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.

$$I = \frac{p_0^2}{2\rho v} \qquad \Delta p_m = (v\rho\omega)s_m$$

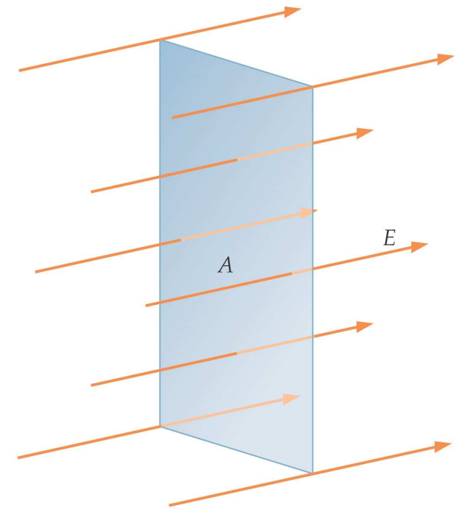
The intensity of sound waves also follow an inverse square law.

Sound Intensity

Notice that sound waves carry energy. We define the intensity I as the rate at which energy E flows through a unit area A perpendicular to the direction of travel of the wave.

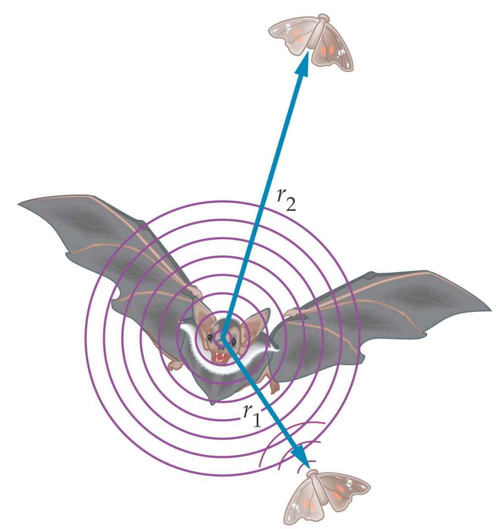
Intensity = Power / Area

$I = P / A = E / (At)$



For a point source, energy spreads out in all directions

→Area of a sphere $A = 4 \pi r^2$



Intensity with distance from a point source

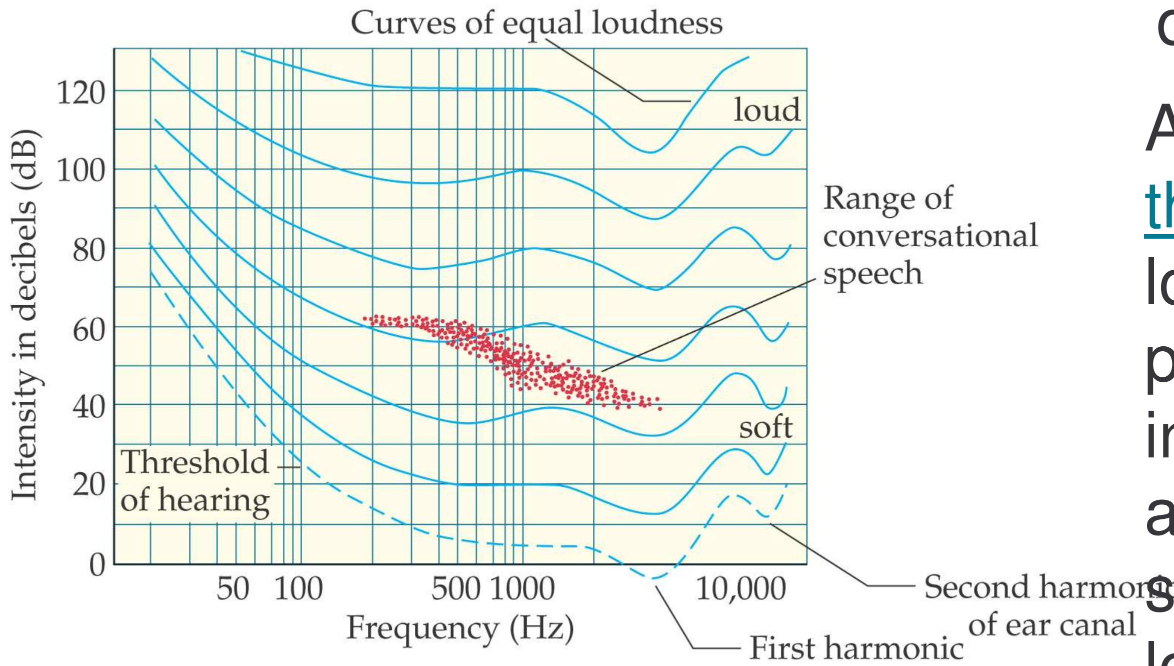
Applet Intensity

Loudness is not simply sound intensity!

Loudness of a sound 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 $\beta = (10\text{dB})\log\frac{I}{I_0}$



dB are decibels

A general "rule of thumb" for loudness is that the power must be increased by about a factor of ten to sound twice as loud.

A decibel is one tenth of a **bel** (**B**). Devised by engineers of the Bell Telephone Laboratory to quantify the reduction in audio level over a 1 mile (1.6 km) length of standard telephone cable, the bel was originally called the *transmission unit* or *TU*, but was renamed in 1923 or 1924 in honor of the laboratory's founder and telecommunications pioneer Alexander Graham Bell. In many situations, however, the bel proved inconveniently large, so the decibel has become more common.

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

$$\beta = (10\text{dB})\log\frac{I_0}{I_0} = 0$$

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

$$\beta = (10\text{dB})\log\frac{100I_0}{I_0} = 20dB$$

$$\beta = (10\text{dB})\log\frac{1000I_0}{I_0} = 30dB$$

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?

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

Solve for I, the intensity of a sound wave:

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

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

The intensity of an isotropic source is defined by:

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

$$= (1.3\times 10^{-5}\,\text{W/m}^2)4\pi(25\,\text{m})^2 = 0.10\ \text{Watts}$$

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

$$\beta_1 = (10\text{dB})\log\frac{I}{I_0} = 80\,\text{dB} \qquad \beta_2 = (10\text{dB})\log\frac{I}{I_0} = 90\,\text{dB}$$

Subtracting:

$$\beta_2 - \beta_1 = 10\,\text{dB} = 10\,\text{dB}\left(\log\frac{\text{I}_2}{\text{I}_0} - \log\frac{\text{I}_1}{\text{I}_0}\right)$$

$$10\,\text{dB} = 10\,\text{dB}\left(\log\frac{\text{I}_2}{\text{I}_1}\right)$$

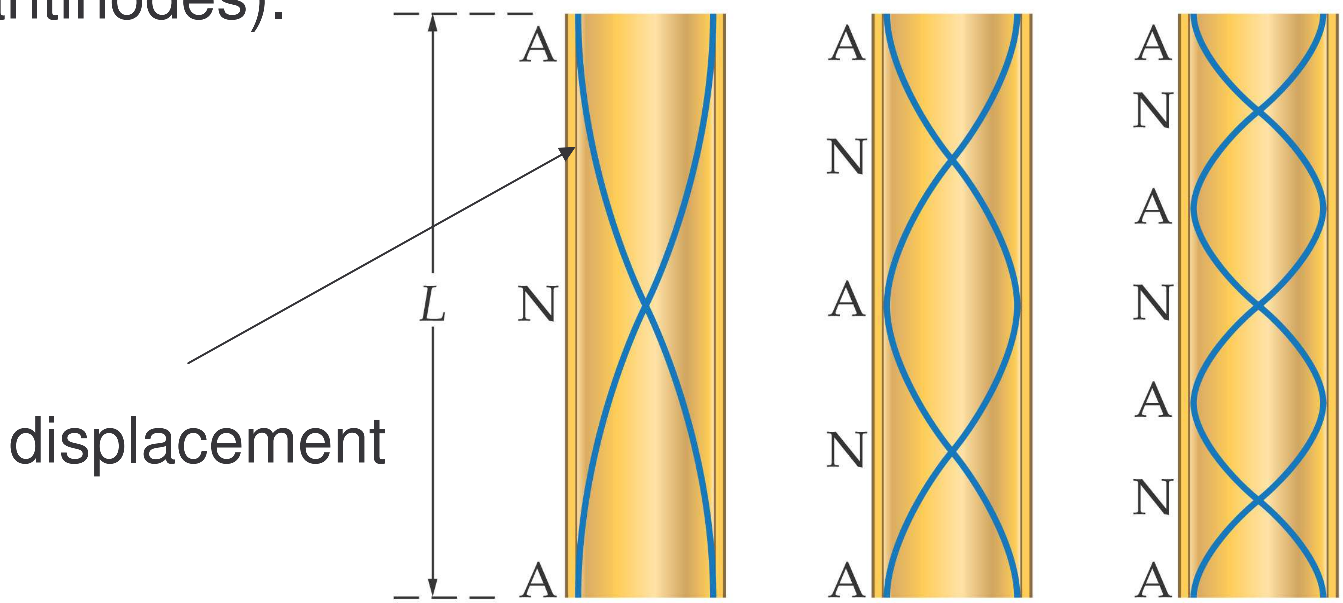
$$\frac{\text{I}_2}{\text{I}_1} = 10^1$$

$$I_2 = 10 I_1$$

Standing Sound Waves

Consider a pipe open at both ends:

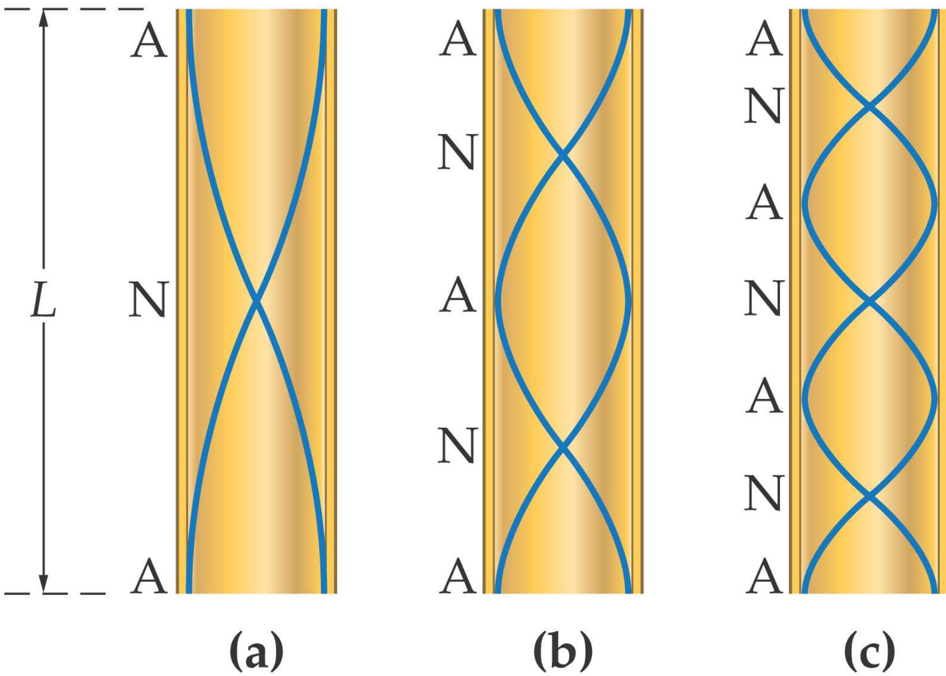
The ends of the pipe are open to the atmosphere. The open ends must be pressure nodes (and displacement antinodes).



Applet pressure / displacement Applet standing wave in open tube

The distance between two adjacent antinodes is ½λ. Each pair of antinodes must have a node in between.

The fundamental mode (it has the fewest number of antinodes) will have a wavelength of 2L.



The next standing wave pattern to satisfy the conditions at the ends of the pipe will have one more node and one more antinode than the previous standing wave. Its wavelength will be L.

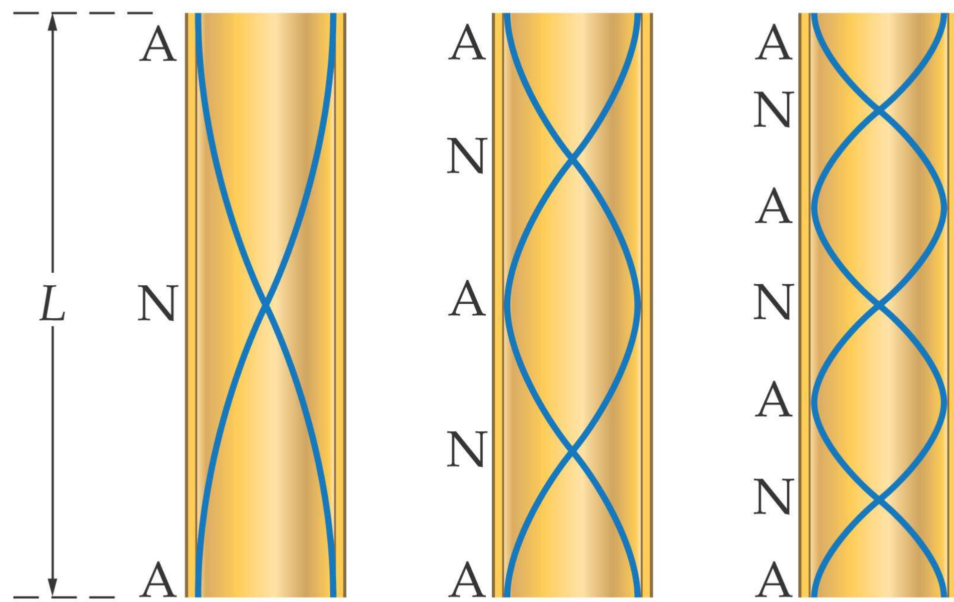
The general result for standing waves in a tube open at both ends is

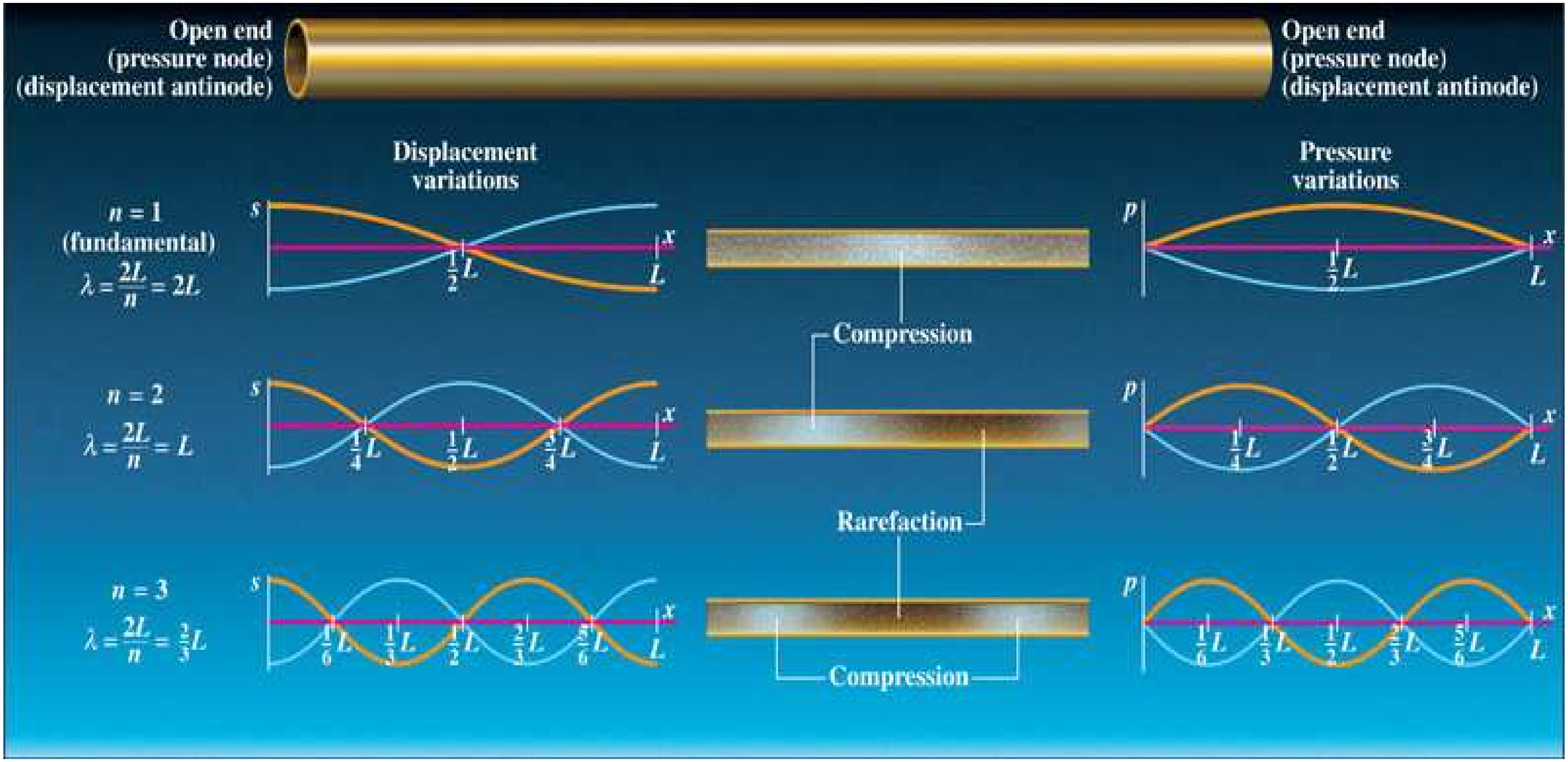
$$\lambda_n = \frac{2L}{n}$$

where n=1, 2, 3,…

$$f_n = \frac{v}{\lambda_n} = \frac{nv}{2L} = nf_1$$

f_1 is the fundamental frequency.



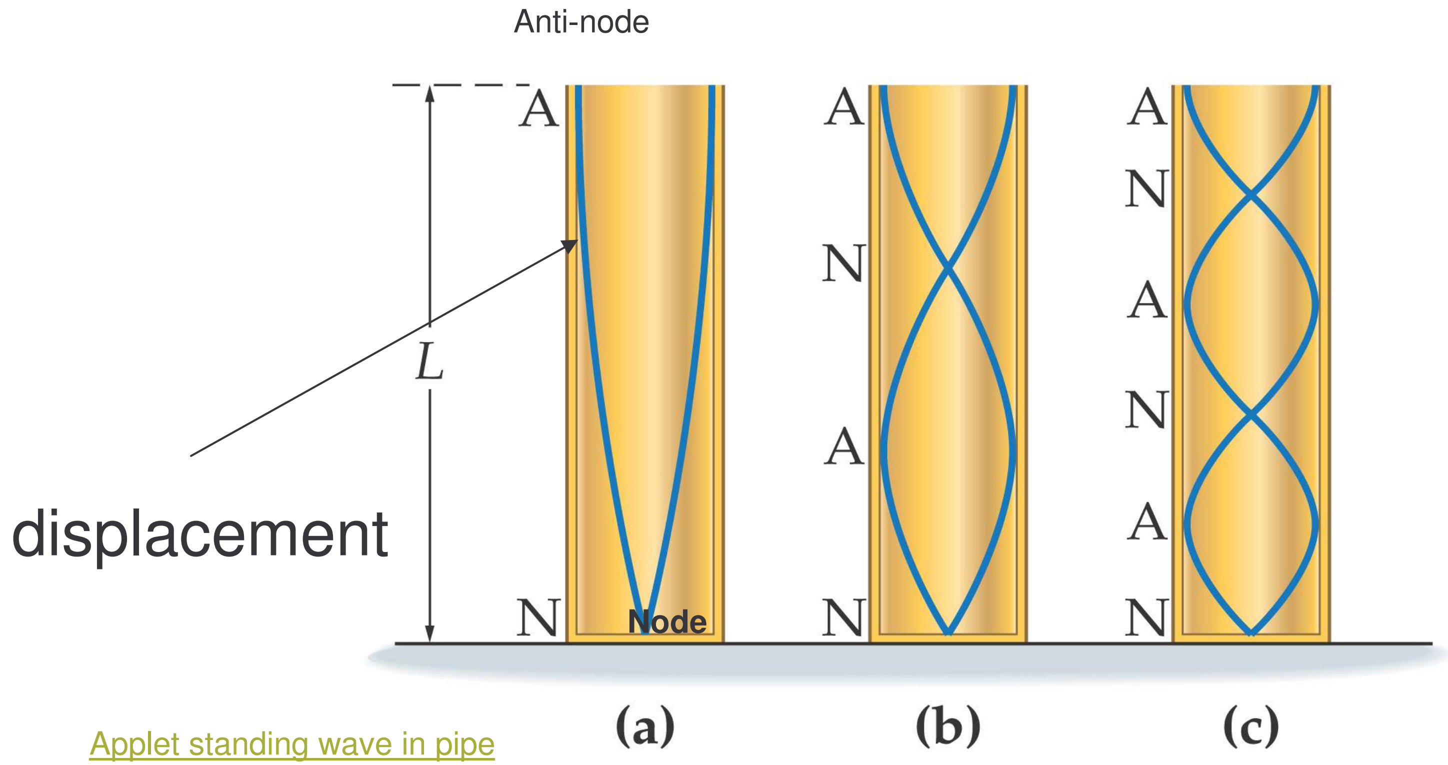


Open end
(pressure node)
(displacement antinode)
Open end
(pressure node)
(displacement antinode)
Displacement variations
Pressure variations
n = 1
(fundamental)
λ = 2L/n = 2L
n = 2
λ = 2L/n = L
n = 3
λ = 2L/n = 2/3 L
Compression
Rarefaction
Compression

Now consider a pipe open at one end and closed at the other.

As before, the end of the pipe open to the atmosphere must be a pressure node (and a displacement antinode).

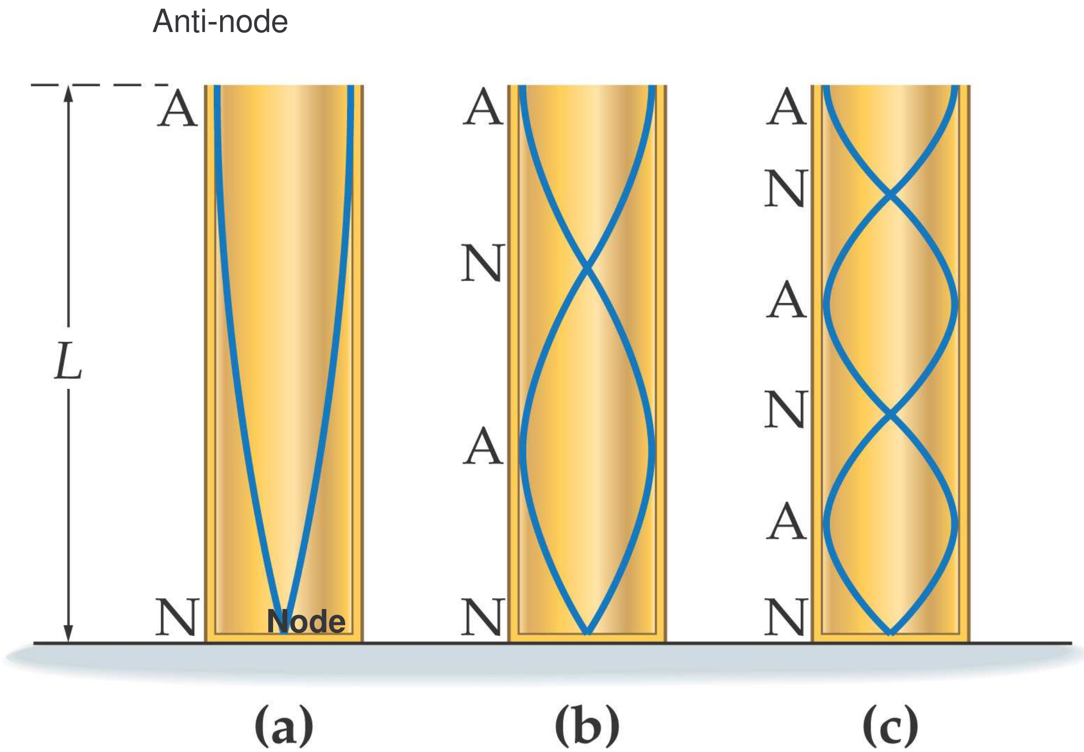
The closed end of the pipe must be a displacement node (and a pressure antinode).



Applet standing wave in pipe

One end of the pipe is a pressure node, the other a pressure antinode. The distance between a consecutive node and antinode is one-quarter of a wavelength.

Here, the fundamental mode will have a wavelength of 4L.

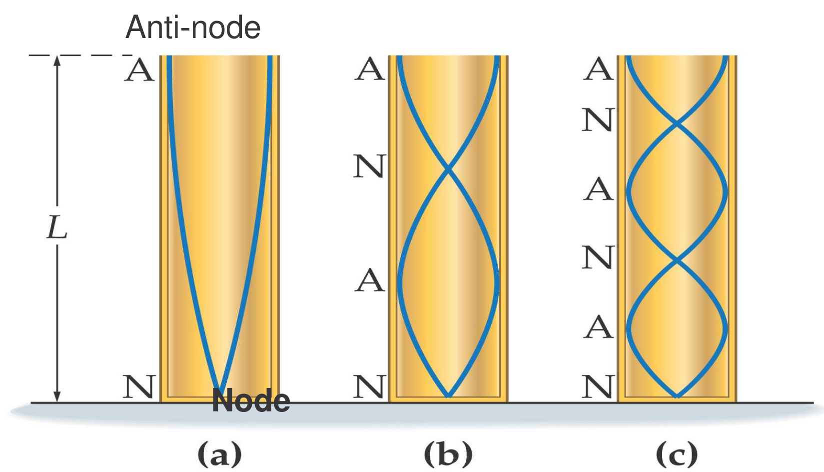


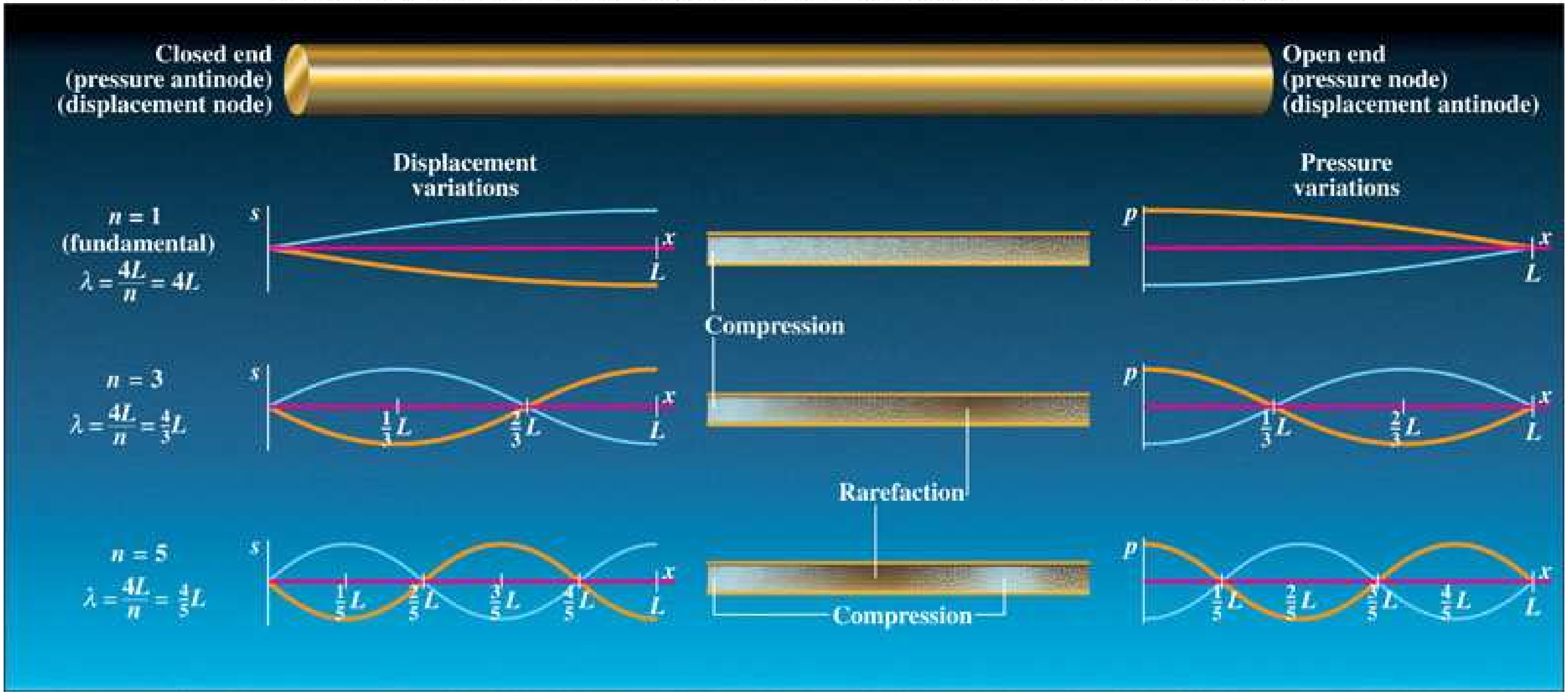
The next standing wave to satisfy the conditions at the ends of the pipe will have one more node and one more antinode than the previous standing wave. Its wavelength will be (4/3)L.

The general result for standing waves in a tube open at one end and closed at the other is

$$\lambda_n = \frac{4L}{n}$$ where n=1, 3, 5,…. n (odd values only!!)

$$f_n = \frac{v}{\lambda_n} = \frac{nv}{4L} = nf_1$$ f_1 is the fundamental frequency.

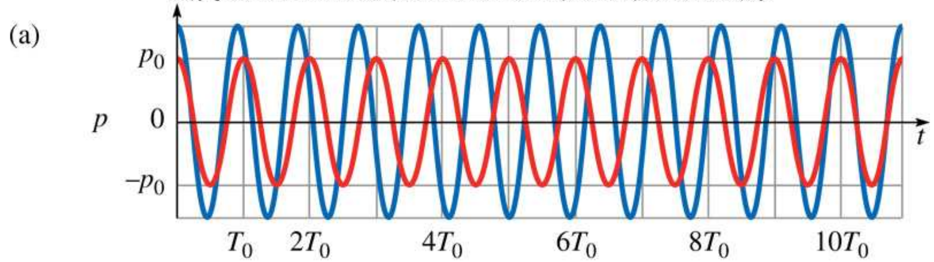




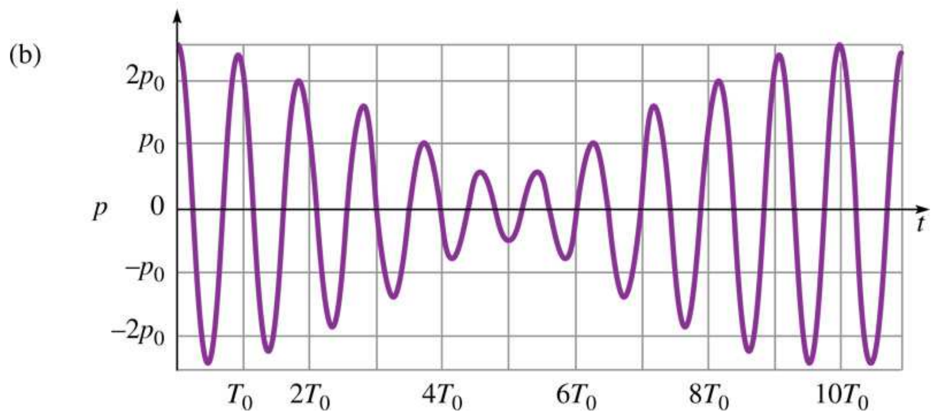
Closed end
(pressure antinode)
(displacement node)
Open end
(pressure node)
(displacement antinode)
Displacement variations
Pressure variations
n = 1
(fundamental)
λ = 4L/n = 4L
n = 3
λ = 4L/n = 4/3 L
n = 5
λ = 4L/n = 4/5 L
Compression
Rarefaction
Compression

Beats

When two waves with nearly the same frequency are superimposed, the result is a pulsation called beats.



Two waves of different frequency



Superposition of the above waves

The beat frequency is $\Delta f = f_1 - f_2$

If the beat frequency exceeds about 15 Hz, the ear will perceive two different tones instead of beats.

The Doppler Effect

When a moving object emits a sound, the wave crests appear bunched up in front of the object and appear to be more spread out behind the object. This change in wave crest spacing is heard as a change in frequency.

The results will be similar when the observer is in motion and the sound source is stationary and also when both the sound source and observer are in motion.

<u>As a rule of thumb:</u> When the motion of detector and source is toward the other, there is an upward shift in the frequency. When the motion of detector and source is away from each other there is a downward shift in frequency.

Three cases: Moving Observer, Moving Source or both observer and source are in motion

CASE I: Moving Observer

We know that the wavelength of a stationary source: $f = v/\lambda$

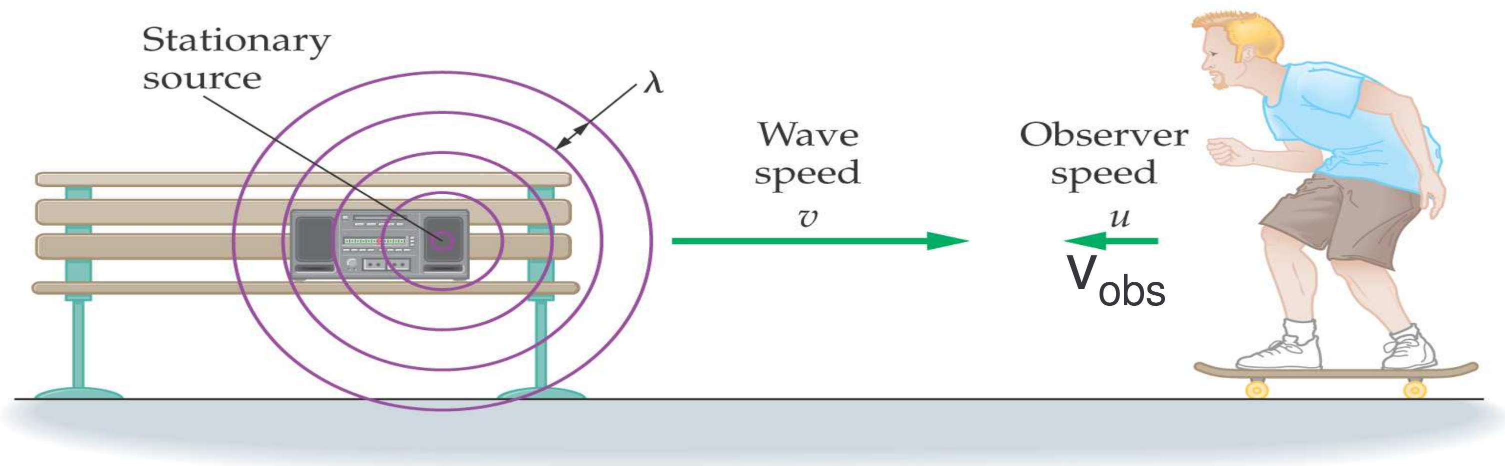
If observer moves towards the source with speed v_{obs} more compressions move past the observer per time (higher f).

$f' = v'/\lambda = (v+ v_{obs})/ \lambda = (v+ v_{obs})/ (v/f) = f\,(1+ v_{obs} /v)$

If observer moves away less compressions move past the observer:

$v' = (v - v_{obs})$ and $f' = f\,(1 - v_{obs} /v)$

Doppler Effect for moving observer: $f' = (1 \pm v_{obs} /v)\, f$



http://www.kettering.edu/~drussell/Demos/doppler/doppler.html

CASE II: Moving Source

Towards the observer:

$\lambda' = vT - uT = (v - u)T$

Away from the observer:

$\lambda' = vT + uT = (v + u)T$

And therefore with **$v = \lambda' f'$**

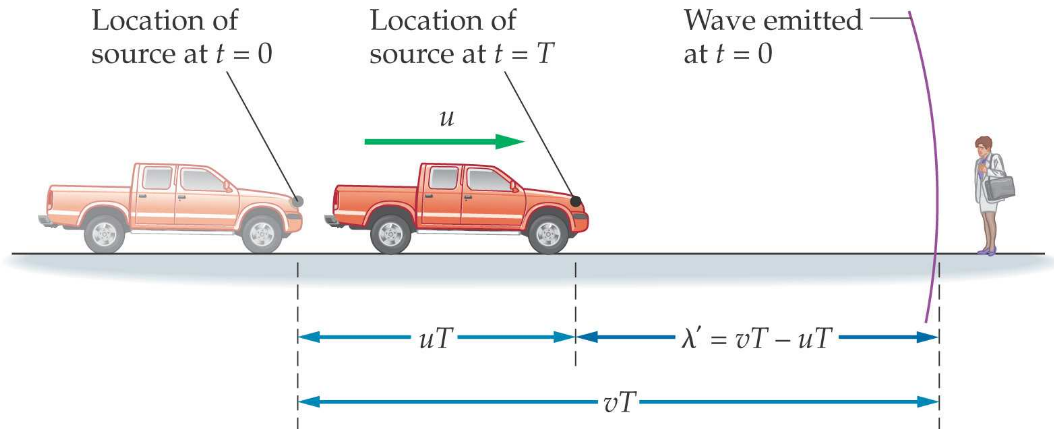
$f' = v/\lambda' = v/(v-u)T = v/(v-u)\ (1/f)$

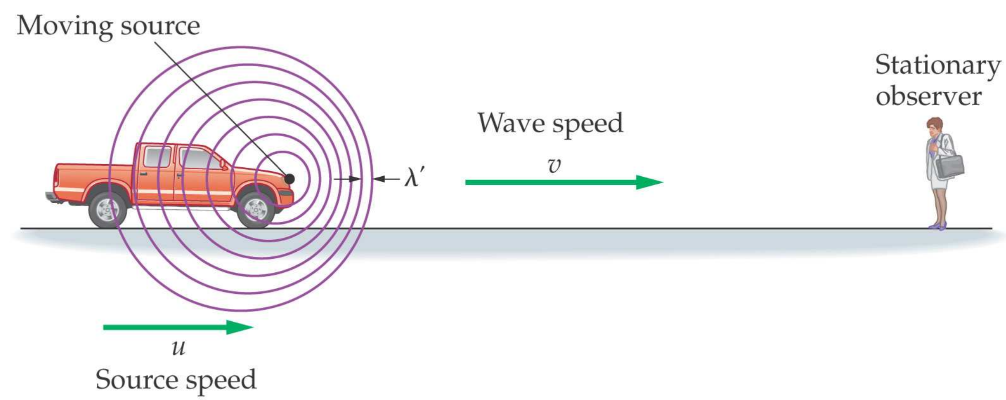
$= f\ (1/(1-u/v))$

and

$f' = v/\lambda' = v/(v+u)T = v/(v+u)$

$(1/f) = f\ (1/(1+u/v))$





Doppler Effect for moving source http://www.kettering.edu/~drussell/Demos/doppler/doppler.html

With $u = v_{source}$

$$f' = \left(\frac{1}{1 \mp {v_{source}}/{v}} \right) f$$

The Doppler Effect formula

Towards source / detector

$$f_o = \left(\frac{1 \pm \frac{v_o}{v}}{1 \mp \frac{v_s}{v}} \right) f_s$$

Away from source / detector

f_o is the observed frequency.

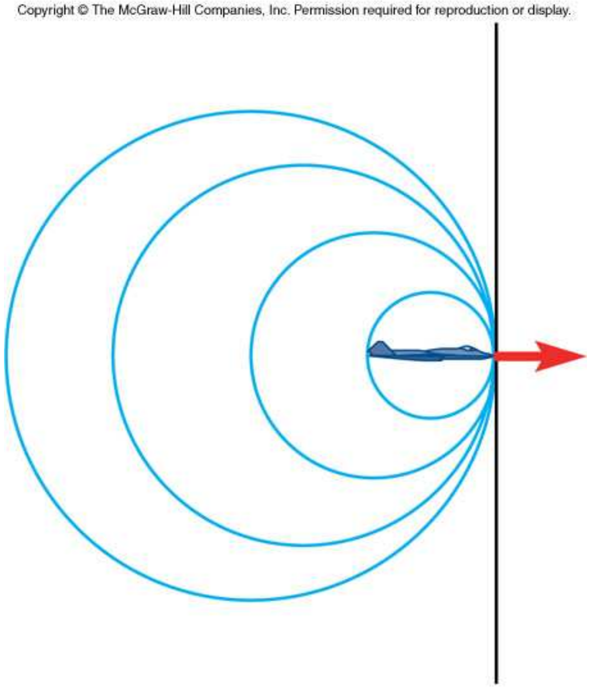
f_s is the frequency emitted by the source.

v_o is the observer's **velocity.**

v_s is the source's **velocity.**

v is the speed of sound.

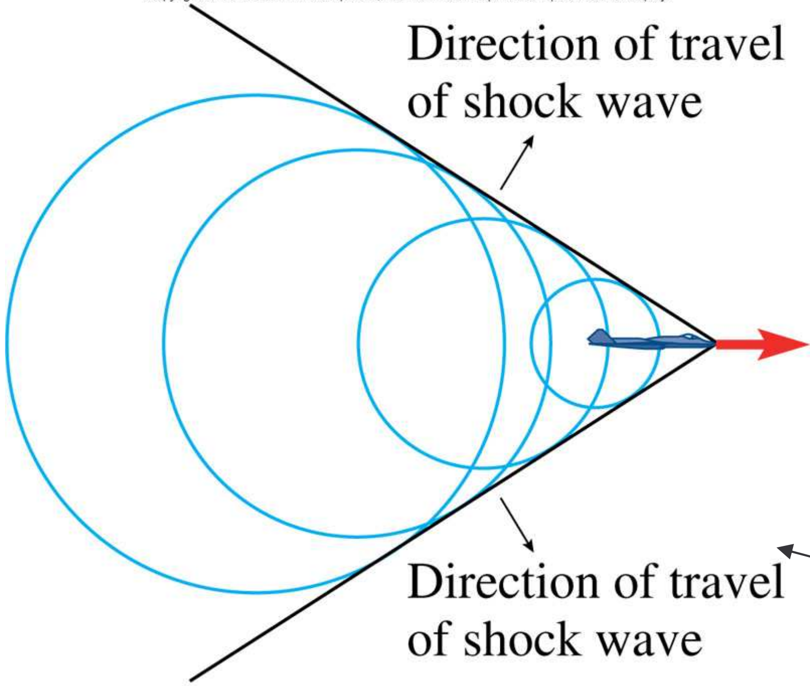
Shock Waves



(b)

If a plane were traveling at the speed of sound , what would the wave crests looks like?

They would be bunched up in front of the aircraft and an observer (to the right) would measure λ=0.

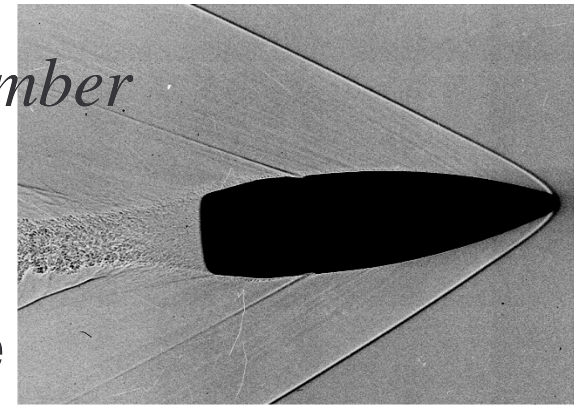


(c)

$$\sin\theta = \frac{v}{v_s} \quad (Mach\ cone\ angle)$$

$$\frac{v_s}{v} : Mach\ number$$

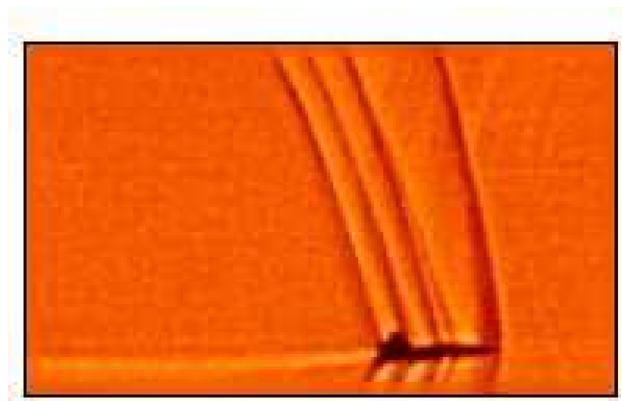
Mach cone



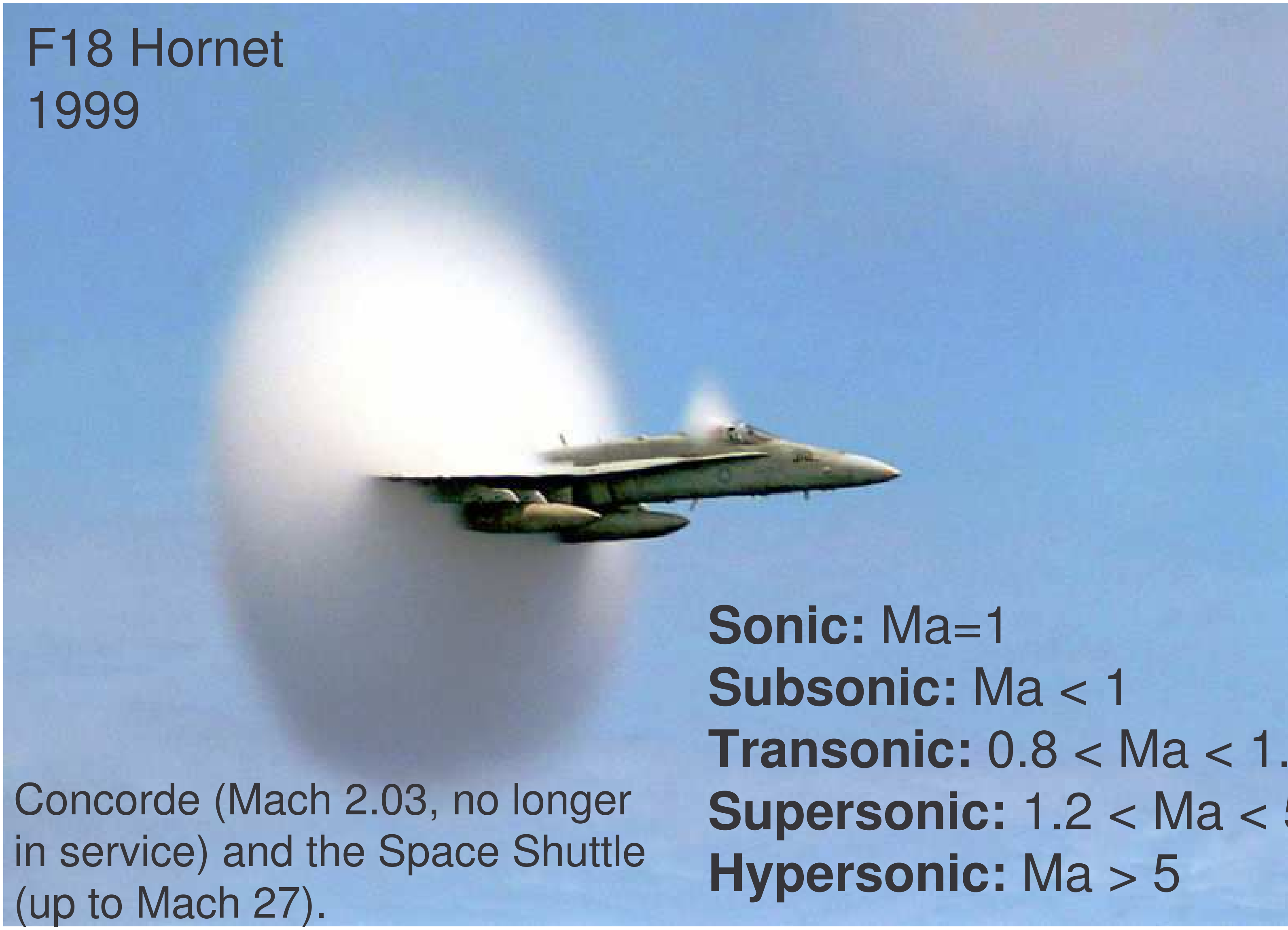
If the source moves with a speed greater than that of sound then the wave crests pile up on top of each other forming a cone-shaped shock wave.

http://www.kettering.edu/~drussell/Demos/doppler/doppler.html

A supersonic aircraft usually produces two sonic booms, one from the aircraft's nose and the other from its tail, resulting in a double thump.



F18 Hornet
1999



Sonic: Ma=1
Subsonic: Ma < 1
Transonic: 0.8 < Ma < 1.2
Supersonic: 1.2 < Ma < 5
Hypersonic: Ma > 5

Concorde (Mach 2.03, no longer in service) and the Space Shuttle (up to Mach 27).

*named after Austrian physicist and philosopher Ernst Mach.

Echolocation

also called **Biosonar**

Sound waves can be sent out from a transmitter of some sort; they will reflect off any objects they encounter and can be received back at their source. The time interval between emission and reception can be used to build up a picture of the scene.