Chapter 17

Sound Waves

Modified by P. Lam 8_7_2018

Topics for Chapter 17

- Decibel scale for sound intensity
- Standing waves re-visit (resonance frequencies)
- Constructive and destructive interference
- Beat frequency
- Doppler effect
- Shock waves
- ** Actually, all of the above phenomena apply to other types of waves as well. **

The logarithmic decibel scale of loudness

- Read the table from bottom up.

Table 16.2 Sound Intensity Levels from Various Sources (Representative Values)

Source or Description of Sound	Sound Intensity Level, β (dB)	I/I_o		Intensity, I (W/m^2)
Military jet aircraft 30 m away	140	10^{14}		10^2
Threshold of pain	120	10^{12}		1
Riveter	95	$10^{9.5}$		3.2×10^{-3}
Elevated train	90	10^9		10^{-3}
Busy street traffic	70	10^7		10^{-5}
Ordinary conversation	65	$10^{6.5}$		3.2×10^{-6}
Quiet automobile	50	10^5		10^{-7}
Quiet radio in home	40	10^4		10^{-8}
Average whisper	20	10^2		10^{-10}
Rustle of leaves	10	10^1		10^{-11}
Threshold of hearing at 1000 Hz	0	10^0	$I_o =$	10^{-12}

$$\beta \equiv (10dB)\log_{10}\frac{I}{I_o} \Rightarrow I = I_o 10^{\frac{\beta}{10dB}}$$

The logarithmic decibel scale of loudness

- (a) Given a sound intensity is 35 decibels. What its intensity in W/m^2?

- (b) Given a sound intensity, I_1, is β_1. Let $I_2=2I_1$, its intensity is how many dB above β_1?

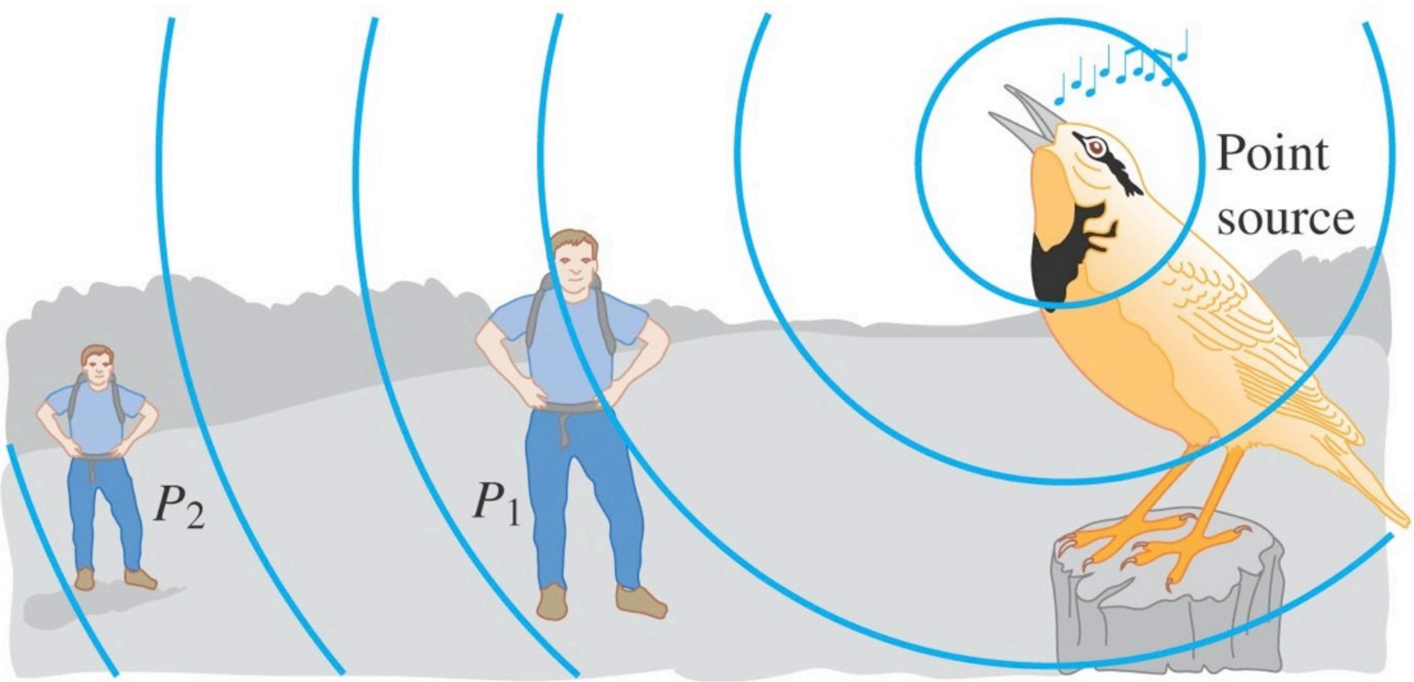
- (c) Let $I_3=I_1/2$, its intensity is how many dB below β_1?

Note: When used as a relative scale as the example above, the dB scale is applicable to other intensities besides sound intensity.

The sound intensity (decibel scale) vs distance

Given: The intensity at P_1 (4 meters from the bird) is 20 dB.

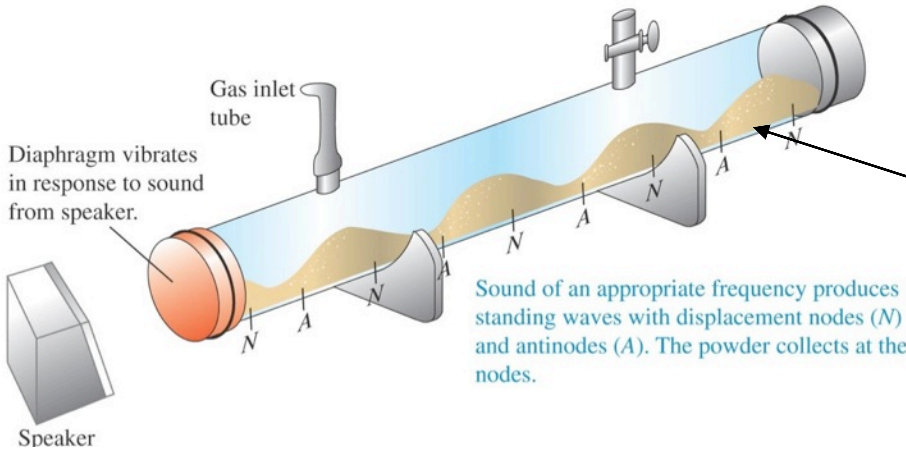
What is the intensity at P_2 (8 meters from the bird) in dB?



Hint: P_2 is a fraction of P_1, what is that fraction?

Standing sound waves and normal modes

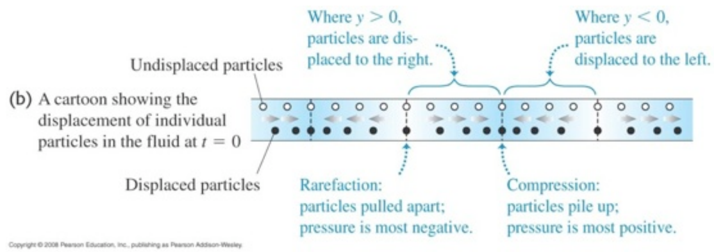
- standing sound waves inside a tube => resonance frequencies

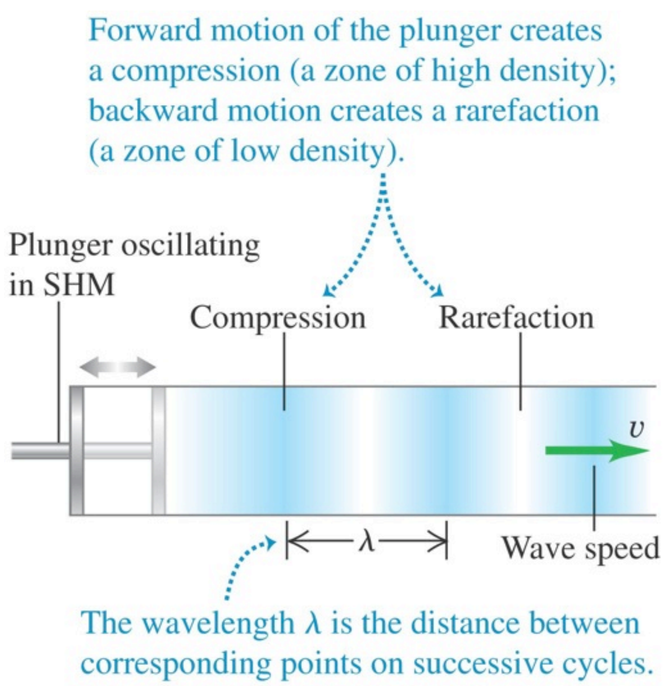


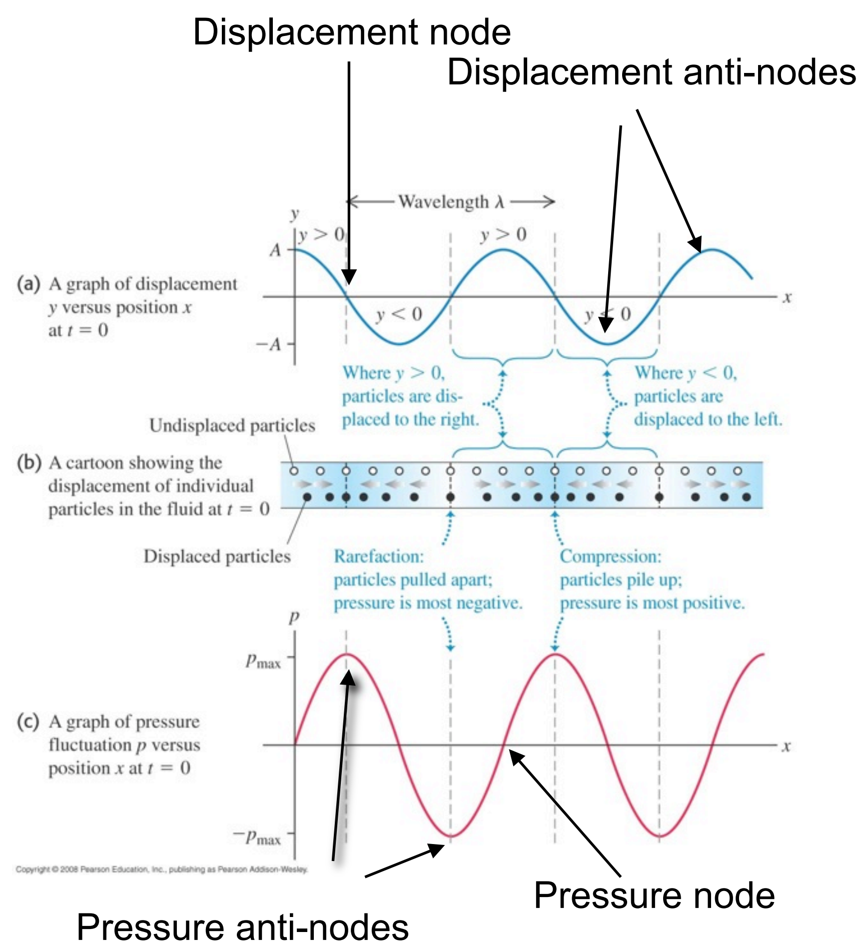
What does this graph represent?

Representation of a sound wave

- For example, sound wave in air is the displacement of air molecules away from their equilibrium positions, which causes region of compression (high pressure) and region of rarefaction (low pressure).





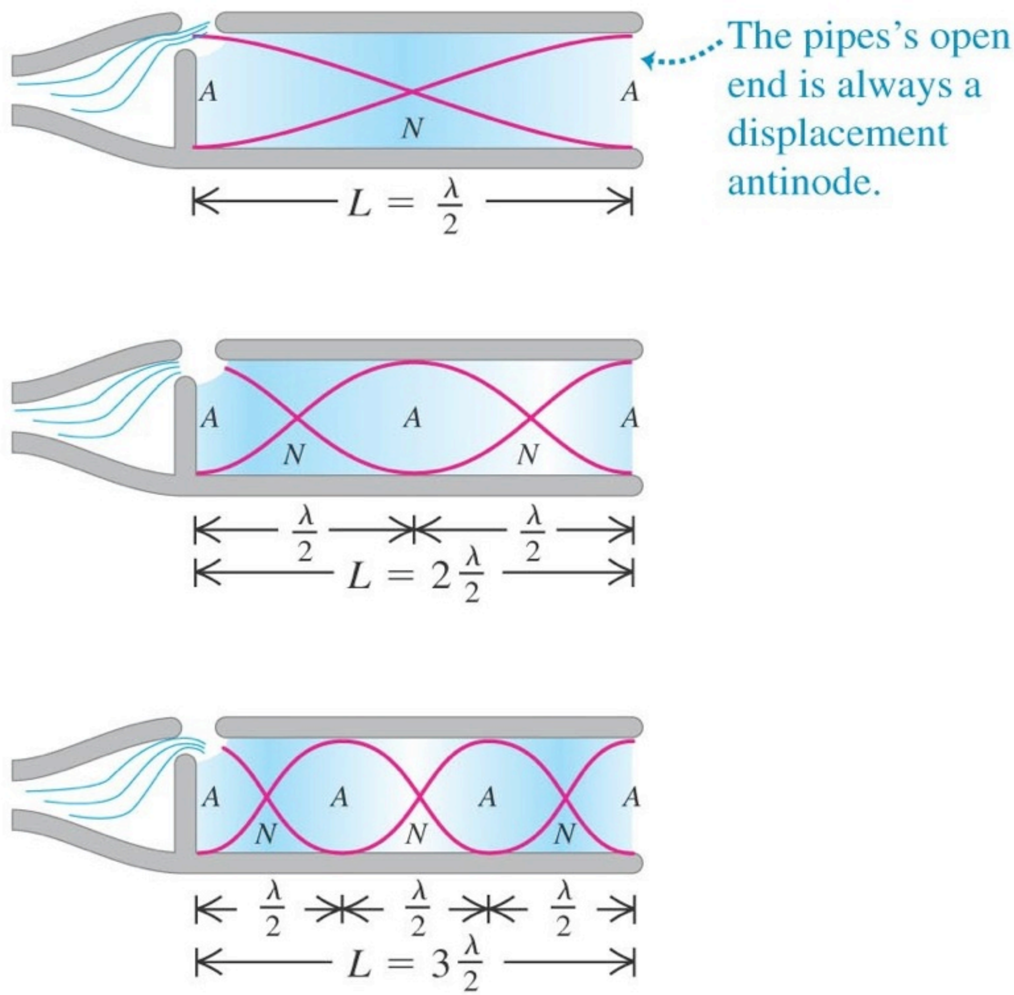


Resonance frequencies in a pipe with two open ends

(a)
Fundamental: $f_1 = \dfrac{v}{2L}$

(b)
Second harmonic: $f_2 = 2\dfrac{v}{2L} = 2f_1$

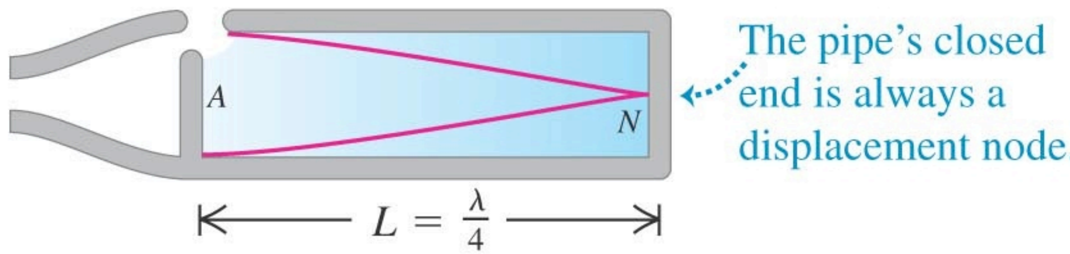
(c)
Third harmonic: $f_3 = 3\dfrac{v}{2L} = 3f_1$



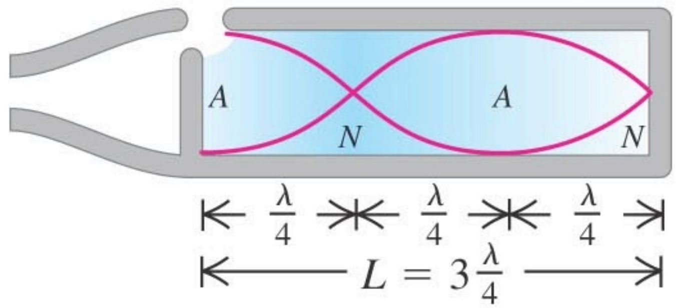
Resonance frequencies similar to those of vibration string with both end fixed.

Resonance frequencies in a pipe with one end open and one end closed

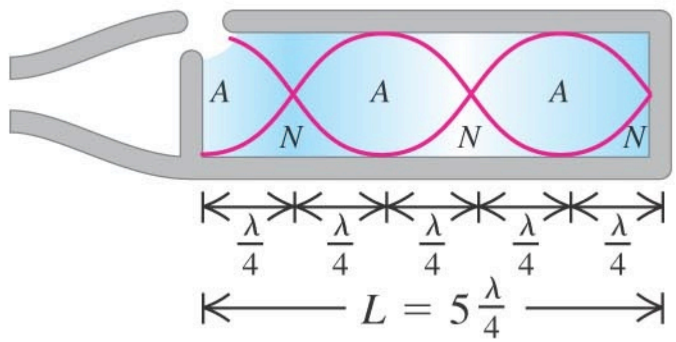
(a)
Fundamental: $f_1 = \frac{v}{4L}$



(b)
Third harmonic: $f_3 = 3\frac{v}{4L} = 3f_1$



(c)
Fifth harmonic: $f_5 = 5\frac{v}{4L} = 5f_1$



Note: Only the odd harmonics

Examples of resonance wavelengths and frequencies

A 1-meter long organ pipe has two ends open.

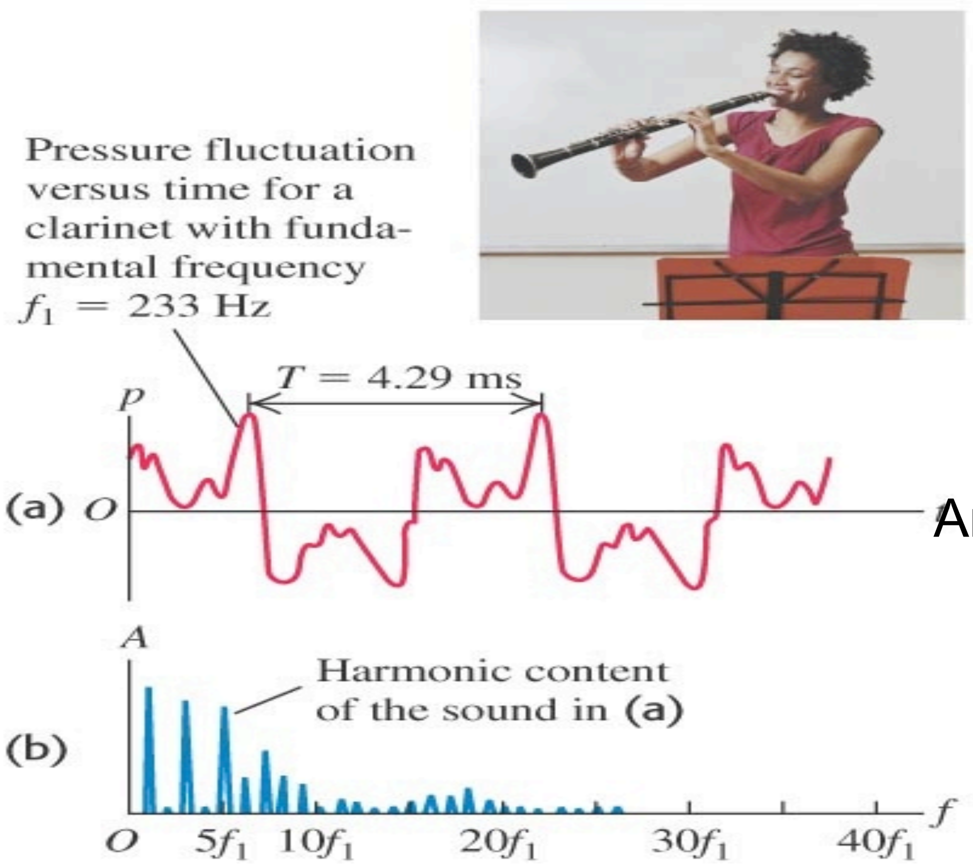
Given the speed of sound in air = 331 m/s.

(a) Find the three lowest resonance frequencies of this organ pipe.

(b) Now close one-end of this organ pipe, find the three lowest resonance frequencies of this organ pipe.

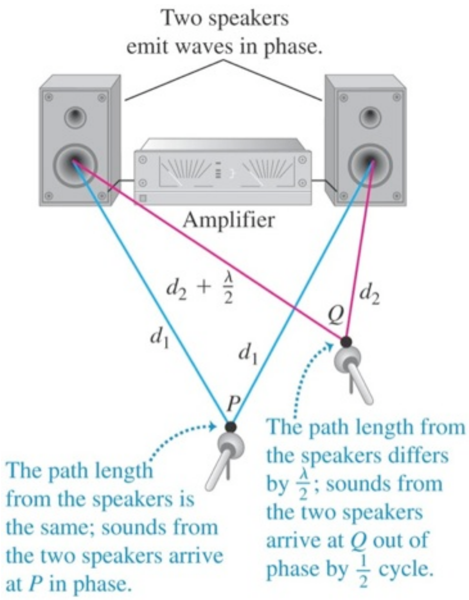
Different instruments give the same pitch different "favor"

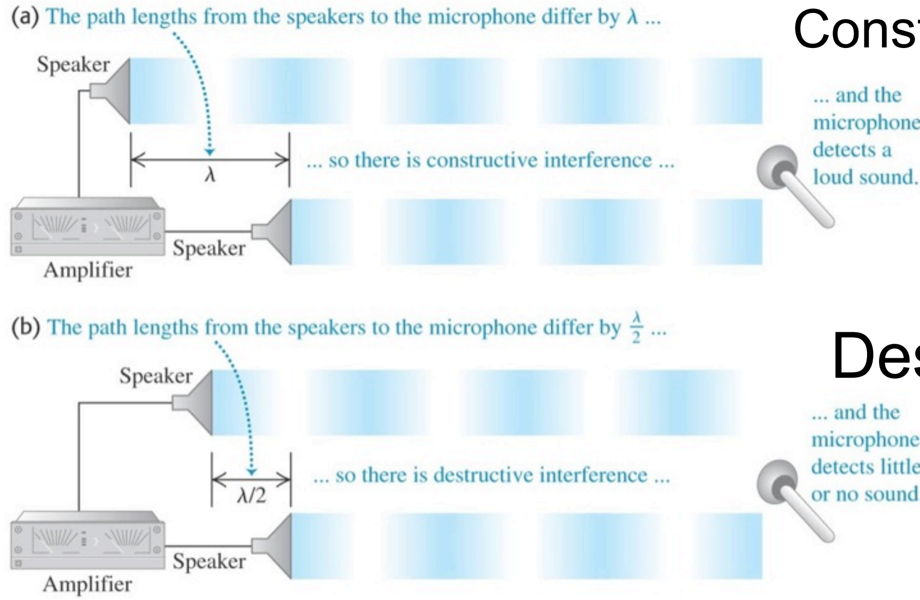
- The same note, say middle c, played on a piano, on a trumpet, on a clarinet, on a tuba, will all be the same pitch (same fundamental frequency=256 Hz), but they will sound different because of the different amount of higher harmonic contents (overtones).



Amplitude as a function of time

Wave interference … destructive or constructive





Constructive

Destructive

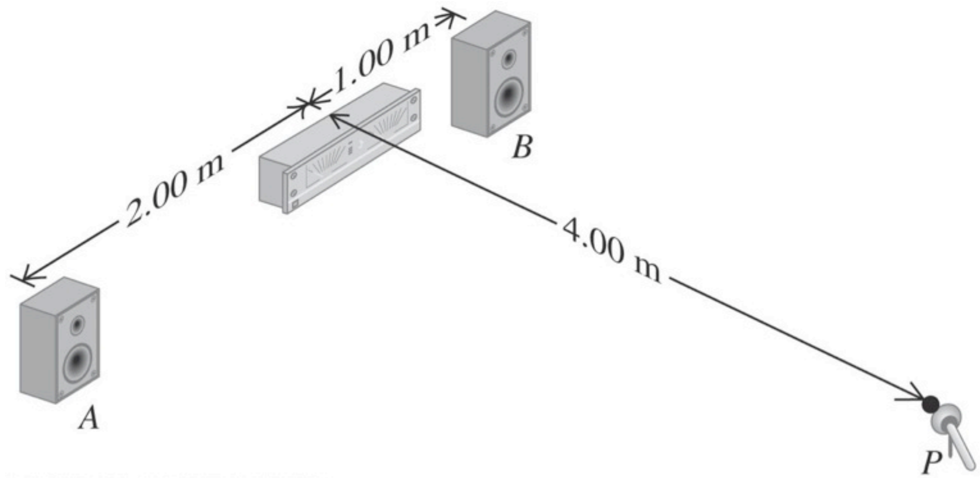
Both sources must be the same frequency.

Constructive interference: When path lengths from the two sources differ by $n\lambda$, $n = 0, 1, 2, 3, \ldots$, i.e. 0, λ, 2λ, etc.

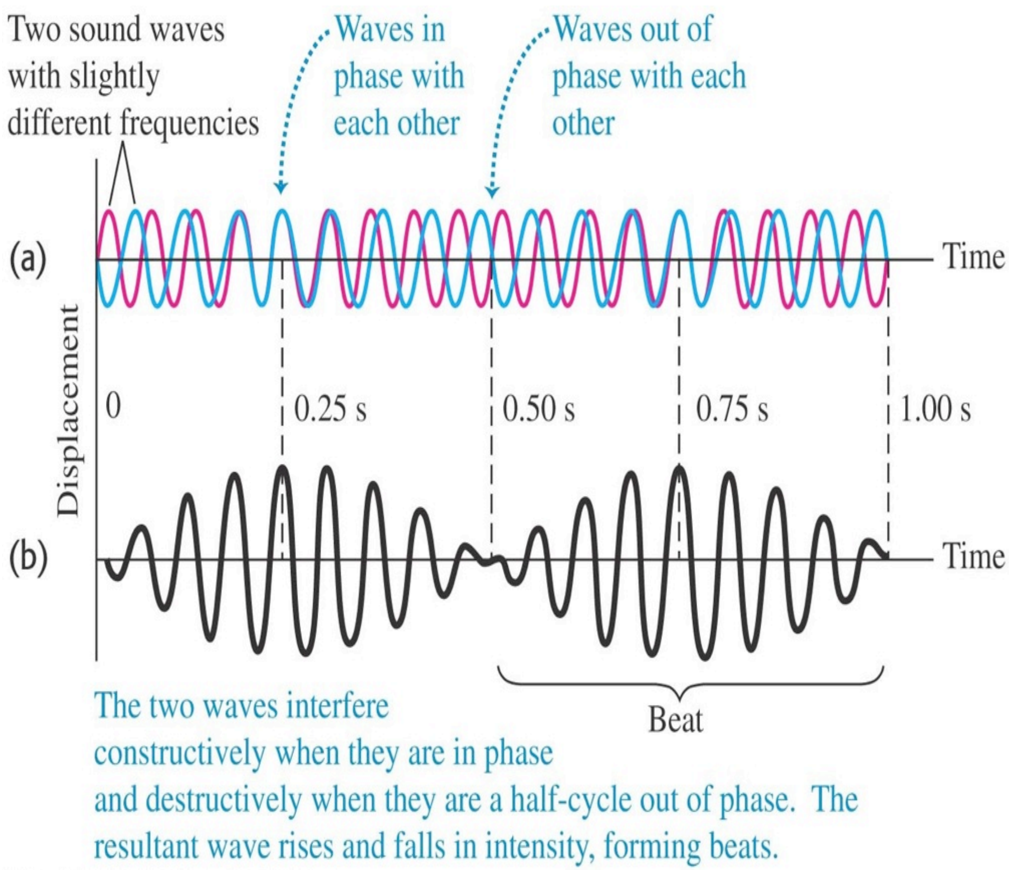
Destructive interference: When path lengths from the two sources differ by $(n + \frac{1}{2})\lambda$, i.e. $\frac{\lambda}{2}, \frac{3\lambda}{2}, \frac{5\lambda}{2}, etc.$

Sounds playing on a speaker system can interfere

- Both speakers are driven by the same amplifier (same frequency and in phase). Given the speed of sound=331m/s.
- (a) At what frequencies will constructive interference occur?
- (b) At what frequencies will destructive interference occur?



Slightly mismatched frequencies cause audible "beats"



$$A\cos\omega_1 t + A\cos\omega_2 t$$

$$Let\ \bar{\omega} = \frac{\omega_1+\omega_2}{2}; \Delta = \frac{\omega_1-\omega_2}{2}$$

$$A\cos(\bar{\omega}+\Delta)t + A\cos(\bar{\omega}-\Delta)t$$

$$= 2A\cos\bar{\omega}t\cos\Delta t$$

Combine sound waves of slightly different frequency (in the case above, f_1=18Hz, f_2=16Hz, the beat frequency=18-16=2Hz.)

Example of beat frequency

Two guitars (A & B) produce a beat frequency of 4 cycles per second when played together (say the E-strings on both guitars)

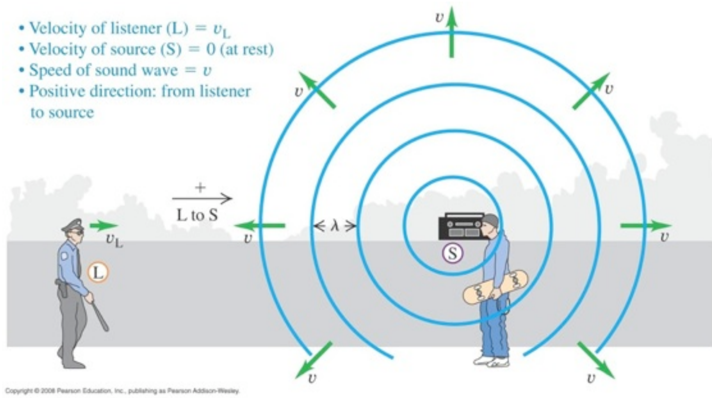
You tighten guitar A's string, now the beat frequency is 1 cycle per second.

(A) Which guitar was at lower frequency initially?

(B) Which guitar is at lower frequency after guitar A's string is tighten?

The Doppler Effect - moving toward each other

- If the listener is moving *toward* the source
- OR the source is moving *toward* the listener,
- the listener hears a *higher* frequency, but the formula are slightly different (will derive formulae in class)



➞ listener is moving toward the source:

$$f_L = \left(1 + \frac{v_L}{v}\right) f_S; \quad v = \text{ wave speed (sound speed)}$$

➞ source is moving toward the listener:

$$f_L = \left(\frac{1}{1 - \frac{v_S}{v}}\right) f_S; \quad v = \text{ wave speed (sound speed)}$$

No picture :(

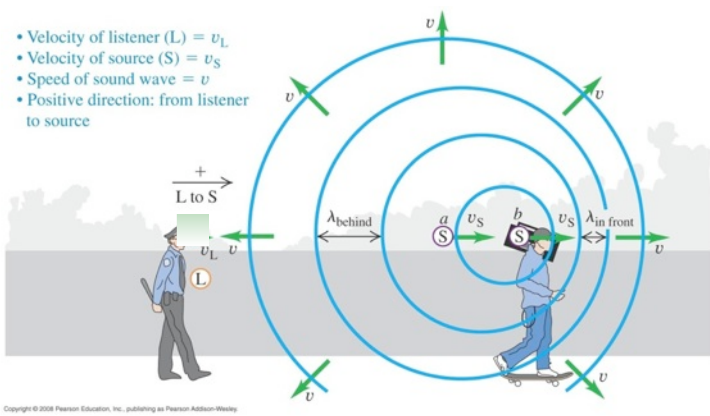
If both are moving toward each other =>

$$f_L = \left(\frac{1 + \frac{v_L}{v}}{1 - \frac{v_S}{v}}\right) f_S$$

The Doppler Effect - moving away from each other

- If the listener is moving *away* from the source
- OR the source is moving *away* from the listener,
- the listener hears a *lower* frequency, the formula can be obtained from the moving toward case by using negative velocity.

No picture :(



→ listener is moving away from the source:

$$f_L = \left(1 - \frac{v_L}{v}\right) f_S; \quad v = \text{ wave speed (sound speed)}$$

→ source is moving away from the listener:

$$f_L = \left(\frac{1}{1 + \frac{v_S}{v}}\right) f_S; \quad v = \text{ wave speed (sound speed)}$$

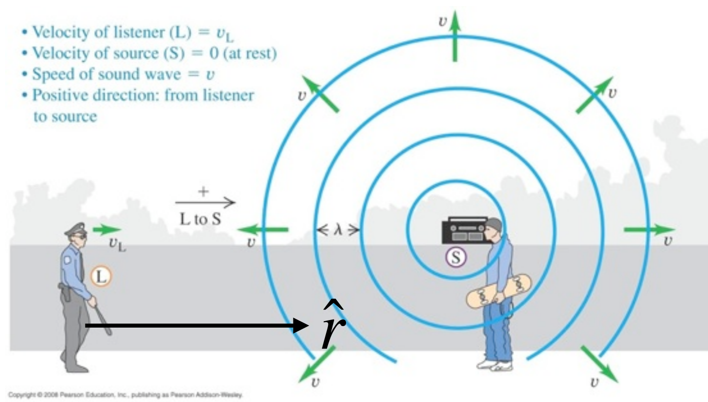
If both are moving away from each other => $f_L = \left(\frac{1 - \frac{v_L}{v}}{1 + \frac{v_S}{v}}\right) f_S$

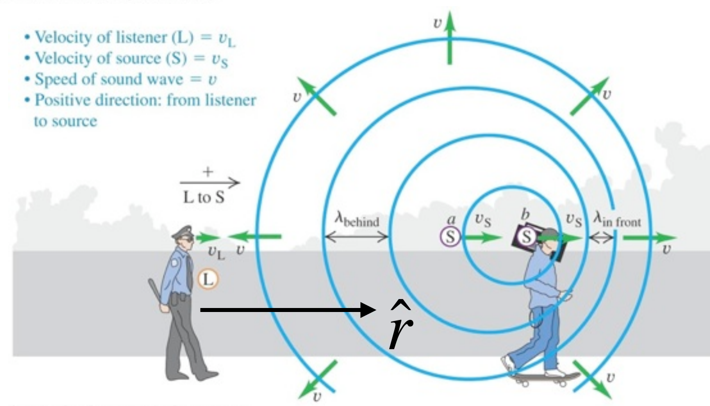
The Doppler Effect -combine

- How do we keep track of all the various possible relative motions of the listener and the source???
- Answer: use vectors.

Let $\hat{r}$ = unit vector pointing from the Listener to the Source.

$$\text{then } f_L = \frac{\left(1 + \dfrac{\vec{v}_L \bullet \hat{r}}{v}\right)}{\left(1 + \dfrac{\vec{v}_S \bullet \hat{r}}{v}\right)} f_S$$





Although this is a fool-proof method,

do check your answer against the basic concepts:

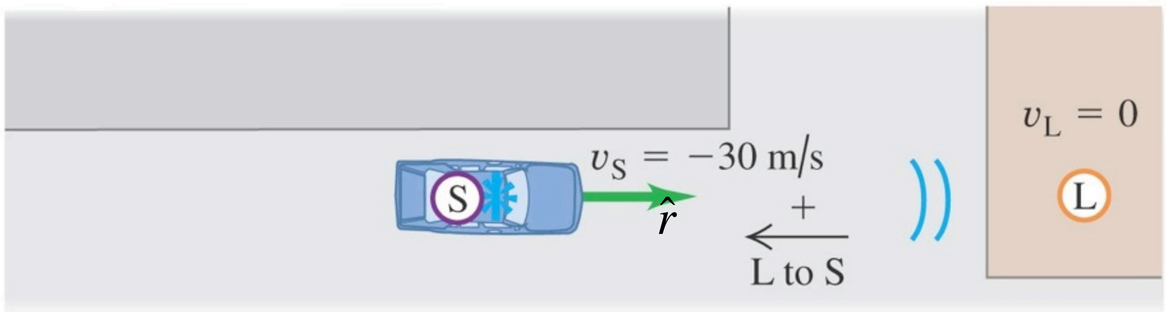
Moving toward => higher frequency

Moving away => lower frequency

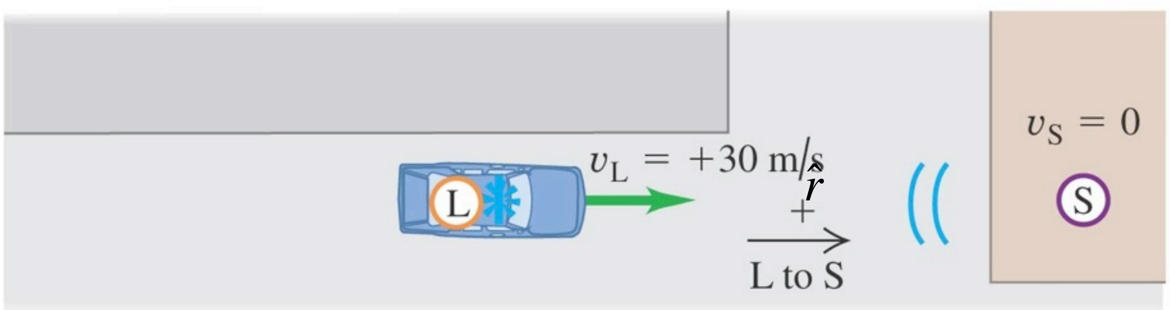
A double Doppler shift

- See figures below. Police siren = f_S=300Hz. The sound bounds off wall and comes back to the police car. What frequency does the police hear? Given sound speed=340 m/s.

(a) Sound travels from police car's siren (source S) to warehouse ("listener" L).



(b) Reflected sound travels from warehouse (source S) to police car (listener L).

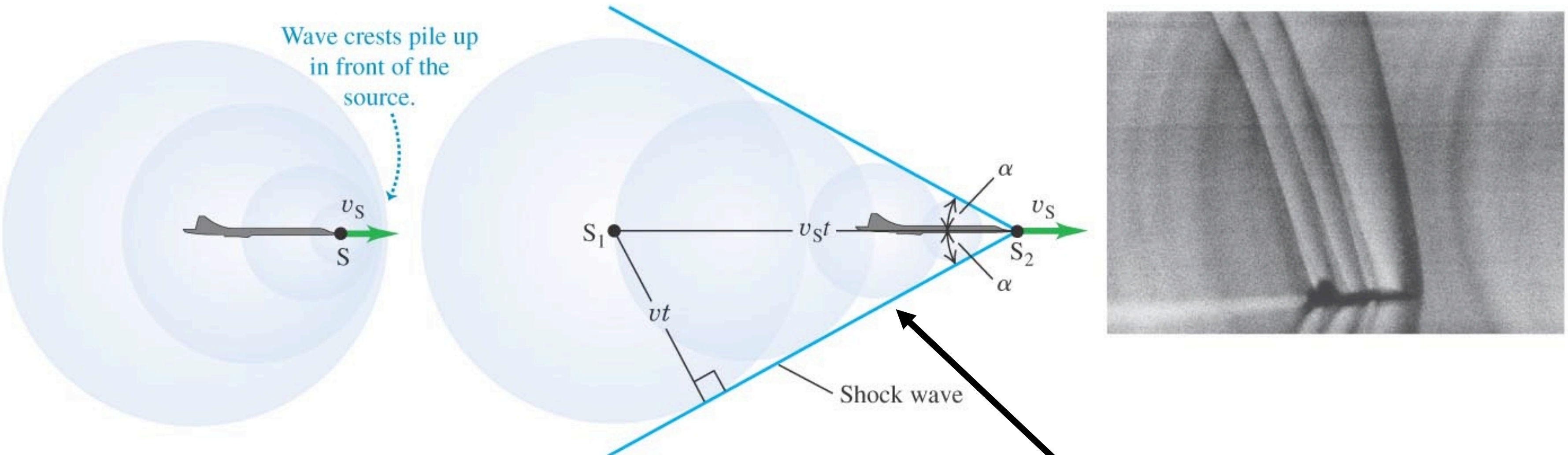


Shock wave - when $v_{object} > v_{sound}$

(a) Sound source S (airplane) moving at nearly the speed of sound

(b) Sound source moving faster than the speed of sound

(c) Shock waves around a supersonic airplane



$$\frac{v_{object}}{v_{sound}} \equiv \text{Mach number}$$

$$\alpha = \text{"Mach angle"}$$

Region of extremely high pressure difference

$$\sin\alpha = \frac{v_{sound}t}{v_{object}t} = \frac{1}{\text{Mach number}}$$

Note: The sound waves are created by the airplane flying through the air, NOT from a speaker inside the airplane or from its engine.