This is not a replacement for your textbook. It is essential to study from your textbook!

Objectives

Ch 17: Waves 2

17.1 Speed of sound

17.2 Traveling sound waves

17.3 Interference

17.4 Intensity and sound level

17.5 Sound waves resonances

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17.7 The Doppler effect

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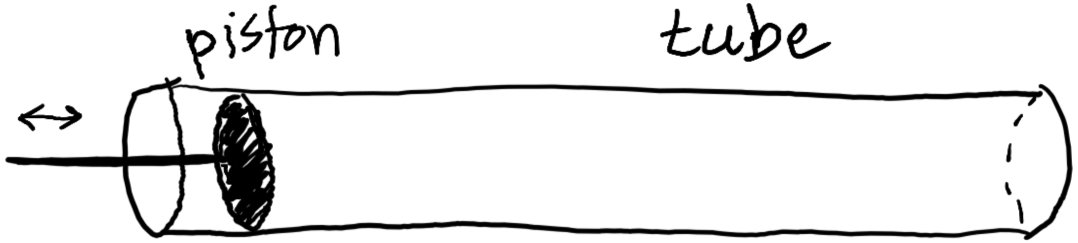
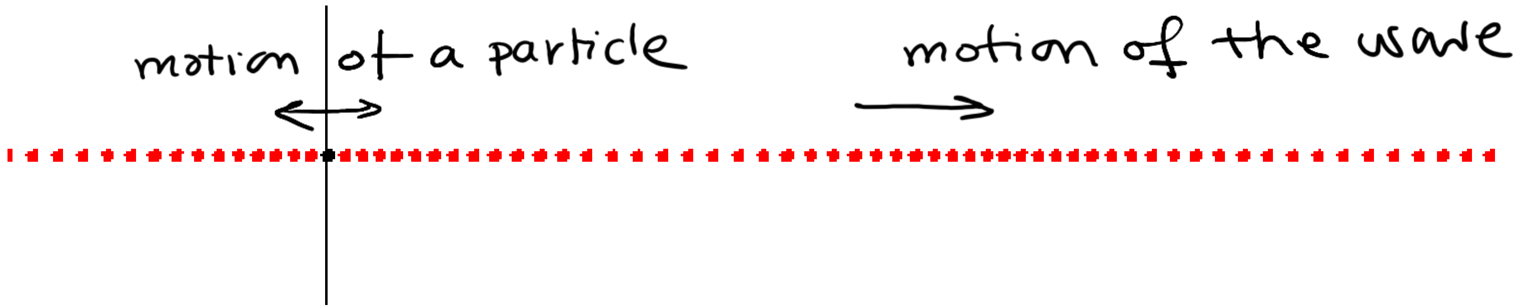
Sound waves are mechanical waves $\Longrightarrow$ They need medium to travel

Sound waves are longitudinal waves





17.1 Speed of Sound

Bulk modulus

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

speed of sound

density of the medium

	v (m/s)
air (0°C)	331
air (20°C)	343
water	1500
steel	6000

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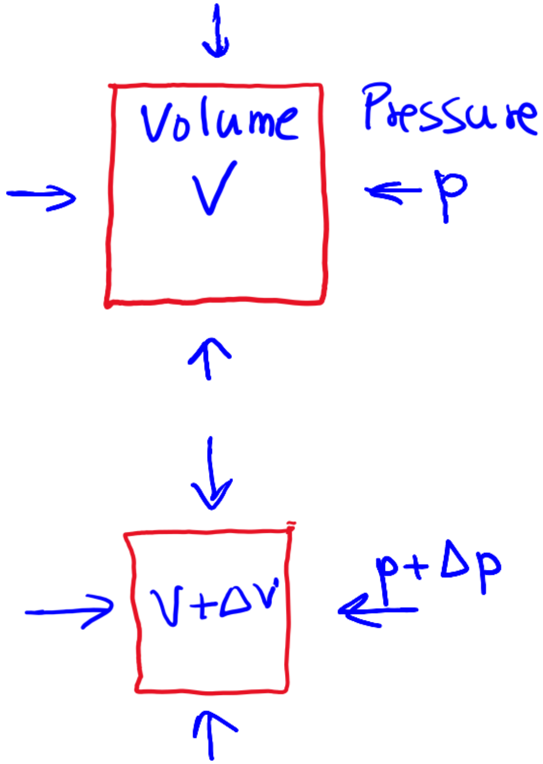
change in pressure

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

change in volume

original volume

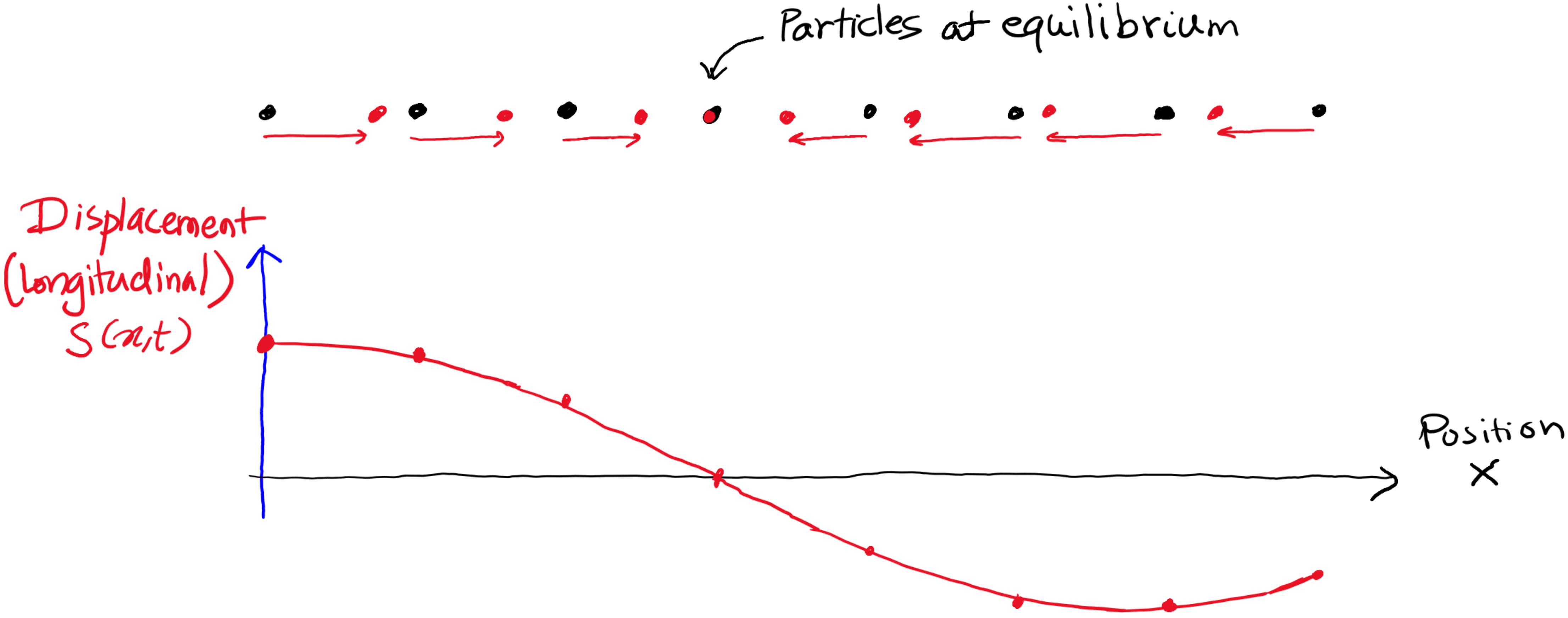


B is always positive

Higher $B \Rightarrow$ less compressible medium

$$B_{steel} \gg B_{air}$$

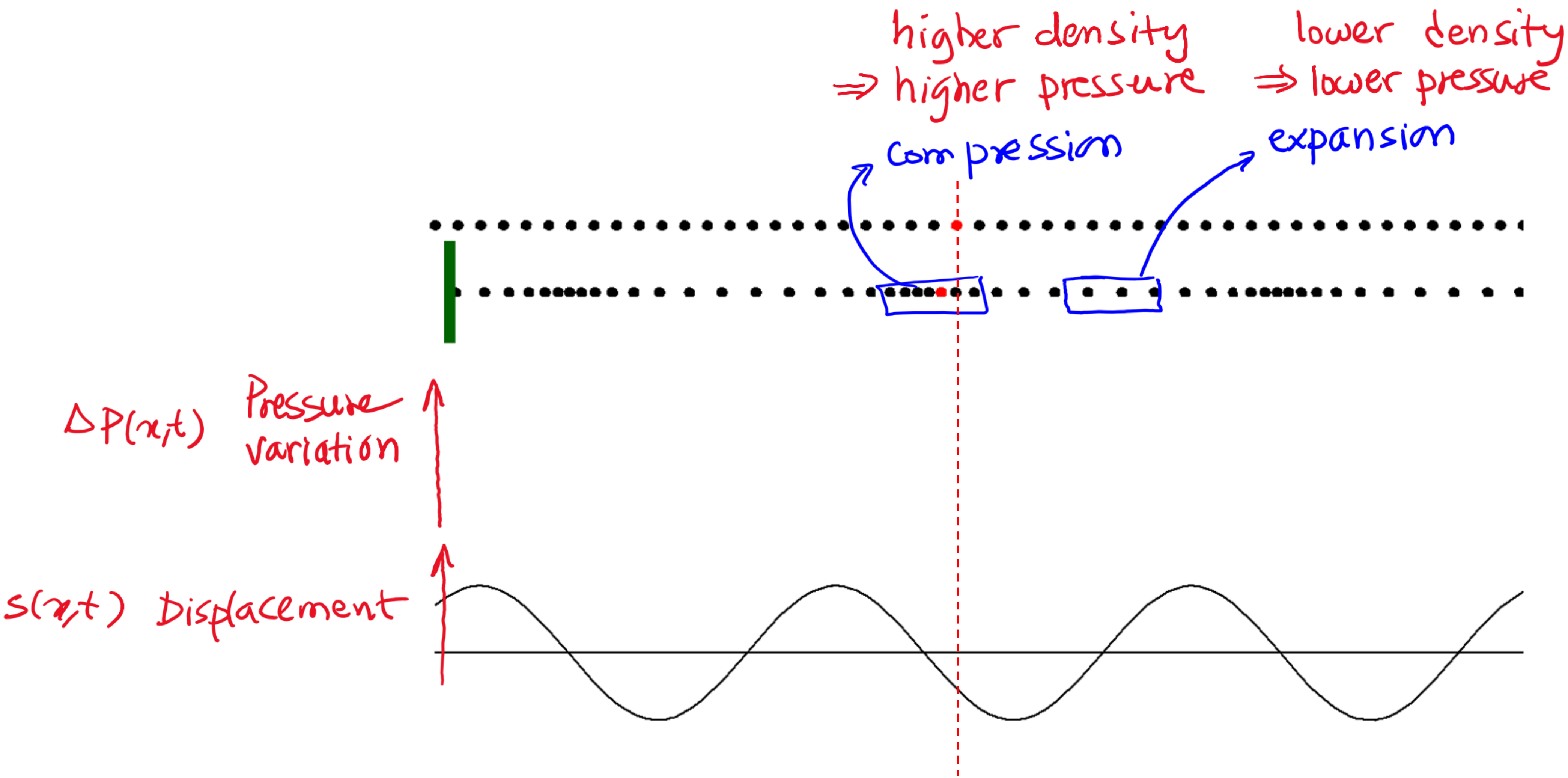
17-2 Traveling sound waves



$$s(x,t) = s_m \cos(kx - \omega t)$$

Displacement → $s(x,t)$

Displacement amplitude → s_m

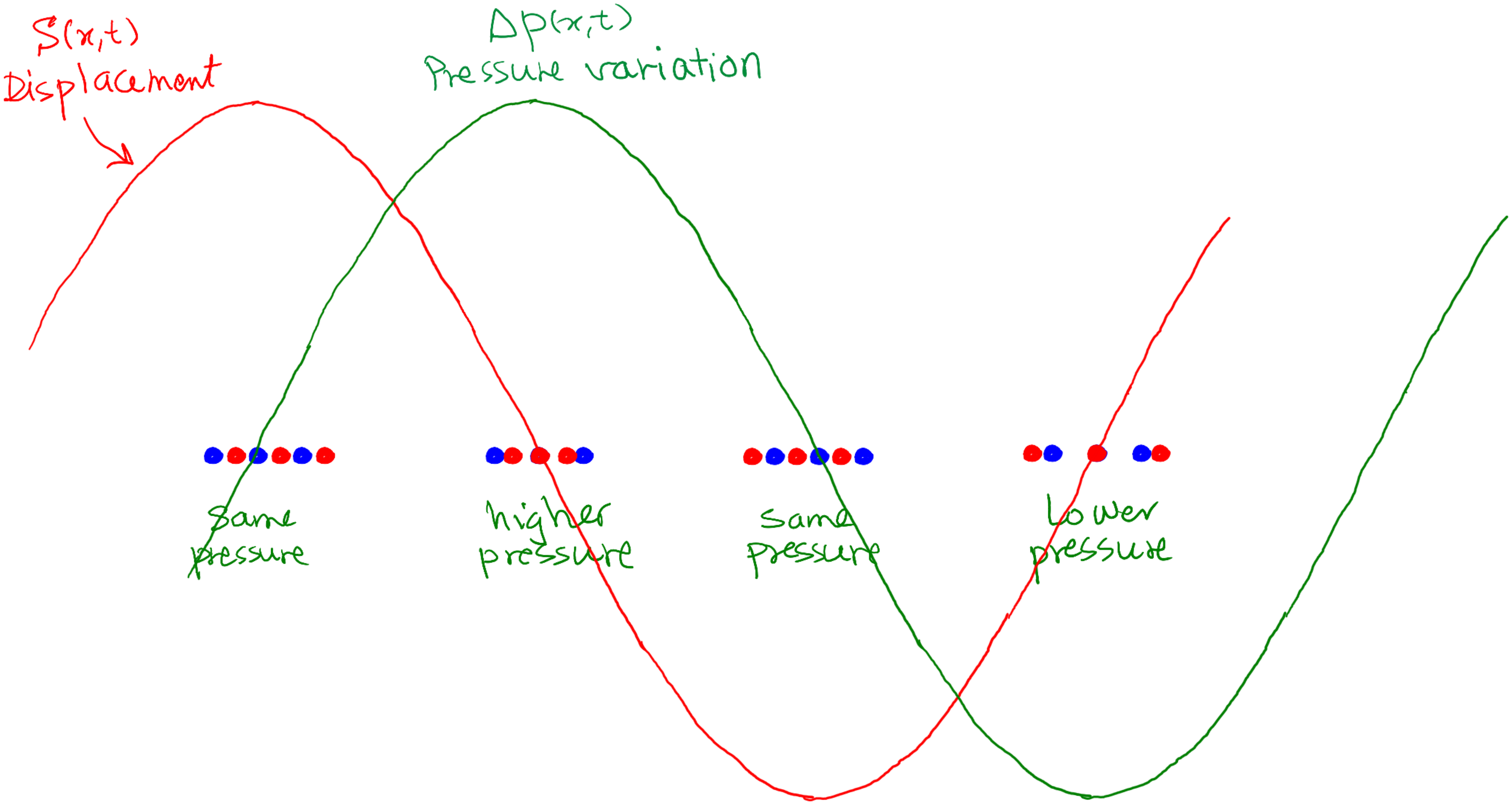


Displacement wave $\quad s(x,t) = s_m \cos(kx - \omega t)$

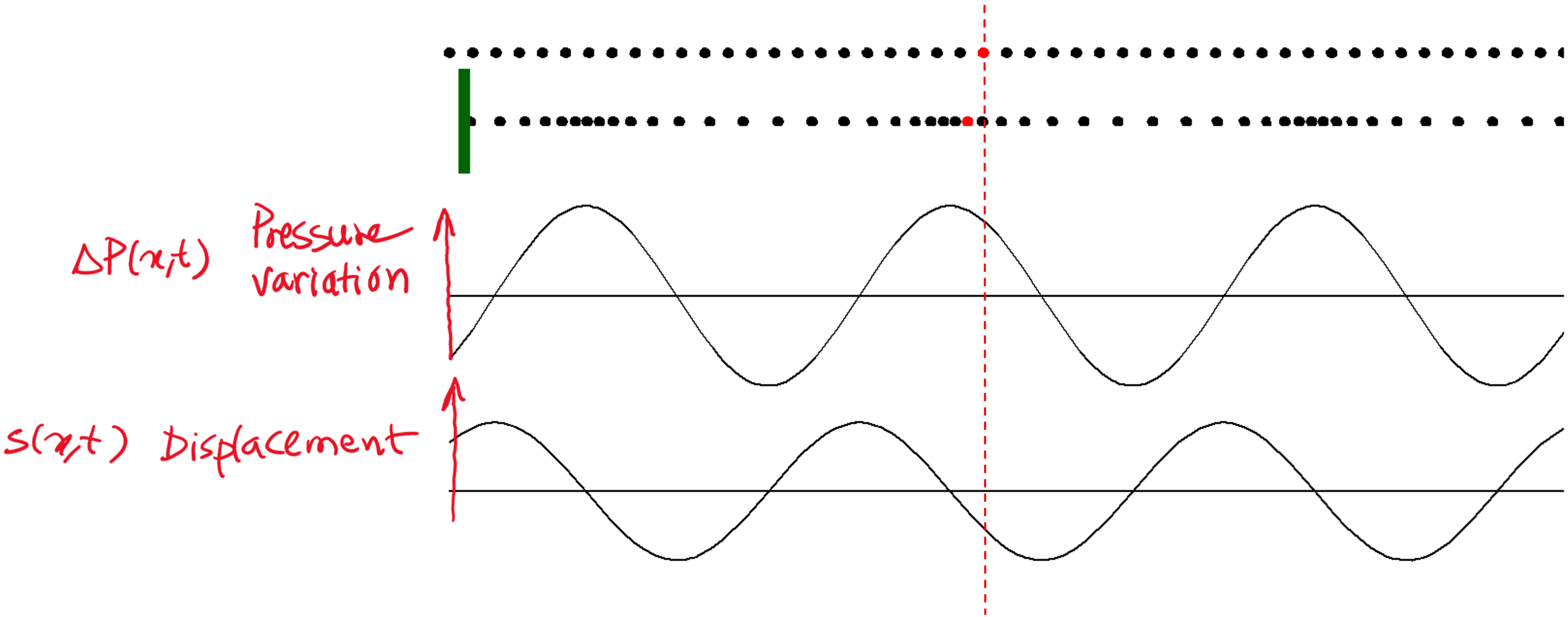
Displacement amplitude

Pressure wave $\quad \Delta p(x,t) = \Delta p_m \sin(kx - \omega t)$

Pressure amplitude



δ(x,t)
Displacement
Δp(x,t)
Pressure variation
same pressure
higher pressure
same pressure
Lower pressure



Displacement wave $\quad s(x,t) = s_m \cos(kx - \omega t)$

Displacement amplitude

Pressure wave $\quad \Delta p(x,t) = \Delta P_m \sin(kx - \omega t)$

Pressure amplitude

$$\Delta P_m = v \rho \omega S_m$$

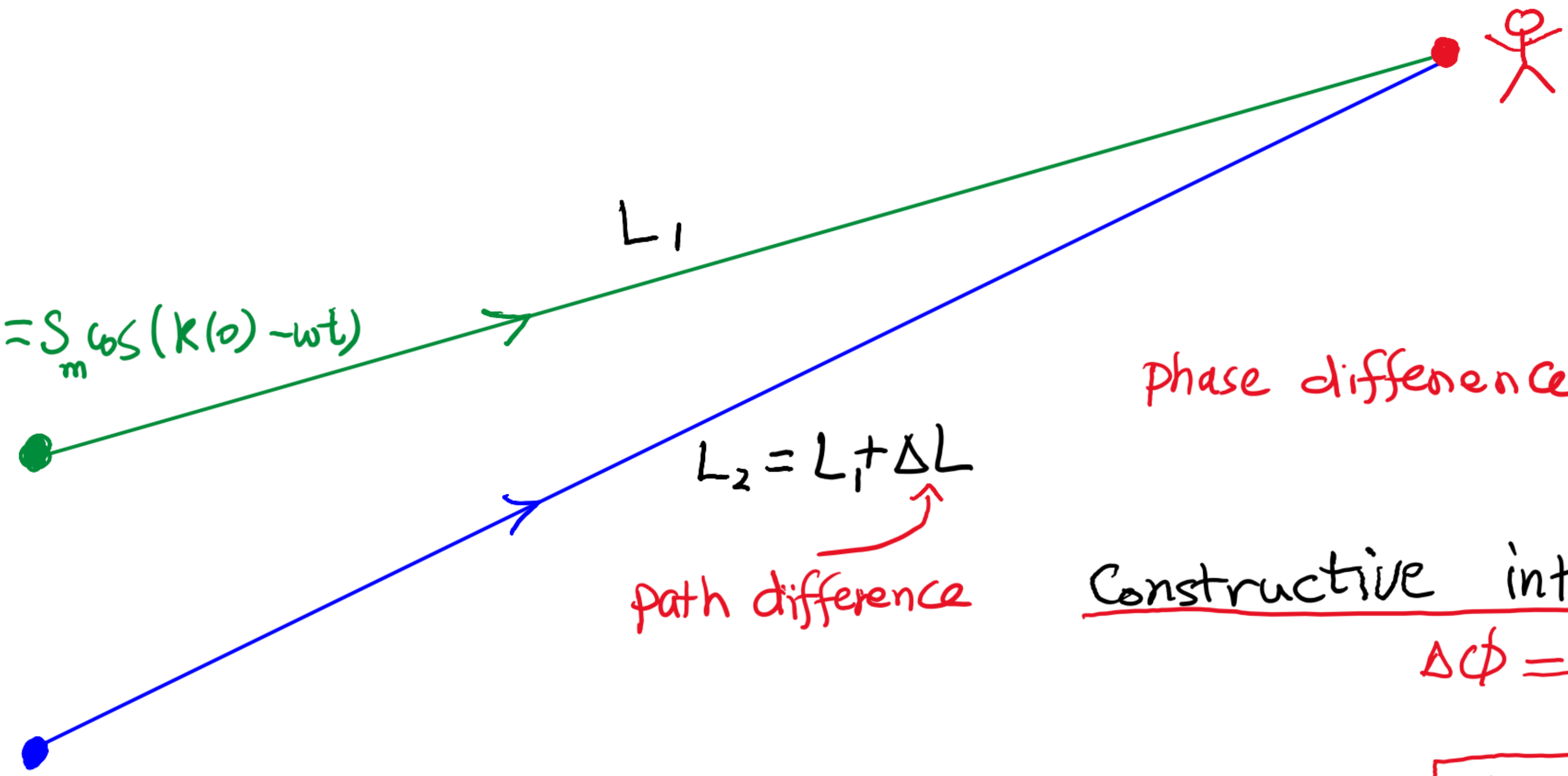
Pressure amplitude (ΔP_m), speed of sound (v), density (ρ), angular frequency (ω), Displacement amplitude (S_m)

You can hear from $f = 20\text{ Hz}$ to 20 kHz

Most sensitive at 1000 Hz

At 1000 Hz	S_m	ΔP_m
Loudest sound	10 μm (10^{-6})	30 Pa
Faintest Sound	10 pm (10^{-12})	30 μPa
	$\lambda = 0.34\text{ m}$	atmospheric Pressure $= 10^5$ Pa

17.3 Interference



$S_1 = S_m \cos(kL_1 - \omega t)$

$S_2 = S_m \cos(kL_2 - \omega t)$

$S_2 = S_m \cos(kL_1 - \omega t + k\Delta L)$

$k\Delta L = \Delta\phi$

$S_1 = S_m \cos(k(0) - \omega t)$

$L_2 = L_1 + \Delta L$ — path difference

phase difference $\Delta\phi = \frac{2\pi}{\lambda}\Delta L$

$S_2 = S_m \cos(k(0) - \omega t))$

Constructive interference

$\Delta\phi = \frac{2\pi}{\lambda}\Delta L = n(2\pi)$ $\quad n = 0, \pm 1, \ldots$

$\Rightarrow \boxed{\Delta L = n\lambda}$

Destructive interference

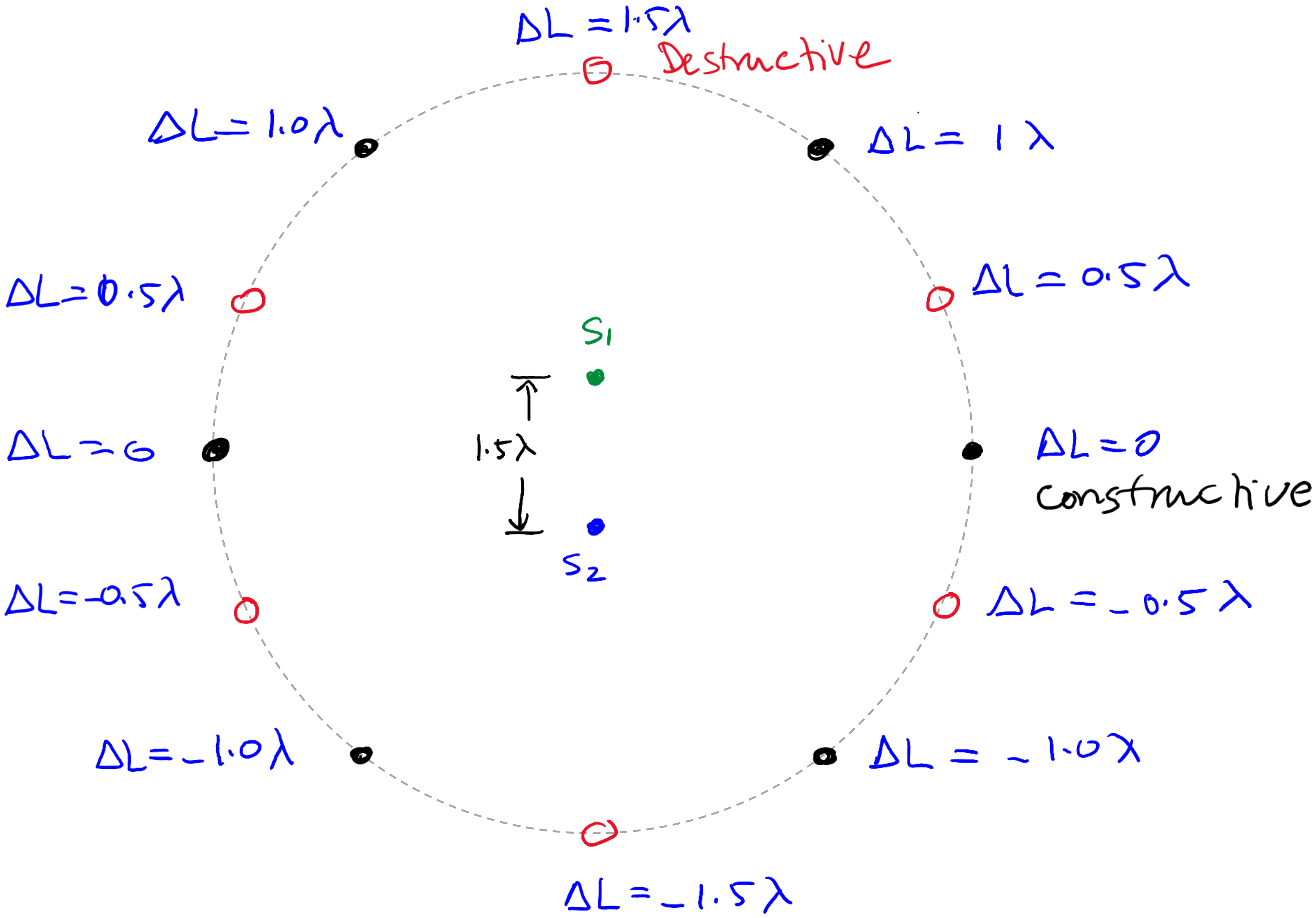
$\Delta\phi = \frac{2\pi}{\lambda}\Delta L = (2n+1)\pi$

$\Rightarrow \boxed{\Delta L = (n + \frac{1}{2})\lambda}$

Two point sources emit sound waves of the same wavelength.

They are in phase.

Example



ΔL = 1.5λ
Destructive
ΔL = 1.0λ
ΔL = 1 λ
ΔL = 0.5λ
ΔL = 0.5λ
S1
1.5λ
S2
ΔL = 0
ΔL = 0
constructive
ΔL = -0.5λ
ΔL = -0.5 λ
ΔL = -1.0λ
ΔL = -1.0λ
ΔL = -1.5λ

17.4 Intensity

Intensity of a sound wave

Average power transmitted

$$I \equiv \frac{P}{A}$$

area

For a sinusoidal wave

$$I = \frac{1}{2}\rho v \omega^2 s_m^2$$

Displacement amplitude

density

Speed of sound

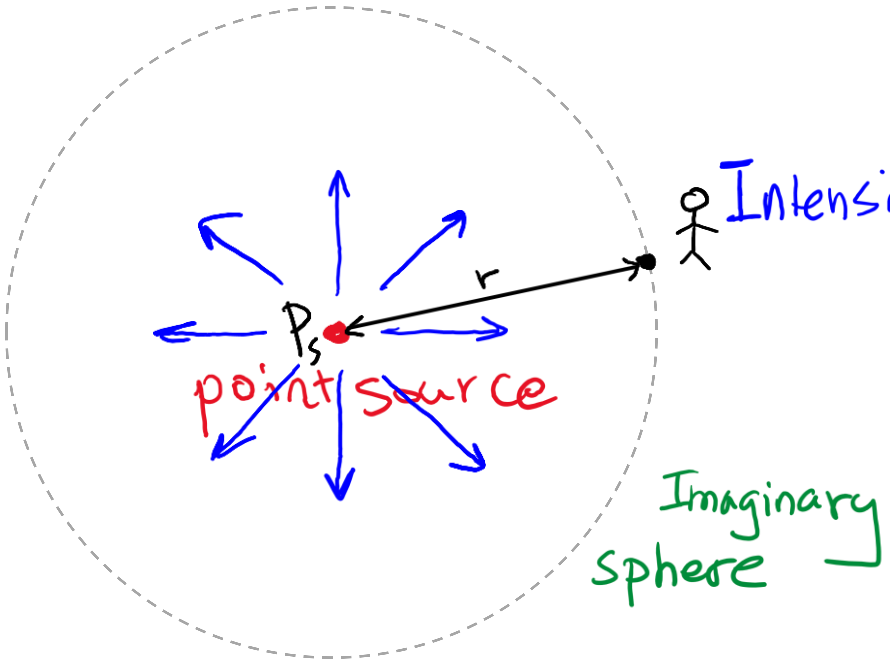
angular frequency

Wave on a string

$$P_{avg} = \frac{1}{2}\mu v \omega^2 y_m^2$$

Intensity at distace r from a point source

For a point source, Sound is emitted isotropically (equal intensity in all directions)



P_s = power of the source

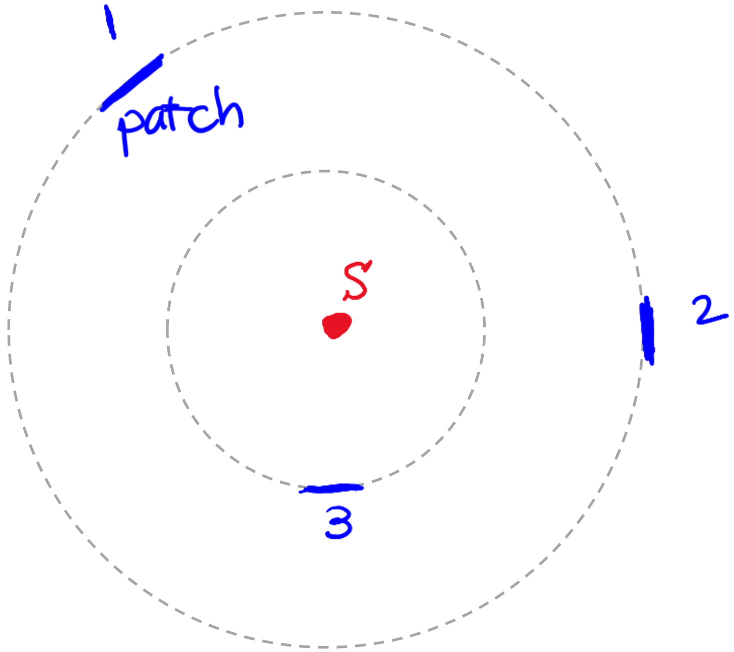
All energy of the source must pass through the surface of the sphere

The intensity at distace r from the source

$$\boxed{I = \frac{P}{A} = \frac{\text{Power of the source}}{\text{Area of the sphere}} = \frac{P_s}{4\pi r^2}}$$

Intensity decreases with the square of the distance from the source.

Question



compare the intensity of sound at the patches

$$I = \frac{P_s}{4\pi r^2} \Longrightarrow I_3 > I_1 = I_2$$

If the patches recieve the same power, compare their areas

$$I = \frac{P}{A} \Rightarrow A = \frac{P}{I} \Longrightarrow A_3 < A_1 = A_2$$

Sound level

highest sound you can hear

$$S_m = 10\,\mu m \Rightarrow I = 1\,\frac{W}{m^2} \Rightarrow \beta = 120$$

lowest sound you can hear

$$S_m = 10\,pm \Rightarrow I = 10^{-12}\,\frac{W}{m^2} \Rightarrow \beta = 0$$

For a sinusoidal wave

$$I = \frac{1}{2}\rho v \omega^2 s_m^2$$

$\rho = 1.2\ kg/m^3$

$v = 343\ m/s$

Most sensitive $f = 1000\ Hz$

$\omega = 2\pi(1000)\ \frac{rad}{s}$

Sound level β is a simpler way to express intensity

Sound level

Intensity

$$\boxed{\beta \equiv 10 \log \frac{I}{I_0}}$$

reference intensity $\equiv 10^{-12}\,\frac{W}{m^2}$

measured in dB

deci bell

related to 10

Graham Bell

Example

An ear plug decreases the sound level by 20 dB.

$$\frac{\text{final intensity}}{\text{initial intensity}} = \frac{I_f}{I_i} = ?$$

$$\beta = 10 \log \frac{I}{I_0}$$

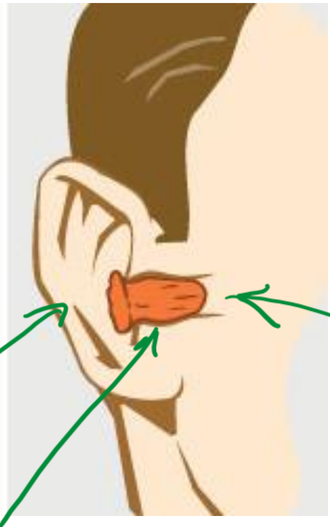
$$\boxed{\log a - \log b = \log \frac{a}{b}}$$

$$\beta_f - \beta_i = -20$$

$$\cancel{10} \log \frac{I_f}{I_0} - \cancel{10} \log \frac{I_i}{I_0} = -\overset{2}{\cancel{20}}$$

$$\log \frac{I_f}{\cancel{I_0}} \cdot \frac{\cancel{I_0}}{I_i} = -2 \Rightarrow \log \frac{I_f}{I_i} = -2$$

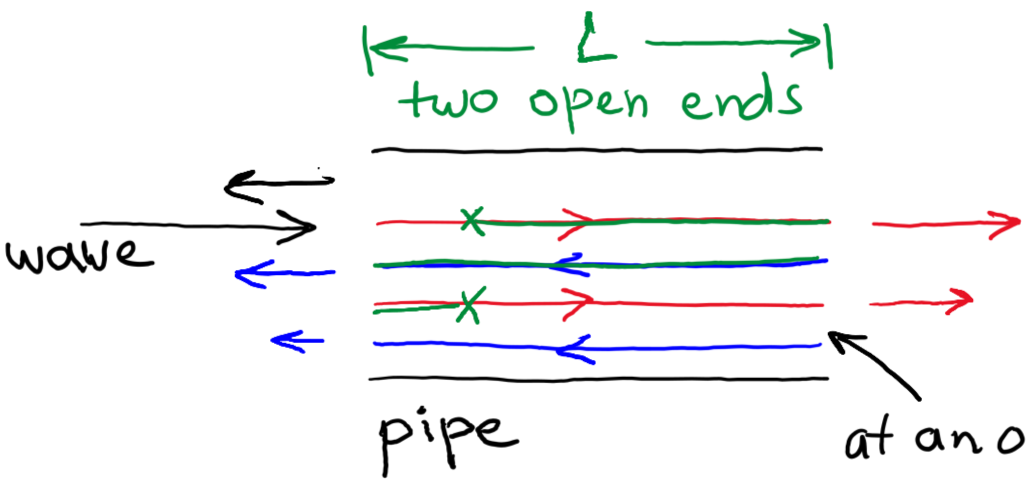
$$10^{\log \frac{I_f}{I_i}} = 10^{-2} \Rightarrow \frac{I_f}{I_i} = 10^{-2} = 0.01$$



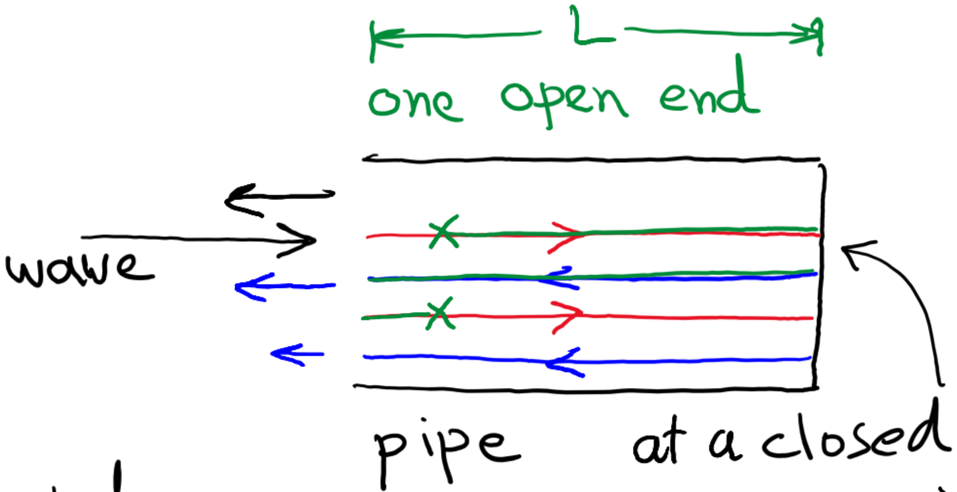
β increases by 10 every time the sound intensity is multiplied by 10

$$\Delta\beta = 10x \Rightarrow \frac{I_f}{I_i} = 10^x$$

17-5 Sound wave resonance



at an open end, waves are not inverted (antinode)



at a closed end, waves are inverted (node) $\Rightarrow$ add $\frac{\lambda}{2}$

At resonance, right-going waves are in phase

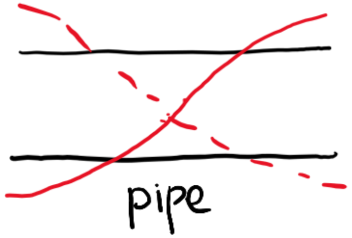
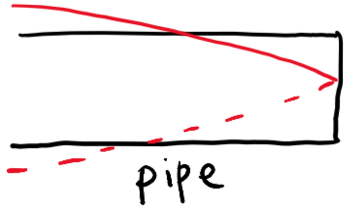
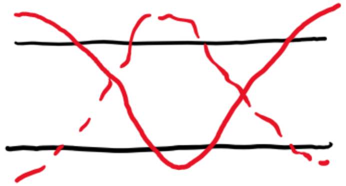
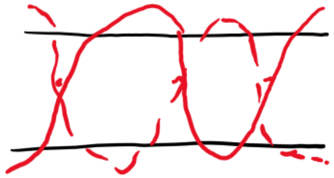
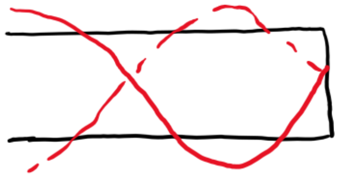
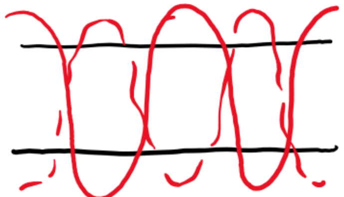
$$2L = n\lambda \qquad n = 1, 2, 3, \ldots$$

$$2L + \frac{1}{2}\lambda = \bar{n}\lambda \qquad \bar{n} = 1, 2, 3, \ldots$$

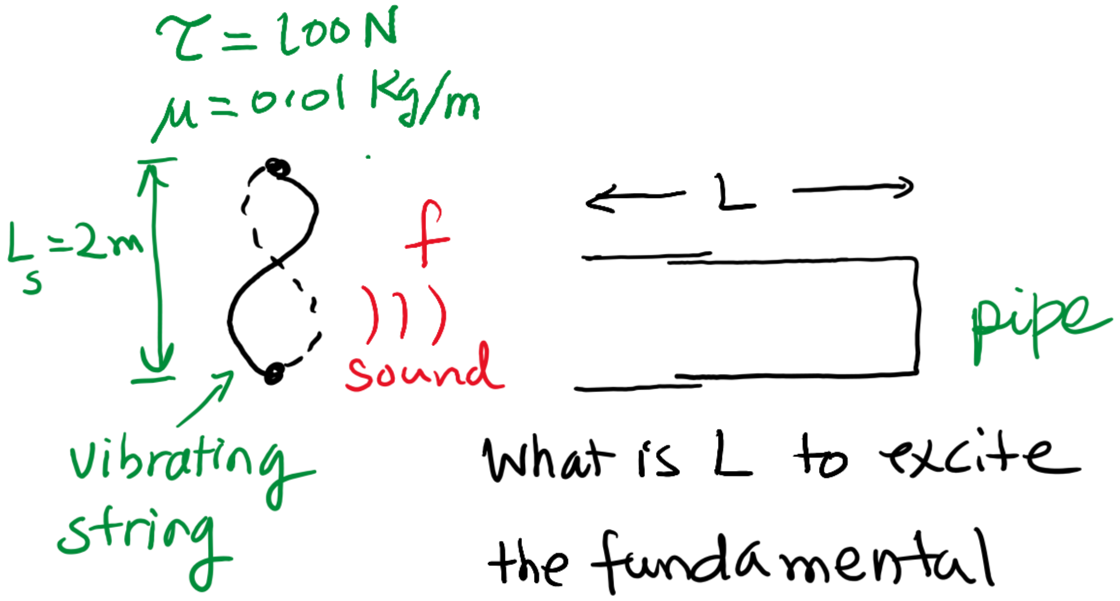
resonant wavelength	$\lambda_n = \frac{2L}{n}$	$\lambda_n = \frac{4L}{\underbrace{2\bar{n}-1}_{n}}$
resonant frequency	$f_n = \frac{v}{\lambda} = n\frac{v}{2L}$ $(n = 1, 2, 3, \ldots)$	$f_n = n\frac{v}{4L}$ $(n = 1, 3, 5, \ldots)$

Resonant frequencies

Closed end → node
open end → antinode

	n	$\lambda_n = \frac{2L}{n}$		odd n	$\lambda_n = \frac{4L}{n}$	
The first harmonic (The fundamental mode)	1	$\lambda_1 = \frac{2L}{1}$		1	$\lambda_1 = \frac{4L}{1}$	
The second harmonic	2	$\lambda_2 = \frac{2L}{2}$		2	missing	
The third harmonic	3	$\lambda_3 = \frac{2L}{3}$		3	$\lambda_3 = \frac{4L}{3}$	
The fourth harmonic	4	$\lambda_4 = \frac{2L}{4}$		4	missing	

Example



What is L to excite the fundamental mode by the string?

for the string

$$f = n\frac{v_s}{2L_s} = n\frac{\sqrt{\tau/\mu}}{2L_s}$$

$$f = 2\,\frac{\sqrt{\frac{100}{0.01}}}{2(2)} = 50\ Hz$$

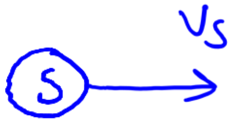
for the pipe

$$f = n\frac{v}{4L} = 1\,\frac{343}{4L}$$

$$50 = \frac{343}{4L} \Rightarrow L = \frac{343}{4(50)}\ m$$

17.7 Doppler effect

The Doppler effect is the change in the detected frequency because of a relative motion between the source of sound and the detector.



Source

f = frequency emitted by the source

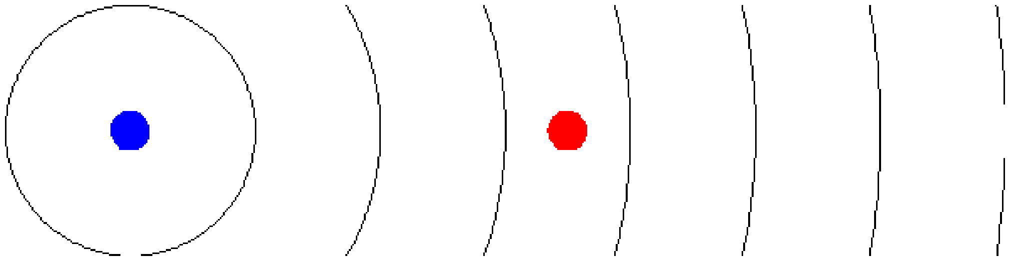
Detector

f' = frequency detected by the detector

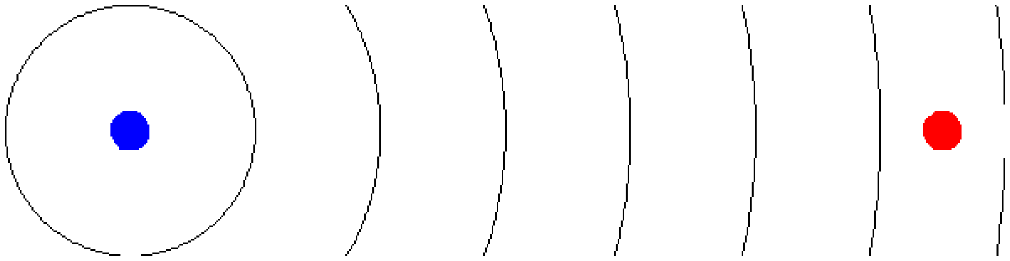
<u>Example</u> loud speaker
siren

<u>Example</u> microphone
ear

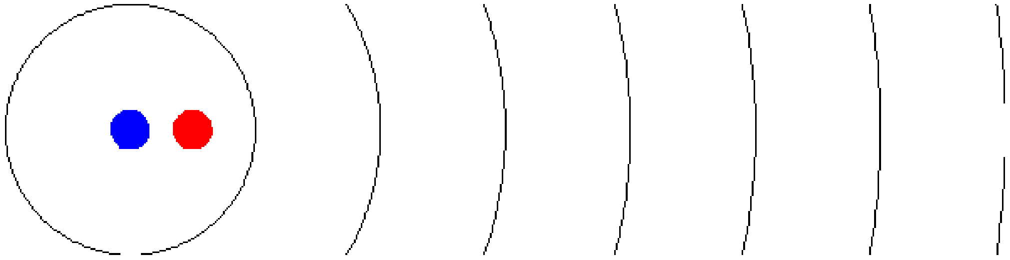
v_s and v_D are measured relative to the air.



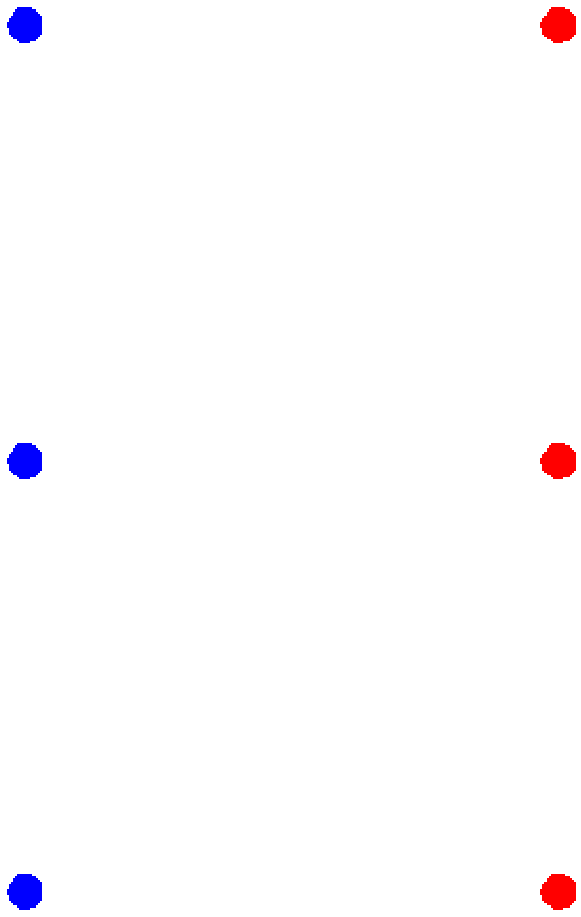
$f' = f$



$f' > f$



$f' < f$



$$f' = f$$

$$f' > f$$

$$f' < f$$

speed of sound

speed of detector relative to air

$$f' = f\,\frac{v \pm v_D}{v \pm v_S}$$

frequency detected by the detector

frequency emitted by the source

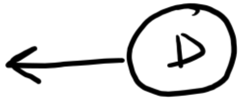
speed of source relative to air

Choose the sign such that when the source or detector moves toward the other, you get a higher frequency, and when the source or detector moves away from the other, you get a lower frequency.

Toward $\longrightarrow$ higher f' Away $\longrightarrow$ lower f'

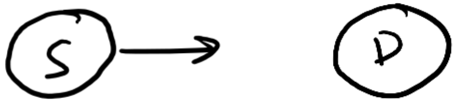
$$f' = f\,\frac{v \pm v_D}{v \pm v_S}$$

$$f' = f\,\frac{v - v_D}{v}$$



$$f' = f\,\frac{v + v_D}{v}$$

$$f' = f\,\frac{v}{v + v_S}$$

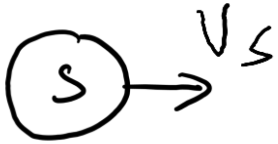


$$f' = f\,\frac{v}{v - v_S}$$

$$f' = f\,\frac{v + v_D}{v - v_S}$$

Question

Compare f and f'



$f' > f$

$$f' = f\,\frac{V - V_D}{V - V_s}$$

need to know V_D and V_s to compare.

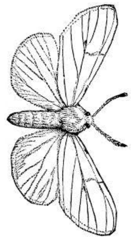
Example

Bat

$v_b = 13$ m/s

$f_{be} = 66$ kHz

Moth



$v_m = 8$ m/s

$f_{md} = ?$

What frequency f_{md} does the moth detect?

$$f' = f\,\frac{v \pm v_D}{v \pm v_s}$$

Detector moves away

$$f_{md} = f_{be}\,\frac{v - v_m}{v - v_b}$$

source moves toward

$$f_{md} = 66\times10^3\,\frac{343-8}{343-13} = 67\text{ kHz}$$

Example

Bat

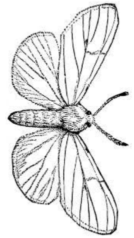
$v_b = 13$ m/s

$f_{be} = 66$ kHz

$f_{bd} = ?$

Moth

echo



$v_m = 8$ m/s

$f_{md} = 67$ kHz

$= f_{me}$

What frequency f_{bd} does the bat detect?

$$f' = f \, \frac{v \pm v_D}{v \pm v_s}$$

detector moves toward

$$f_{bd} = f_{me} \, \frac{v + v_b}{v + v_m}$$

source moves away

$$f_{bd} = 67 \times 10^3 \, \frac{343 + 13}{343 + 8} = 68 \text{ kHz}$$