Chapter 16

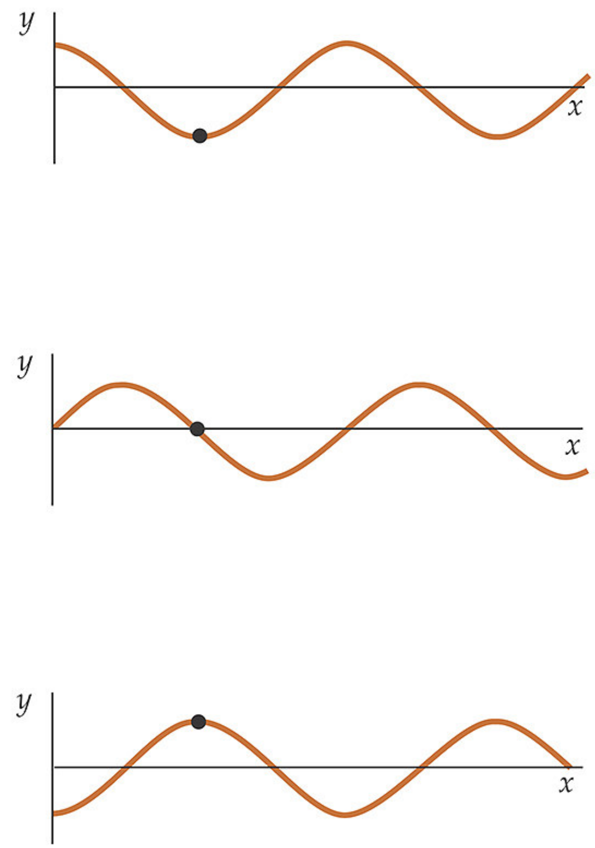
Traveling Waves

Traveling Waves

- Simple Wave Motion
- Periodic Waves
- Waves in Three Dimensions
- Waves Encountering Barriers
- The Doppler Effect

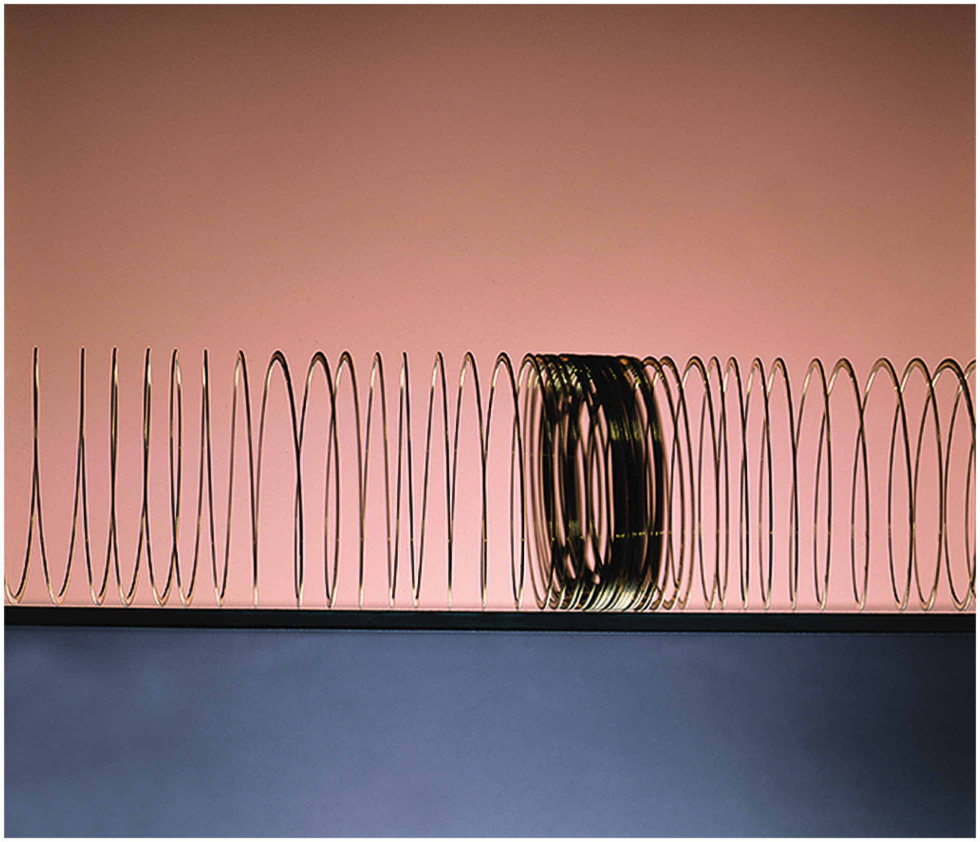
Transverse Waves

(a)

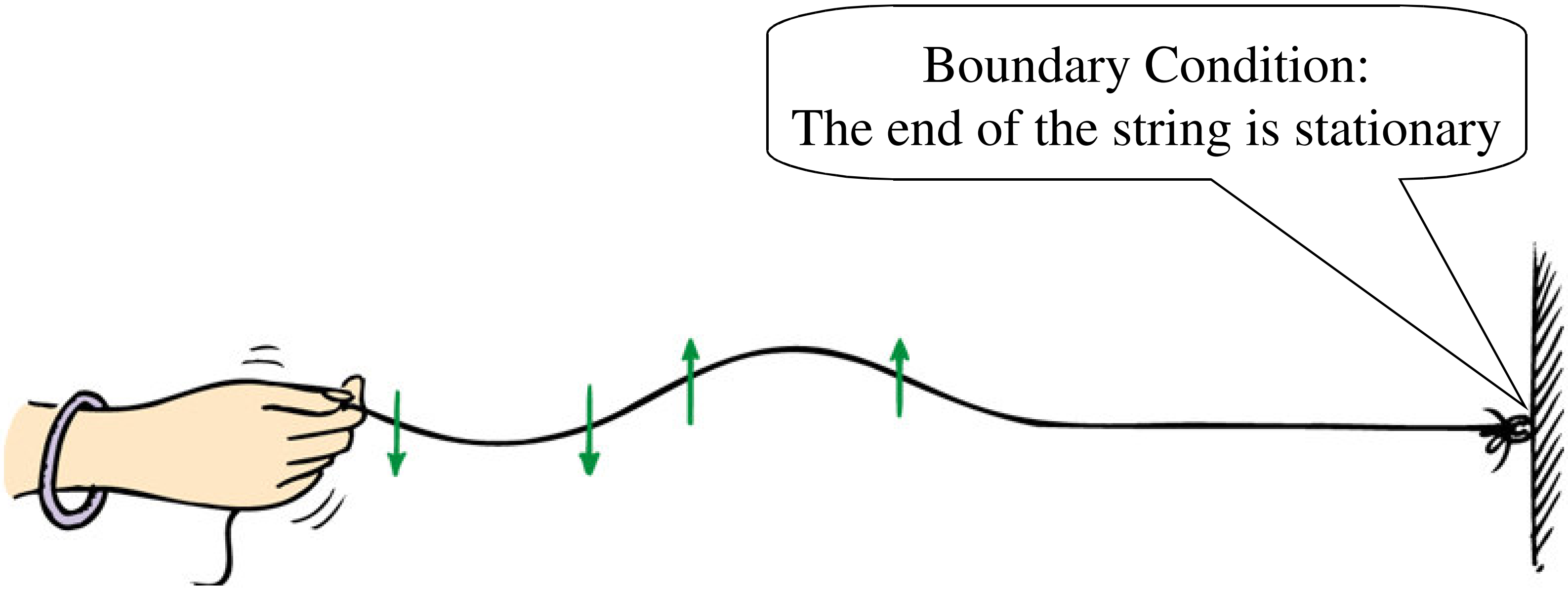


(b)

Longitudinal Waves



The Excitation of a Transverse Wave

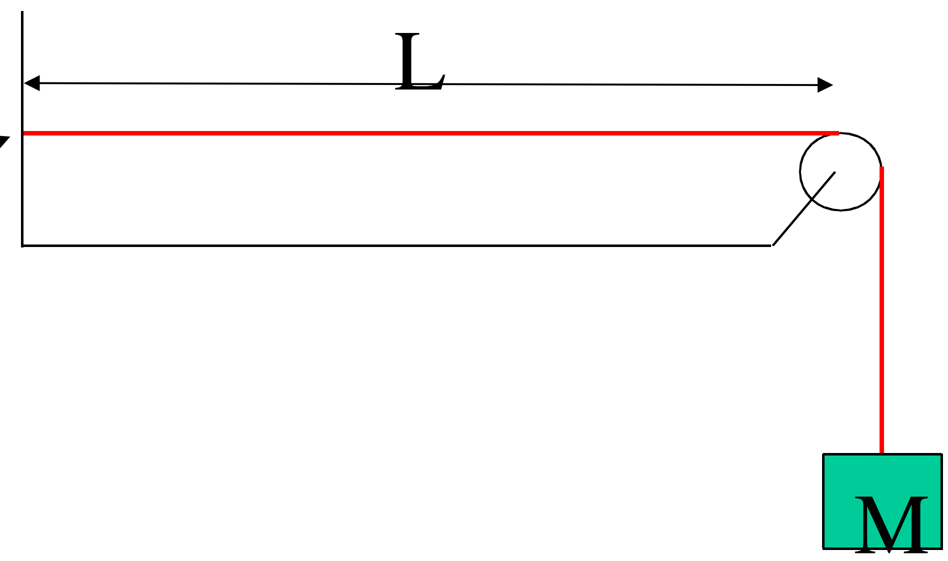


The speed with which the string is moved vertically is independent of the speed with the wave travels horizontally down the string.

Transverse Waves on a String

Attach a mass to a string to provide tension. The string is then shaken at one end with a frequency f.

Attach a wave driver here



Transverse Waves on a String

A wave traveling on this string will have a speed of

$$v = \sqrt{\frac{F}{\mu}}$$

where F is the force applied to the string (tension) and μ is the mass/unit length of the string (linear mass density).

Transverse Waves on a String

Example: When the tension in a cord is 75.0 N, the wave speed is 140 m/s. What is the linear mass density of the cord?

The speed of a wave on a string is $$v = \sqrt{\frac{F}{\mu}}$$

Solving for the linear mass density:

$$\mu = \frac{F}{v^2} = \frac{75.0\ \text{N}}{(140\ \text{m/s})^2} = 3.8 \times 10^{-3}\ \text{kg/m}$$

Speed of Sound in Various Materials

Increasing attractive force ↓

Speed of Sound (m/s)		
	Heavy	Light
Gas	300 (Air)	900 (He)
Liquid	1000	1500
Solid	1900 (Lead)	6000 (Steel)

High mass Low Mass

$$v = \sqrt{\frac{F}{\mu}} = \sqrt{\frac{Force}{Inertia}}$$

String

$$v = \sqrt{\frac{B}{\rho}}$$

Liquid

$$v = \sqrt{\frac{Y}{\rho}}$$

Solid

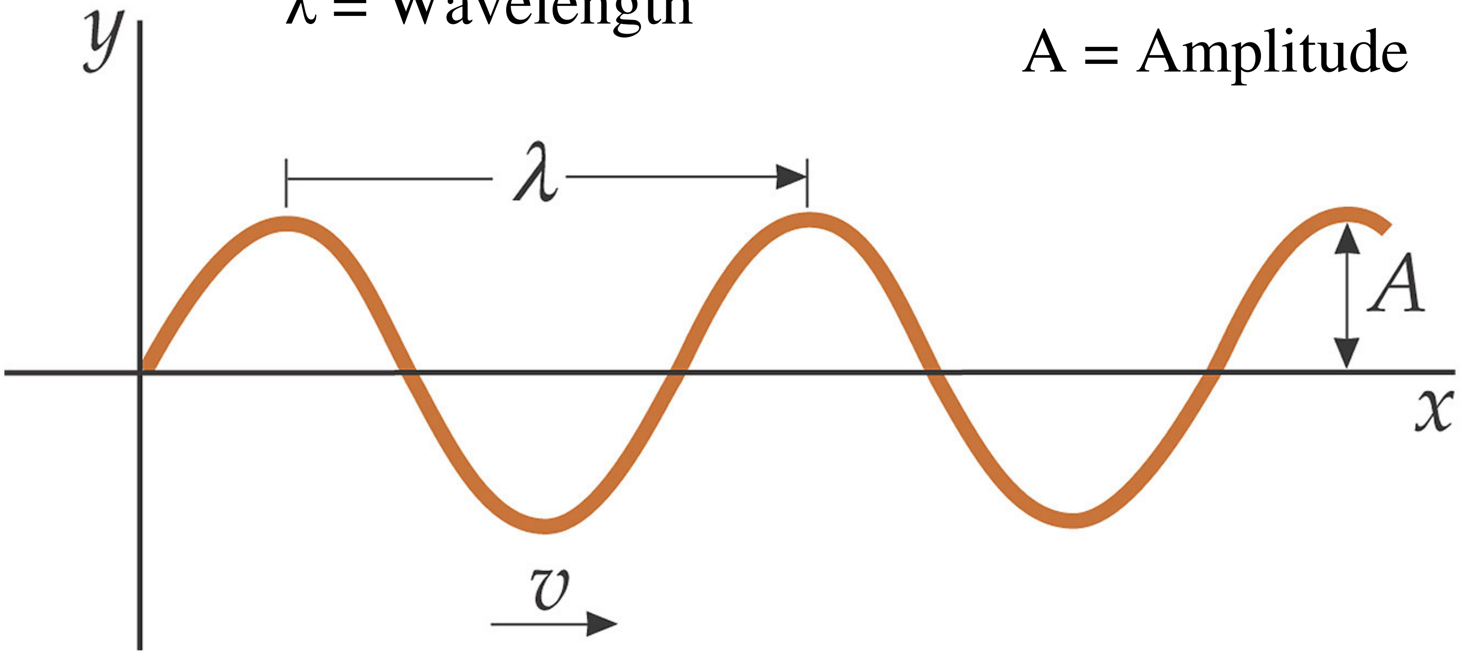
Periodic Waves

The period T is measured by the amount of time it takes for a point on the wave to go through one complete cycle of oscillations. The frequency is then $f = 1/T$.

Wave Nomenclature

λ = Wavelength

A = Amplitude

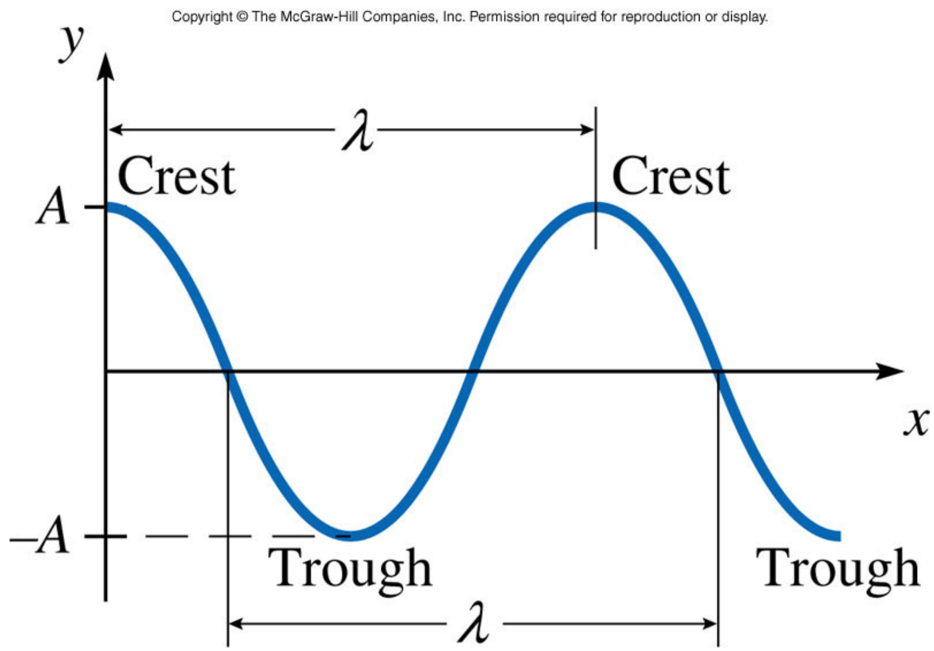


v = wave velocity

Periodic Waves

One way to determine the wavelength is by measuring the distance between two consecutive crests.

The maximum displacement from equilibrium is amplitude (A) of a wave.



Periodic Waves

Example: What is the wavelength of a wave whose speed and period are 75.0 m/s and 5.00 ms, respectively?

$$v = \lambda f = \frac{\lambda}{T}$$

Solving for the wavelength:

$$\lambda = vT = (75.0\ \text{m/s})(5.00\times10^{-3}\ \text{s}) = 0.375\ \text{m}$$

Wave Properties

Particle Speed	Wave Speed
• Simple Harmonic Motion • $V_p = A\omega \sin(\omega t)$ • Determined by source	• Determined by properties of the medium • $v = \sqrt{\frac{F}{\mu}} = \sqrt{\frac{Force}{Inertia}}$

The Full Wave Equation

$$\frac{\partial^2 y}{\partial x^2} - \frac{1}{v^2}\frac{\partial^2 y}{\partial t^2} = 0$$

$$y(t) = A\sin(kx - \omega t)$$

$$k = \frac{2\pi}{\lambda}; \quad \omega = 2\pi f = \frac{2\pi}{T}$$

$$y(t) = A\sin\left[2\pi\left(\frac{x}{\lambda} - \frac{t}{T}\right)\right]$$

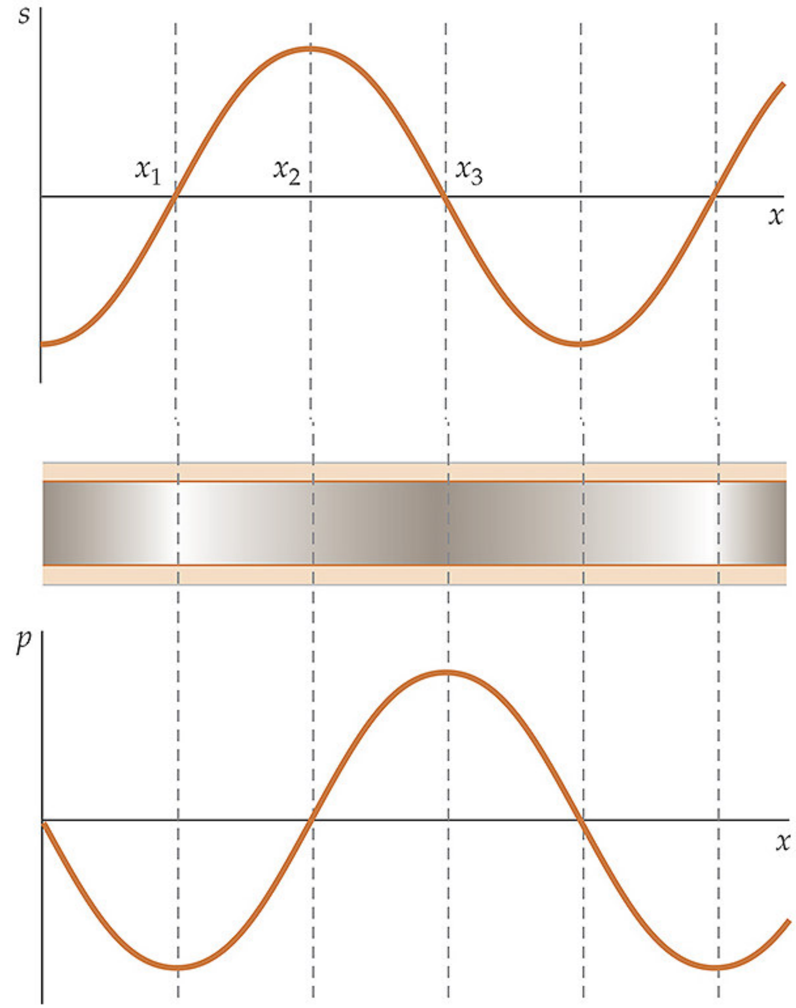
Traveling with the wave the phase is constant

$$\frac{x}{\lambda} - \frac{t}{T} = Constant$$

$$\frac{dx}{\lambda} - \frac{dt}{T} = 0$$

$$\frac{dx}{dt} = \frac{\lambda}{T} = \lambda f = v$$ Wave velocity

Sound Waves



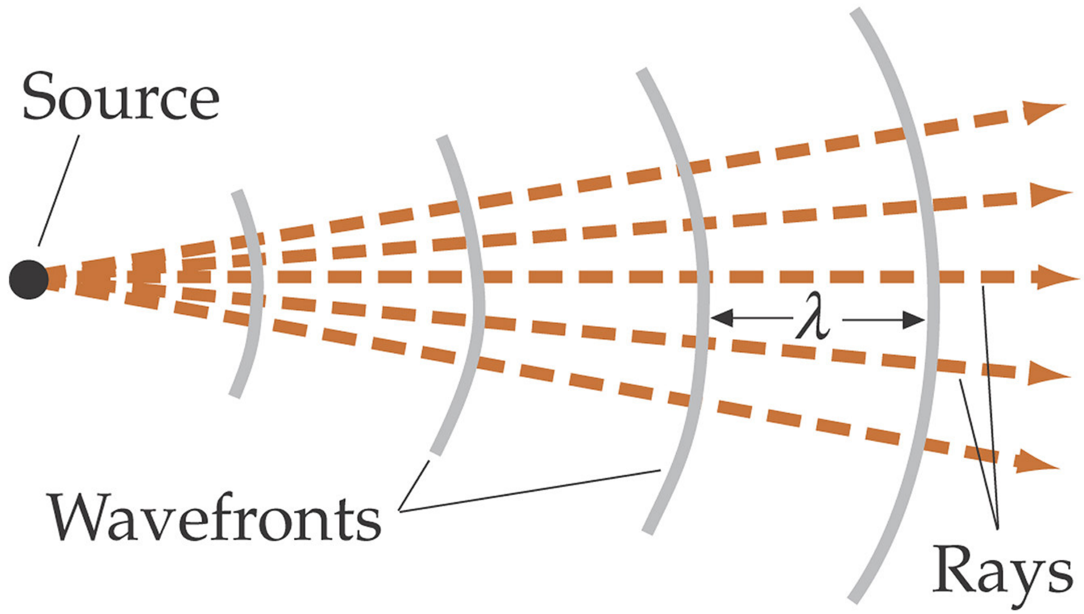
Displacement

Sound waves are compression waves and are longitudinal in nature.

Pressure

The pressure (i.e. density) variation is easier to follow

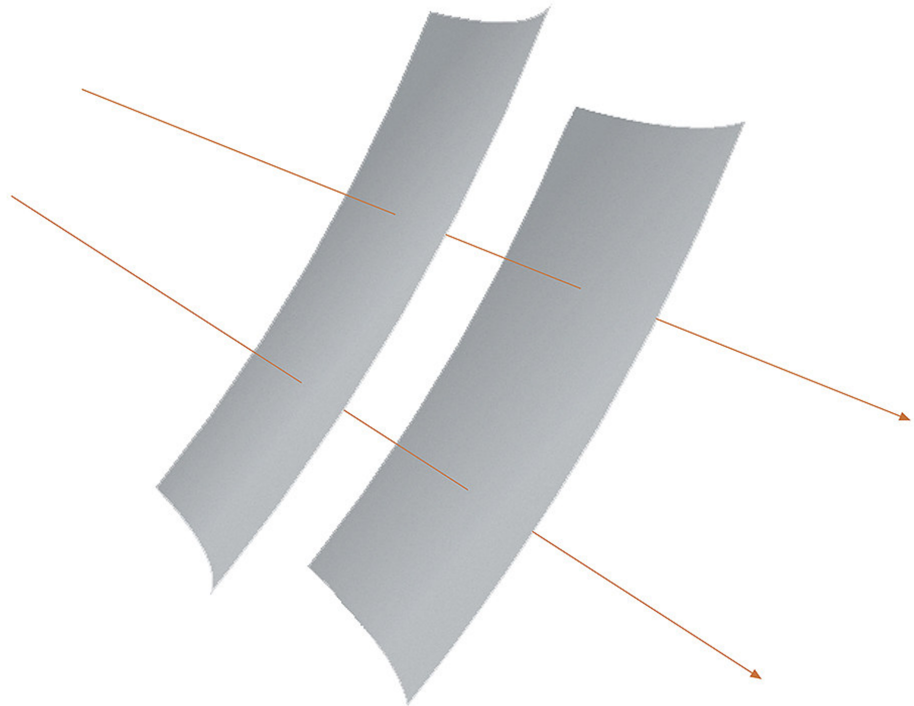
Wave Fronts and Rays



The wave fronts represent positions of constant phase.

The rays are perpendicular to these wave fronts and point in the direction the wave is traveling.

Plane Wave Wave Fronts and Rays



Far from a spherical source the wave front approximates a plane wave.

Waves and Energy Transport

Intensity is a measure of the amount of energy/sec that passes through a square meter of area perpendicular to the wave's direction of travel.

$$I = \frac{Power}{4\pi\, r^2} = \frac{P}{4\pi\, r^2}$$

Intensity has units of watts/m^2 .

This is an inverse square law. The intensity drops as the inverse square of the distance from the source.

(Light sources appear dimmer the farther away from them you are.)

Waves and Energy Transport

Example: At the location of the Earth's upper atmosphere, the intensity of the Sun's light is 1400 W/m^2. What is the intensity of the Sun's light at the orbit of the planet Mercury?

$$I_{\mathrm{e}} = \frac{P_{\mathrm{sun}}}{4\pi\, r_{\mathrm{es}}^2} \qquad\qquad I_{\mathrm{m}} = \frac{P_{\mathrm{sun}}}{4\pi\, r_{\mathrm{ms}}^2}$$

Divide one equation by the other (take a ratio):

$$\frac{I_{\mathrm{m}}}{I_{\mathrm{e}}} = \frac{\dfrac{P_{\mathrm{sun}}}{4\pi\, \mathrm{r}_{\mathrm{ms}}^2}}{\dfrac{P_{\mathrm{sun}}}{4\pi\, \mathrm{r}_{\mathrm{es}}^2}} = \left(\frac{r_{\mathrm{es}}}{r_{\mathrm{ms}}}\right)^2 = \left(\frac{1.50\times 10^{11}\ \mathrm{m}}{5.85\times 10^{10}\ \mathrm{m}}\right)^2 = 6.57$$

$$I_{\mathrm{m}} = 6.57 I_{\mathrm{e}} = 9200\ \mathrm{W/m^2}$$

Wave Intensity - Sound Waves

$$I = \frac{P_{avg}}{A} = \frac{P_{avg}}{4\pi\ r^2}$$

$$P_{avg} = \frac{(\Delta E)_{avg}}{\Delta t} = \eta_{avg} A v$$

$$I = \frac{P_{avg}}{A} = \eta_{avg} v = \left(\tfrac{1}{2} \frac{P_0^2}{\rho v^2} \right) v$$

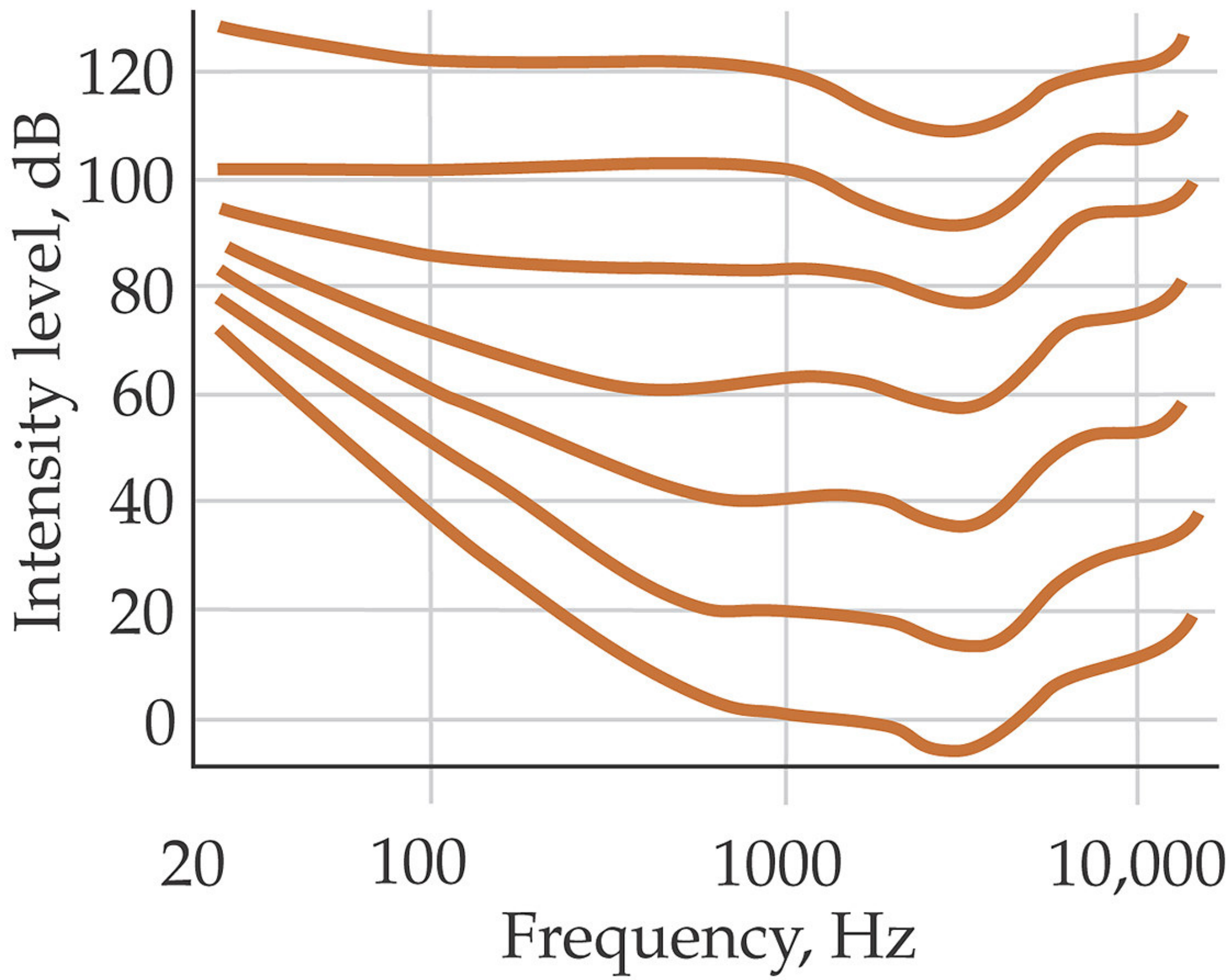
The energy density approach is very useful for electromagnetic waves.

Sound Intensity

Table 15-1 Intensity and Intensity Level of Some Common Sounds ($I_0 = 10^{-12}$ W/m^2)

Source	I/I_0	dB	Description
	10^0	0	Hearing threshold
Normal breathing	10^1	10	Barely audible
Rustling leaves	10^2	20	
Soft whisper (at 5 m)	10^3	30	Very quiet
Library	10^4	40	
Quiet office	10^5	50	Quiet
Normal conversation (at 1 m)	10^6	60	
Busy traffic	10^7	70	
Noisy office with machines; average factory	10^8	80	
Heavy truck (at 15 m); Niagara Falls	10^9	90	Constant exposure endangers hearing
Old subway train	10^{10}	100	
Construction noise (at 3 m)	10^{11}	110	
Rock concert with amplifiers (at 2 m); jet takeoff (at 60 m)	10^{12}	120	Pain threshold
Pneumatic riveter; machine gun	10^{13}	130	
Jet takeoff (nearby)	10^{15}	150	
Large rocket engine (nearby)	10^{18}	180	

Sound Intensity vs Frequency



Sound Levels and Decibels

Amplitude & Intensity of Sound Waves

For sound waves:

$I \propto p_0^2$ p_0 is the pressure amplitude and

$I \propto s_0^2$ s_0 is the displacement amplitude.

The intensity of sound waves follows an inverse square law.

Sound Loudness is measured by the logarithm of the intensity.

The threshold of hearing is at an intensity of 10^{-12} W/m^2.

Sound intensity level is defined by - dB are decibels

$$\beta = (10\text{dB})\log\frac{I}{I_0}$$

Decibels are used when the signal can cover many orders of magnitude. They help turn multiplication into addition and division into subtraction.

Example: The sound level 25 m from a loudspeaker is 71 dB. What is the rate at which sound energy is being produced by the loudspeaker, assuming it to be an isotropic source?

$$\text{Given:} \quad \beta = (10\,\text{dB})\log\frac{I}{I_0} = 71\,\text{dB}$$

Solve for I, the intensity of a sound wave:

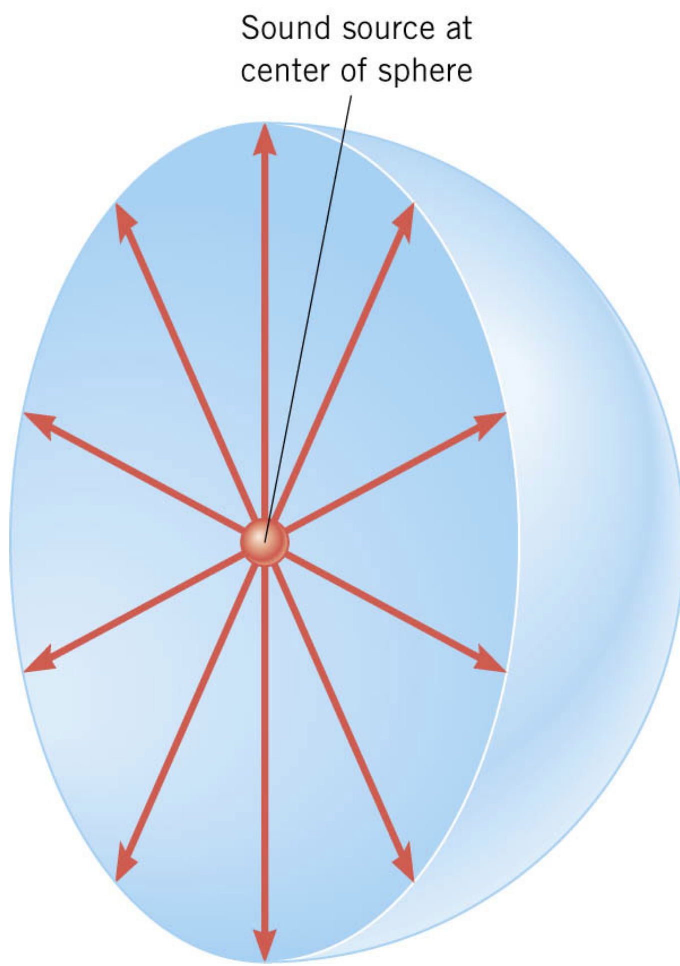
$$\log\frac{I}{I_0} = 7.1$$

$$\frac{I}{I_0} = 10^{7.1}$$

$$I = I_0 10^{7.1} = \left(10^{-12}\,\text{W/m}^2\right)\left(10^{7.1}\right) = 1.3\times10^{-5}\ \text{W/m}^2$$

Sound Energy Traveling in Three Dimensions

Assuming an isotropic source means that we are assuming that the energy from that source travels in all directions equally



Example continued:

The intensity of an isotropic source is defined by:

$$I = \frac{P}{4\pi r^2}$$

$$P = I\,4\pi r^2$$

$$= (1.3\times10^{-5}\ \mathrm{W/m^2})4\pi(25\ \mathrm{m})^2$$

$$= 0.10\ \mathrm{Watts}$$

Logarithm Refresher

Rules

1. Inverse properties: $\log_a (a^x) = x$ and $a^{(\log_a(x))} = x$

2. Product: $\log_a (xy) = \log_a (x) + \log_a (y)$

3. Quotient: $\log_a (x/y) = \log_a (x) - \log_a (y)$

4. Power: $\log_a (x^p) = p \log_a (x)$

5. Change of base formula: $\log_a (x) = \log_b (x) / \log_b (a)$

Careful!!

$\log_a (x + y) <> \log_a (x) + \log_a (y)$

$\log_a (x - y) <> \log_a (x) - \log_a (y)$

Example: Two sounds have levels of 80 dB and 90 dB. What is the difference in the sound intensities?

$$\beta_1 = (10dB)\log\frac{I_1}{I_0} = 80\ dB \qquad \beta_2 = (10dB)\log\frac{I_2}{I_0} = 90\ dB$$

Subtracting:

$$\beta_2 - \beta_1 = 10\ \mathrm{dB} = 10\ \mathrm{dB}\left(\log\frac{I_2}{I_0} - \log\frac{I_1}{I_0}\right)$$

$$10\ \mathrm{dB} = 10\ \mathrm{dB}\left(\log\frac{I_2}{I_1}\right)$$

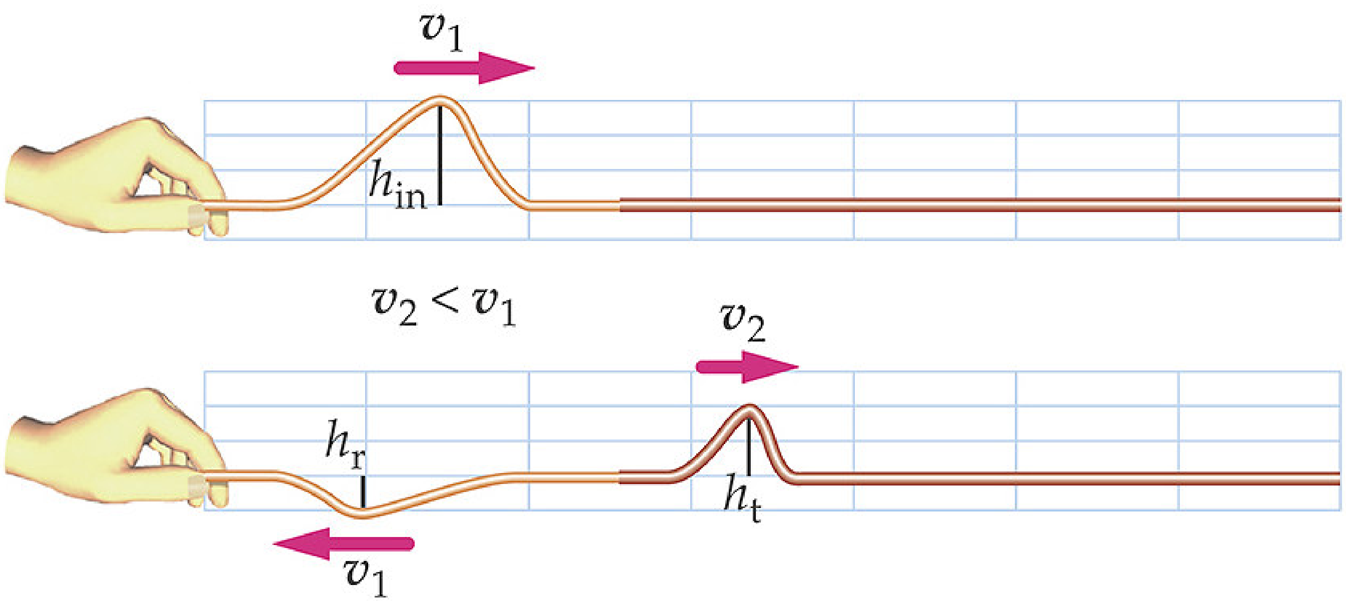
$$\log\left(\frac{I_2}{I_1}\right) = 1$$

$$\frac{I_2}{I_1} = 10^1$$

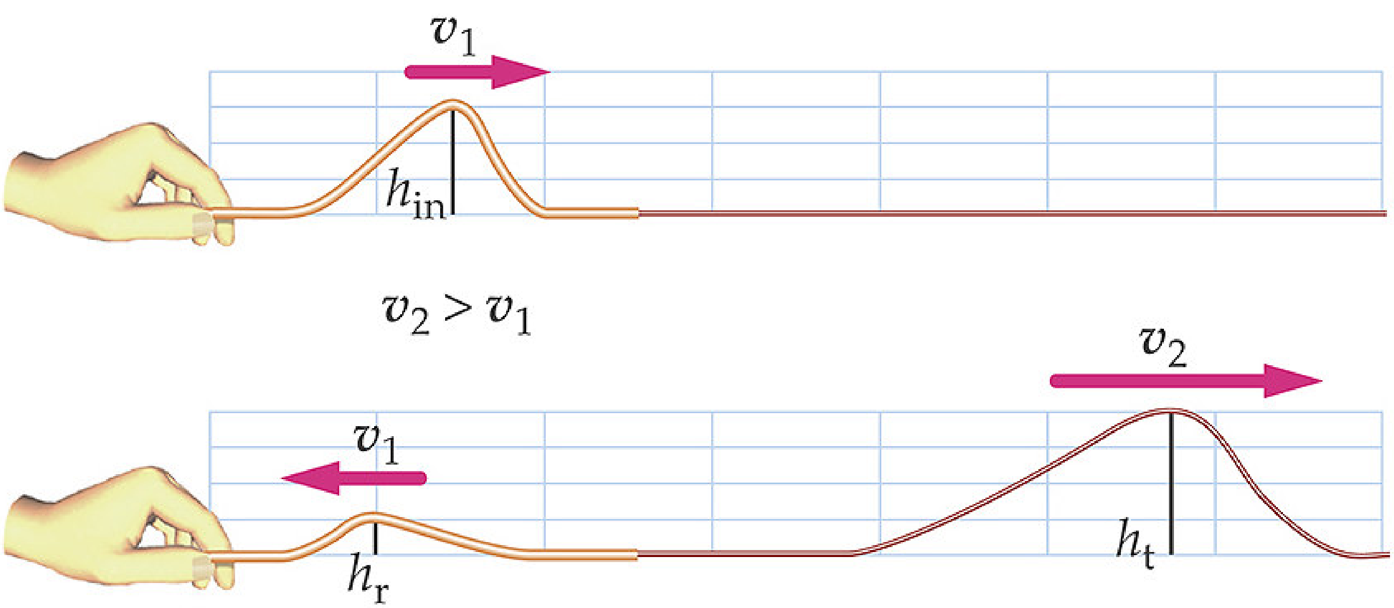
and $I_2 = 10\ I_1$

Reflected and Transmitted Waves

Reflected Waves - More Dense



Reflected Waves - Less Dense



Reflection and Transmission Coefficients

$$\left.\begin{aligned} r &= \frac{h_r}{h_i} = \frac{v_2 - v_1}{v_2 + v_1} \\ \tau &= \frac{h_t}{h_i} = \frac{2v_2}{v_2 + v_1} \end{aligned}\right\}$$

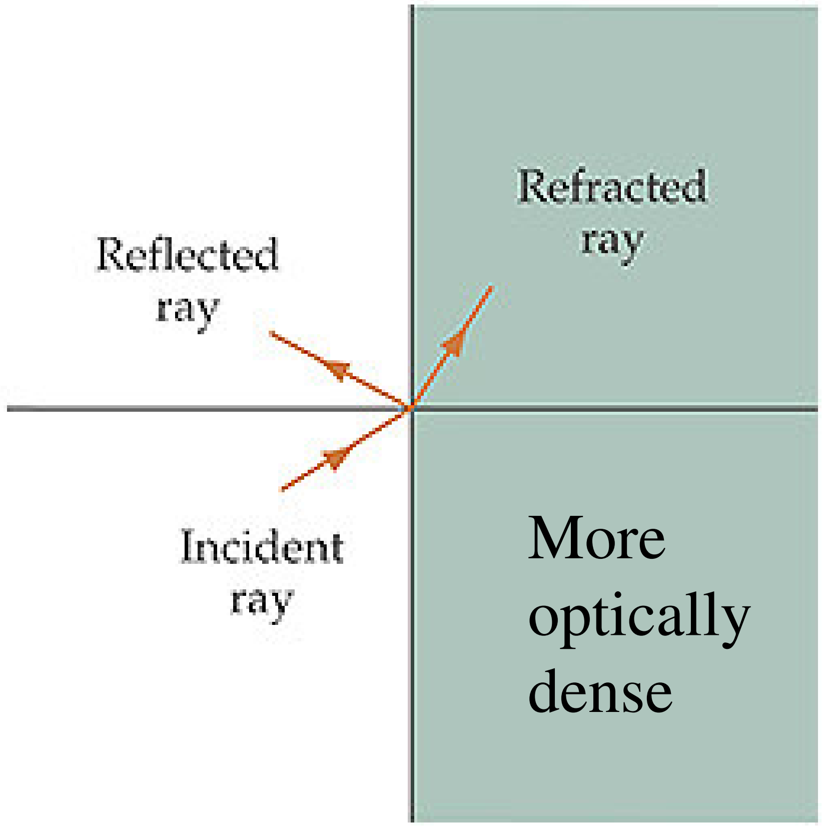
Fresnel relations

Energy Consevation in Waves

$$1 = r^2 + \frac{v_1}{v_2}\tau^2$$

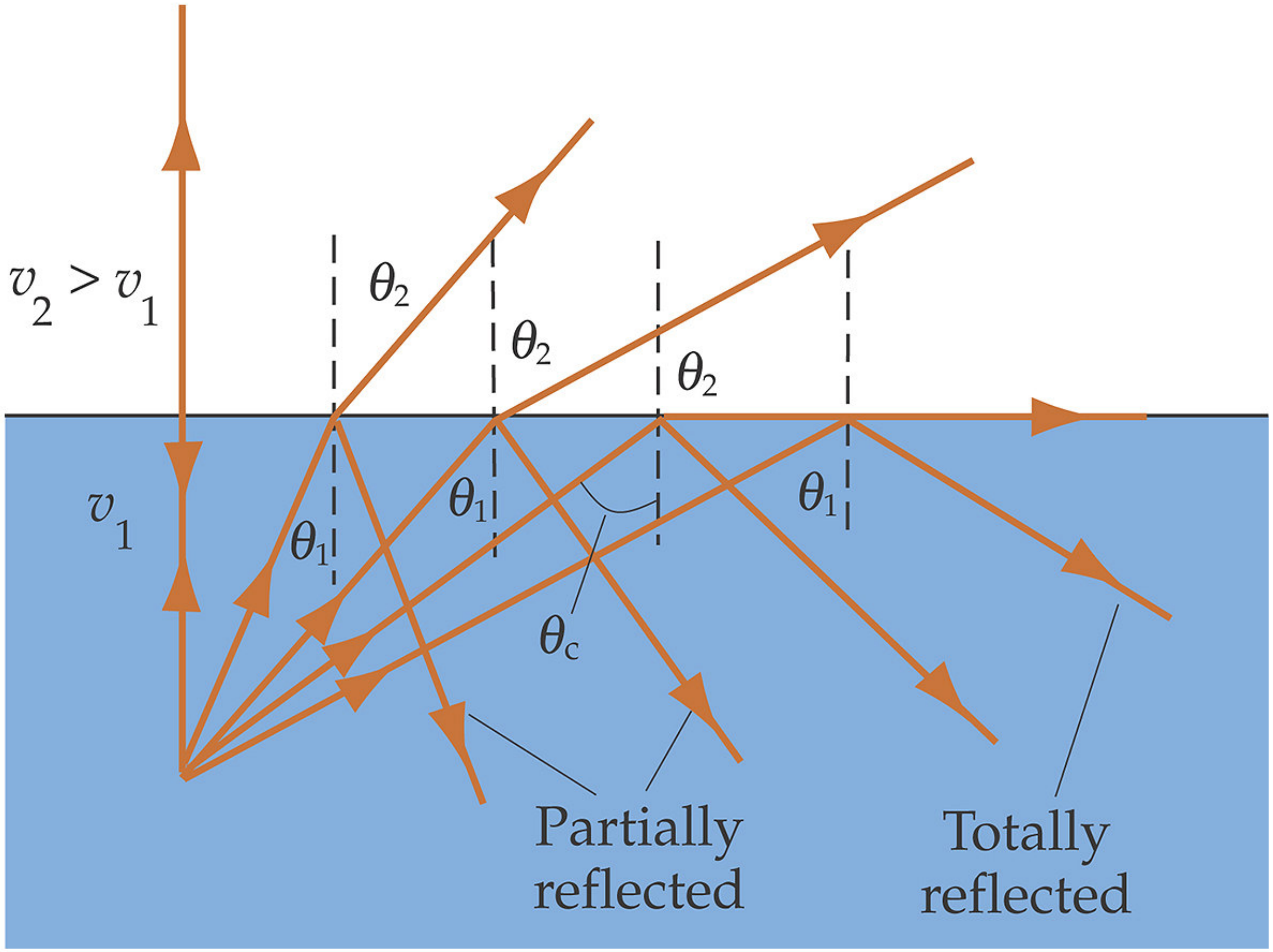
Reflected Waves - Light

Less optically dense



More optically dense

Reflection & Refraction - Light



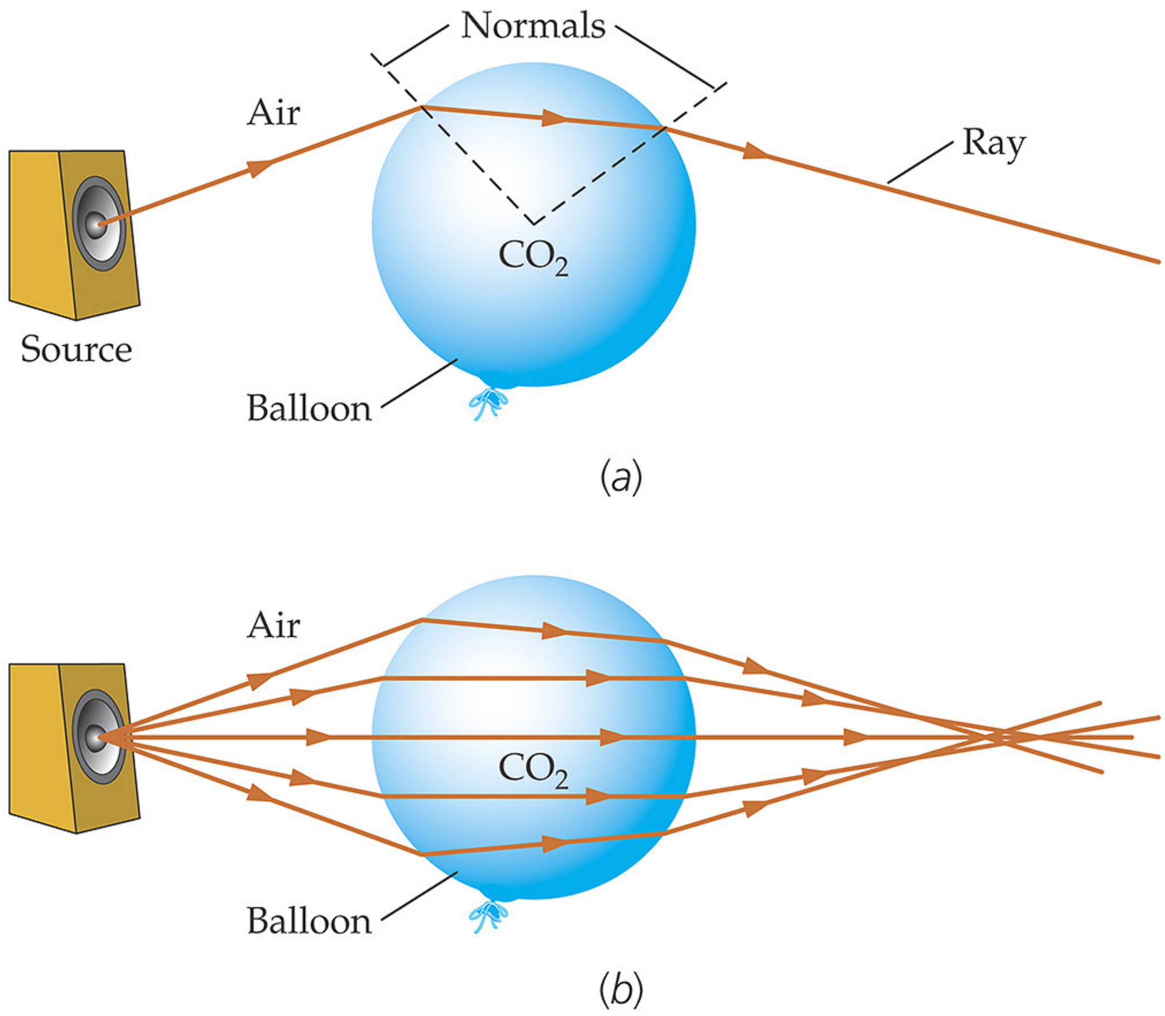
The Frequency is Constant

The **frequency** of the transmitted wave **remains the same**. However, both the wave's speed and wavelength are changed such that:

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

The transmitted wave will also suffer a change in propagation direction (**refraction**).

Refraction of Sound



(a) (b)

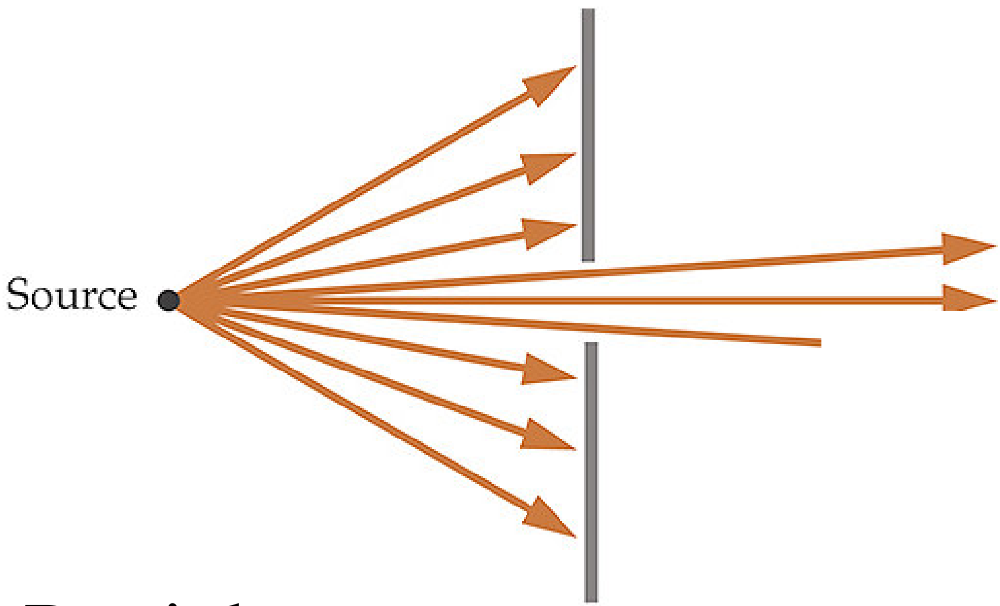
Diffraction

Diffraction is the spreading of a wave around an obstacle in its path and it is common to all types of waves.

The size of the obstacle must be similar to the wavelength of the wave for the diffraction to be observed.

Larger by 10x is too big and
smaller by (1/10)x is too small.

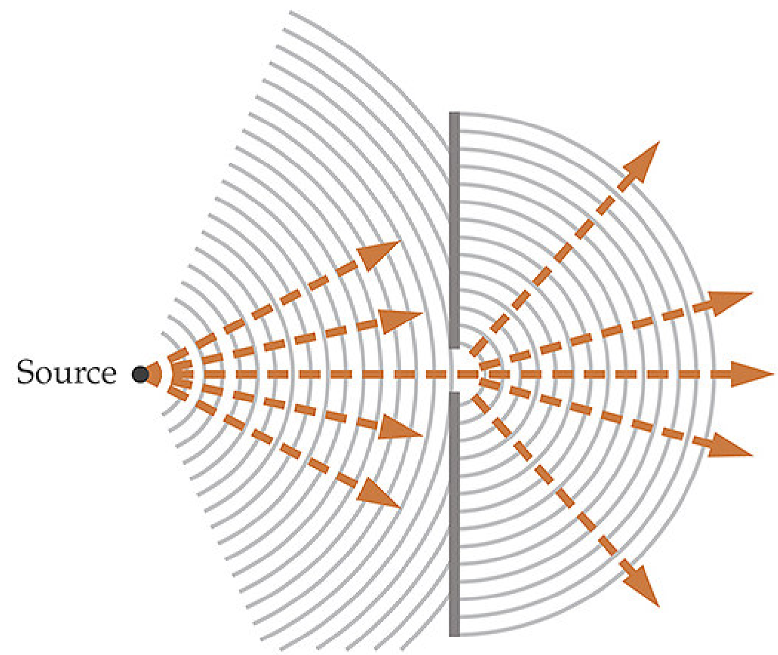
Comparison of Particles & Waves



(a)

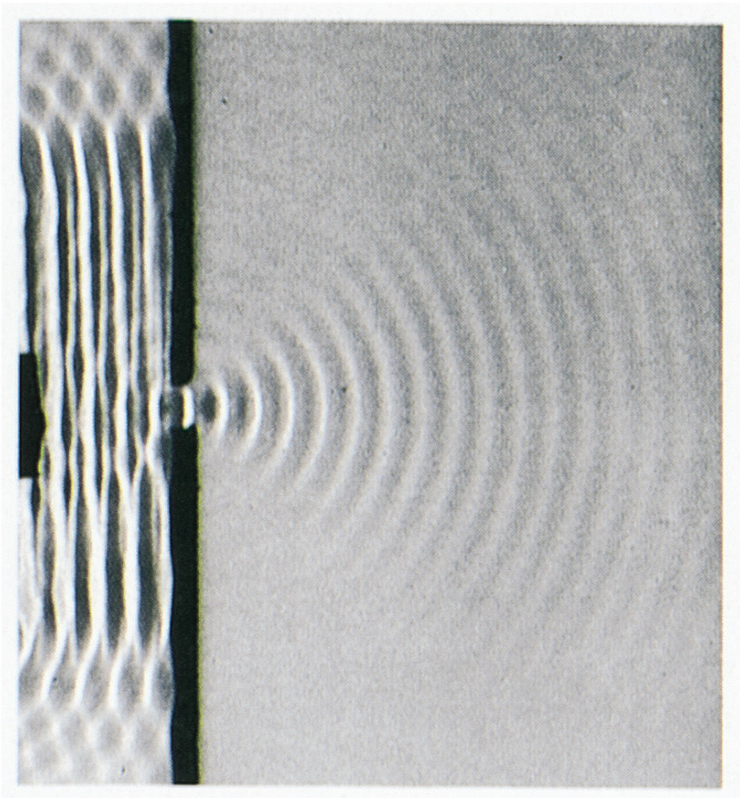
Particles

Waves



(b)

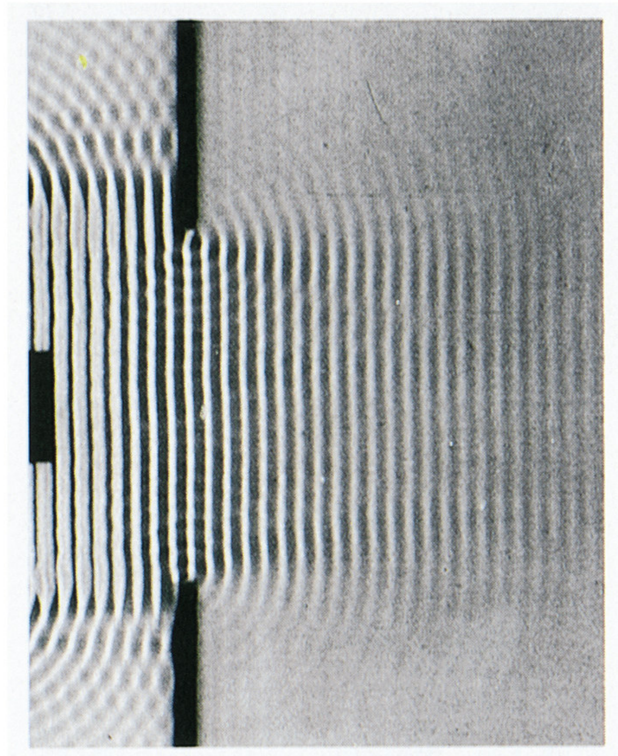
Wave Diffraction



The size of the slit is about the same as the wavelength of the water ways. As a result the diffraction of the wave has a noticeable effect.

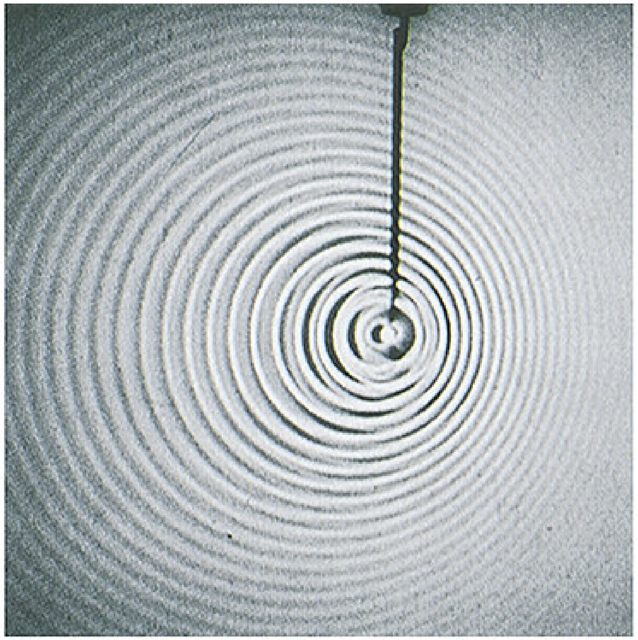
A plane wave has been effectively turned into a point source.

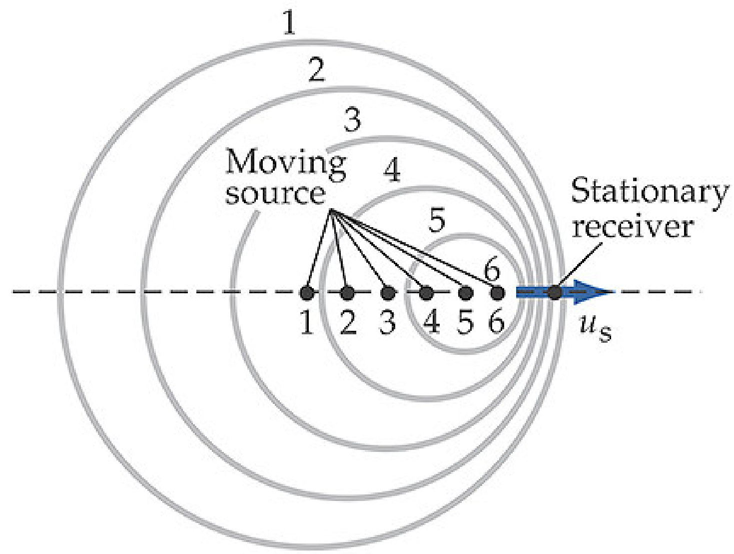
Wave Diffraction



The diffraction effect is less noticeable if the opening is much wider than the wavelength of the waves.

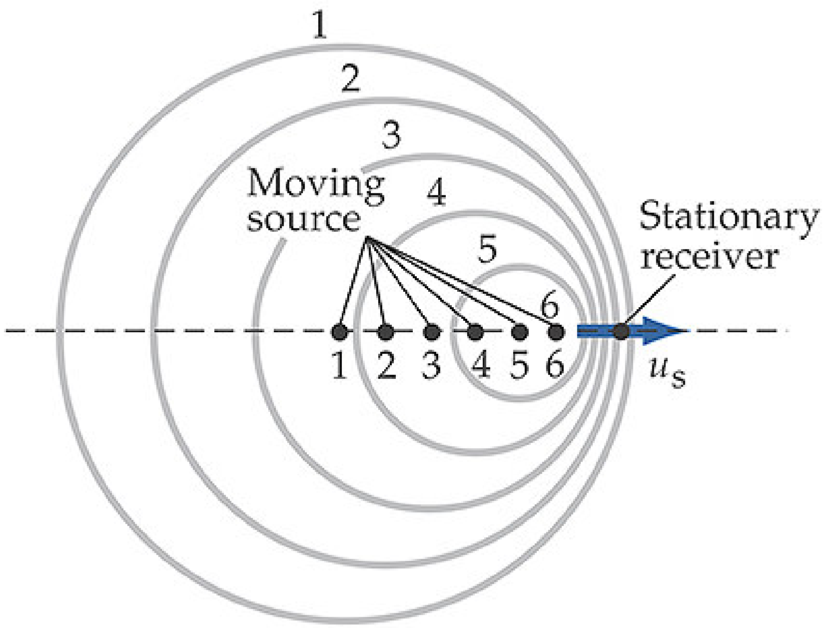
Doppler Effect





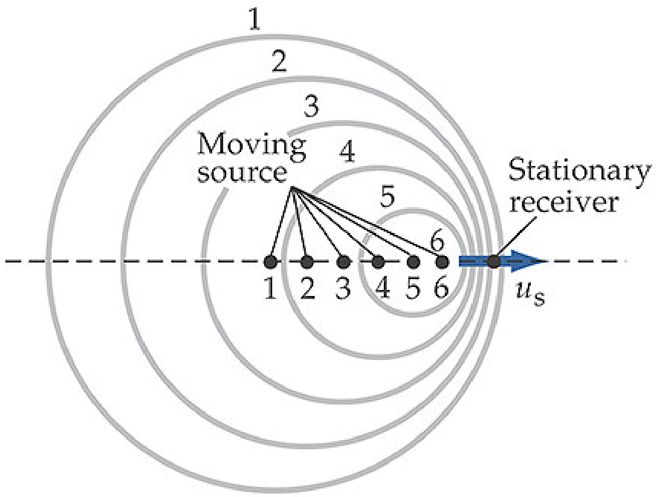
A source of periodic waves in a ripple tank has a velocity to the right. Wavelength is compressed in front and stretched out in back.

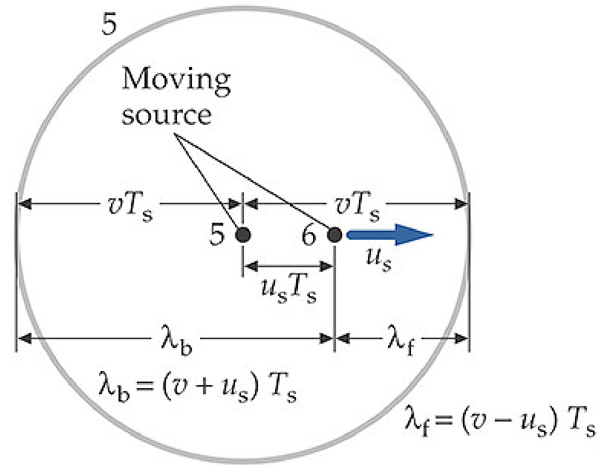
Doppler Effect



The familiar effect of the drop in frequency of the siren after the fire truck passes by is due to the Doppler Effect.

Doppler Effect



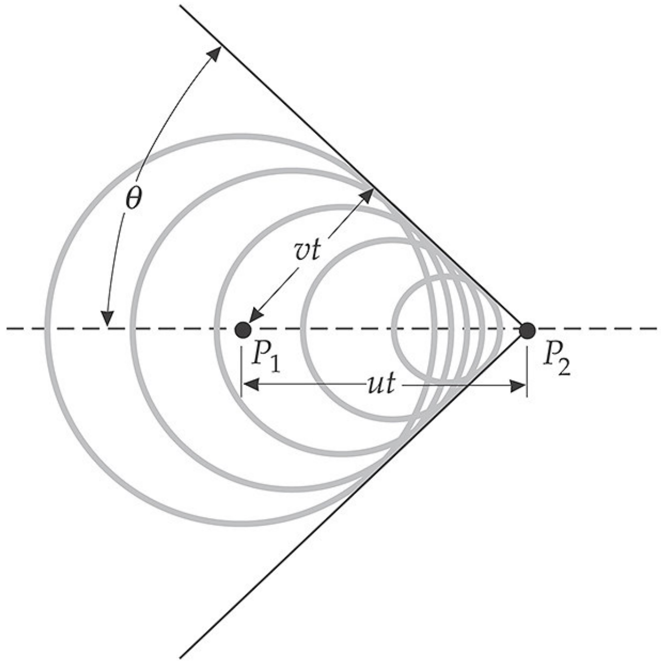


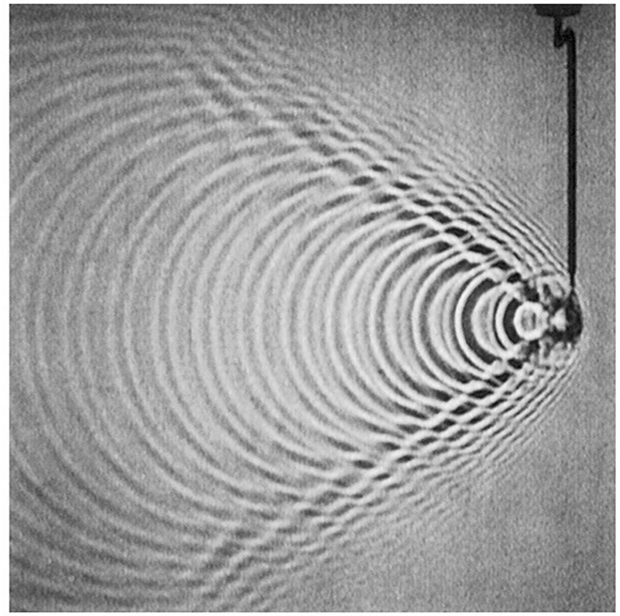
$$f_r = \frac{v \pm u_r}{v \pm u_s} f_s$$

To use the formula remember the frequency increases when the source moves toward the receiver and when the receiver moves toward the source.

If the source is moving toward the receiver, choose the minus sign in the denominator. If the receiver is moving toward the source choose the plus sign in the numerator.

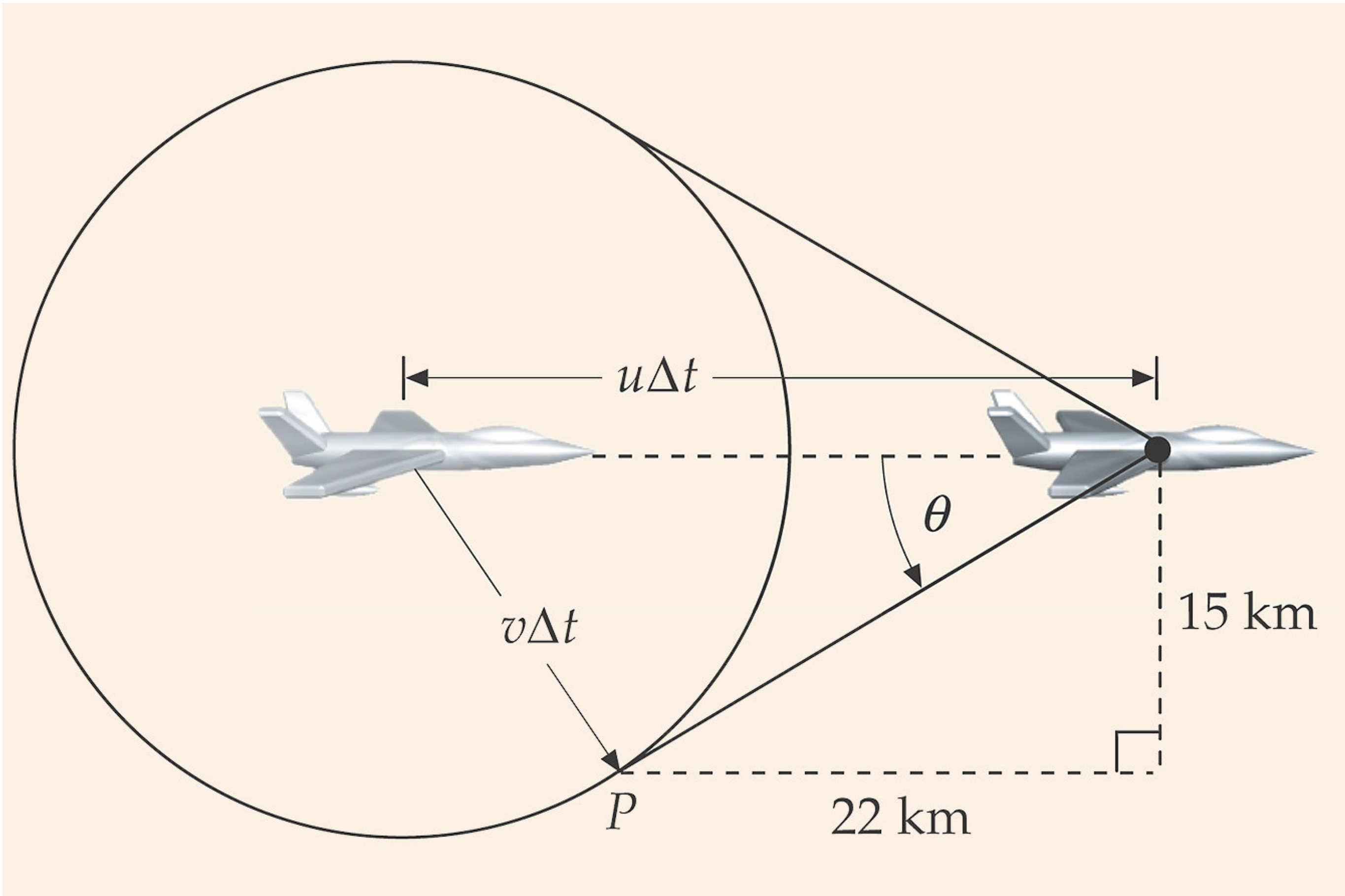
“Supersonic” Waves





To achieve this “supersonic” effect the object must be traveling faster than the speed of waves in that medium.

Supersonic Waves



These are actual photos of aircraft breaking the sound barrier. This phenomenon only happens at the instant an Aircraft breaks the sound barrier And it literally appears like the aircraft goes through a wall.

http://www.youtube.com/watch?v=QX04ySm4TTk&feature=related

End of Chapter 15

Extra Slides