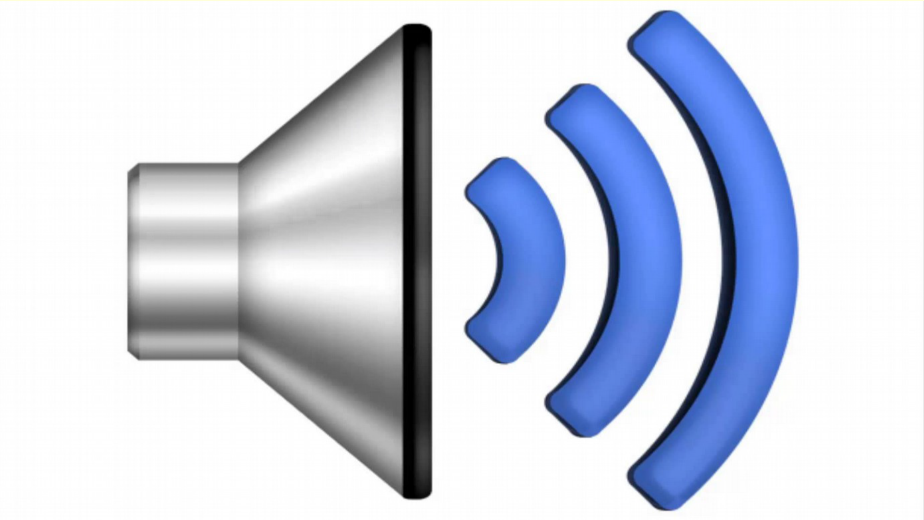
WHAT IS SOUND?



A SHORT JOURNEY THROUGH ACOUSTICAL PHYSICS

(by Fabrizia De Bernardi)

Let's do a short review and learn a little vocabulary

https://www.youtube.com/watch?v=RVyHkV3wlyk

https://www.youtube.com/watch?v=Jw_aGOrTDPo

https://www.youtube.com/watch?v=v3CvAW8BDHI

https://www.youtube.com/watch?v=E-SPpUhzYZY

Sound is always generated by a vibrating source like a string, a membrane of a drum or the vocal chords.

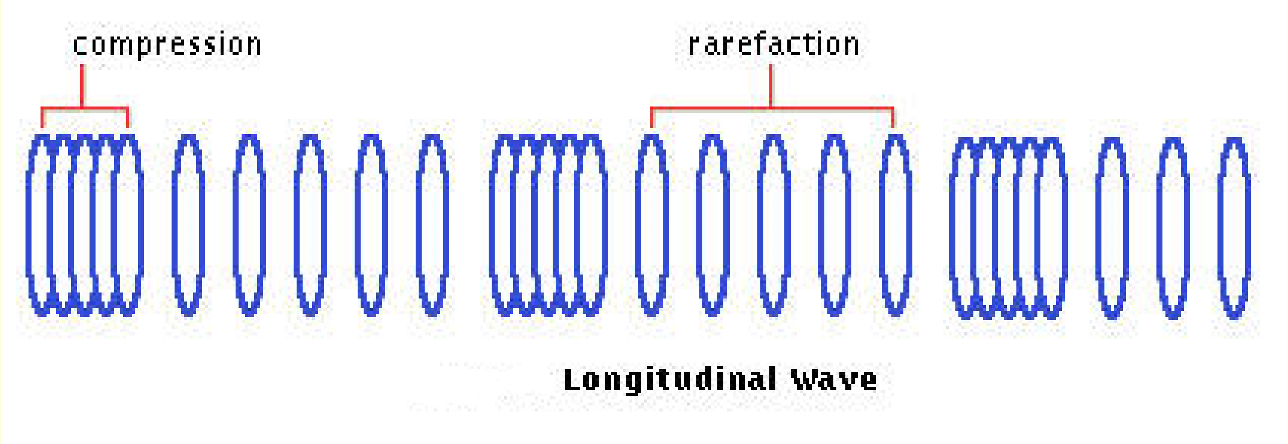
This vibration is transmitted to the air and travels through the air or other materials, that can be gases, solids or liquids.

Sound waves can propagate through a medium.

Sound can't be transmitted through a vacuum!!

Sound waves are *longitudinal* waves.

The pressure changes in a sinusoidal way, creating bands of compression and rarefaction of the air.



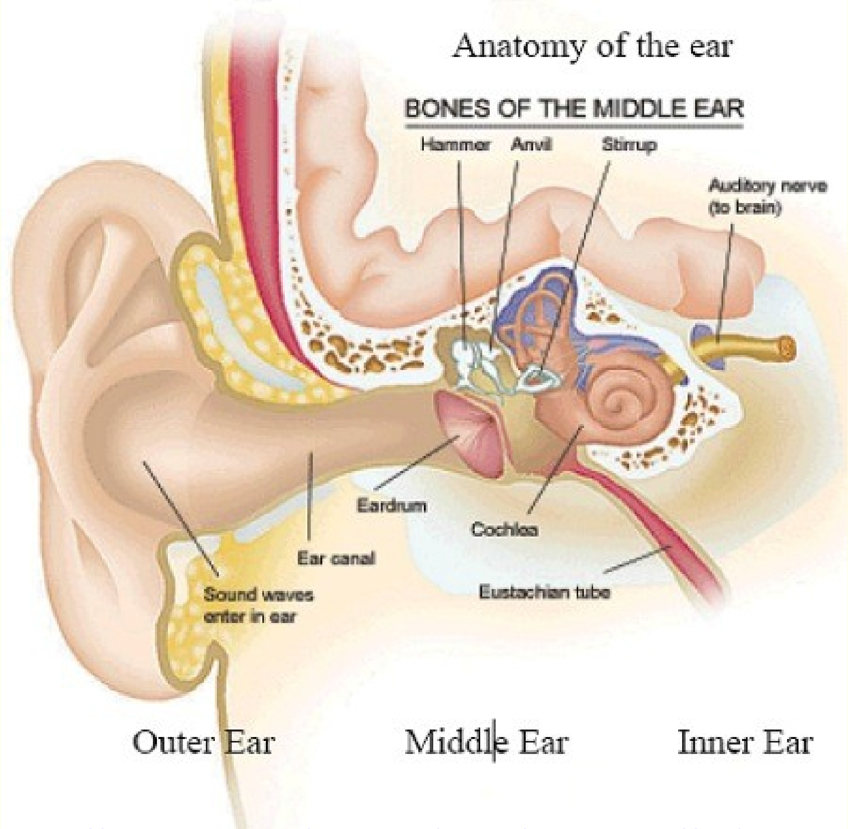
The speed of sound in air is around 343 m/s at ambient temperature.

This velocity changes very much in other media.

https://www.youtube.com/watch?v=GkNJvZINSEY

Gasses (*0°C*)	**Substance**	**Speed of Sound** (*m/s*)
	Carbon Dioxide	259
	Hydrogen	1284
	Helium	965
	Nitrogen	334
	Oxygen	316
	Air (21% Oxygen, 78% Nitrogen)	331
	Air (20°C)	344
Liquids (*25°C*)	Glycerol	1904
	Sea Water (3.5% salinity)	1535
	Water	1493
	Mercury	1450
	Kerosene	1324
	Methyl Alcohol	1103
	Carbon Tetrachloride	926
Solids	Diamond	12000
	Pyrex Glass	5640
	Iron	5960
	Granite	6000
	Aluminum	5100
	Brass	4700
	Copper (annealed)	4760
	Gold	3240
	Lead (annealed)	2160
	Rubber (gum)	1550

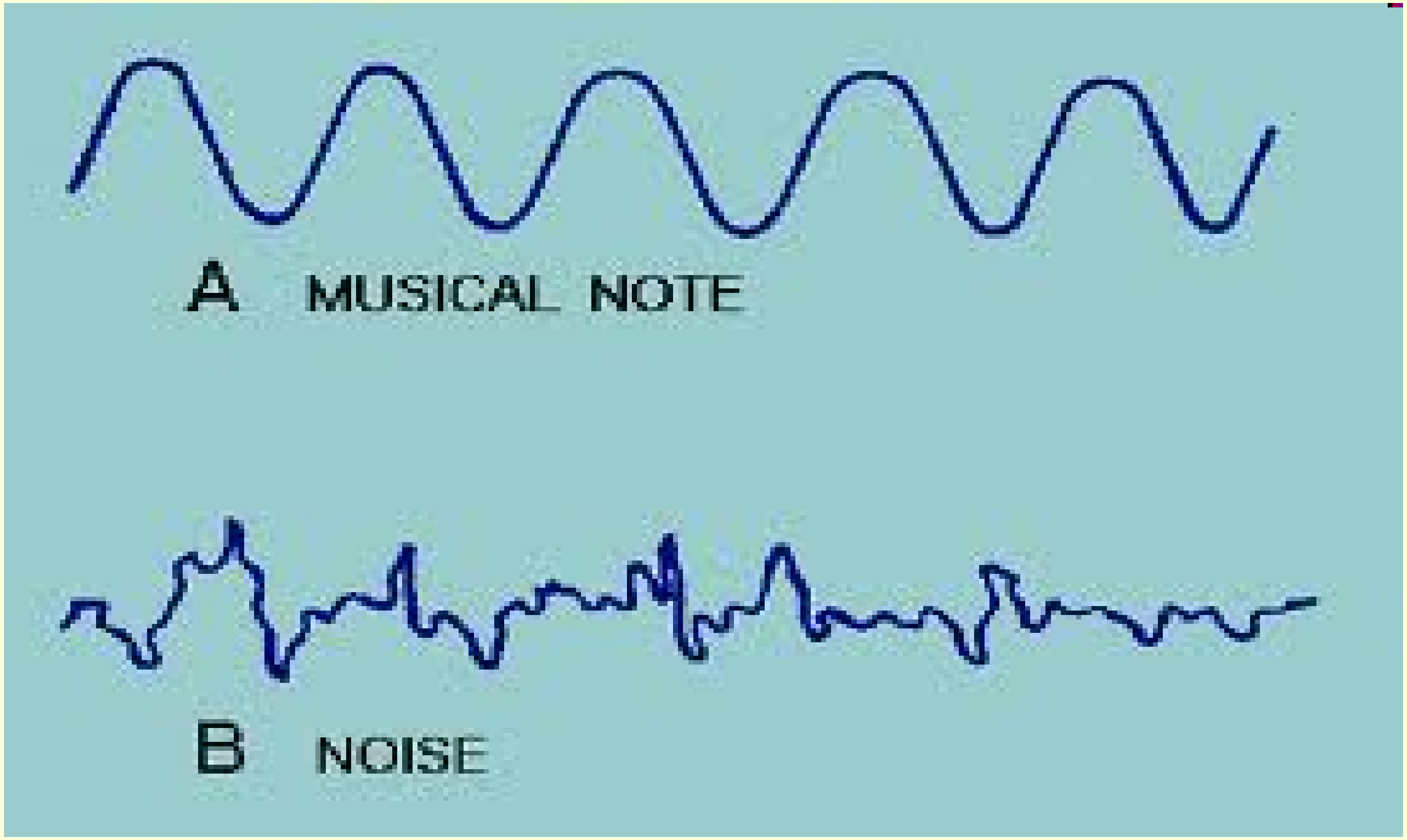
This vibration of the air comes to our ears.
The membrane of the eardrum begins to vibrate and passes on the impulse to a chain of little bones, till the vibration is transformed into an electric impulse and sent to our brain through the auditory nerve.



https://www.youtube.com/watch?v=3G5jiXl2LSM

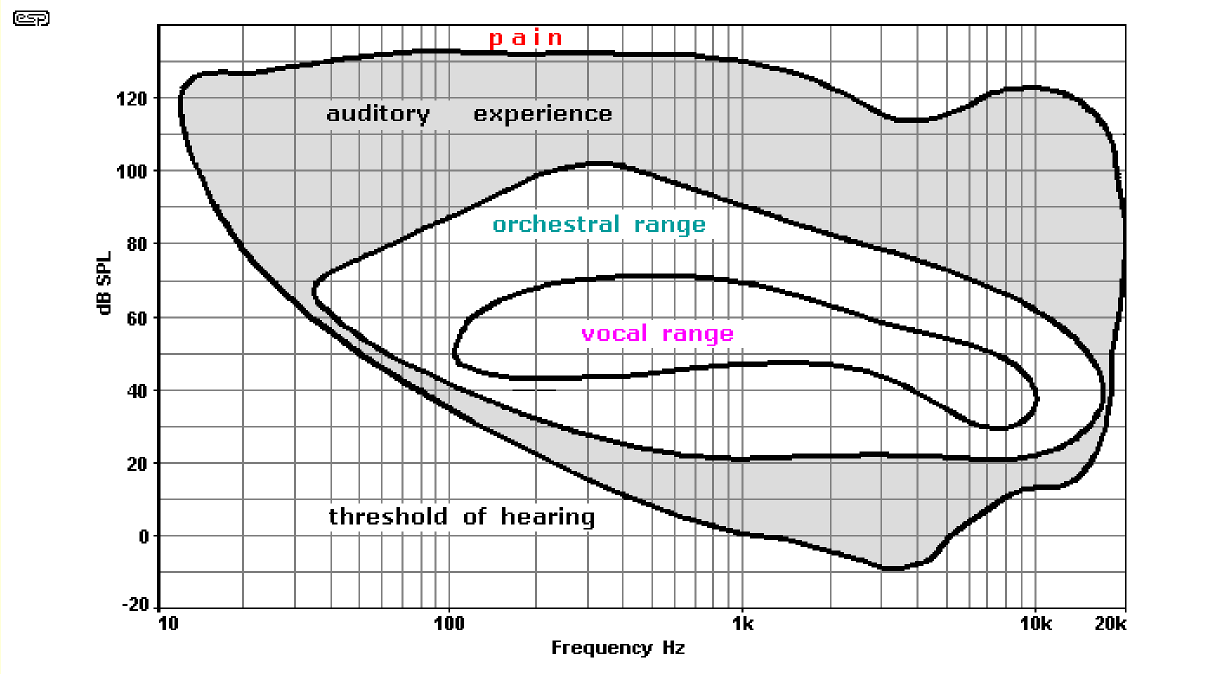
Sounds and noises

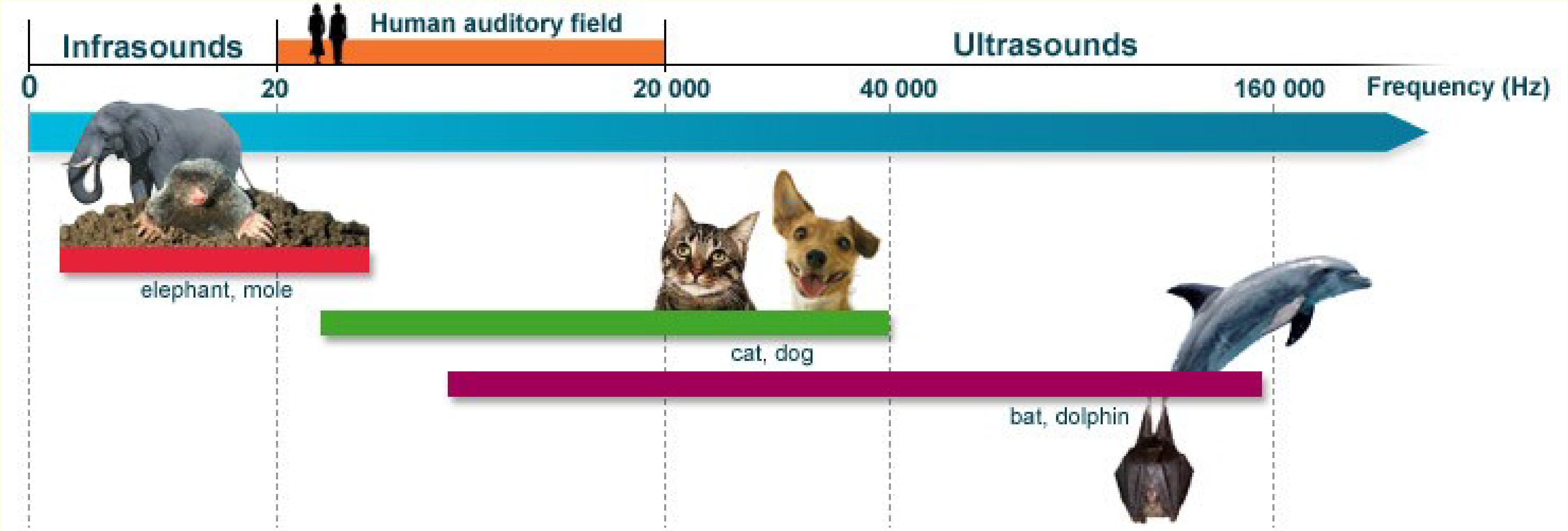
We call *sound* a regular vibration that can be represented with a sinusoidal wave



The human ear can receive sound waves in a limited band of frequencies, between **20** and **20.000 Hz**, but there are ultrasounds in higher frequencies and infrasounds in lower frequencies.

Some animals, like dolphins and bats, can hear these particular frequencies.



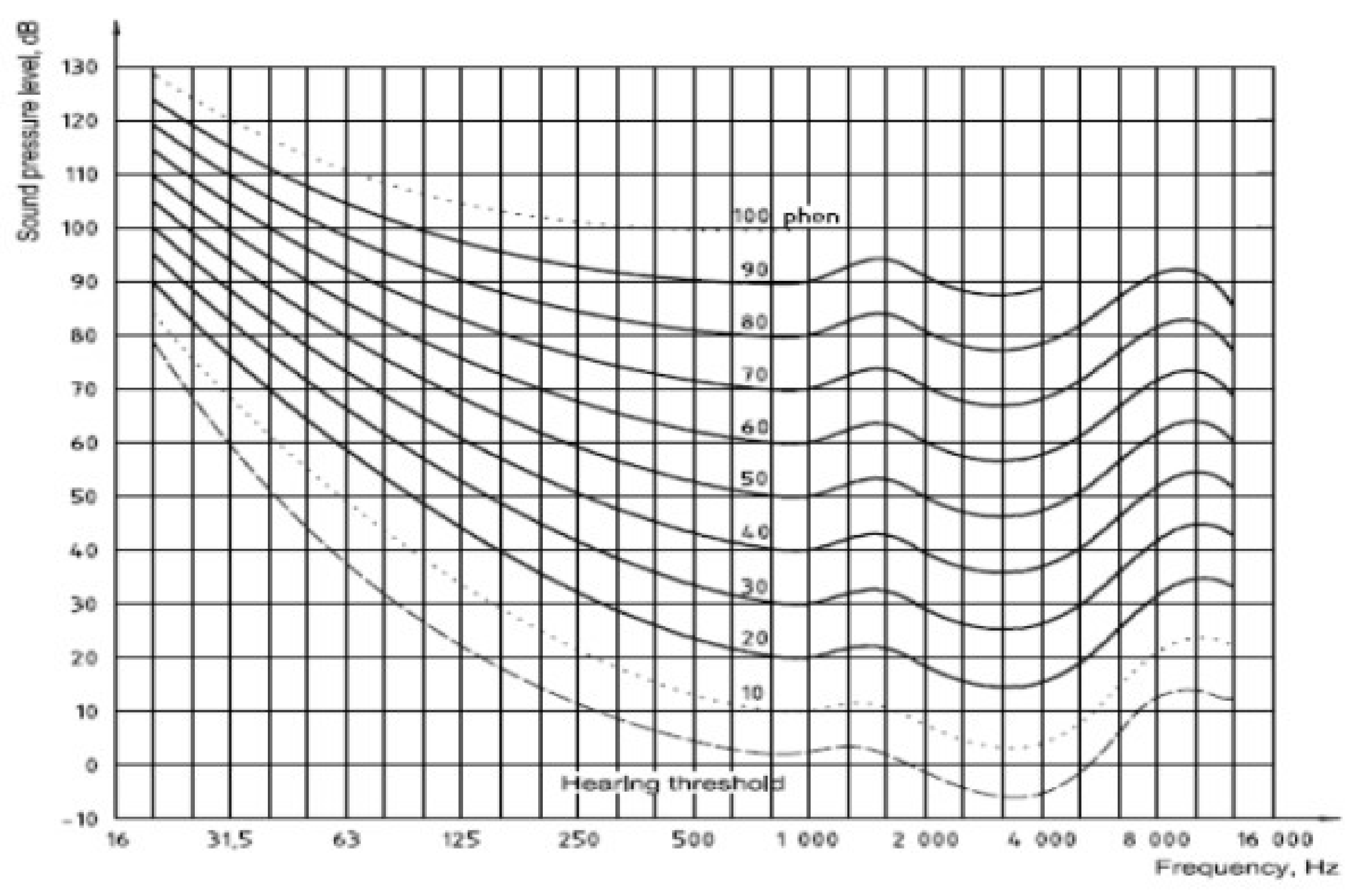


What range of frequencies can animals hear?

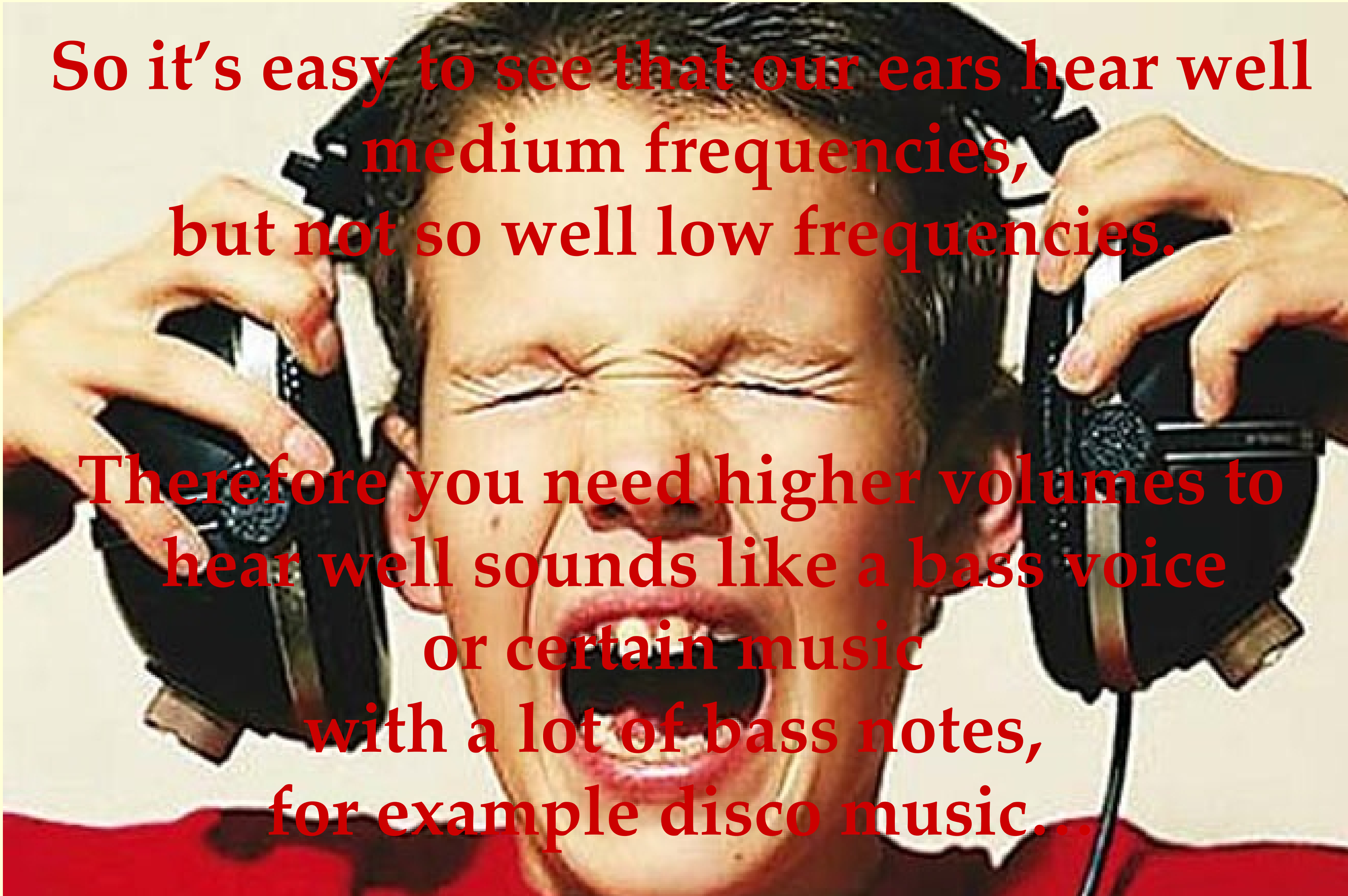
Experience your hearing range

https://www.youtube.com/watch?v=qNf9nzvnd1khttps://www.youtube.com/watch?v=qNf9nzvnd1k

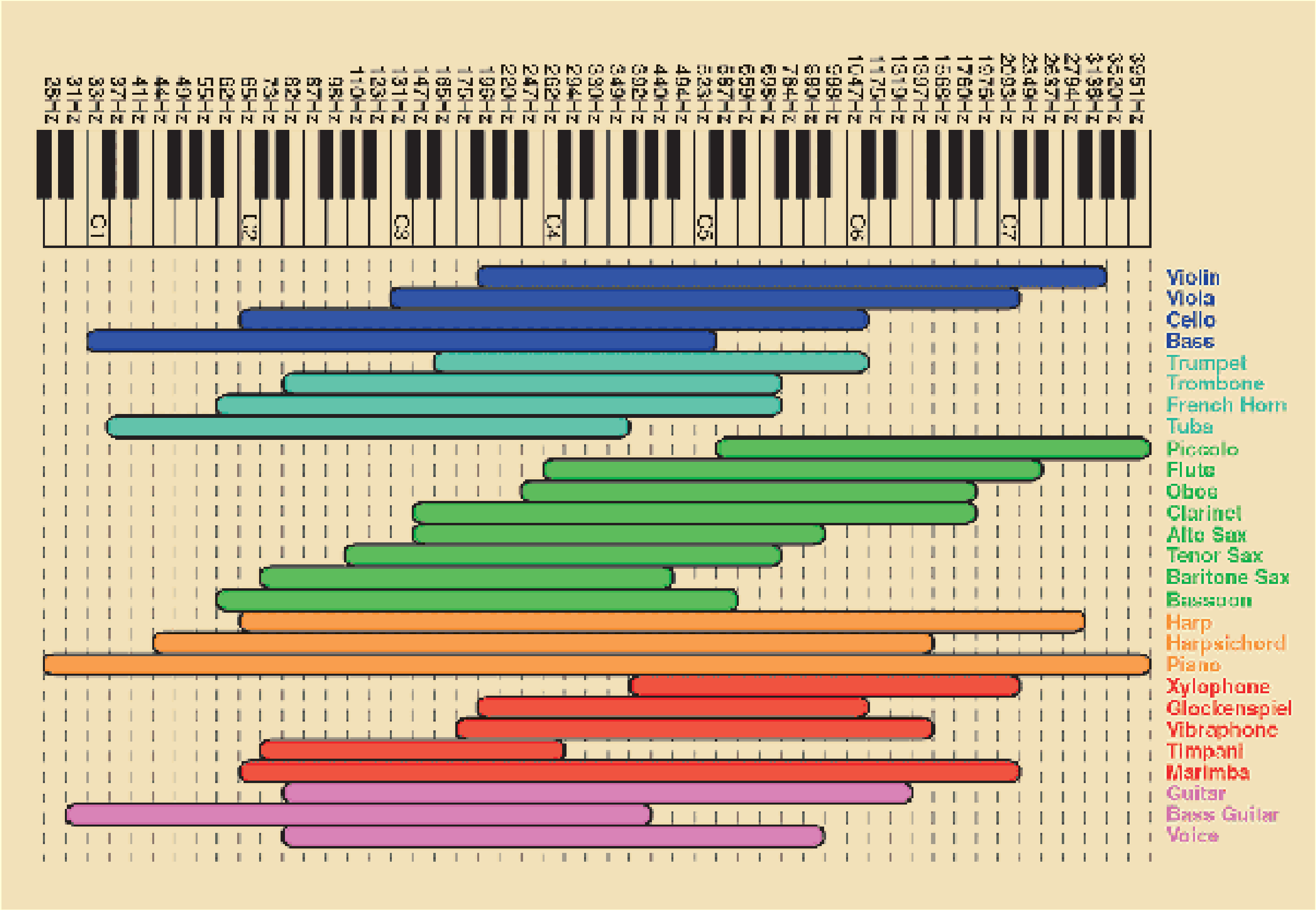
Isophonic curves



In the previous slide you have seen
a diagram of the
isophonic curves.
Every point of each curve is
characterized by a couple of values:
frequency and volume.
For all the points of a curve
the quality
of your hearing is the same.


So it’s easy to see that our ears hear well
medium frequencies,
but not so well low frequencies.
Therefore you need higher volumes to
hear well sounds like a bass voice
or certain music
with a lot of bass notes,
for example disco music…

The best performance of human hearing coincides with the so called “**zone of music**”, almost the frequencies you can find in a piano.



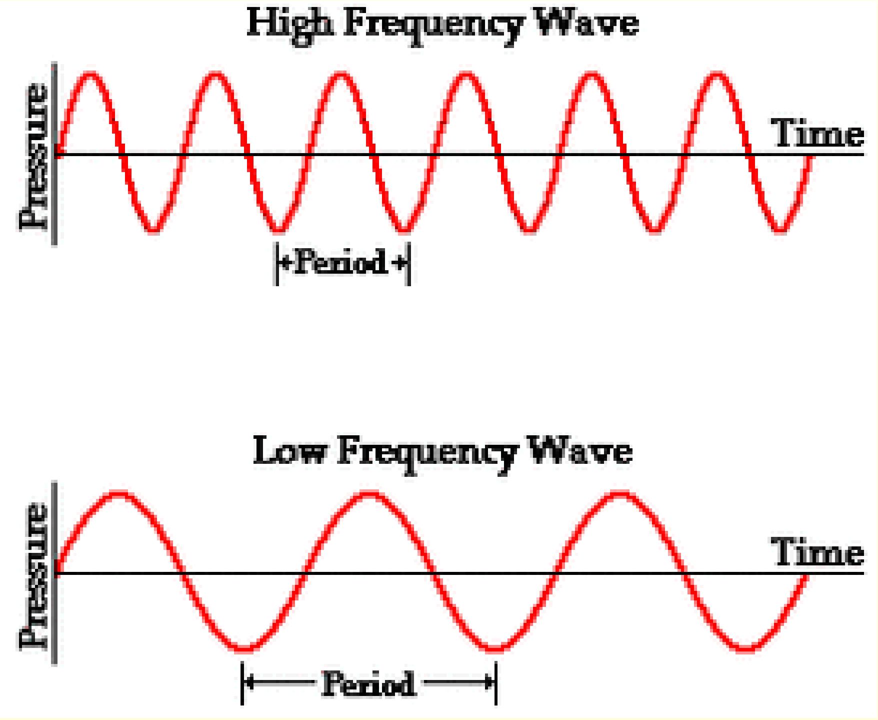
DISTINGUISHING PROPERTIES OF SOUND

There are three typical quantities characterizing sound waves

Property	Physical Quantity
PITCH	FREQUENCY
LOUDNESS	AMPLITUDE
TIMBRE/ TONE	HARMONICS/ OVERTONES

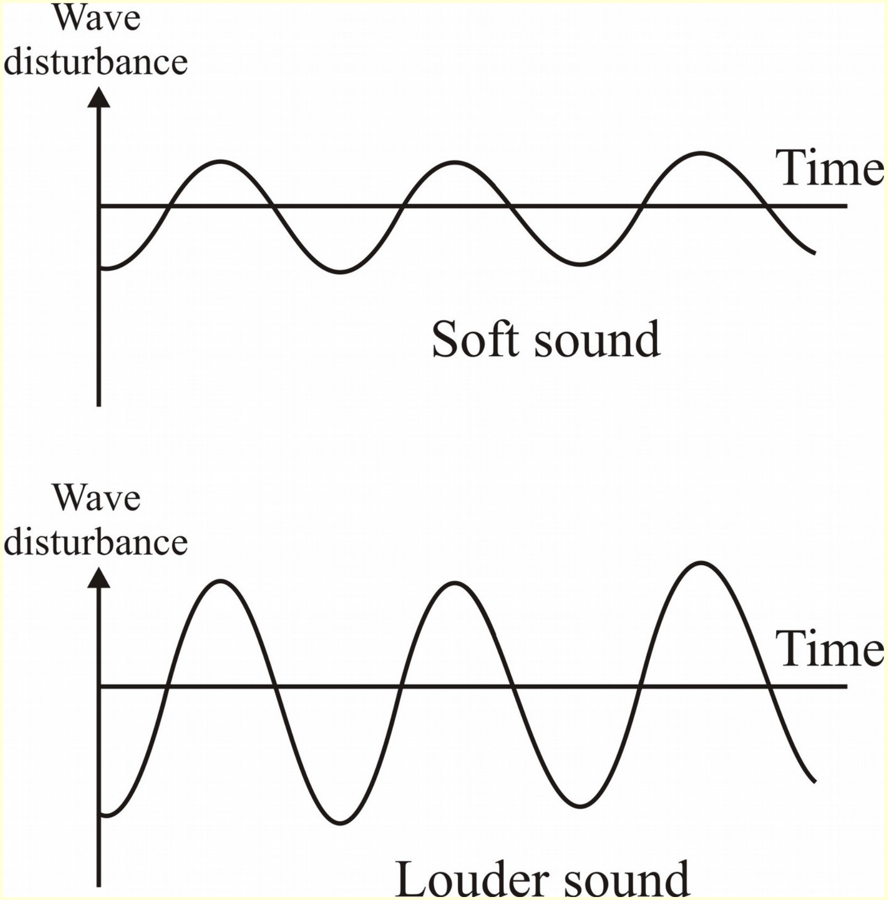
PITCH-FREQUENCY

Frequency represents the number of oscillations
in a second (cycles per second).
Here you can see two waves; they have the same amplitude,
but the first one has a double frequency.
It means that the corresponding sound
is higher than the second one,
precisely
it is an octave higher.
Periods are inversely
proportional to
frequencies.

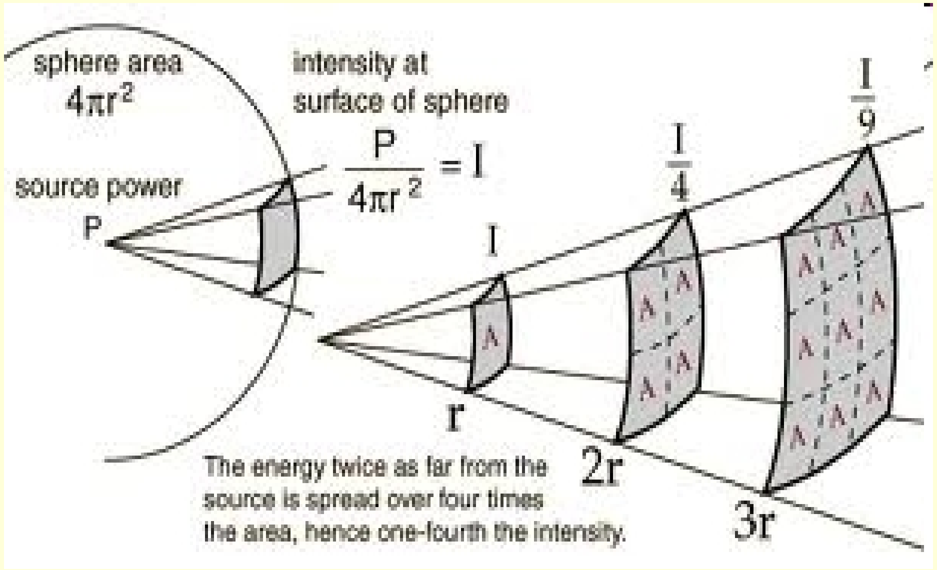


LOUDNESS-AMPLITUDE

In this picture you can see two sound waves, they have the same frequency but different amplitude: the second wave produces a louder sound than the first one.



Amplitude is related to the **intensity** of a sound or **loudness**, that is energy carried by a sound wave in a unit of time and surface that is the medium power per unit of surface.



$$I = \frac{E}{t \cdot S} = \frac{P_m}{S}$$

The intensity decreases when distance increases, precisely

$$I \propto \frac{1}{r^2}$$

It is measured in $\frac{W}{m^2}$

SUBJECTIVE INTENSITY

We have seen that our ears don't have the same sensitivity for all sound frequencies.

So it is useful to express the loudness of sounds through an empirical law that describes the ***physiological sensation or sound intensity level***, it is measured in *decibel, dB:*

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

Sound level describes the actual response of our ears.

$$I_0 = 10^{-12} \frac{W}{m^2}$$

is the threshold of hearing and it corresponds to

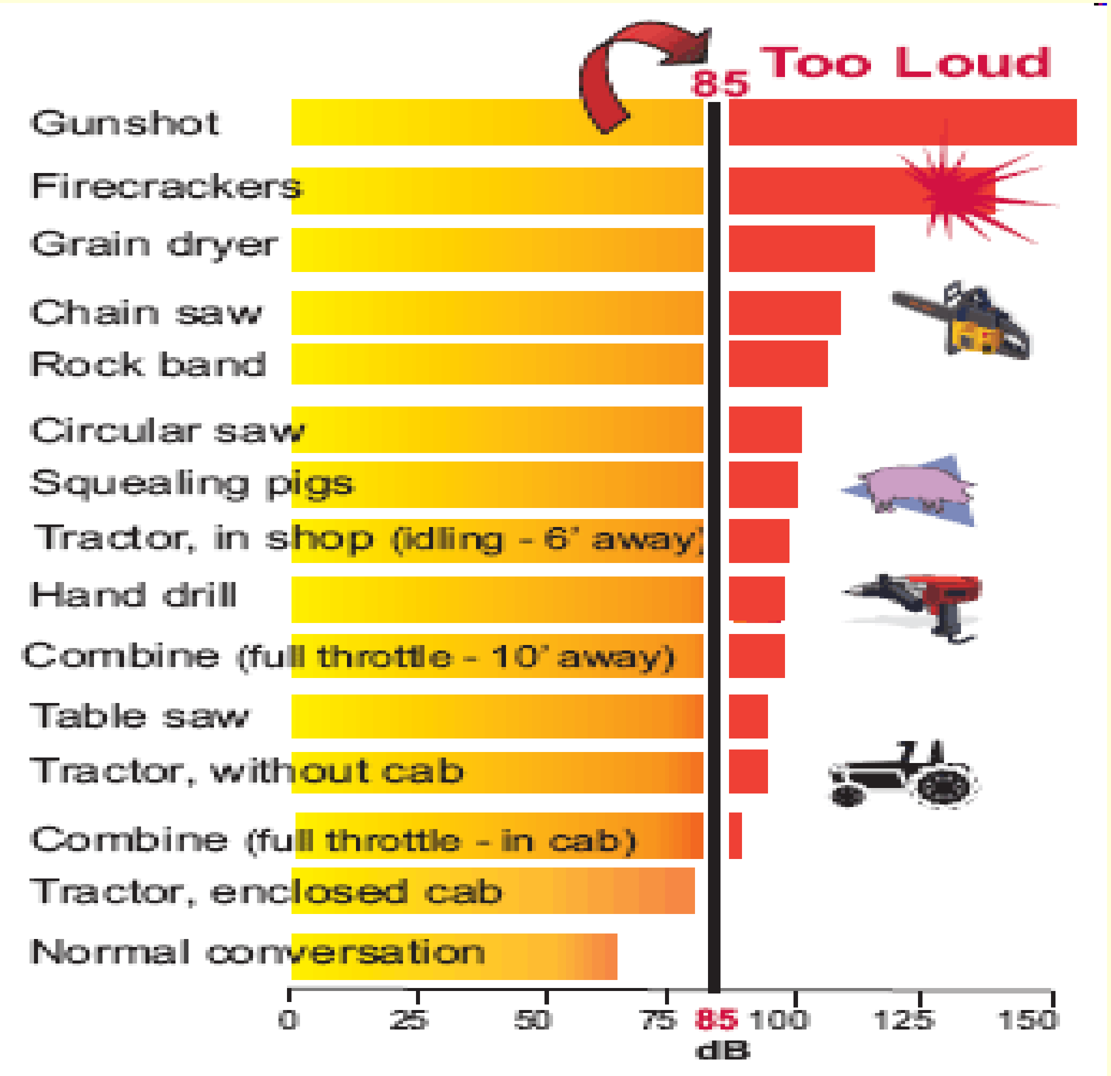
$$\beta = 10 Log \frac{I_0}{I_0} = 10 Log 1 = 0 dB$$

$$I = 1 \frac{W}{m^2}$$

is the threshold of pain and it corresponds to

$$\beta = 10 Log \frac{10^0}{10^{-12}} = 10 Log 10^{12} = 120 dB$$

Sound levels



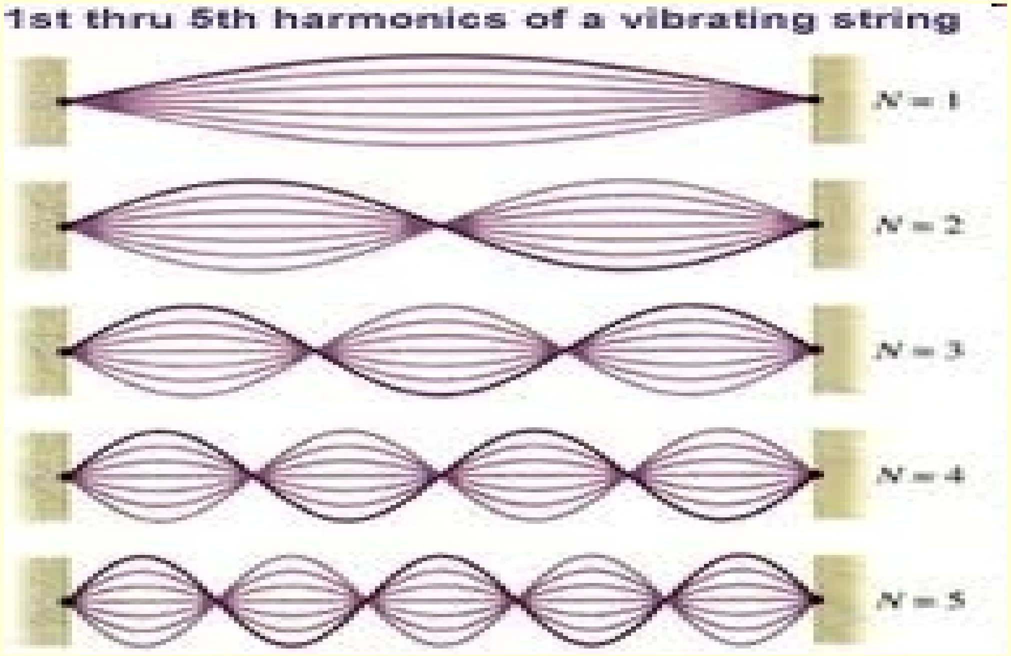
An intensity of 120 dB coincides with the threshold of pain; a 160 dB level causes the breaking of the eardrum. But also a prolonged exposure to pressure levels around 80-90 dB is very dangerous for our ears.

Source	Sound Level (dB)	Intensity (W/m^2)
Nearby jet airplane	150	1000
Machine gun	130	10
Siren, rock concert (**Threshold of Pain**)	120	1
Subway, power mower	100	1×10^{-2}
Busy traffic	80	1×10^{-4}
Vacuum	70	1×10^{-5}
Normal conversation	50	1×10^{-7}
Mosquito buzzing	40	1×10^{-8}
Whisper	30	1×10^{-9}
Rustling leaves	10	1×10^{-11}
Threshold of hearing	0	1×10^{-12}

Table modified from Serway & Vuille. *College Physics*. Boston, MA: Brooks/Cole (2012).

TIMBRE and OVERTONES

We have studied that standing waves have an infinite numbers of typical vibration frequencies; we call them "**resonance frequencies**", "**harmonic frequencies**" or "**overtones**".



$$f_n = \frac{nV}{2L} = \frac{n}{2}\sqrt{\frac{T}{mL}}$$

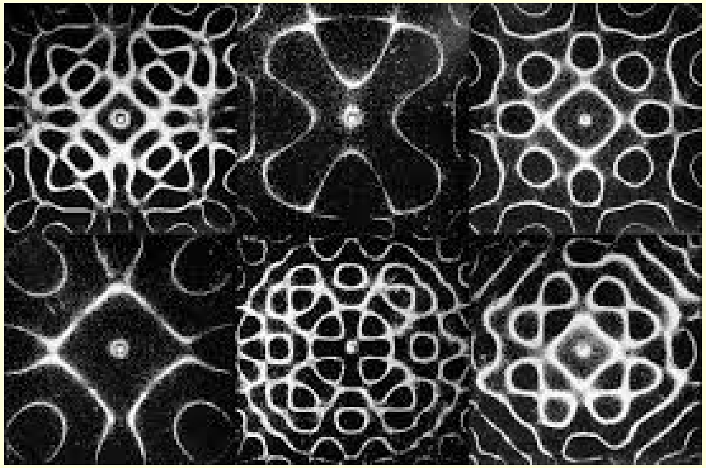
$$\lambda_n = \frac{2L}{n}$$

Prof. Lewin's lecture about standing waves (9′- 22′)

https://www.youtube.com/watch?v=D_RIzl1uCxY

Chladni's plates

You can see standing waves also on a vibrating surface



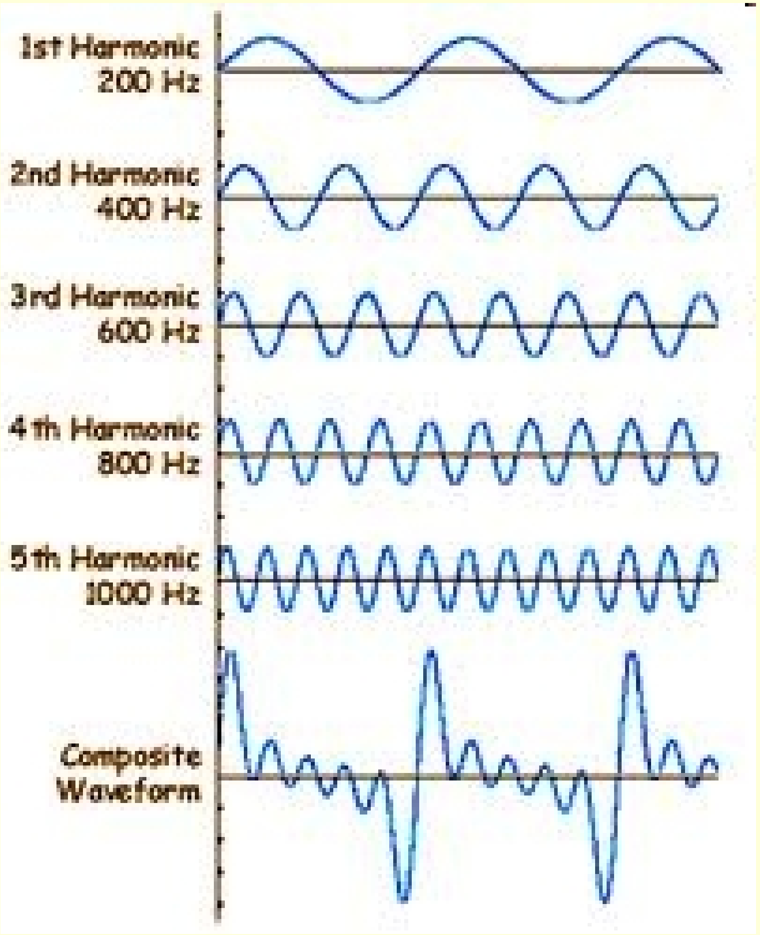
https://www.youtube.com/watch?v=wvJAgrUBF4w

A tuning fork or a computer
can produce
a pure sound.
This perfect sound is represented
by a sine or a cosine wave

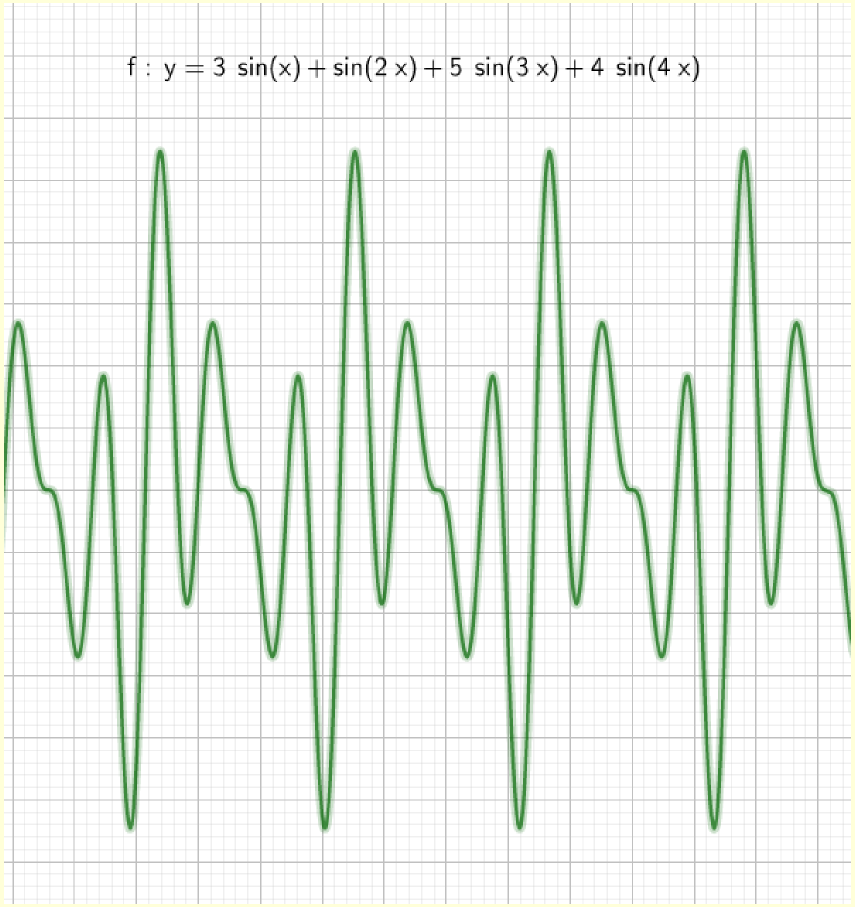
https://www.youtube.com/watch?v=stxtqkZzJ-U

Click here to hear its sound

Sounds produced by music instruments or human voices are not simple waves.
They are given by the superposition of many sinusoidal waves, corresponding to the overtones of the fundamental frequency of the sound.
The composite wave is not a simple sine or cosine wave;
it has a particular shape.



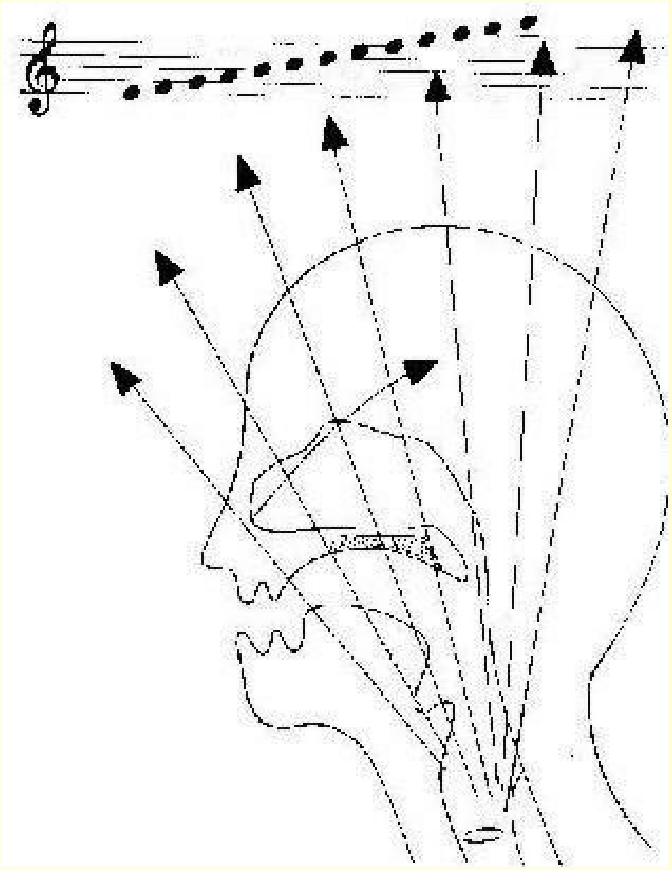
Any voice and any instrument
has typical overtones with a
specific amplitude for every frequency.
So the function given by the addition
of all the harmonics
is different from instrument to instrument
depending on the preponderance
of some overtones over others.



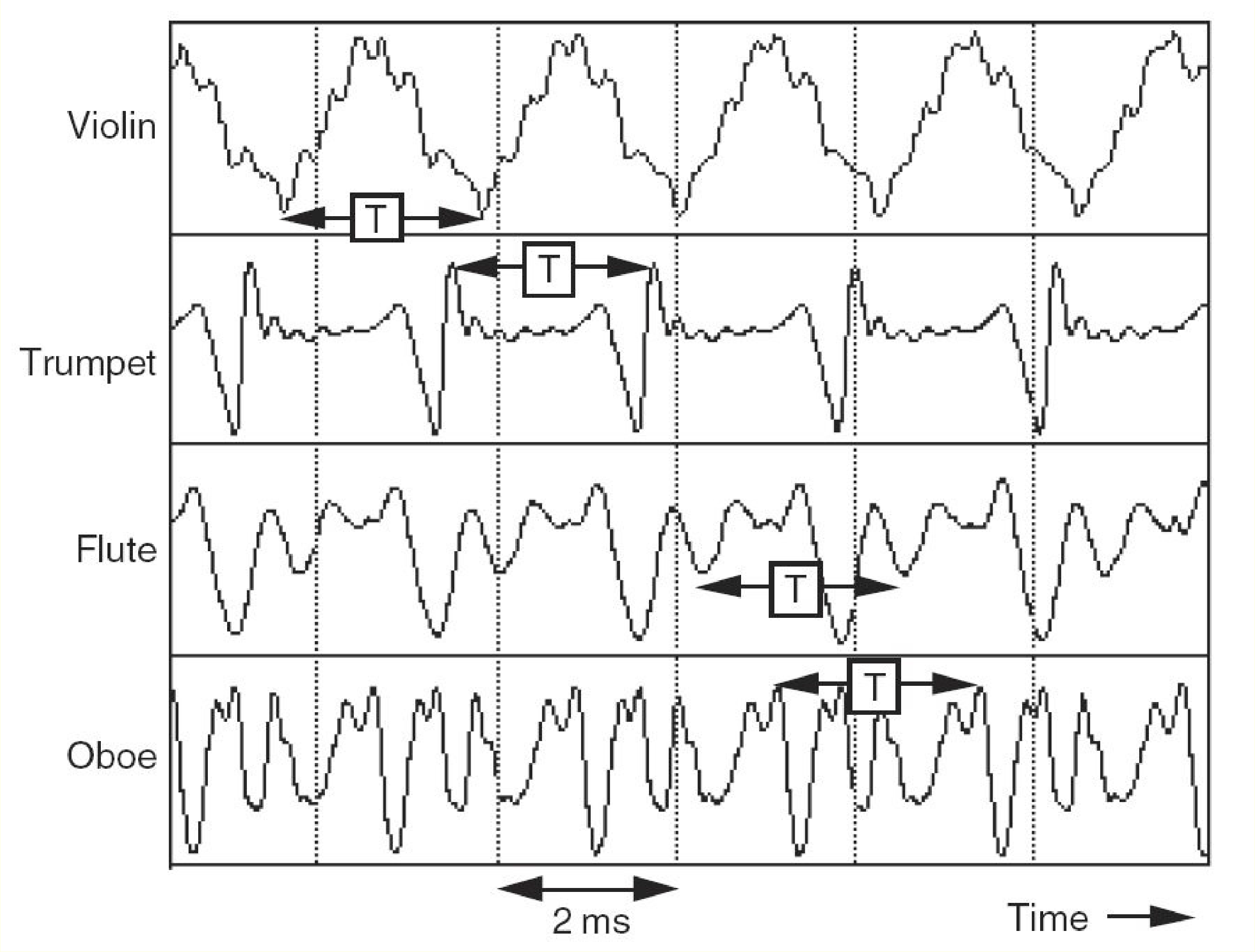
The amplitude of the harmonics is different and the pattern of the complex waves is different too

So the composite waveform is different
from voice to voice,
from instrument to instrument.
The same note, played by a piano
or by a violin or sung by a singer,
produces quite a different effect
on your brain.
This the reason why you can distinguish
the source of the sound.

This property of a sound is called
Timbre or ***Tone.***
Timbre is given by the particular shape of the **sounding board** of each instrument.
Also the tone of a voice is related to the resonance cavities in human body, especially skull bones.

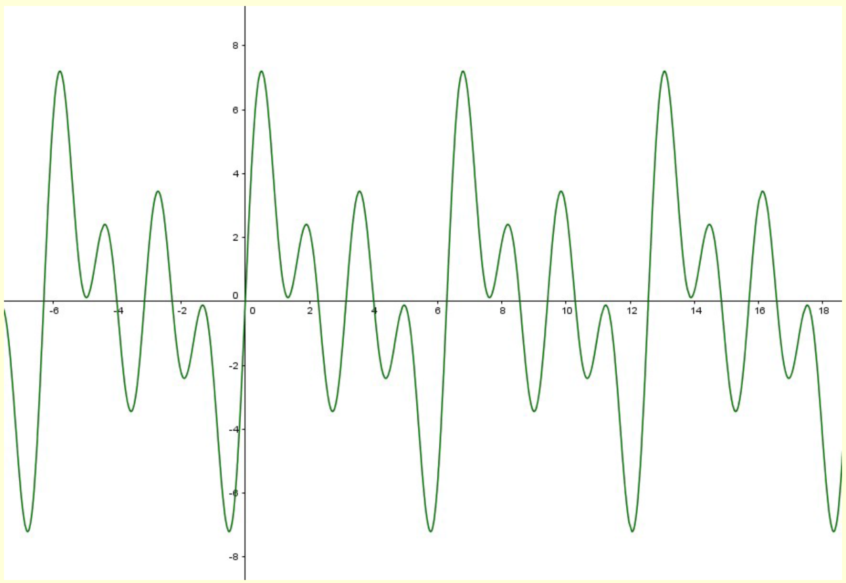


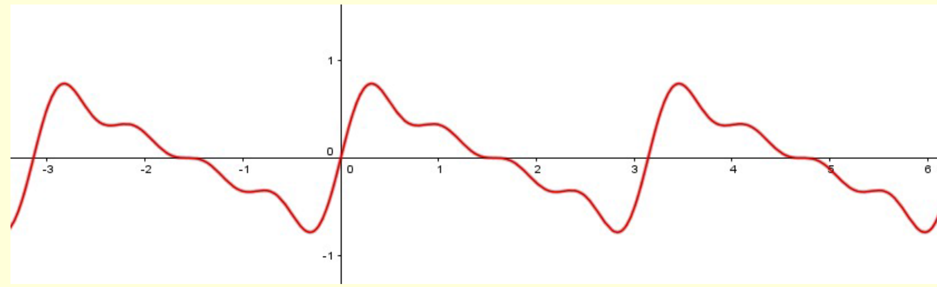
The same note played by different instruments



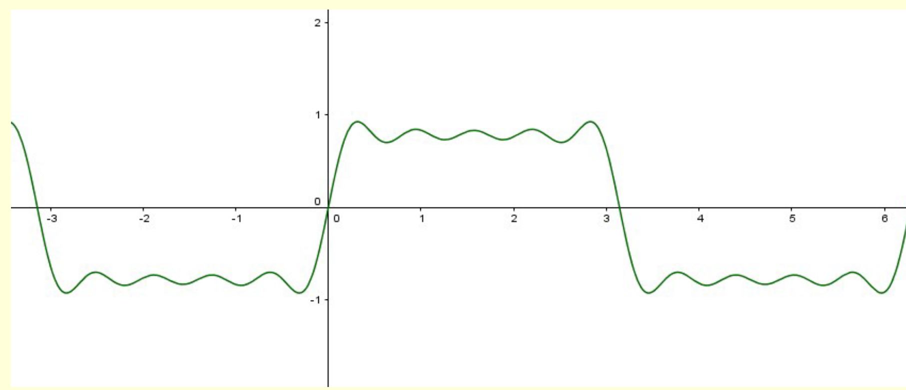
We can try to build something similar with Geogebra

Complex sound



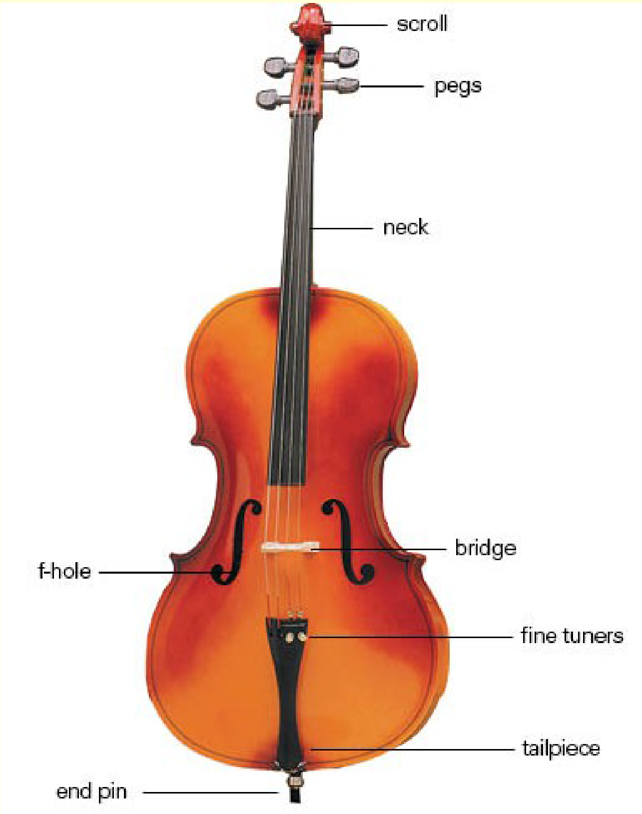


Sawtooth wave



Square wave

A pure sound,
like the one
produced by a diapason,
is not very pleasant.



Singers and music players work hard to take a good sound out of their instrument or their throat.

Voices and instruments rich in low frequencies produce a higher number of audible harmonics; so a bass voice or a cello sound richer and more pleasant than higher sounds, like those given out by a “piccolo”. Our ears can hear up to 40 overtones.

Low notes produce a high number of overtones in the range of the best audible frequencies.

Music zone includes 30 to 4180 Hz notes.

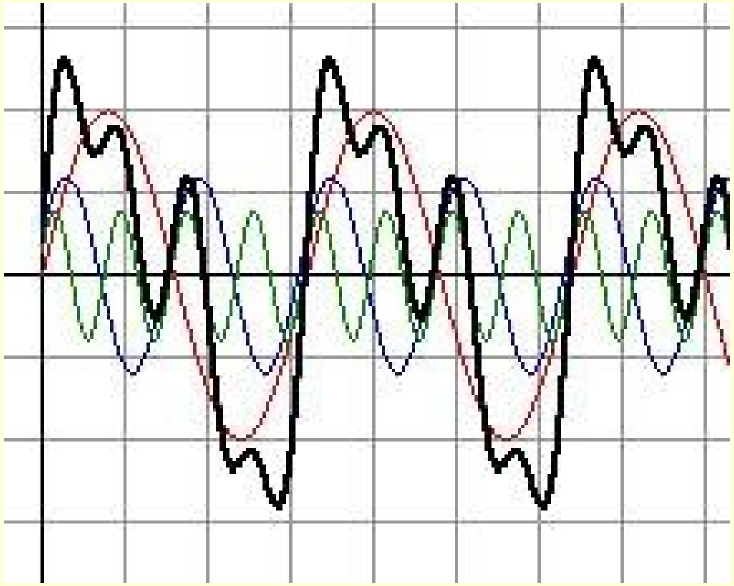
110	523	3951	Fundamental Frequency
220	1046	7902	H
330	1569	11853	A
440	2092	15804	R
550	2615	19755	M
660	3138	23706	O
770	3661	27657	N
880	4184	31608	I
990	4707	35559	C
1100	5230	39510	S
1210	5753	43461	
1320	6276	47412	
1430	6799	51363	
1540	7322	55314	
1650	7845	59265	
1760	8368	63216	
1870	8891	67167	
1980	9414	71118	
2090	9937	75069	
2200	10460	79020	
2310	10983	82971	
2420	11506	86922	
2530	12029	90873	
2640	12552	94824	
2750	13075	98775	
2860	13598	102726	
2970	14121	106677	
3080	14644	110628	
3190	15167	114579	
3300	15690	118530	
3410	16213	122481	
3520	16736	126432	
3630	17259	130383	
3740	17782	134334	
3850	18305	138285	
3960	18828	142236	
4070	19351	146187	
4180	19874	150138	
4290	20397	154089	
4400	20920	158040	

Some videos about timbre and overtones

https://www.youtube.com/watch?v=nlv5bylQDsE

https://www.youtube.com/watch?v=VRAXK4QKJ1Q

https://www.youtube.com/watch?v=q-Z4kndewSw



A german singer shows overtones chant technique

https://www.youtube.com/watch?v=VGbFB91eM34

Some people are able to sing
two tones at the same time
reinforcing one of the overtones

https://www.youtube.com/watch?v=X9QVlXoxGBE

Hymn to joy and overtones chant

Let's do a reading by Sir James Jeans about the timbre (next slide),

watch a video about organ stops

https://www.youtube.com/watch?v=irbk3JW5ebc

Sir James Jeans
British physicist
and mathematician

and listen a little GREAT music…

https://www.youtube.com/watch?v=e4uXwzMIadc

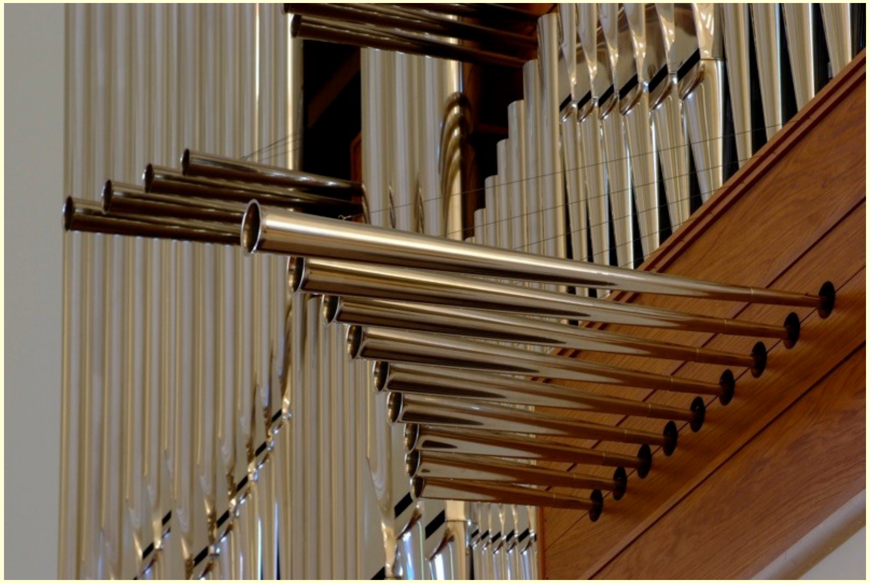
https://www.youtube.com/watch?v=XKRj-T4I-e8

https://www.youtube.com/watch?v=MIckvcf69wo

Timbre and the Harmonic Analysis of Sound

By *timbre* is meant the distinguishing or characteristic quality of a sound; it is by their timbre that we recognise an instrument, a voice or the quality of an organ-stop, regardless of the pitch or intensity of the note it is sounding.

The investigations of Helmholtz proved that the timbre of a sound is determined by the proportions in which the various natural harmonics are heard in it. It is obvious that something of this kind must be true. We know, for instance, that the more we hear of the higher harmonics in any sound, the farther we get away from the dull quality of the tuning-fork, which is characterised by a



complete absence of upper harmonics. Thus we may say that the upper harmonics add life, richness and interest to the foundation tone. And as they are all at least an octave higher in pitch, they will obviously add brilliance, and possibly shrillness also.

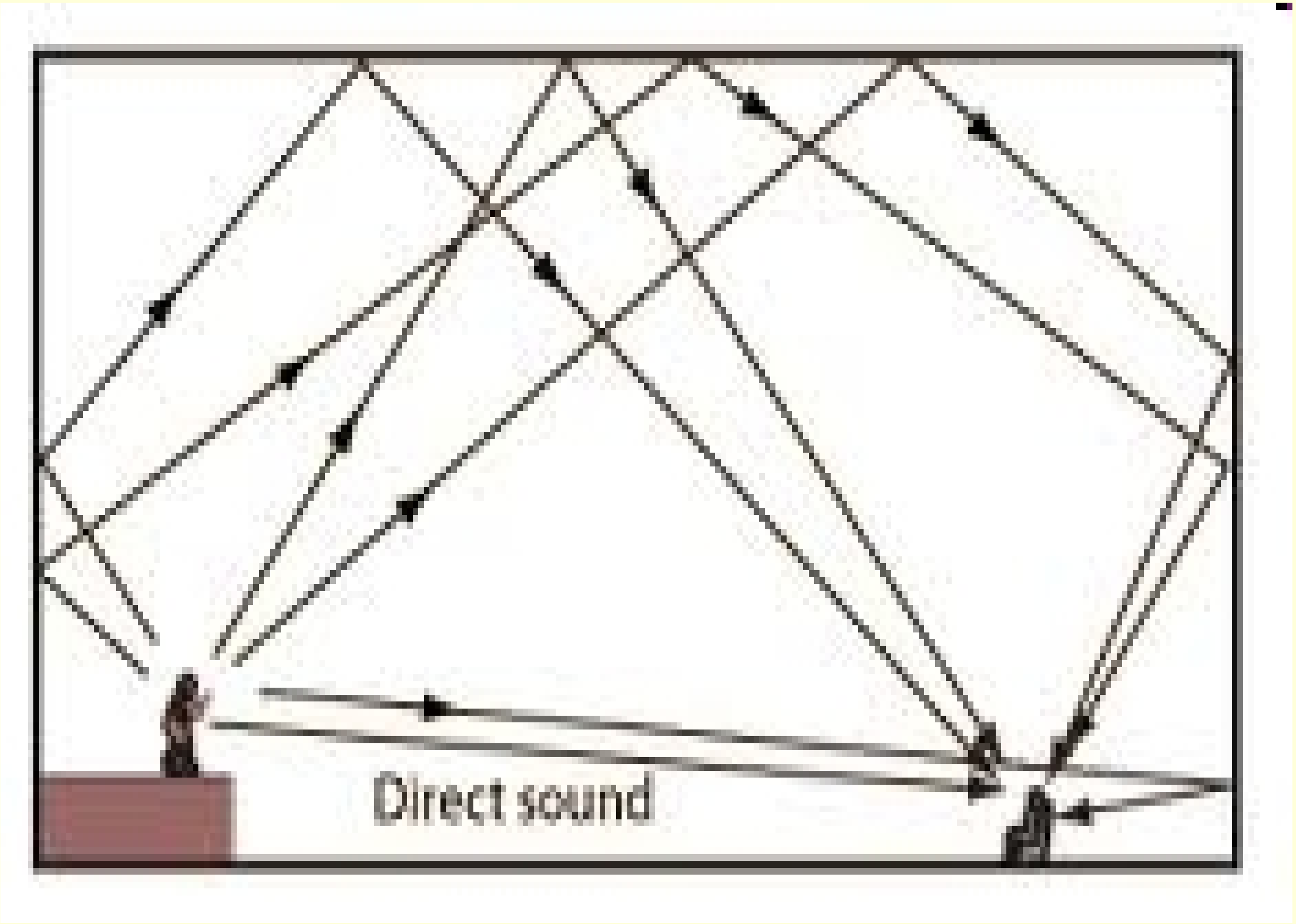
The detailed effects of the various harmonics are a matter for careful study. There are several devices which enable us to blend harmonics as we please, and study the result. On large organs, the choir manual frequently contains stops which sound the first eight (or even more) harmonics separately, and by combining these in various ways, sounds of different timbre can be produced, and their harmonic composition noted. The great manuals of old organs often contained similar selections of stops. There are also various electrical instruments which permit of the harmonics being blended in any relative strengths we desire.

Sir James Jeans, Science and Music

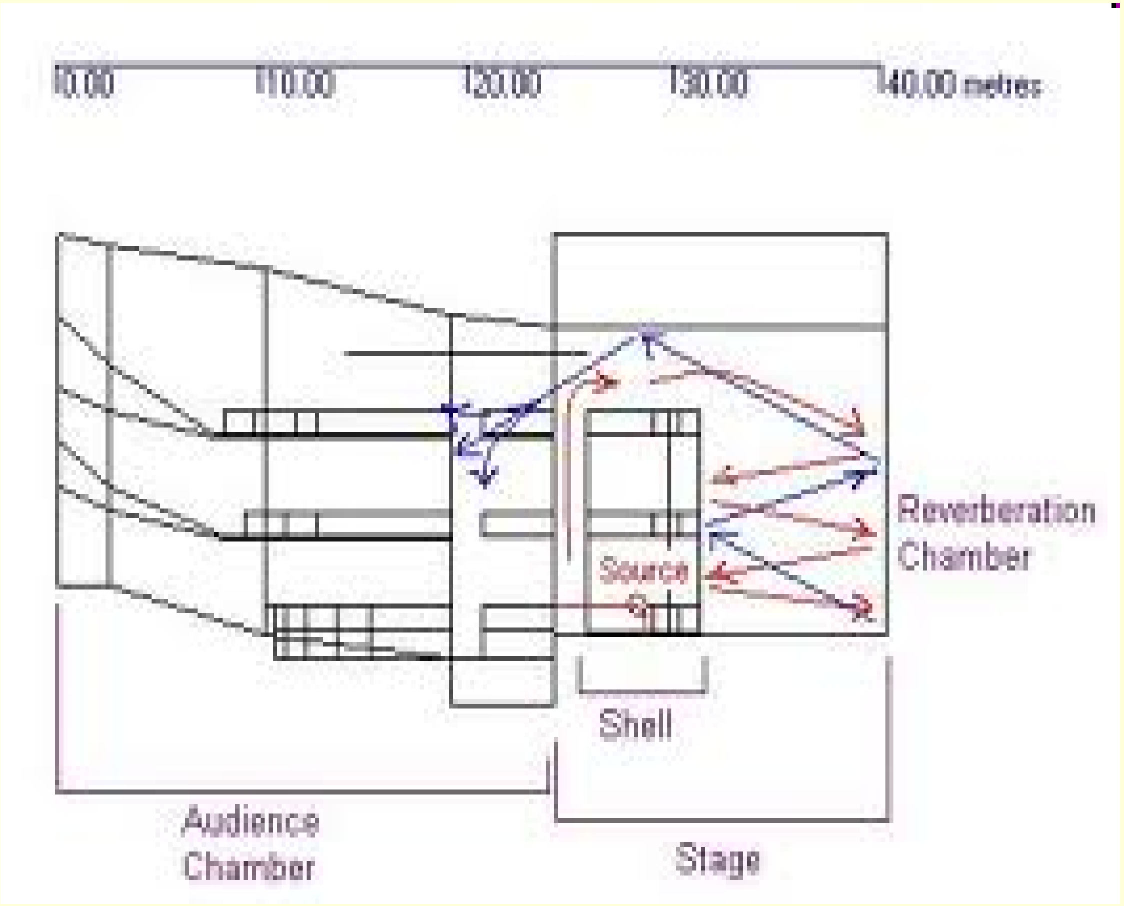
REFLECTION OF SOUND

Sound waves <u>reflect</u> just like
every wave does.
So, if you speak or sing in a room,
sound reflects against the walls and the
superposition of the direct waves with the
reflected waves makes the sound louder.
That happens because your ears can’t
separate two sounds if they are nearer than
1/10 sec.
This is the <u>reverberation</u> of sound.

The reflection of a voice in a room



Engineers who project concert halls must pay particular attention to reverberation.



In fact some reverberation
is necessary to make music audible
everywhere in the room,
but the sound repercussion
must not be too lengthy,
otherwise people would hear
a sort of sound jam…
and it would not be pleasant.

https://www.youtube.com/watch?v=cvr-TRuOzqM

(anechoic and reverberation rooms)

Our ears can distinguish sounds if they are separated by an interval of 1/10 sec.

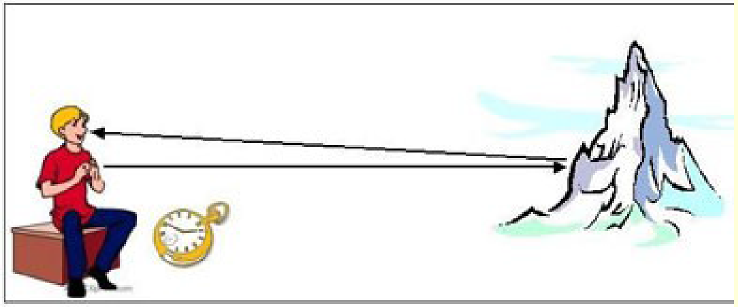
So it's easy to calculate the <u>shortest distance</u> between the sound source and the reflecting wall you must have to hear the echo of your voice.

ECHO

ECHO

ECHO

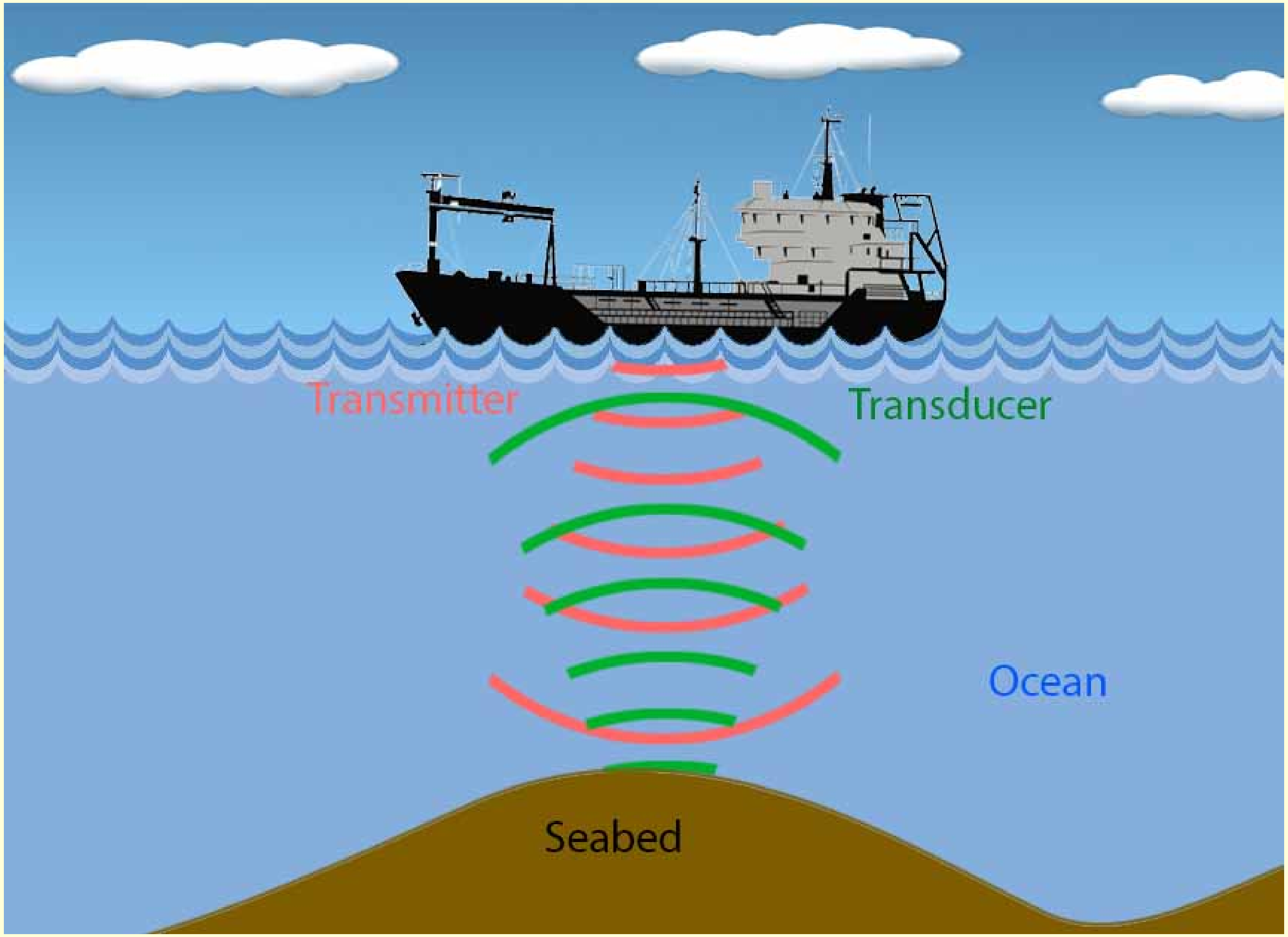
ECHO



$$2D = 340\, m/s \cdot \frac{1}{10}\, s = 34\, m$$

$$D = 17\, m$$

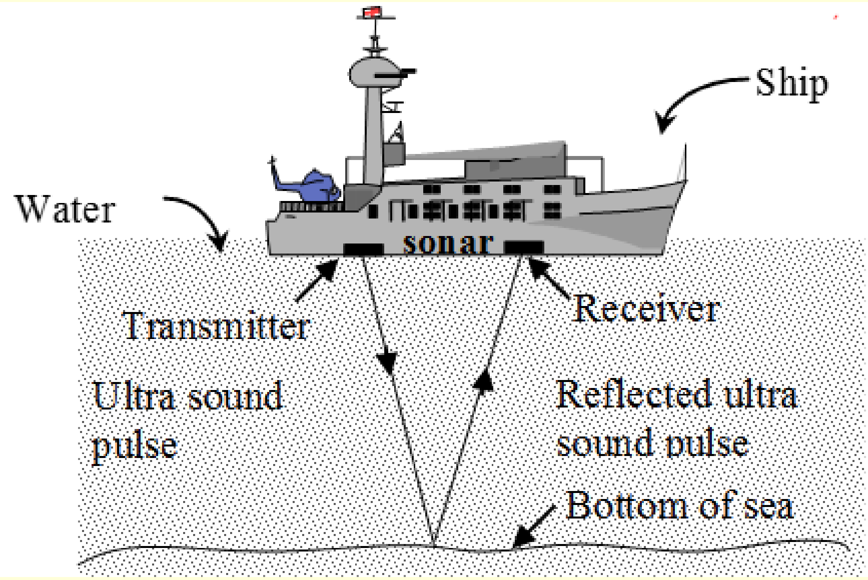
The Sonar works on the reflection of sound waves in the water.



Sonar is used to develop nautical charts, execute seafloor mapping, locate shipwrecks and predict underwater hazards.

In fact, Sonar's patent was authorized after witnessing the events that led to the Titanic's tragic sinking.

Its primary purpose was to identify objects lurking beneath the ocean's surface in order to avoid underwater collisions.



Assuming that the speed of sound in water is 1500 m/s and it takes 0.4 s for an echo,

distance = speed x time = = 1500 m/s x 0.4 s = 600 m

An echo however is the time there and back so the depth of the water is half this:

→ D = 300 m

INTERFERENCE OF SOUND

Sound waves interfere
like every wave does.
We have already studied the
characteristics of this phenomenon.
So you should remember
the conditions that cause
"constructive or destructive interference".
With regard to sound, there is a particular
phenomenon related to interference,
which is called "**beats**".

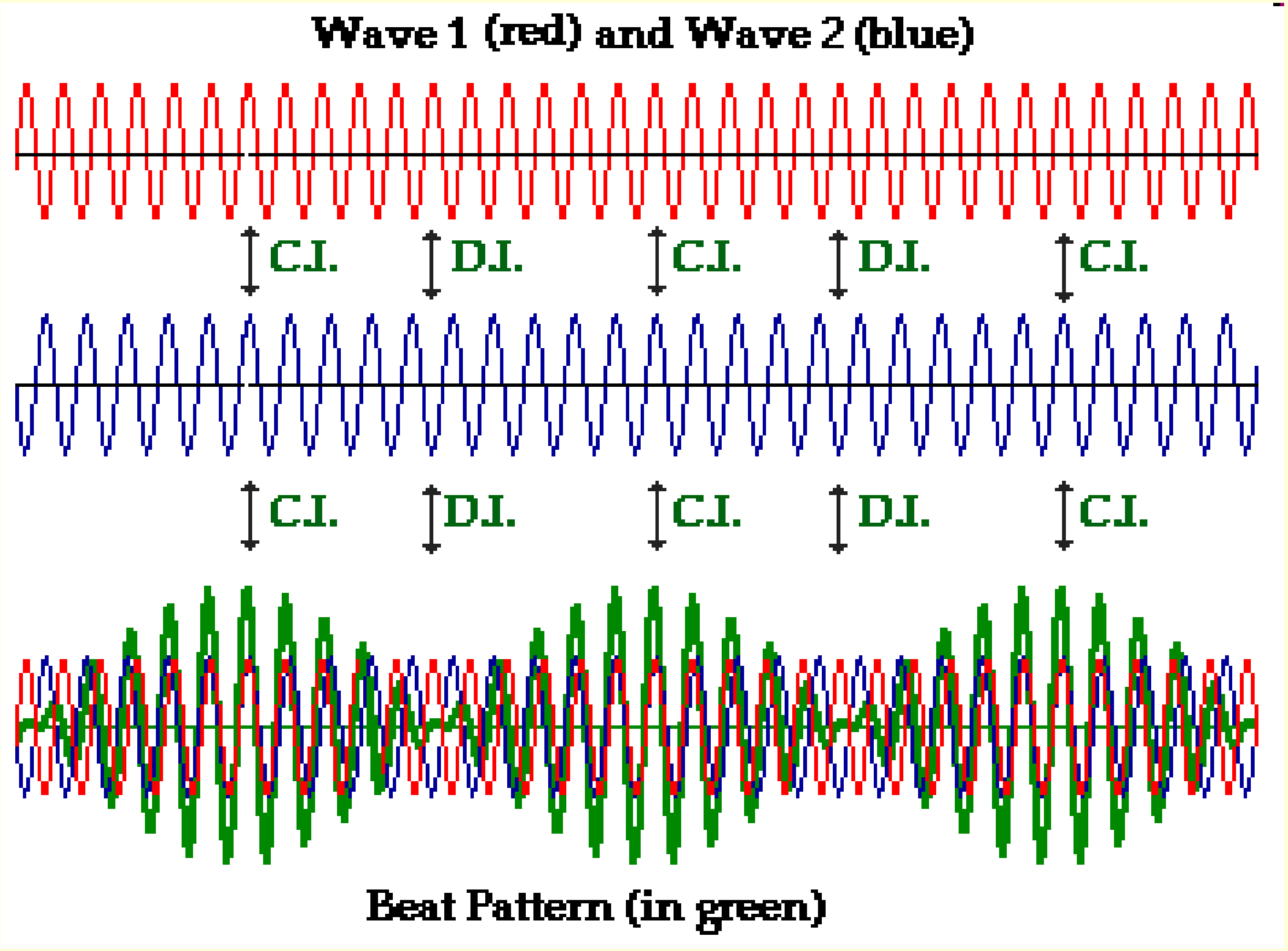
BEATS

Beats take place when there is interference between two waves that have quite **a similar frequency**. Their superposition generates a typical sound of variable amplitude.

Amplitude changes in a sinusoidal way with a frequency called "**beat frequency**". This frequency is given by the difference of the two single frequencies:

$$f_{beats} = \left| f_2 - f_1 \right|$$

So beats are slower if the difference between frequencies is small and faster if the difference is bigger.



The frequency of the resulting wave is given by

$$f = \frac{f_1 + f_2}{2}$$

Let's watch a short video about beats

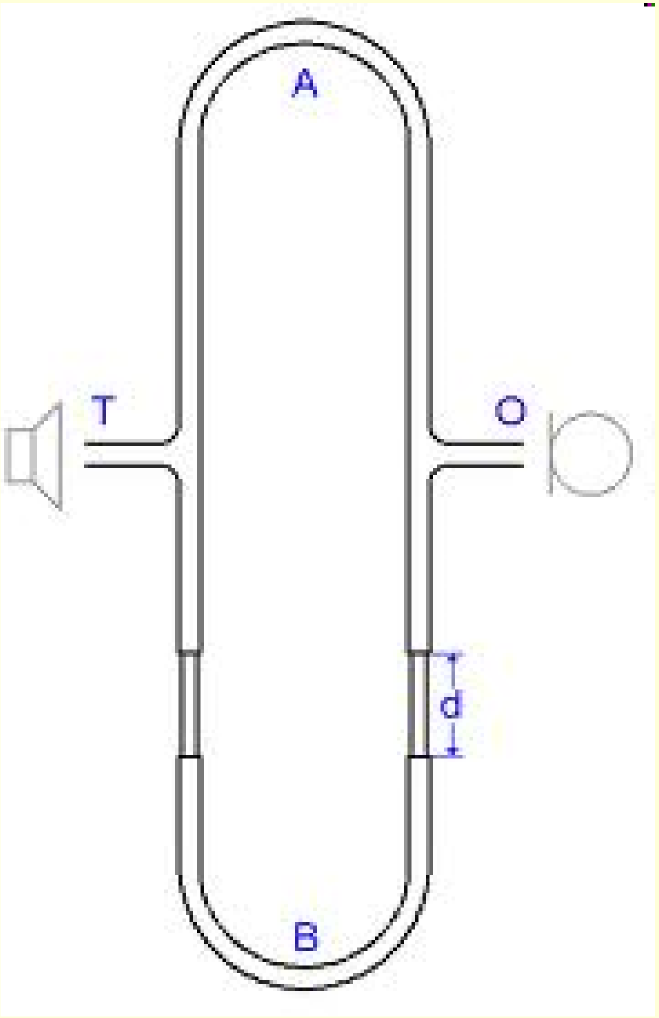
https://www.youtube.com/watch?v=IQ1q8XvOW6g

Try to create a geogebra file to visualize beats!

Beats are a phenomenon that musicians know very well.
They are used to tune instruments and to create particular effects, for example, with organs.
If you are listening to a singing choir and you hear beats…, probably some singers are not well-tuned.

Laboratory: Quincke Tube

You can experiment interference of sound waves
using an instrument called
Quincke Tube
from the name
of its inventor.
The sound produced
by a loudspeaker
goes into the two
branches of the tube.
Your ear is near
the other hole.



The tube seems a little like
a "slide trombone"
so you can change
the length of one branch
pulling it out.

When the two branches have the same length or the difference between them is a multiple of the wave length of the sound λ,

there will be constructive interference,

so you will hear a louder sound.

When the difference between the two lengths is a multiple of an half wave length, you will hear a very weak sound or nothing at all, because there will be destructive interference.

THE AIM OF YOUR EXPERIMENT

So you can calculate the sound wave length measuring the distance between points of constructive interference and points of destructive interference.
If you know the frequency of the sound, you can get the speed of sound.
If you assume that the speed of sound is around 340 m/s, you can derive its frequency.

GOOD WORK TO EVERYBODY!