Waves & Sound

Waves

- disturbance that propagates through space & time
- usually with transfer of energy

- Mechanical
  requires a medium
- Electromagnetic
  no medium required

Mechanical waves:

sound, water, seismic .... 'the wave'

Electromagnetic waves:

all light - radio, microwave, infrared, visible ...

Waves travel & transfer energy from place to place
- need not be permanent displacement
- e.g., oscillation about fixed point

Today:
- mechanical waves only (mostly NO EM)
- build up to sound ...

Mechanical waves require a medium
- it must be an elastic medium
- cannot be perfectly stiff or perfectly pliable ... no wave!

everything moves in unison
only translation

all particles move independently
no propagation

Most mechanical waves are of two sorts:

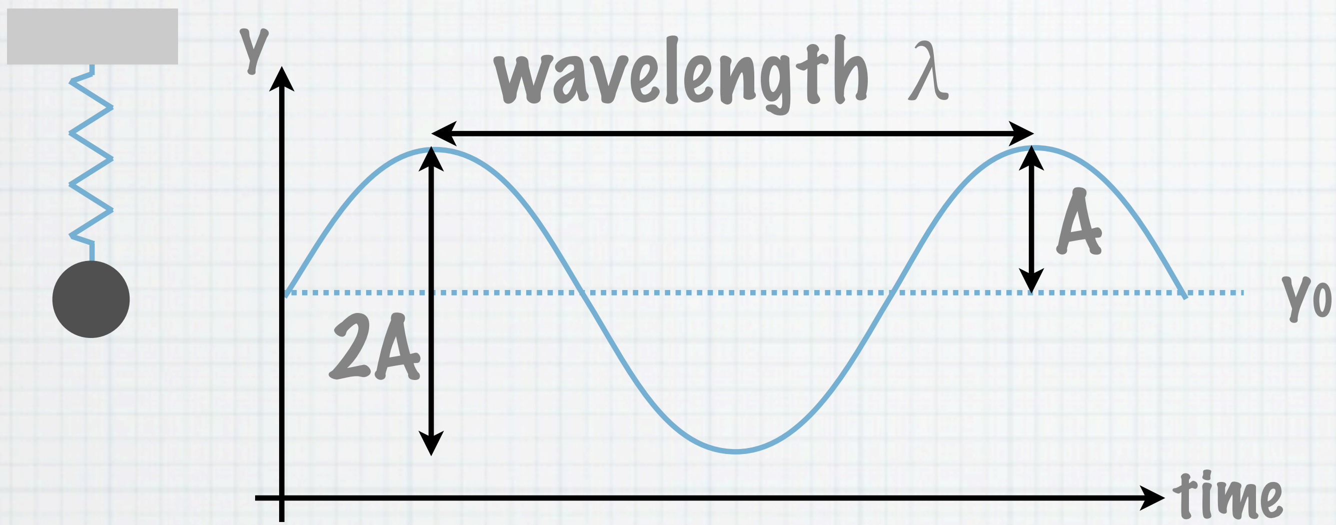
"Mass-spring" type : particles oscillating

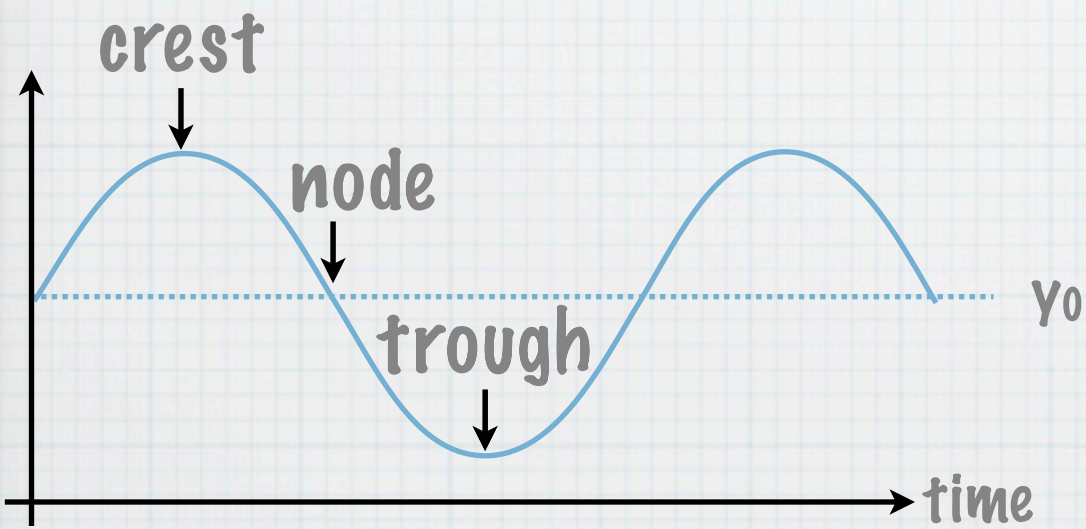
"Density" type : spatial & temporal density variations

... so far as we are concerned, at least

Describing waves

example: position of a mass on a spring

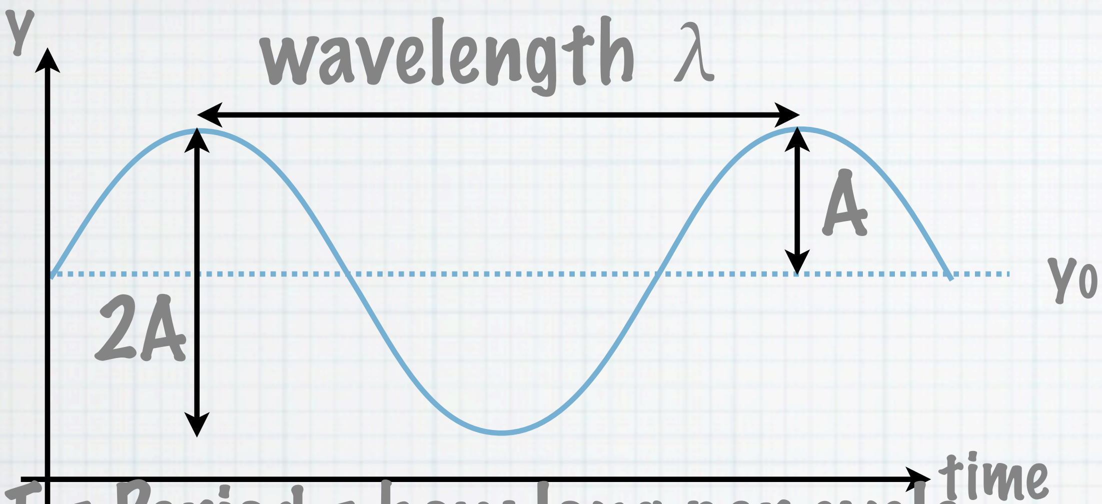




A = amplitude = intensity

λ = wavelength = char. size

f = frequency, full periods/sec



T = Period = how long per cycle

λ characterizes SPATIAL variation

f characterizes TIME variation

T = 1/f or f = 1/T

frequency - wavelength - velocity:

λ f = v = velocity of wave propagation

or vT = λ .... travel one wavelength per period

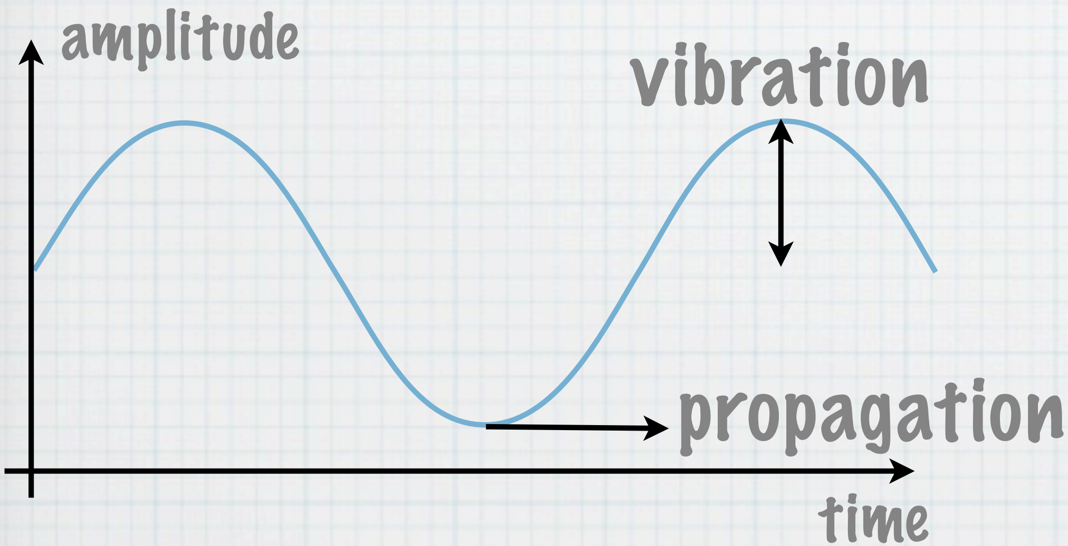
simplest wave:

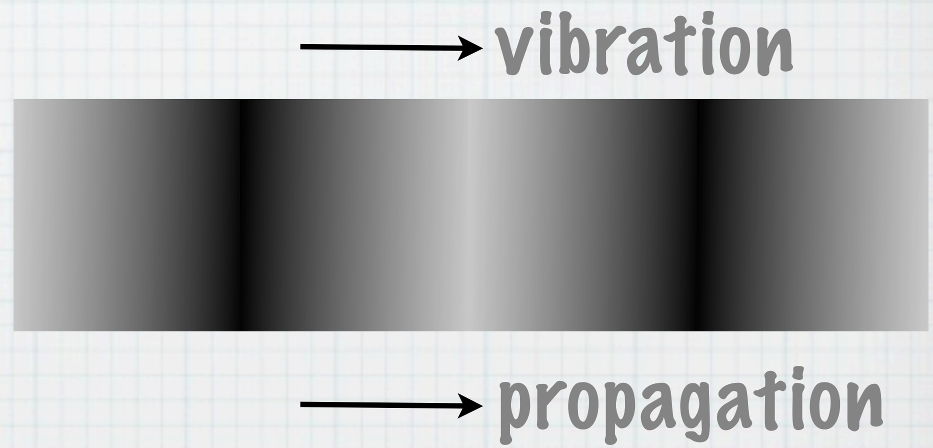
$$f(x,t) = A\sin\left(2\pi f t - \frac{2\pi}{\lambda}x\right)$$

Characteristics of waves

they have Crests & Troughs
- intensity varies periodically. "vibration"

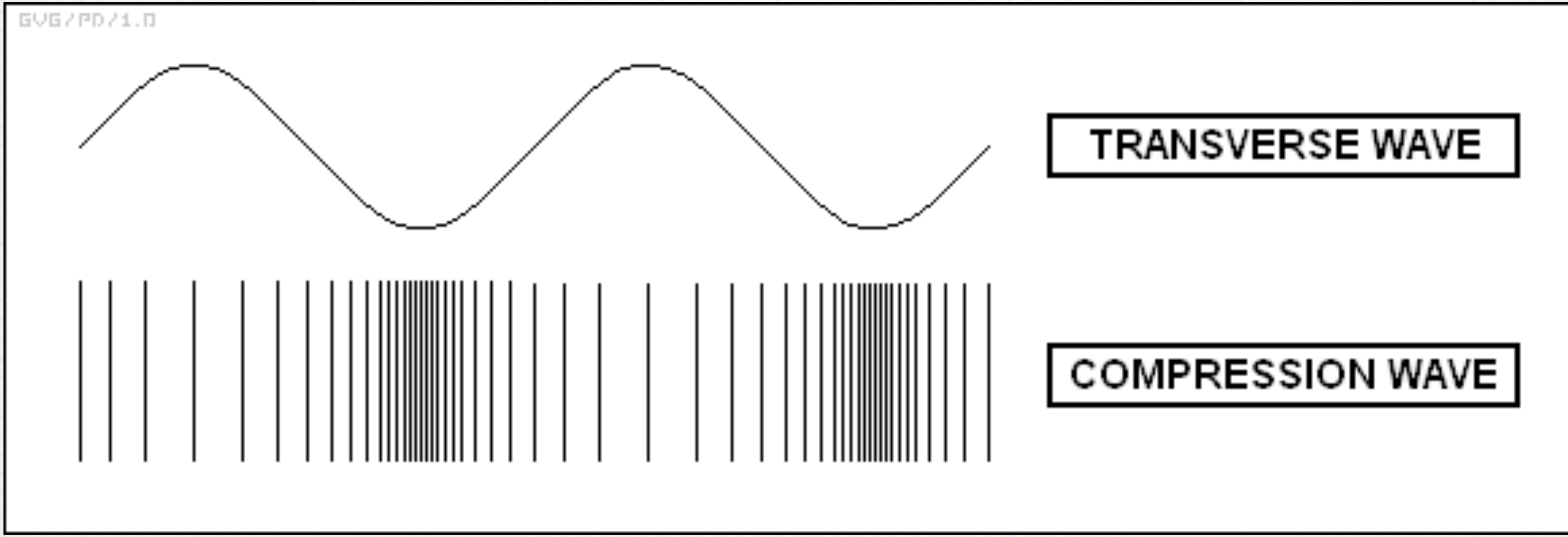
Longitudinal	Transverse
vibrations are **PERPENDICULAR** to propagation	vibrations are **PARALLEL** to propagation





string, EM waves

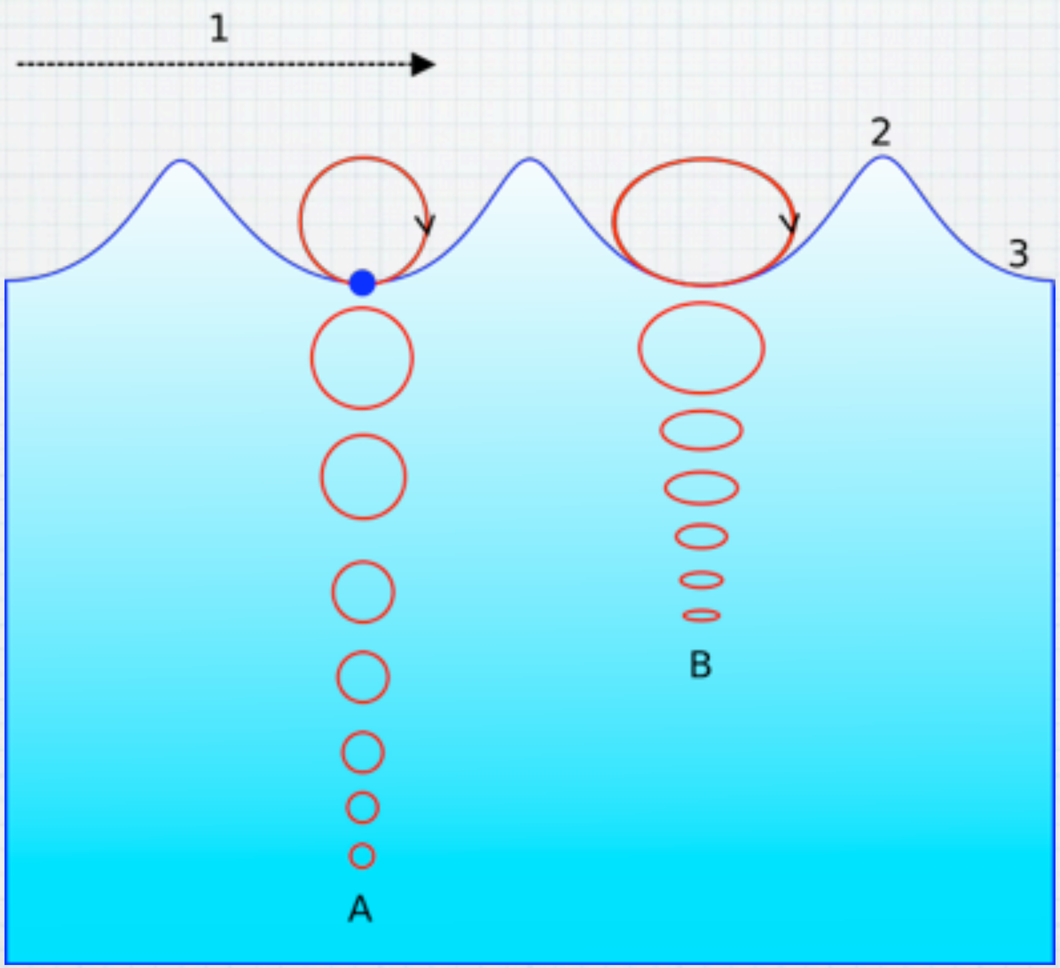
sound


GVG/PD/1.0
TRANSVERSE WAVE
COMPRESSION WAVE

of course, there are in between cases

mixed transverse & longitudinal

e.g., objects bobbing up & down on a water wave



Under typical conditions, all waves can:

<u>reflect</u>: change direction after hitting a reflecting surface

<u>refract</u>: change direction after hitting a refracting surface

<u>diffract</u>: bend as they interact with objects

(when object's size is near wavelength)

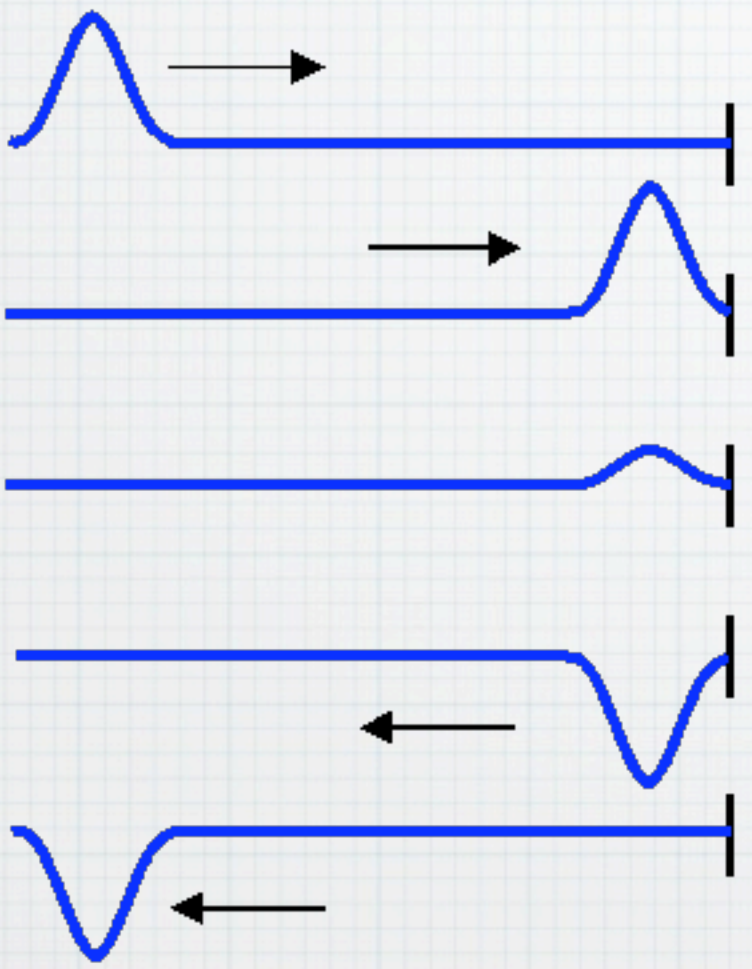
<u>interfere</u>: superposition of colliding waves

<u>disperse</u>: split up by frequency

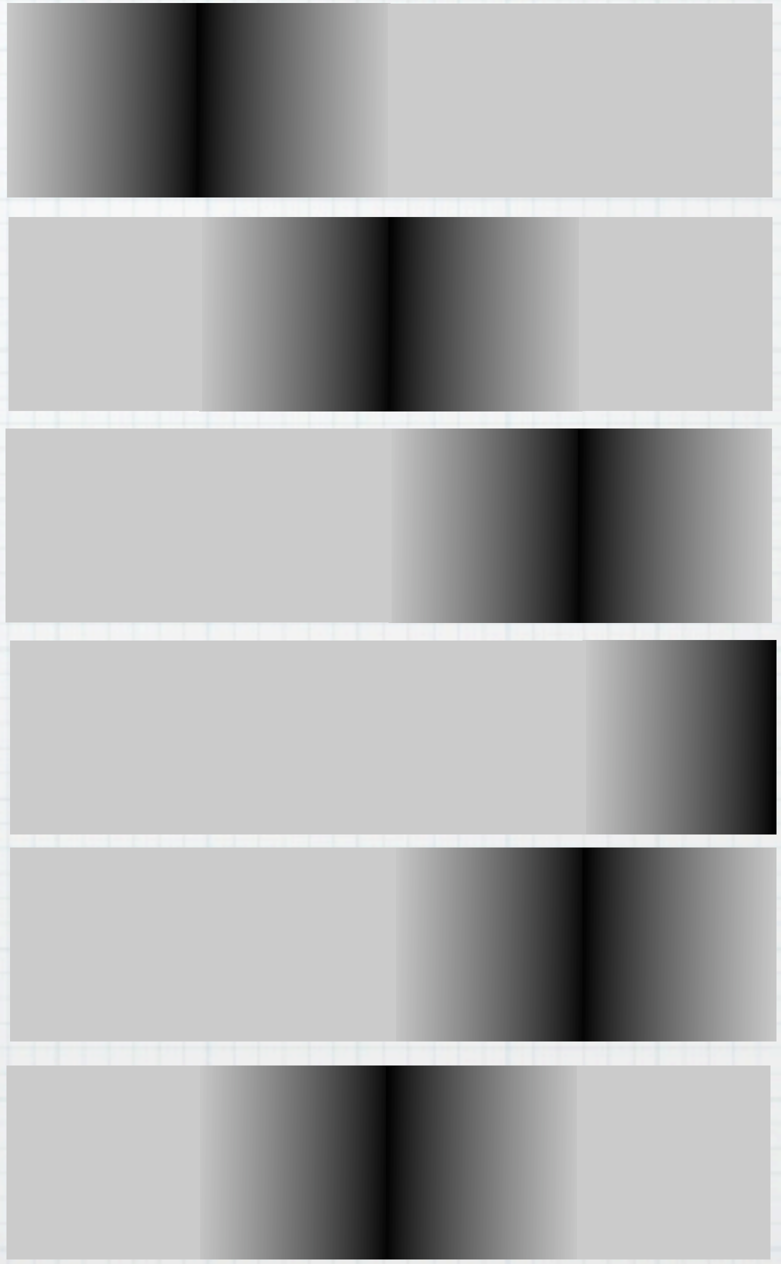
<u>move in a straight line</u>: propagation ... not always (standing)

Reflection

pulse on a string

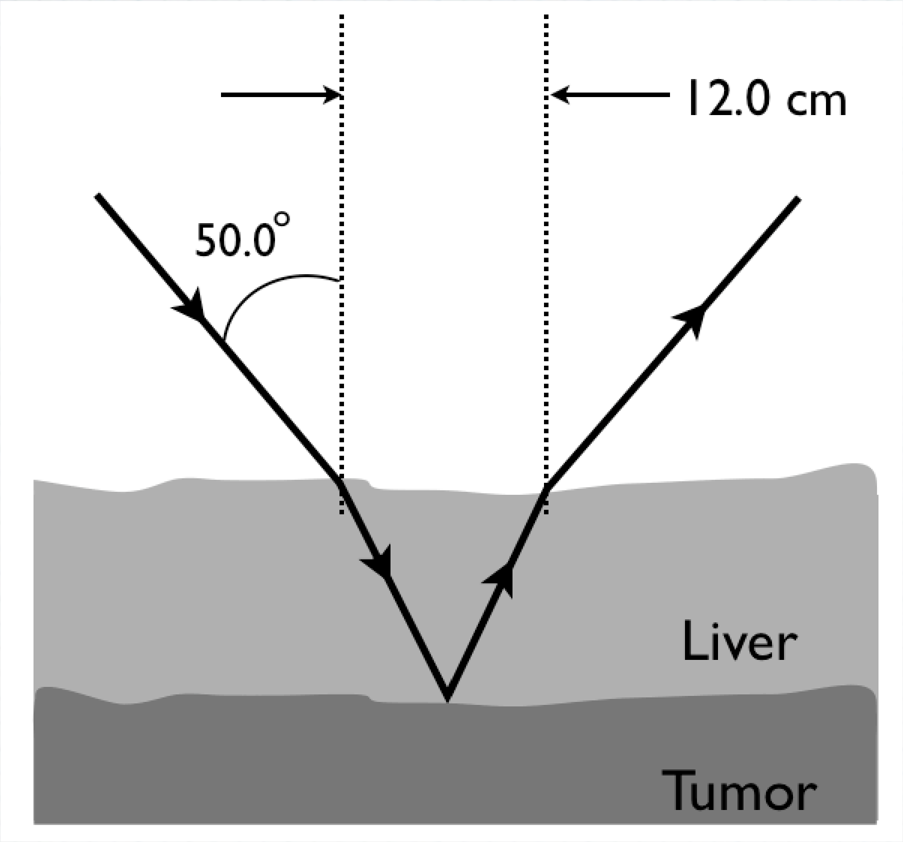


density wave

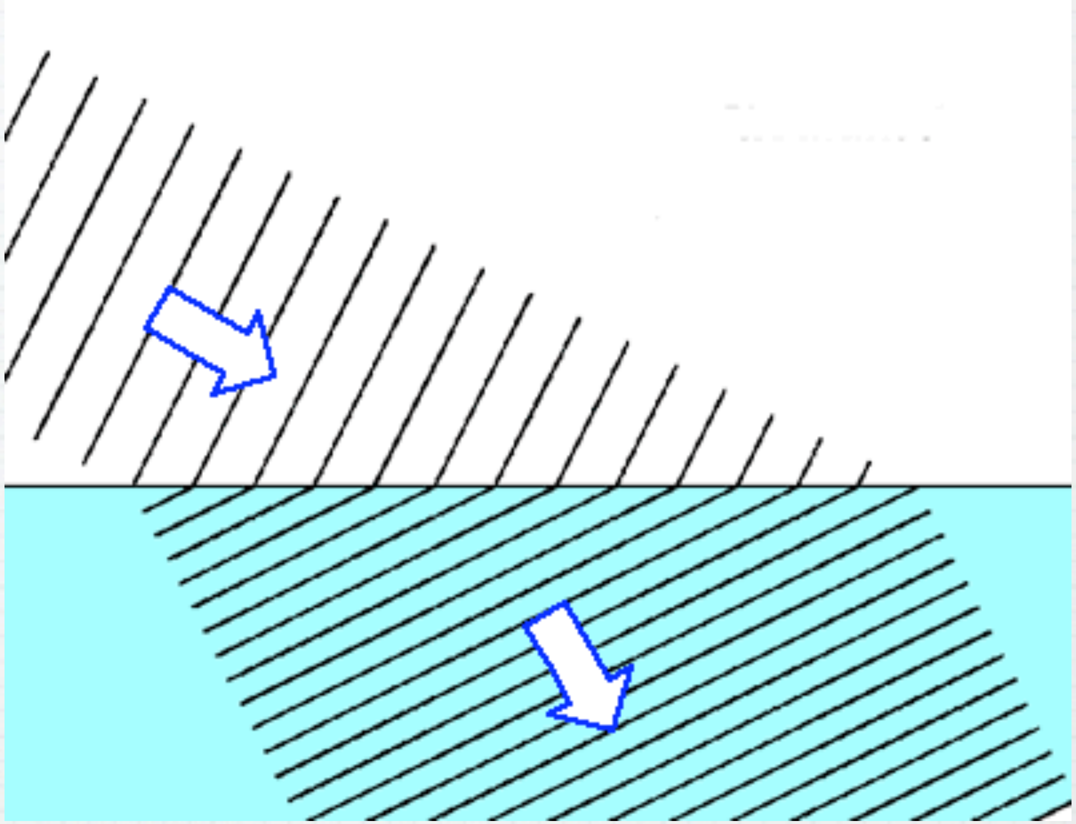


Refraction

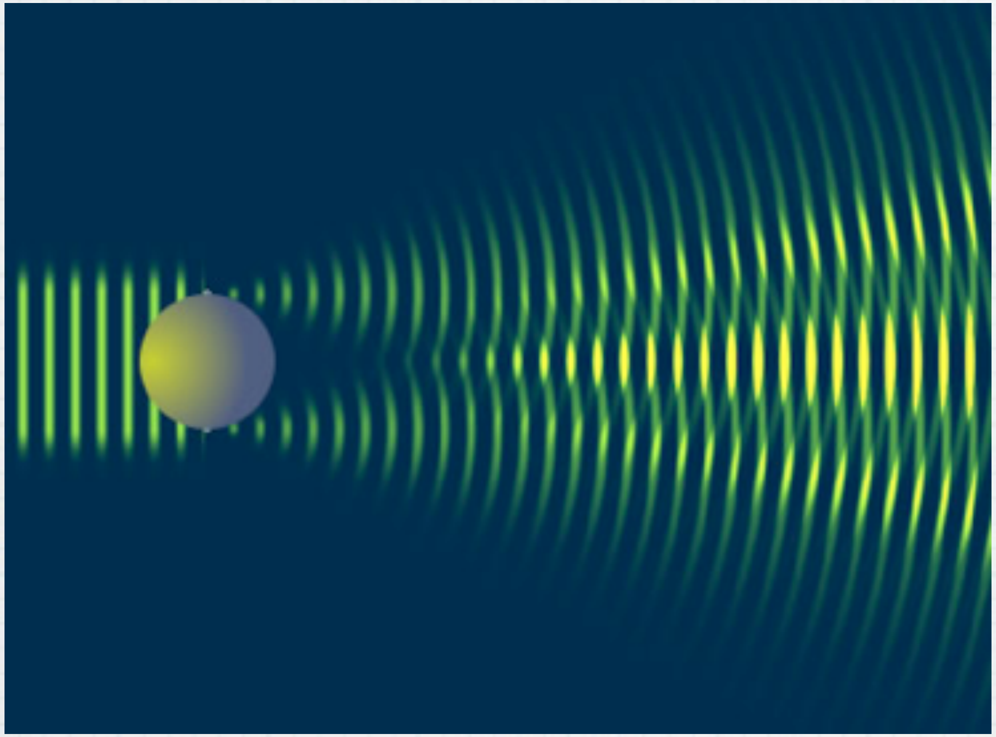
light & heavy string

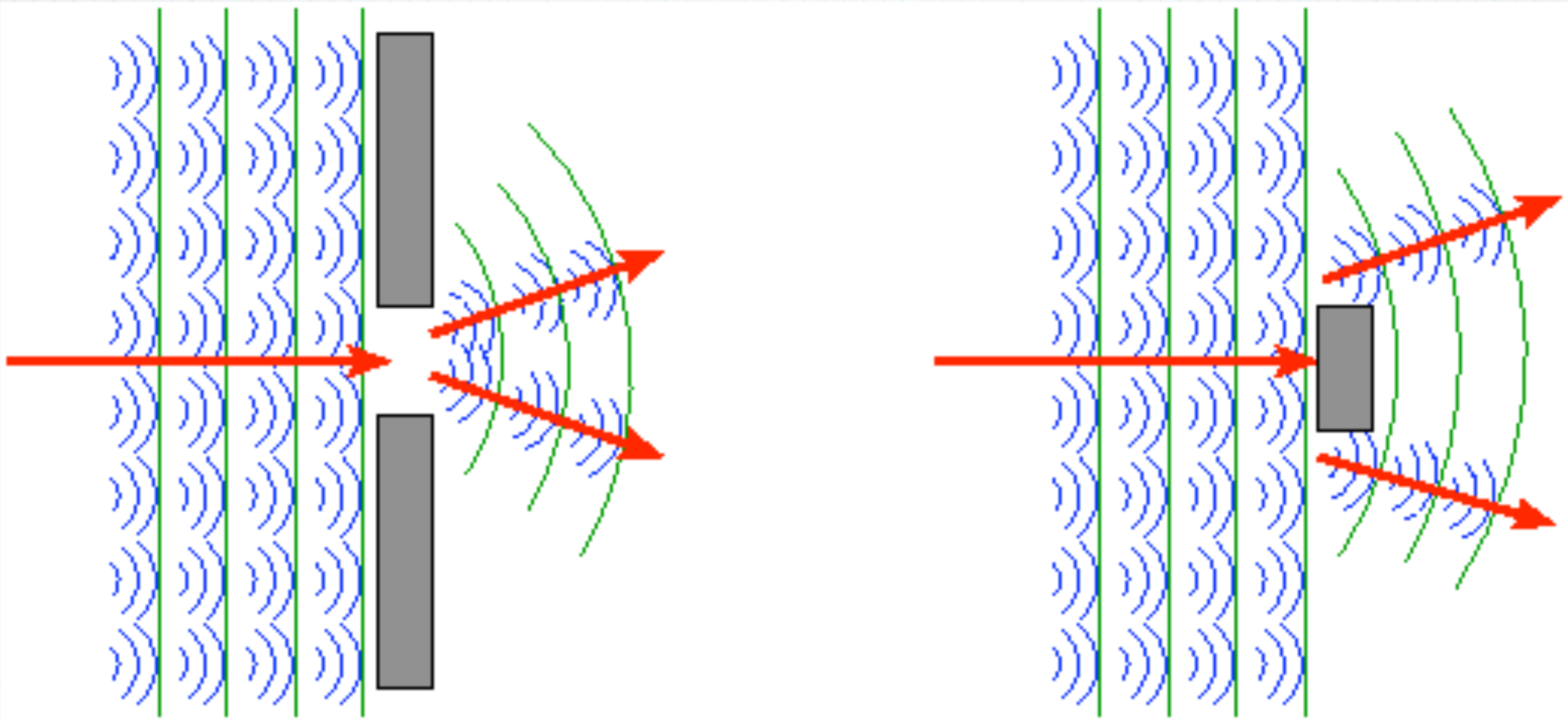


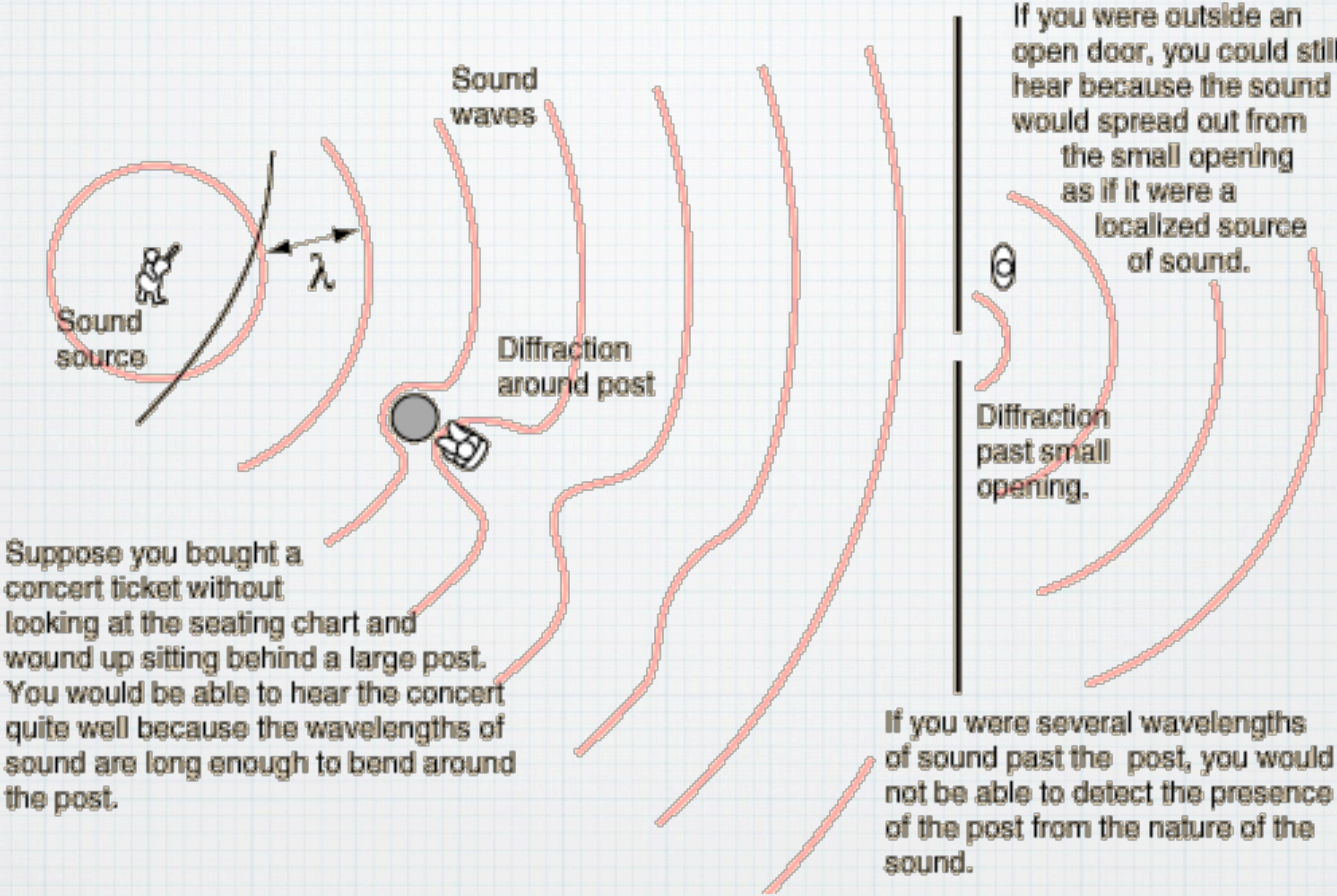
density wave at a boundary

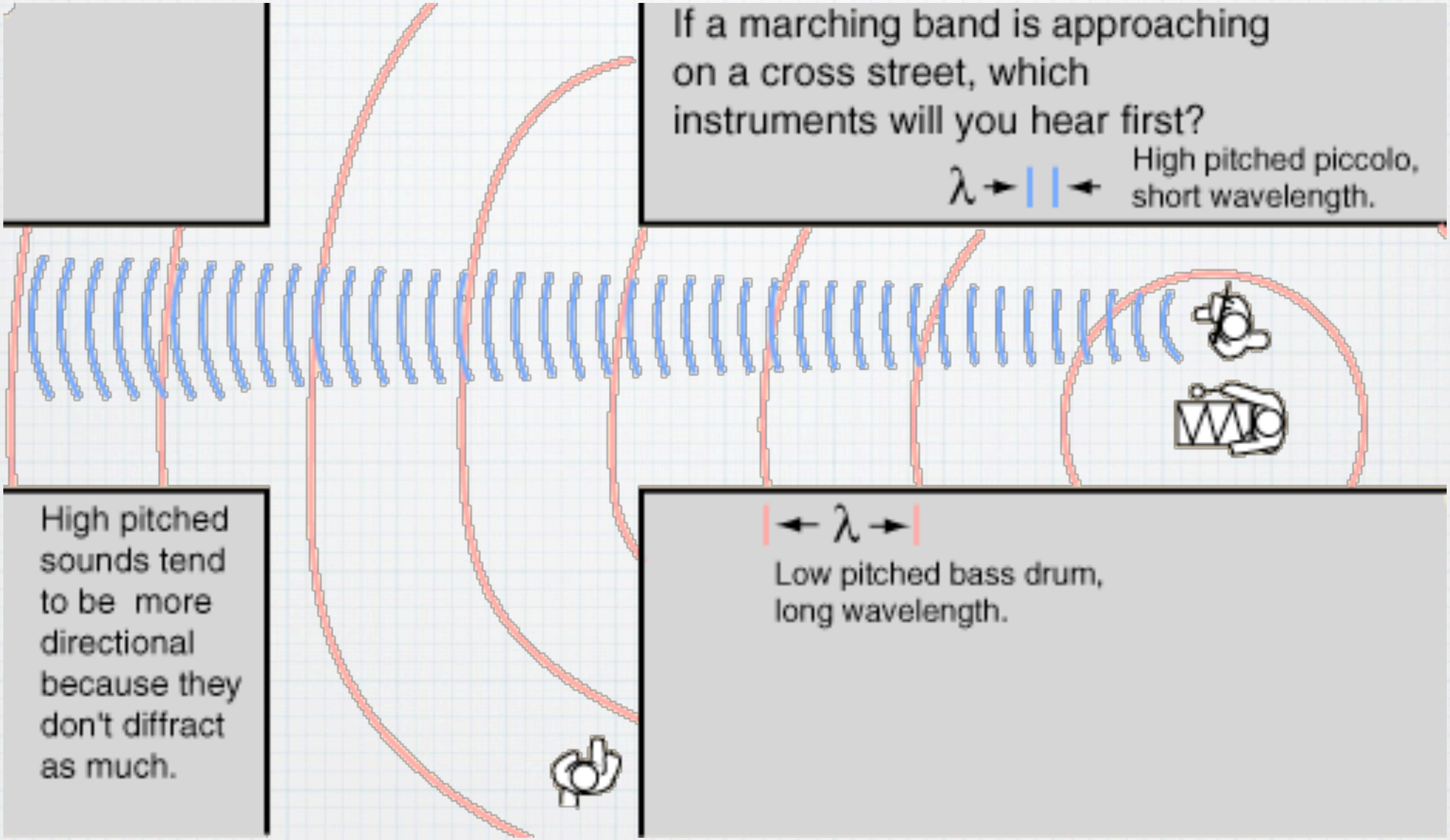


Diffraction

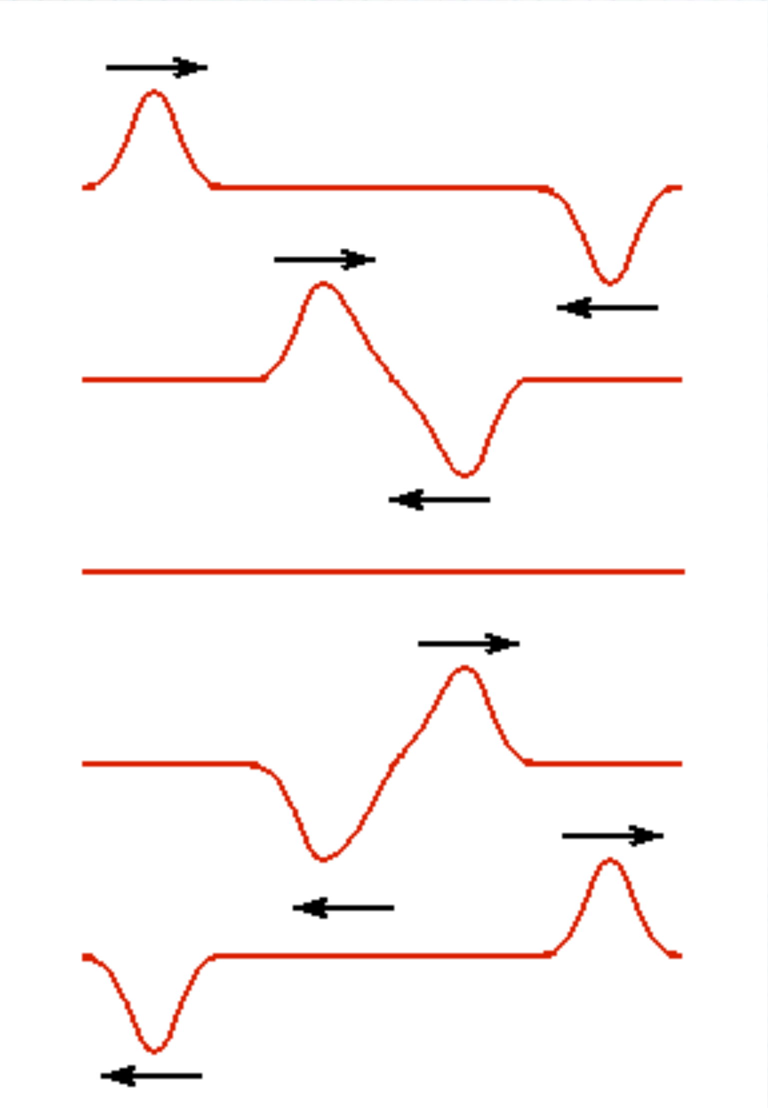


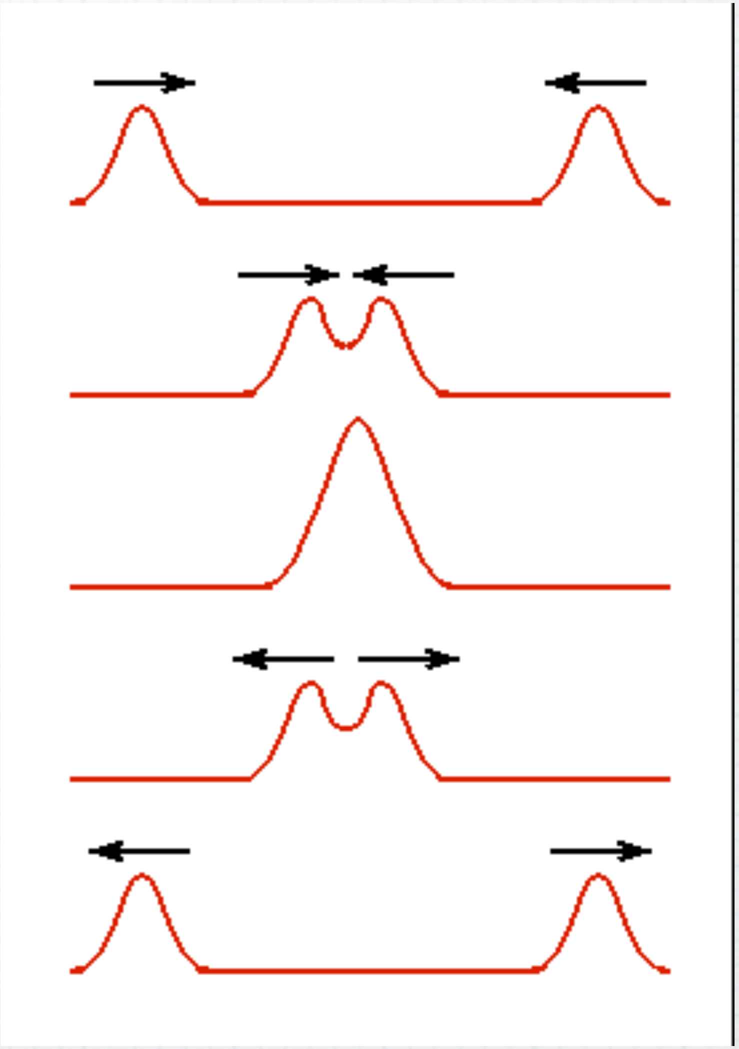



Sound waves
λ
Sound source
Diffraction around post
Suppose you bought a concert ticket without looking at the seating chart and wound up sitting behind a large post. You would be able to hear the concert quite well because the wavelengths of sound are long enough to bend around the post.
If you were outside an open door, you could still hear because the sound would spread out from the small opening as if it were a localized source of sound.
Diffraction past small opening.
If you were several wavelengths of sound past the post, you would not be able to detect the presence of the post from the nature of the sound.

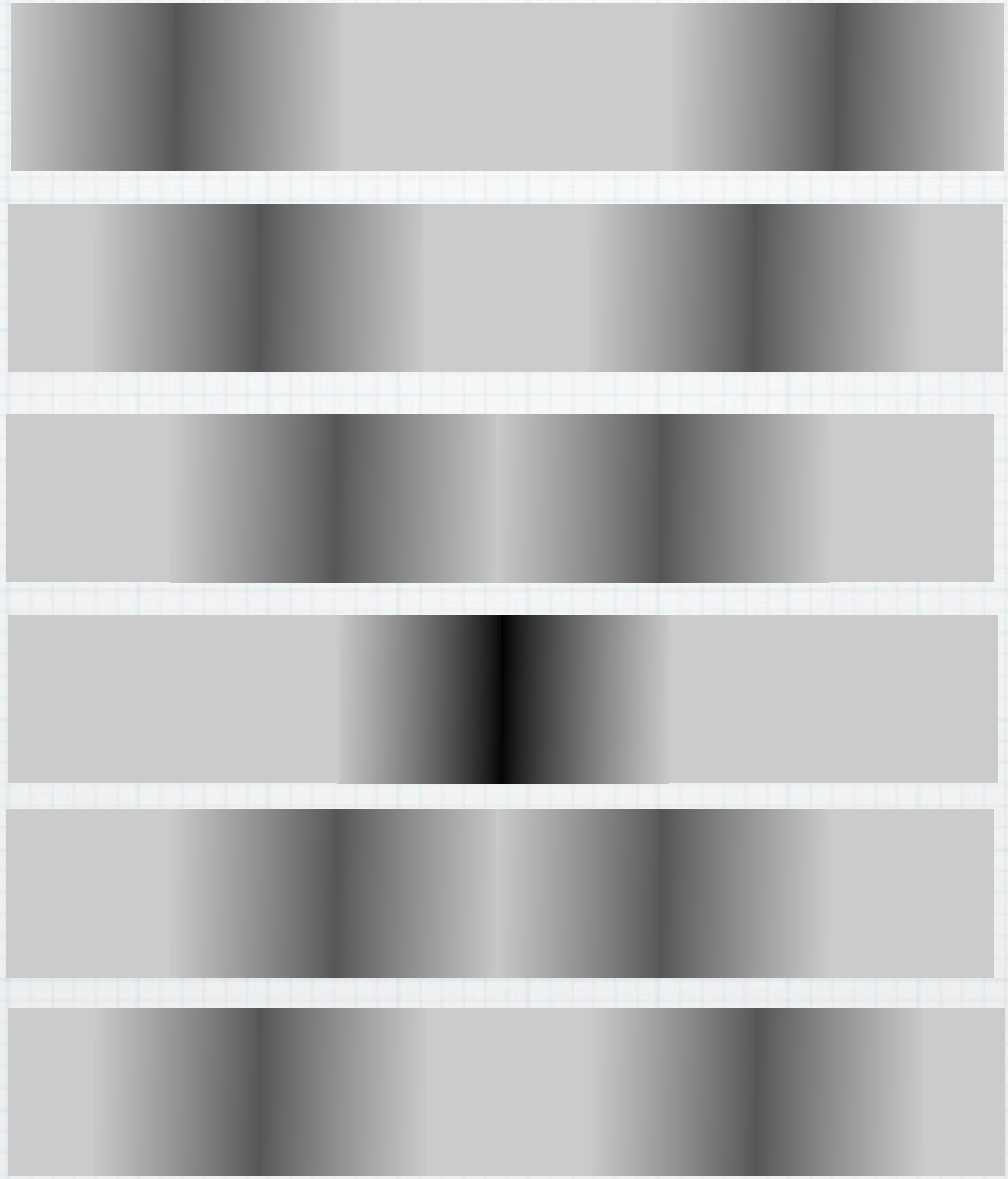

If a marching band is approaching on a cross street, which instruments will you hear first?
λ
High pitched piccolo, short wavelength.
λ
Low pitched bass drum, long wavelength.
High pitched sounds tend to be more directional because they don't diffract as much.

Superposition





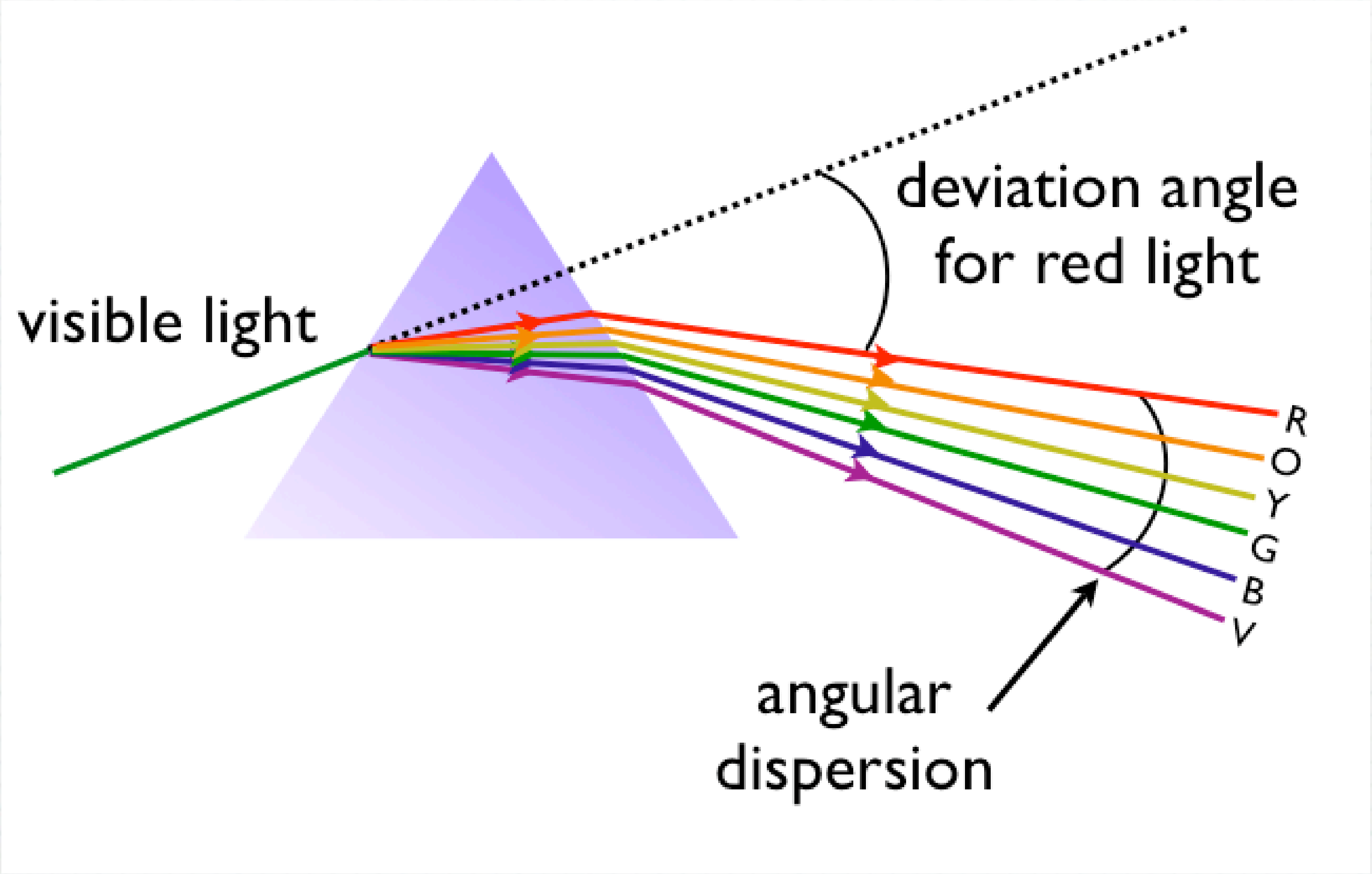
similarly with density waves!



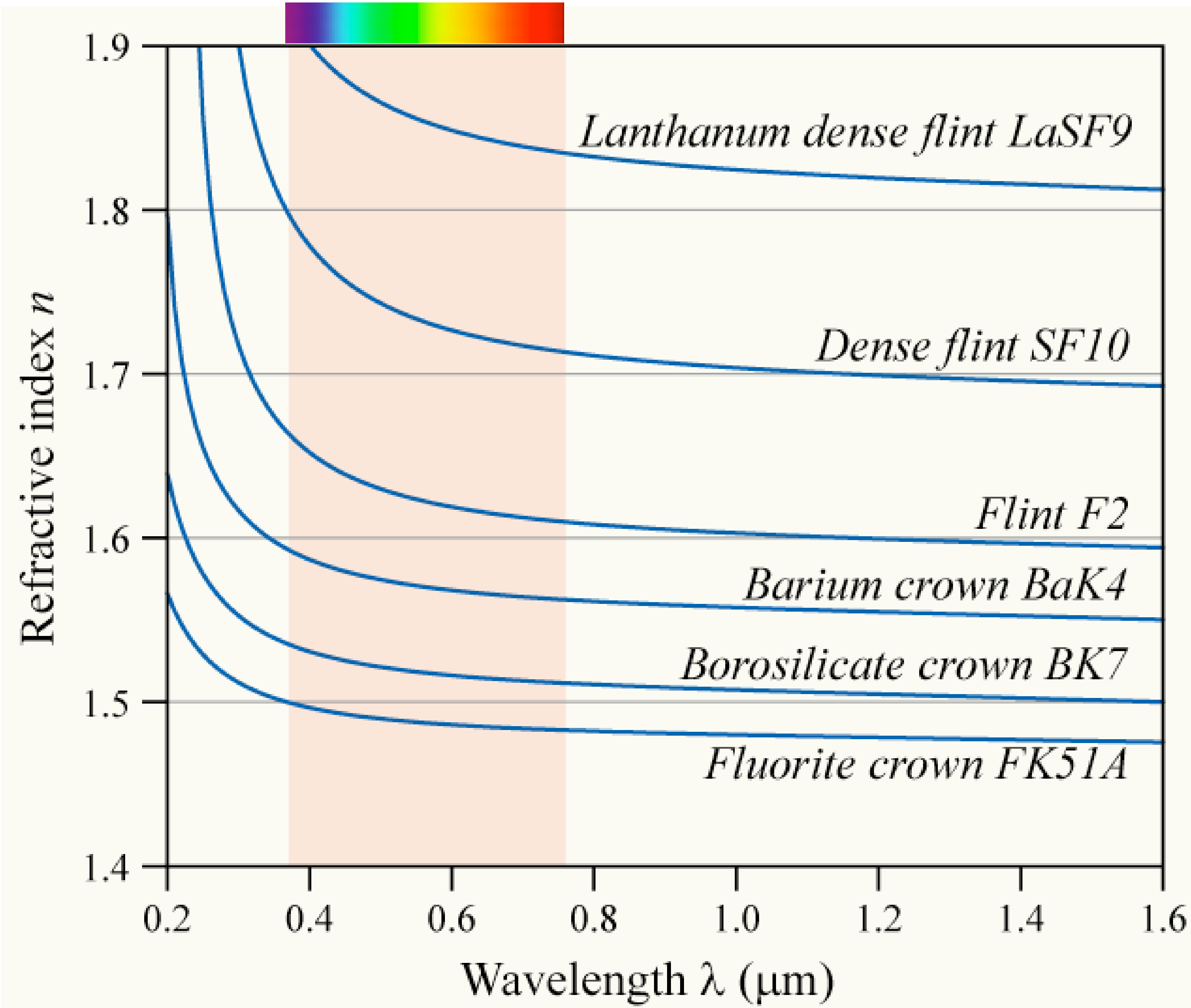
Dispersion

speed of wave depends on wavelength

- blue light waves are slower in glass
- take a longer path



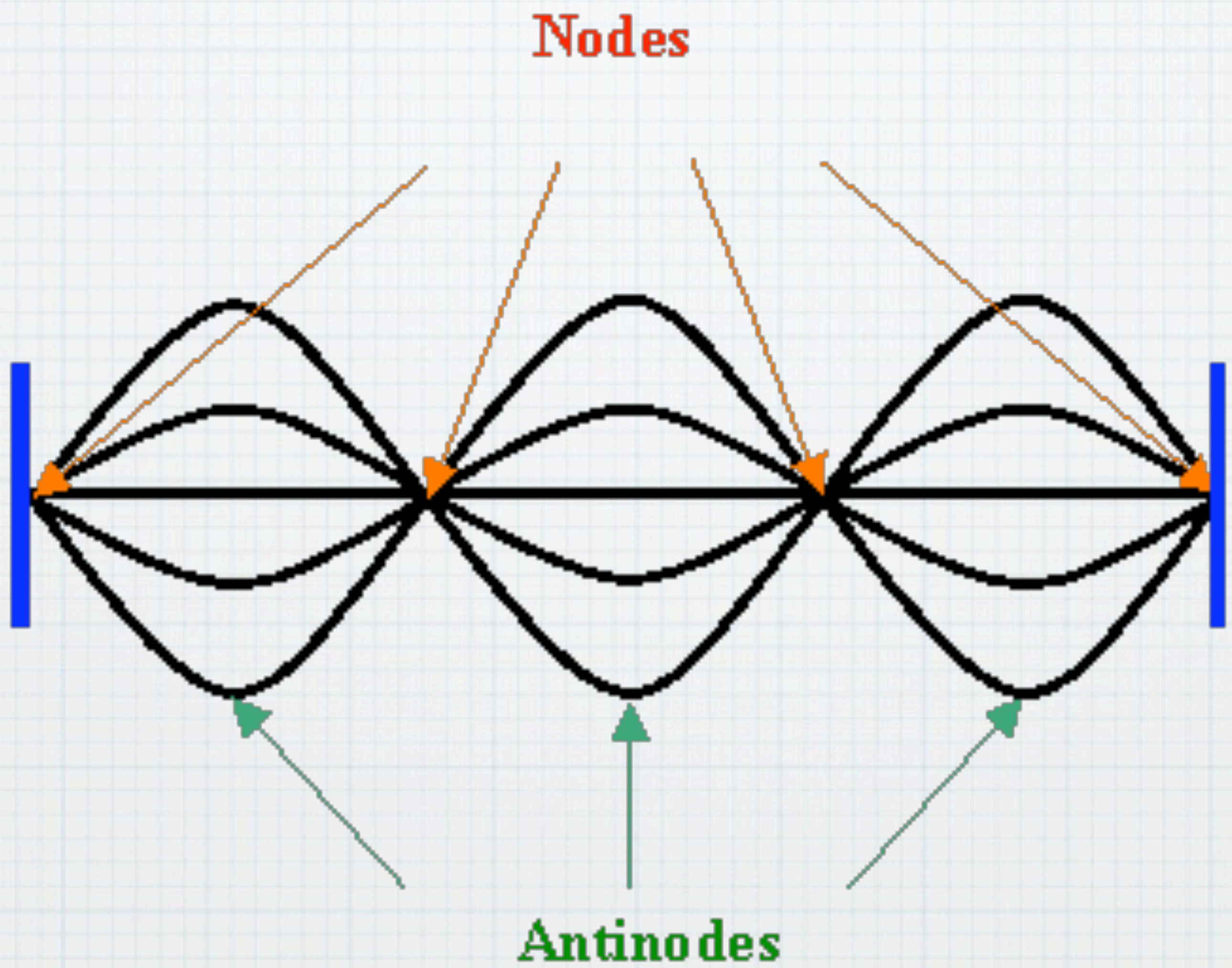
water: longer wavelengths travel faster!



Lanthanum dense flint LaSF9
Dense flint SF10
Flint F2
Barium crown BaK4
Borosilicate crown BK7
Fluorite crown FK51A
Refractive index n
1.9
1.8
1.7
1.6
1.5
1.4
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
Wavelength λ (μm)

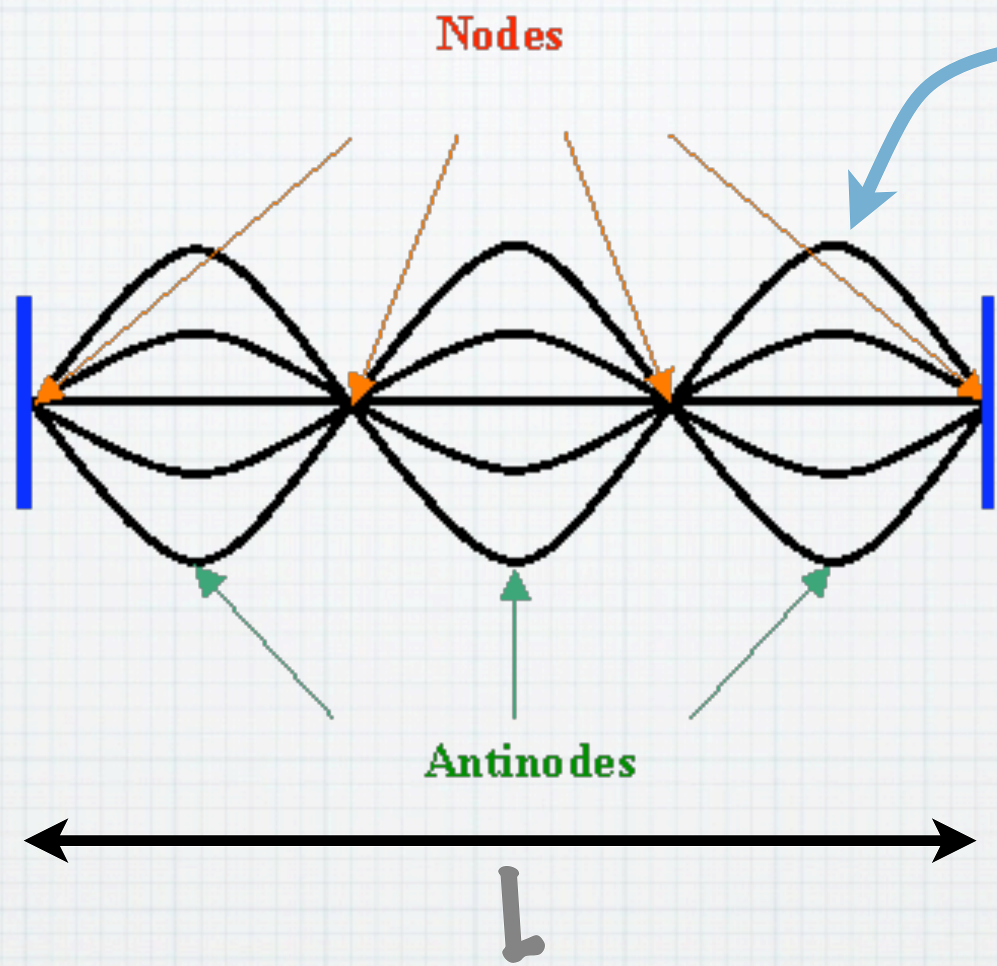
Straight line propagation

waves *can* travel in a straight line
but they need not - standing waves



Standing waves must meet special conditions

geometry ...

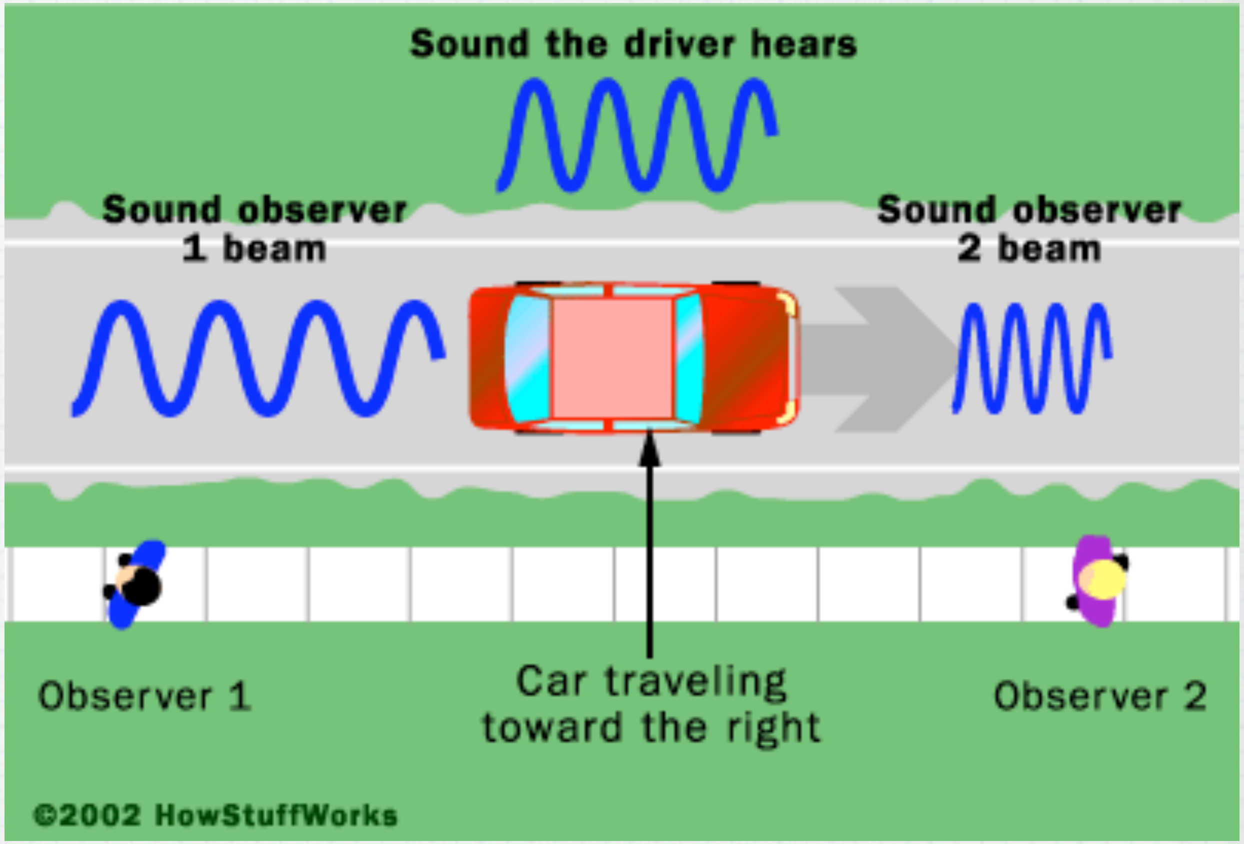


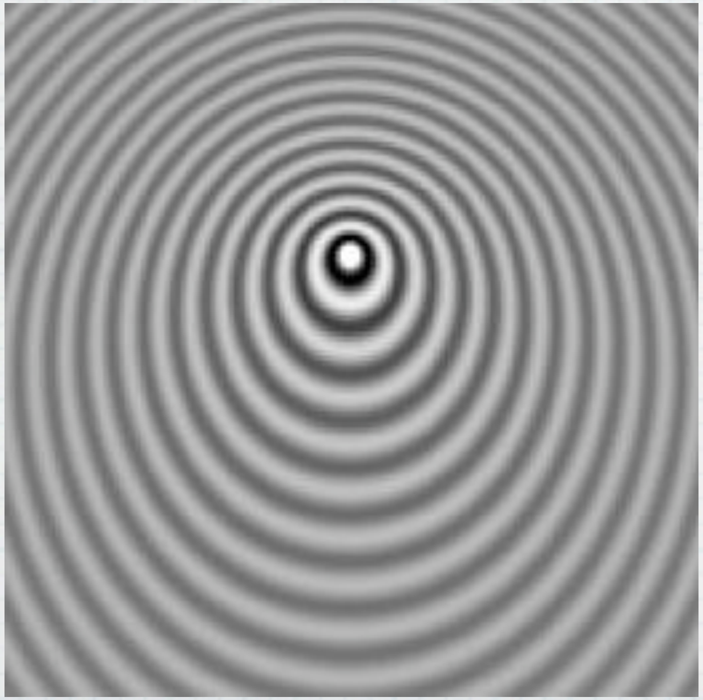
Position varies in time

for end points to be fixed: $$\frac{n\lambda}{2} = L$$

we will come back to this ...

Doppler Effect:
moving relative to waves



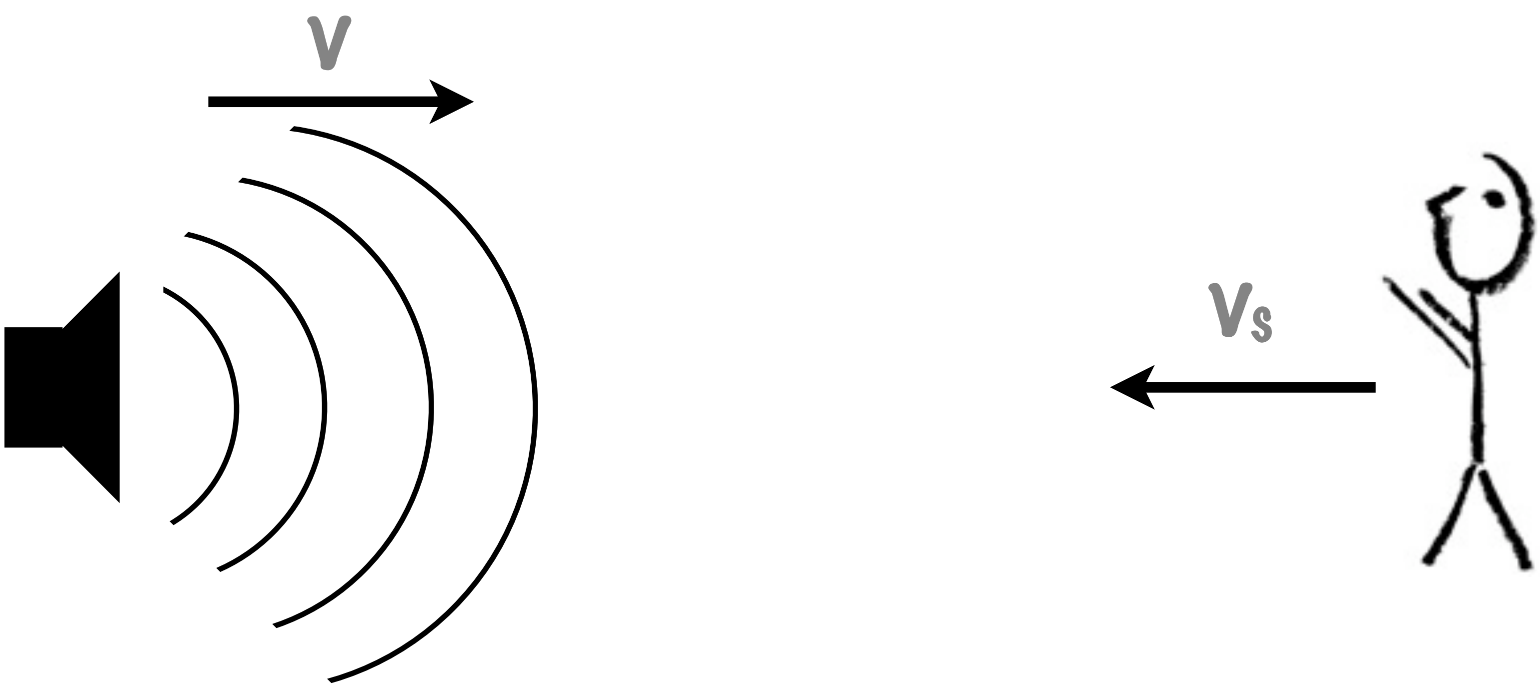


in one period T, you move closer to the source by $v_s T$

the waves appear squashed together

the apparent frequency (1/T) is still velocity / wavelength

approaching the source



$$f' = \frac{v}{\lambda - v_s T} = \frac{v}{v/f - v_s T} = \frac{v}{v/f - v_s/f} = \left(\frac{v}{v - v_s}\right) f$$

Approaching the source:
pitch (freq) seems higher

$$f' = \left(\frac{v}{v - v_s} \right) f$$

Moving away from source:
pitch (freq) seems lower

$$f' = \left(\frac{v}{v + v_s} \right) f$$

Only has to do with RELATIVE motion!
e.g., ambulance - driver hears no change

similarly: doesn't matter who is moving

happens for light too - receding galaxies
have "red shift" (lower freq)

If this bumper sticker is blue,

you're driving too fast!

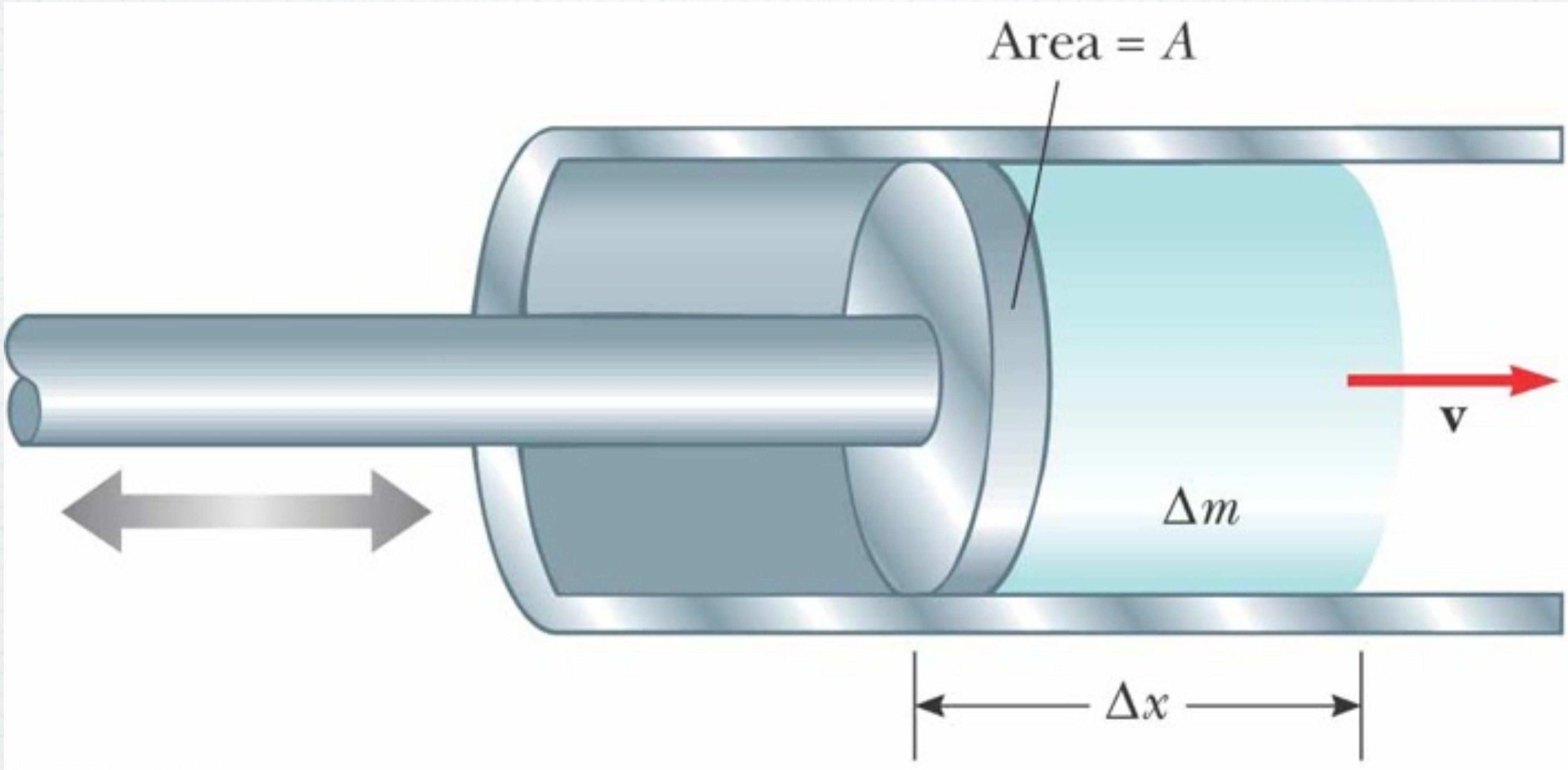
Sound in air

most sound = waves produced by vibrations of a material

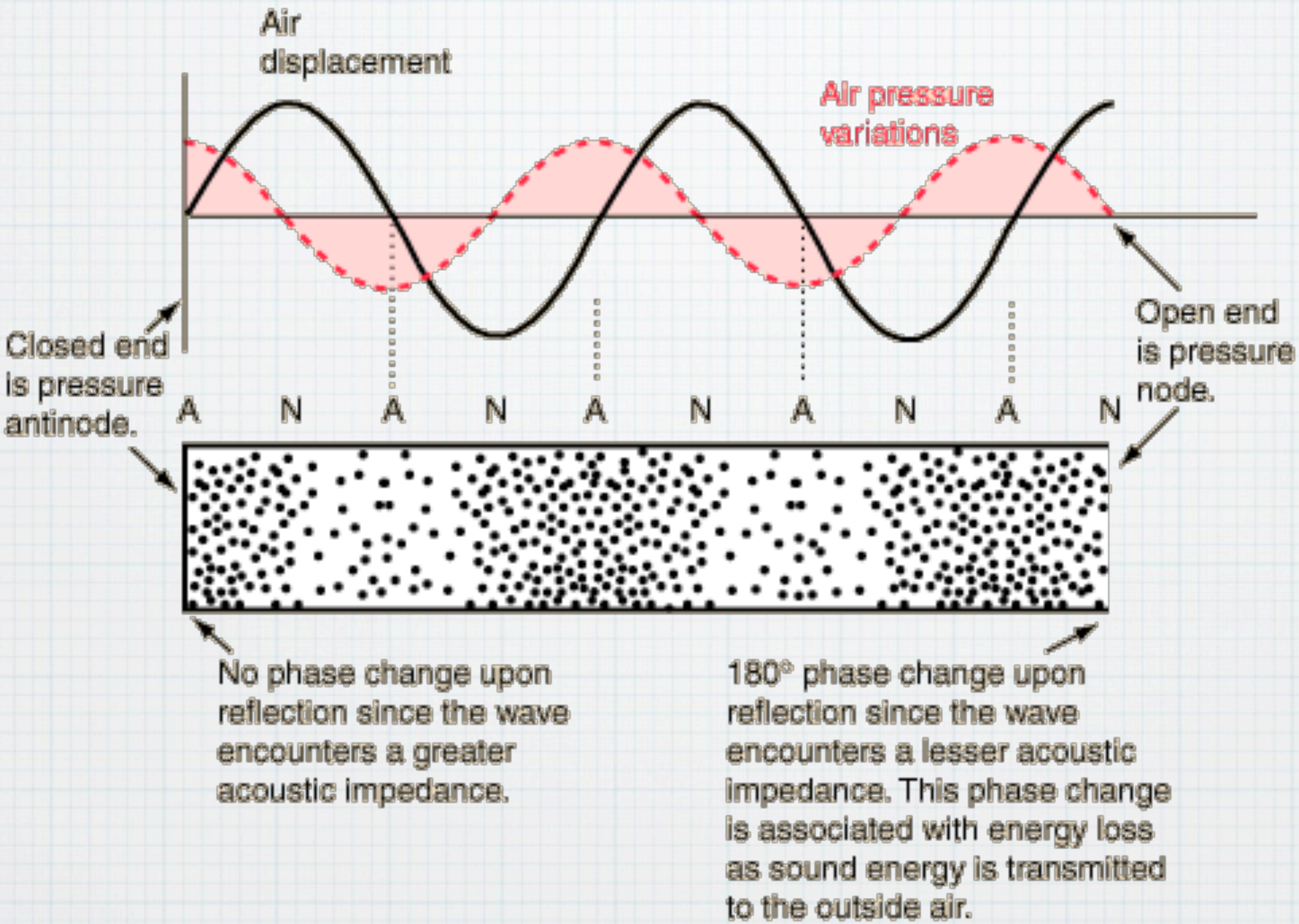
e.g., guitar string, saxophone reed, column of air

original vibration stimulates a larger one
sounding board

sound = compression / rarefaction waves in a medium
Density Waves


Area = A
v
Δm
Δx

Production of a standing wave in an air column involves reflections from both the closed end and the open end of the column.



MAX pressure = MIN velocity

Sound carries ENERGY in density waves = pressure modulation

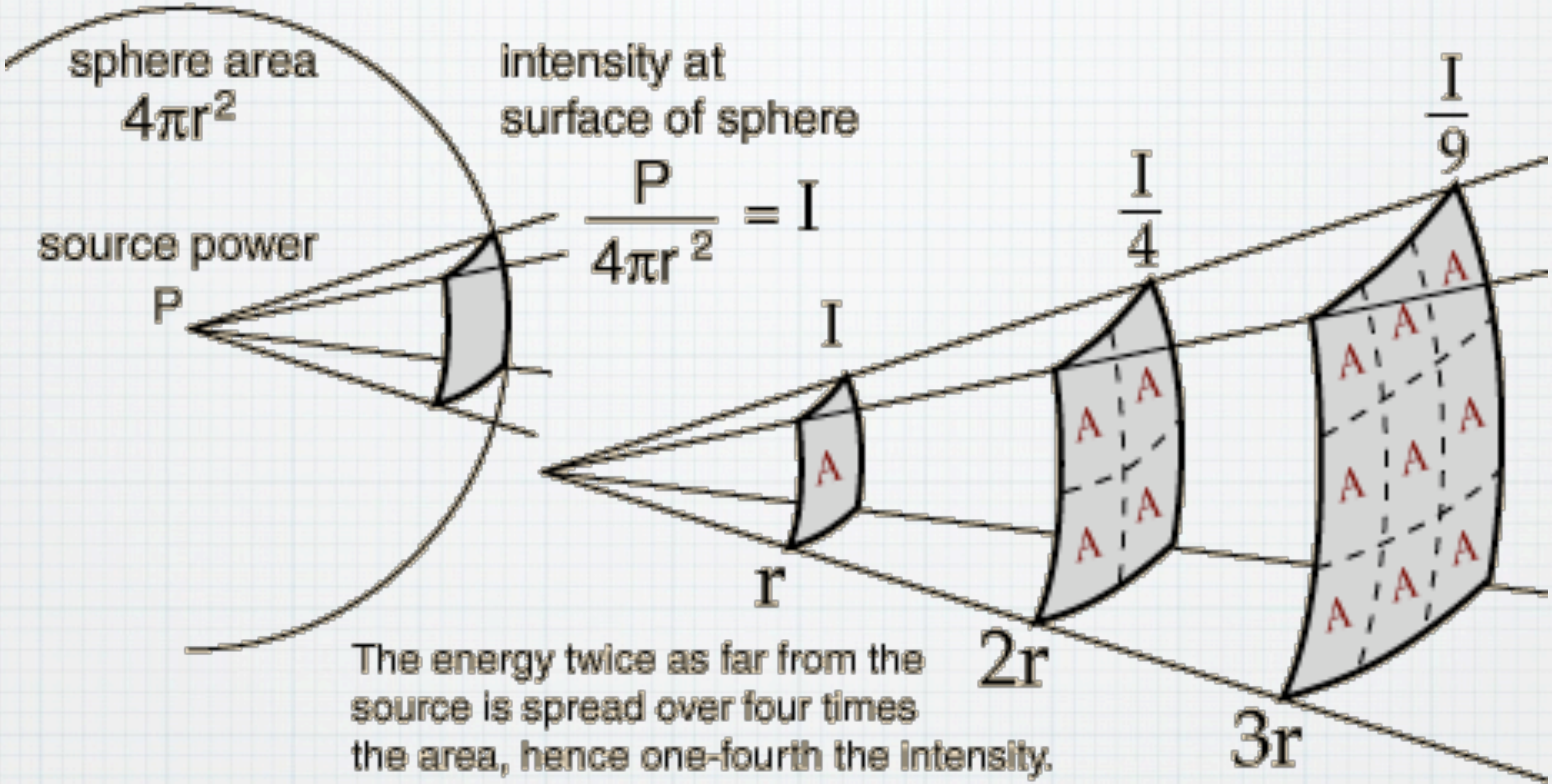
P = F/A = (F*d)/(A*d) = W/V = (energy)/(volume)

variation of pressure = variation of energy density

sound <u>power</u> = (energy)/(time)

sound intensity = (power)/(unit area)

$$intensity \sim \frac{1}{(\mathrm{dist})^2} \sim (\mathrm{pressure})^2$$


sphere area
4πr²
intensity at
surface of sphere
source power
P
P / 4πr² = I
I
I/4
I/9
A
r
2r
3r
The energy twice as far from the source is spread over four times the area, hence one-fourth the intensity.

our hearing: max & min pressures differ by a MILLION times

max/min power differs by a million times

sound intensity covers a huge range ... use a log scale

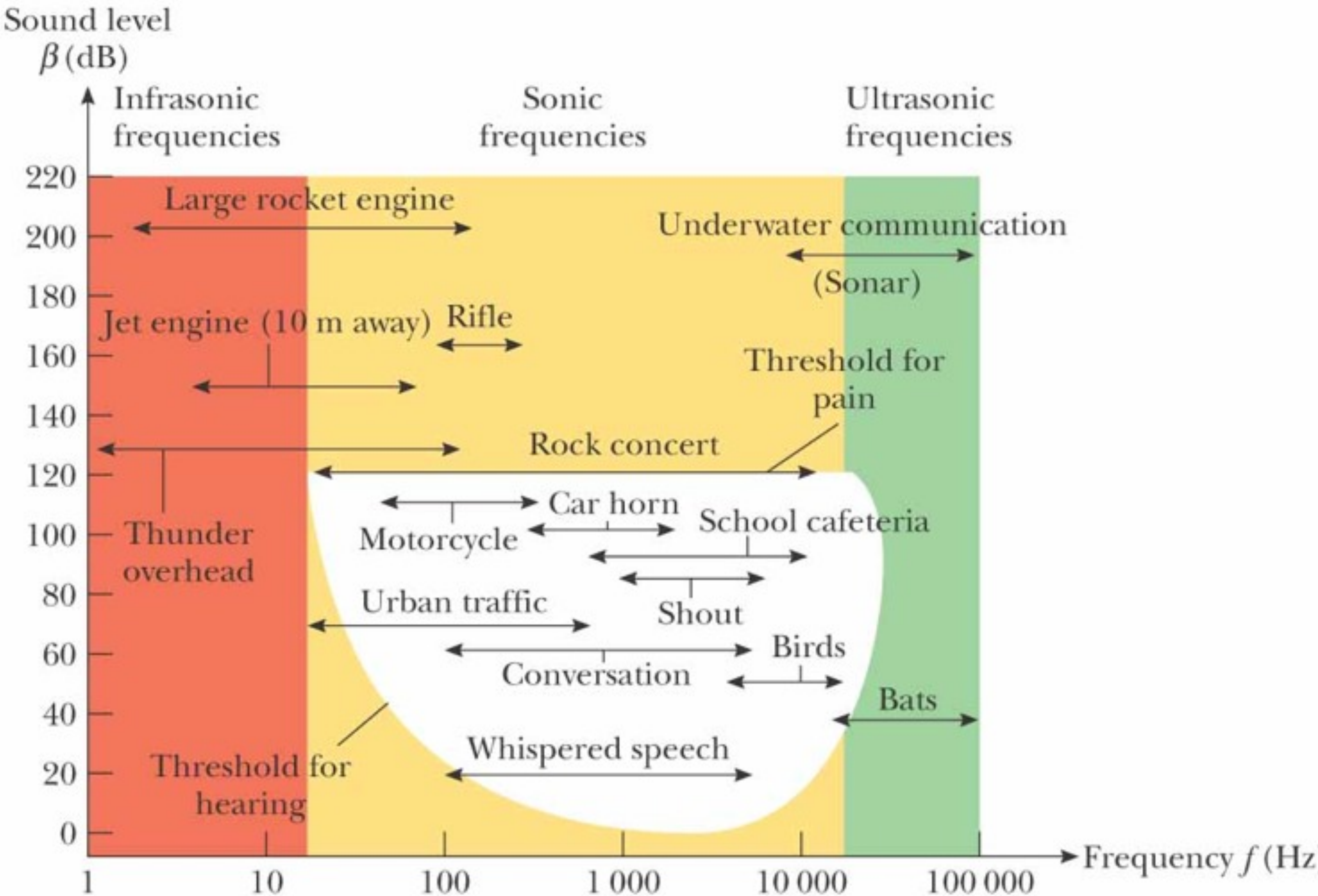
$$dB = 10 \log \left[\frac{\text{power}}{\text{reference}} \right] = 20 \log \left[\frac{\text{pressure}}{\text{reference}} \right]$$

(power goes as pressure squared)

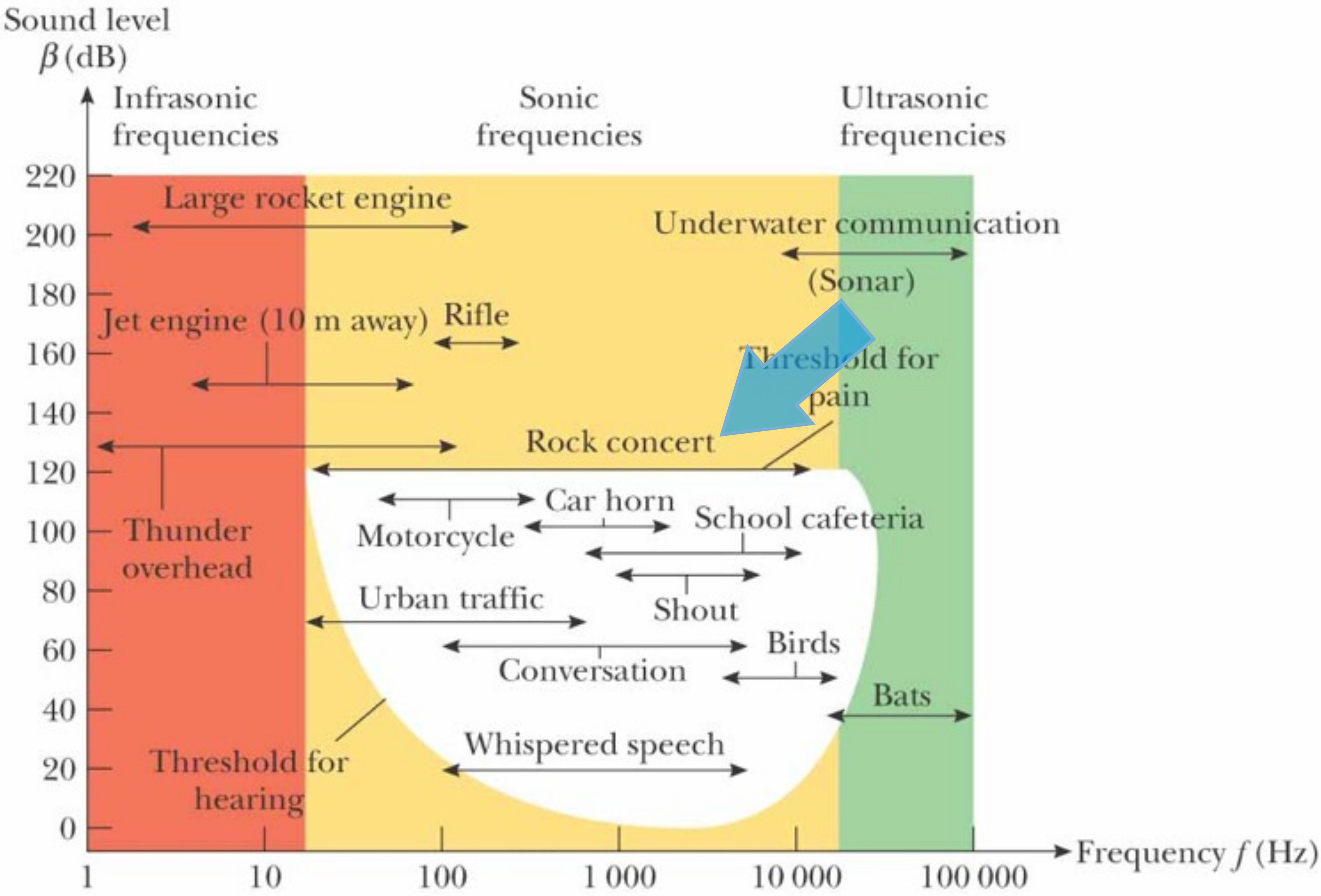
reference pressure = 20 μPa (tiny! atmosphere = 101,325 Pa)

1 Pa = 1 N/m^2 pressure difference would be 94 dB !!

Source of sound	RMS sound pressure	sound pressure level
	Pa	dB re 20 μPa
Nuclear Weapon explosion		approx 248
1883 Krakatoa eruption		approx 180 at 100 miles
Stun grenades		170-180
rocket launch equipment acoustic tests		approx. 165
threshold of pain	100	134
hearing damage during short-term effect	20	approx. 120
jet engine, 100 m distant	6–200	110–140
jackhammer, 1 m distant / discotheque	2	approx. 100
hearing damage from long-term exposure	0.6	approx. 85
traffic noise on major road, 10 m distant	0.2–0.6	80–90
moving automobile, 10 m distant	0.02–0.2	60–80
TV set – typical home level, 1 m distant	0.02	approx. 60
normal talking, 1 m distant	0.002–0.02	40–60
very calm room	0.0002–0.0006	20–30
quiet rustling leaves, calm human breathing	0.00006	10
auditory threshold at 2 kHz – undamaged human ears	0.00002	0



Sound level
β (dB)
Infrasonic frequencies
Sonic frequencies
Ultrasonic frequencies
220
200
180
160
140
120
100
80
60
40
20
0
Large rocket engine
Underwater communication
(Sonar)
Jet engine (10 m away)
Rifle
Threshold for pain
Rock concert
Car horn
School cafeteria
Motorcycle
Thunder overhead
Urban traffic
Shout
Birds
Conversation
Bats
Whispered speech
Threshold for hearing
1
10
100
1 000
10 000
100 000
Frequency f (Hz)



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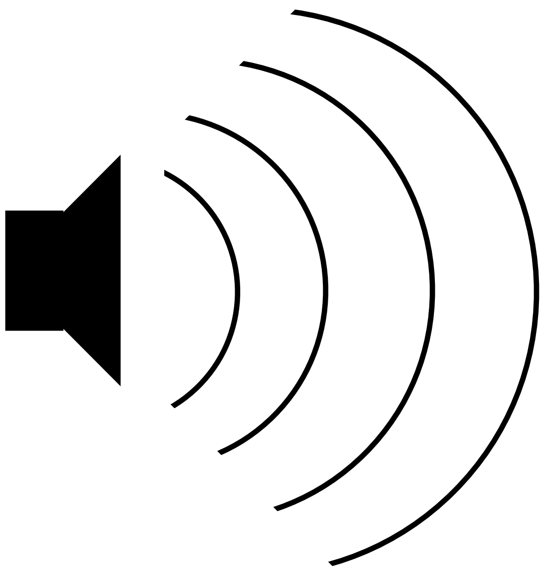
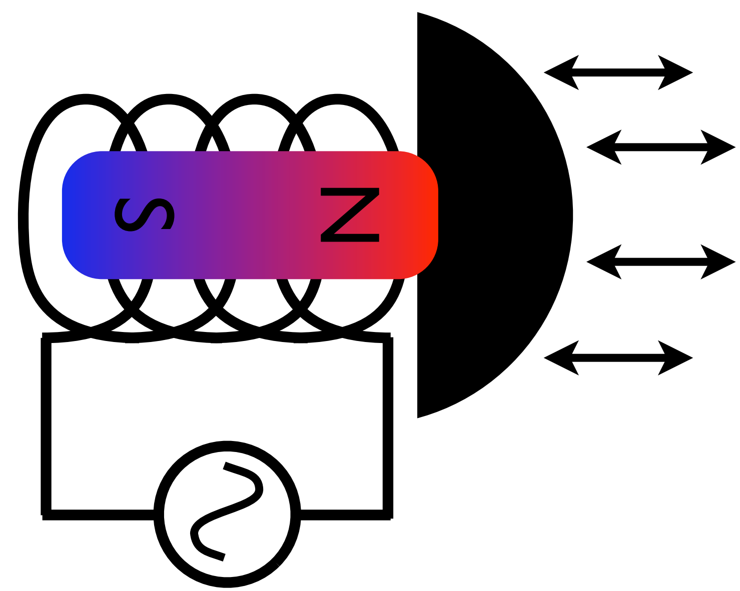
Conversation
Bats
Whispered speech
Threshold for hearing
1
10
100
1 000
10 000
100 000
Frequency f (Hz)

Speaker cone forces surrounding air to compress/rarefy

moves by induction!

cone pushes nearby air molecules, which hit others ...



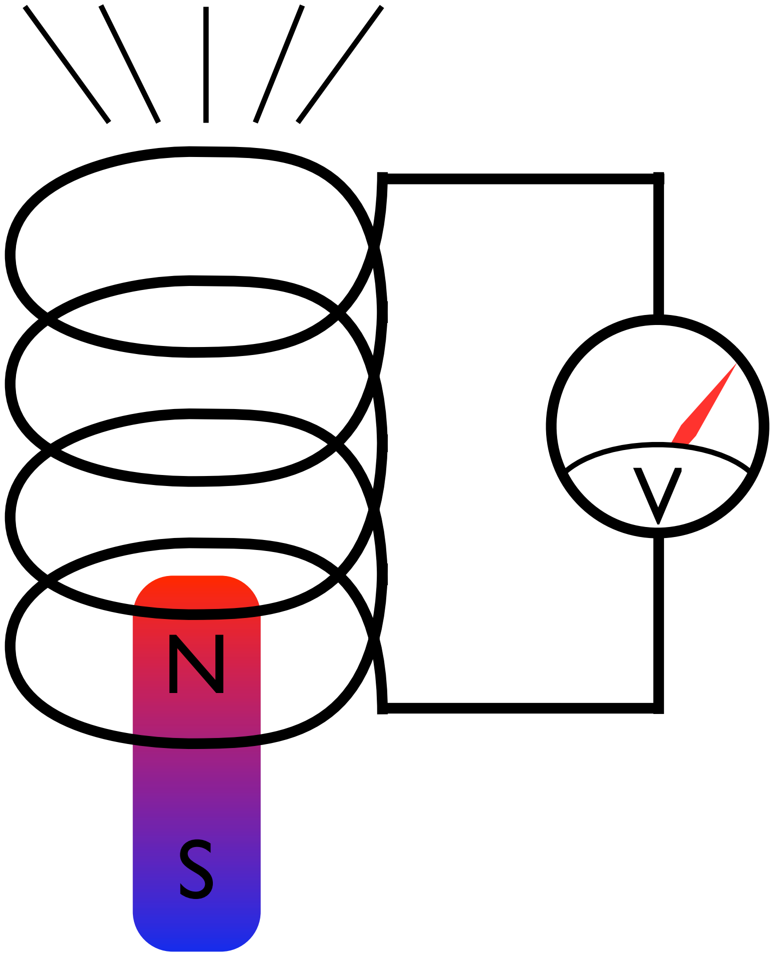


(can use the opposite for a microphone ...)

sound in - vibrates coil in magnet

time-changing flux induces voltage

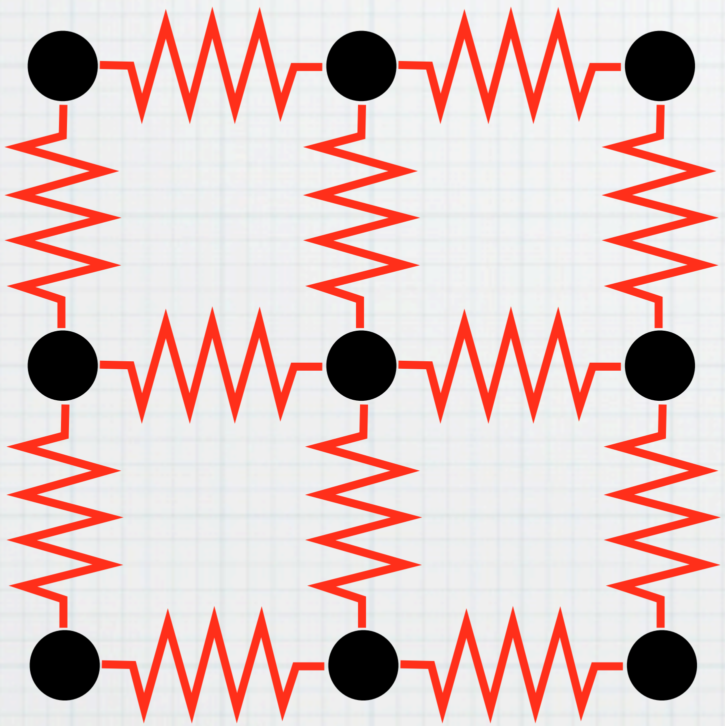
voltage can be amplified, used to drive a speaker!



How to transmit sound in a medium?

must have a degree of ELASTITCITY

i.e., a restoring force



Solids

bonds are like springs

atoms respond to each other's motions

speed of sound <-> crystal structure

bonding

bond strength <-> speed of sound

Liquids

also true ... but less so

Gasses, like air?
- "restoring force"?
  - creation of partial vacuum / lower pressure region
  - air moves in to fill void

Horribly inefficient

Depends on PRESSURE of gas

Depends on WHAT GAS

vacuum (e.g., space) - nothing there to compress/expand

(solid in vacuum ... still OK)

Result: sound is really slow in air

faster in : Warm air (0.6 m/s per °C)
Humid air (slightly)

about one MILLIONTH light speed

e.g.., golf ball struck 500m away

light:

$$\delta t_{\text{light}} = \frac{\delta x}{c} \approx 1.6\,\mu\text{sec}$$

sound:

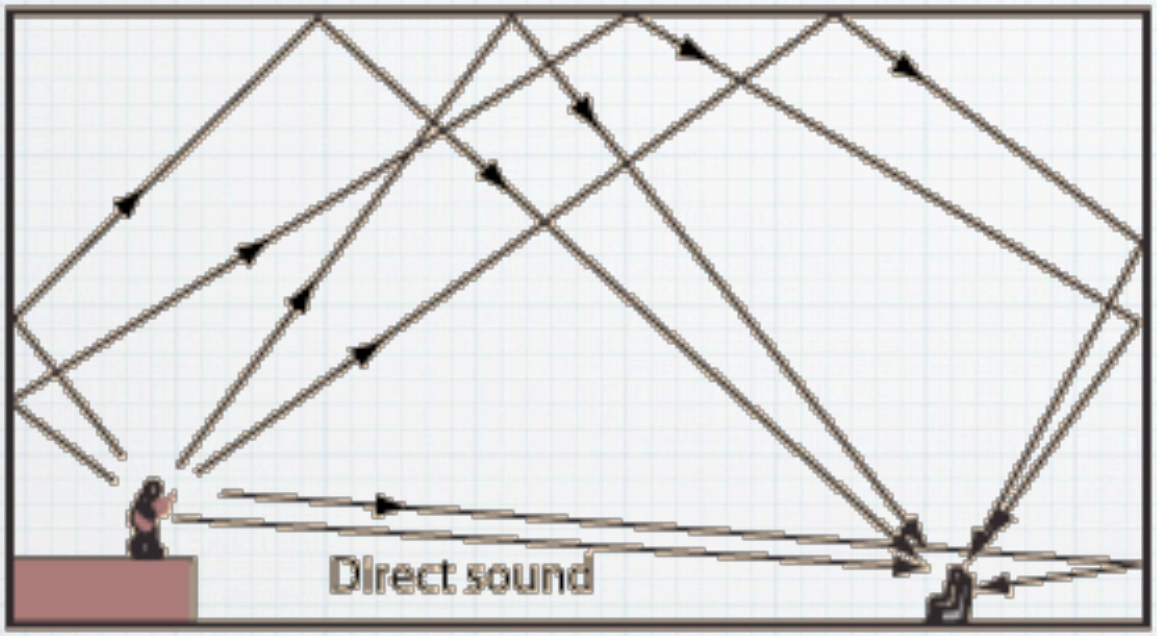
$$\delta t_{\text{sound}} = \frac{\delta x}{340\,\text{m/s}} \approx 1.5\,\text{sec}$$

Speed of Sound in Various Media

Medium	v (m/s)
Gases	
Hydrogen (0°C)	1 286
Helium (0°C)	972
Air (20°C)	343
Air (0°C)	331
Oxygen (0°C)	317
Liquids at 25°C	
Glycerol	1 904
Seawater	1 533
Water	1 493
Mercury	1 450
Kerosene	1 324
Methyl alcohol	1 143
Carbon tetrachloride	926
Solids[a]	
Pyrex glass	5 640
Iron	5 950
Aluminum	6 420
Brass	4 700
Copper	5 010
Gold	3 240
Lucite	2 680
Lead	1 960
Rubber	1 600

Sound can be REFLECTED like other waves

Reverberation



different paths from source to observer are possible

slight difference in path length = time lag

Yuck.

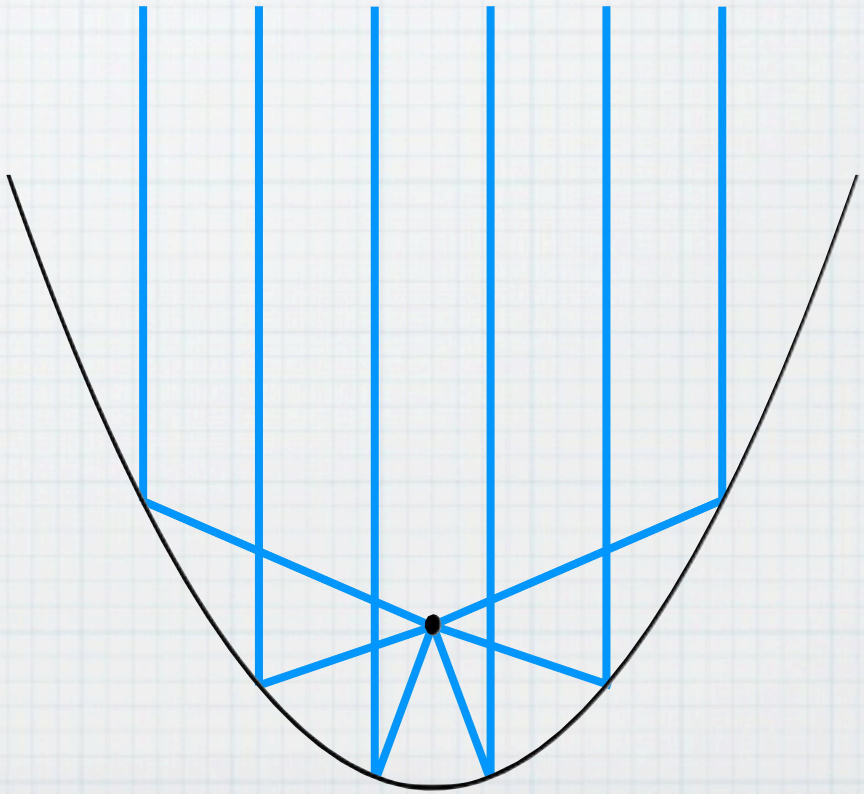
For good sound, this effect must be optimized

walls too reflective: reverb problems

walls too reflective: “dead” sound, low level

reflected sound = “lively” & “full” ... like in the shower

Ultimate: parabolic reflector

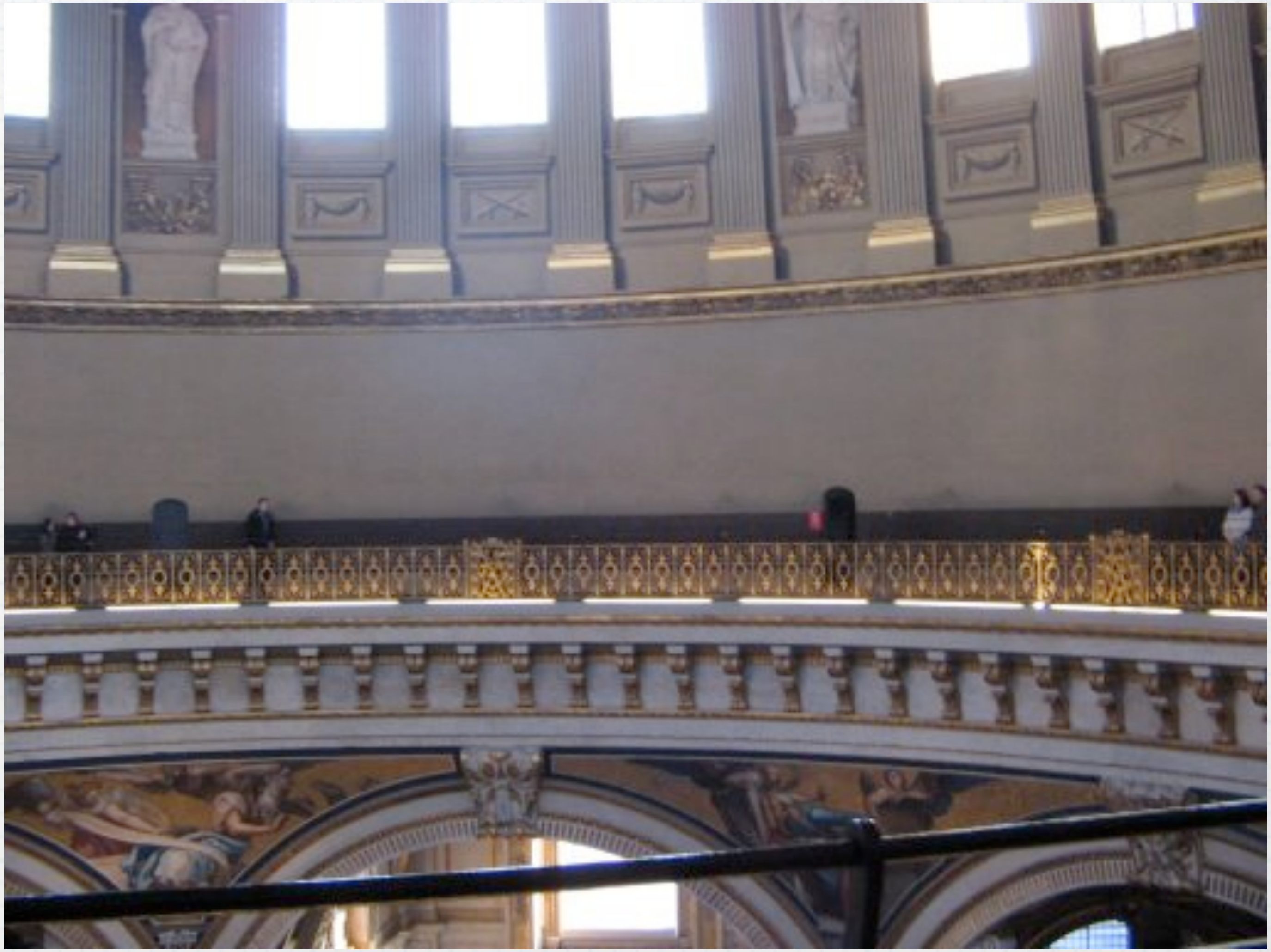


a.k.a. “whispering gallery”

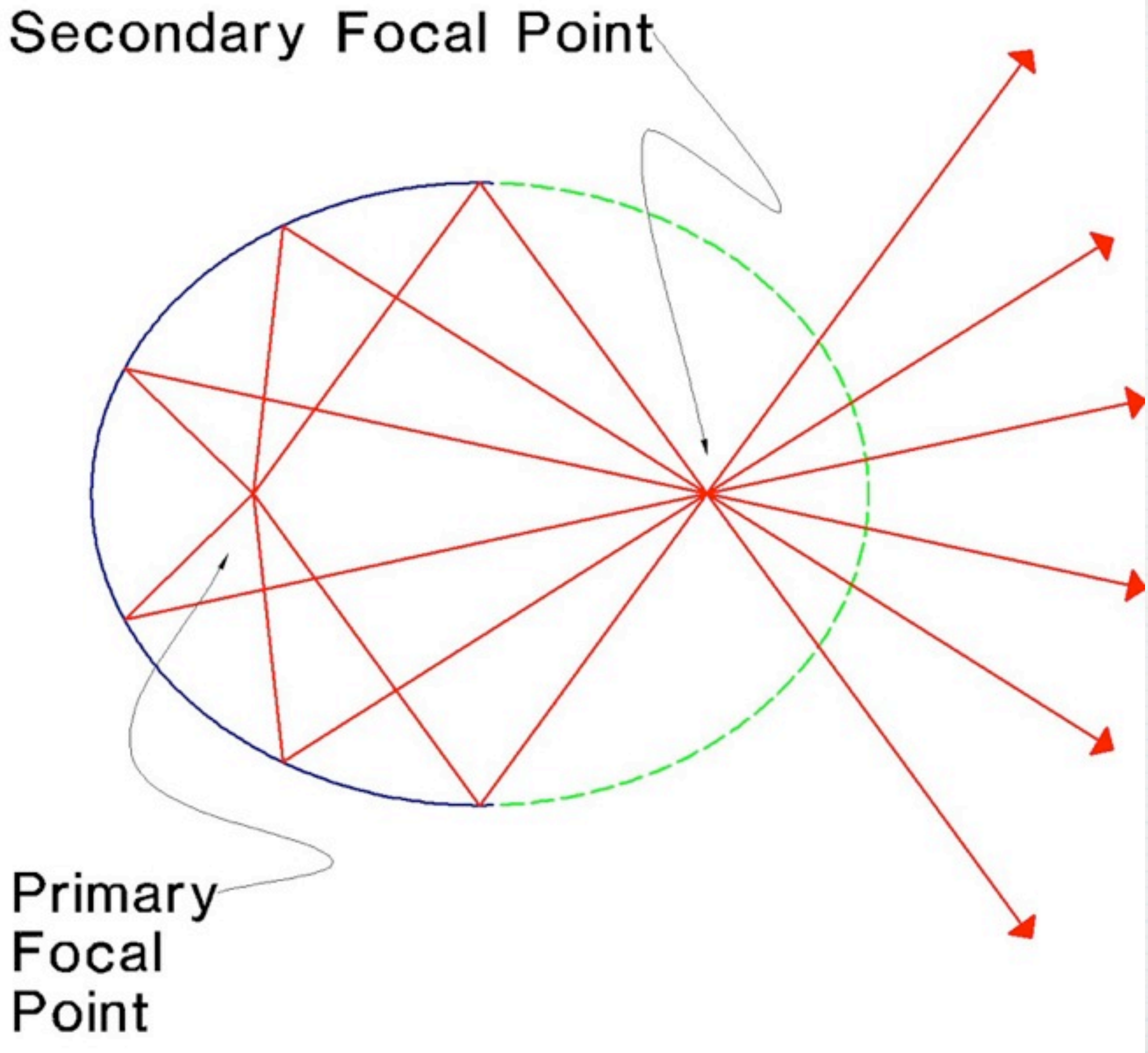
parabolic or elliptical room

St. Paul’s cathedral

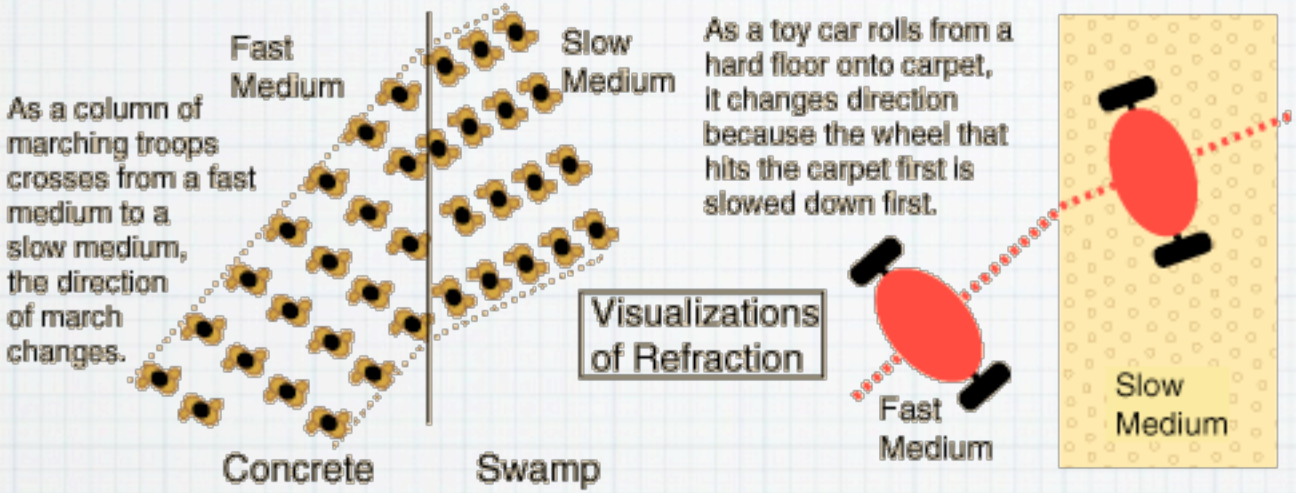
London



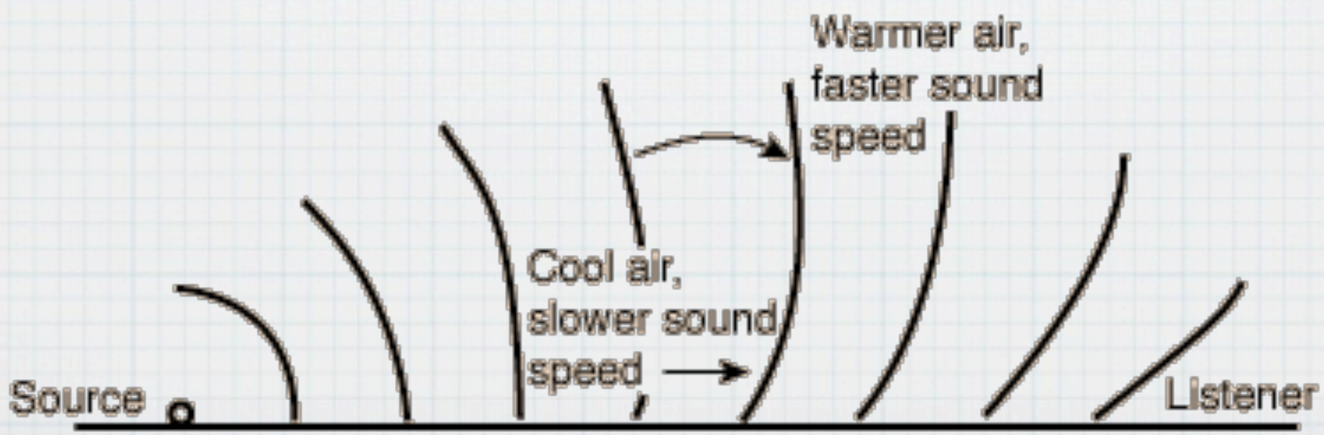
can hear a whisper across the room

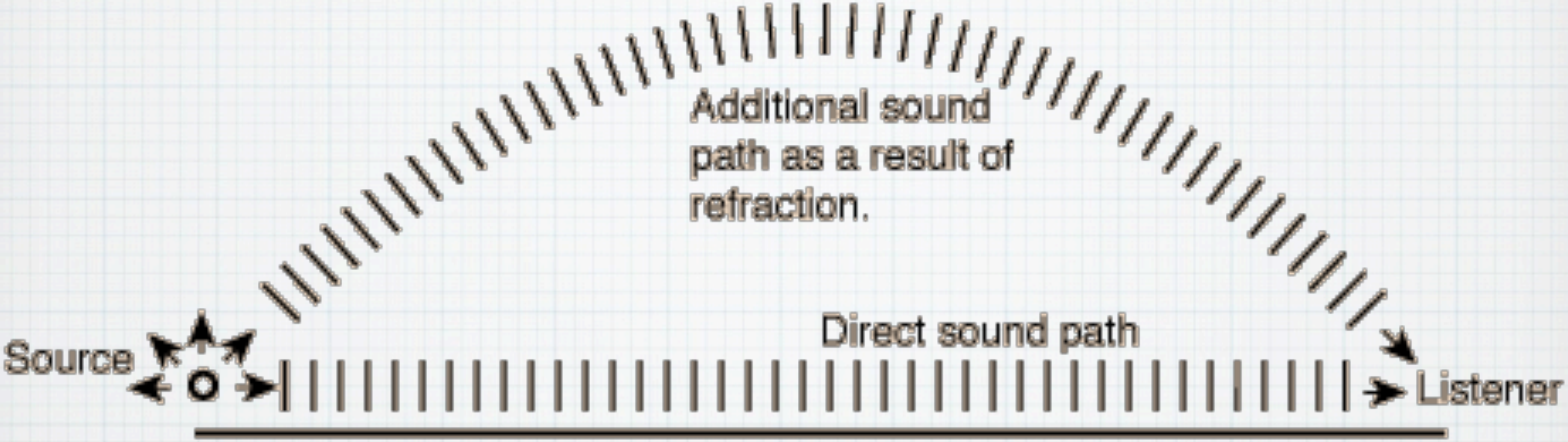

Secondary Focal Point
Primary
Focal
Point

Refraction of sound



If the air above the earth is warmer than that at the surface, sound will be bent back downward toward the surface by refraction.





Normally, only the direct sound is received.

Refraction can add some additional sound

Effectively amplifies the sound.

Natural amplifiers can occur over cool lakes.

Natural (resonance) frequencies

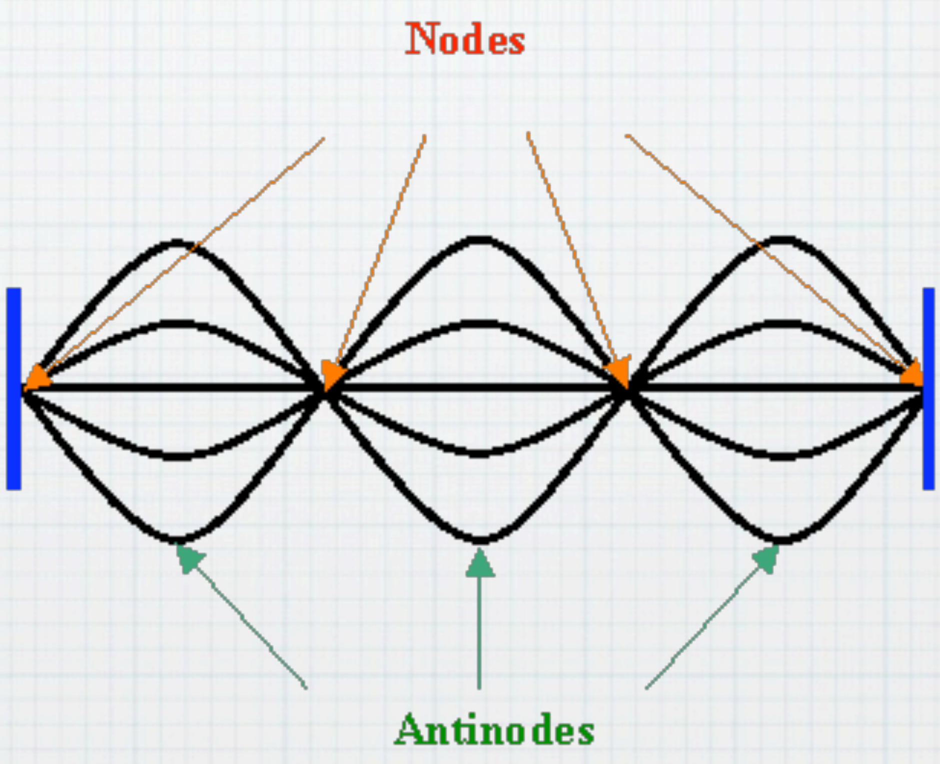
objects have characteristic vibration modes - unique sounds

composition
shape
density
elasticity

<- depends on all these

e.g., string

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

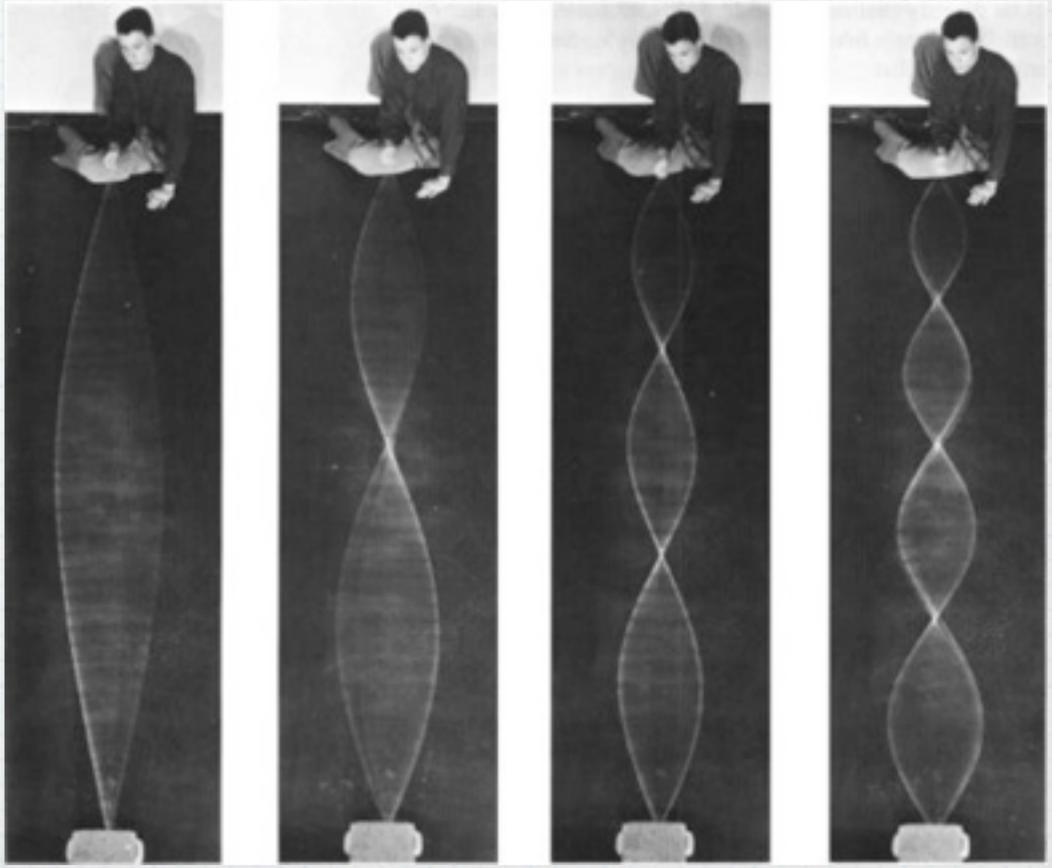


geometry dictates allowed frequencies
fundamental + overtones (harmonics)

$$L = n\frac{\lambda}{2} \quad \text{and} \quad \lambda f = v$$

$$\Longrightarrow L = \frac{nv}{2f} \qquad \Longrightarrow \boxed{f = \frac{nv}{2L}}$$

guitar strings: frets change L



what is the velocity v ???

Velocity is related to:

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

T = Tension (force)
μ = mass per unit length (weight)

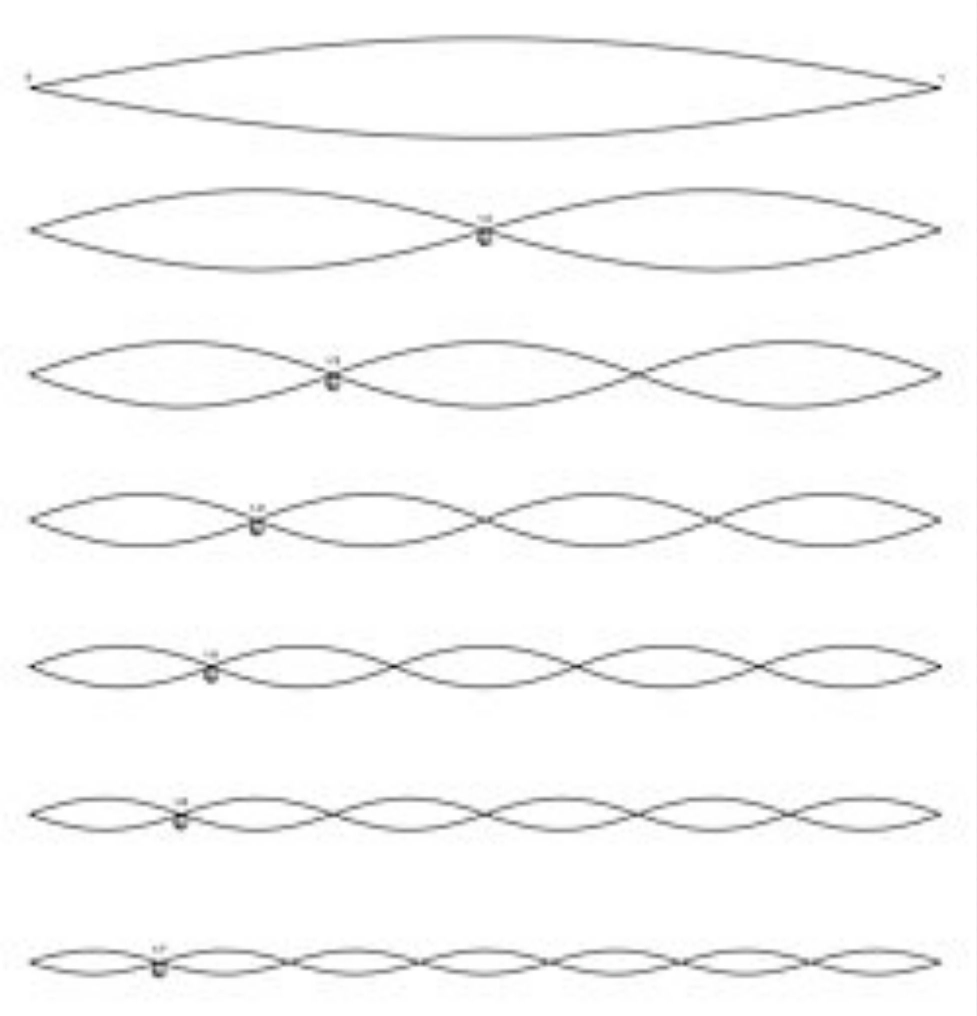
$$f = \frac{n}{2L}\sqrt{\frac{T}{\mu}}$$

string fixed at both ends

change L via FRETS
tune via TENSION
range via MASS

shorter = higher pitch
tighter = higher pitch
thinner = higher pitch

(same deal for a piano, less the frets)



fundamental (n=1)

1st overtone / 2nd harmonic (n=2)

3rd harmonic (n=3)

4th harmonic (n=4)

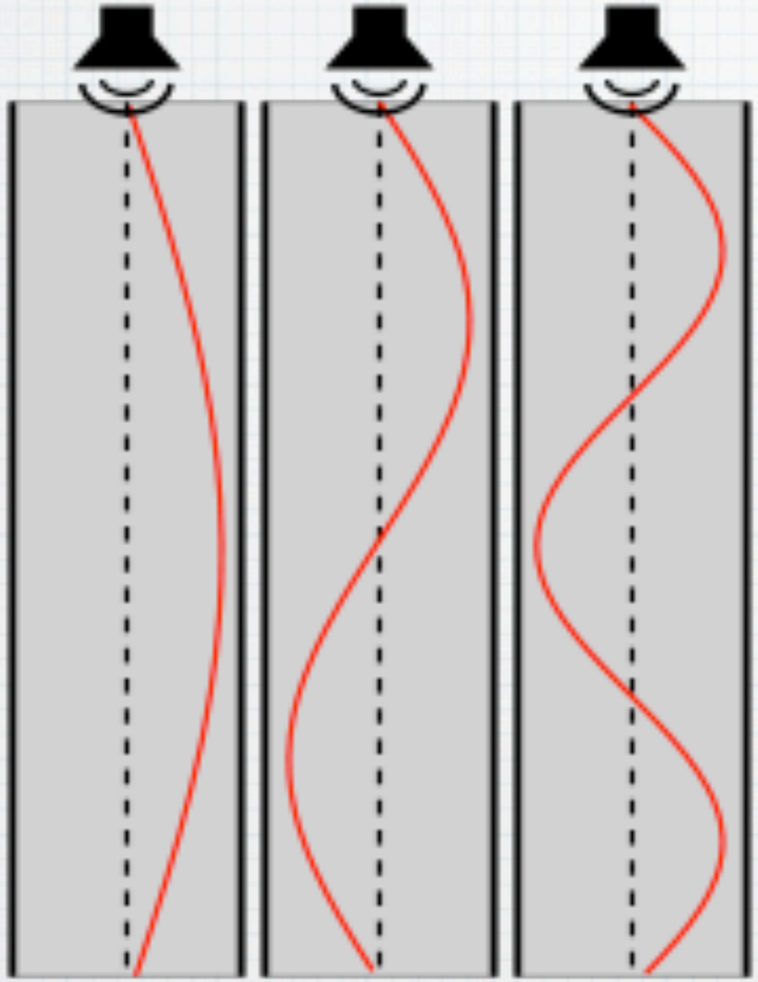
...

...

it is different if ends are not fixed!

example: air columns (pipe organ)

we can set up resonance in a fixed tube of air
pipe open at both ends



STANDING WAVES set up in tube

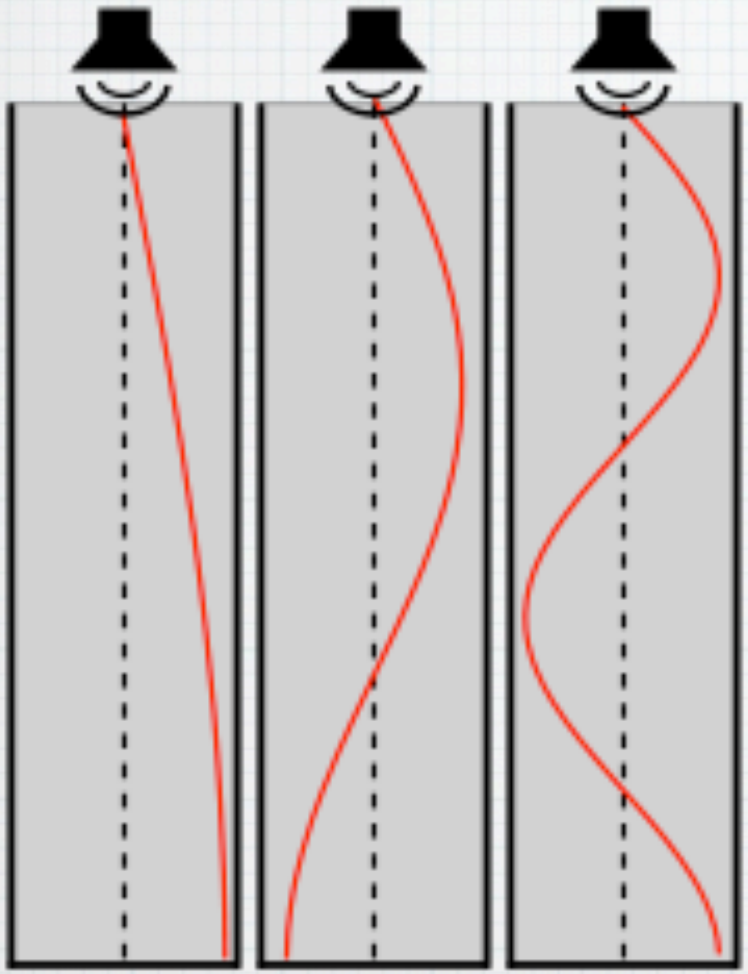
need nodes at the ends
max velocity
zero pressure difference

math? same as for the string

$$f = \frac{nv}{2L}$$

v = 340 m/s for air at RT

Things are different when we close one end of the pipe!



air velocity is ZERO at one end!

effectively, twice as long
pitch is twice as low

$$f = \frac{nv}{4L}$$

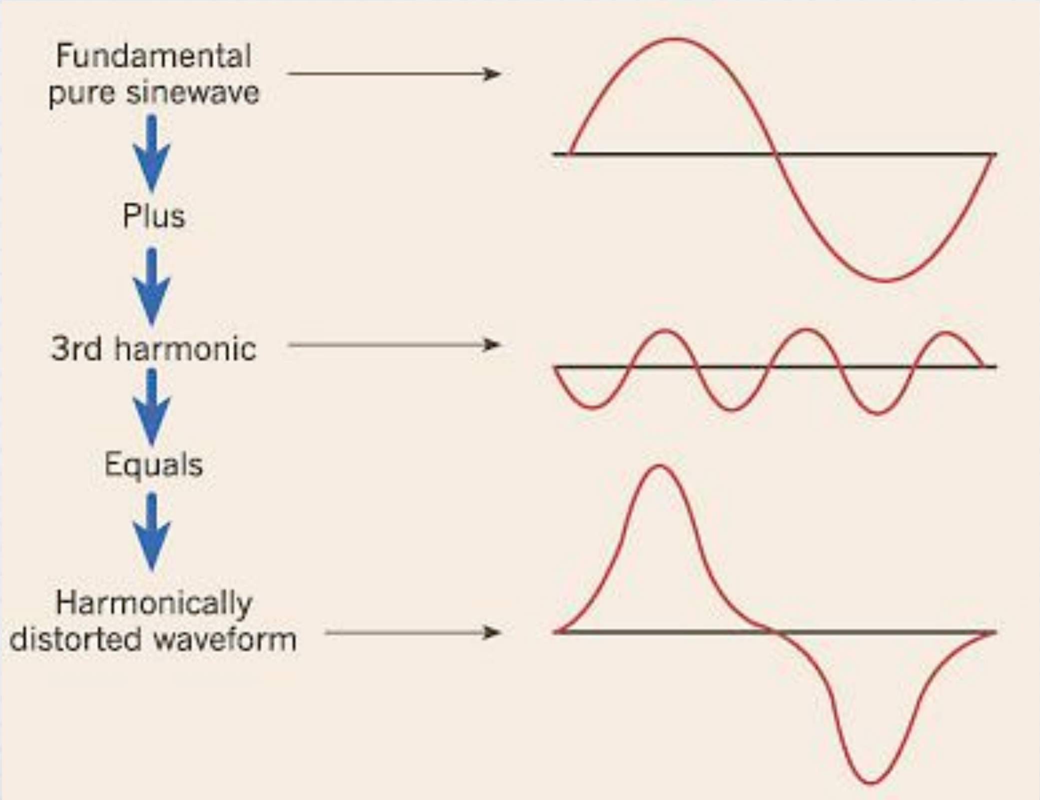
(now n must be ODD for waves to fit)

OPEN - OPEN pipes : like strings, all harmonics present

OPEN - CLOSED pipes : only ODD harmonics, 2x lower pitch

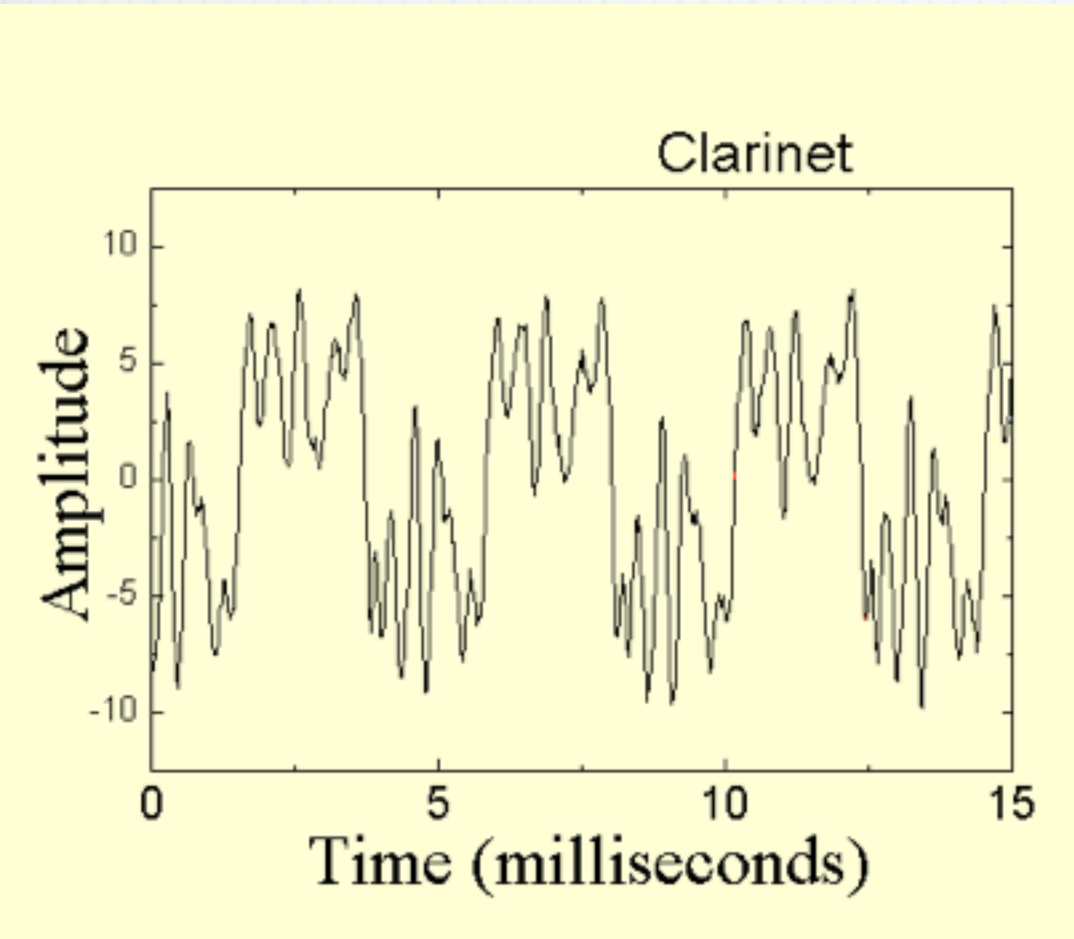
presence (or absence) of harmonics changes “tone”

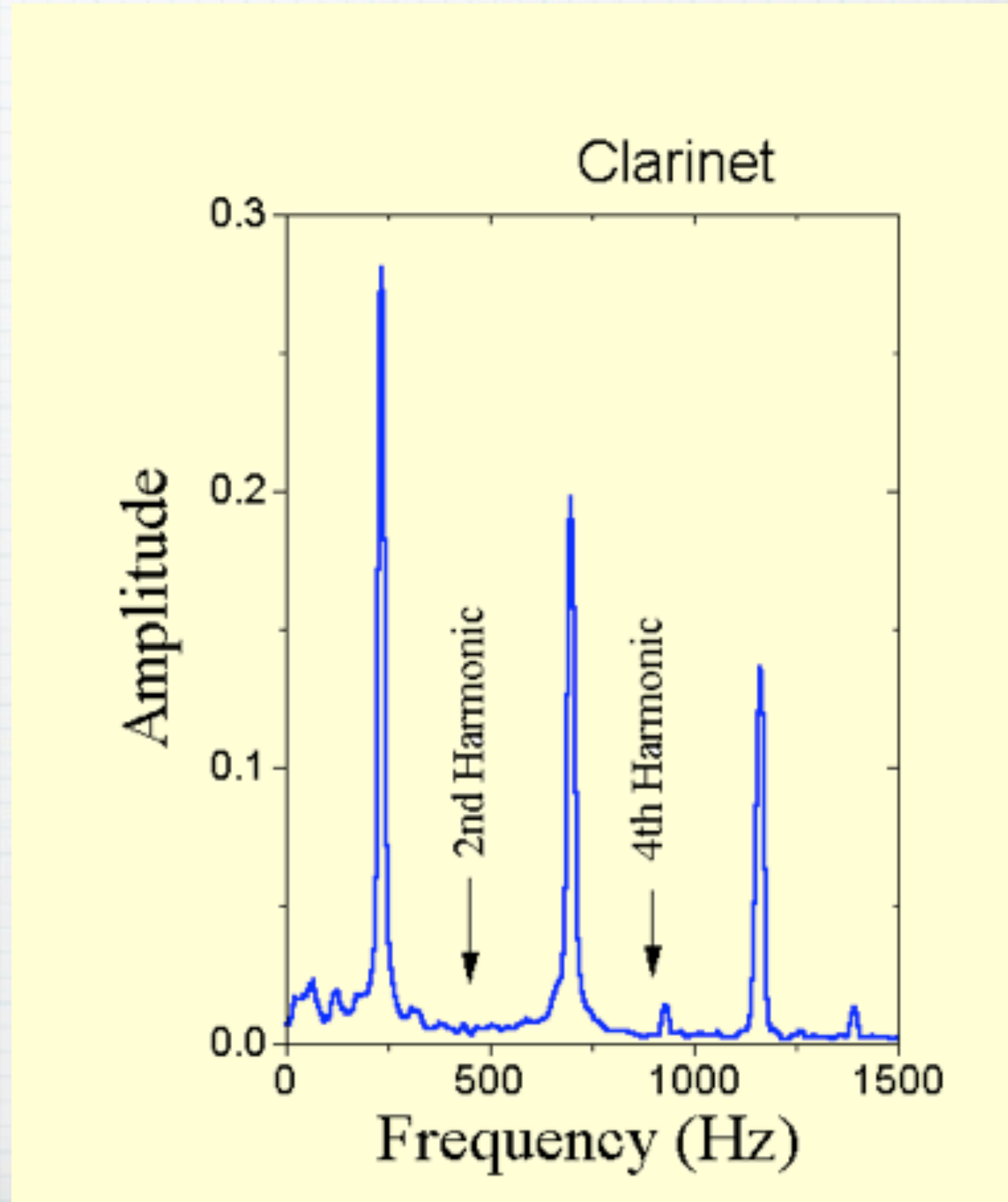
waveform = sum of fundamental + harmonics!

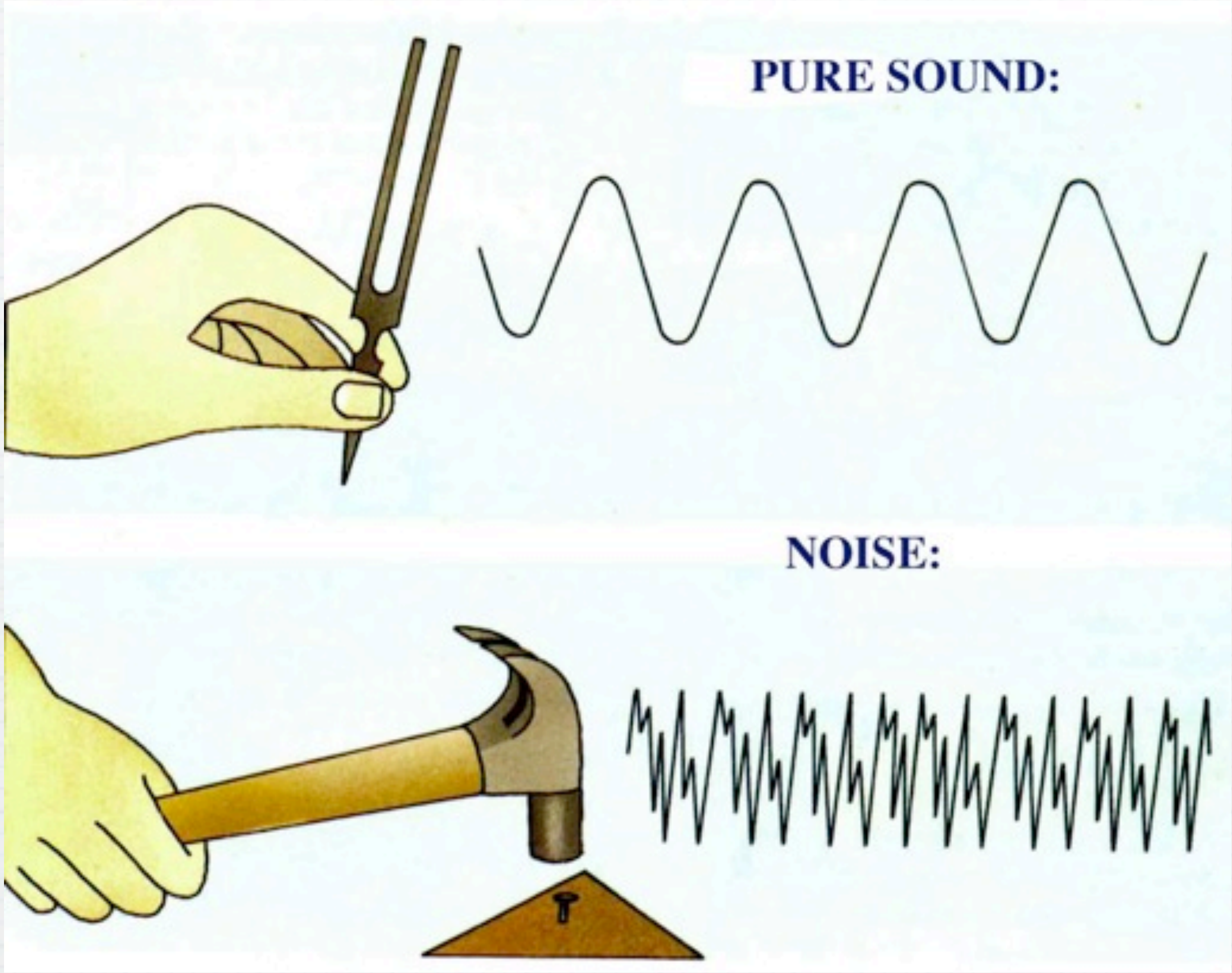


A clarinet is CLOSED on one end
only odd harmonics

"warm" & "dark" compared to saxophone - all harmonics





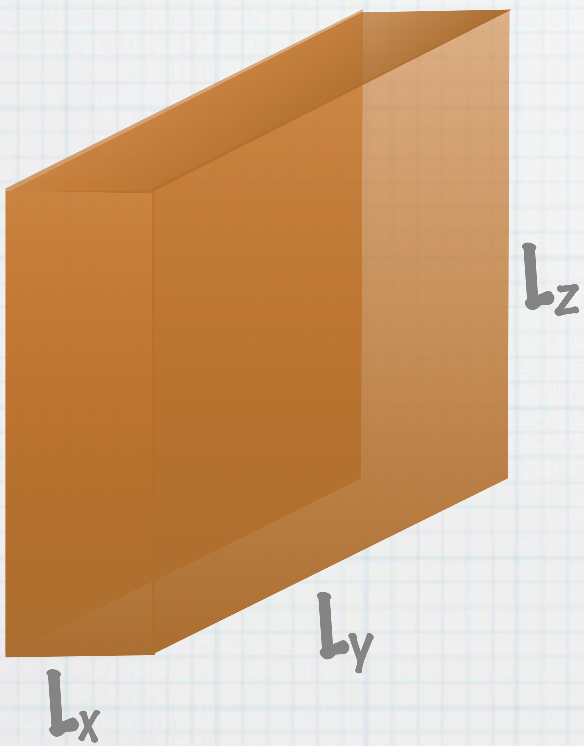

PURE SOUND:
NOISE:

Pitch and frequency

Harmonic Identity	Common Name	Example	Multiple of Fundamental Freq	Ratio (this identity/last octave)
1	Fundamental	A_2 - 110Hz	1x	1/1 = 1x
2	Octave	A_3 - 220 Hz	2*x*	2/1 = 2*x* (also 2/2 = 1*x*)
3	Perfect Fifth	E_3 - 330 Hz	3*x*	3/2 = 1.5*x*
4	Octave	A_4 - 440 Hz	4*x*	4/2 = 2*x* (also 1*x*)
5	Major Third	$C\#_4$ - 550 Hz	5*x*	5/4 = 1.25*x*
6	Perfect Fifth	E_4 - 660 Hz	6*x*	6/4 = 1.5*x*
7	"Perfect Seventh"	$?_4$ - 770 Hz	7*x*	7/4 = 1.75*x*
8	Octave	A_5 - 880 Hz	8*x*	8/4 = 2*x* (also 1*x*)

What about a tuning fork?
(or any 3D solid)

fit wavelengths in each dimension



$$f = \frac{v}{2}\sqrt{\left(\frac{l}{L_x}\right) + \left(\frac{m}{L_y}\right) + \left(\frac{n}{L_z}\right)}$$

l, m, n are integers

Aluminum : v = 4900m/s

say, 1 x 1 x 0.5cm block

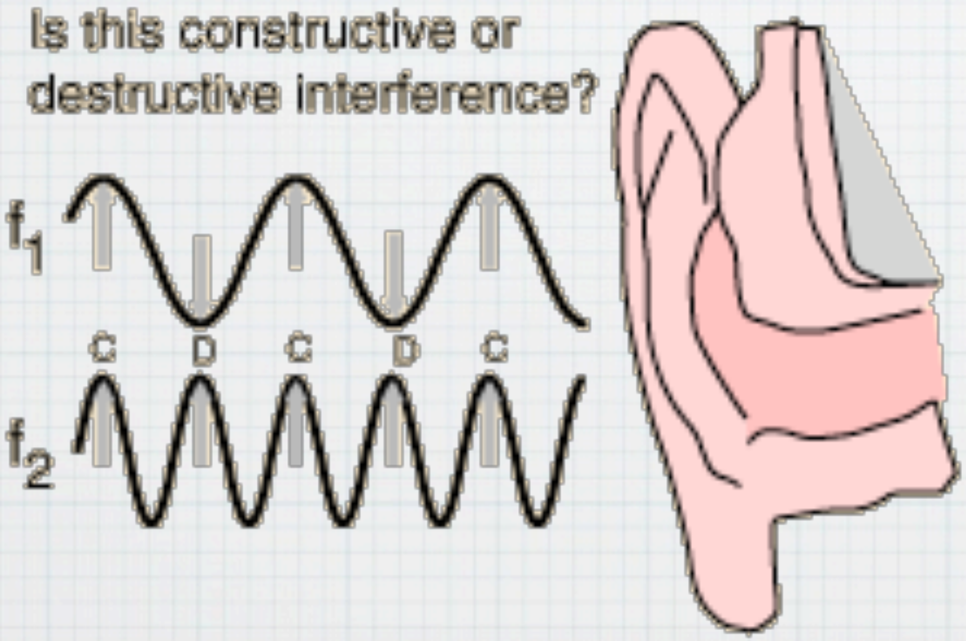
f = 3500 Hz = A_7
(3 octaves above middle C)

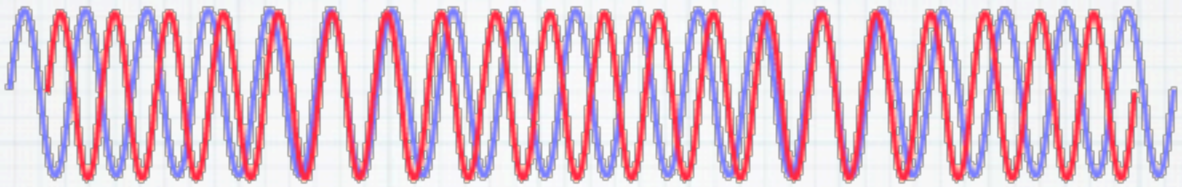
Interference

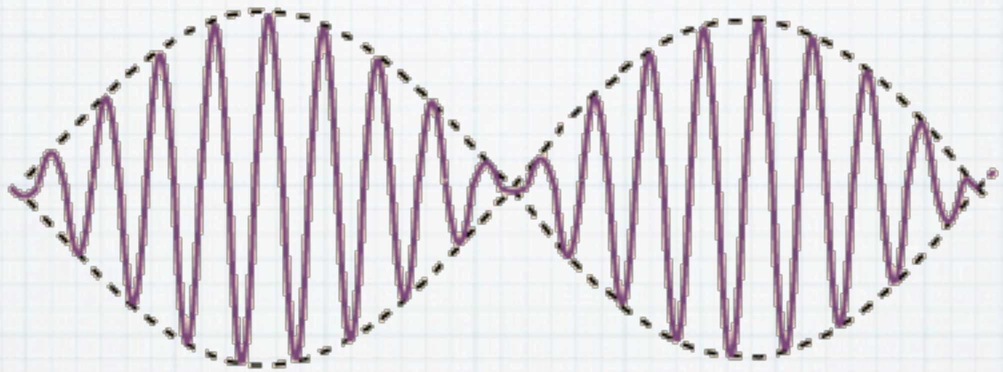
two sound waves of different frequencies
alternating constructive and destructive interference

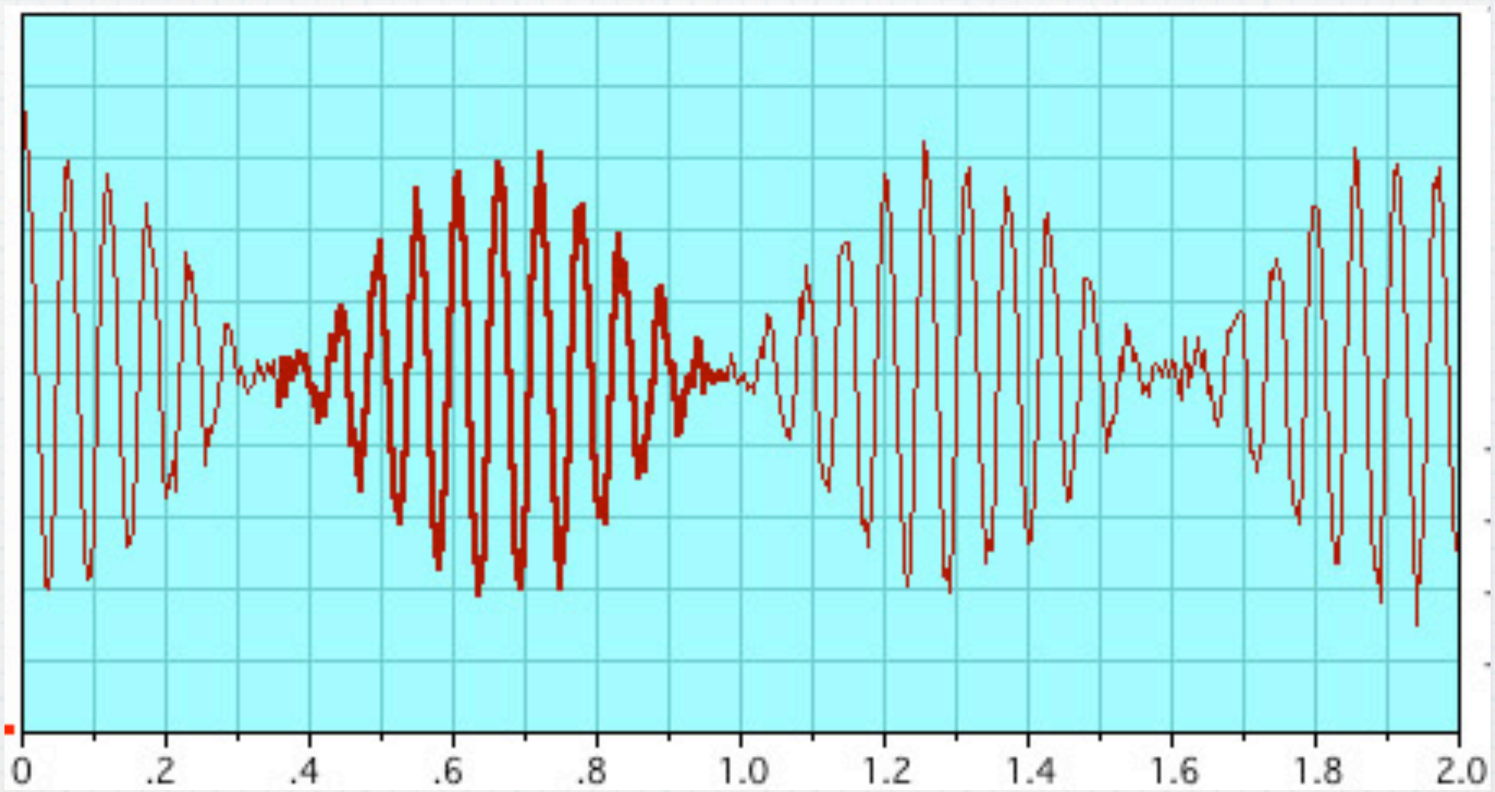
causes the sound to "beat"

beat frequency = difference in frequency of the two waves.








0
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0

beats

beats

sweep
one
generator

sweep
one
generator