

Waves

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**

**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 waves are of two sorts:

“String” type :

particles oscillating perpendicular to propagation

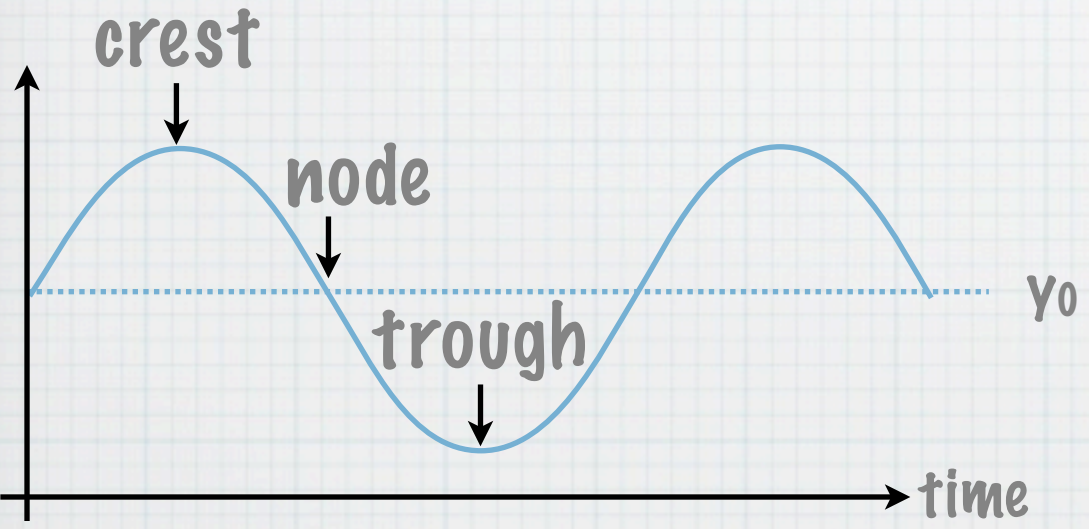
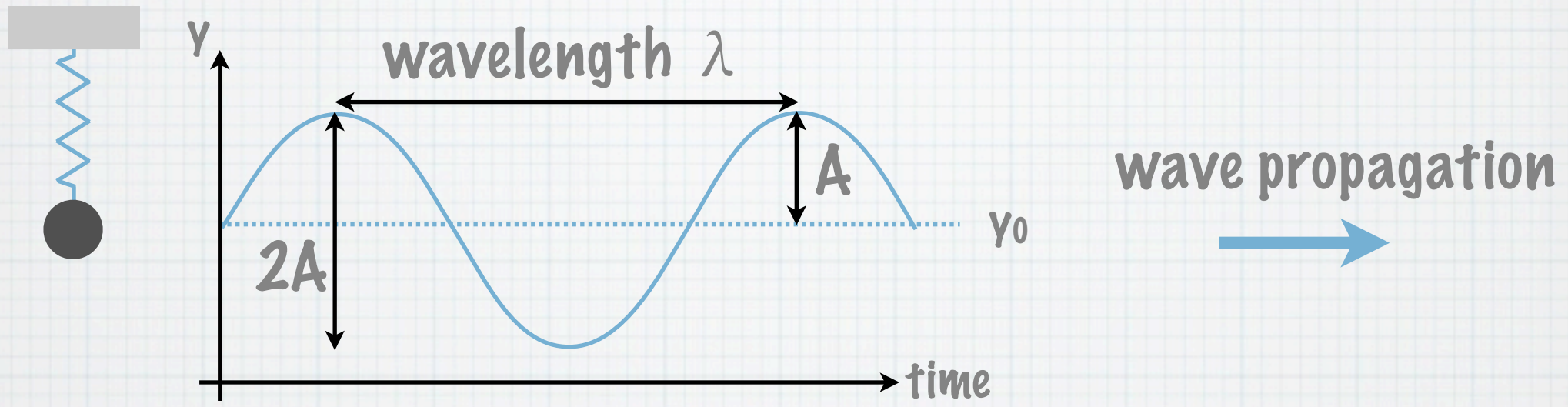
“Density” type :

particles oscillating parallel to propagation

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

Describing waves

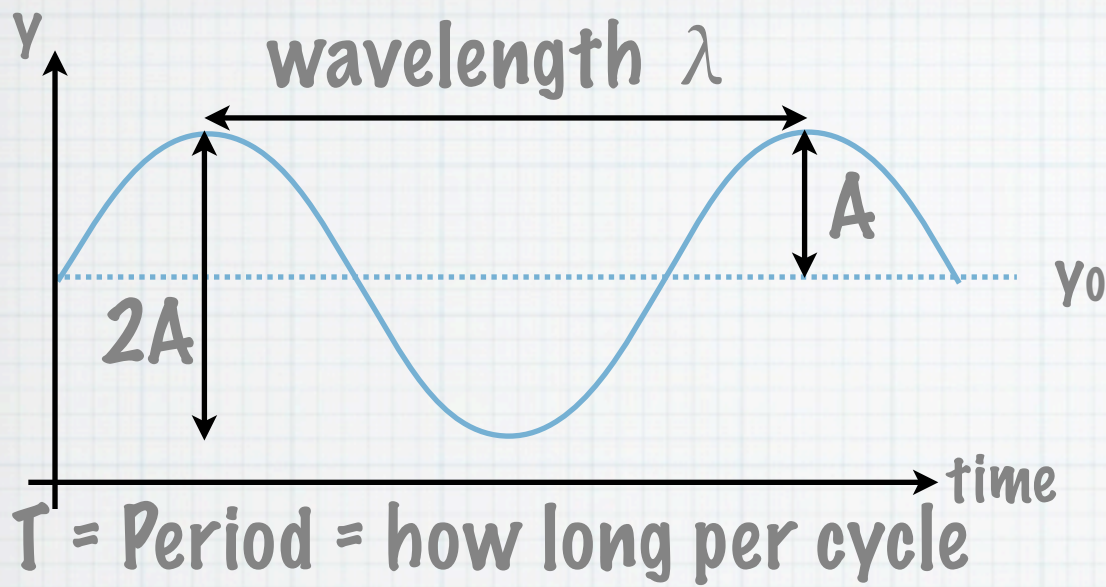
example: mass on a spring; oscillation perp. to wave direction



A = amplitude = intensity

λ = wavelength = char. size

f = frequency, full periods/sec



λ characterizes
SPATIAL variation

f characterizes
TIME variation

$$T = 1/f \quad \text{or} \quad f = 1/T$$

frequency - wavelength - velocity:

$\lambda f = v = \text{velocity of wave propagation}$

or $vT = \lambda$ travel one wavelength per period

simplest wave:

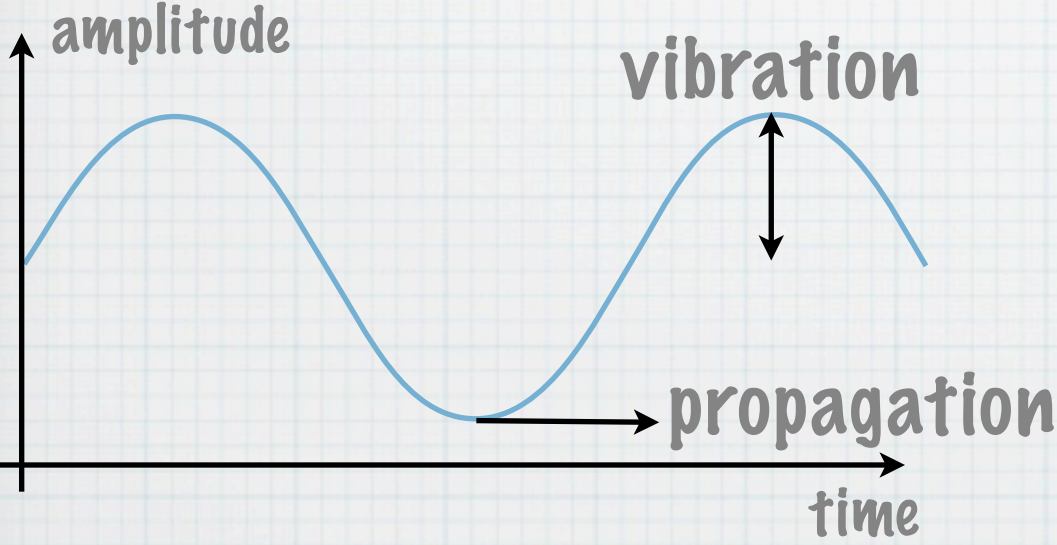
$$f(x, t) = A \sin \left(2\pi ft - \frac{2\pi}{\lambda} x \right)$$

Characteristics of waves

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

Longitudinal

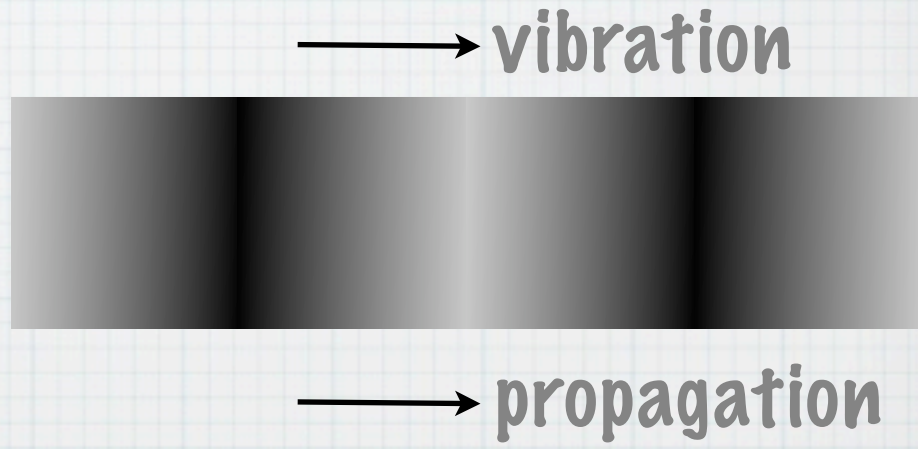
vibrations are **PERPENDICULAR** to propagation



string, EM waves

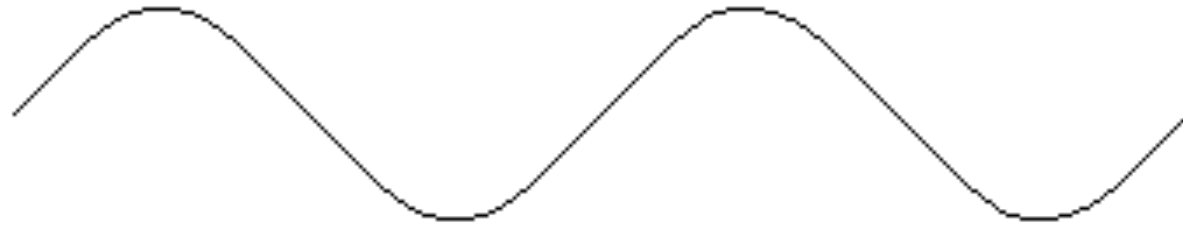
Transverse

vibrations are **PARALLEL** to propagation

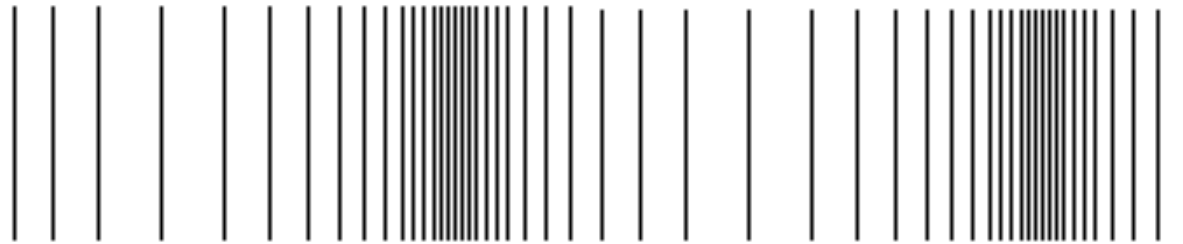


sound

GVG/PD/1.0



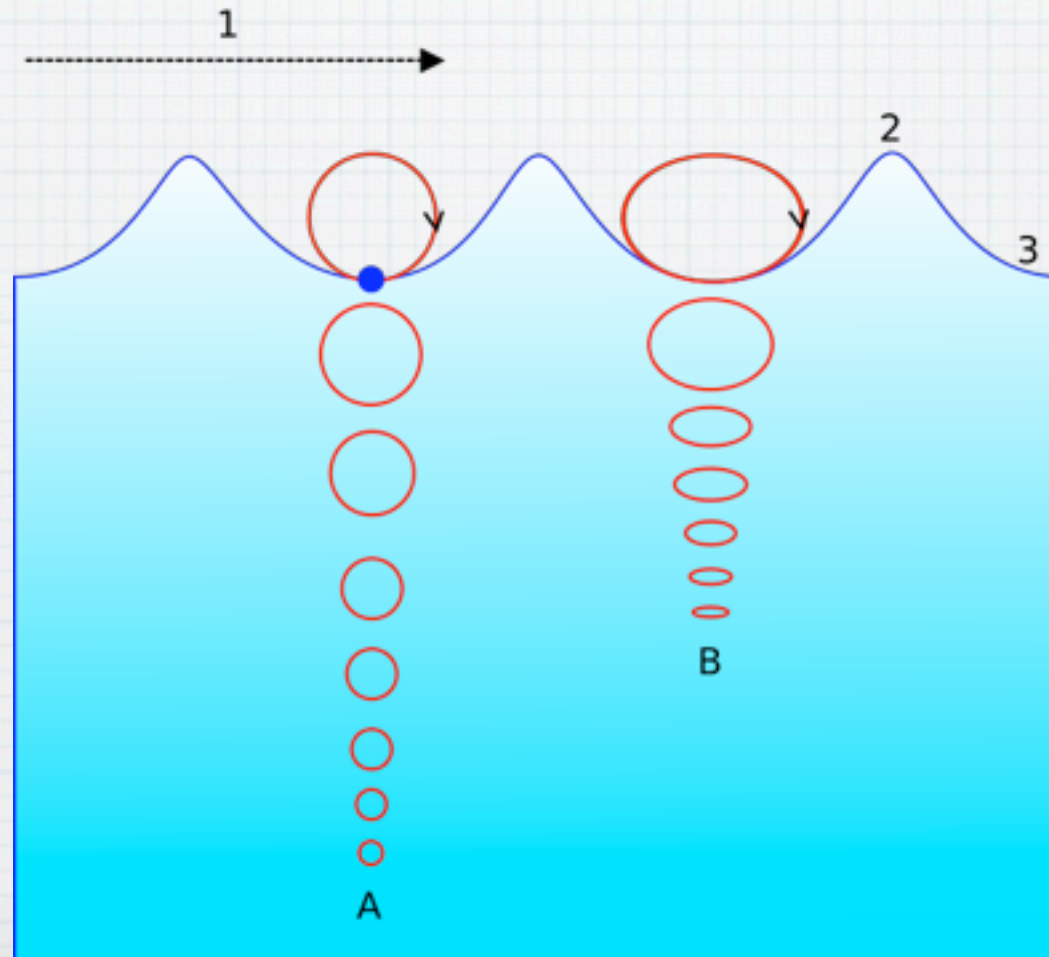
TRANSVERSE WAVE



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:

reflect: change direction after hitting a reflecting surface

refract: change direction after hitting a refracting surface

diffract: bend as they interact with objects

(when object's size is near wavelength)

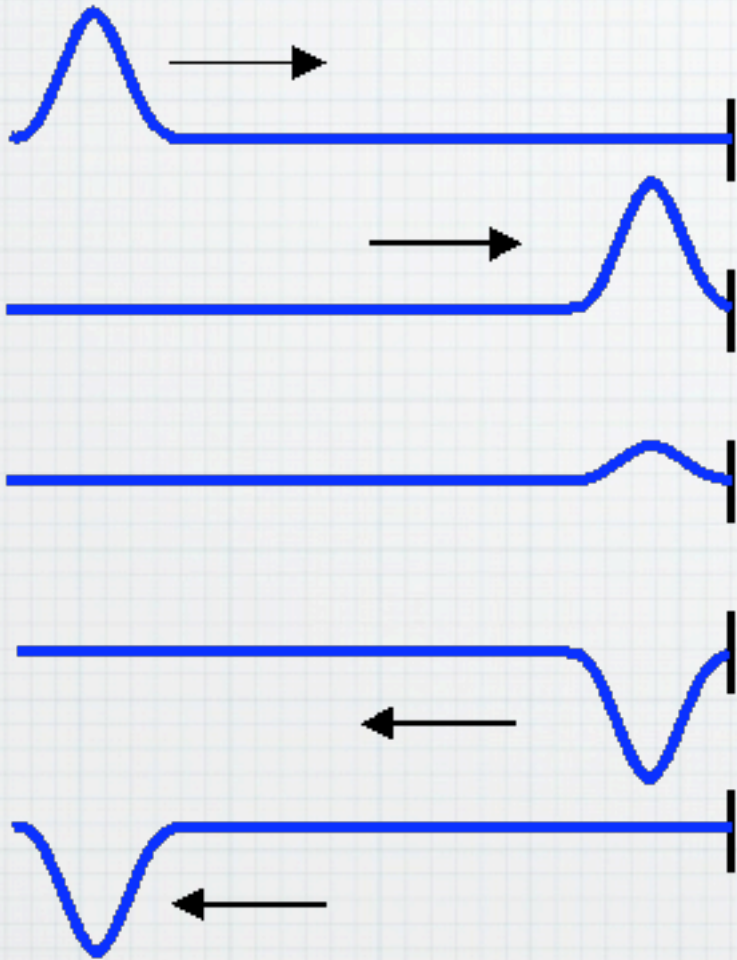
interfere: superposition of colliding waves

disperse: split up by frequency

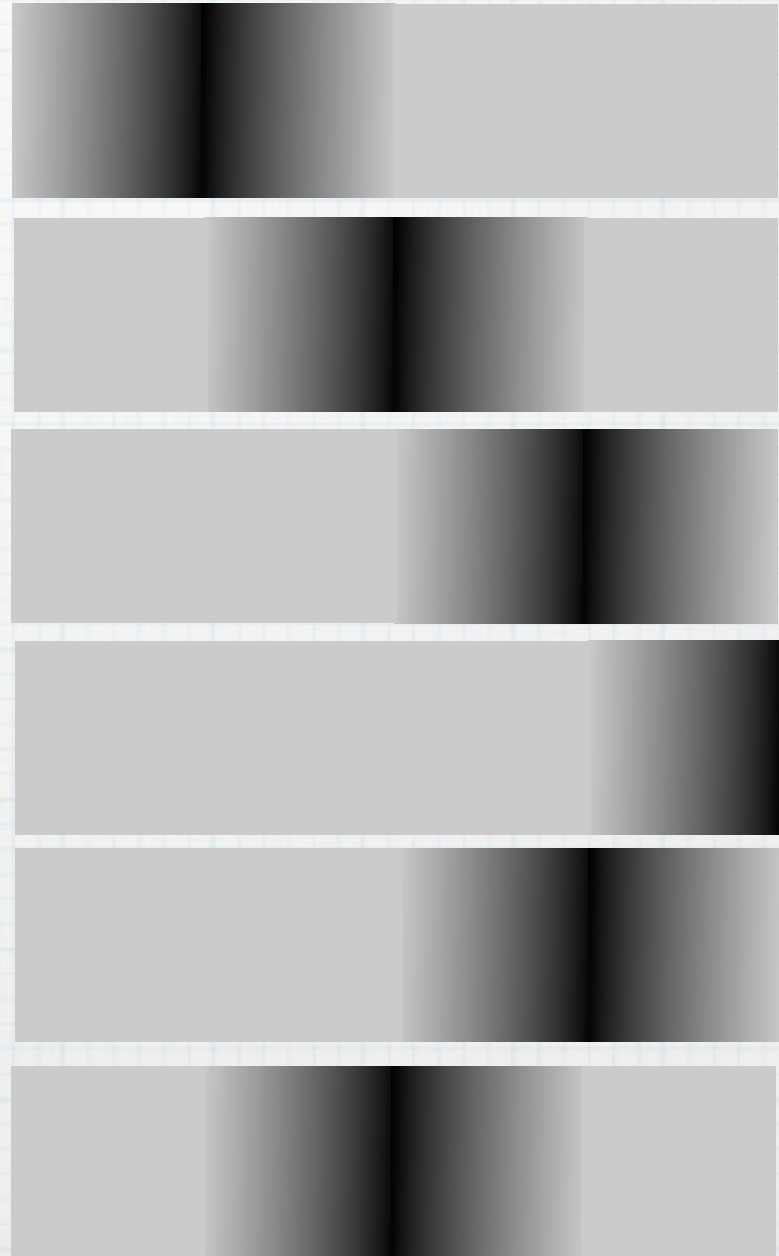
move in a straight line: propagation ... not always (standing)

Reflection

pulse on a string

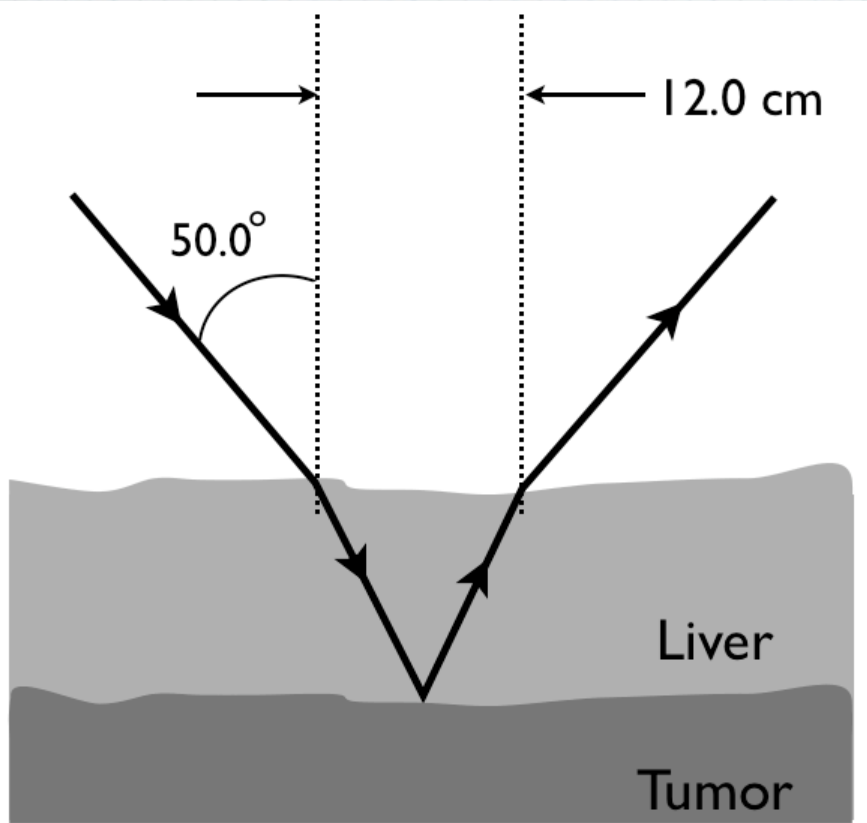


density wave

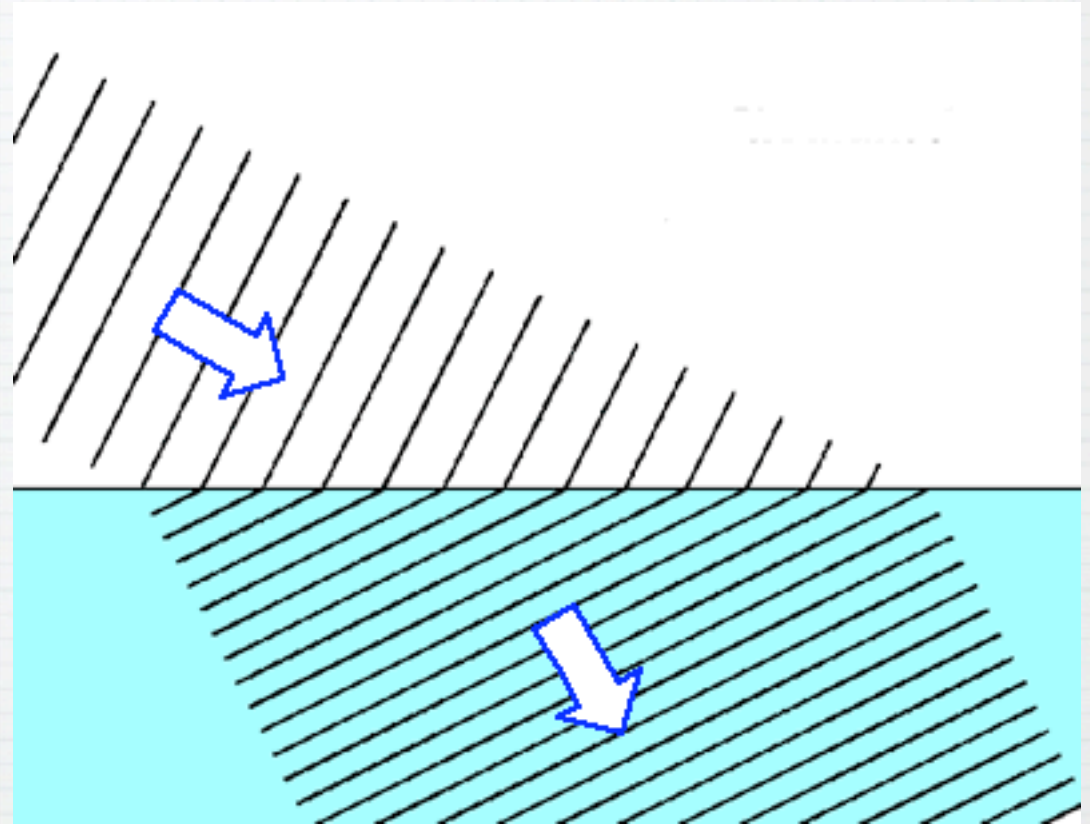


Refraction

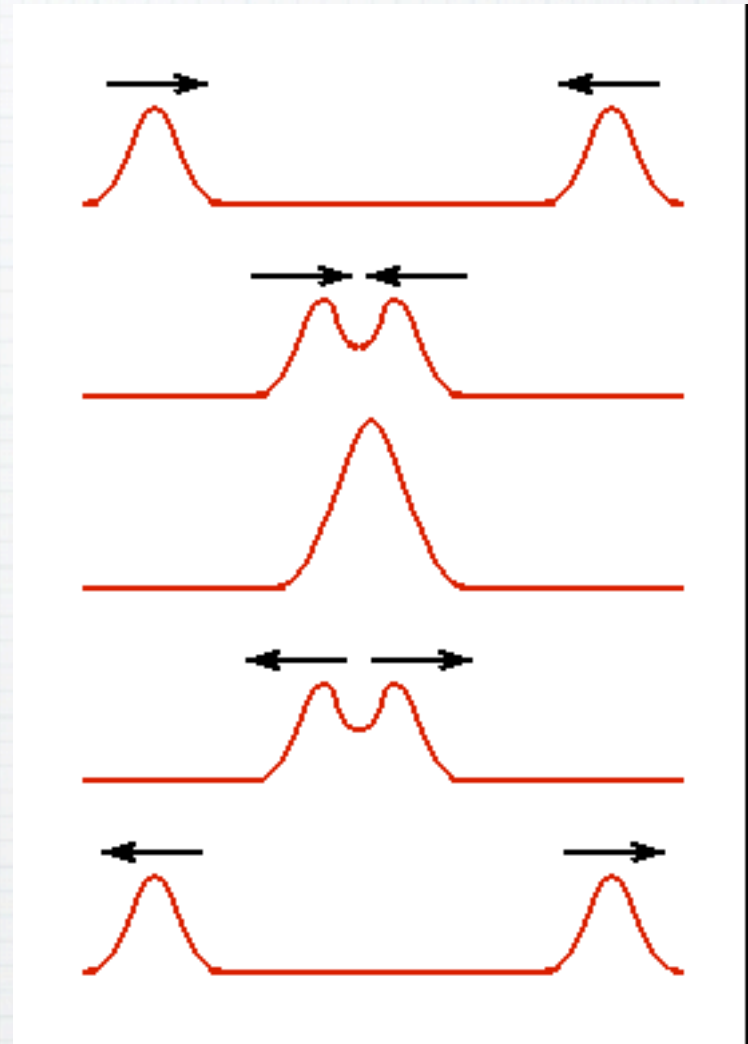
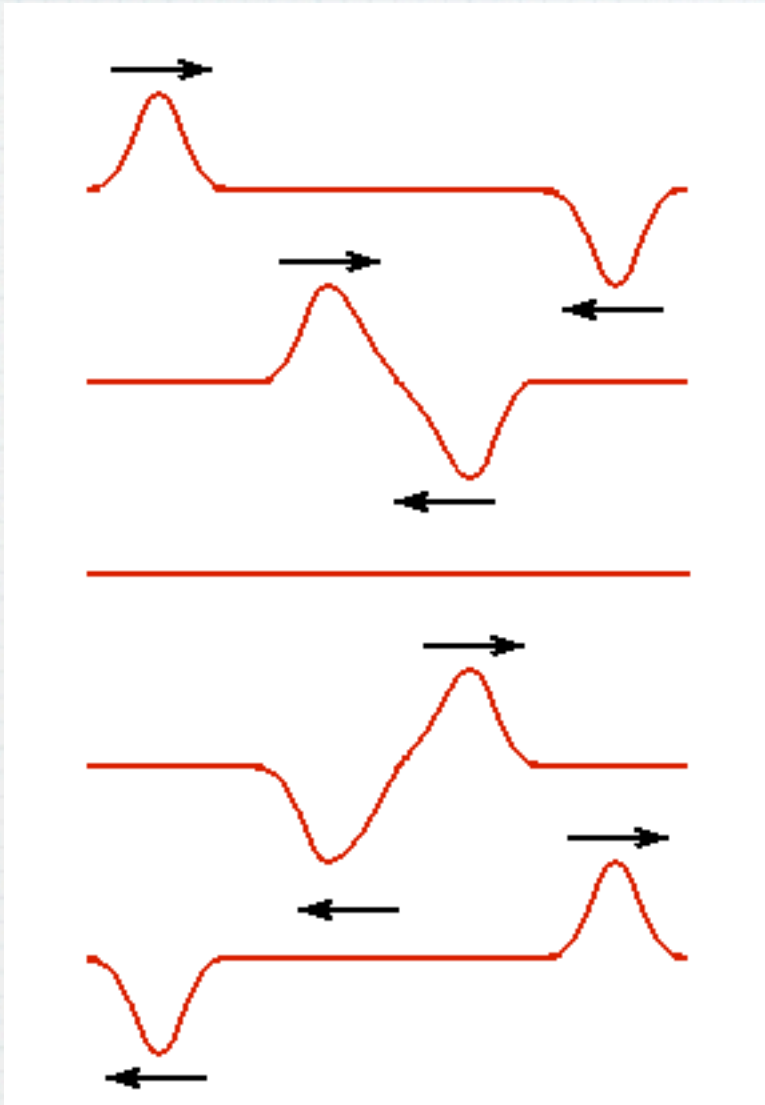
light & heavy string



density wave at a boundary



Superposition



similarly with density waves!

[REDACTED]

[REDACTED]

[REDACTED]

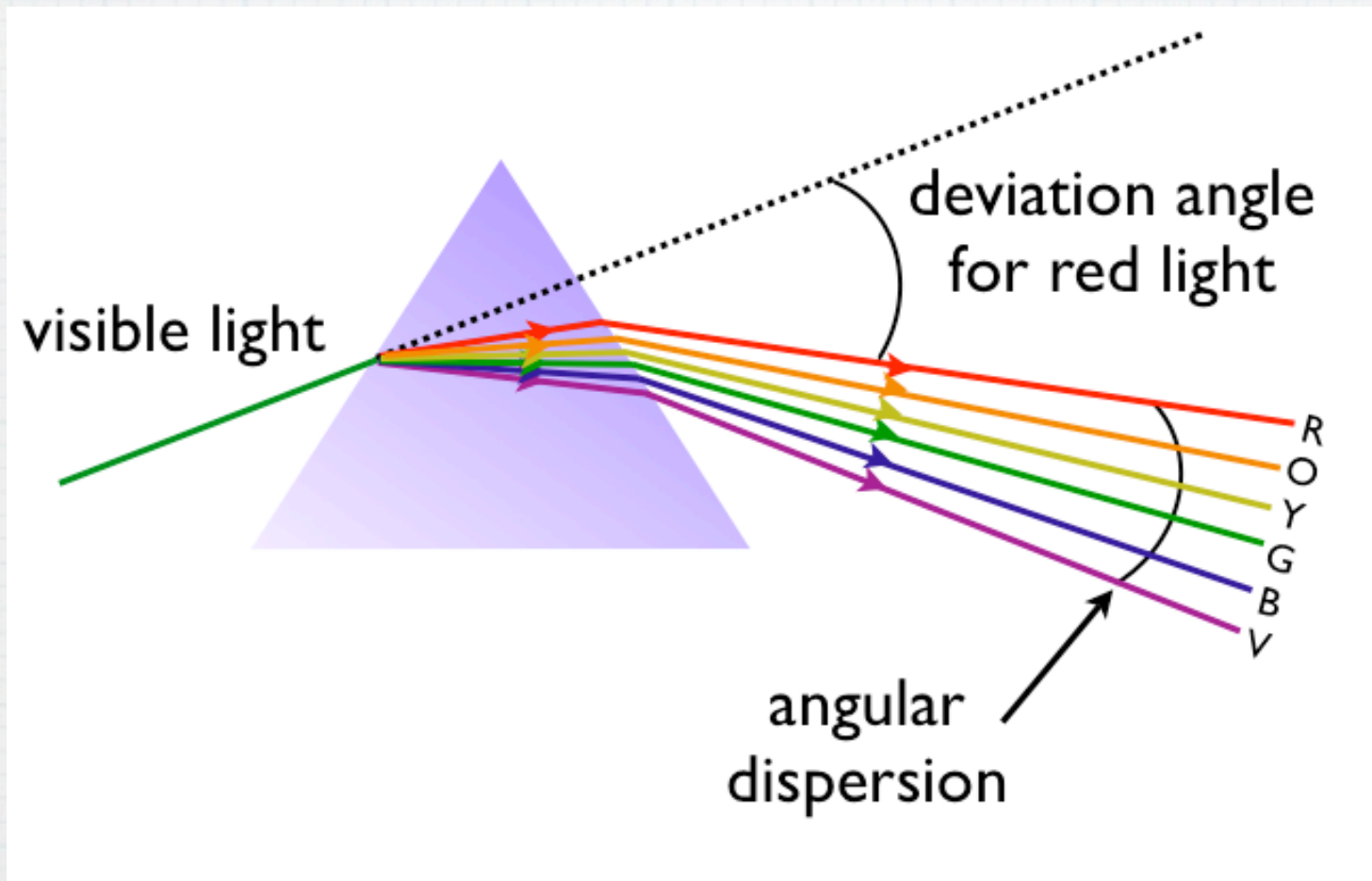
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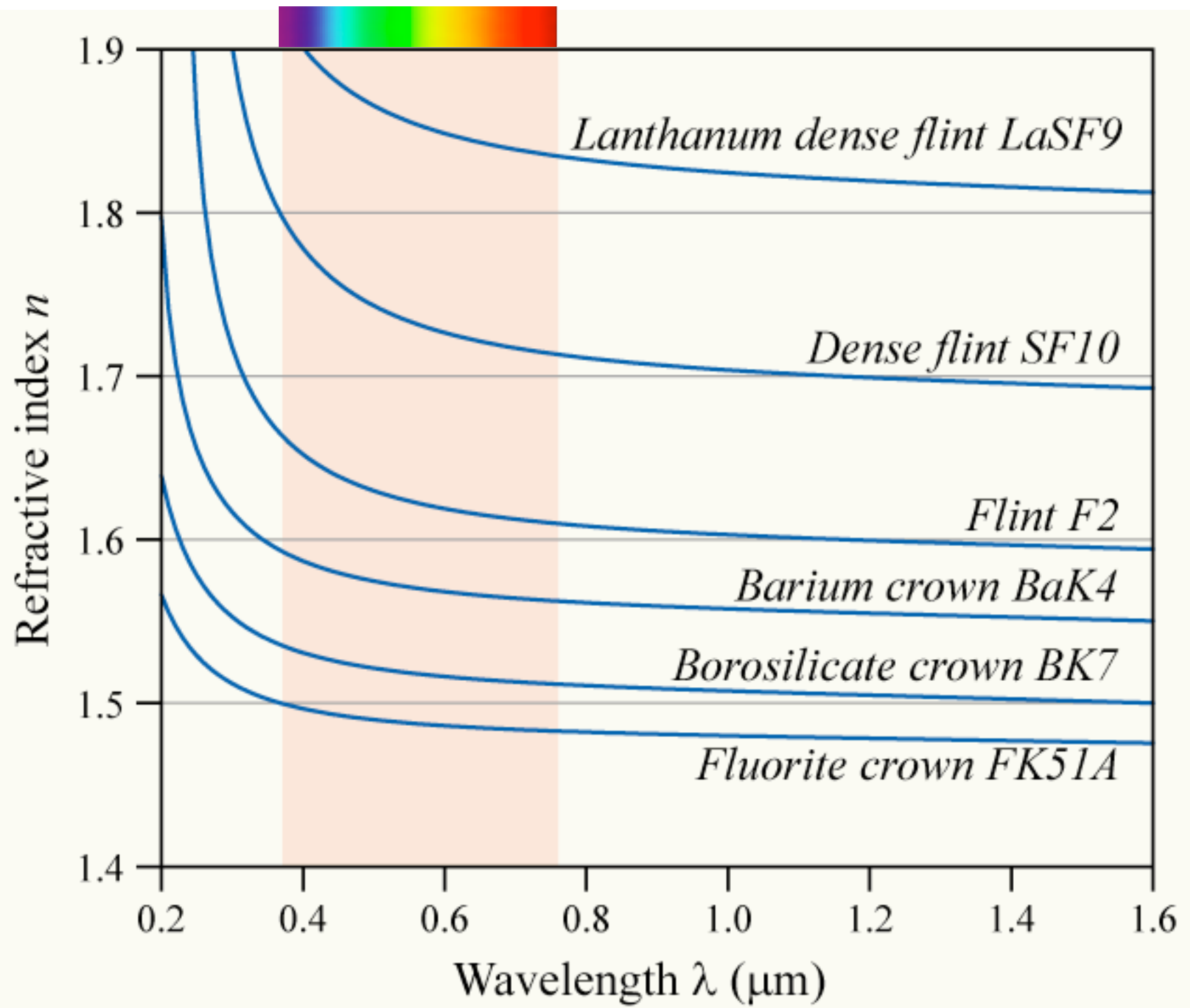
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Dispersion

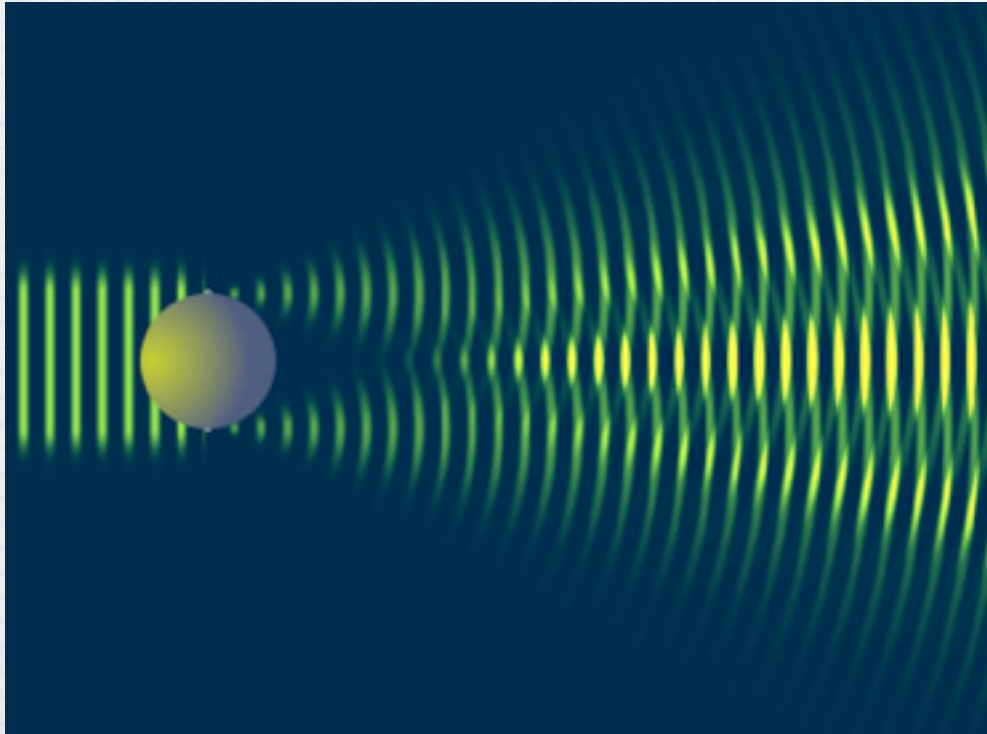
speed of wave depends on wavelength
blue light waves are slower in glass
take a longer path



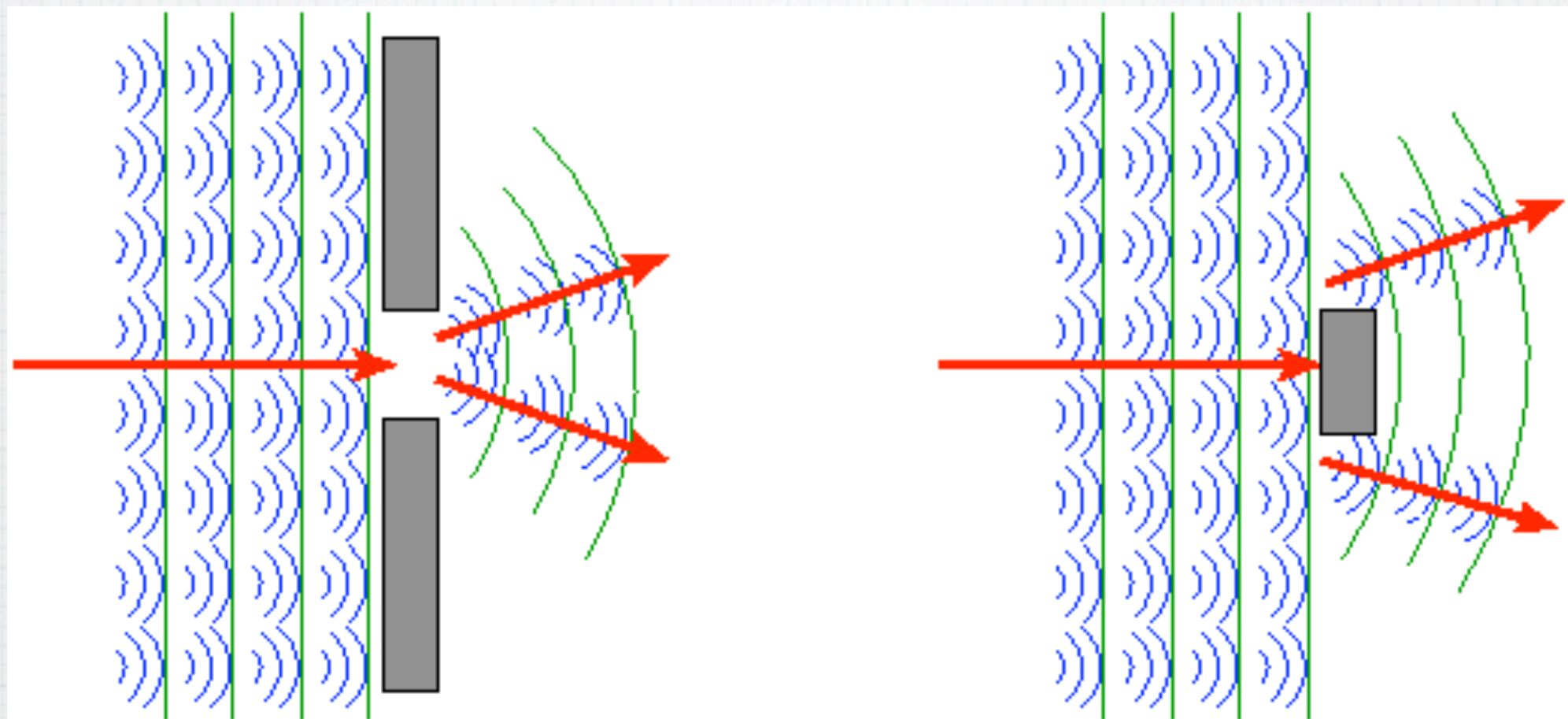
water: longer wavelengths travel faster!

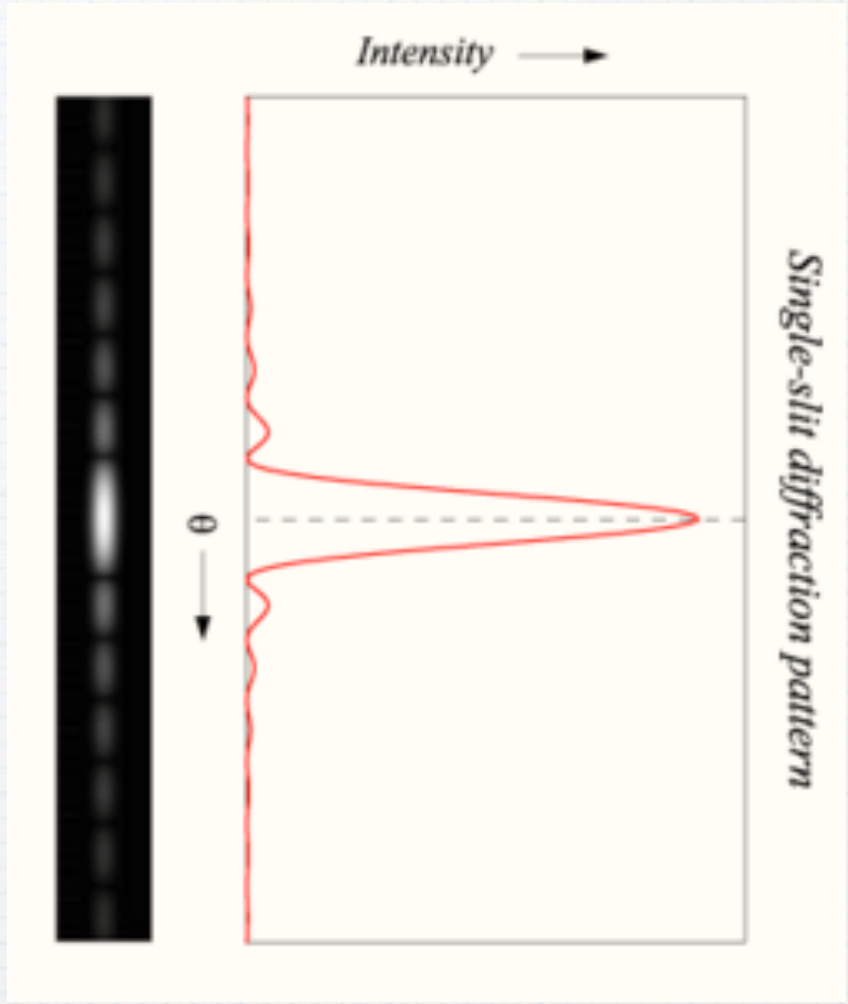
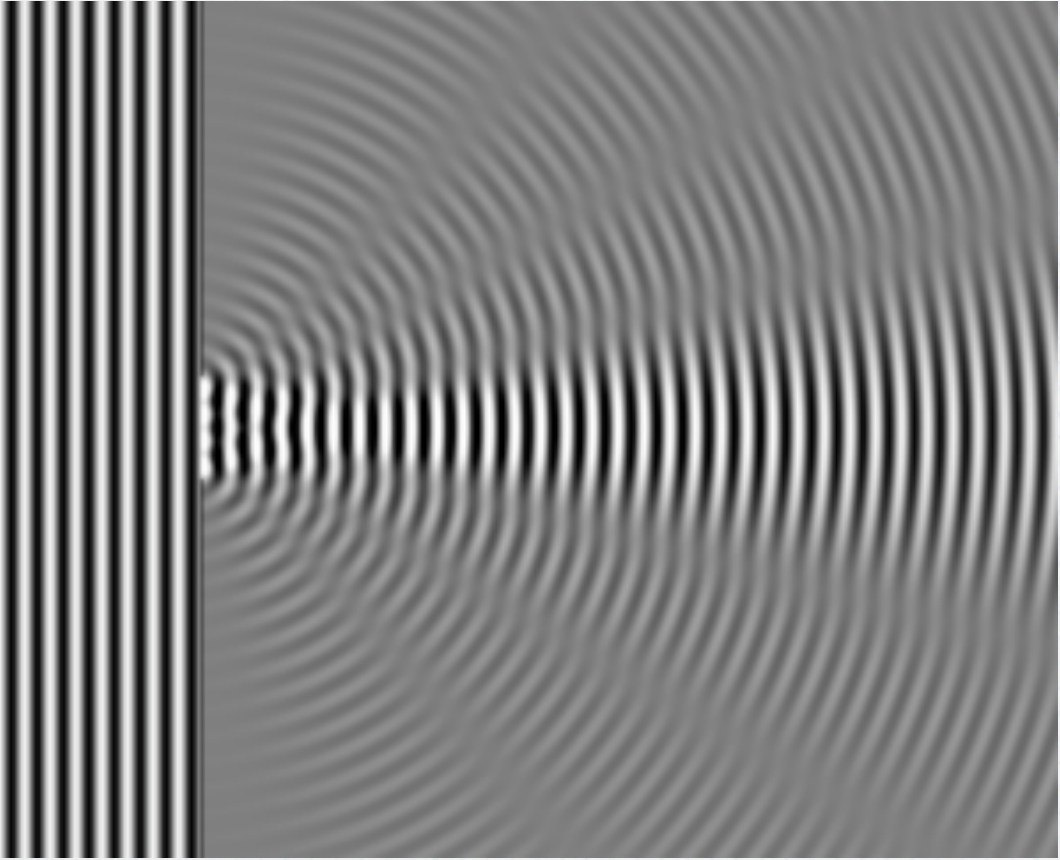


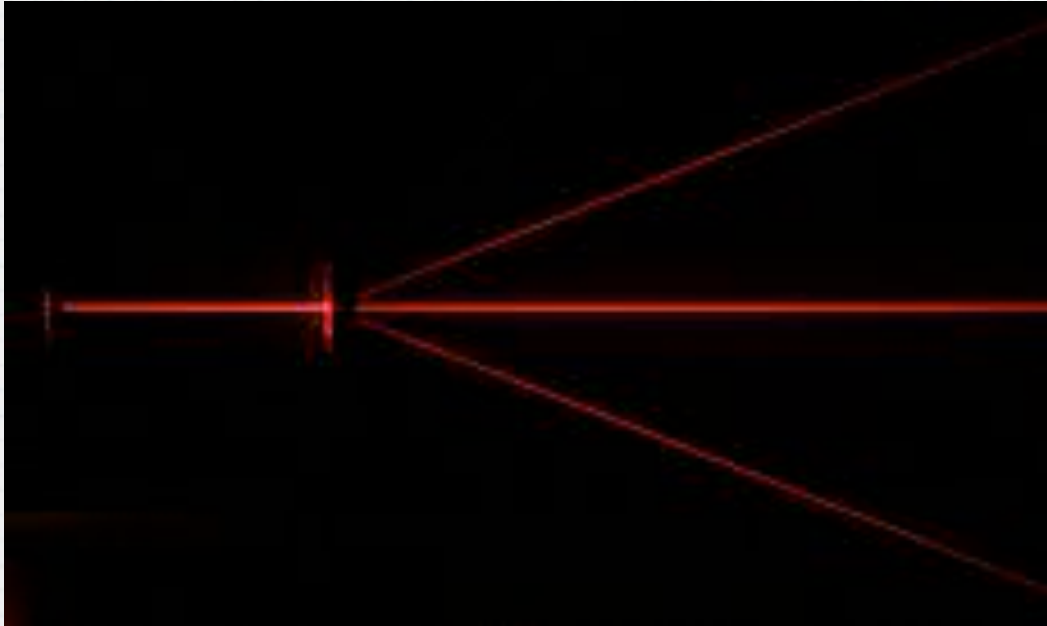
Diffraction



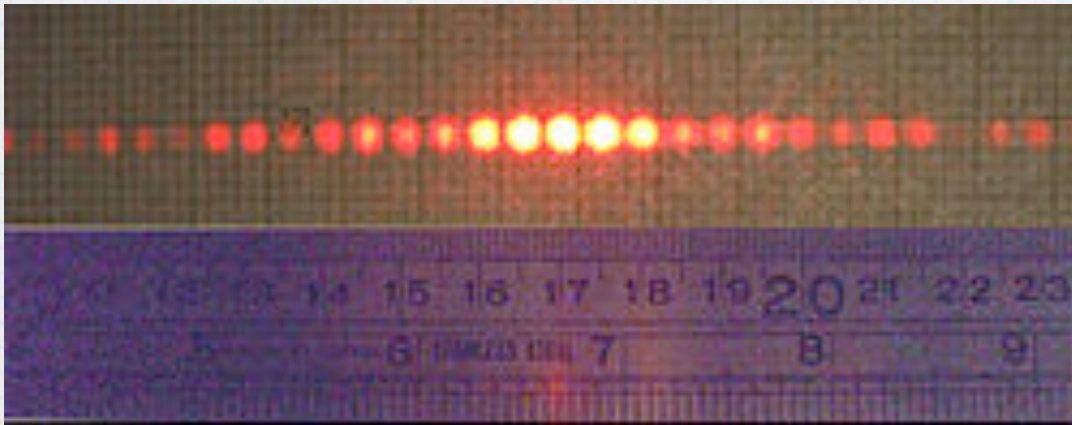
We'll use this today
depends on wavelength of light
can use it to measure wavelengths





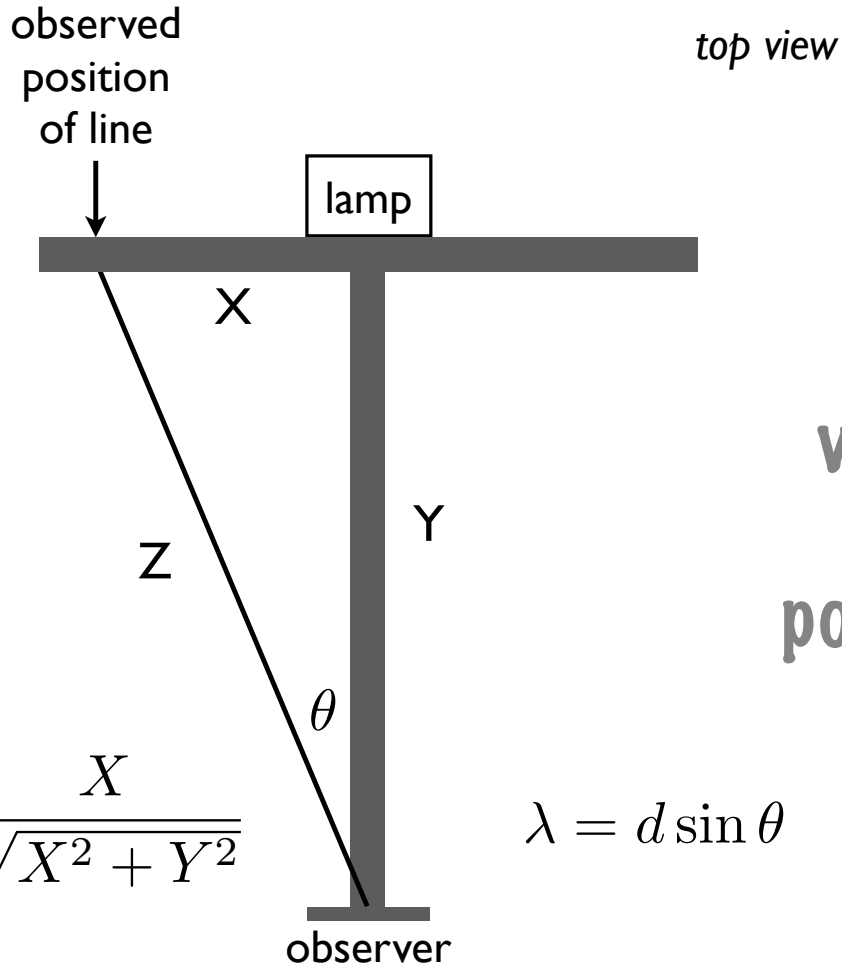


diffraction of a red laser



projected onto paper

distance between spots depends on wavelength!



$$\sin \theta = \frac{X}{\sqrt{X^2 + Y^2}}$$

$$\lambda = d \sin \theta$$

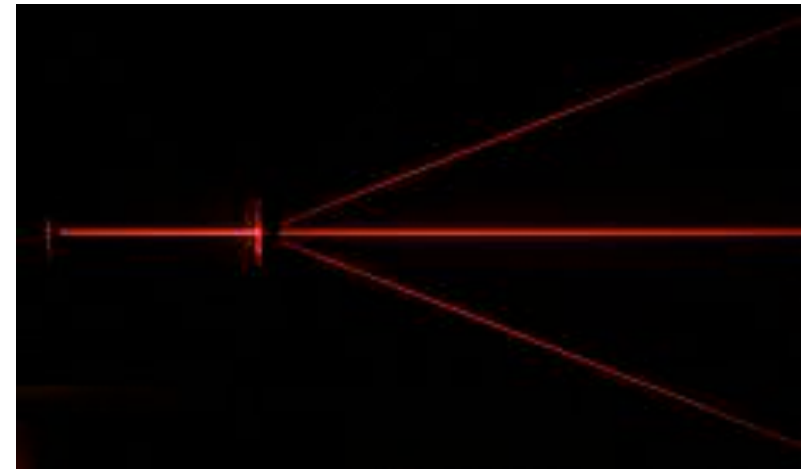
our experiment:
view lamp through grating

we see diffracted spot pattern

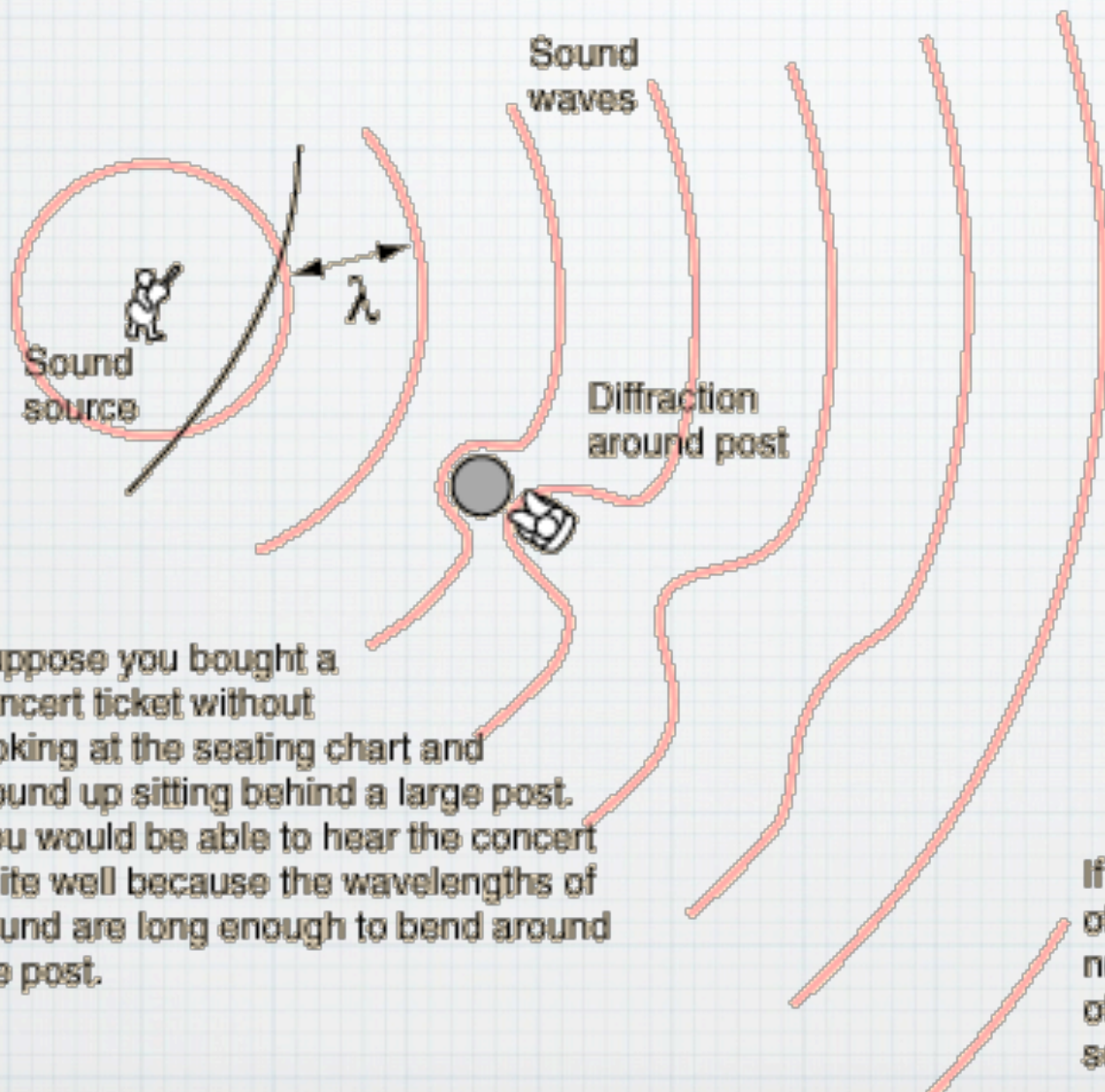
position of line gives wavelength!

some colors of light diffracted more than others ...

larger angle = larger wavelength
= more toward blue

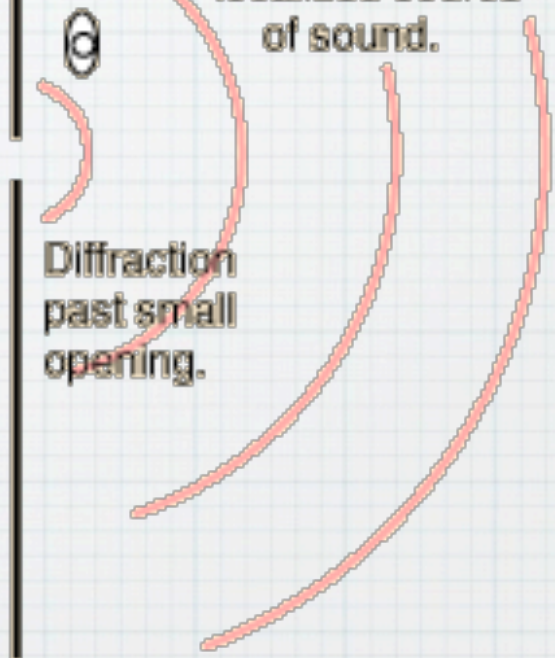


This happens with sound too!

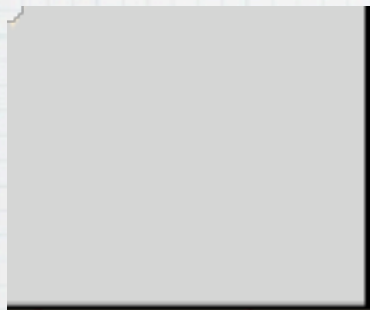


Suppose you bought a concert ticket without looking at the seating chart and wound up sitting behind a large post. You would be able to hear the concert quite well because the wavelengths of sound are long enough to bend around the post.

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.



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.

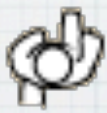
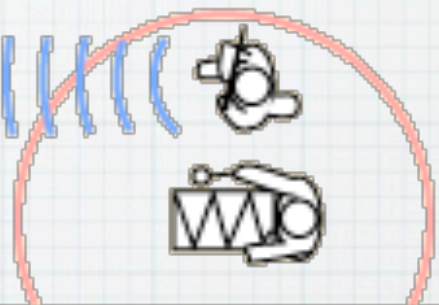


If a marching band is approaching on a cross street, which instruments will you hear first?

$\lambda \rightarrow || \leftarrow$ High pitched piccolo, short wavelength.

High pitched sounds tend to be more directional because they don't diffract as much.

$| \leftarrow \lambda \rightarrow |$
Low pitched bass drum, long wavelength.



What haven't we seen?

Diffraction.

So that's next week.

So, what are our light sources next week?

(1) Atomic vapor discharge lamps

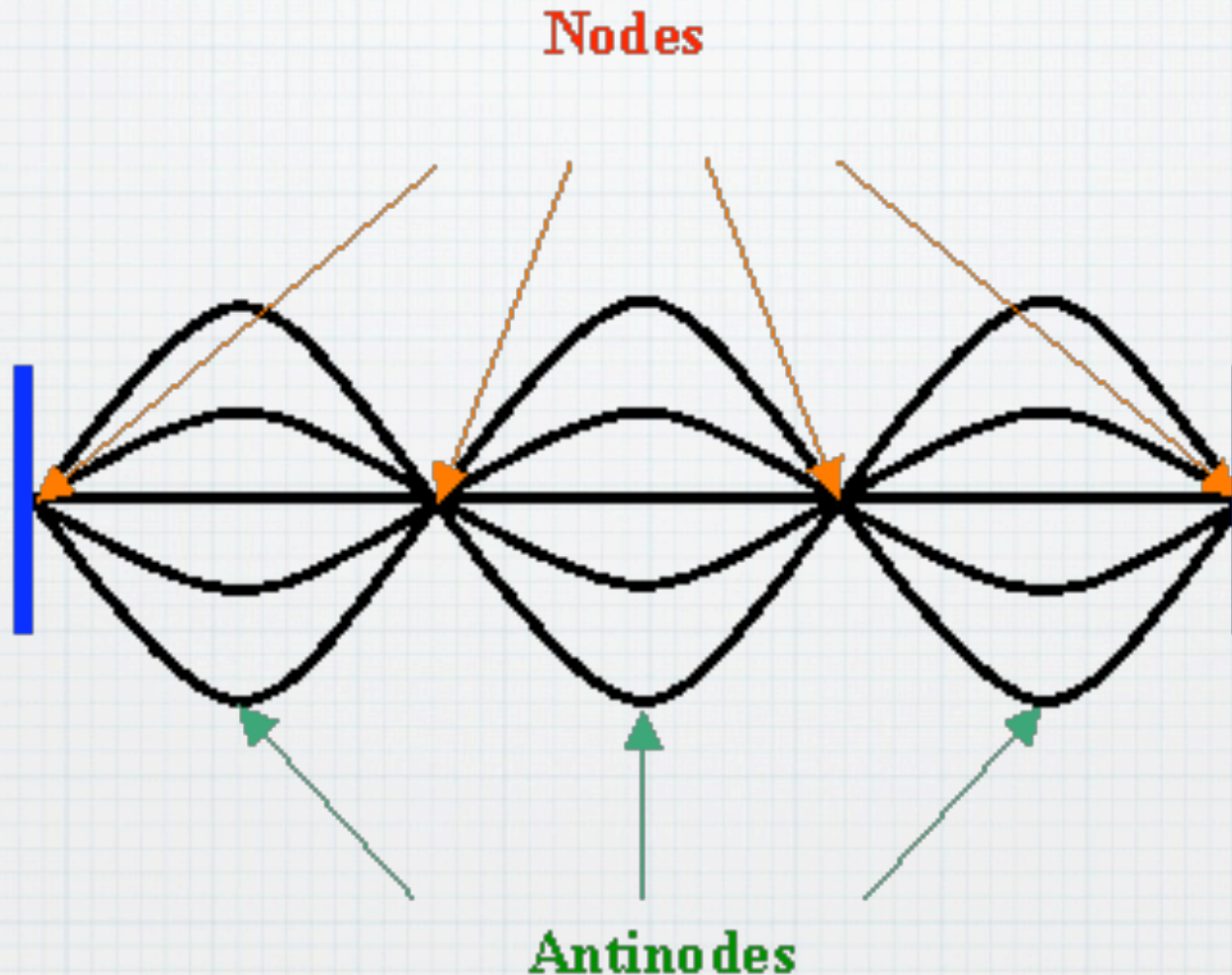
(2) Light-emitting diodes

(1) The discrete nature of atomic energy levels means that excited atoms only give off specific colors of light.

(2) Light energy controlled by specific single energy transition

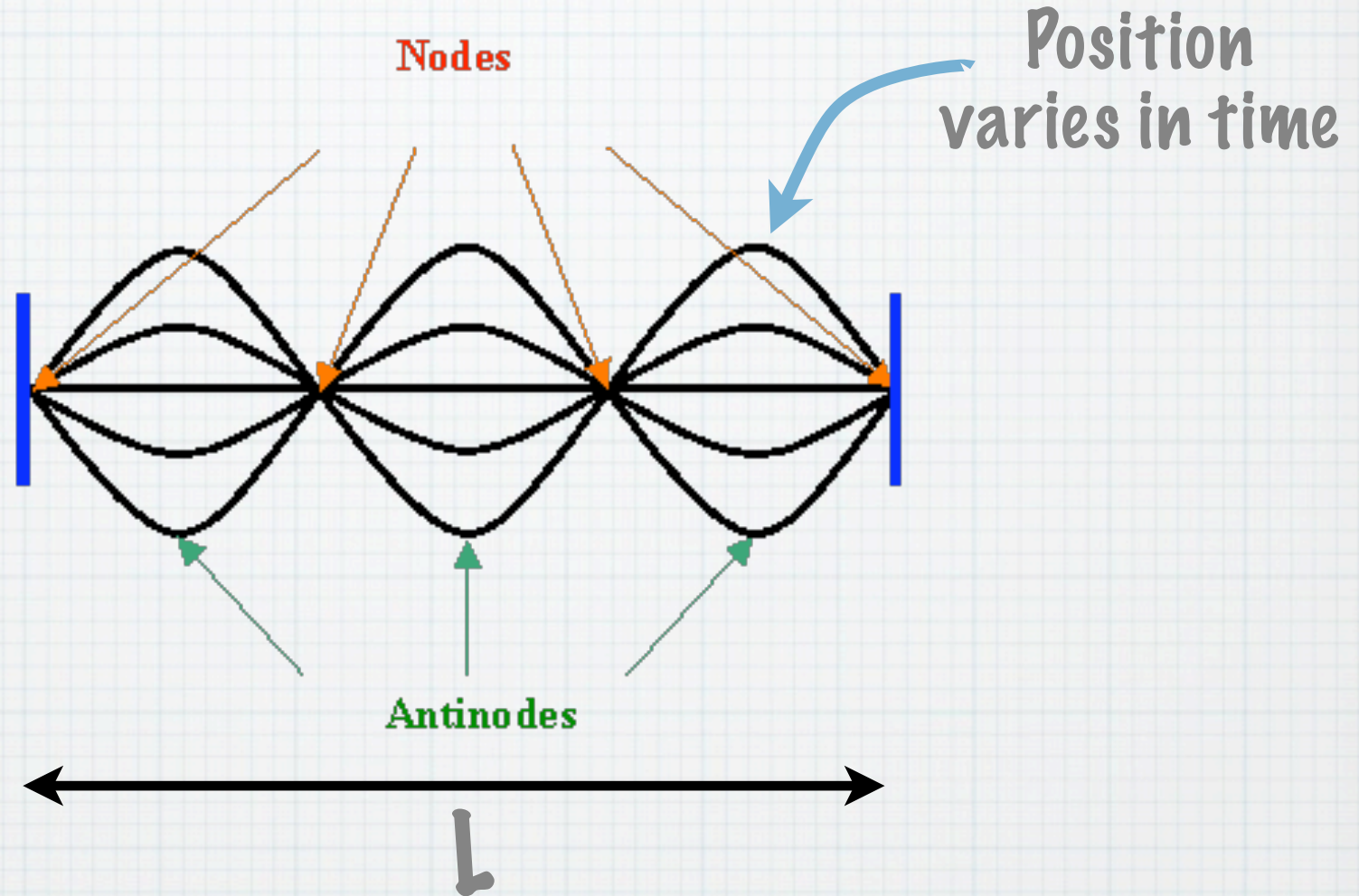
Straight line propagation

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



Standing waves must meet special conditions

geometry ...

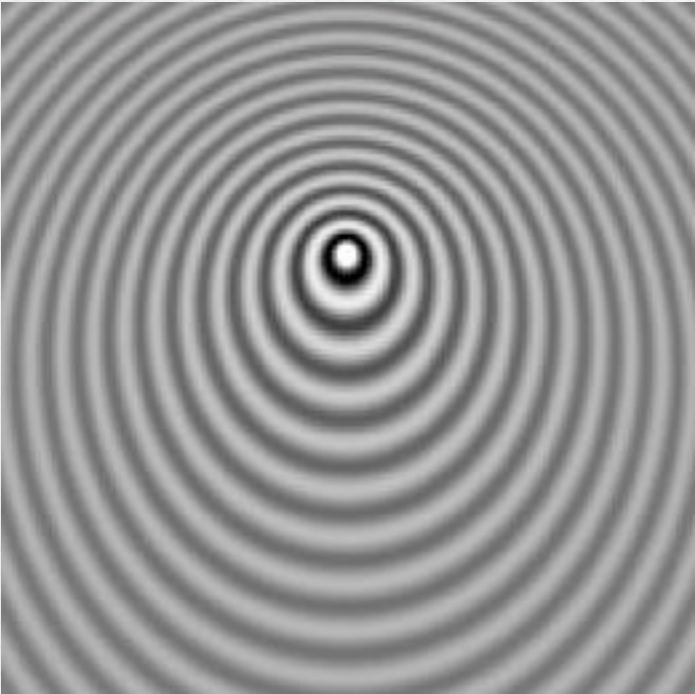
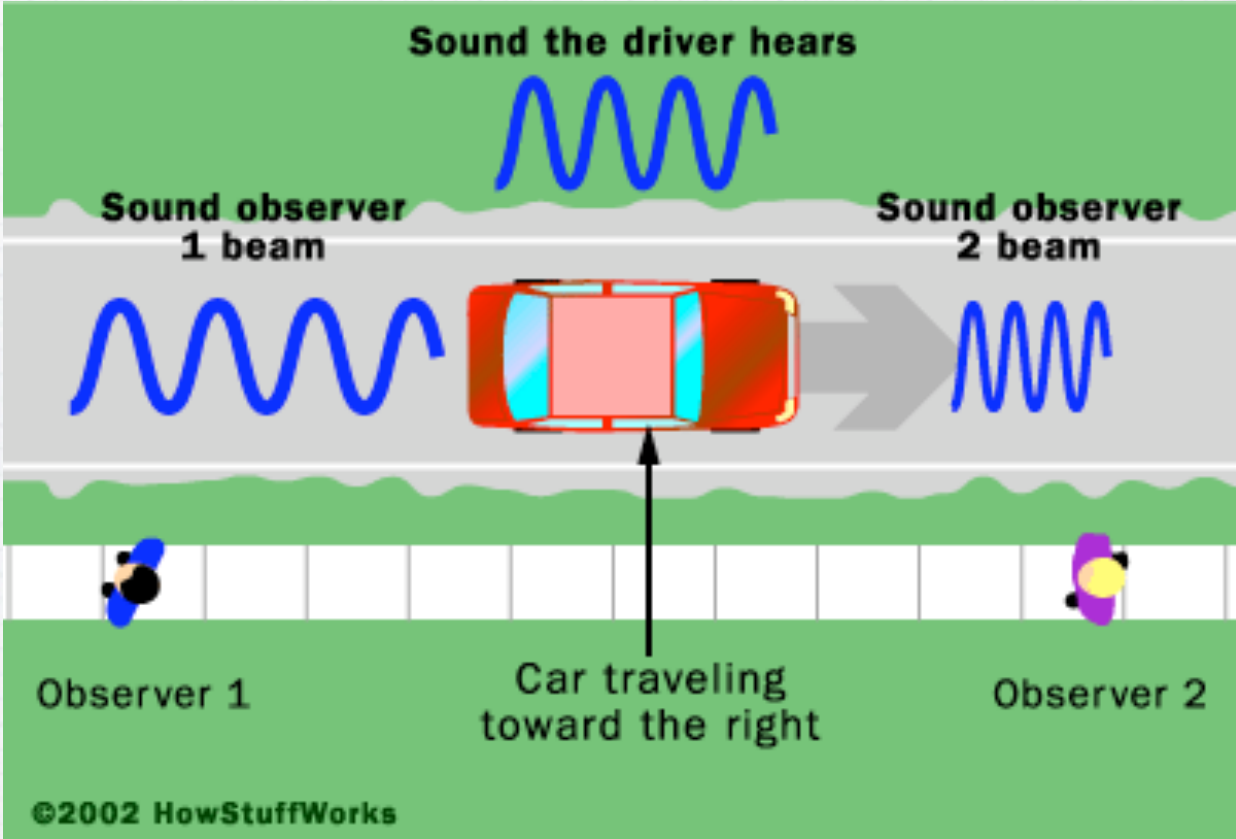


for end points to be fixed:

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

we will come back to this ...

Doppler Effect: moving relative to waves

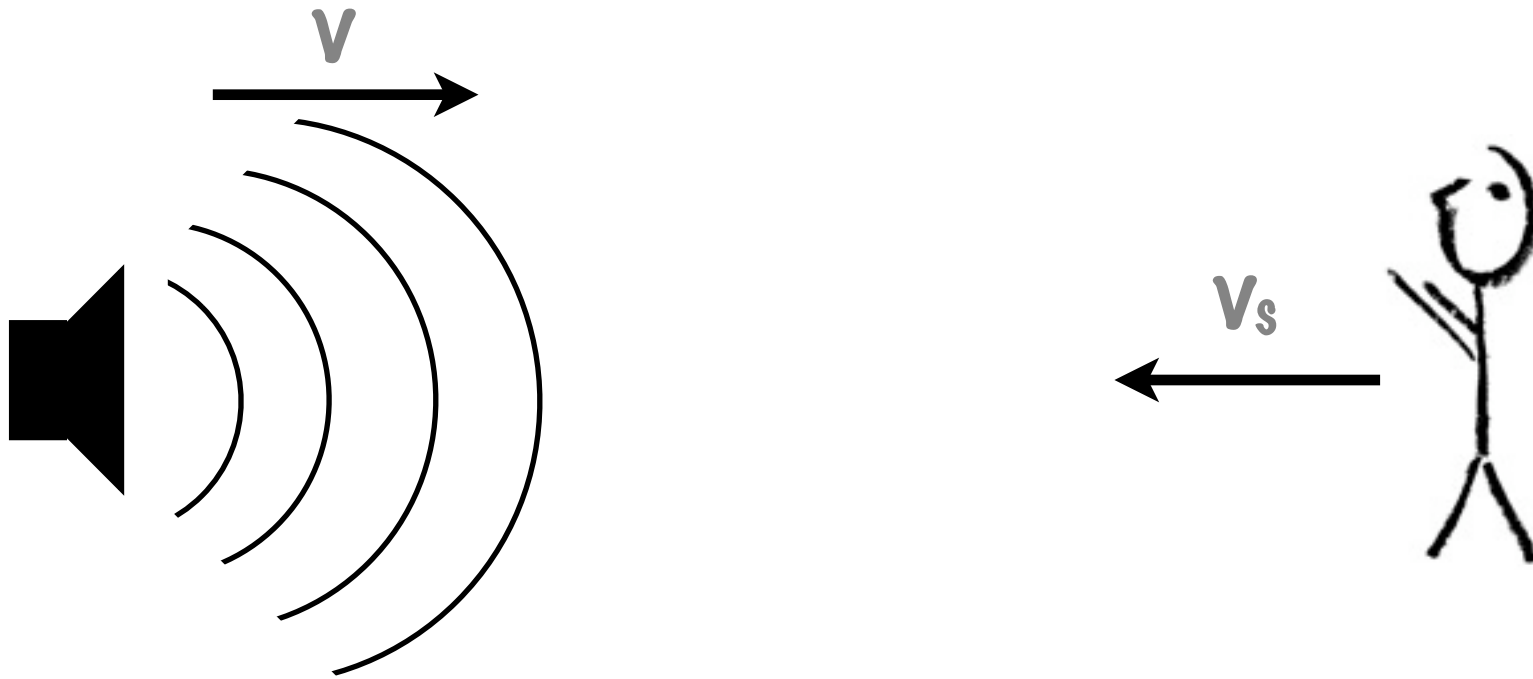


in one period T , you move closer to the source by $v_s T$

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)

Via relativity, it works with light too ...

*If this bumper sticker is blue,
you're driving too fast!*

why ?

Sound in air

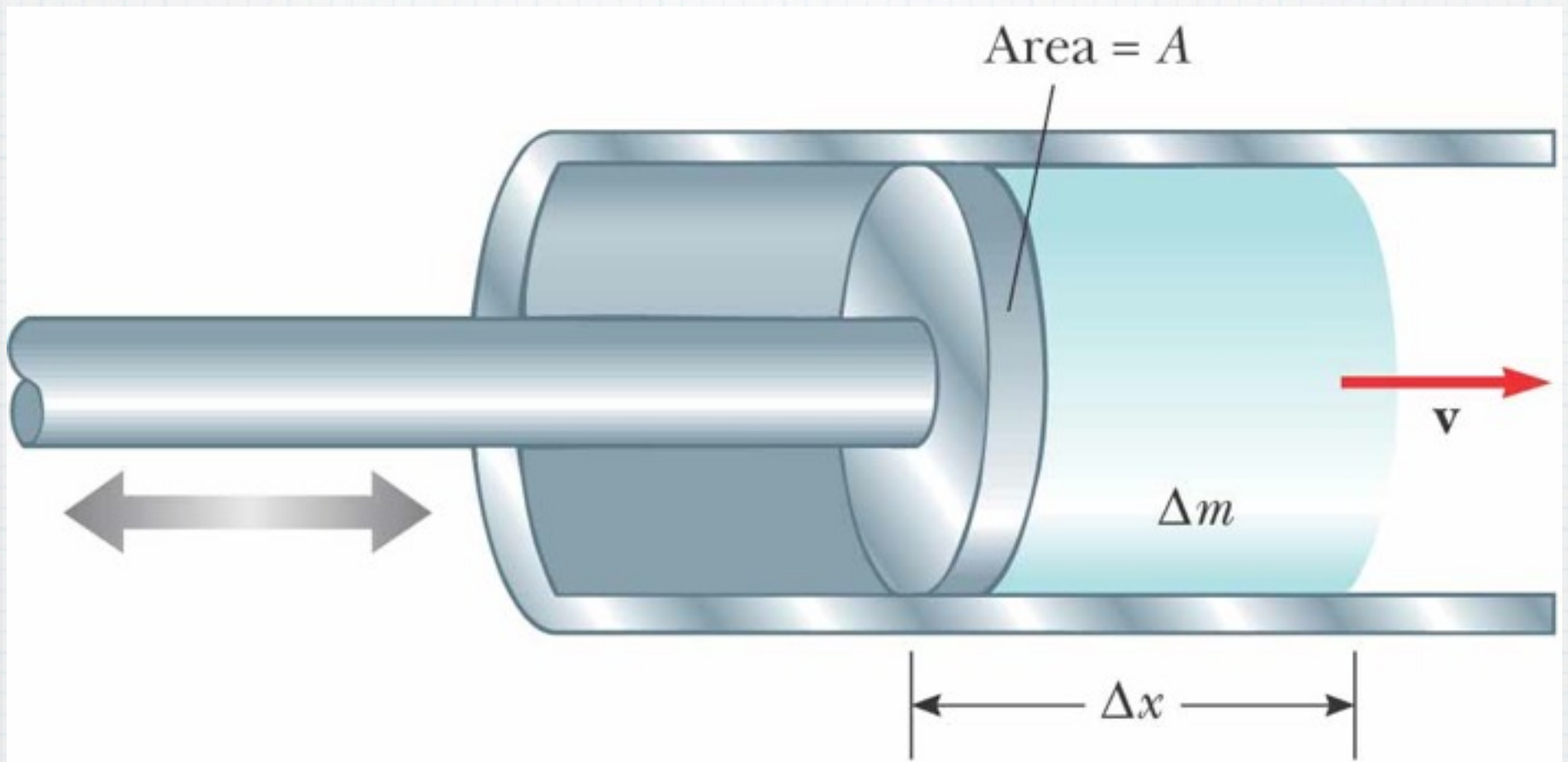
most sound = waves produced by vibrations of a material

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

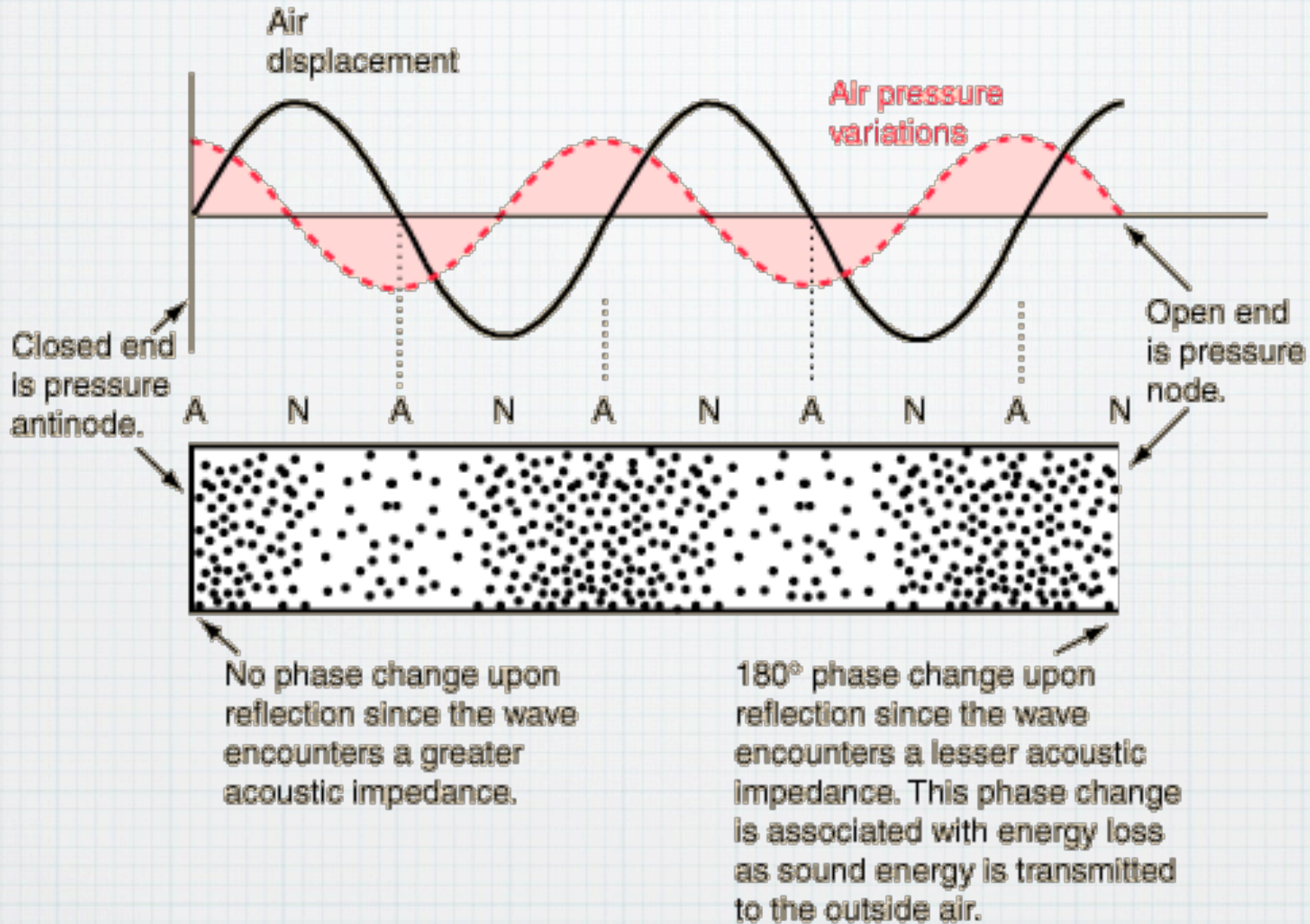
original vibration stimulates a larger one
sounding board

sound = compression / rarefaction waves in a medium
Density Waves





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

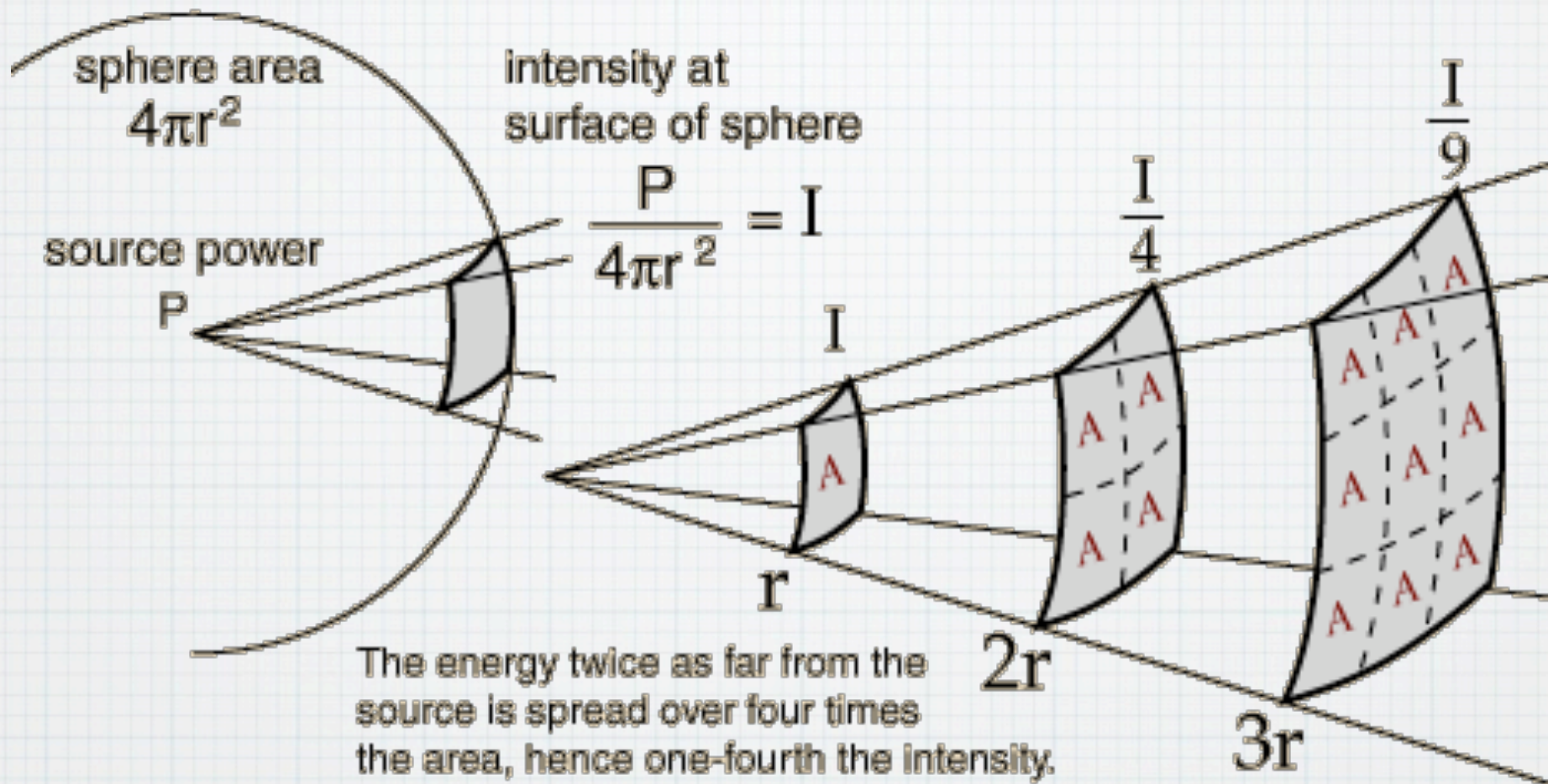
$$P = F/A = (F*d)/(A*d) = W/V = (\text{energy})/(\text{volume})$$

variation of pressure = variation of energy density

sound power = (energy)/(time)

sound intensity = (power)/(unit area)

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



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)

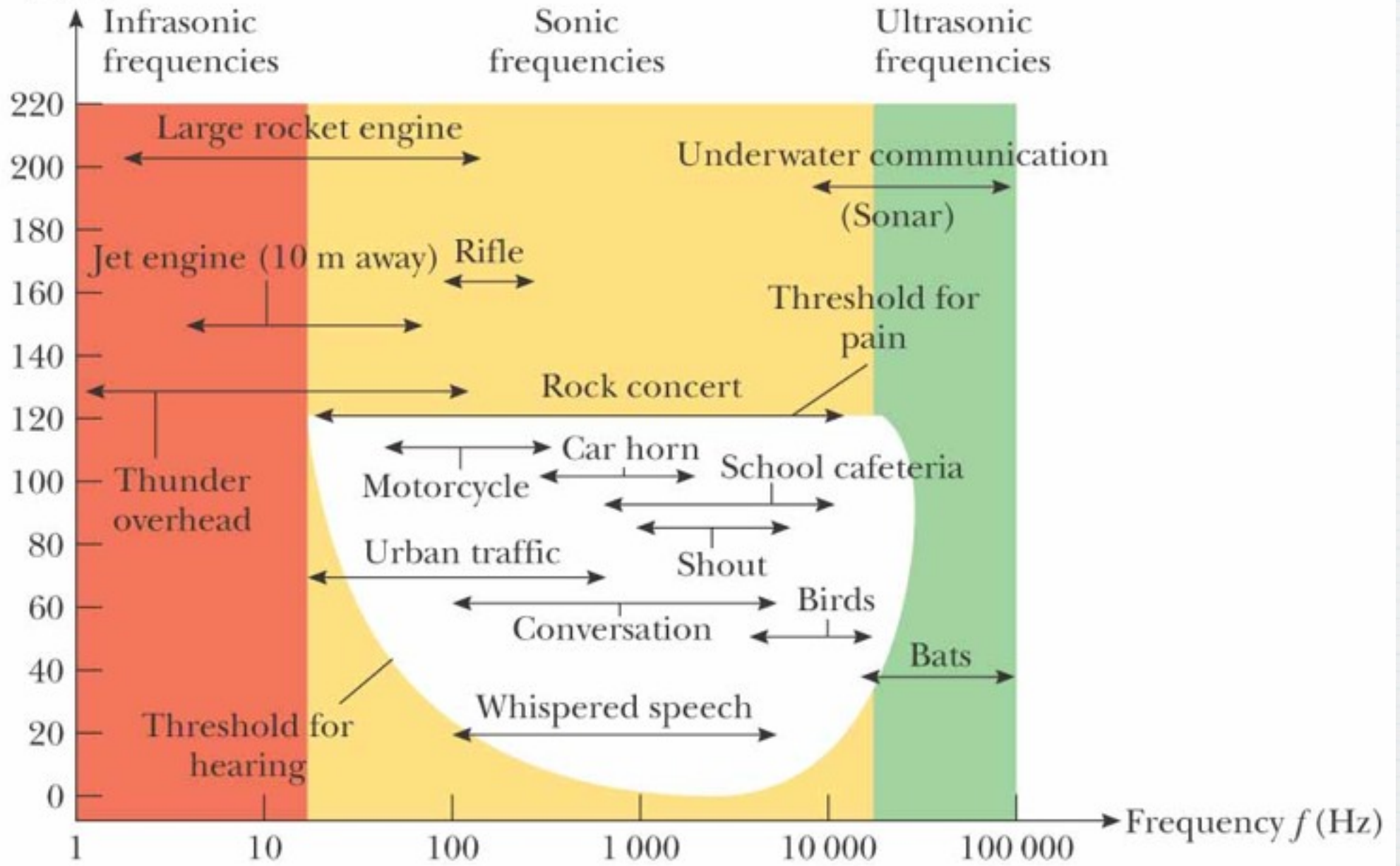
reference pressure = 20 μPa (tiny! atmosphere = 101,325 Pa)

1 Pa = 1 N/m² pressure difference would be 94 dB !!

Source of sound	RMS sound pressure	sound pressure level
	Pa	dB re 20 μ Pa
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

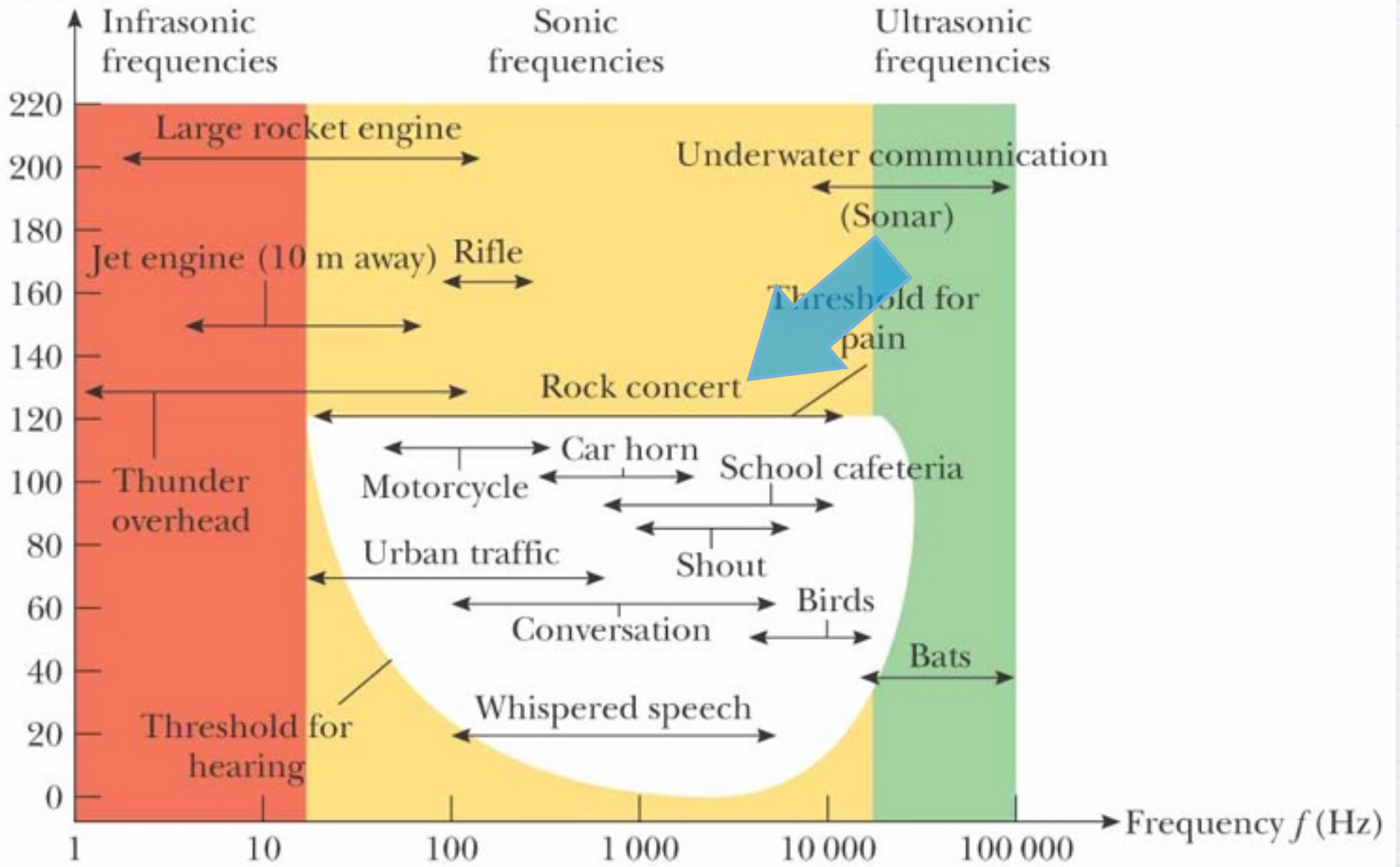
Sound level

β (dB)



Sound level

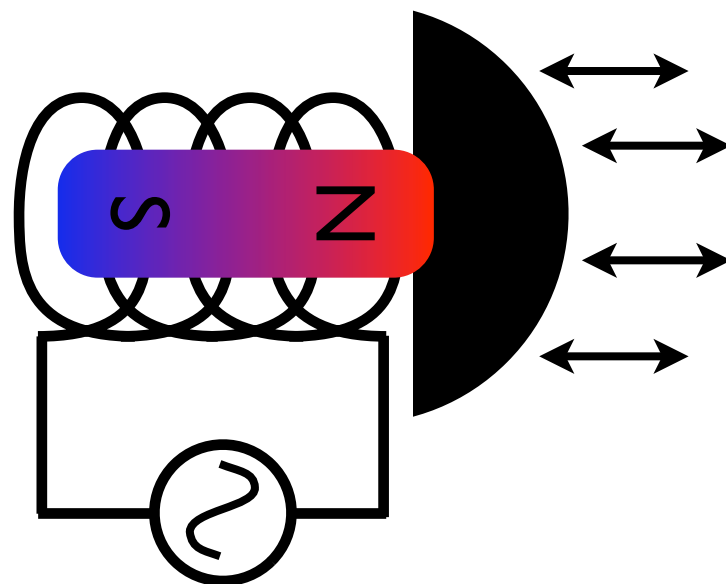
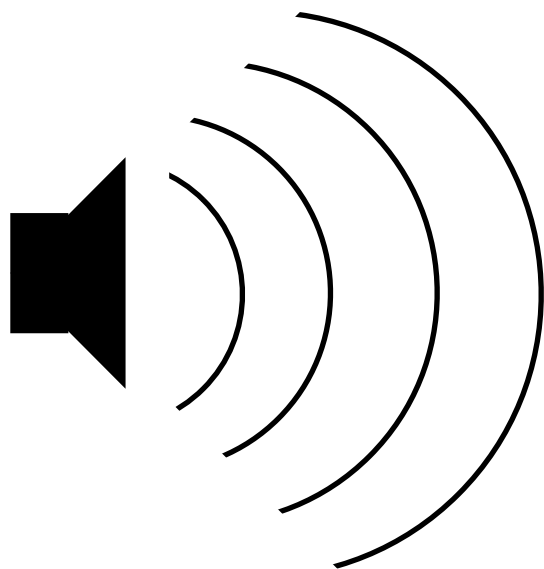
β (dB)



Speaker cone forces surrounding air to compress/rarefy

moves by induction!

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

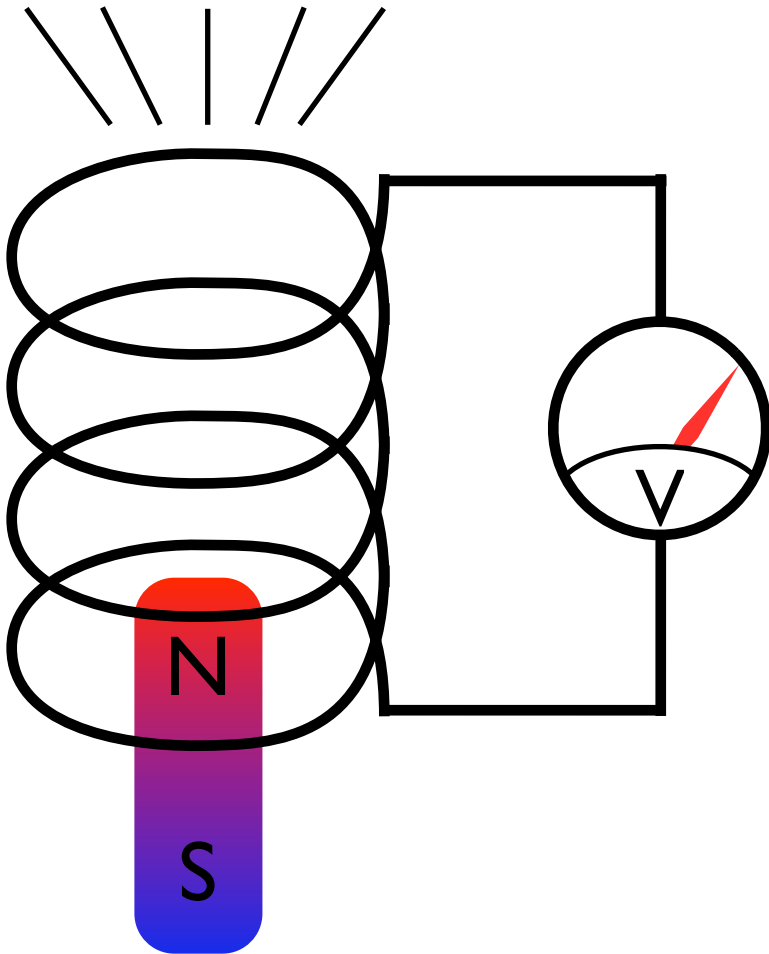


(can use the opposite for a microphone ...)

sound in - vibrates coil in magnet

time-changing flux induces voltage

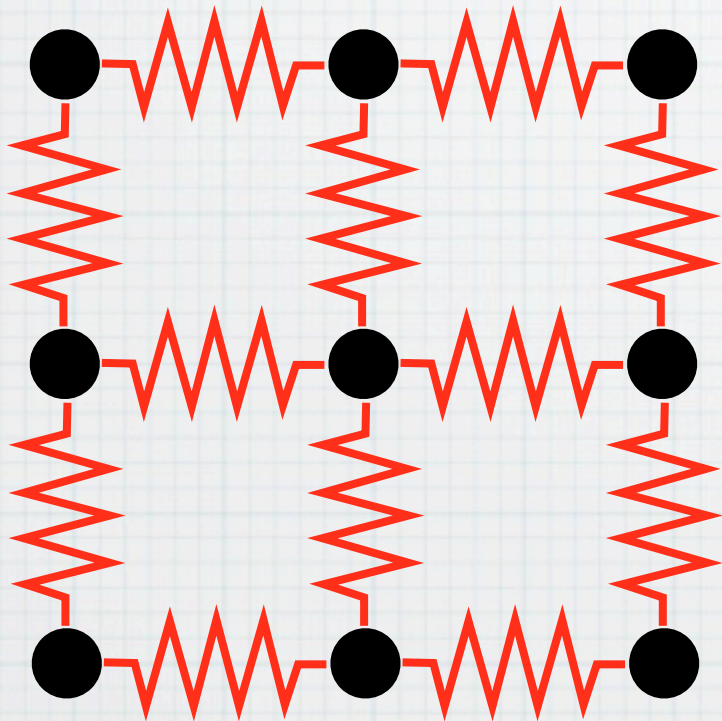
voltage can be amplified, used to drive a speaker!



How to transmit sound in a medium?

must have a degree of **ELASTICITY**

i.e., a restoring force



Solids

bonds are like springs
atoms respond to each other's motions
speed of sound \leftrightarrow crystal structure
bonding

bond strength \leftrightarrow 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:

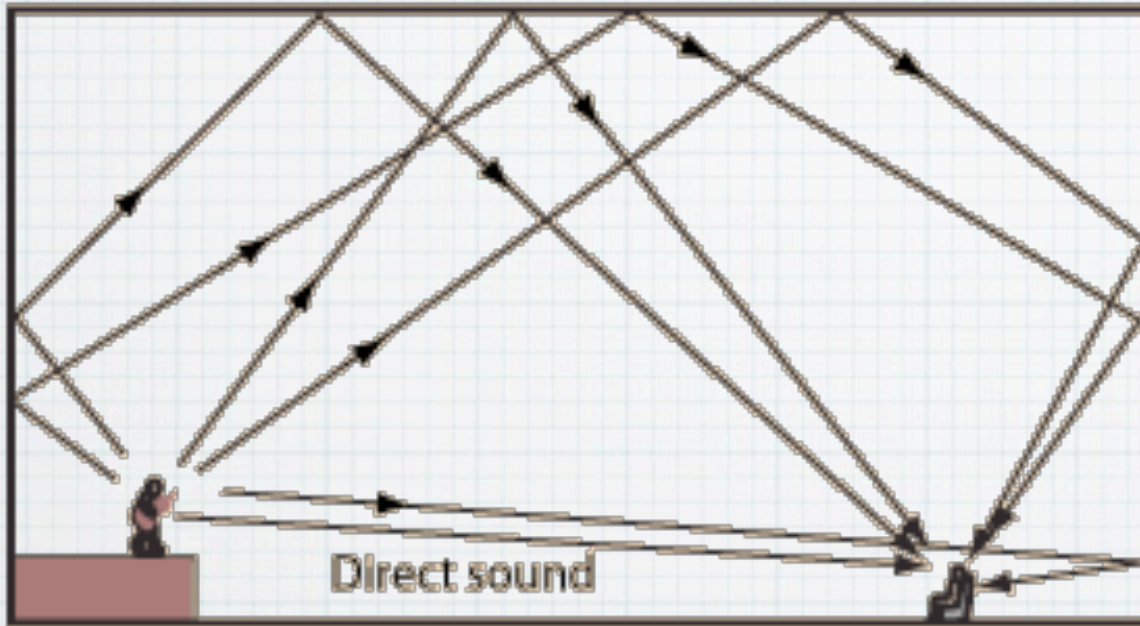
$$\delta t_{\text{sound}} = \frac{\delta x}{340 \text{ m/s}} \approx 1.5 \text{ sec}$$

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.

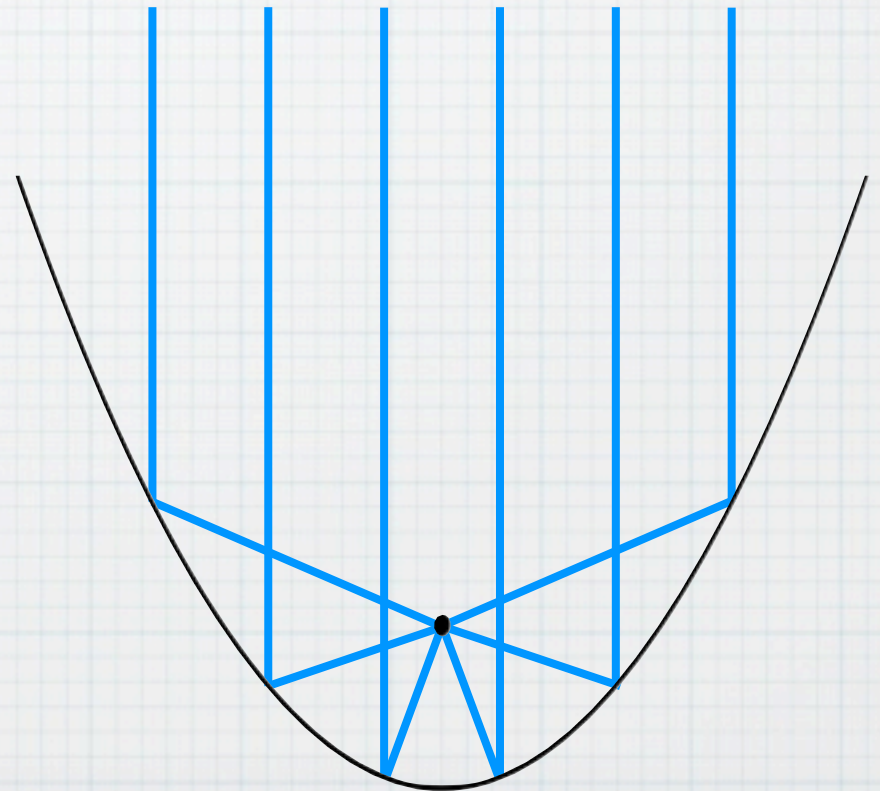
For good sound, this effect must be optimized

walls too reflective: reverb problems

walls too reflective: "dead" sound, low level

reflected sound = "lively" & "full" ... like in the shower

Best:
parabolic or elliptical reflector



a.k.a. “whispering gallery”

parabolic or elliptical room

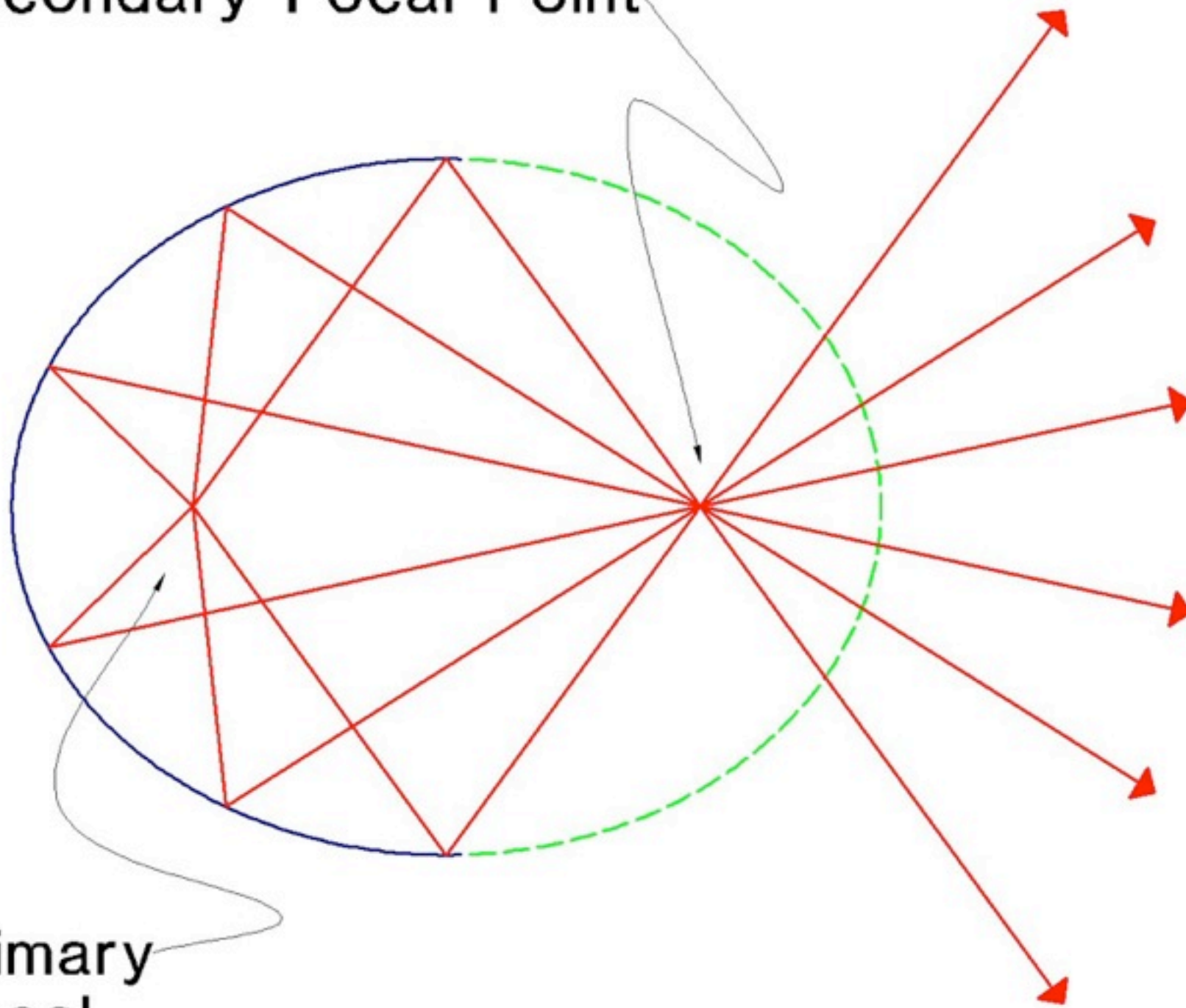
St. Paul's cathedral

London

can hear a whisper
across the room

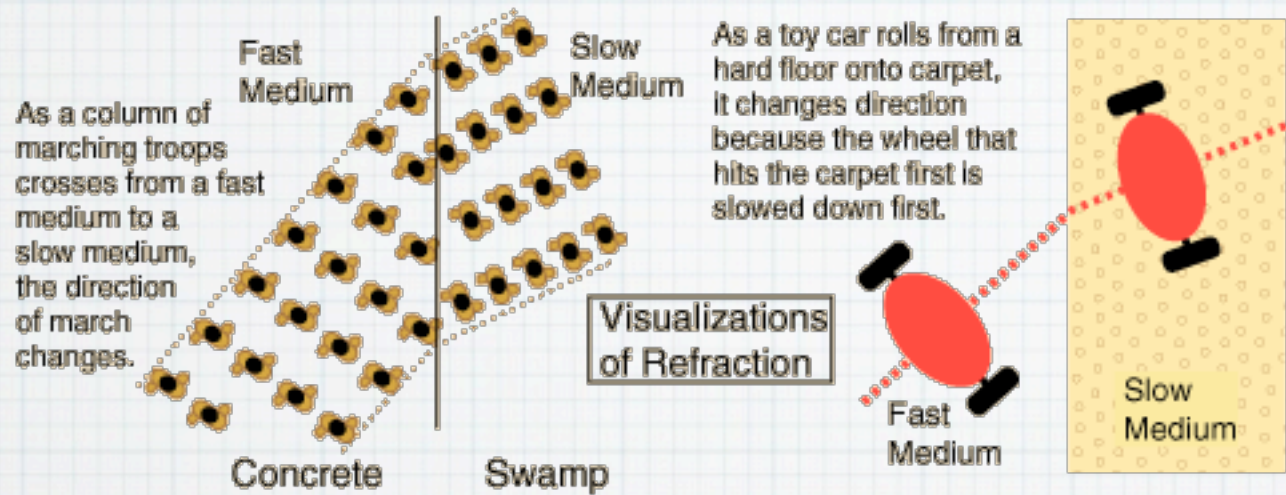


Secondary Focal Point

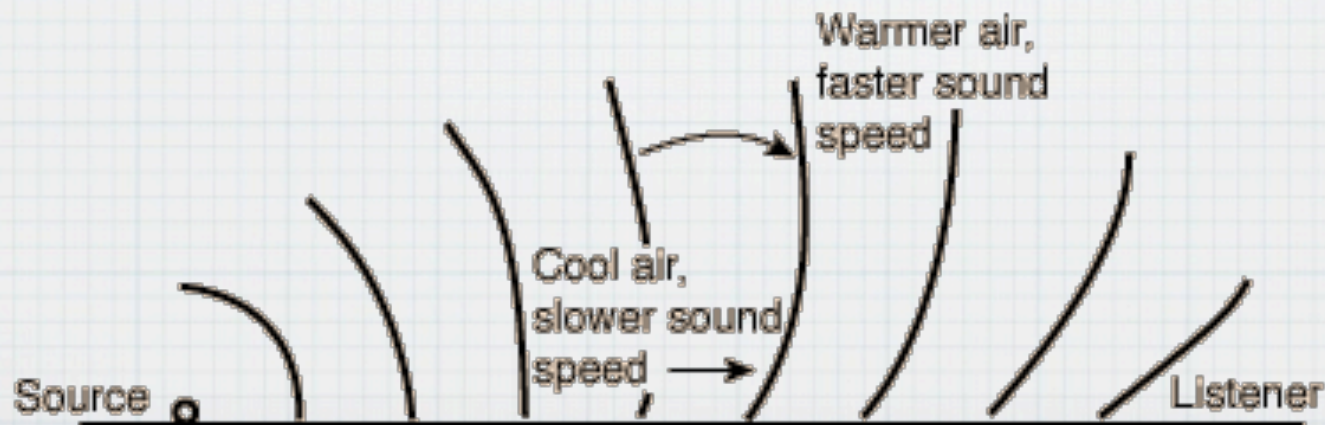


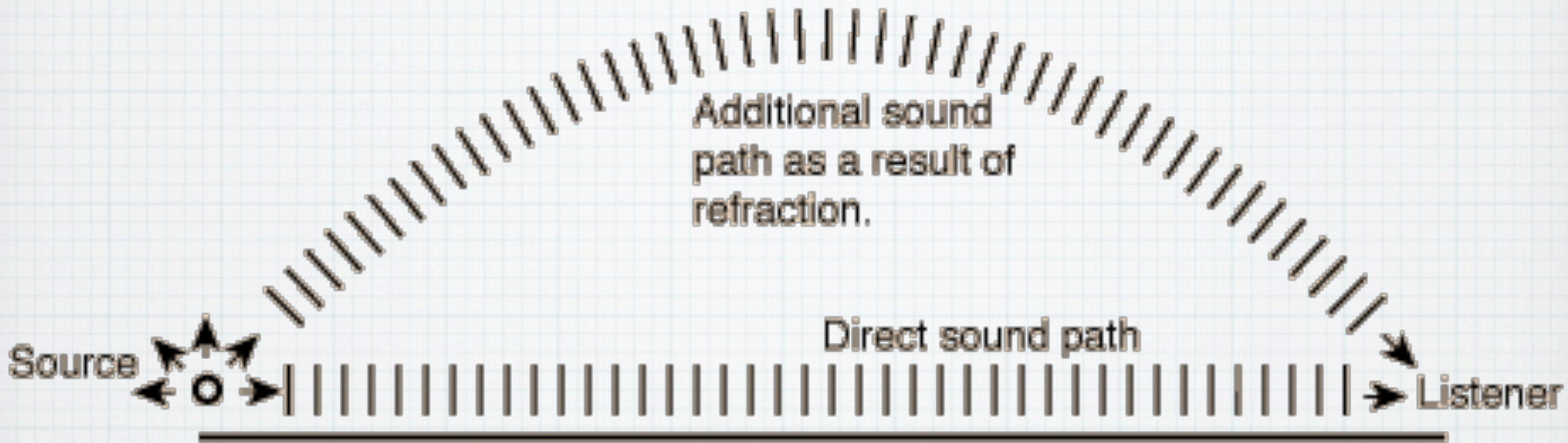
Primary
Focal
Point

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

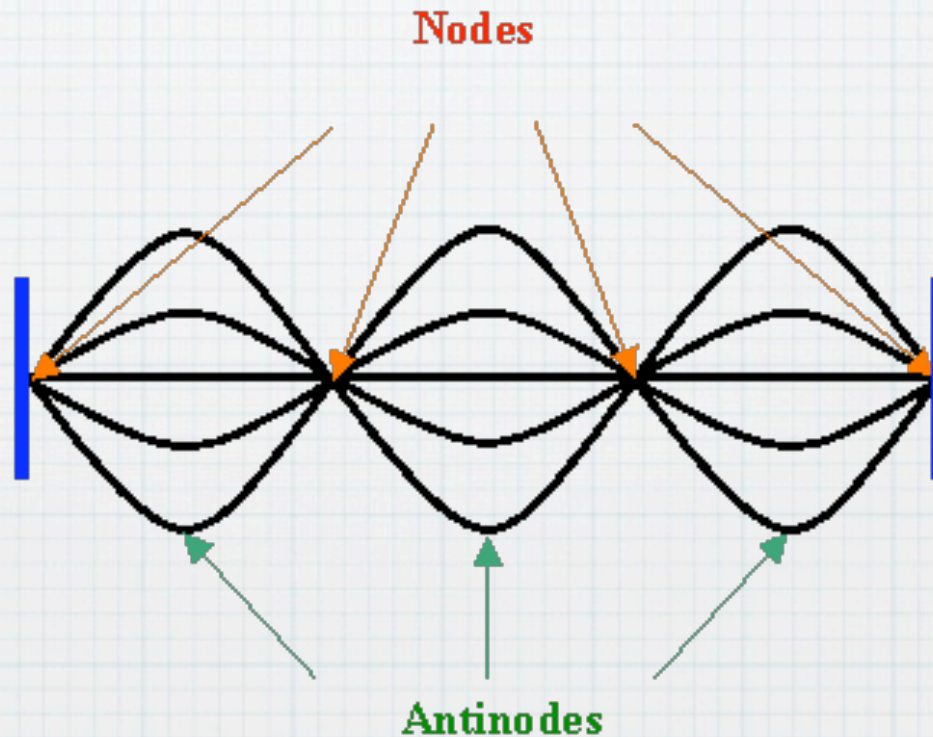
objects have characteristic vibration modes - unique sounds

composition
shape
density
elasticity

<- depends on all these

e.g., string

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



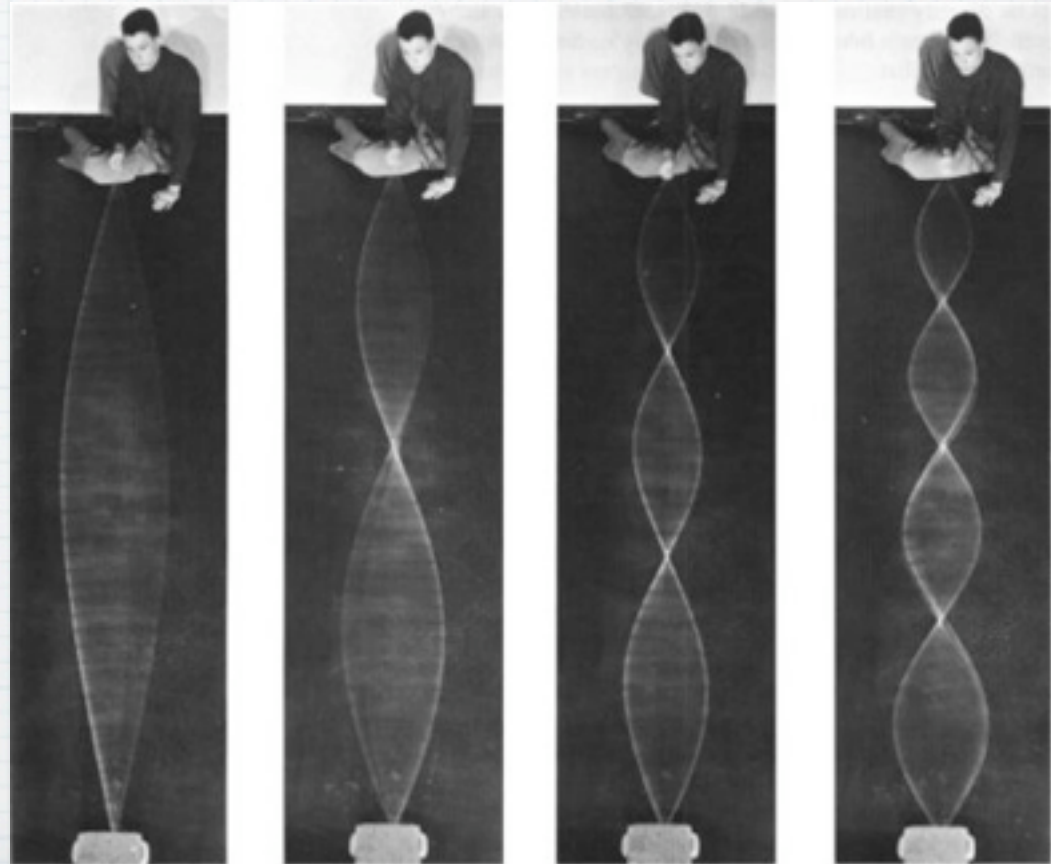
geometry dictates allowed frequencies
fundamental + overtones (harmonics)

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

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

guitar strings: frets change L

what is the velocity v ???



Velocity is related to:

T = Tension (force)

μ = mass per unit length (weight)

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

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

string fixed at both ends

change L via FRETTS

tune via TENSION

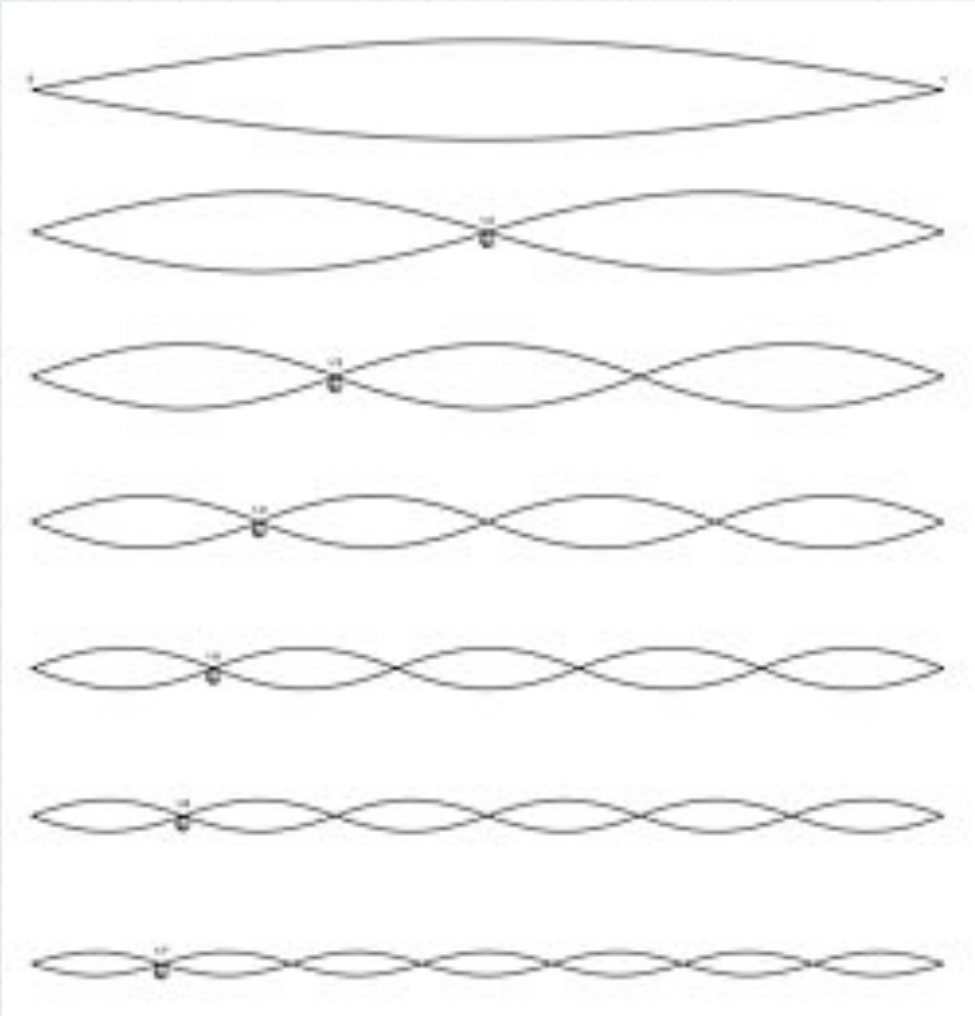
range via MASS

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 ($n=4$)

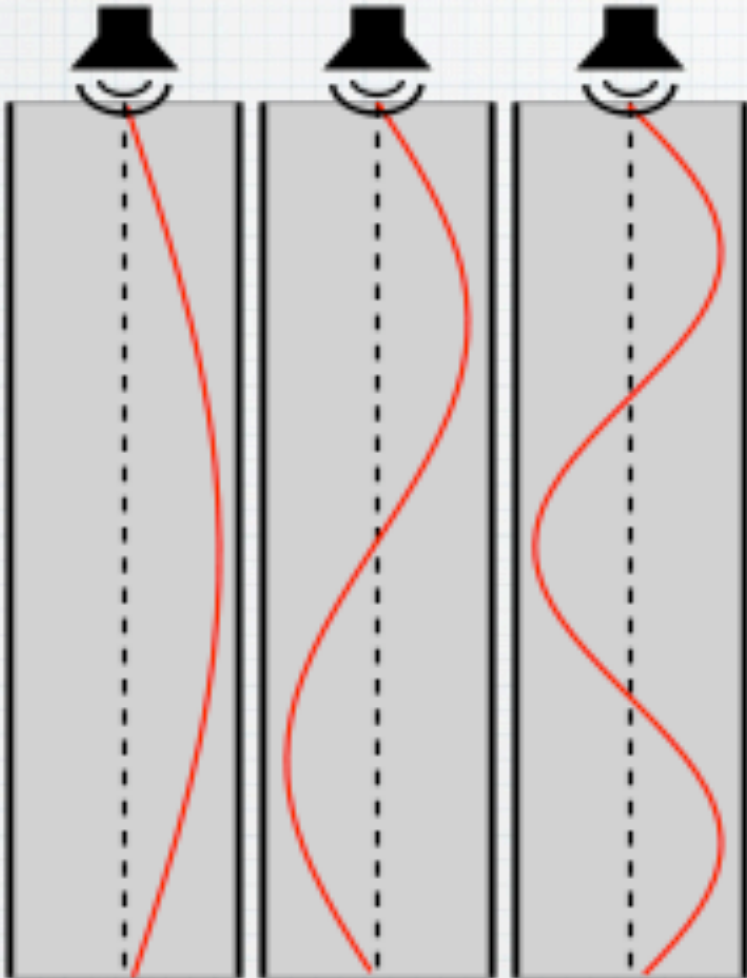
...

...

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

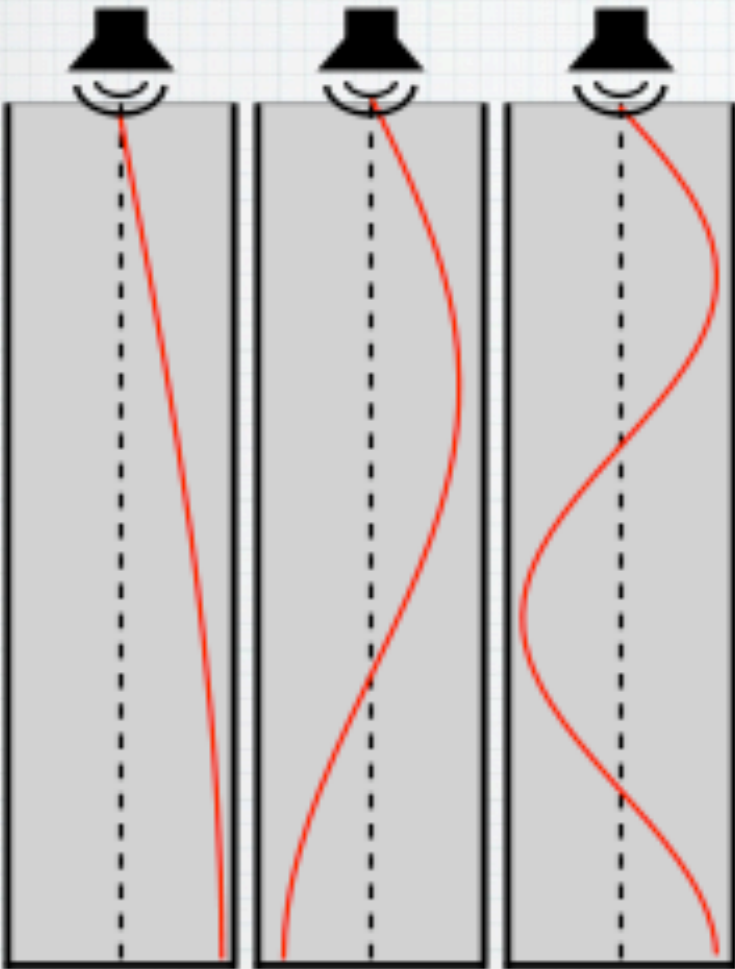
zero pressure difference

math? same as for the string

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

$v = 340 \text{ m/s}$ 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

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

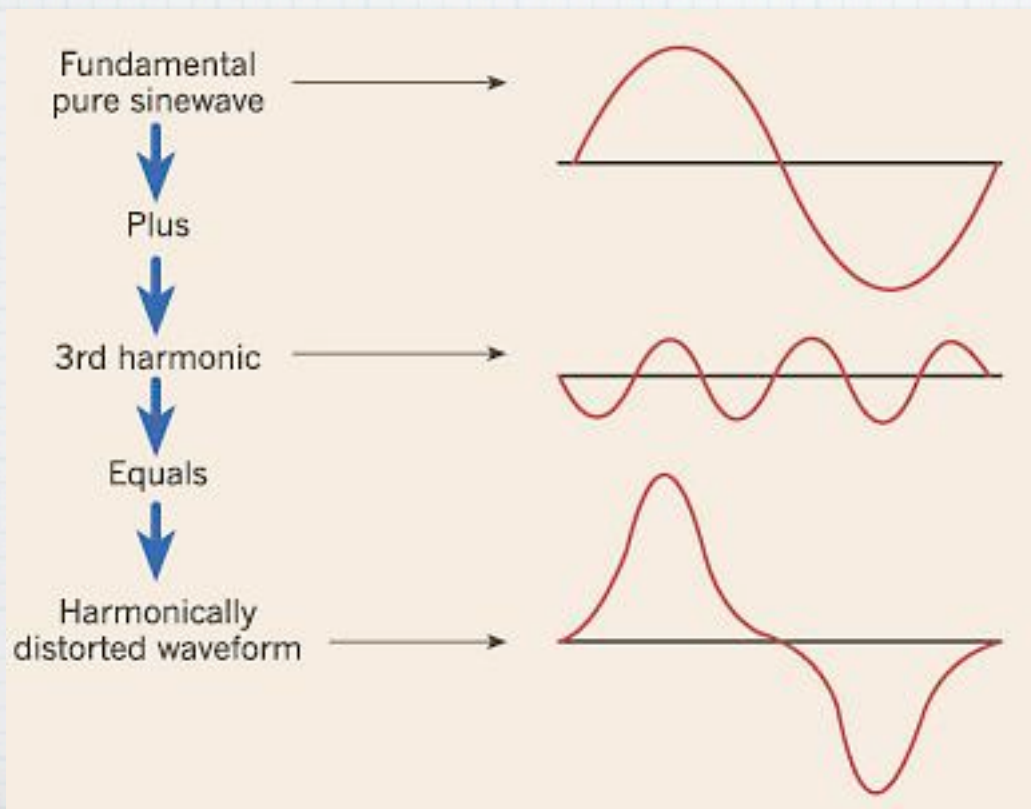
(now n must be ODD for waves to fit)

OPEN - OPEN pipes : like strings, all harmonics present

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

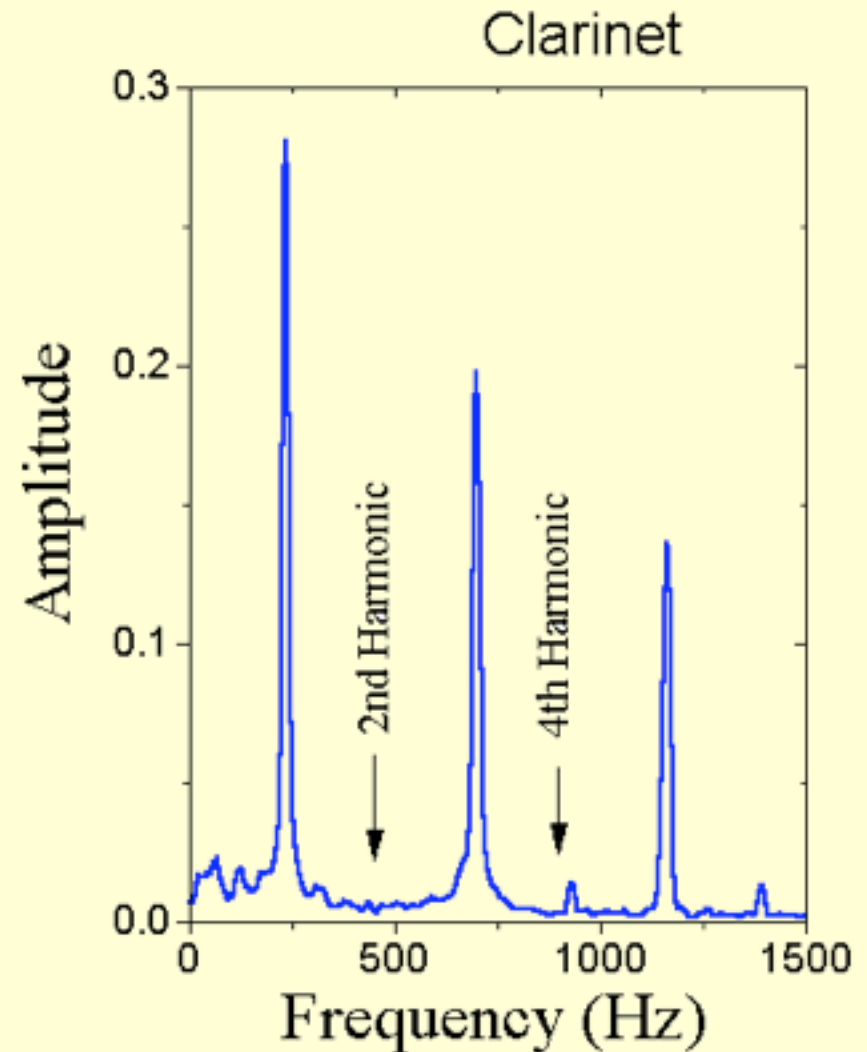
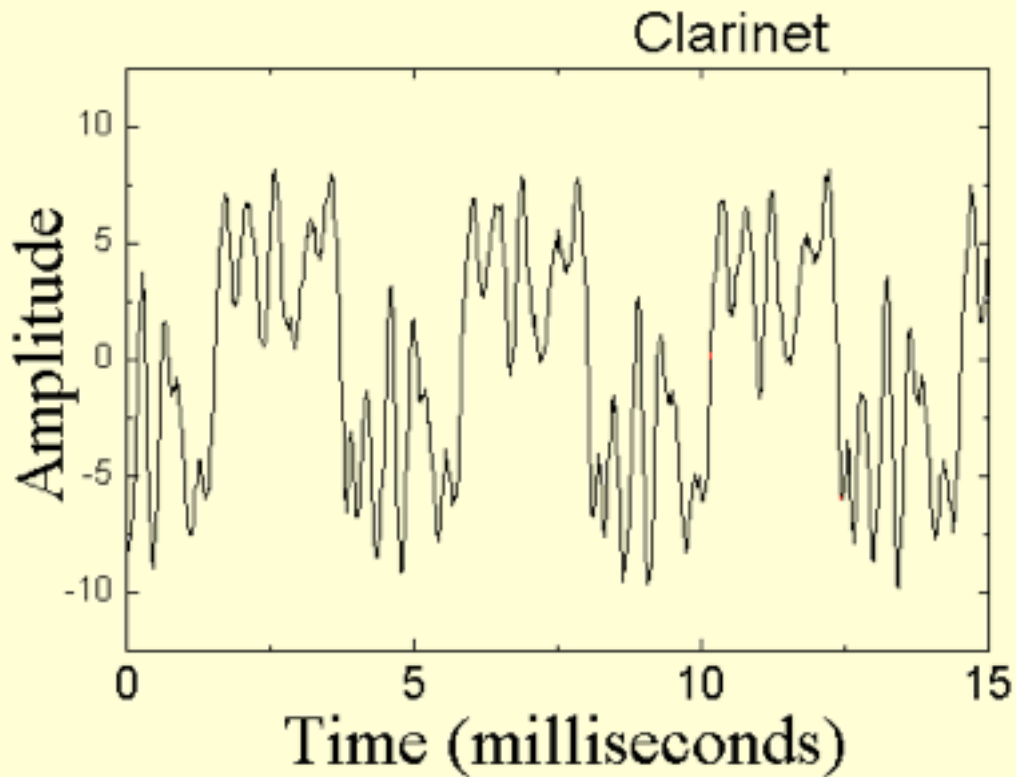
presence (or absence) of harmonics changes "tone"

waveform = sum of fundamental + harmonics!

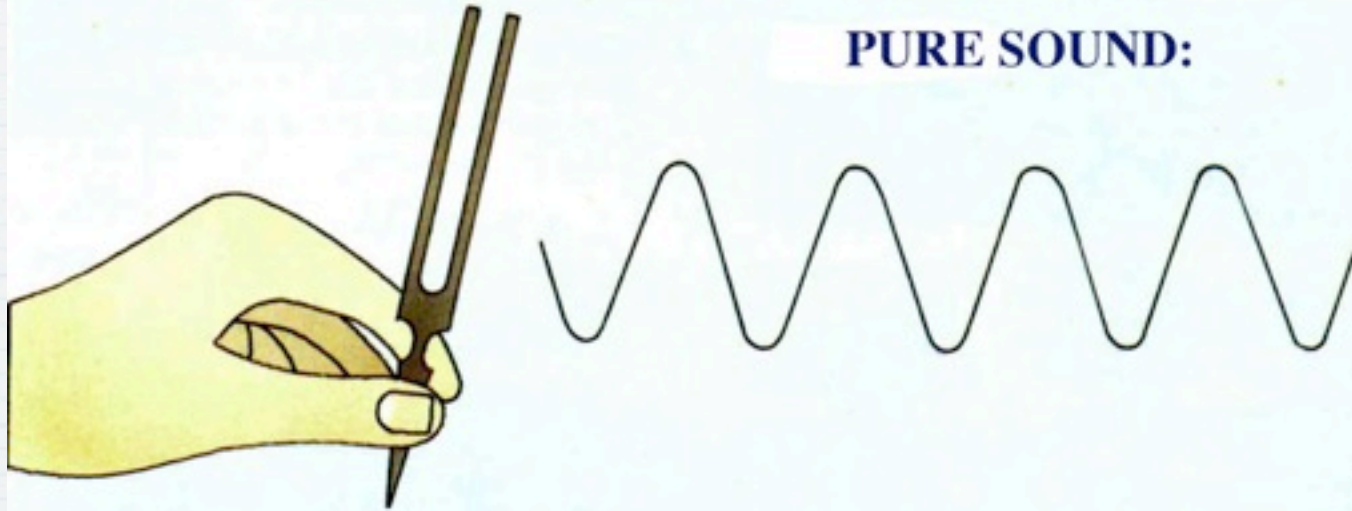


A clarinet is **CLOSED** on one end
only odd harmonics

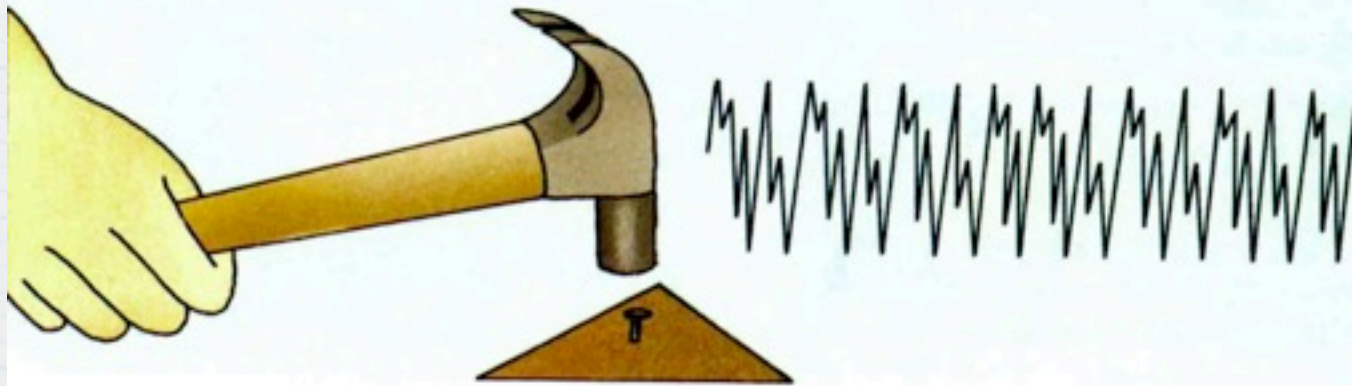
“warm” & “dark” compared to saxophone - all harmonics



PURE SOUND:



NOISE:

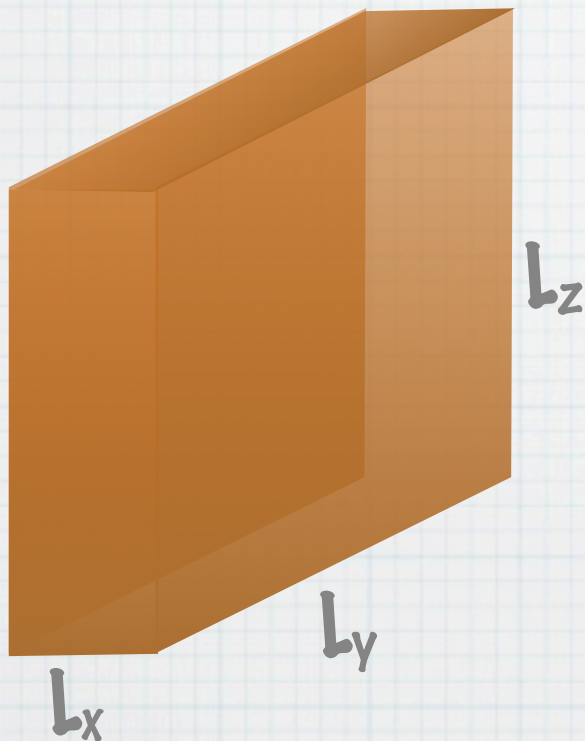


Pitch and frequency

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	2x	2/1 = 2x (also 2/2 = 1x)
3	Perfect Fifth	E ₃ - 330 Hz	3x	3/2 = 1.5x
4	Octave	A ₄ - 440 Hz	4x	4/2 = 2x (also 1x)
5	Major Third	C# ₄ - 550 Hz	5x	5/4 = 1.25x
6	Perfect Fifth	E ₄ - 660 Hz	6x	6/4 = 1.5x
7	"Perfect Seventh"	? ₄ - 770 Hz	7x	7/4 = 1.75x
8	Octave	A ₅ - 880 Hz	8x	8/4 = 2x (also 1x)

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

fit wavelengths in each dimension



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

l, m, n are integers

Aluminum : $v = 4900\text{m/s}$

say, $1 \times 1 \times 0.5\text{cm}$ block

$$f = 3500 \text{ Hz} = A_7$$

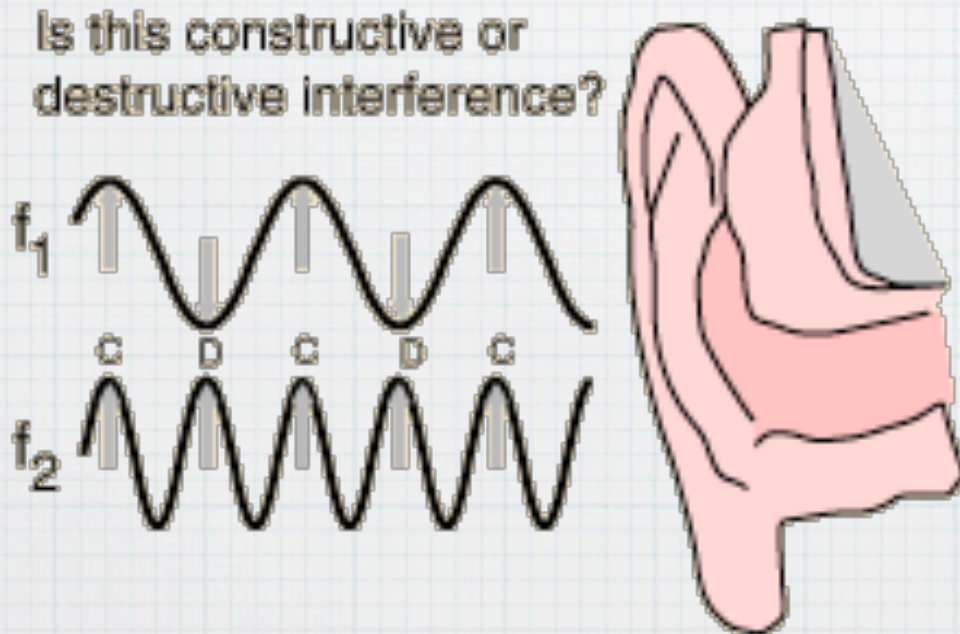
(3 octaves above middle C)

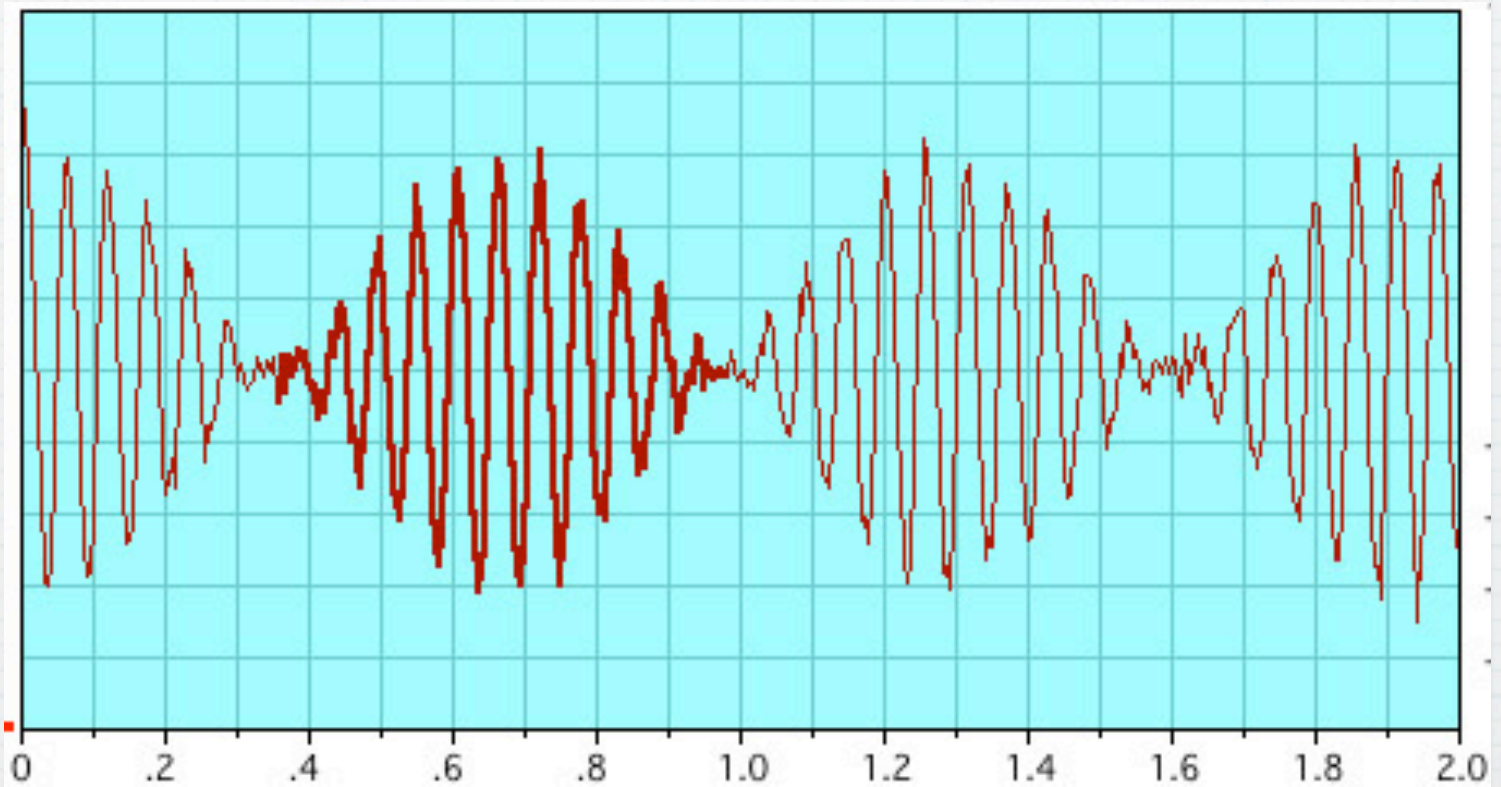
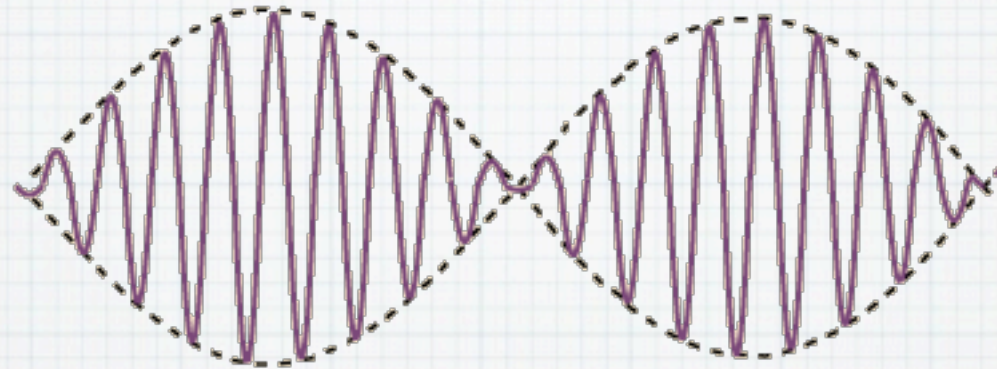
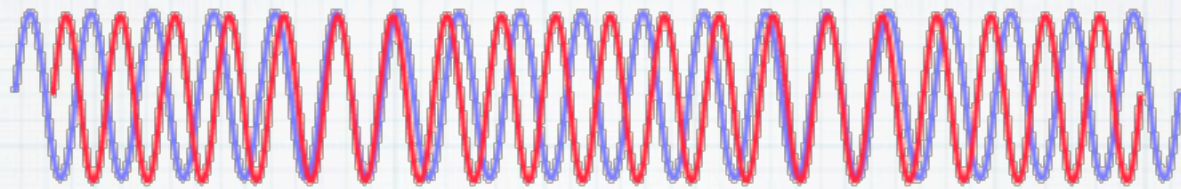
Interference

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.





beats

beats

**sweep
one
generator**

**sweep
one
generator**