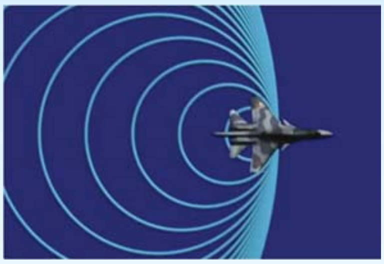
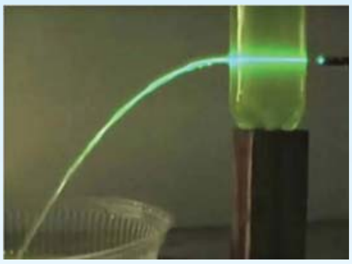
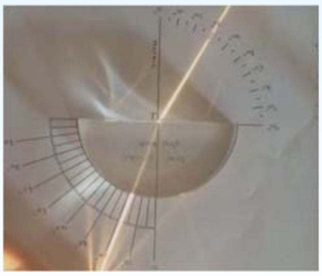
Vågrörelselära och optik



Kapitel 16 - Ljud

Vågrörelselära och optik

Kurslitteratur: University Physics by Young & Friedman

Harmonisk oscillator:	Kapitel 14.1 – 14.4
Mekaniska vågor:	Kapitel 15.1 – 15.8
Ljud och hörande:	Kapitel 16.1 – 16.9
Elektromagnetiska vågor:	Kapitel 32.1 & 32.3 & 32.4
Ljusets natur:	Kapitel 33.1 – 33.4 & 33.7
Stråloptik:	Kapitel 34.1 – 34.8
Interferens:	Kapitel 35.1 – 35.5
Diffraktion:	Kapitel 36.1 - 36.5 & 36.7

Vågrörelselära och optik

Tid	Må 02-nov	Ti 03-nov	On 04-nov	To 05-nov	Fr 06-nov
08-10	Kvantfysik (A)	Våglära/optik (A) kap 14	Kvantfysik (A)	Våglära/optik (A)	Kvantfysik (A)
10-12	Intro period 2 (A) Informationssökning (A)	Kvantfysik (A)	Våglära/optik kap 14+15 ÄFYA11 (L218)	Kvantfysik (A)	Kvantfysik (A) kap 15
13-15	Utvärdering (A) 12-13	Övningar Optik&Våg (L218-19)	SI gp6-10 (L219) ÄFYA11 (L218)	SI gp11-15 (L219)	Övningar Optik&Våg (L218-19)
15-17					

Tid	Må 09-nov	Ti 10-nov	On 11-nov	To 12-nov	Fr 13-nov
08-10	Kvantfysik (A)	Våglära/optik (A) kap 16	Våglära/optik (A) kap 16+32	Kvantfysik (A)	Kvantfysik (A)
10-12	Våglära/optik kap 15+16 ÄFYA11 (L218)	Kvantfysik (A)	Kvantfysik (A)	Våglära/optik (A) kap 32+33	Våglära/optik (A) kap 33
13-15	SI gp1-5 (L219) ÄFYA11 (L218)	Övningar Optik&Våg (L218-19)	ÄFYA11 (l218) SI gp6-10 (L219)	SI gp1-5 (L218) SI gp11-15 (L219)	Övningar Optik&Våg (L218-19)
15-17					

Tid	Må 16-nov	Ti 17-nov	On 18-nov	To 19-nov	Fr 20-nov
08-10	Kvantfysik (A)	Våglära/optik (A) kap 34	Kvantfysik (A)	Våglära/optik (A) kap 35	Våglära/optik (A) kap 36
10-12	Våglära/optik (A) kap 34	Kvantfysik (A)	Våglära/optik (A) kap 34+35	Våglära/optik (A) kap 36 ÄFYA11 (L218)	Kvantfysik (A)
13-15	SI gp6-10 (L219)	Övningar Optik&Våg (L218-19)	Seminar.gen.gång (A) 12-13 SI gp1-5 (L218) 13-15 SI gp11-15 (L219) 13-15	Labbintroduktion (A) O2-O3, K1-K3	Övningar Optik&Våg (L218-19)
15-17					

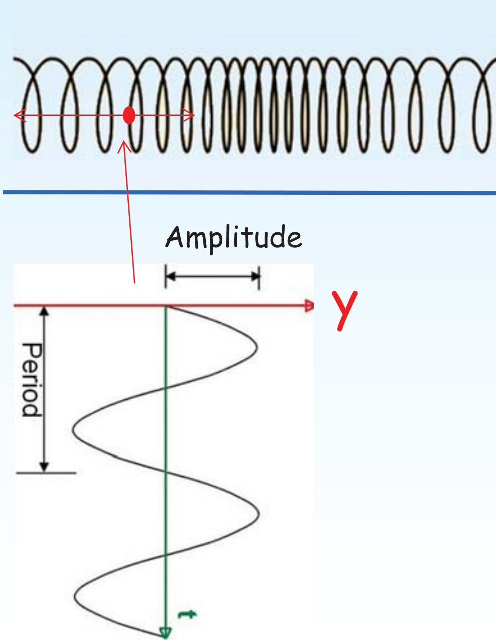
Sound & Pressure

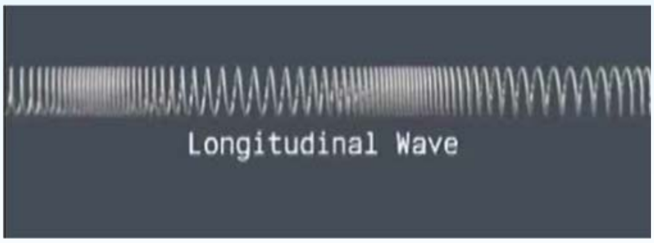
Sound as pressure waves

Sound & Pressure

Longitudinal sinusoidal wave

$v = \omega / k$





$$y(x,t) = A\cos(kx - \omega t)$$

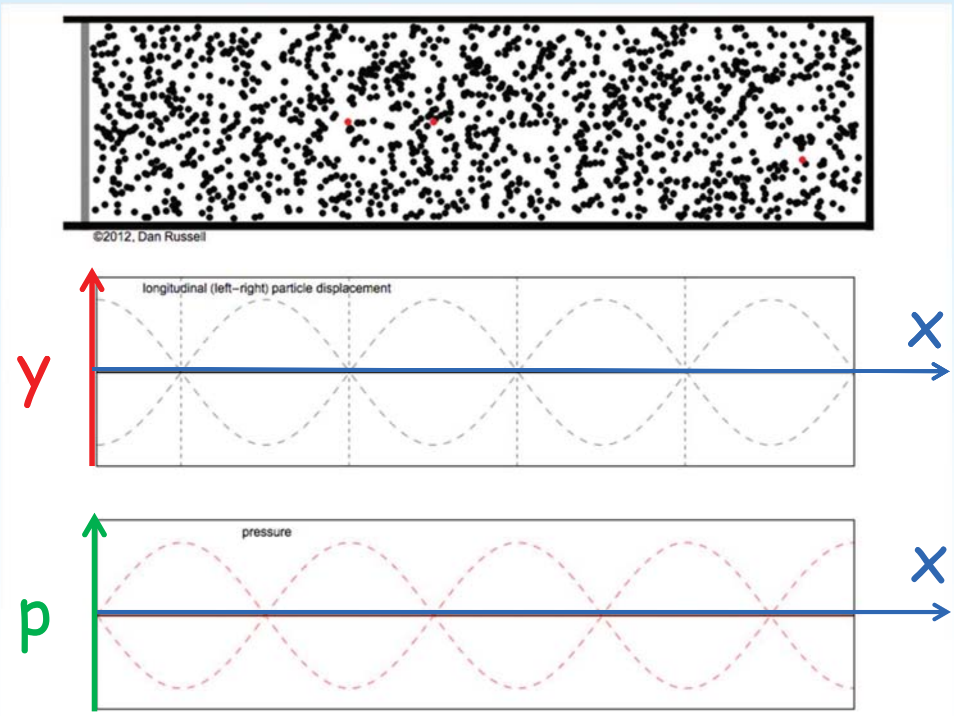
$k = 2\pi/\lambda \qquad \omega = 2\pi/T$

Sound & Pressure

Piston moving in and out:

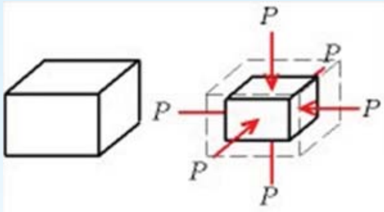
Air molecule movement:

Pressure:



Sound & Pressure

Bulk modulus



The bulk modulus measures a mediums resistance to uniform compression:

$$B = -V\frac{\Delta p}{\Delta V}$$

Δp → Pressure change

ΔV → Volyme change

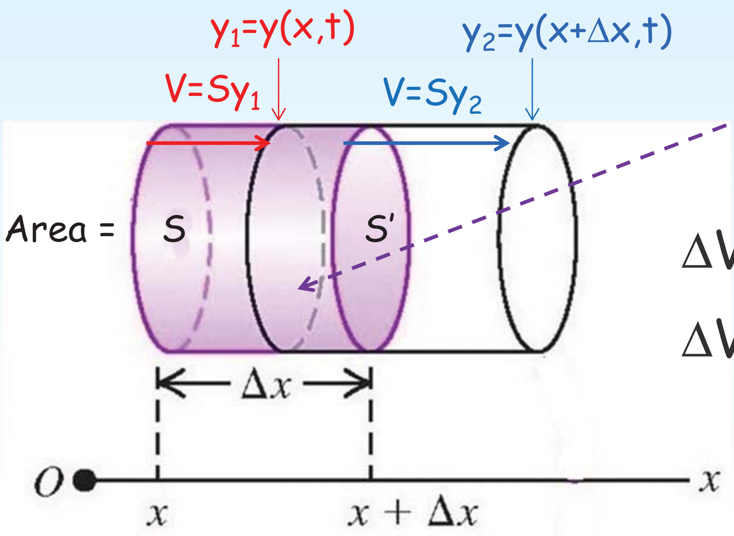
The change in pressure after a change of volume:

$$\Delta p = -B\,\Delta V/V$$

Pressure increase: $\Delta p > 0$ and $\Delta V < 0$

Sound & Pressure

A soundwave is moving the area S to y_1 and the area S' to y_2.

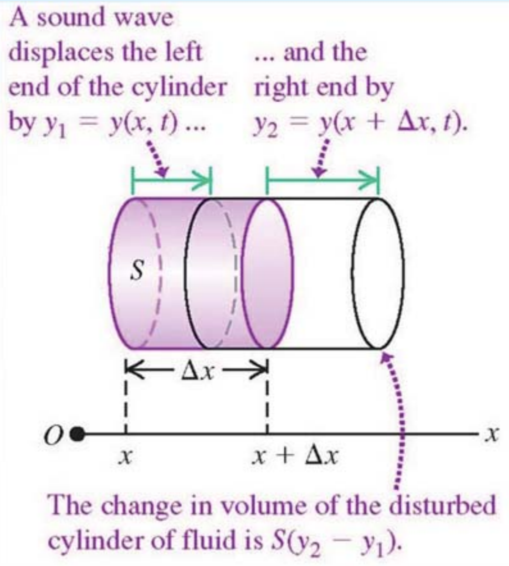


$$V = S\,\Delta x$$

$$\Delta V = Sy_2 - Sy_1$$

$$\Delta V = S[\,y(x+\Delta x,t) - y(x,t)]$$

Sound & Pressure



$$\Delta V = S(y_2 - y_1) = S[y(x + \Delta x, t) - y(x, t)]$$

$$V = S\,\Delta x$$

$$\frac{dV}{V} = \lim_{\Delta x \to 0} \frac{S[y(x + \Delta x, t) - y(x, t)]}{S\,\Delta x} = \frac{\partial y(x, t)}{\partial x}$$

$$\Delta p = -B\,\Delta V/V$$

Let $p(x, t)$ be the instantaneous pressure fluctuation

$$p(x, t) = -B\frac{\partial y(x, t)}{\partial x}$$

$$y(x, t) = A\cos(kx - \omega t)$$

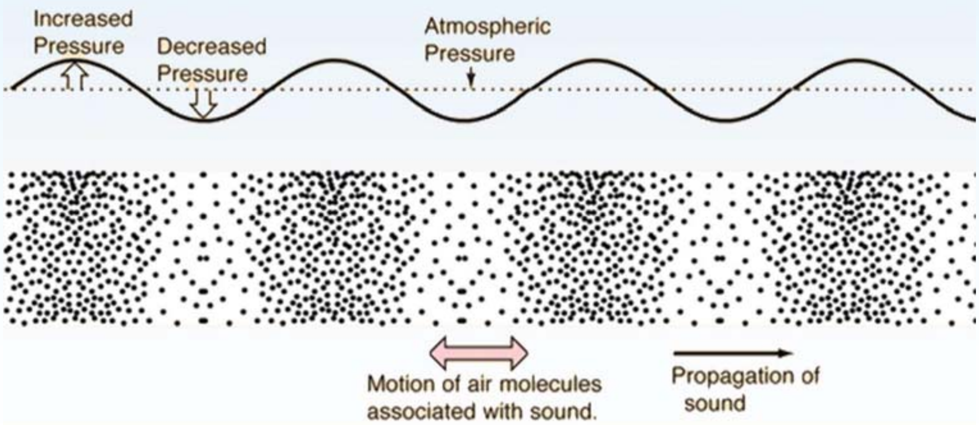
$$p(x, t) = BkA\sin(kx - \omega t)$$

Sound & Pressure

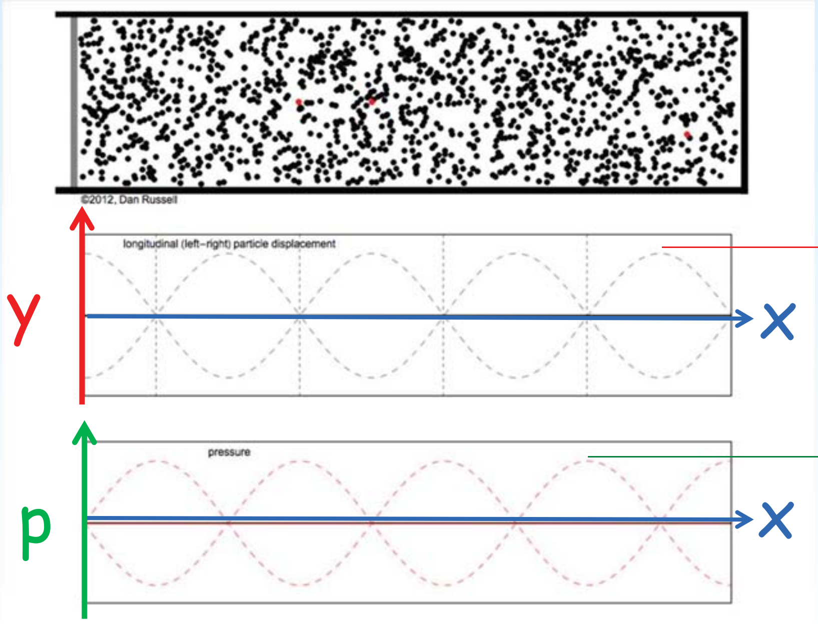
$$p(x, t) = BkA\sin(kx - \omega t)$$

The pressure amplitude
The maximum pressure fluctuation

$$p_{max} = BkA$$



Sound & Pressure



$$y(x,t) = A\cos(kx - \omega t)$$

$$p(x,t) = BkA\sin(kx - \omega t)$$

Sound & Pressure

Human hearing

Audible range: 20-20 kHz the human frequency range.

Loudness: Higher pressure amplitude ➡ Higher loudness
(at constant frequency)

Different frequency ➡ Different loudness
(at constant pressure amplitude)

Pitch: Higher frequency ➡ High pitch

Higher pressure amplitude ➡ Usually higher pitch

Timbre: Tone color or harmonic content.
Instruments with the same fundamental frequency can have different harmonic content.

Problem solving

In a sinusoidal sound wave of moderate loudness, the maximum pressure variations are about 3.0×10^{-2} Pa above and below atmospheric pressure. Find the corresponding maximum displacement if the frequency is 1000 Hz. In air at normal atmospheric pressure and density, the speed of sound is 344 m/s and the bulk modulus is 1.42×10^5 Pa.

$$k = \frac{\omega}{v} = \frac{2\pi f}{v} = \frac{(2\pi \text{ rad})(1000 \text{ Hz})}{344 \text{ m/s}} = 18.3 \text{ rad/m}$$

$$p_{max} = BkA$$

$$A = \frac{p_{max}}{Bk} = \frac{3.0 \times 10^{-2} \text{ Pa}}{(1.42 \times 10^5 \text{ Pa})(18.3 \text{ rad/m})} = 1.2 \times 10^{-8} \text{ m}$$

The velocity of sound in a liquid

Kinematics

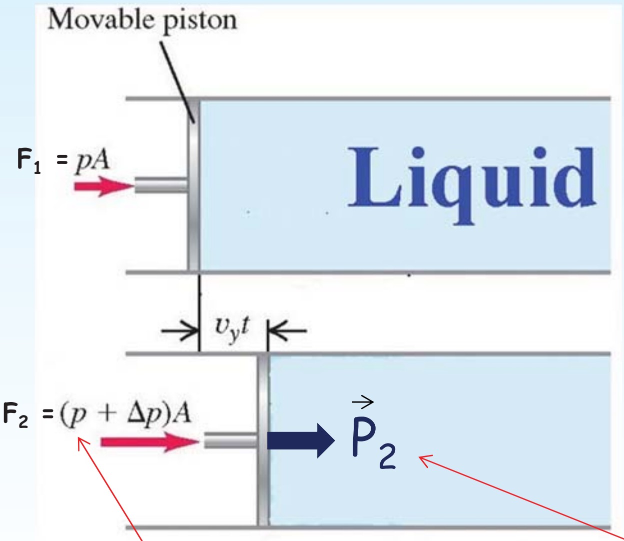
Momentum: $\vec{p} = m\vec{v}$

Impuls: $\vec{J} = \int_{t_1}^{t_2} \Sigma \vec{F}\, dt$

The Momentum-Impuls theorem: $\vec{J} = \vec{p}_2 - \vec{p}_1$

The impulse is equal to the change of momentum !

Sound - velocity



$$\vec{J} = \int_{t_1}^{t_2} \Sigma \vec{F}\, dt$$

$$\vec{J} = (\vec{F}_2 - \vec{F}_1)\, t = \Delta p\, A\, t$$

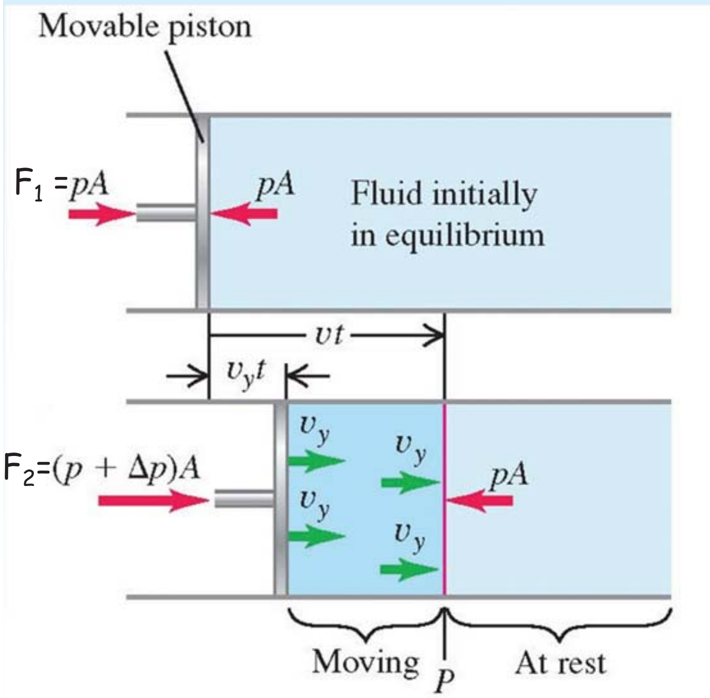
$$\vec{J} = \vec{p}_2 - \vec{p}_1$$

$$\vec{J} = \vec{P}_2 - \vec{P}_1 = \vec{P}_2 - 0 = m\, v_y$$

Pressure

Momentum

Sound - velocity

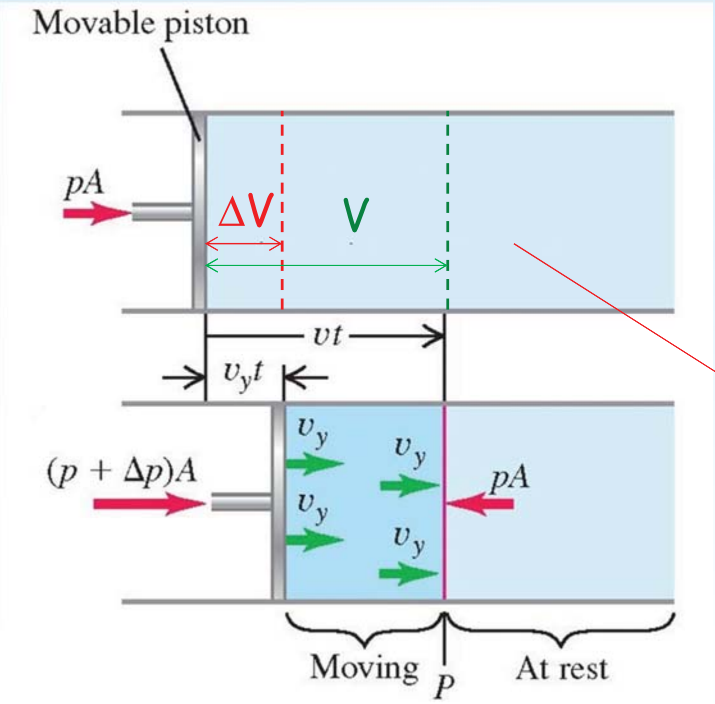


Sound in a liquid

Time = 0:
P: pressure in the liquid
A: area of the piston
F_1: force on the piston
ρ: density of the liquid

Time = t:
v_y = velocity of the piston
v = velocity of the wave
$v_y t$ = distance the piston has moved
vt = distance the wave has moved
Δp = increase of pressure
F_2: force on the piston

Sound - velocity



The bulk modulus measures a mediums resistance to uniform compression:

$$B = -V\frac{\Delta p}{\Delta V}$$

Δp → Pressure change

ΔV → Volyme change

$$\Delta p = -B\,\Delta V / V$$

$V = A v t$

$\Delta V = -A v_y t$

Volume is decreasing

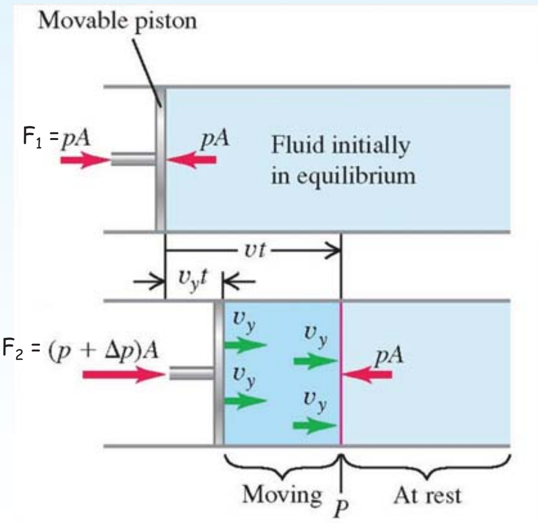
$$\Delta p = B\frac{v_y}{v}$$

Sound - velocity

$$\vec{J} = \int_{t_1}^{t_2} \Sigma\vec{F}\,dt$$

$$\vec{J} = (\vec{F}_2 - \vec{F}_1)\,t = \Delta p\,A\,t = B\,A\,t\,v_y / v$$

$$\Delta p = B\frac{v_y}{v}$$



$$\vec{J} = \vec{p}_2 - \vec{p}_1 = \vec{p}_2 \qquad \vec{p} = m\vec{v}$$

$$\vec{J} = \vec{P}_2 = m\,v_y = \rho\,V\,v_y = \rho\,A\,v\,t\,v_y$$

$$\vec{J} = \vec{J} \qquad B\frac{v_y}{v}At = \rho v t A v_y$$

$$v = \sqrt{\frac{B}{\rho}} \quad \text{(speed of a longitudinal wave in a fluid)}$$

Sound - velocity

General: $$v = \sqrt{\frac{\text{Restoring force returning the system to equilibrium}}{\text{Inertia resisting the return to equilibrium}}}$$

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

F: String tension
μ: Mass per unit length

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

B: Bulk modulus
ρ: Density

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

Y: Young's module
ρ: Density

Gas: $$v = \sqrt{\frac{B}{\rho}} = \sqrt{\frac{\gamma P}{\rho}} = \sqrt{\frac{\gamma RT}{M}}$$

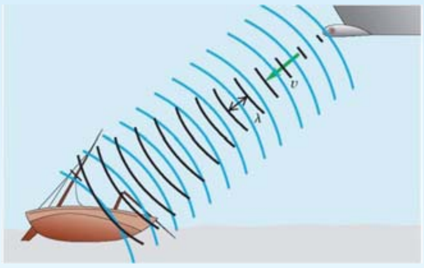
γ: Adiabatic index
P: Pressure = nRT / V
ρ: Density = m/V
R: Gas constant = 8.31 J/mol per K
T: Absolute temperature in K
M: Molar mass = m / n

Sound & Problems

Problem solving

Sound & Problems

A ship uses a sonar system to locate underwater objects. Find the speed of sound waves in water and find the wavelength of a 262-Hz wave. $B = 2.18 \cdot 10^9$ Pa for water



$$v = \sqrt{\frac{B}{\rho}} = \sqrt{\frac{2.18 \times 10^9 \text{ Pa}}{1.00 \times 10^3 \text{ kg/m}^3}} = 1480 \text{ m/s}$$

$$\lambda = \frac{v}{f} = \frac{1480 \text{ m/s}}{262 \text{ s}^{-1}} = 5.65 \text{ m}$$

Sound & Problems

Find the speed of sound in air at $T = 20°\text{C}$, and find the range of wavelengths in air to which the human ear (which can hear frequencies in the range of 20–20,000 Hz) is sensitive. The mean molar mass for air (a mixture of mostly nitrogen and oxygen) is $M = 28.8 \times 10^{-3}$ kg/mol and the ratio of heat capacities is $\gamma = 1.40$

$$T = 20°\text{C} = 293 \text{ K}$$

$$v = \sqrt{\frac{\gamma RT}{M}} = \sqrt{\frac{(1.40)(8.314 \text{ J/mol} \cdot \text{K})(293 \text{ K})}{28.8 \times 10^{-3} \text{ kg/mol}}} = 344 \text{ m/s}$$

$\lambda = v / f$

$\lambda = 344 / 20 = 17$ m for f = 20 Hz

$\lambda = 344 / 20000 = 1.7$ cm for f = 20 kHz

The power and intensity of sound

The power in general: $P = \vec{F} \cdot \vec{v}$ (instantaneous rate at which force $\vec{F}$ does work on a particle)

Wave power (P):
The instantaneous rate at which energy is transfered along the wave.

Unit: W or J/s

$$P(x,t) = F_y(x,t)v_y(x,t) = -F\frac{\partial y(x,t)}{\partial x}\frac{\partial y(x,t)}{\partial t}$$

Wave intensity (I):
Average power per unit area through a surface perpendicular to the wave direction.

Unit: W/m^2

$$I = P_{av} / A_{rea}$$

Sound – power & intensity

The wave function:

$$y(x,t) = A\cos(kx - \omega t)$$

$$v_y(x,t) = \frac{\partial y(x,t)}{\partial t} = \omega A \sin(kx - \omega t)$$

The pressure function:

$$p(x,t) = BkA\sin(kx - \omega t)$$

Pressure is equal to force per unit area

The wave power:

$$P(x,t) = F_y(x,t)v_y(x,t)$$

The wave power per unit area:

$$\mathrm{P(x,t)} = p(x,t)v_y(x,t) = [BkA\sin(kx - \omega t)][\omega A\sin(kx - \omega t)] = B\omega kA^2\sin^2(kx - \omega t)$$

Sound – power & intensity

The wave power per unit area:

$$\mathrm{P(x,t)} = B\omega kA^2\sin^2(kx - \omega t)$$

Intensity = Average wave power per unit area:

$$I = P_{av} / A_{rea} = \tfrac{1}{2} B \omega k A^2$$

Because the average of $\sin^2(x)$ is $\frac{1}{2}$

$$v = \omega / k$$

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

$$k = \omega / \sqrt{\frac{B}{\rho}}$$

$$I = \tfrac{1}{2}\sqrt{\rho B}\,\omega^2 A^2$$ (intensity of a sinusoidal sound wave)

Sound – power & intensity

$$I = \frac{1}{2}\sqrt{\rho B}\,\omega^2 A^2 \quad \text{(intensity of a sinusoidal sound wave)}$$

The pressure amplitude
The maximum pressure fluctuation $p_{max} = BkA$

$k = \omega / \sqrt{\frac{B}{\rho}}$

$p_{max} = B\,A\,\omega / \sqrt{\frac{B}{\rho}} \Longrightarrow A^2\omega^2 = p_{max}^2 / (\rho B)$

$$I = \frac{p_{max}^2}{2\sqrt{\rho B}}$$

The intensity is proportional to the square of the pressure amplitude

Sound & Problems

Problem solving

Sound & Problems

Find the intensity of the sound wave with $p_{max} = 3.0 \times 10^{-2}$ Pa. Assume the temperature is 20°C so that the density of air is $\rho = 1.20\ kg/m^3$ and the speed of sound is $v = 344\ m/s$.

$$I = \frac{p_{max}^2}{2\sqrt{\rho B}}$$

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

$$I = \frac{p_{max}^2}{2\rho v} = \frac{(3.0 \times 10^{-2}\ Pa)^2}{2(1.20\ kg/m^3)(344\ m/s)}$$
$$= 1.1 \times 10^{-6}\ J/(s \cdot m^2) = 1.1 \times 10^{-6}\ W/m^2$$

Sound & Problems

What are the pressure and displacement amplitudes of a 20-Hz sound wave with the same intensity as the 1000-Hz sound wave of

$p_{max} = 3.0 \times 10^{-2}$ Pa, $\rho = 1.20\ kg/m^3$, $v = 344\ m/s$, $I = 1.1 \times 10^{-6}\ W/m^2$

$I = ½ P_{max}^2 / \sqrt{\rho B}$

since $\sqrt{\rho B}$ is a constant P_{max} is the same if I is the same.

$P_{max} = 3.0 \cdot 10^{-2}$ Pa

$$I = \frac{1}{2}\sqrt{\rho B}\,\omega^2 A^2 \quad \text{(intensity of a sinusoidal sound wave)}$$

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

$$I = v\rho\omega^2 A^2 / 2 \Rightarrow A^2 = 2I / (v\rho\omega^2)$$

$$A^2 = 2 \times 1.1 \times 10^{-6} / (344 \times 1.20 \times (40\pi)^2) \qquad A = 0.60\ \mu m$$

Sound & Problems

For an outdoor concert we want the sound intensity to be 1 W/m^2 at a distance of 20 m from the speaker array. If the sound intensity is uniform in all directions, what is the required acoustic power output of the array?

Intensity is average power per unit area $\qquad I = P_{av} / A_{rea}$

The intensity through a sphere with radius r $\qquad I = \frac{P}{4\pi r^2}$

The intensity through a hemisphere with radius r $\qquad I = \frac{P}{2\pi r^2}$

$$P = 2\pi r^2 I = 2.5 \text{ kW}$$

Sound - Decibel

The decibel scale of the intensity

Sound - Decibel

Intensity in the unit of decibel (dB)

$$\beta = (10\text{ dB})\log\frac{I}{I_0} \qquad \text{(definition of sound intensity level)}$$

$I_0 = 10^{-12}$ W/m^2 is a reference intensity
It is roughfly the threshold of human hearing

β = 0 dB for $I = I_0$
β = 120 dB for I = 1 W/m^2

Sound - Decibel

Source or Description of Sound	Sound Intensity Level, β (dB)	Intensity, I (W/m^2)
Military jet aircraft 30 m away	140	10^2
Threshold of pain	120	1
Riveter	95	3.2×10^{-3}
Elevated train	90	10^{-3}
Busy street traffic	70	10^{-5}
Ordinary conversation	65	3.2×10^{-6}
Quiet automobile	50	10^{-7}
Quiet radio in home	40	10^{-8}
Average whisper	20	10^{-10}
Rustle of leaves	10	10^{-11}
Threshold of hearing at 1000 Hz	0	10^{-12}

Problem solving

A 10-min exposure to 120-dB sound will temporarily shift your threshold of hearing at 1000 Hz from 0 dB up to 28 dB. Ten years of exposure to 92-dB sound will cause a *permanent* shift to 28 dB. What sound intensities correspond to 28 dB and 92 dB?

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

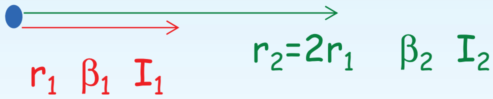
$$I = I_0 10^{\beta/10}$$

$I_0 = 10^{-12}$ W/m^2

$$I_{28\text{ dB}} = (10^{-12}\text{ W/m}^2)10^{2.8} = 6.3 \times 10^{-10}\text{ W/m}^2$$
$$I_{92\text{ dB}} = (10^{-12}\text{ W/m}^2)10^{9.2} = 1.6 \times 10^{-3}\text{ W/m}^2$$

Sound & Problems

Consider an idealized bird (treated as a point source) that emits constant sound power, with intensity obeying the inverse-square law If you move twice the distance from the bird, by how many decibels does the sound intensity level drop?



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

$$\begin{aligned}\beta_2 - \beta_1 &= (10\text{ dB})\left(\log\frac{I_2}{I_0} - \log\frac{I_1}{I_0}\right)\\ &= (10\text{ dB})[(\log I_2 - \log I_0) - (\log I_1 - \log I_0)]\\ &= (10\text{ dB})\log\frac{I_2}{I_1}\end{aligned}$$

$$\frac{I_1}{I_2} = \frac{r_2^{\,2}}{r_1^{\,2}} \quad \text{(inverse-square law for intensity)}$$

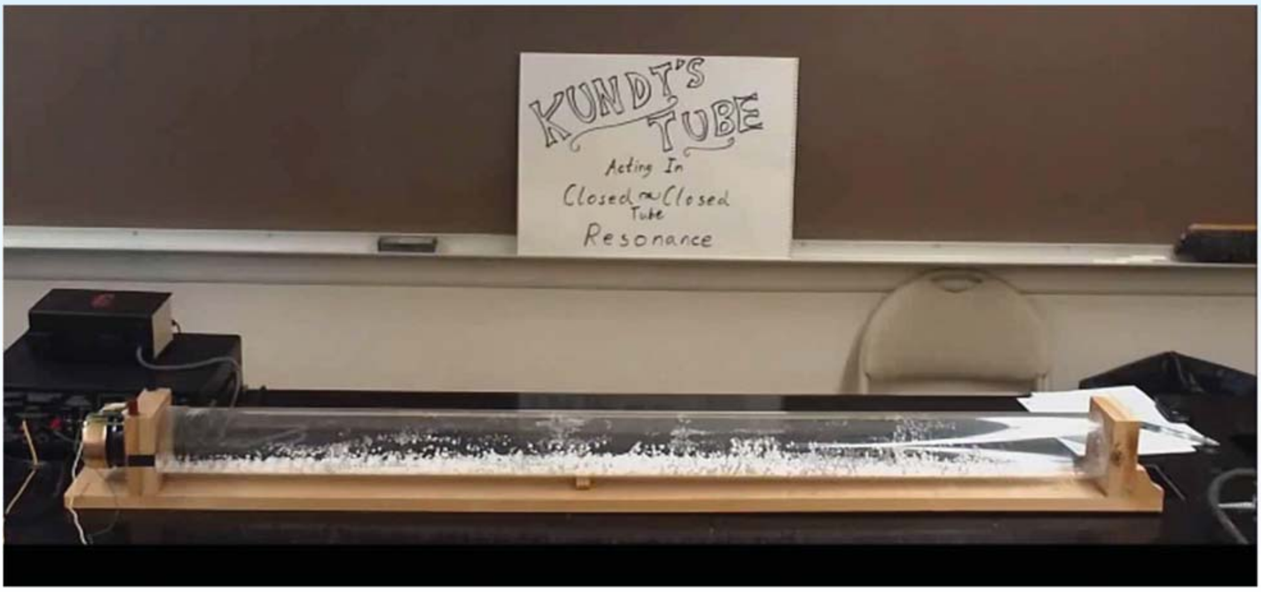
$$\beta_2 - \beta_1 = (10\text{ dB})\log\frac{I_2}{I_1} = (10\text{ dB})\log\tfrac{1}{4} = -6.0\text{ dB}$$

Sound – Standing waves

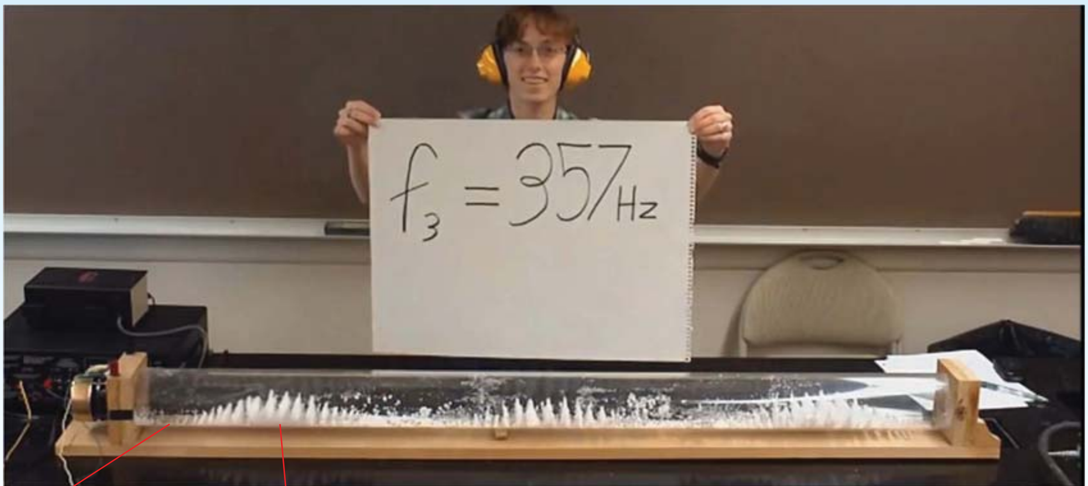
Sound and standing waves

Sound – Standing waves

Kundt's tube



Sound – Standing waves



Displacement antinode	Displacement node
Maximum movement	Minimum movement
Minimum pressure changes	Maximum pressure changes

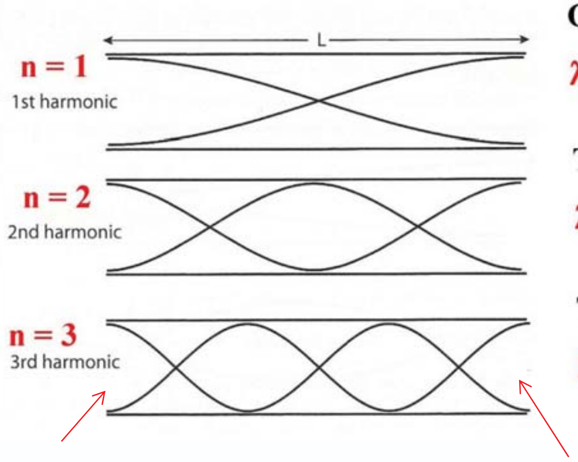
λ = 95 cm

$v = \lambda f = 0.95 \times 357 = 339$ m/s

Sound – Standing waves

Standing wave in an open pipe

$\lambda_n = \frac{2}{n}L$ $f_n = \frac{v}{\lambda_n}$ where the velocity (v) is the same for all n



Antinode Antinode

One half wave

$\lambda_1 = \frac{2}{1}L$ $f_1 = \frac{v}{\lambda_1} = \frac{v}{2L}$

Two half waves

$\lambda_2 = \frac{2}{2}L$ $f_2 = \frac{v}{\lambda_2} = \frac{v}{L} = 2f_1$

Three half wave

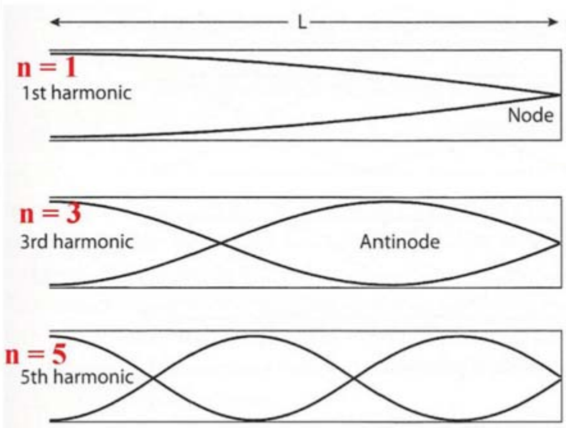
$\lambda_3 = \frac{2}{3}L$ $f_3 = \frac{v}{\lambda_3} = \frac{v}{2/3L} = 3f_1$

Sound – Standing waves

Standing wave in a closed pipe

$\lambda_n = \frac{4}{n}L$ $f_n = \frac{v}{\lambda_n}$ where the velocity (v) is the same for all n

Here the pressure is atmospheric giving displacement antinode (pressure node)



One quarter wave

$\lambda_1 = \frac{4}{1}L$ $f_1 = \frac{v}{\lambda_1} = \frac{v}{4L}$

Three quarter wave

$\lambda_3 = \frac{4}{3}L$ $f_3 = \frac{v}{\lambda_2} = \frac{v}{4/3L} = 3f_1$

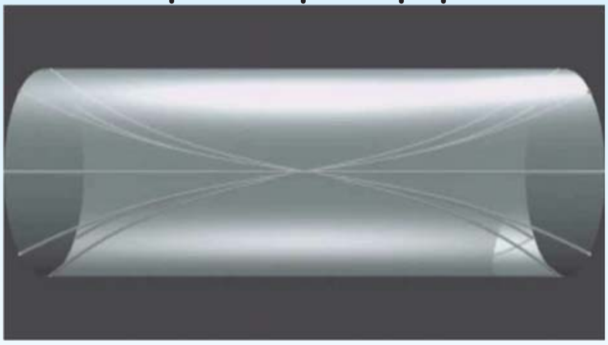
Five quarter wave

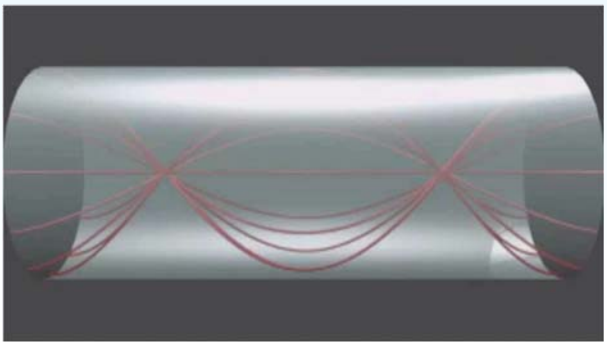
$\lambda_5 = \frac{4}{5}L$ $f_5 = \frac{v}{\lambda_5} = \frac{v}{4/5L} = 5f_1$

NOTE that n = 2, 4, 6 cannot happen in a closed pipe

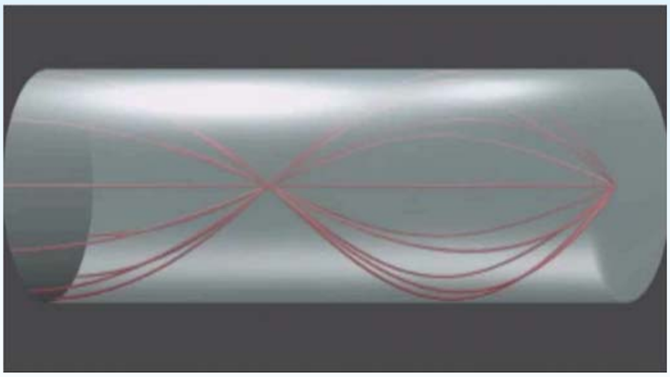
Sound – Standing waves

Open-open pipe





Open-closed pipe



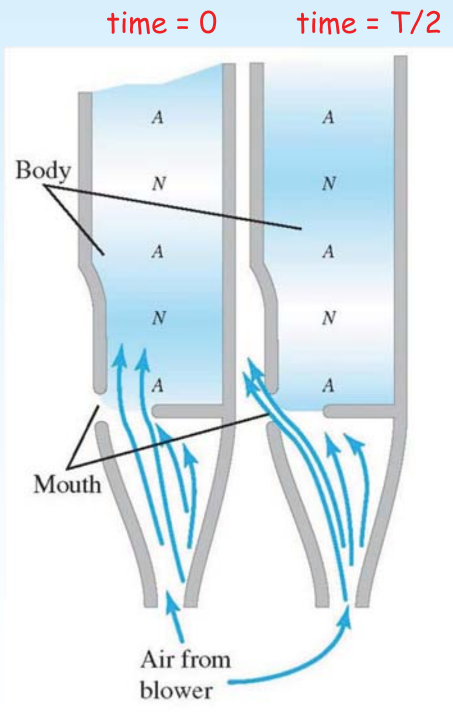
Sound – Standing waves

Organpipe: Airflow from below.

Standing wave: If the airspeed and pipelengths are choosen correctly.

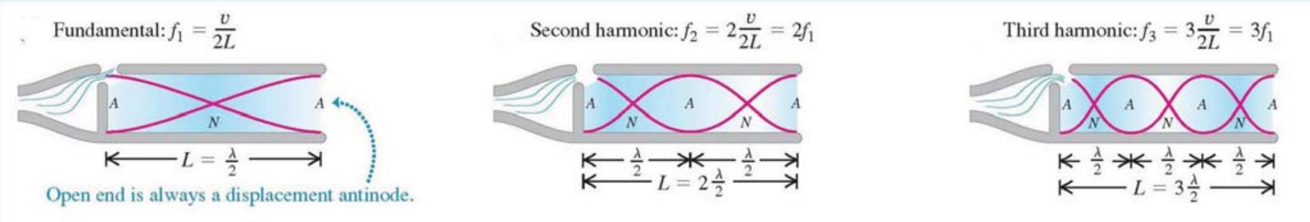
Mouth: Pipe is open at the bottom and gives a pressure node (displacement antinode).

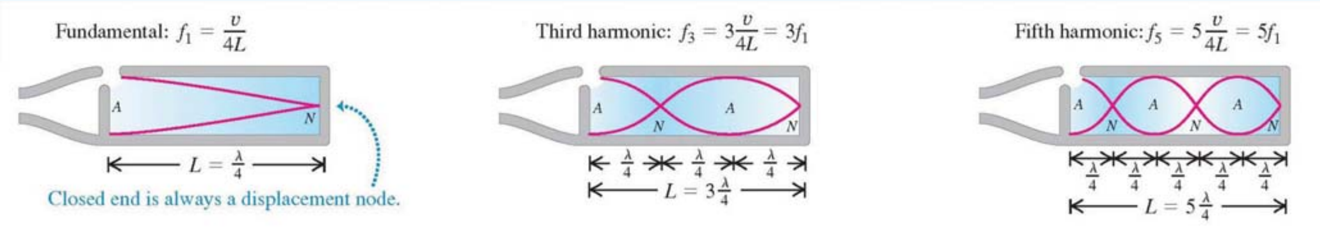
Airflow: Depending on time the air flow will either go into the pipe or out through the mouth.



Sound – Standing waves

The pipe can be open-open or open-closed





Remember: The distance between two nodes is $\lambda/2$

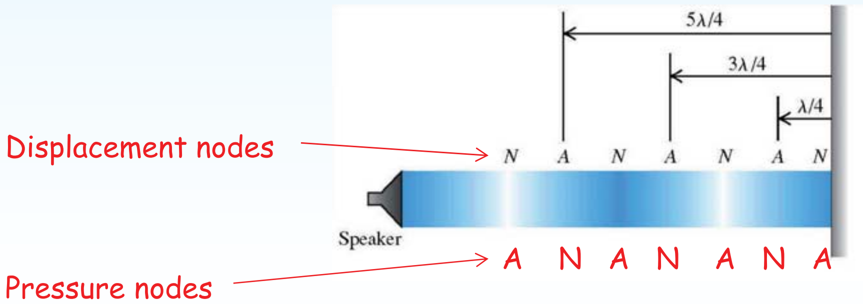
Sound & Problems

Problem solving

Sound & Problems

A directional loudspeaker directs a sound wave of wavelength λ at a wall   At what distances from the wall could you stand and hear no sound at all?

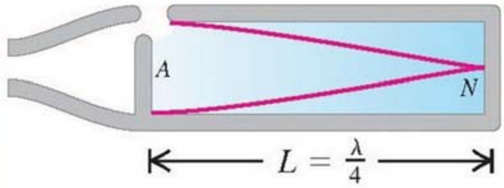
Your ear detects pressure variations in the air; you will therefore hear no sound if your ear is at a *pressure node*, which is a displacement antinode. The wall is at a displacement node



Sound & Problems

On a day when the speed of sound is 345 m/s, the fundamental frequency of a particular stopped organ pipe is 220 Hz.   How long is this pipe?

Fundamental: $f_1 = \frac{v}{4L}$



$$L_{\text{stopped}} = \frac{v}{4f_1} = \frac{345\ \text{m/s}}{4(220\ \text{s}^{-1})} = 0.392\ \text{m}$$

Sound & Problems

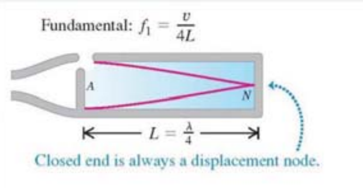
The second *overtone* of this pipe has the same wavelength as the third *harmonic* of an *open* pipe. How long is the open pipe?

$v = 345$ m/s

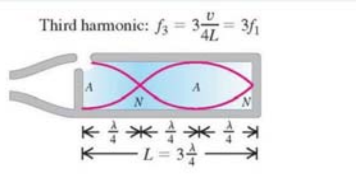
$f_1 = 220$ Hz

$L_{stopped} = 0.932$ m

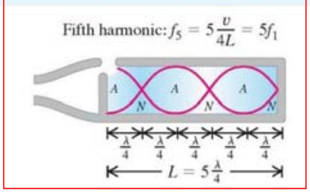
Fundamental frequency



First overtone

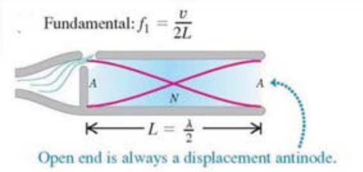


Second overtone

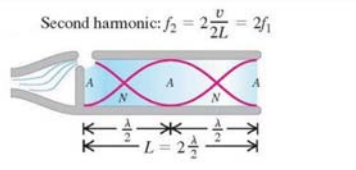


$f_5 = 5f_1 = 1100$ Hz

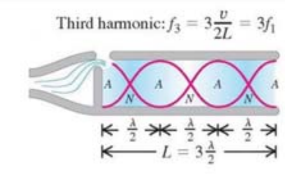
Fundamental



Second harmonic



Third harmonic



$v = 345$ m/s

$f_3 = 1100$ Hz

$L_{open} = 3v / (2f_3) = 0.470$ m

Sound – Resonance

Sound and resonance

Sound & Problems

Resonance

Many mechanical systems have normal mode frequencies of oscillation. In these modes every particle in the system oscillates with simple harmonic oscillation.

If an outside drivingforce is applied that varies with a normal mode frequency then the system is in resonance and the amplitude of the oscillations can increase.

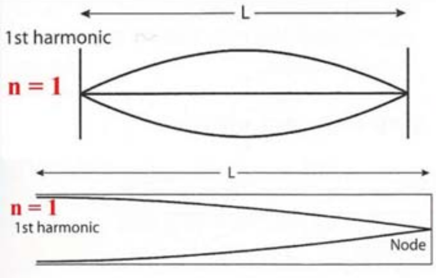
In this case the drivingforce is continuously adding energy to the system.

Sound & Problems

Problem solving

Sound & Problems

A stopped organ pipe is sounded near a guitar, causing one of the strings to vibrate with large amplitude. We vary the string tension until we find the maximum amplitude. The string is 80% as long as the pipe. If both pipe and string vibrate at their fundamental frequency, calculate the ratio of the wave speed on the string to the speed of sound in air.



One half wave

$\lambda_1 = \frac{2}{1}L \quad f_1 = \frac{v}{\lambda_1} = \frac{v}{2L}$ → $v_{string} = 2L_{string}\, f_{string}$

One quarter wave

$\lambda_1 = \frac{4}{1}L \quad f_1 = \frac{v}{\lambda_1} = \frac{v}{4L}$ → $v_{pipe} = 4L_{pipe}\, f_{pipe}$

$v_{string} / v_{pipe} = 2L_{string}\, f_{string} / 4L_{pipe}\, f_{pipe}$

$f_{string} = f_{pipe}$

$L_{string} = 0.80\, L_{pipe}$

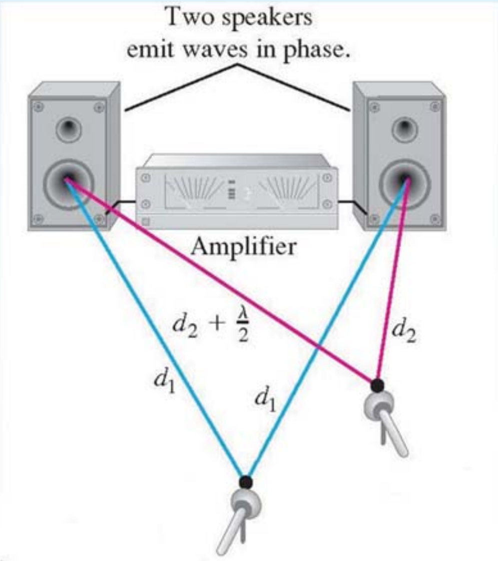
$v_{string} / v_{pipe} = 2 \cdot 0.80 L_{pipe}\, f_{pipe} / 4L_{pipe}\, f_{pipe} = 0.40$

Sound – Interference

Sound and interference

Sound – Interference

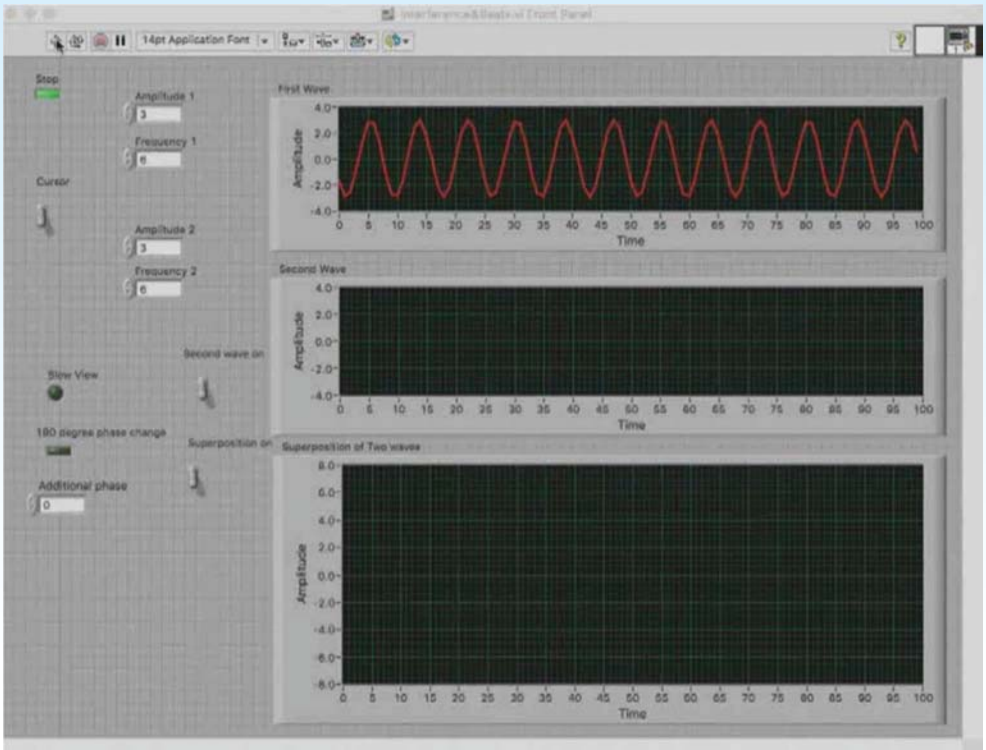
Interference



Two waves that arrives at a point where the distance is different with nλ (n=0,1,2,3...) undergo contructive interference and have a doubled amplitude.

Two waves that arrives at a point where the distance is different with nλ/2 (n=1,3,5...) undergo destructive interference and have a zero amplitude.

Sound – Interference

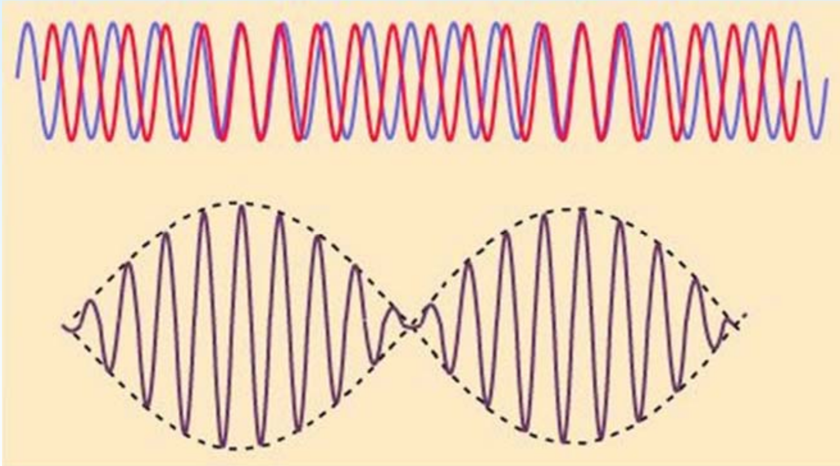


Sound – Interference

BEAT: If two sound waves with slighty different frequencies are added up they give a sound that is going up and down in intensity.

Two waves with different frequency

Their superposition



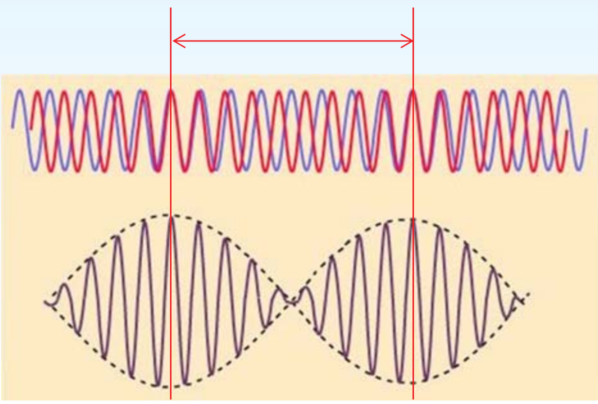
This pulsating sound is only heard if the difference in frequency is < 7 Hz

Sound – Interference

What is the frequency of the beat ?

$T_{beat} = 9T_{red} = 8T_{blue}$

$T_{beat} = nT_a = (n-1)T_b$



$f_{beat} = f_a/n = f_b/(n-1)$

$f_{beat} = f_b/(n-1)$

$n = 1 + f_b/f_{beat} = (f_b + f_{beat}) / f_{beat}$

$f_{beat} = f_a/n$

$f_{beat} = f_a / [(f_b+f_{beat}) / f_{beat}] = f_a\, f_{beat} / (f_b+f_{beat})$

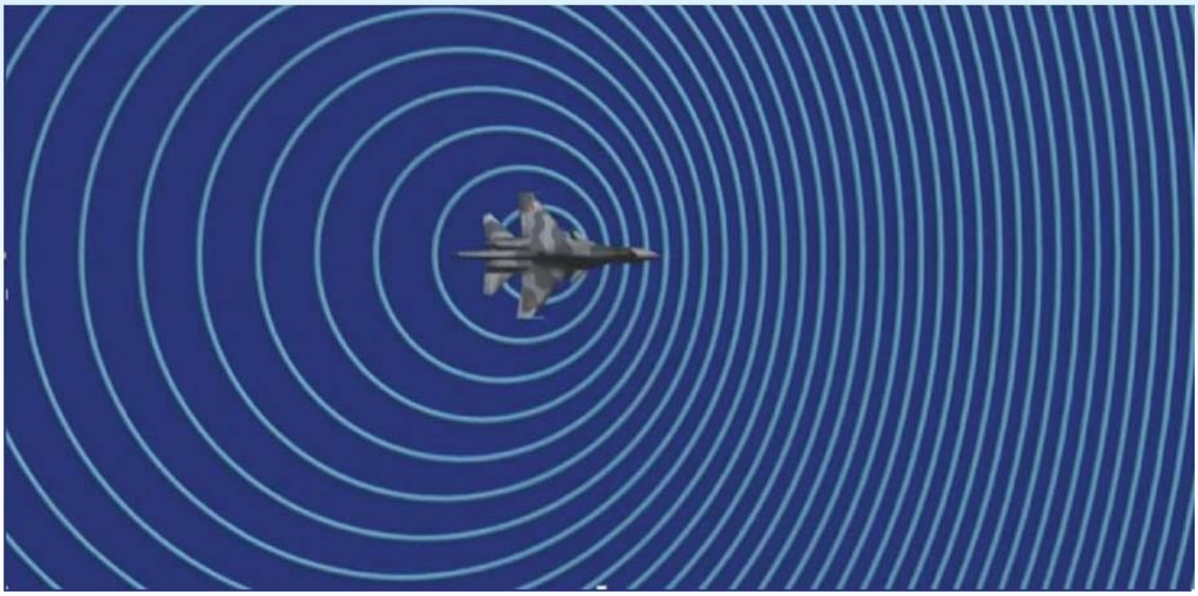
$1 = f_a / (f_b+f_{beat})$

$f_{beat} = f_a - f_b$

The Doppler effect

Sound – Doppler effect

Doppler effect



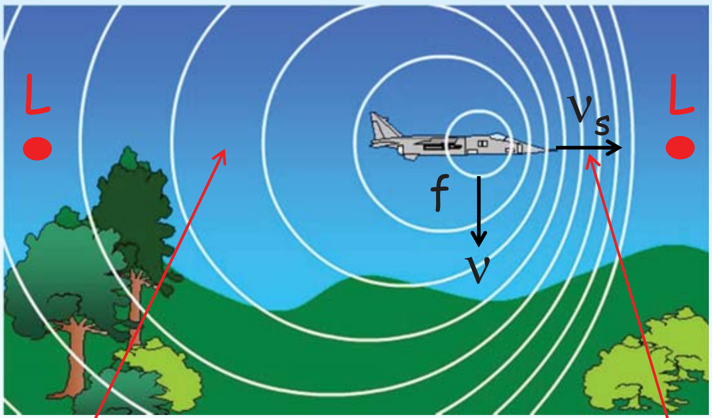
Sound – Doppler effect

The time for a sound wave to reach a listener (L) gets longer if the source (S) is moving away.

⇓

λ_{behind} longer

$$\lambda_{behind} = \frac{v + v_S}{f}$$



$$v = \lambda / T = \lambda f$$

$$\lambda = v / f$$

$$f = v / \lambda$$

The time for a sound wave to reach a listener (L) gets shorter if the source is moving closer.

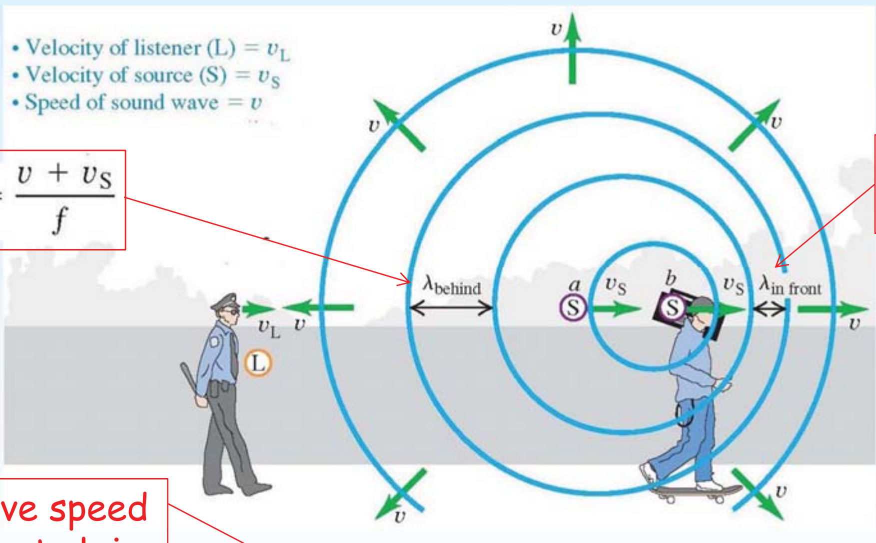
⇓

$\lambda_{in\ front}$ shorter

$$\lambda_{in\ front} = \frac{v - v_S}{f}$$

Sound – Doppler effect

What if the listener is also moving ?



$$\lambda_{behind} = \frac{v + v_S}{f}$$

$$\lambda_{in\ front} = \frac{v - v_S}{f}$$

The wave speed relative to L is $v + v_L$

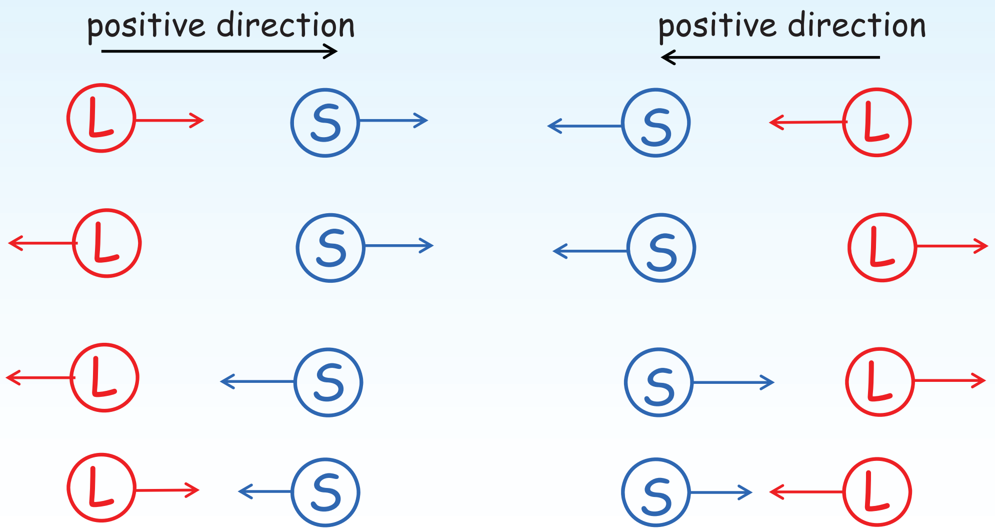
$$f_L = \frac{v + v_L}{\lambda_{behind}} = \frac{v + v_L}{(v + v_S)/f} = \frac{v + v_L}{v + v_S} f$$

change in frequency

Sound – Doppler effect

$$f_L = \frac{v + v_L}{v + v_S} f_S$$

always works if the positive direction is defined as going from the listener to the source.



$$f_L = \frac{v + v_L}{v + v_S} f_S$$

$$f_L = \frac{v - v_L}{v + v_S} f$$

$$f_L = \frac{v - v_L}{v - v_S} f$$

$$f_L = \frac{v + v_L}{v - v_S} f$$

Sound – Doppler effect

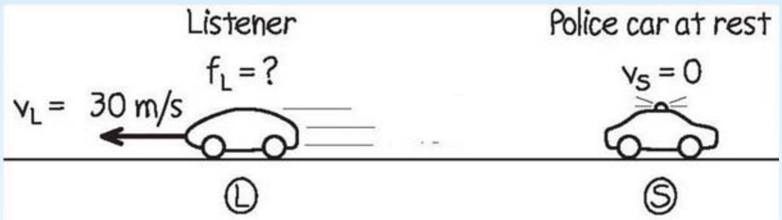
Electromagnetic waves such as light also have a Doppler shift. It can be calculated using the theory of relativity:

$$f_O = \sqrt{\frac{c - v}{c + v}} f_S$$

f_s = the frequency of the source
f_o = the frequency detected by an observer
c = the speed of light
v = the relative velocity of the source with respect to the observer

v is positive if the observer and the source is moving apart
v is negative if the observer and the source is moving towards each other

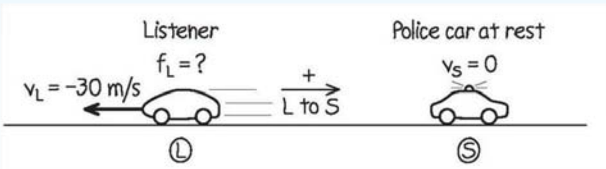
Problem solving



f = 300 Hz

speed of sound = 340 m/s

What frequency does the listener hear ?



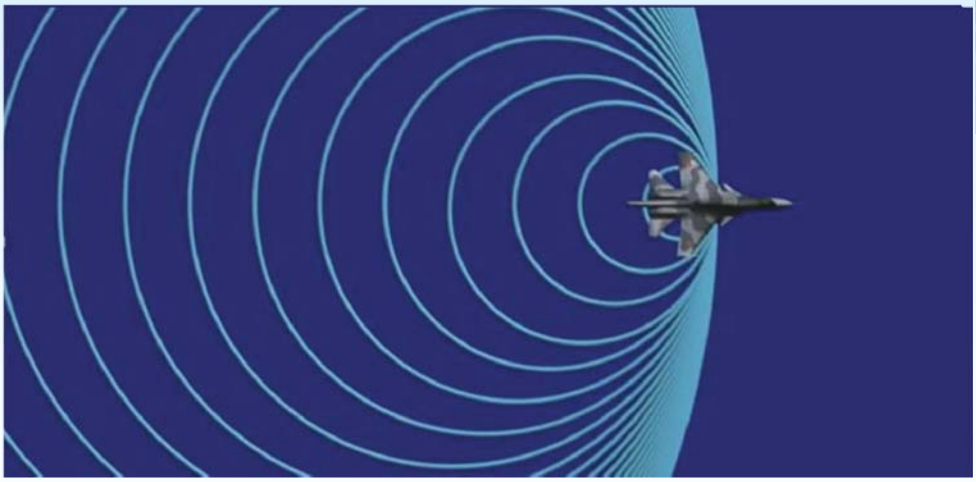
$$f_L = \frac{v + v_L}{v + v_S} f = \frac{340 \text{ m/s} + (-30 \text{ m/s})}{340 \text{ m/s}} (300 \text{ Hz}) = 274 \text{ Hz}$$

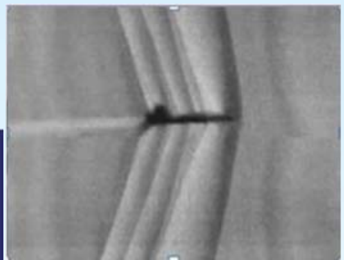
Sound – shockwave

Shockwave

Sound – shockwave

Shock waves





$$\lambda_{\text{in front}} = \frac{v - v_S}{f}$$

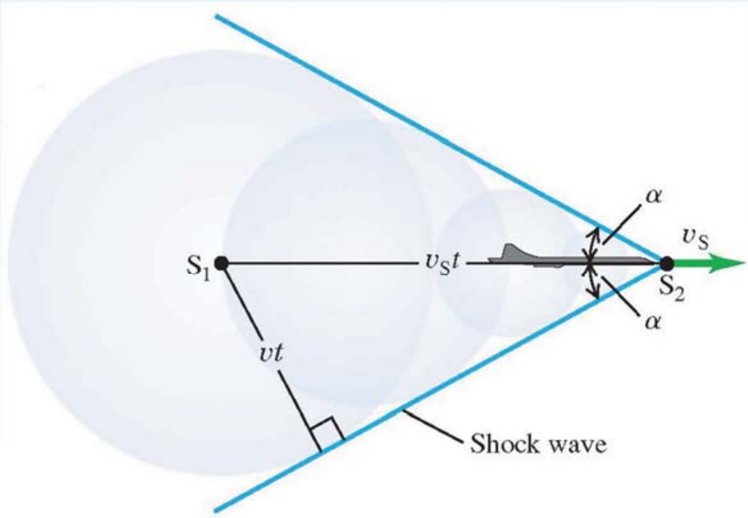
v: Speed of sound
v_s: Speed of the plane

$v_s > v$ Shockwave is created (not only when $v_s = v$)
$v_s > v$ No sound in front of the plane

Sound

A conical shock wave is produced if a plane flies faster than the speed of sound.

A series of circular wave crests from the plane interfere constructively along a line that is given by an angle α.



ν: Speed of sound
ν_s: Speed of the plane

Speed of the plane in Mach number:

$N_M = \nu_s/\nu$

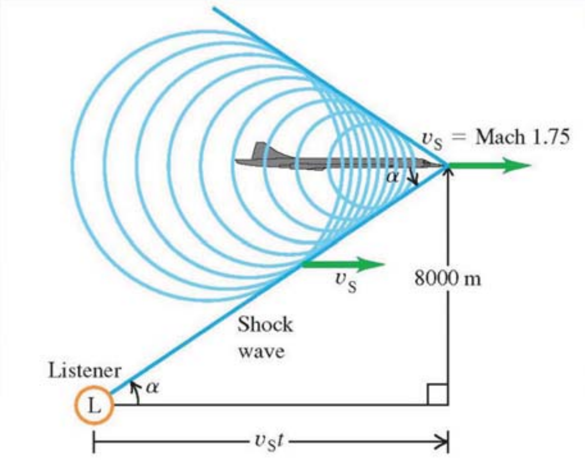
$$\sin\alpha = \frac{vt}{v_S t} = \frac{v}{v_S}$$

Sound & Problems

Problem solving

Sound & Problems

An airplane is flying at Mach 1.75 at an altitude of 8000 m, where the speed of sound is 320 m/s. How long after the plane passes directly overhead will you hear the sonic boom?



$$N_M = v_s/v = 1.75$$

$$v_S = (1.75)(320\ \mathrm{m/s}) = 560\ \mathrm{m/s}$$

$$\sin\alpha = v / v_s = 1 / N_M = 1 / 1.75$$

$$\alpha = \arcsin\frac{1}{1.75} = 34.8^\circ$$

$$\tan\alpha = \frac{8000\ \mathrm{m}}{v_S t}$$

$$t = \frac{8000\ \mathrm{m}}{(560\ \mathrm{m/s})(\tan 34.8^\circ)} = 20.5\ \mathrm{s}$$