules of nitrogen and oxygen all around us. Sound cannot be heard in a vacuum, like outer space.

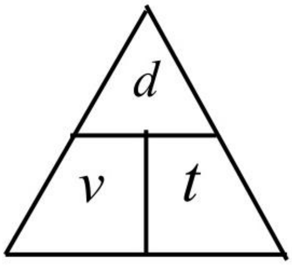


Sound is not thought of as **a transverse wave** because of the behavior of the particles in the medium.
Sound can be thought of as **a longitudinal wave** because of the vibrations of the particles of the medium.

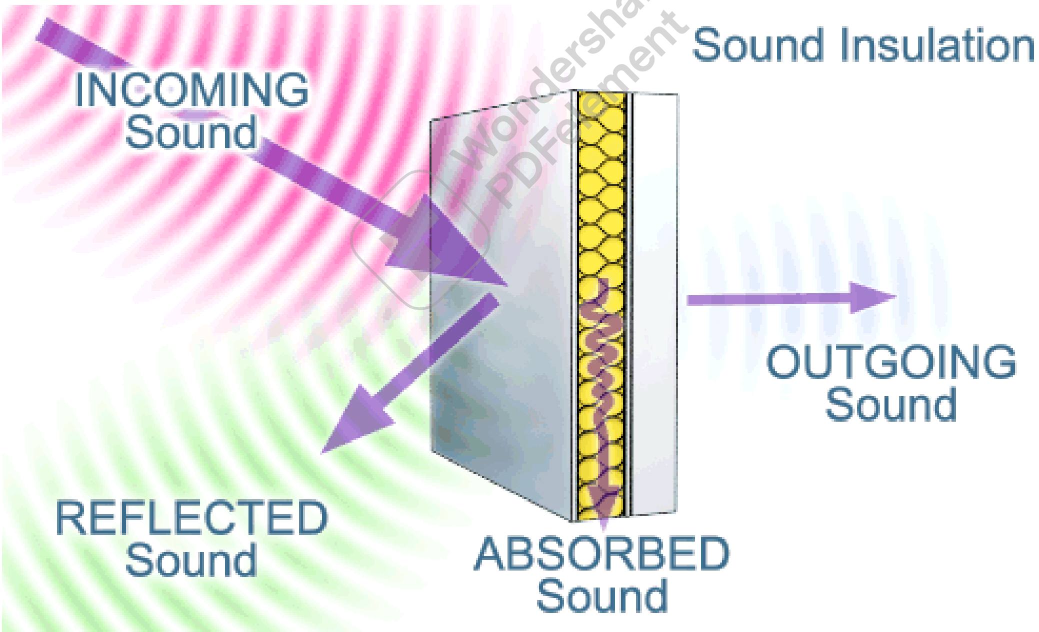
Characteristics of Sound

- Sound can propagate through a medium such as air, water and solids as longitudinal waves and also as a transverse wave in solids.
- The sound waves are generated by a sound source, such as the vibrating diaphragm of a stereo speaker. The sound source creates vibrations in the surrounding medium. As the source continues to vibrate the medium, the vibrations propagate away from the source at the speed of sound, thus forming the sound wave.

- At a fixed distance from the source, the pressure, velocity, and displacement of the medium vary in time.
- At an instant in time, the pressure, velocity, and displacement vary in space.



- During propagation, waves can be reflected, refracted, or attenuated by the medium.

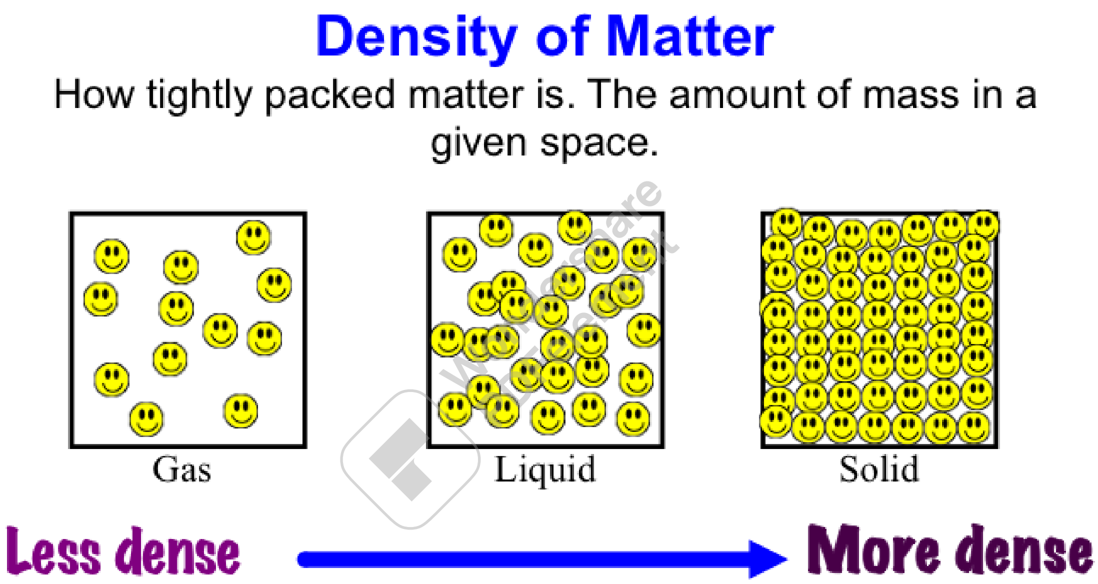


Note that:
The particles of the medium do not travel with the sound wave. This is naturally obvious for a solid, and the same is true for liquids and gases (that is, the vibrations of particles

in the gas or liquid transport the vibrations, while the average position of the particles over time does not change).

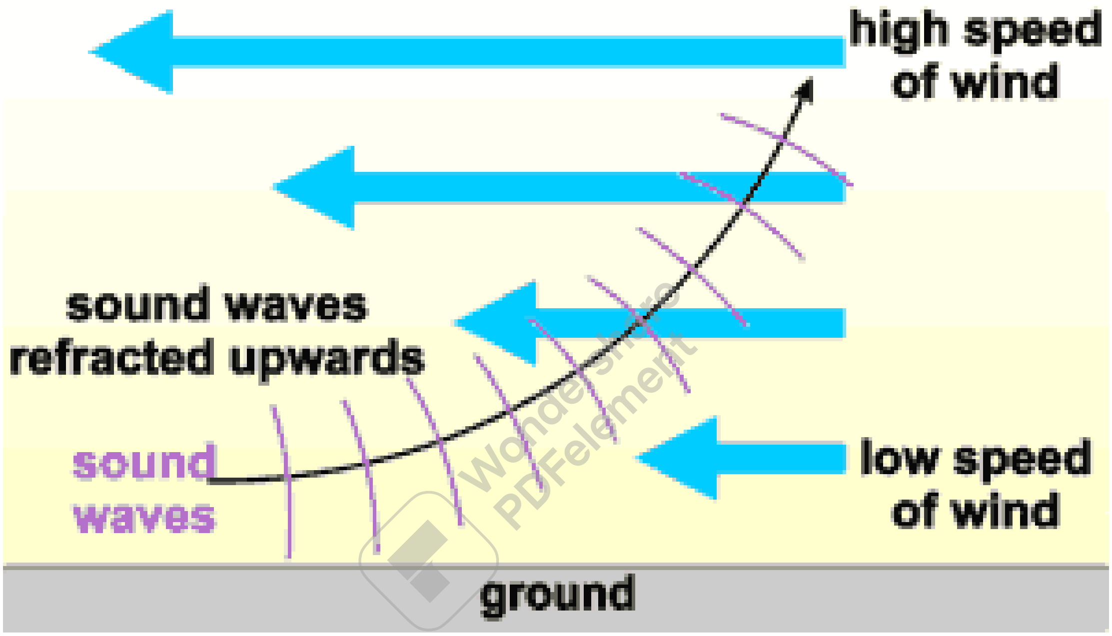
<u>The behavior of sound propagation is generally affected by three things:</u>

1- A complex relationship between the density and pressure of the medium. This relationship, affected by temperature, determines the speed of sound within the medium.



2- Motion of the medium itself. If the medium is moving, this movement may increase or decrease the absolute speed of the sound wave depending on the direction of the movement.

For example, sound moving through wind will have its speed of propagation increased by the speed of the wind if the sound and wind are moving in the same direction. If the sound and wind are moving in opposite directions, the speed of the sound wave will be decreased by the speed of the wind.



3- The viscosity of the medium. Medium viscosity determines the rate at which sound is attenuated. For many media, such as air or water, attenuation due to viscosity is negligible.

Sound units

1. **The Decibel Scale**

Decibel (dB), unit for expressing the ratio between two physical quantities, usually amounts of acoustic or electric power, or for measuring the relative loudness of sounds.

When sound travels through an elastic medium, particles vibrate with variations in pressure amplitude reflected by the wave displacement of compression and rarefaction. The intensity of sound reflects the transmitted power per unit area and is roughly equivalent to the square of the pressure amplitude.

$$\text{Intensity} \sim \text{Pressure}^2$$

As the pressure amplitude doubles, the absolute intensity value increases by four times. The units of absolute intensity level are watts/m^2. Relative sound intensity is measured on the logarithmic scale with decibels (dB) where

$$\text{Relative Intensity (dB)} = 10\log_{10} I/I_o$$

I is the newly measured intensity, while I_o is the original signal intensity which functions as a reference.

2- **Sone** - a unit of perceived loudness equal to the loudness of a 1000-hertz tone at 40 dB above threshold, starting with 1 sone.

3- **Phon** - a unit of subjective loudness.

4- **Hz, hertz** = unit of sound frequency is called hertz (Hz)

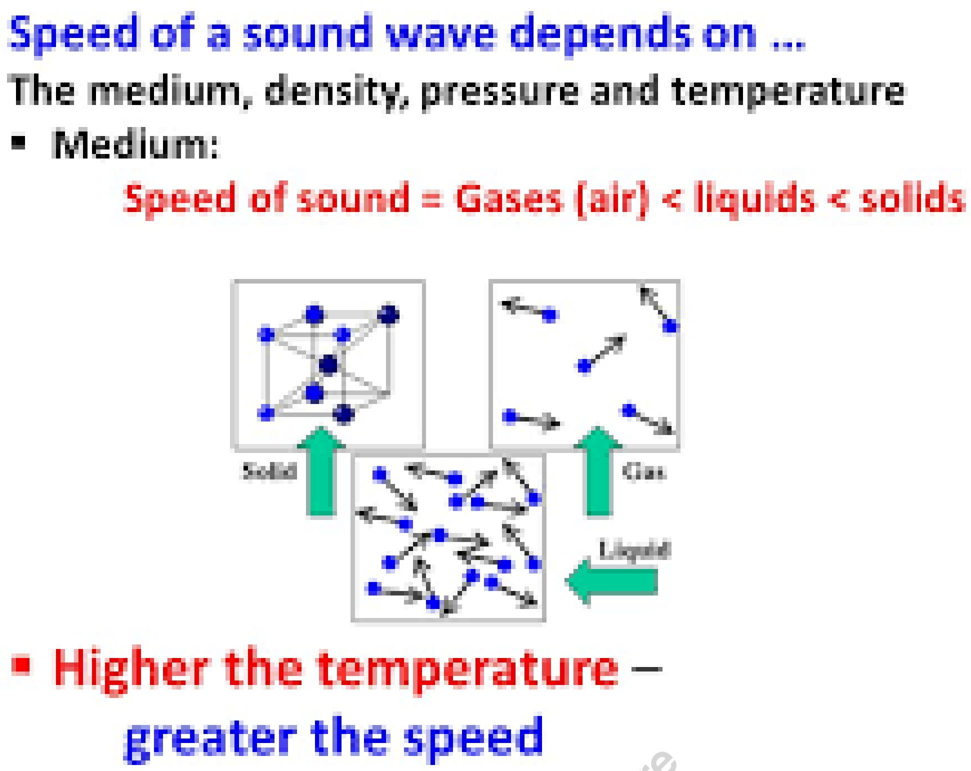
Speed of Sound

The speed of a sound wave in air depends upon the properties of the air, namely the **temperature** and the **pressure**.

The pressure of air, like any gas, will affect the mass density of the air and the temperature will affect the strength of the particle interactions.

The sound waves are in a 3D circular pattern from the origin of the sound because the speed of the wave disturbances is constant. **The speed of sound is about 331.5 m/s at 0° C or 1087 ft/s at 32° F, which translates to 740 mi/hr.**

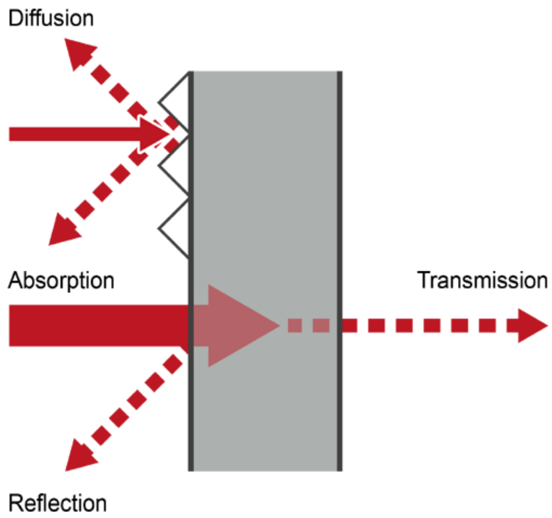
- Sound waves will travel faster in solids than they will in liquids and travel faster in liquids than they do in gases. A sound wave will travel faster in a less dense material than in a denser material. An example is: a sound wave will travel nearly three times faster in Helium as it will in air, which is mostly due to the lower mass of Helium particles as compared to air particles.
- The speed of sound is constant at a given temperature and is constant in each medium.
- The speed of sound changes with temperature changes. In air at 0° C the speed is about 331.5 m/s and increases about 0.60 m/s for every degree C increase in temperature. At 32° F the speed is about 1087 ft/s and increases 1.1 ft/s for every degree F increase in temperature.



- Sound travels faster in warmer temperatures than colder temperatures. The wavelength in warmer temperatures is slightly longer than at freezing temperatures. The frequency, or rate at which the waves pass a given point, of the sound does not change due to a change in temperature that is determined by the frequency at the source of the sound. Sound travels slower in higher layers of the atmosphere than it does just above the surface of the ocean and land.

Sound Waves and Matter

Like all wave forms, sound waves can be either absorbed, transmitted, or reflected when they encounter a different type of matter.



Absorption

Absorption is the process whereby the sound's energy is quickly dissipated by being transformed into other forms of energy. Absorption of sound is very important for engineers who design *sound-proof* rooms. These rooms have walls made of a material that can absorb sound energy.

Transmission

Transmission is the passing of sound energy from one medium to another at a medium boundary. Some of the sound energy may be absorbed in the process. Transmission causes a change in the wavelength of a wave because the sound either speeds up or slows down as it passes into the new medium.

The relationship between the speed of sound, *v*, the wavelength, , and the frequency, *f*, of a sound wave as it is transmitted between two mediums.

Since v_1 f_1 and v_2 f_2,

$$\frac{v_1}{v_2} = \frac{f\lambda_1}{f\lambda_2} = \frac{\lambda_1}{\lambda_2}$$

The change in **wavelength** is directly proportional to the change in **speed**. Longitudinal sound waves moving from a slower to a faster medium behave much like hockey players stepping off the floor onto the ice. As their speed (v) increases, the distance between them (λ) also increases, but the frequency (f) with which they pass any point remains the same.

Example:

A sound wave of wavelength 0.750 m is travelling in air at 0.0°C when it hits a block of steel at the same temperature. What is the wavelength of the sound wave in steel if the speed of sound in steel is 5050 m/s?

Solution and Connection to Theory

Given

$\lambda_{sound} = 0.750$ m $\quad T = 0.0°C \quad v_{steel} = 5050$ m/s $\quad \lambda_{steel} = ?$

Rearrange the equation

$$\frac{\lambda_{sound}}{\lambda_{steel}} = \frac{v_{sound}}{v_{steel}}$$

for λ_{steel}, then substitute and solve.

$$\lambda_{steel} = \lambda_{sound}\left(\frac{v_{steel}}{v_{sound}}\right)$$

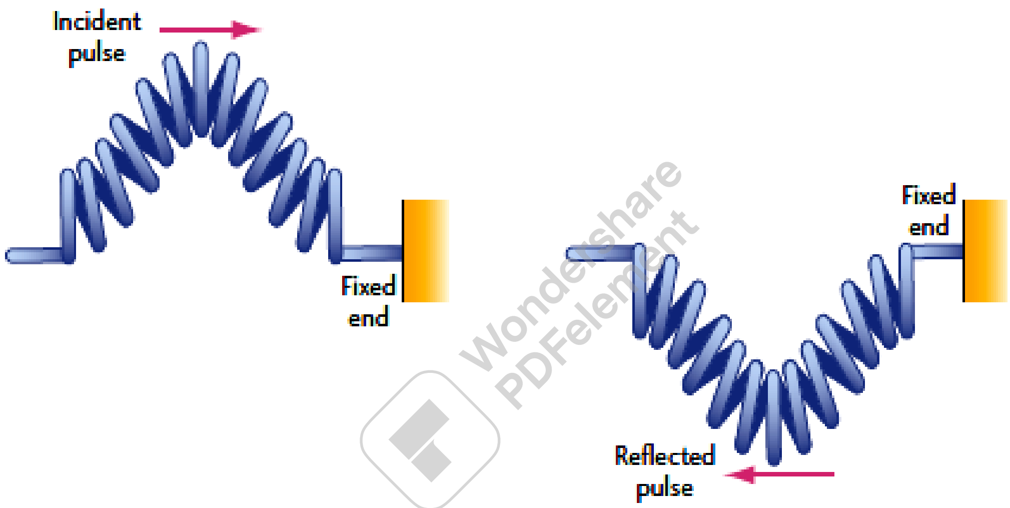
$$\lambda_{steel} = 0.750 \text{ m} \frac{(5050 \text{ m/s})}{(332 \text{ m/s})}$$

$$\lambda_{steel} = 11.4 \text{ m}$$

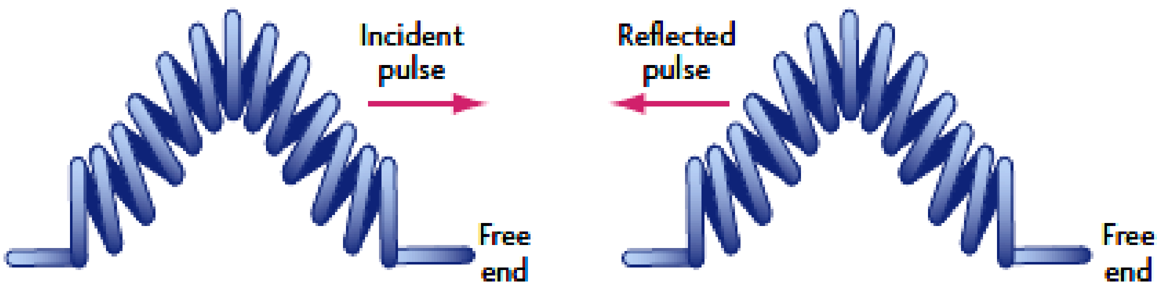
Therefore, the wavelength of sound in steel is 11.4 m.

Reflection

Sound can be absorbed or transmitted as it meets another medium, but it can also have its energy turned back onto itself in the process of **reflection.** In reflection, the wavelength of the returning wave is not altered because there is no change in speed. However, when a sound wave is reflected at a solid boundary, the reflected wave pulse has its **phase shifted by ½ λ** because its amplitude is inverted.



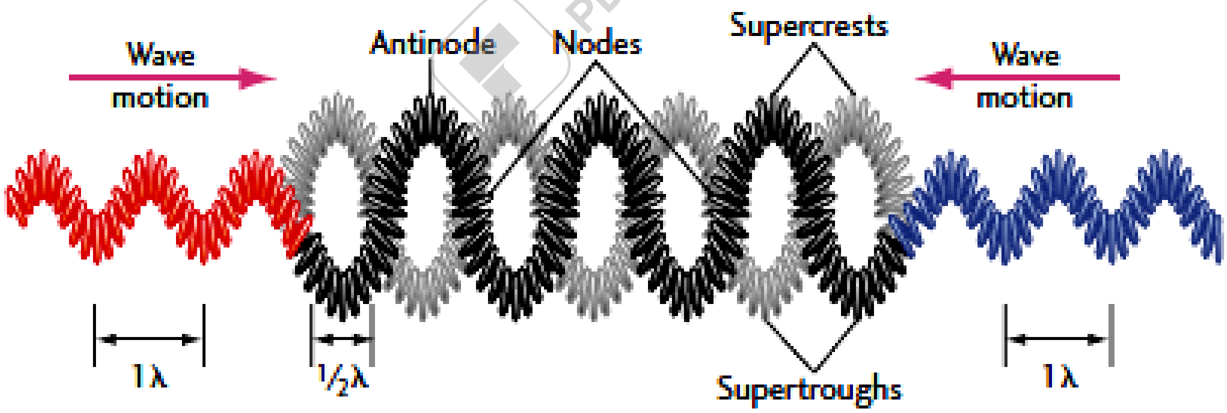
When a wave pulse reflects at **a free end** the wave reflects in the same phase and is not inverted. These two types of reflection will help us to understand what happens in many musical instruments.



Standing Waves — A Special Case of Interference

One of the most important instances of wave interference occurs when a particular wave reflects back on itself (with or without phase inversion) with the same frequency, wavelength, and speed. The resulting wave form, called a **standing wave.**

A standing wave is characterized by points in which the medium does not vibrate, called **nodes**. These nodes are interspersed between sections of medium that alternate between constructive "super crests" and "super troughs," called **antinodes**. In longitudinal sound waves, they are called super compressions and super rarefactions.

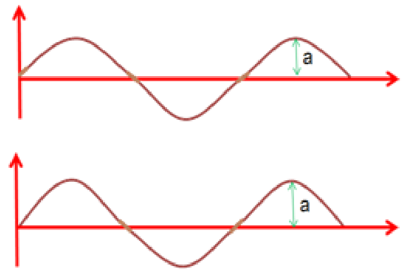
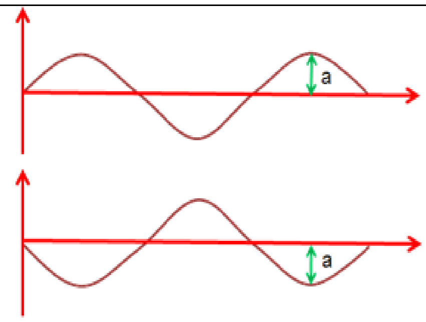
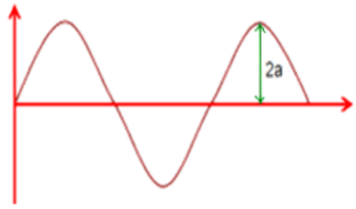
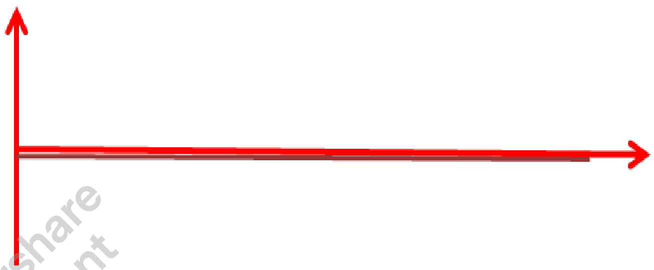


Node: a region of zero amplitude
Antinode: a region of maximum amplitude

Principle of Superposition.

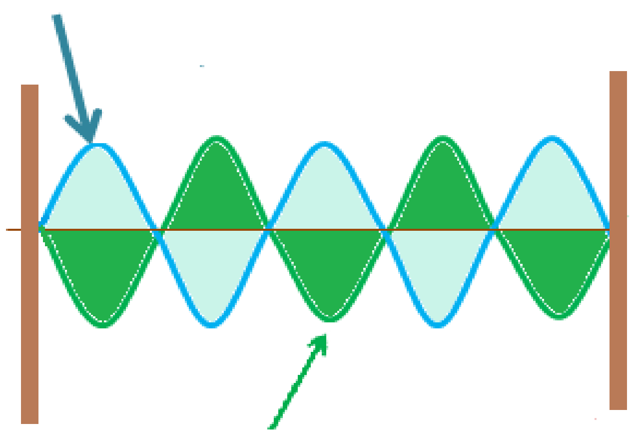
When two waves are in phase with each other they add together (Constructive Interference).

When two waves are 180^0 out of phase with each other they will cancel each other (Destructive Interference).

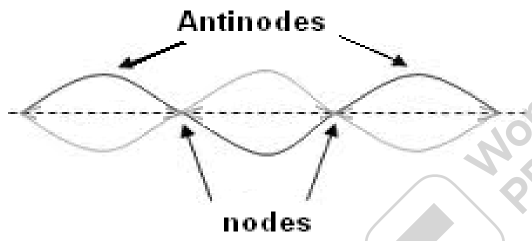
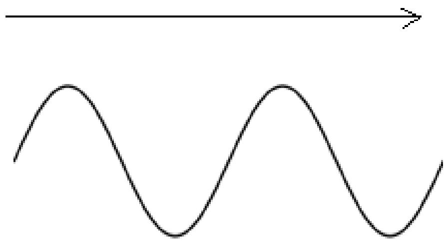
Constructive Interference	Destructive Interference
 *a=Amplitude*	 *a=Amplitude*
 *2a=Amplitude of the resultant wave*	

Conditions for a standing wave

- ➢Both waves should be in the same frequency
- ➢The wave length of two waves should be the same
- ➢Amplitude must be equal or nearly equal to each other
- ➢Should travel in opposite directions



Difference between Standing and Traveling waves

Standing waves	**Traveling waves**
➢ Wave will not move ➢ This is a combination of two waves which move in opposite directions ➢ Stores energy ➢ Consists of nodes and antinodes	➢ The wave will move ➢ This consists of one wave which moves in one direction ➢ Transmits energy ➢ All particles are vibrating
	

Standing waves in strings

When a wave is propagating along a string its linear mass density can be written as follows.

$$\mu = {}^{m}\!/_{L}$$

Here ,

m =Mass of the string

L=Length of the string

μ=Linear mass density

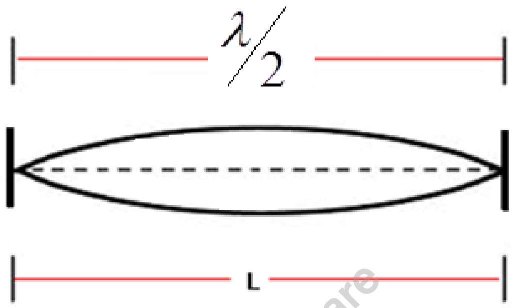
T= Tension of μ on the string

Velocity depends on both tension and linear density.

$$V = \sqrt{T/\mu}$$

$$V = \sqrt{TL/m}$$

The fundamental vibration mode of a stretched string is seen in the figure.



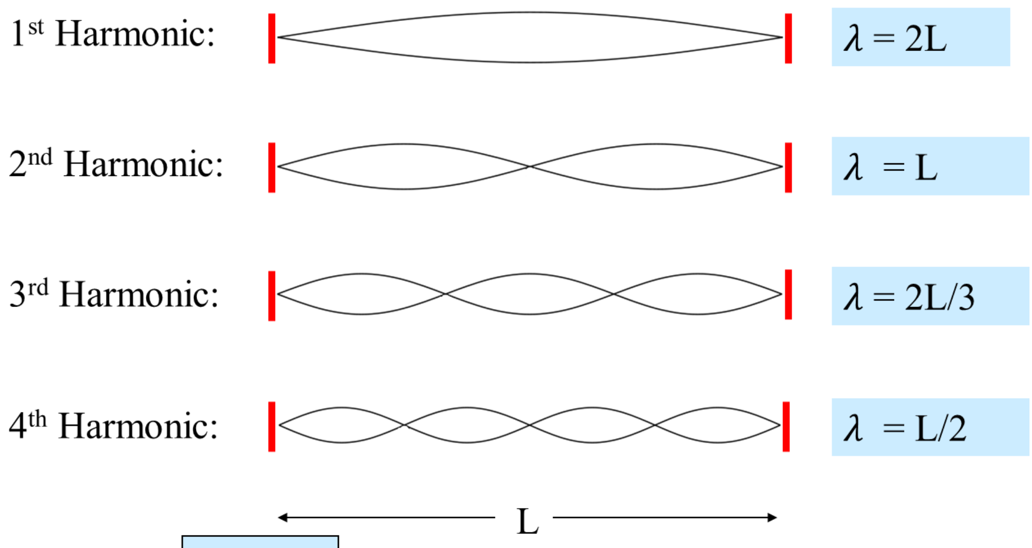
$$L = \lambda/2$$

The wavelength is twice the length of the string.

Hence

$$L = \lambda/2 \qquad V = f\lambda$$

$$\lambda = 2L \qquad V = f\,2L$$



Resonant wavelength formula $\lambda = \frac{2L}{n}$ where: $n = 1,2,3,4,...$

Also, in a string

$$V = \sqrt{\frac{T}{m/L}}$$

T=Tension of the string

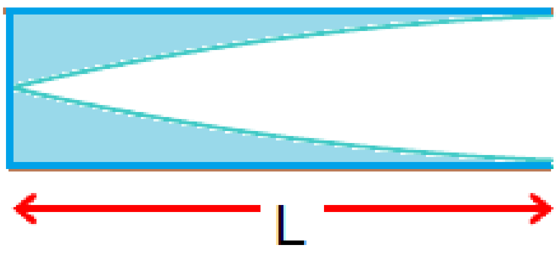
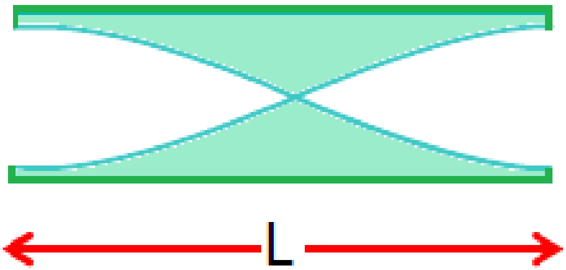
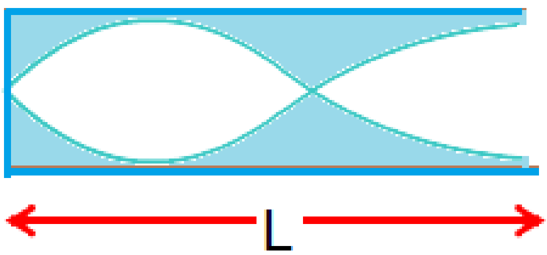
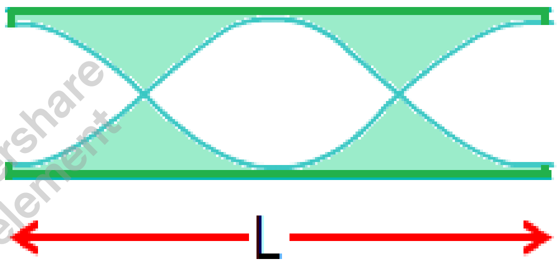
$$\sqrt{\frac{T}{m/L}} = f\,2L$$

L=Length of the string

$$f = \frac{1}{2L}\sqrt{\frac{T}{m/L}}$$

Standing waves in pipes

As you know already standing waves are formed when two progressive waves of the same medium are moving. You can see that at the closed end of a tube there must be a node, because air molecules couldn't vibrate when they contact the wall. Open end should have an antinode since it's air particles are free to vibrations.

Pipes with one open end	Pipes with two open end
	
	

Example:

a 130 cm long string of mass 5.0 g oscillates in its n = 3 mode with a frequency of 175 Hz and a maximum amplitude of 5.0 mm. Calculate both the wavelength of the standing wave and tension in the string.

Solution

so the string, fixed at both ends, form standing waves. Recall that the wavelength of the third harmonic (n= 3) is given by:

$$\lambda_n = \frac{2L}{n} \qquad \longrightarrow \qquad \lambda_3 = \frac{2L}{3} = \frac{2.60}{3} = 0.867\,\text{m} .$$

If the speed of the waves in the string is $v = \nu_3 \lambda_3$, then

$$v = \nu_3 \lambda_3 = (175)\,(0.867) = 151.7\,\text{m}\,\text{s}^{-1} .$$

Of course, the speed of the waves is also given by $v = \sqrt{T_s/\mu}$, and so the tension, T_s, is

$$T_s = \mu v^2 = \frac{m}{L} v^2 = \left(\frac{0.005}{1.30}\right)(151.7)^2 = 88.5\,\text{N} .$$

What is Hearing?

Unlike the senses of smell or taste, which rely on chemical interactions, hearing is a mechanical process in which the ear converts sound waves entering the ear into electrical signals the brain can understand.

How We Hear?

The ear is quite a piece of engineering; a complex organization of bones, hairs, nerves and cells. It is made up of three main parts, outer (1), middle (2) and inner (3 and 4). To hear naturally, each part of the ear needs to work well.

1.Sounds enter the ear canal

When these sound waves reach the ear, they travel down the ear canal and hit the eardrum, making it vibrate.

2.The ear drum and bones of hearing vibrate

Three tiny bones in the middle ear link the vibrating eardrum to a tiny bone structure in the inner ear called the cochlea.

3.Fluid moves through the inner ear

The cochlea is filled with liquid that carries the vibrations to thousands of tiny hair cells.

4.Hearing nerves communicate to the brain

The movement in the fluid causes the cells to carry a message to the nerve that is connected to the brain, which turns the signals into what you hear. The movement in the fluid causes the cells to carry a message to the nerve that is connected to the brain, which turns the signals into what you hear.

To hear the sound traveling through the air, three things have to happen.

1- The sound has to be directed into the hearing part of the ear.
2- The ear has to sense the fluctuations in air pressure.
3- The fluctuations have to be translated into electrical signals that the brain can understand.