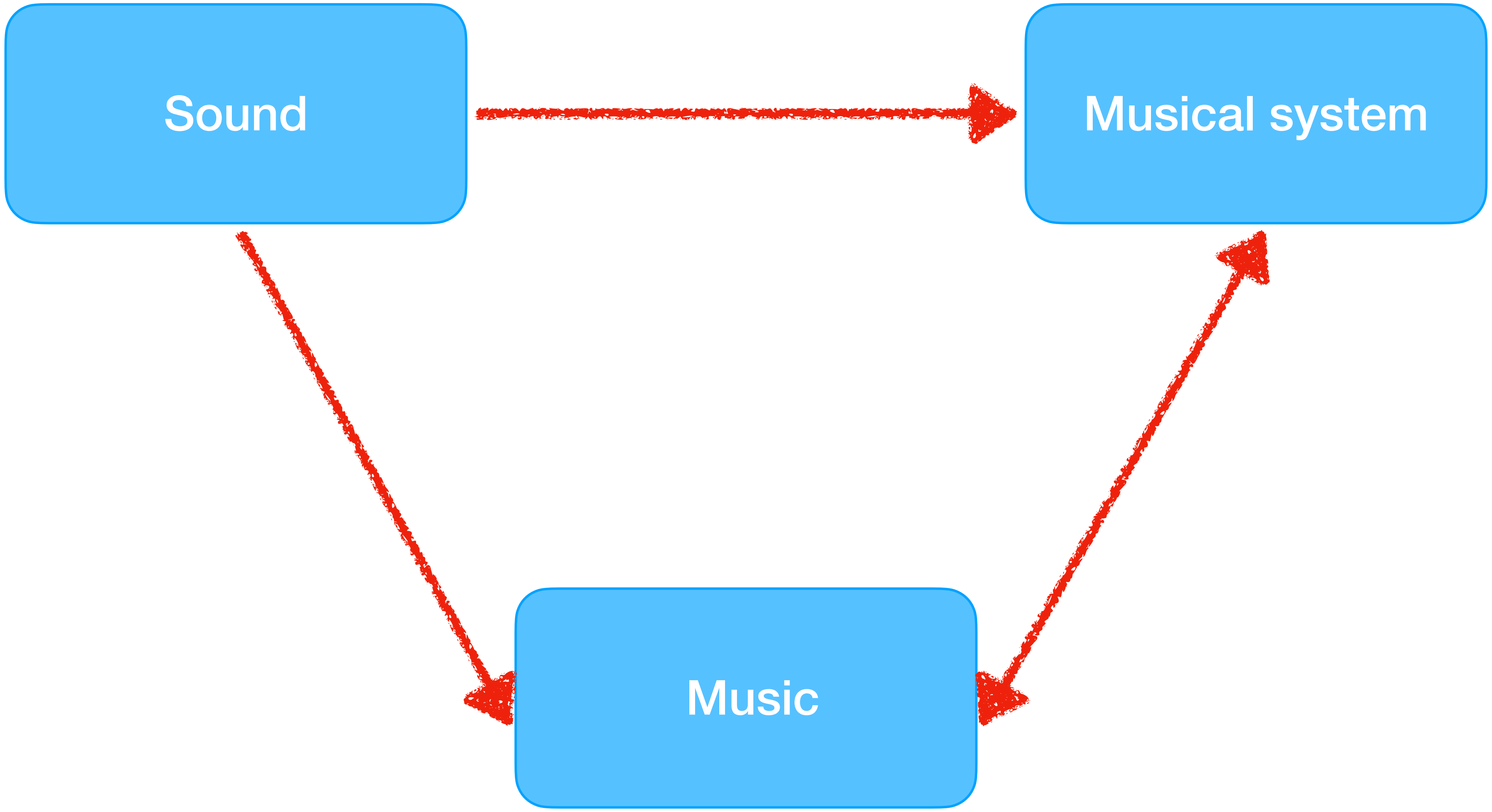
CARMINE-EMANUELE CELLA

INTRODUCTION TO SOUND AND PERCEPTION

MUSIC 159

What is sound?

Is sound cultural?



WAVES

So.. what is sound?

Sound is a **pressure wave** which is created by a vibrating object

These vibrations set particles in the surrounding medium (typical air) in vibrational motion, thus **transporting energy** through the medium

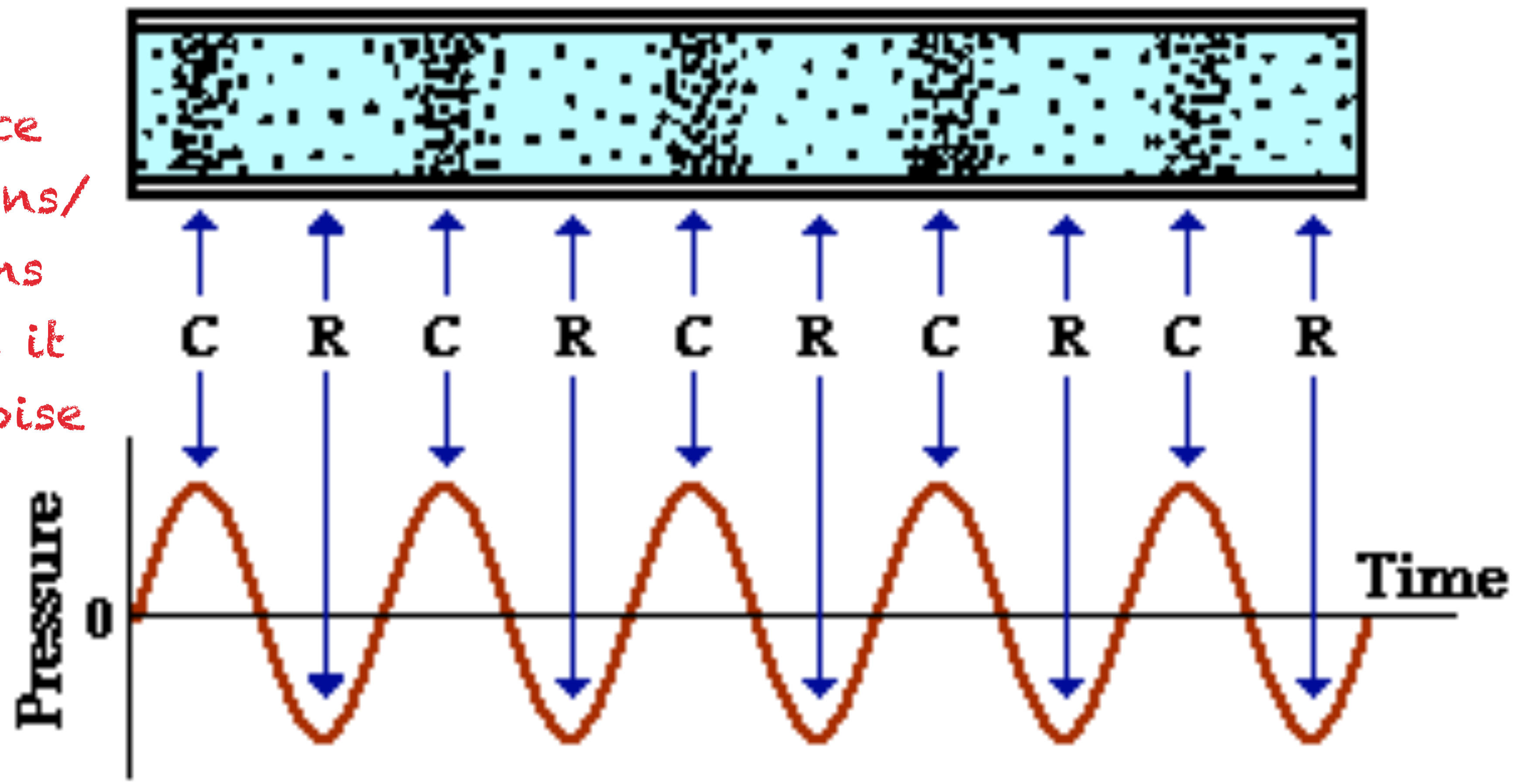
Since the particles are moving in parallel direction to the wave movement, the sound wave is referred to as a **longitudinal** wave

The result of longitudinal waves is the creation of **compressions (C)** and **rarefactions (R)** within the air

SOUND IS A PRESSURE WAVE

The alternating configuration of C and R of particles is described by the graph of a **sine wave** (C~crests, R~troughs)

If the sequence of compressions/ decompressions is not regular, it produces a noise

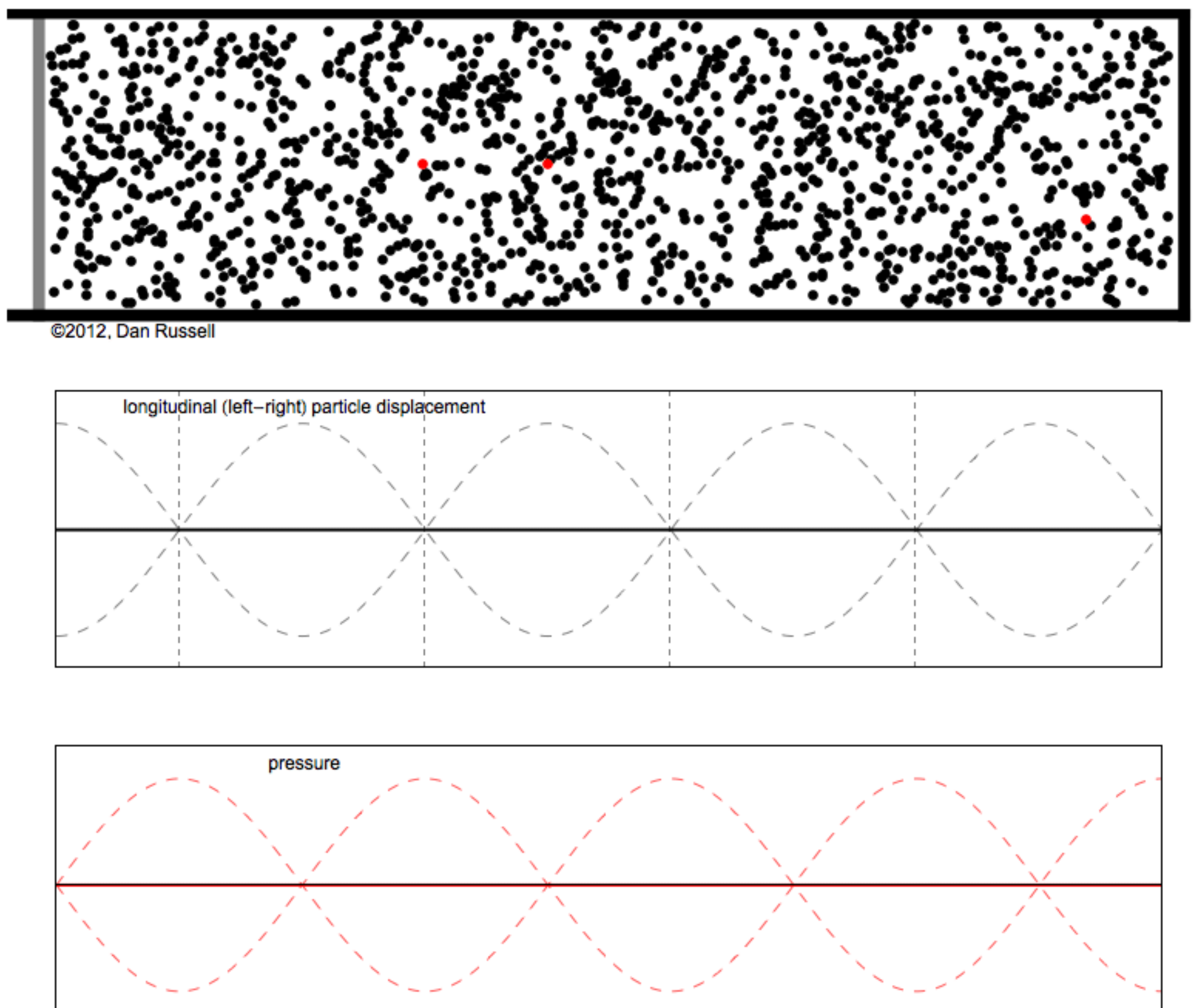


NOTE: "C" stands for compression and "R" stands for rarefaction

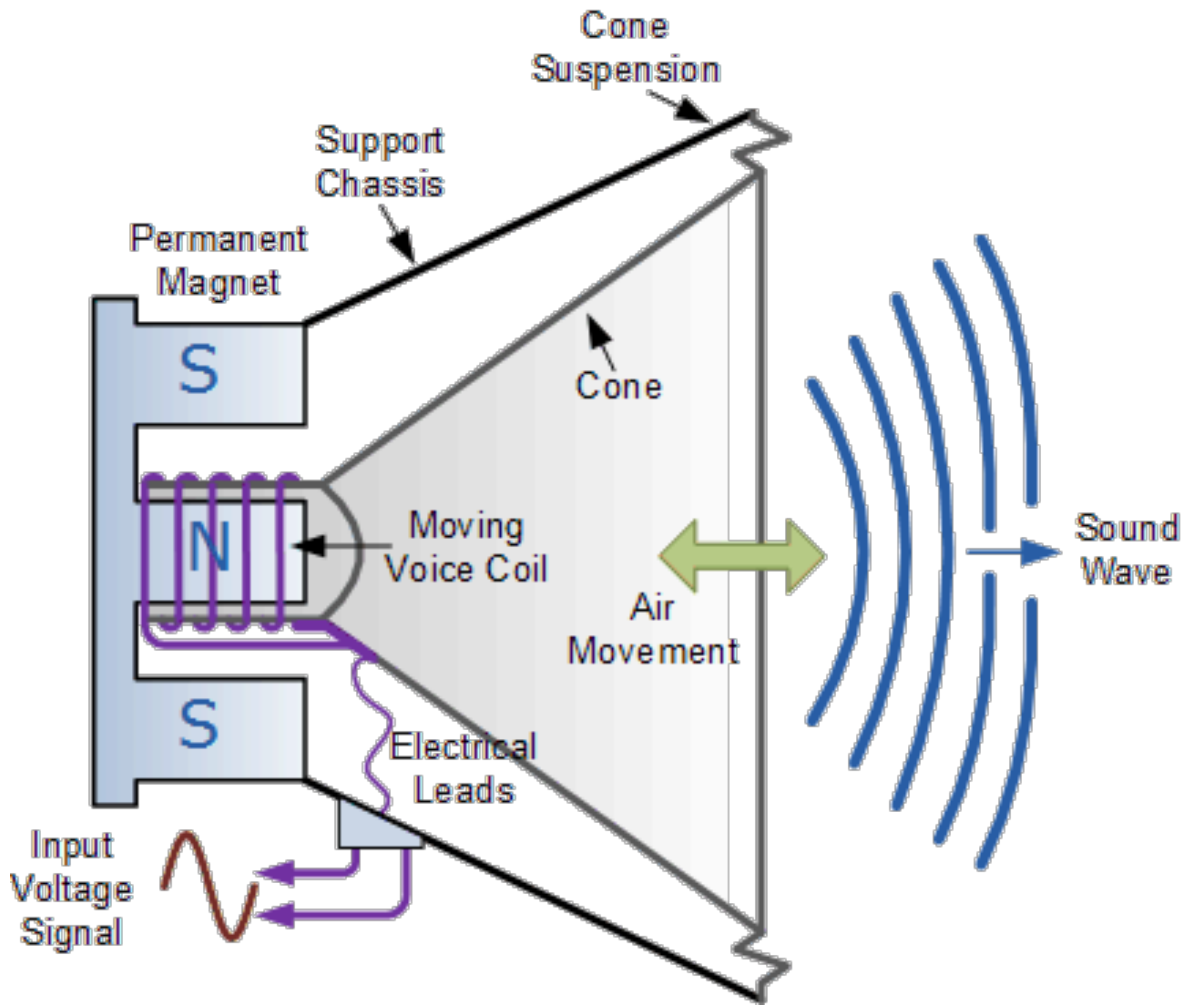
http://www.cs.toronto.edu/~gpenn/csc401/soundASR.pdf

SOUND IS A PRESSURE WAVE

The particles **do not move** down the way with the wave but oscillate back and forth around their individual equilibrium position



Question: can we generate sound pressure with a loudspeaker?



AMPLITUDE, FREQUENCY AND WAVELENGTH

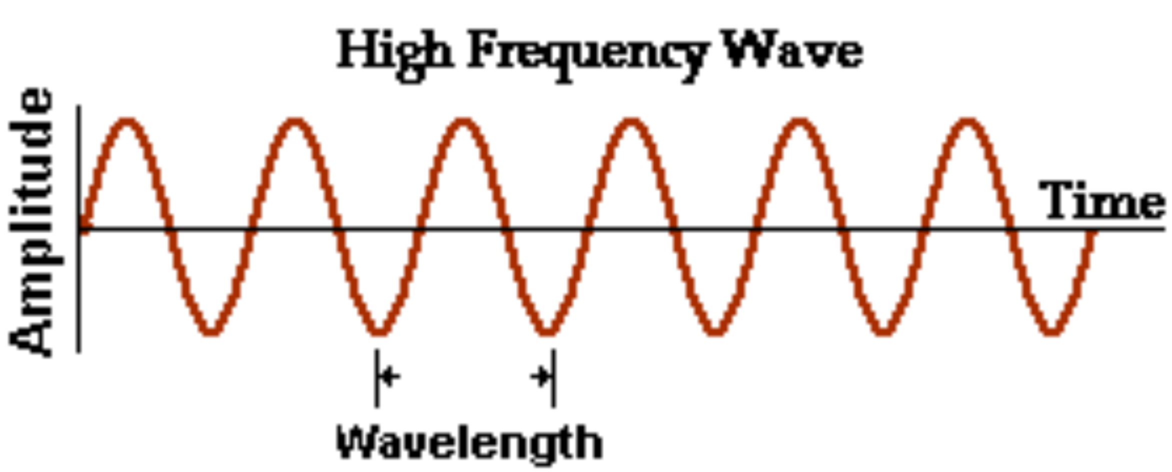
The amount of work done to generate the energy that sets the particles in motion is reflected in the degree of displacement which is measured as the **amplitude** of a sound

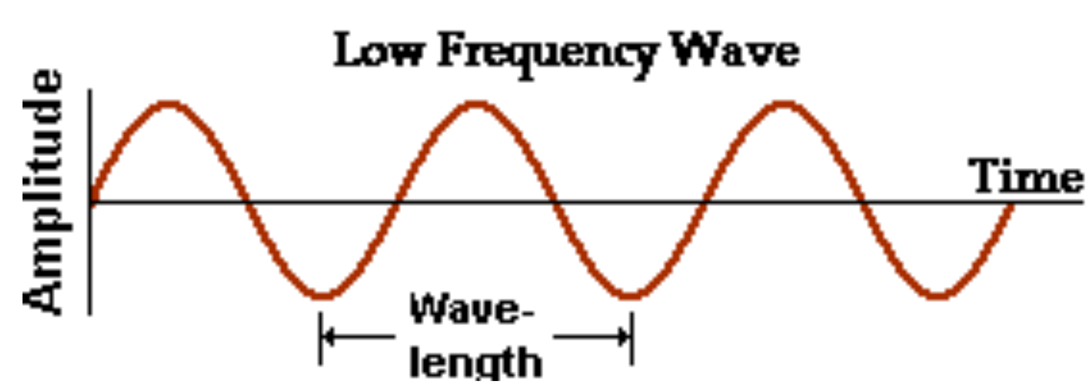
$f = 1/t$

The **frequency** f of a wave is measured as the number of complete back-and-forth vibrations of a particle of the medium per unit of time

1 Hertz (Hz) = 1 vibration/second

Depending on the medium, sound travels at some speed c which defines the **wavelength (period)** $l = c/f$





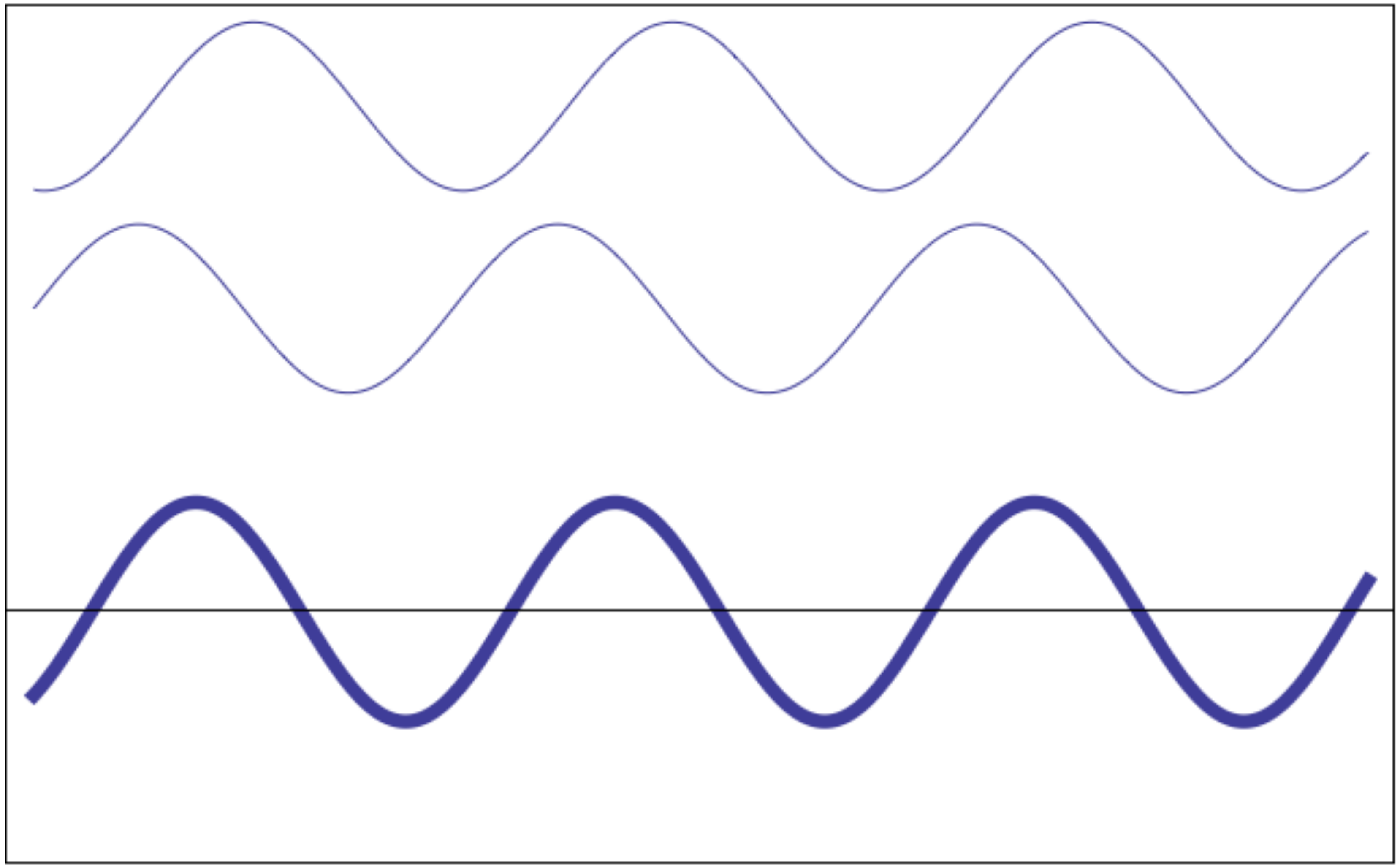
http://www.cs.toronto.edu/~gpenn/csc401/soundASR.pdf

CONSTRUCTIVE AND DESTRUCTIVE INTERFERENCE

Two waves (with the same amplitude, frequency, and wavelength) are travelling in the same direction

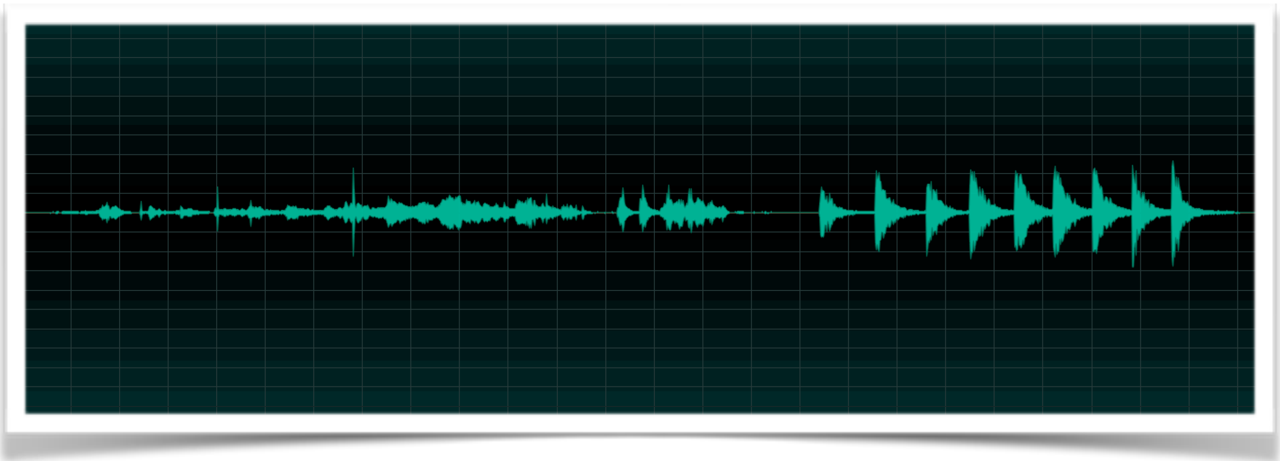
When the two waves are **in-phase** (ϕ=0), they interfere **constructively** and the result has twice the amplitude of the individual waves.

When the two waves have **opposite-phase** (ϕ=180), they interfere **destructively** and cancel each other out.

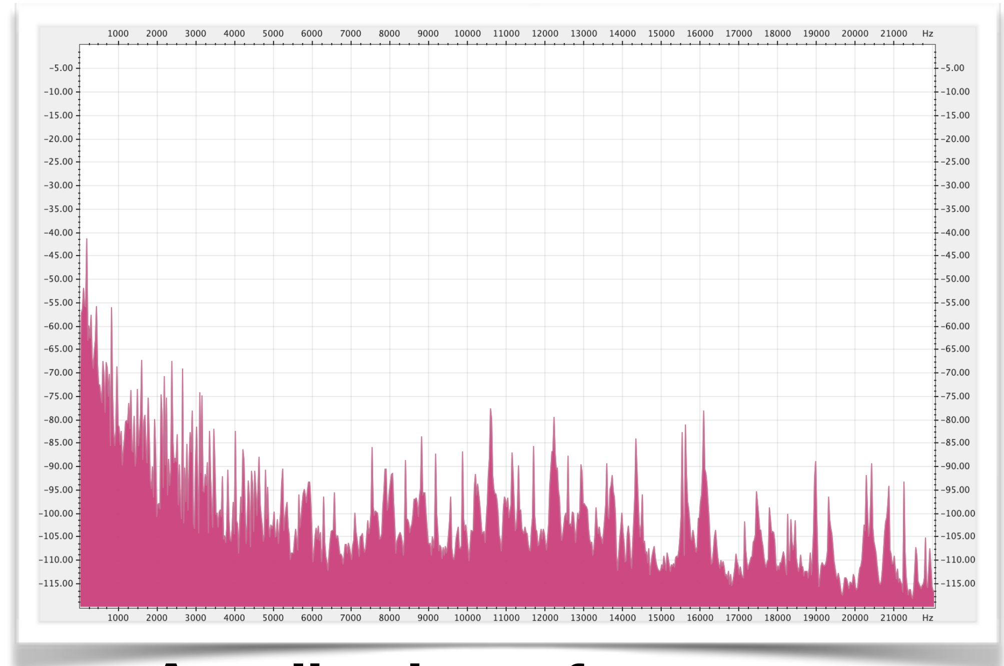


https://www.acs.psu.edu/drussell/Demos/superposition/superposition.html

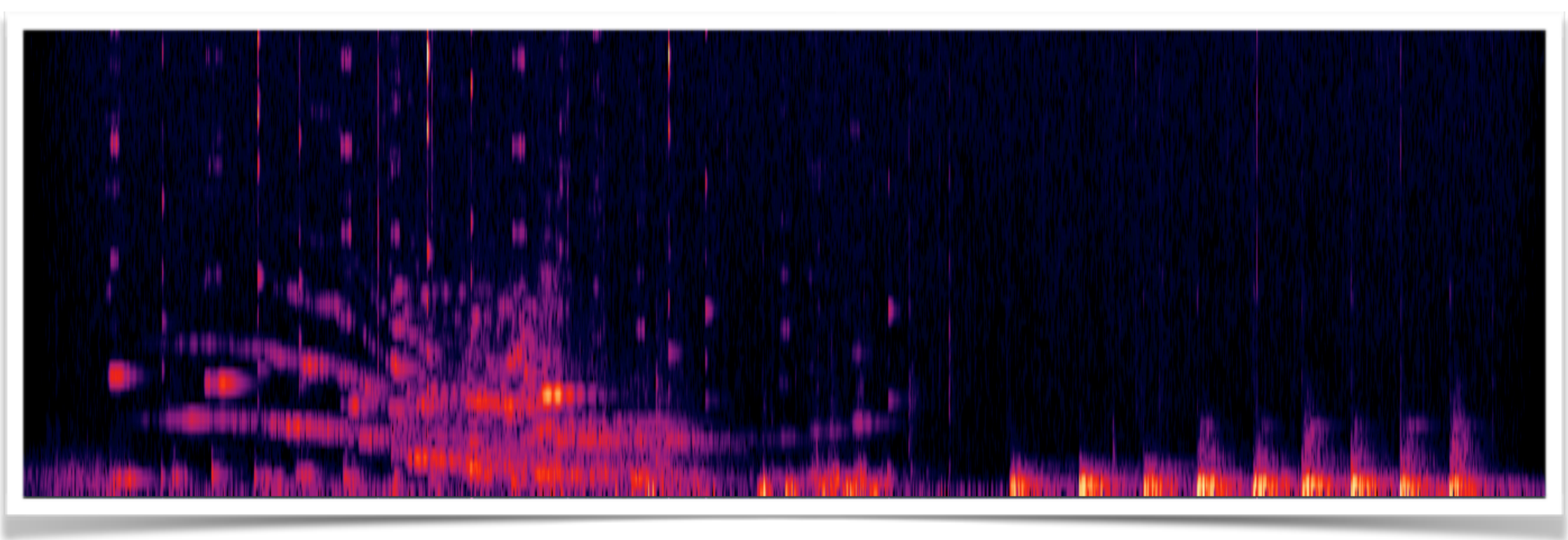
REPRESENTATIONS OF SOUND



Amplitude vs time
(waveform)



Amplitude vs frequency
(spectrum)

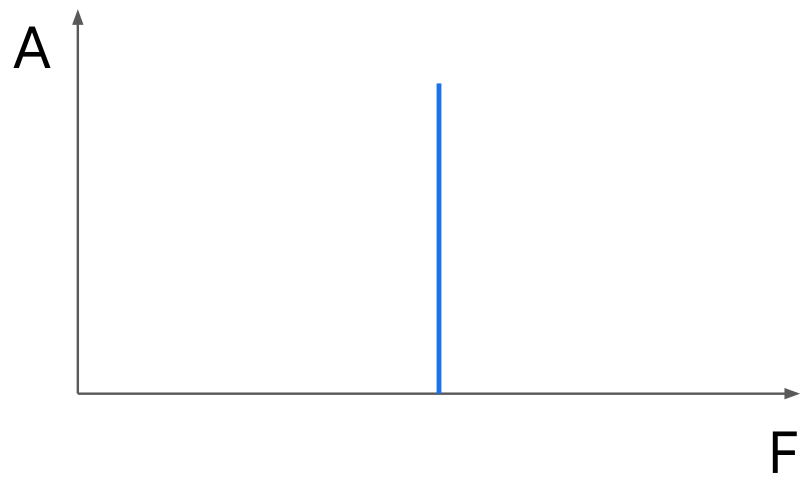


Frequency vs time
(spectrogram)

SPECTRUM OF IMPORTANT SIGNALS

Spectrum is discussed in much more details in 159! For now try to build an intuition...

Sine Wave



White Noise

PERCEPTION

MEASURING THE INTENSITY OF SOUND

The softest audible sound modulates the air pressure by around 10^{-6} Pascal (Pa). The loudest (pain inflicting) audible sound does it by 102 Pa.

Because of this wide range it is convenient to measure sound amplitude on a logarithmic scale in **Decibel (dB)**

Decibel is not a physical unit - it expresses only a ratio for comparing the intensity of two sounds: $10 \log_{10} (I/I_0)$ where I and I_0 are two intensity/power levels ($I \sim P^2$, P is sound pressure)

In order to make it interpretable as a real unit, a fixed pressure **$P_0 = 2*10^{-5}$** Pa is defined (the reference of 0dB corresponds to the threshold of hearing) and the absolute sound pressure P in Decibel is defined as:

$$20 \log_{10} (P/P_0)$$

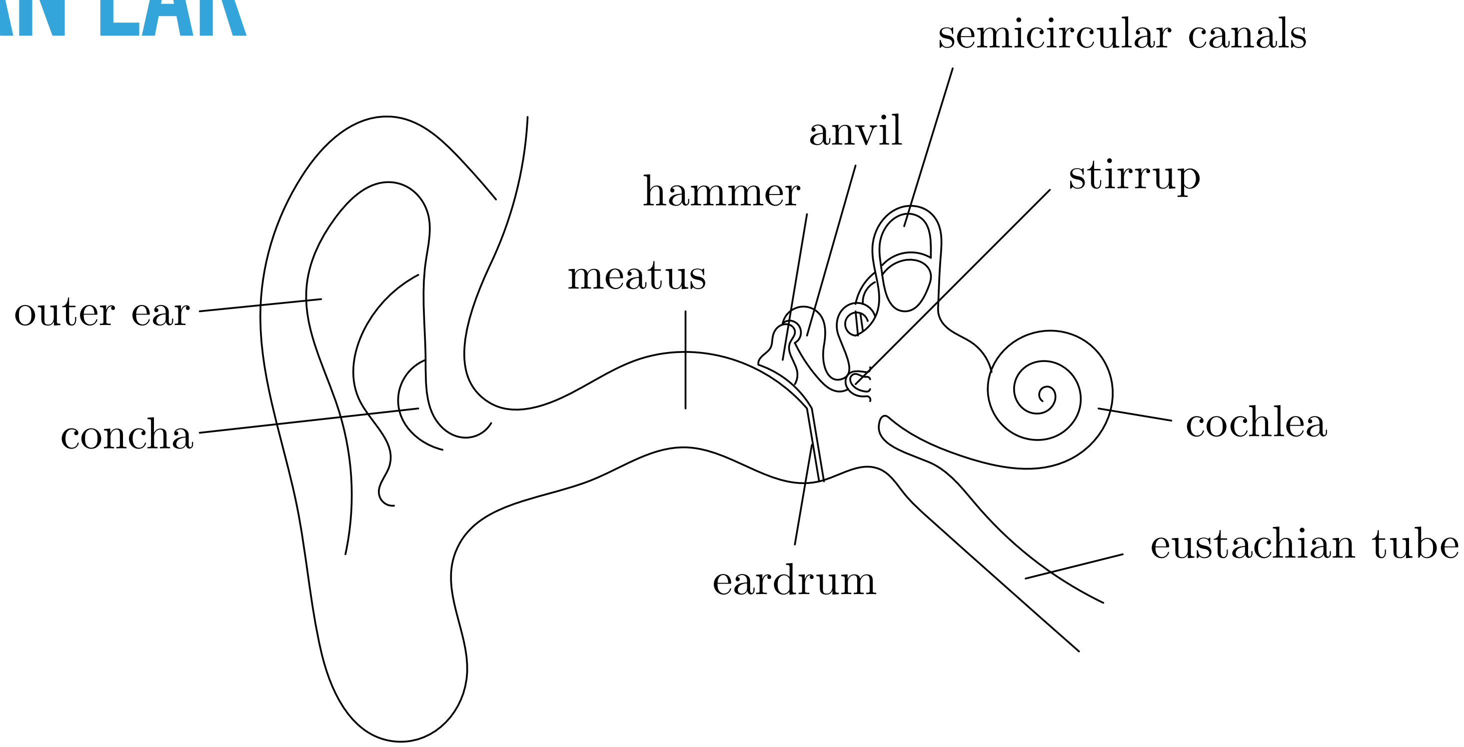
http://www.cs.toronto.edu/~gpenn/csc401/soundASR.pdf

EXAMPLES OF SOUND LEVELS IN DECIBEL

Threshold of hearing	0 dB	softest audible 1000 Hz sound	6 dB
quiet living room	20 dB	soft whispering	25 dB
refrigerator	40 dB	soft talking	50 dB
normal conversation	60 dB	busy city street noise	70 dB
passing motorcycle	90 dB	somebody shouting	100 dB
pneumatic drill	100 dB	helicopter	110 dB
loud rock concert	110 dB	air raid siren	130 dB
pain threshold	120 dB	gunshot	140 dB
rocket launch	180 dB	Instant perforation of eardrum	160 dB

http://www.cs.toronto.edu/~gpenn/csc401/soundASR.pdf

THE HUMAN EAR

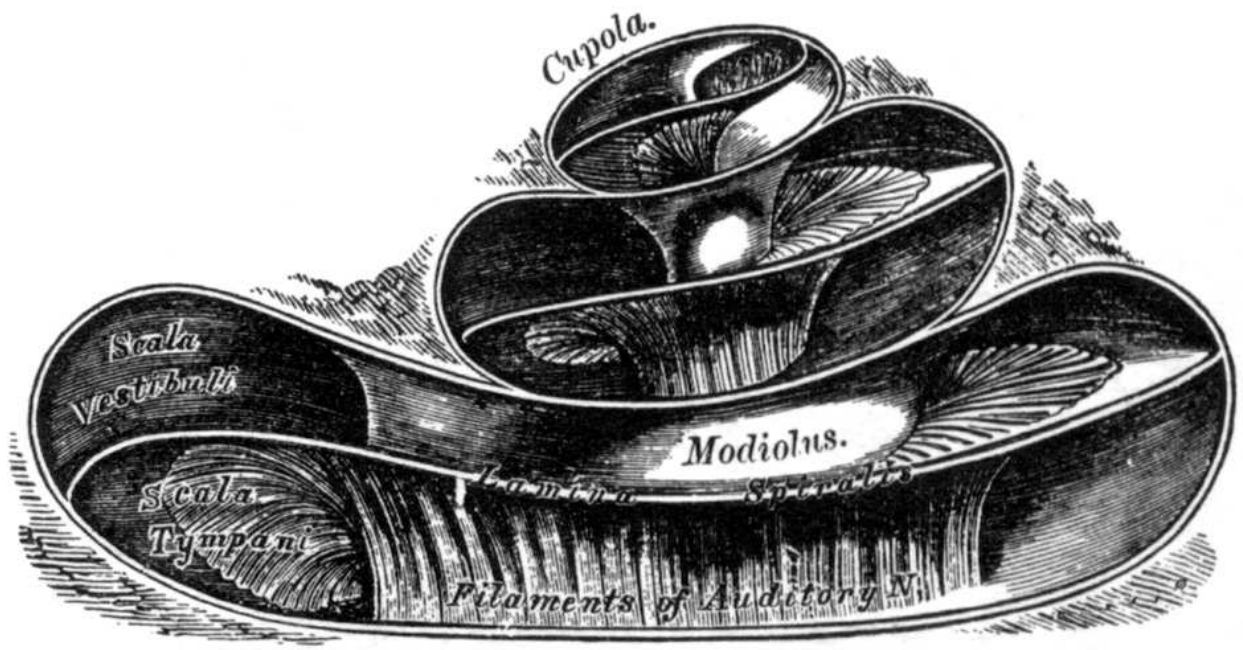


The ear is divided into three parts, called the **outer** ear, the **middle** ear or *tympanum* and the **inner** ear or *labyrinth*.

The ear drum divides the outer ear from the tympanum, which is also filled with air. The tympanum is connected to three very small bones which transmit the movement of the ear drum to the inner ear.

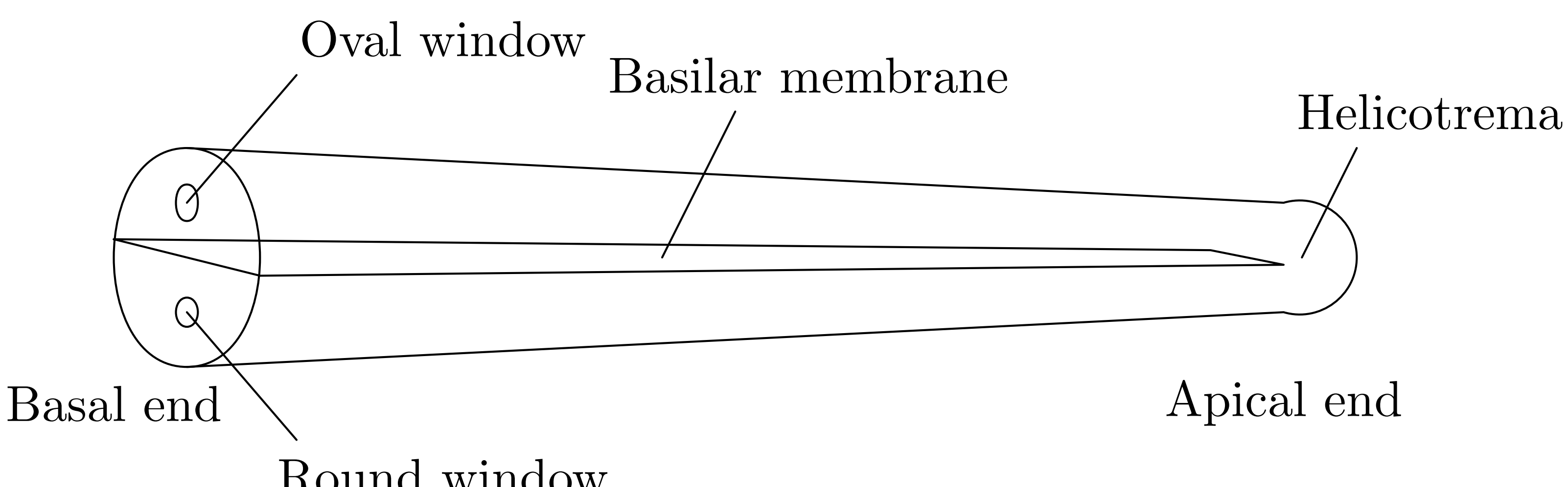
The inner ear, or labyrinth, consists of two parts, the osseous labyrinth, and the membranous labyrinth, contained in it. The osseous labyrinth (hammer, anvil and stapes) is filled with various fluids, and has three parts, the *vestibule*, the semicircular canals and the **cochlea**.

THE COCHLEA



The cochlea laid open. (Enlarged.)

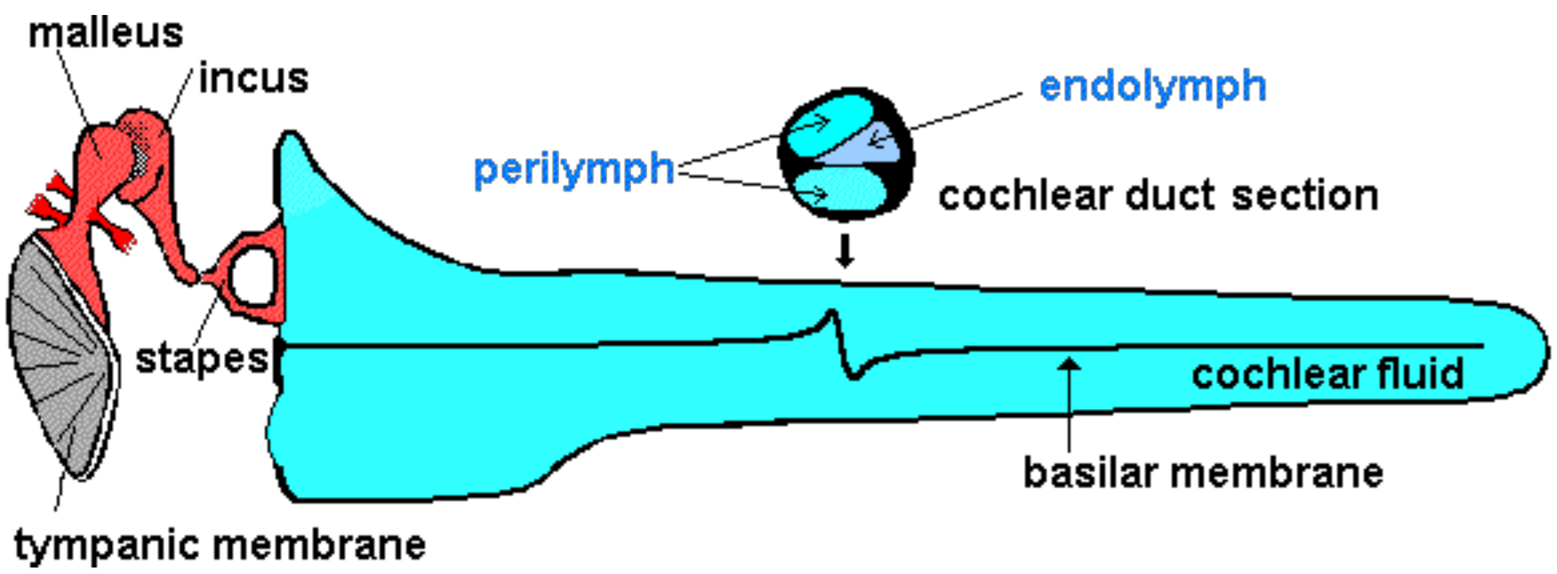
It has a logarithmic structure, that determines how we perceive frequencies



The cochlea, uncoiled

MECHANICS OF SOUND PERCEPTION

When a sound wave reaches the ear, it is focused into the meatus, where it vibrates the ear drum. This causes the hammer, anvil and stapes to move as a system of levers, and so the stapes alternately pushes and pulls the membrana tympani in rapid succession. This causes fluid waves to flow back and forth round the length of the cochlea, and causes the basilar membrane to move up and down.

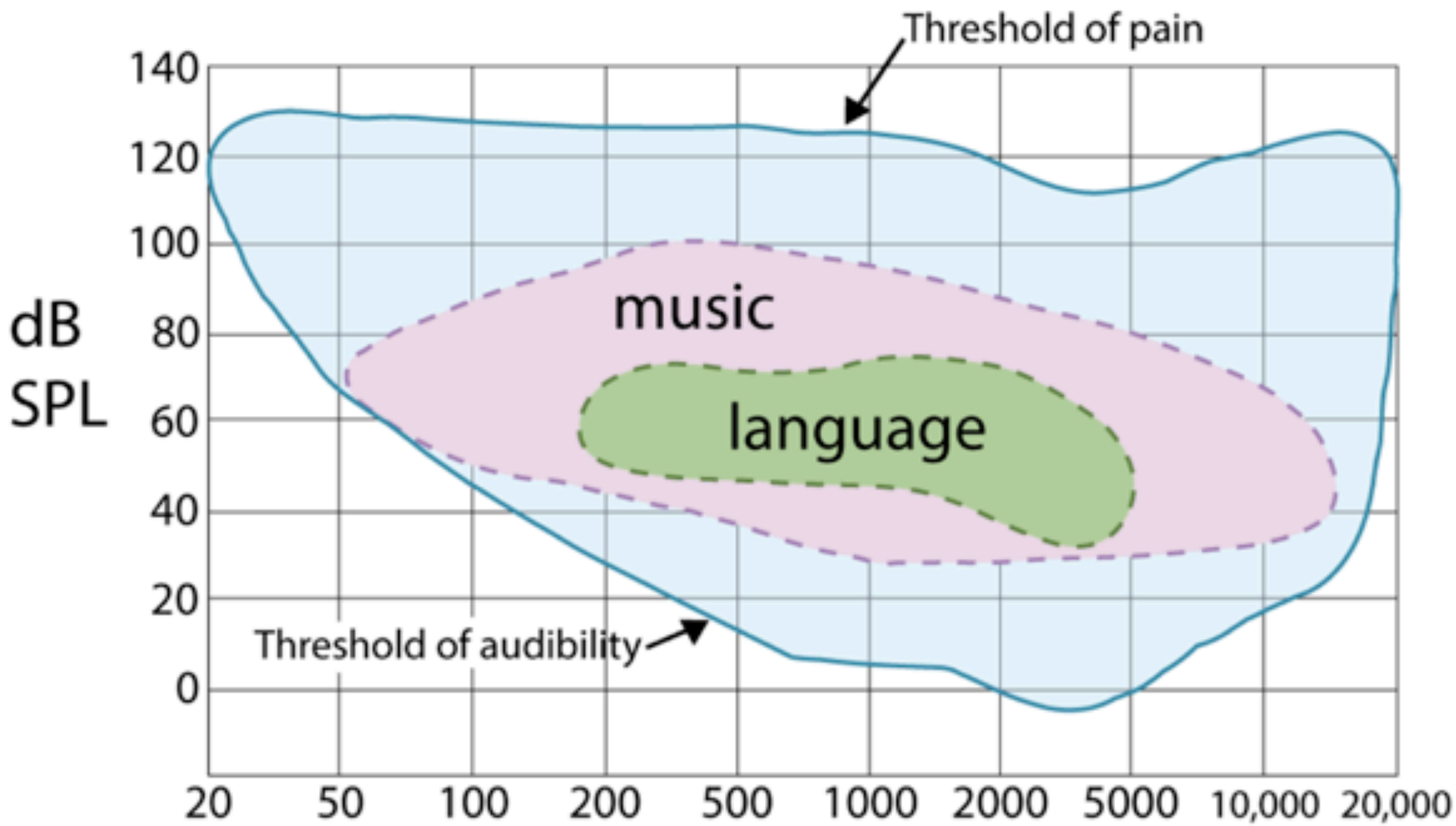


LIMITATIONS OF THE HEAR

The approximate range of frequencies to which the human ear responds is usually taken to be from 20 Hz to 20,000 Hz.

Species	Range (Hz)
Turtle	20–1,000
Goldfish	100–2,000
Frog	100–3,000
Pigeon	200–10,000
Sparrow	250–12,000
Human	20–20,000
Chimpanzee	100-20,000
Rabbit	300–45,000
Dog	50–46,000
Cat	30–50,000
Guinea pig	150–50,000
Rat	1,000–60,000
Mouse	1,000–100,000
Bat	3,000–120,000
Dolphin (*Tursiops*)	1,000–130,000

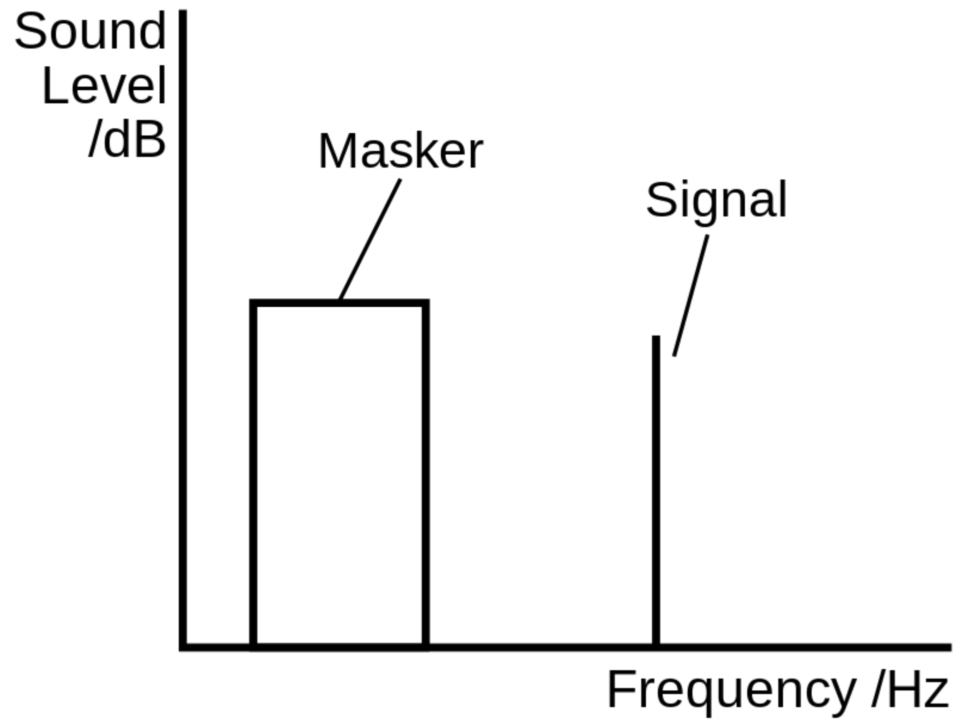
HUMAN AUDITORY FIELD



MASKING EFFECT

Masking effect happens when an intense sound of a lower pitch prevents us from perceiving a weaker sound of a higher pitch, but an intense sound of a higher pitch never prevents us from perceiving a weaker sound of a lower pitch.

The excitation of the basilar membrane caused by a sound of higher pitch is closer to the basal end of the cochlea than that caused by a sound of lower pitch. So to reach the place of resonance, the lower pitched sound must pass the places of resonance for all higher frequency sounds. The movement of the basilar membrane caused by this interferes with the perception of the higher frequencies.



There are several other types of masking

PERCEPTUAL MAPPINGS

Frequency $\rightarrow$ Pitch

Amplitude $\rightarrow$ Loudness

Timbre $\rightarrow$ Tone color

We will discuss timbre in the next lectures!

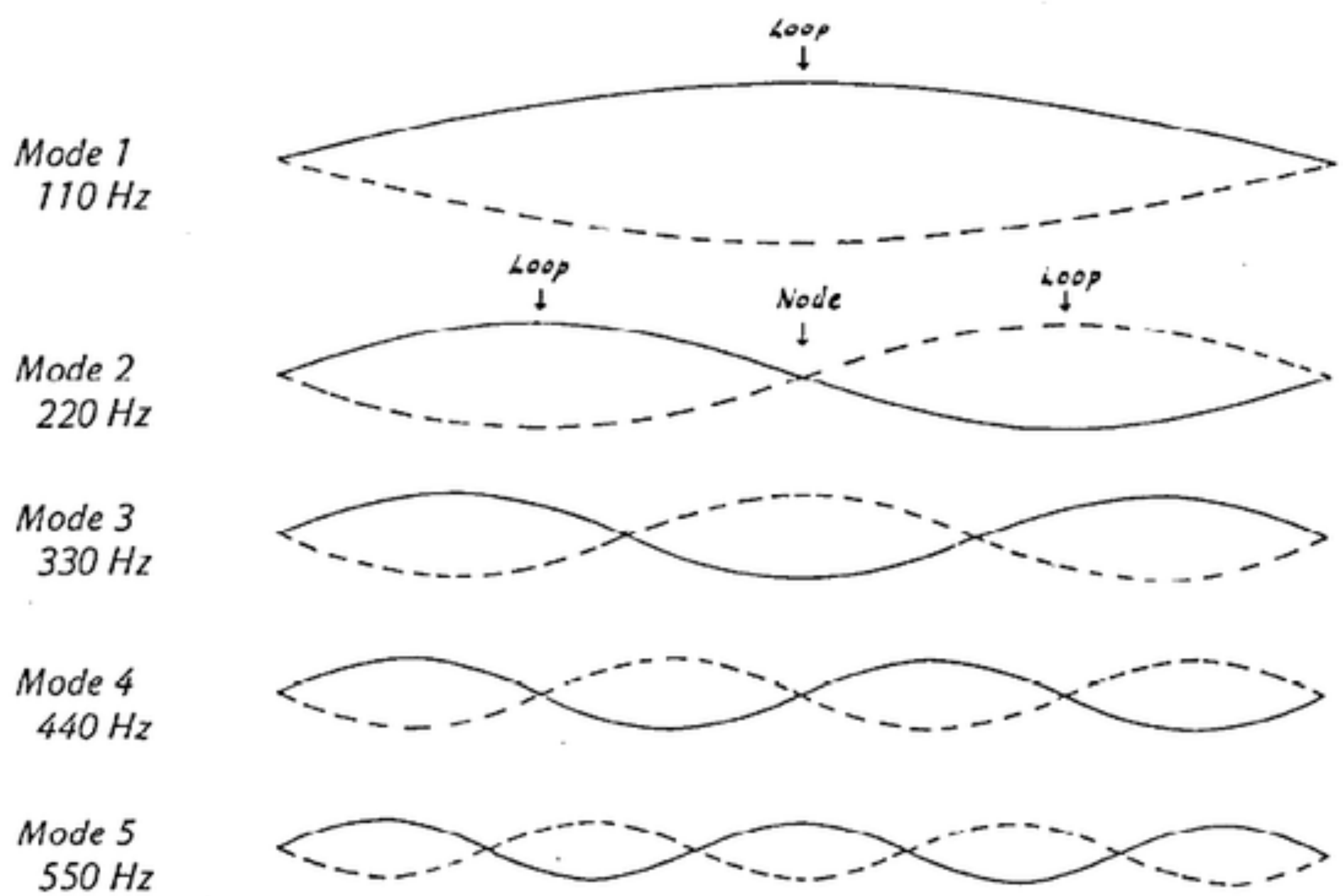
STRINGS, MODES AND HARMONICS

VIBRATING STRING

A vibrating string (anchored at both ends) with a heavy bead attached to the middle of it, exerts a force F on the bead towards the equilibrium position whose magnitude described the by following differential equation

In Benson's book there is more about this equation...

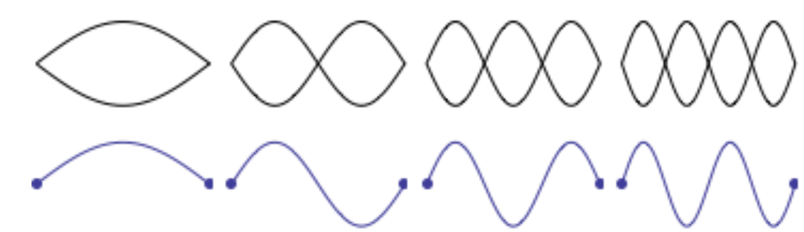
$$\frac{\partial^2 u}{\partial t^2} = c^2 \frac{\partial^2 u}{\partial x^2}.$$



f	L
2f	L/2
3f	L/3
4f	L/4
5f	L/5

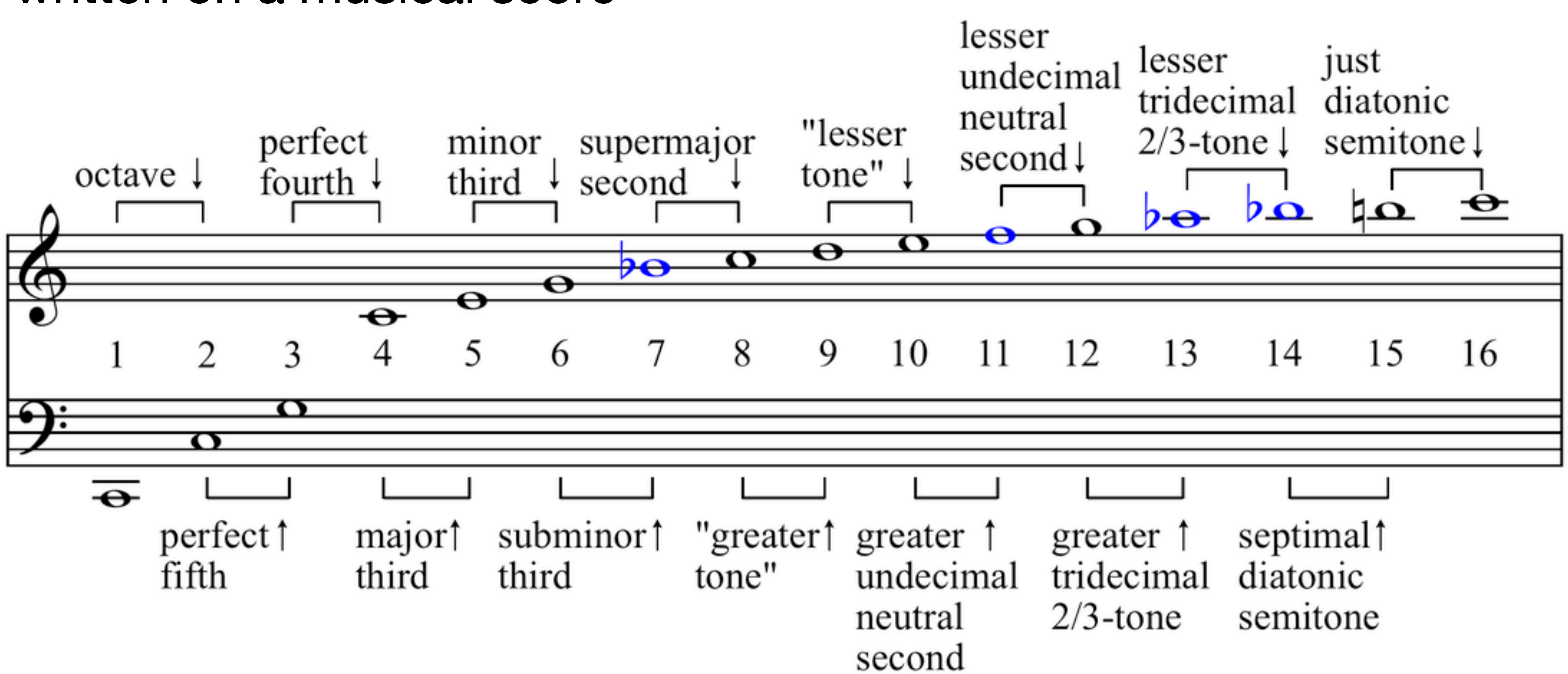
HARMONIC SERIES (OVERTONES)

The sum of all the modes of a string follow is harmonic

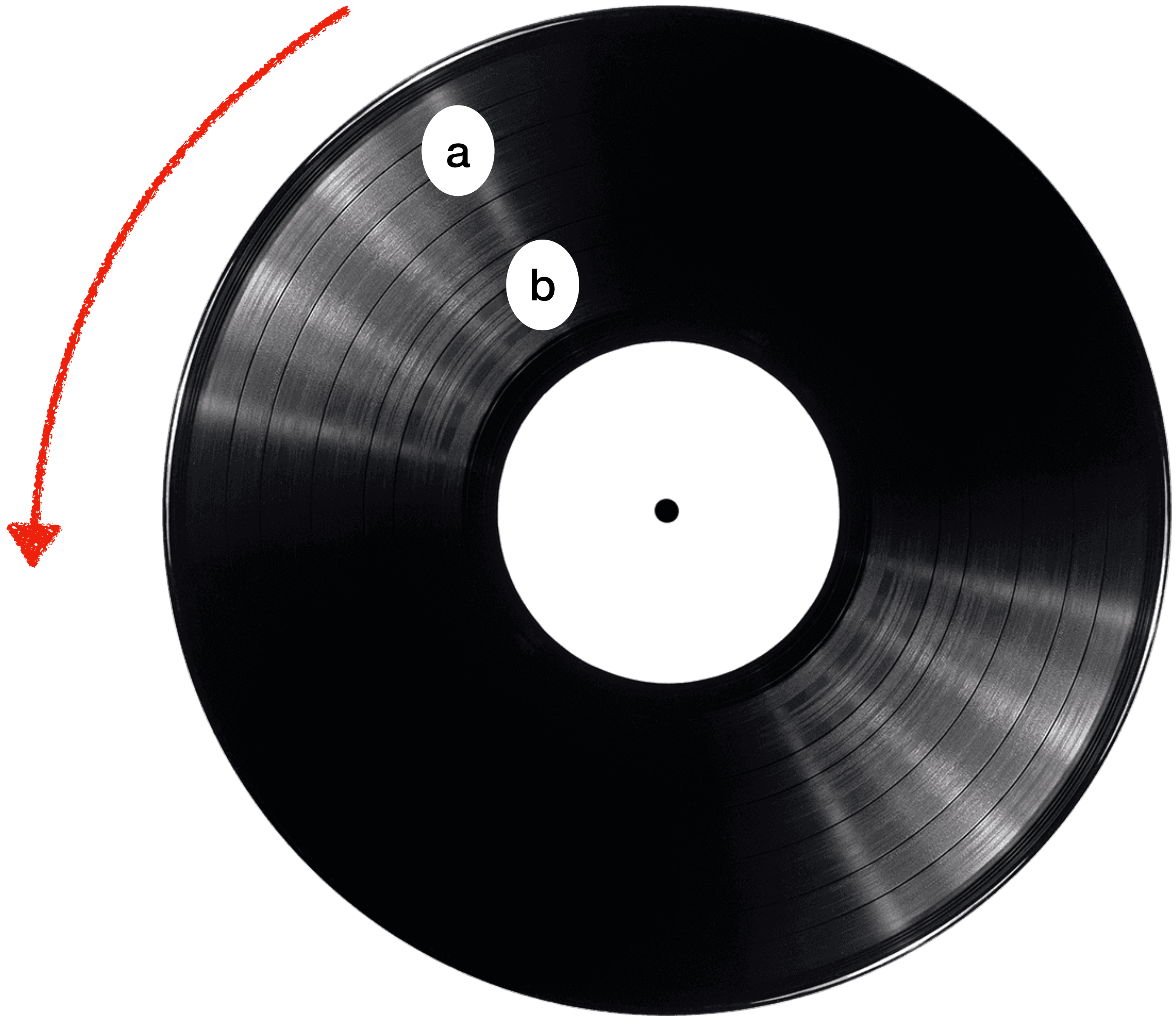


$$V = L + \frac{L}{2} + \frac{L}{3} + \ldots + \frac{L}{n} = \sum_{n=0}^{\infty} \frac{L}{n}$$

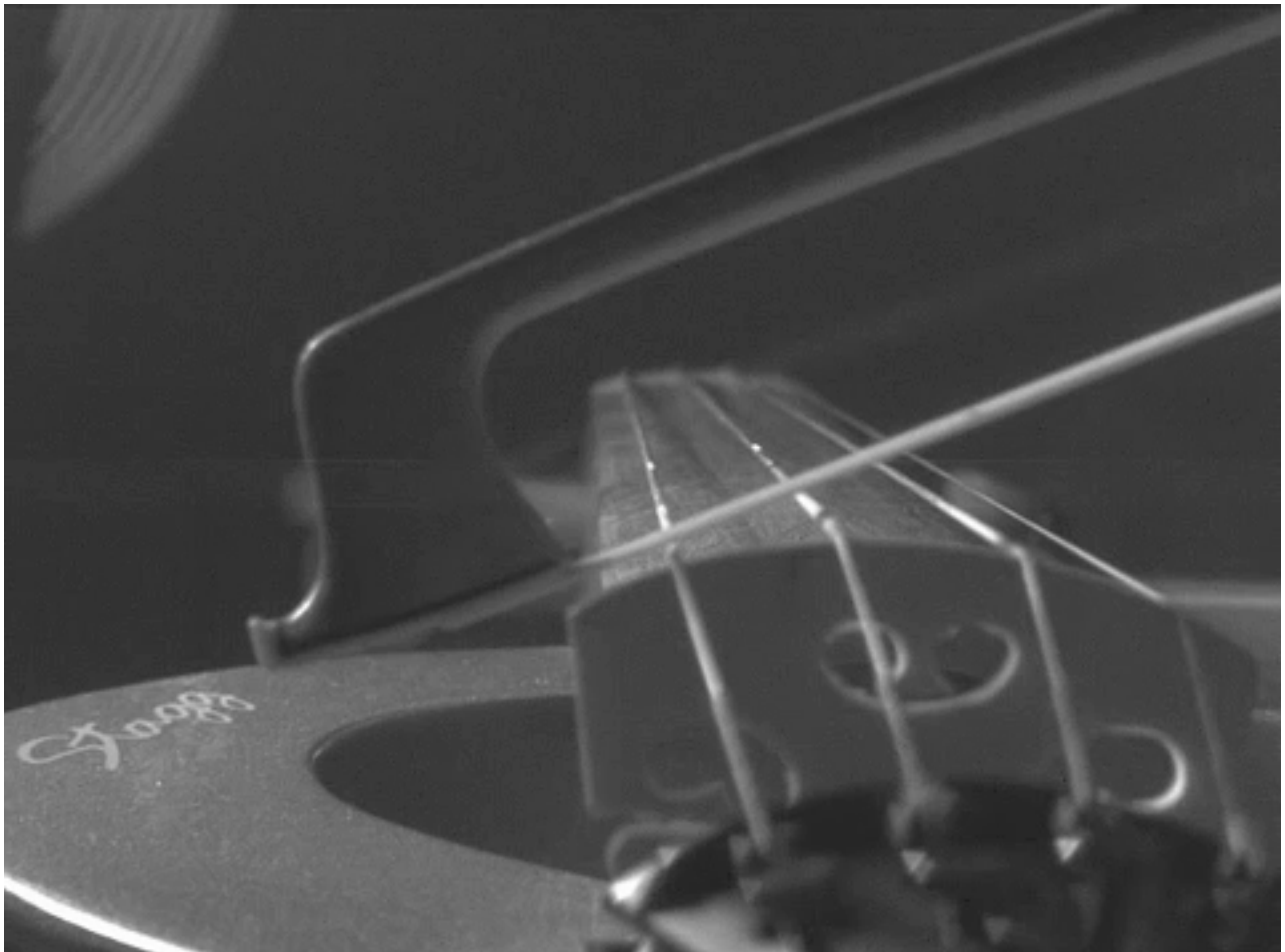
The harmonic series of vibration corresponds to a series of frequencies that can be written on a musical score



HOW DOES THE VINYL WORK?

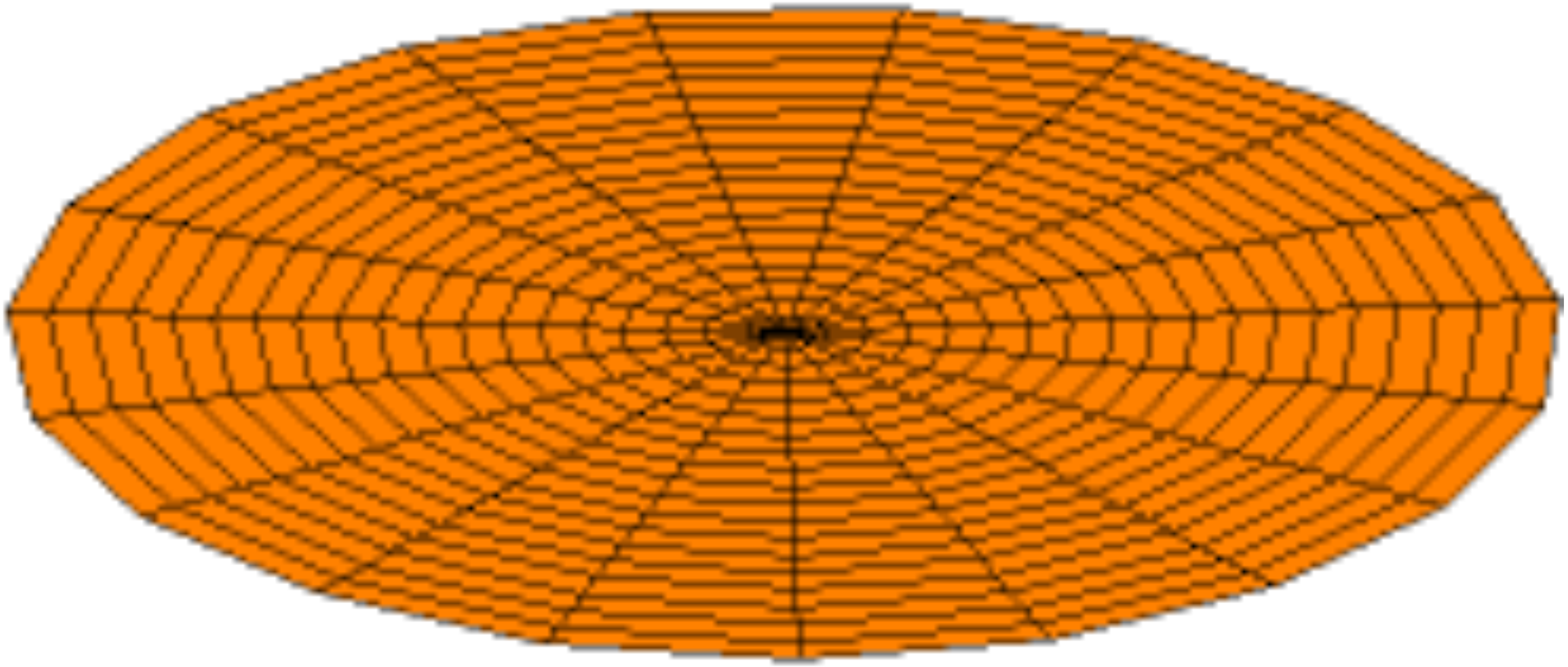


BOWED VIOLIN STRING IN SLOW MOTION

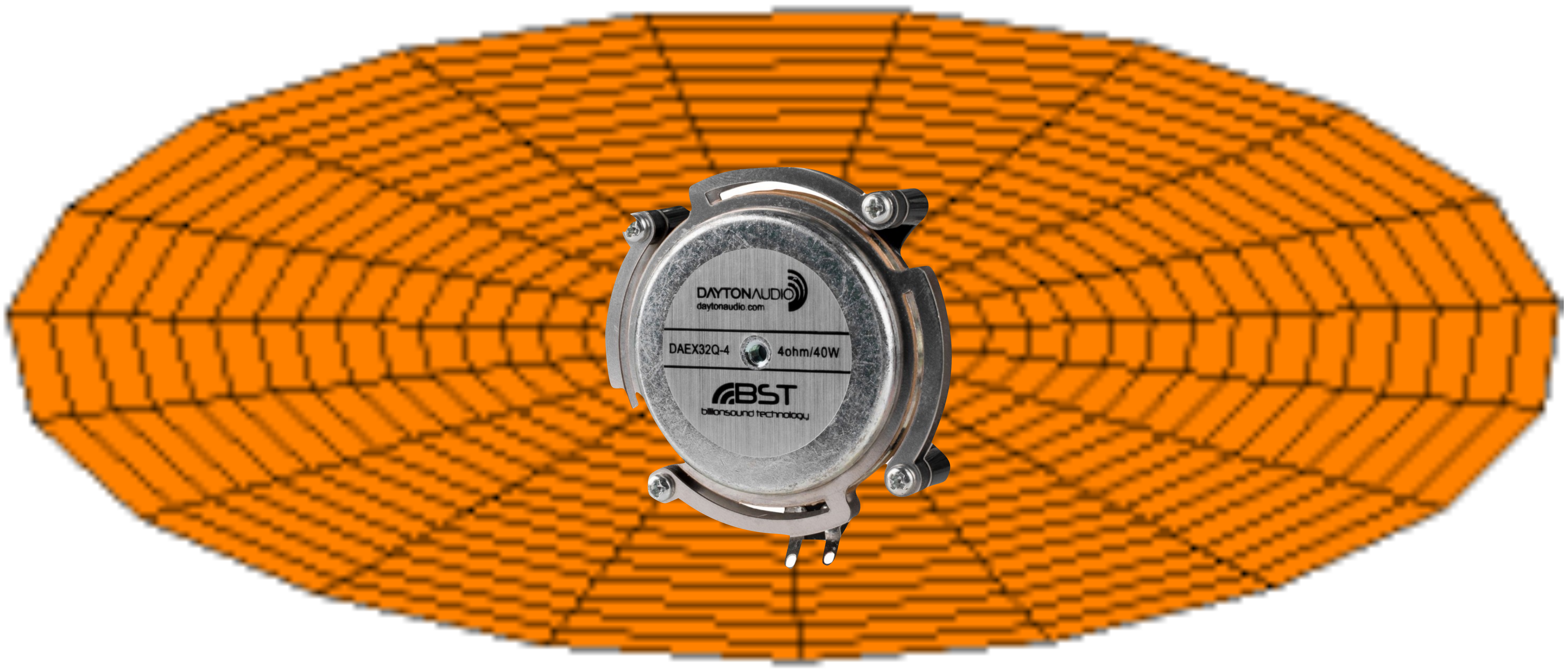


https://www.youtube.com/watch?v=6JeyiM0YNo4

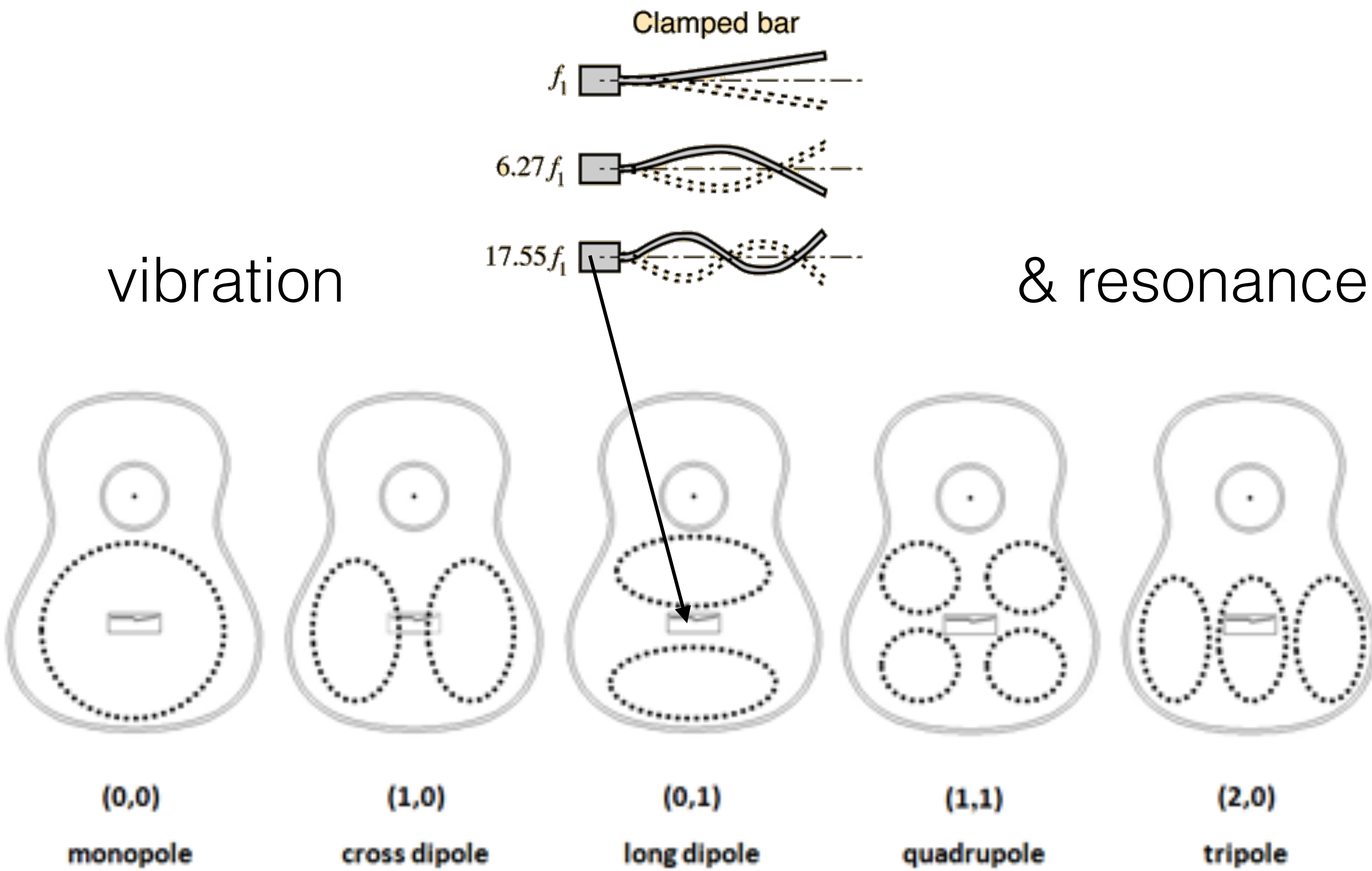
VIBRATING SURFACE



Question: can we induce vibrations with a transducer?



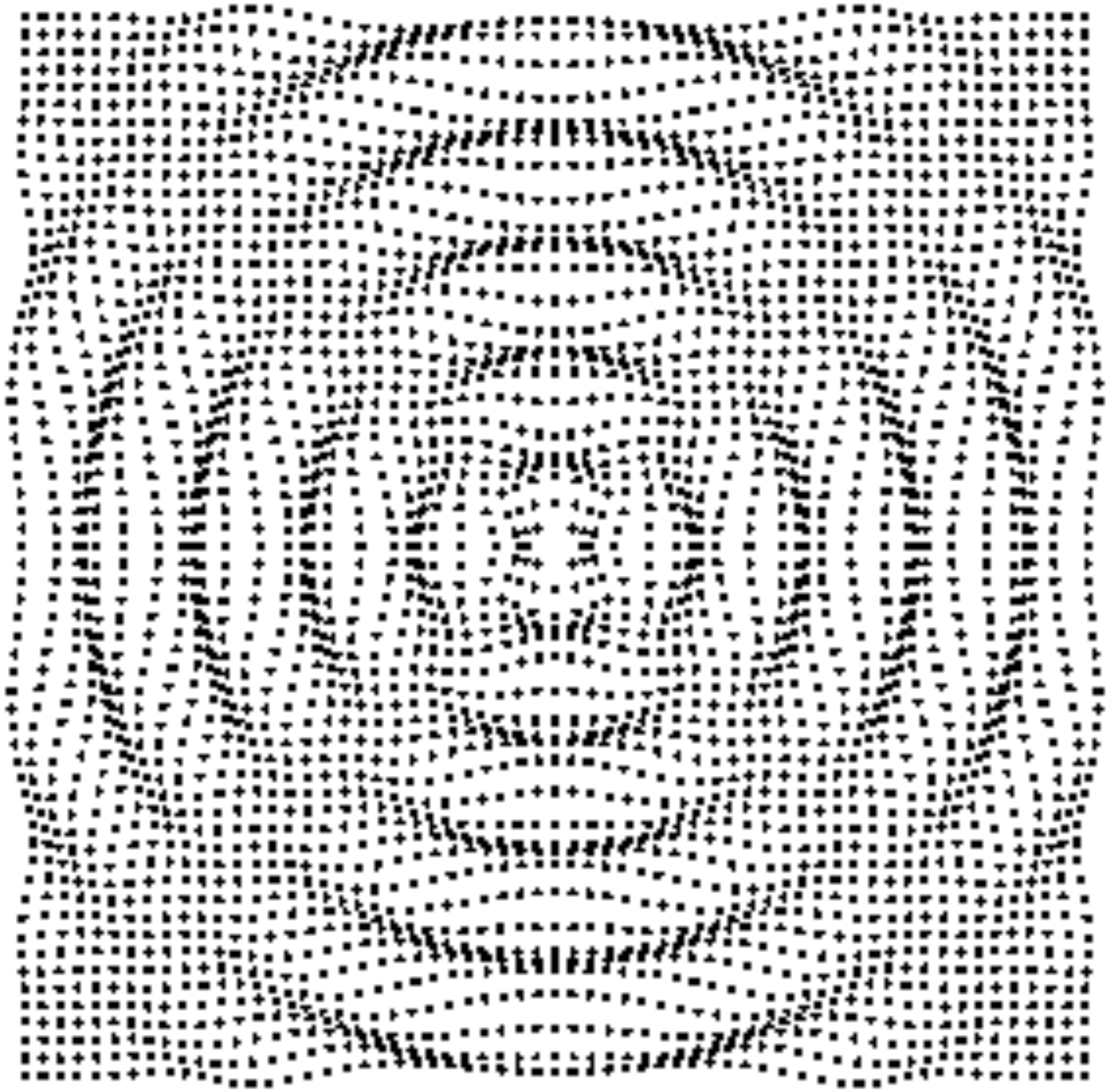
vibration & resonance



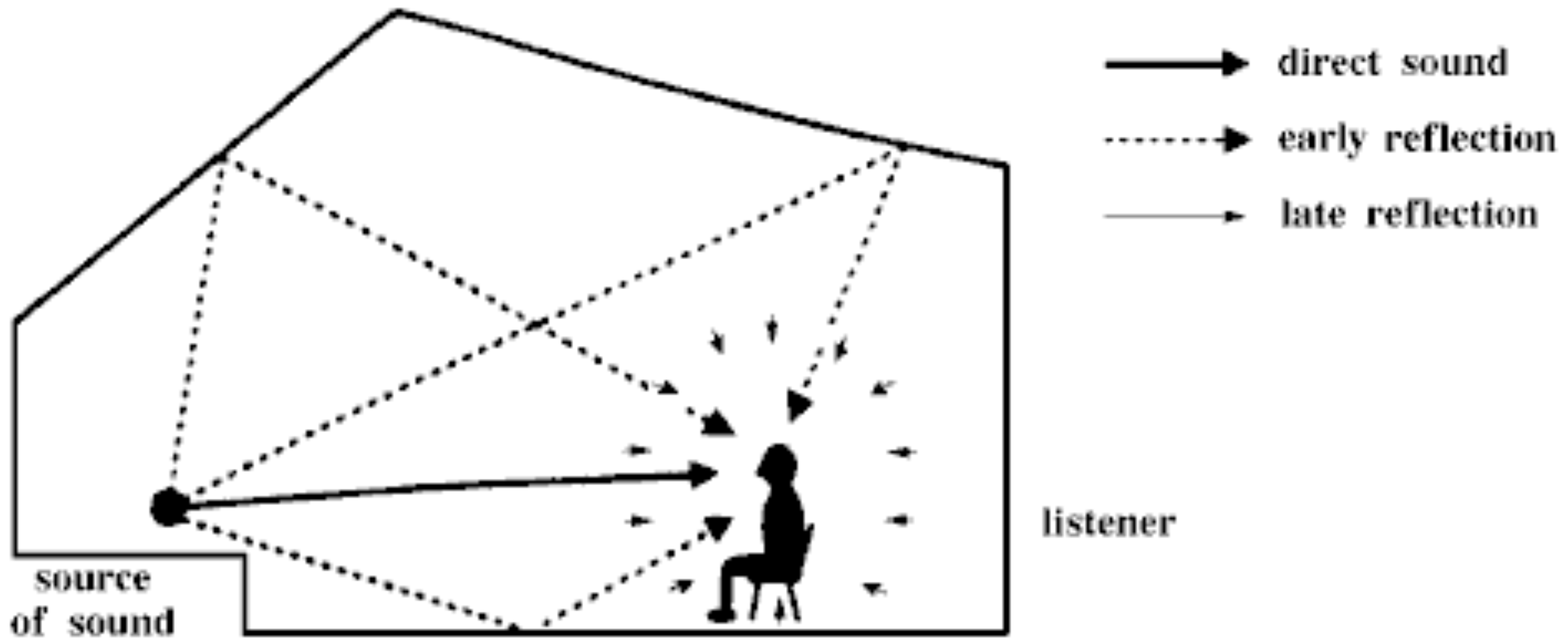
DIFFUSION

SOUND WAVE PROPAGATION

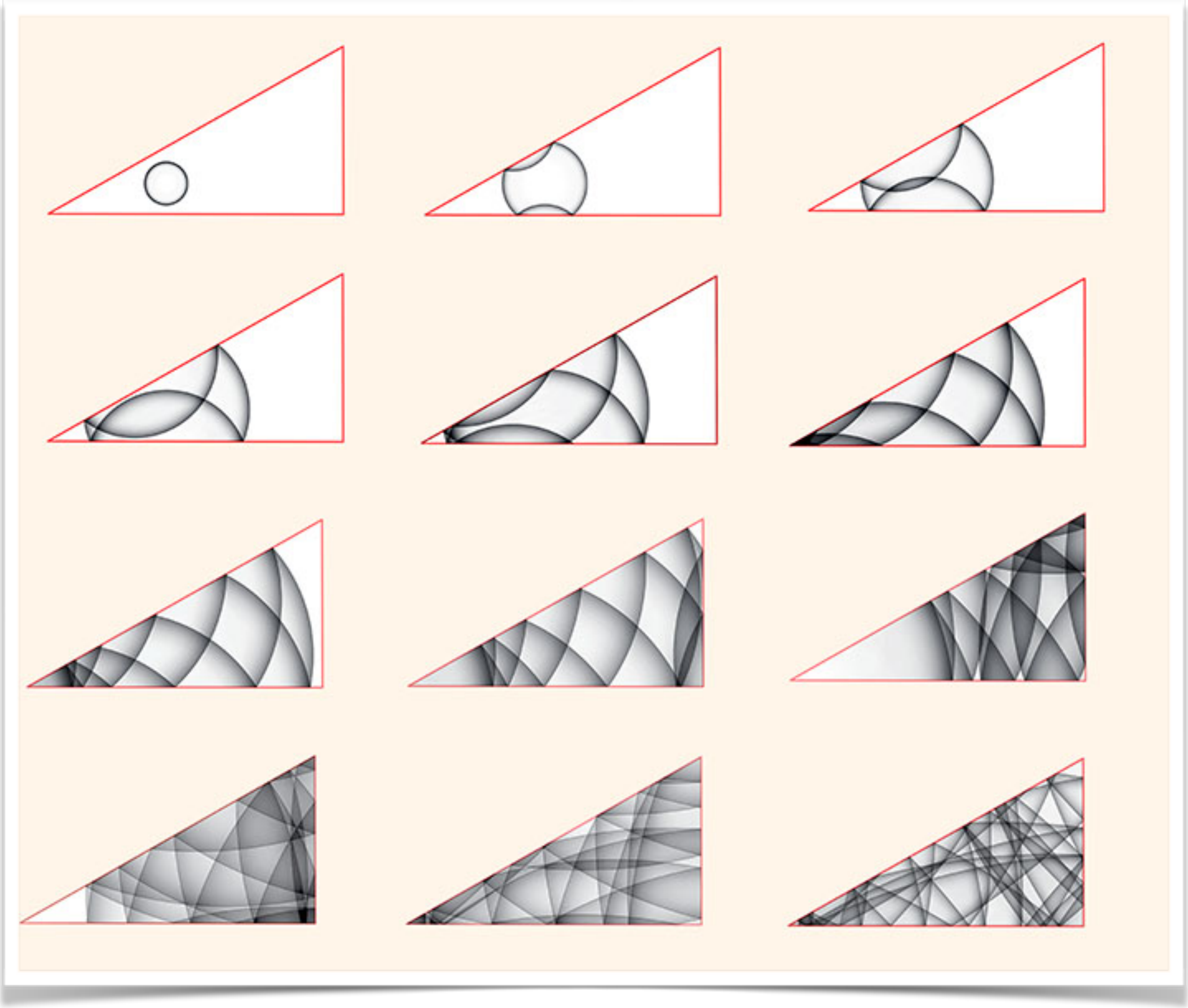
The speed of a sound pressure wave in air is 331.5+0.6Tc m/s , Tc temperature in Celsius



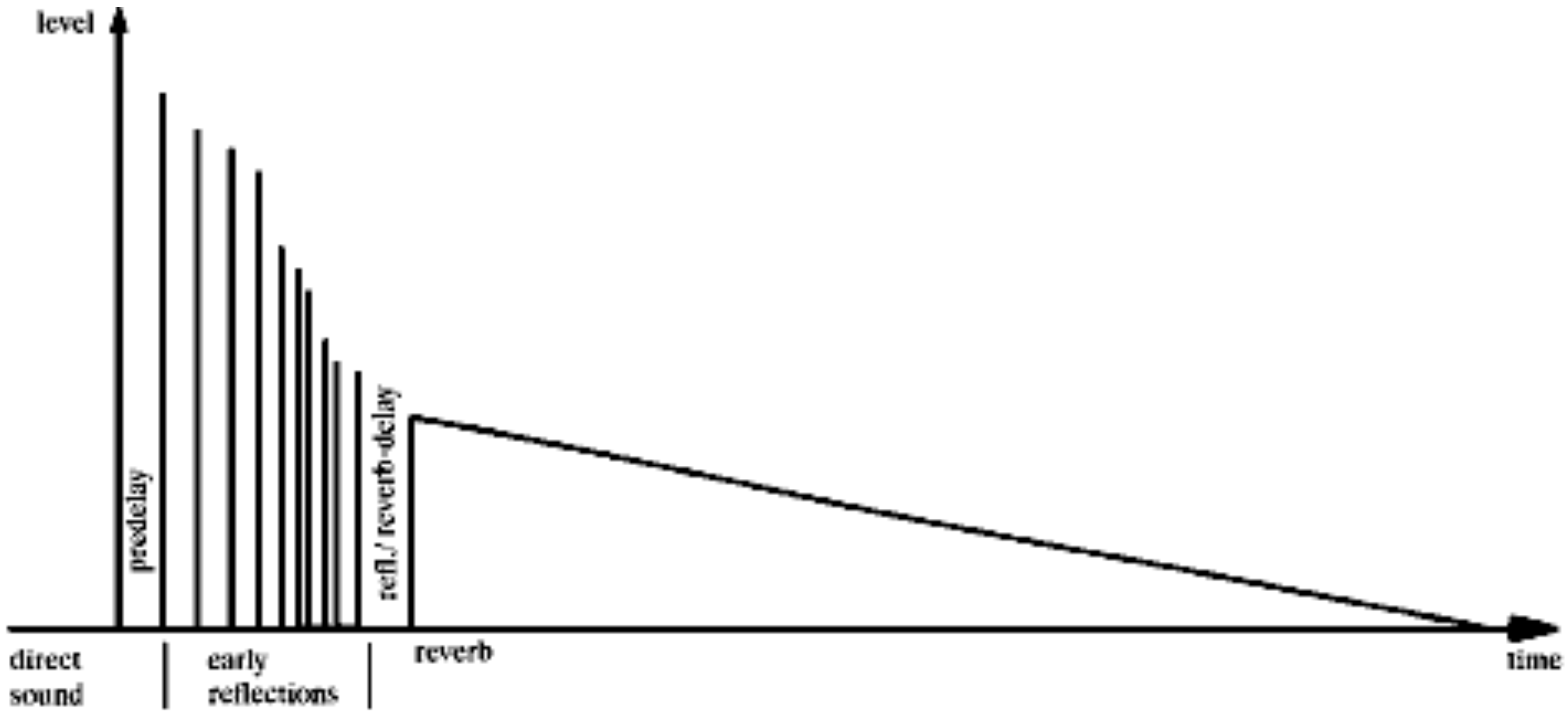
SOUND IN SPACE



REFLECTIONS

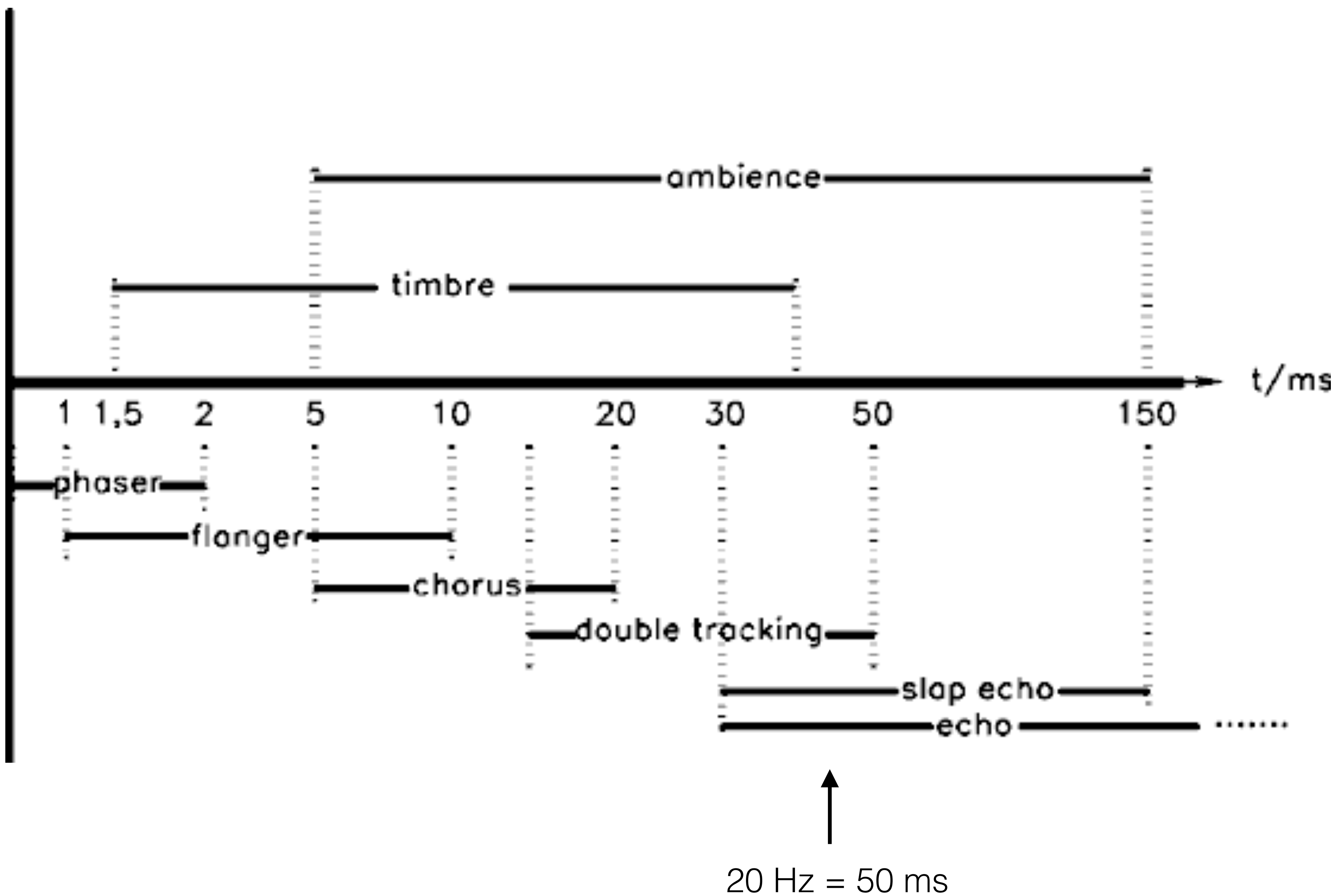


ROOM RESPONSE



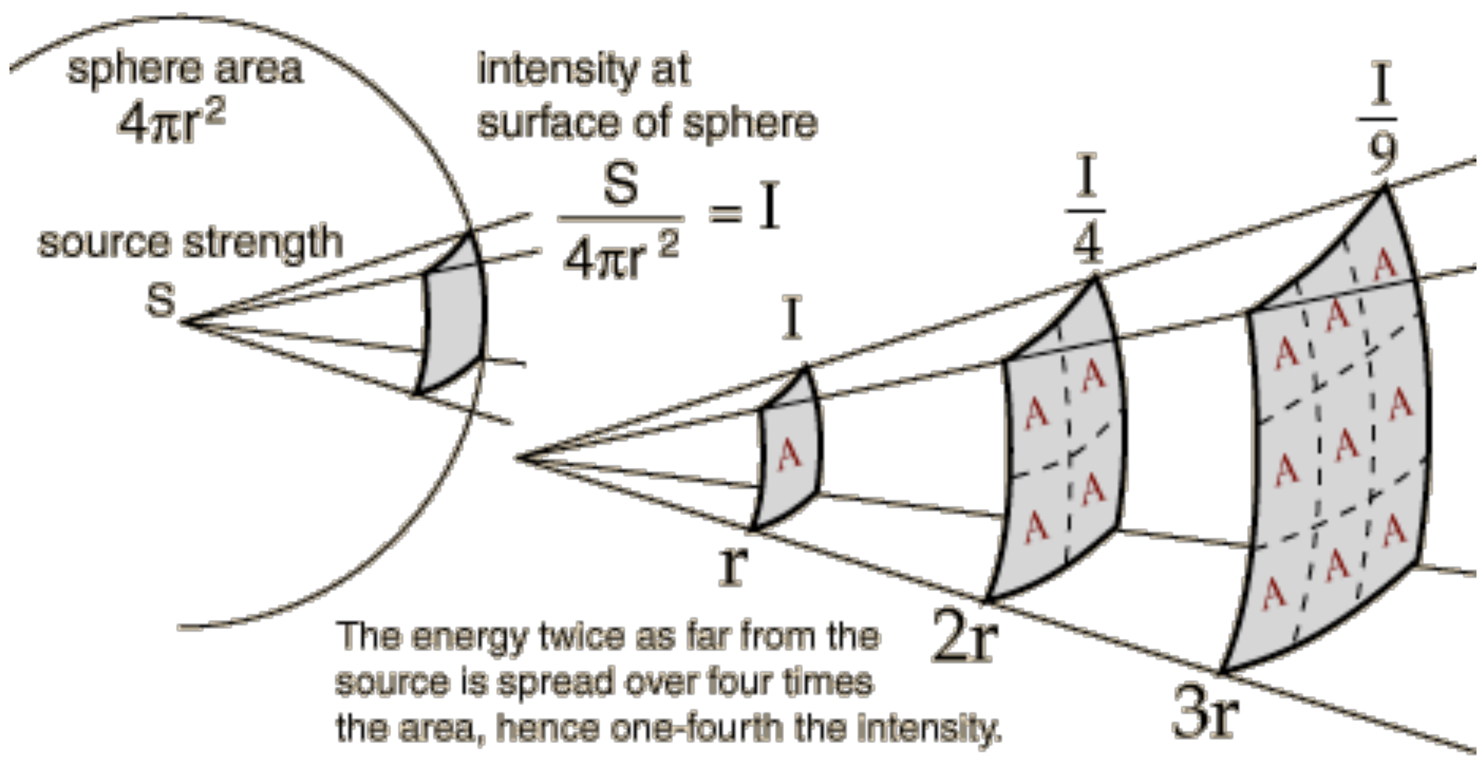
classic impulse response

PERCEPTUAL QUALITIES OF DELAYS



from Deutsche Welle (radio) http://www9.dw-world.de/rtc/infotheque/sound_processors/soundprocessors.html

DISTANCE ATTENUATION (1)

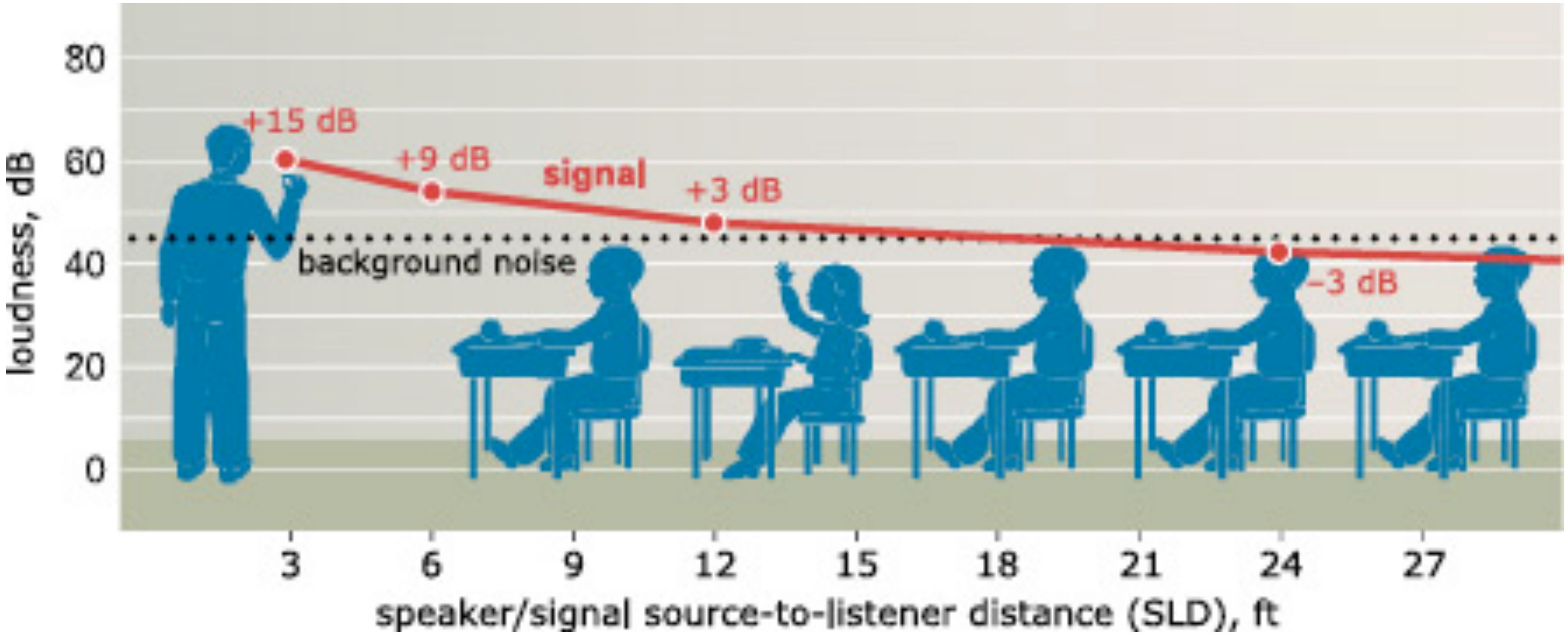


$I \sim P^2 \longrightarrow \boxed{a = 1 / r}$

I = sound intensity

P = sound pressure (amplitude)

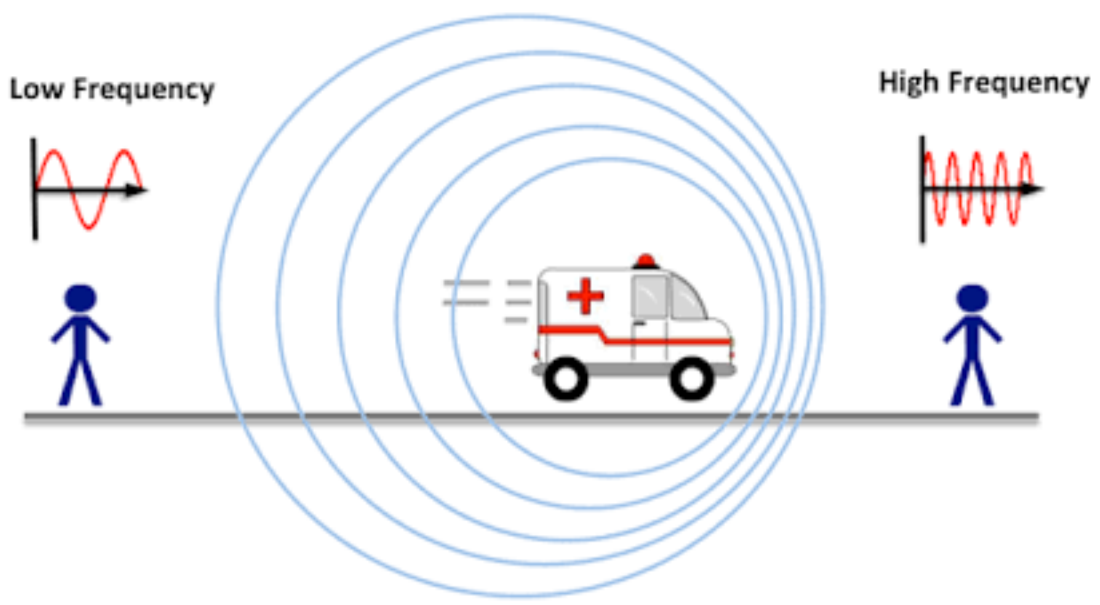
DISTANCE ATTENUATION (2)



DOPPLER EFFECT

The Doppler effect causes the received frequency of a source (the way it is perceived when it gets to its destination) to differ from the initial frequency if there is motion that is increasing or decreasing the distance between the source and the receiver.

This effect is readily observable as a variation in the pitch of a sound between a moving source and a stationary observer.



https://forum.huawei.com/enterprise/en/what-is-the-doppler-effect/thread/510221-100305

THANK YOU!

Suggested exercise:
try to use the freesound.org database of sounds
to create a masking effect!