Acoustics and Ultrasonics: # Lec 3-4

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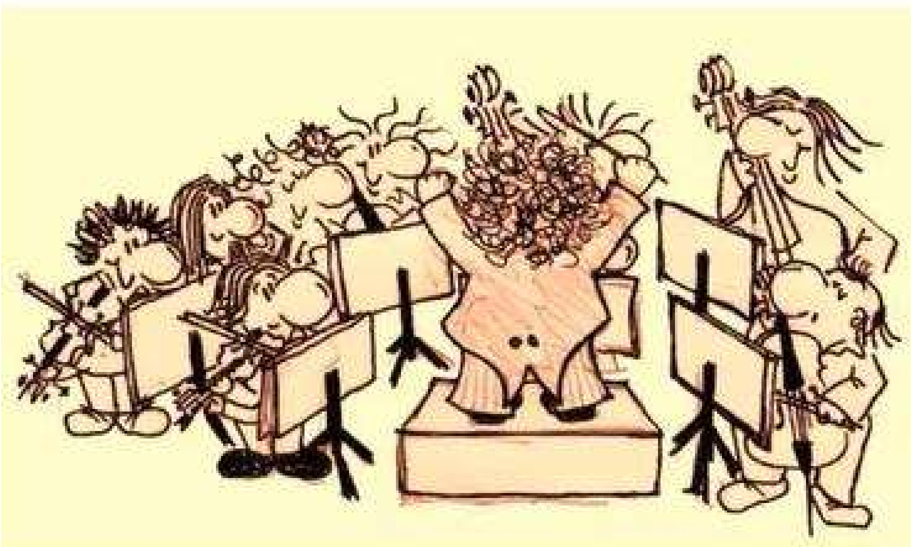
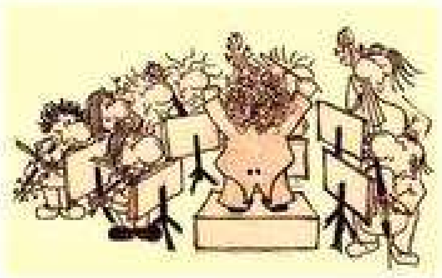
Many sounds at the same time



Easy to hear – and identify – different instruments also when they play at the same time

Easy to distinguish between the two persons – even if they talk at the same time!

How do we do this separation?



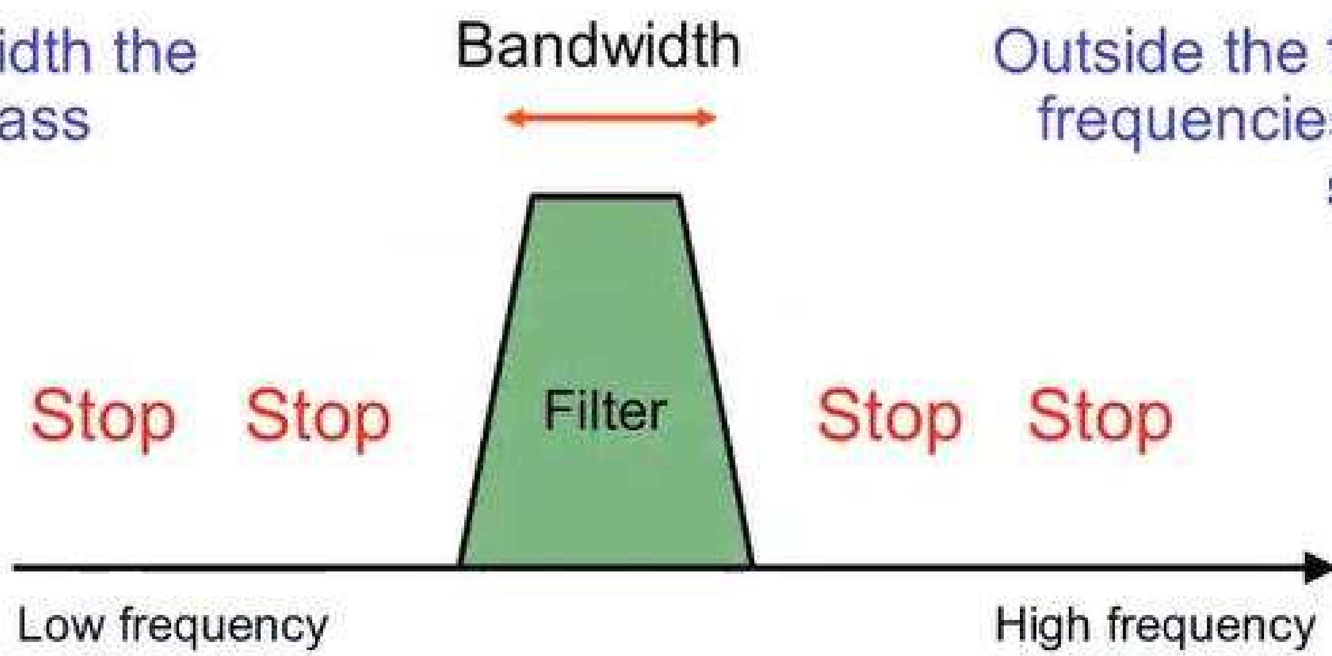
We use our
auditory filters
to separate sounds from various soundsources

The auditory filters are related to the movement of the *Basilar membrane* in the innner ear

Filter principle, band-pass

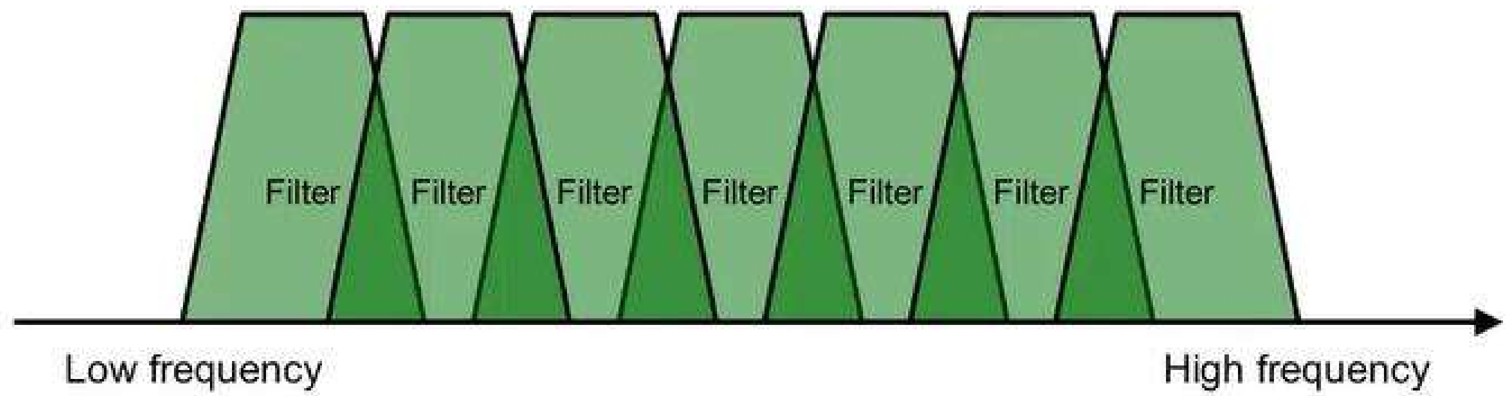
Within the bandwidth the frequencies will pass through the filter

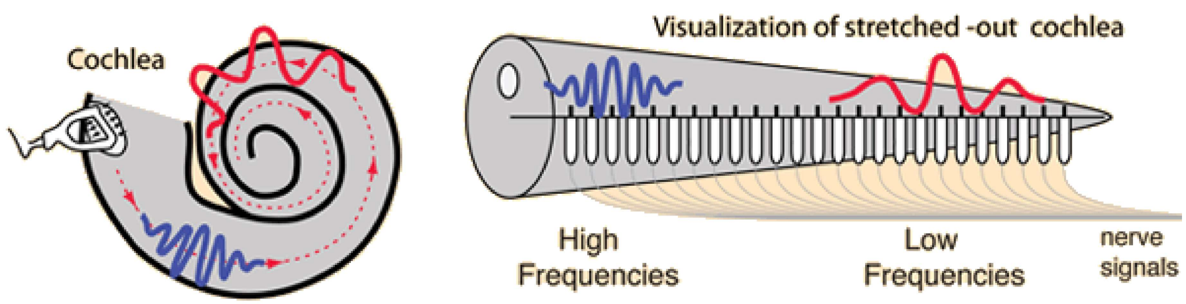
Outside the filter the frequencies will be stopped



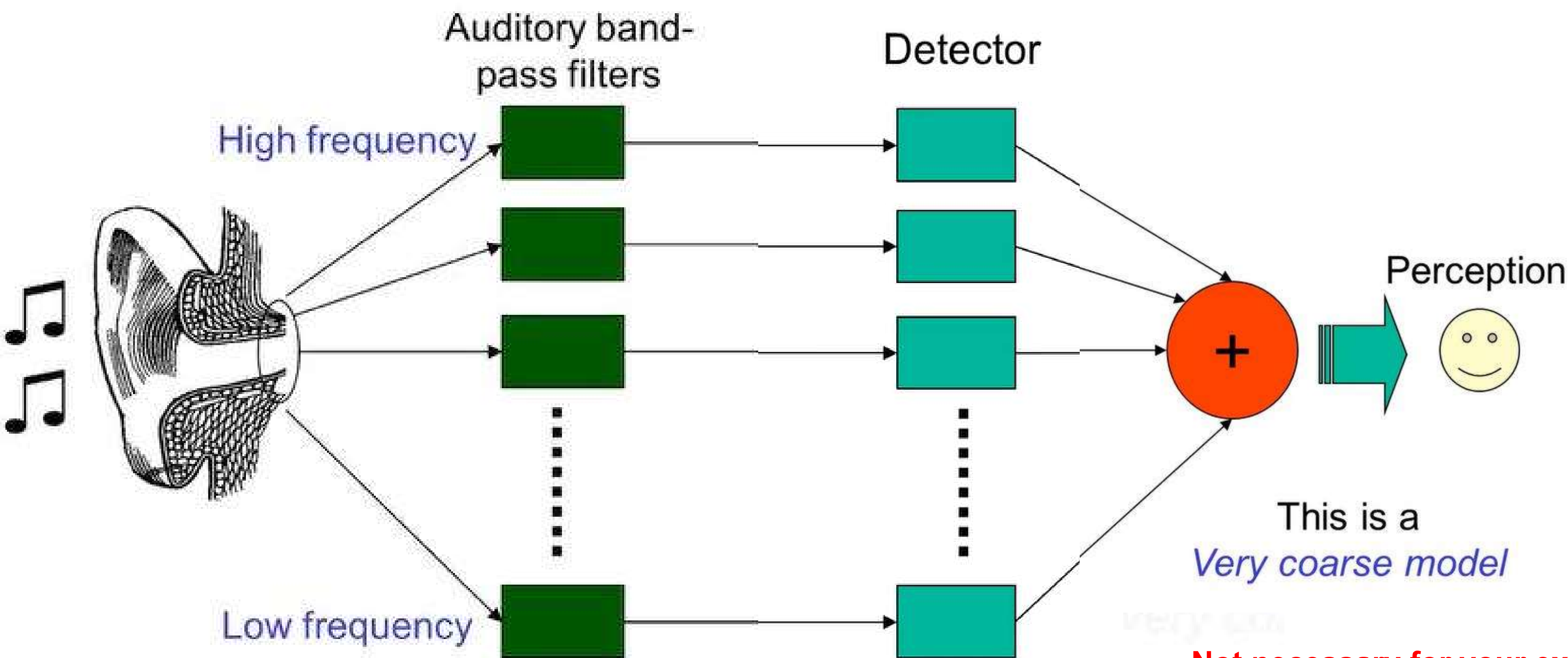
Auditory filters

Many band-pass filters together cover the whole frequency range



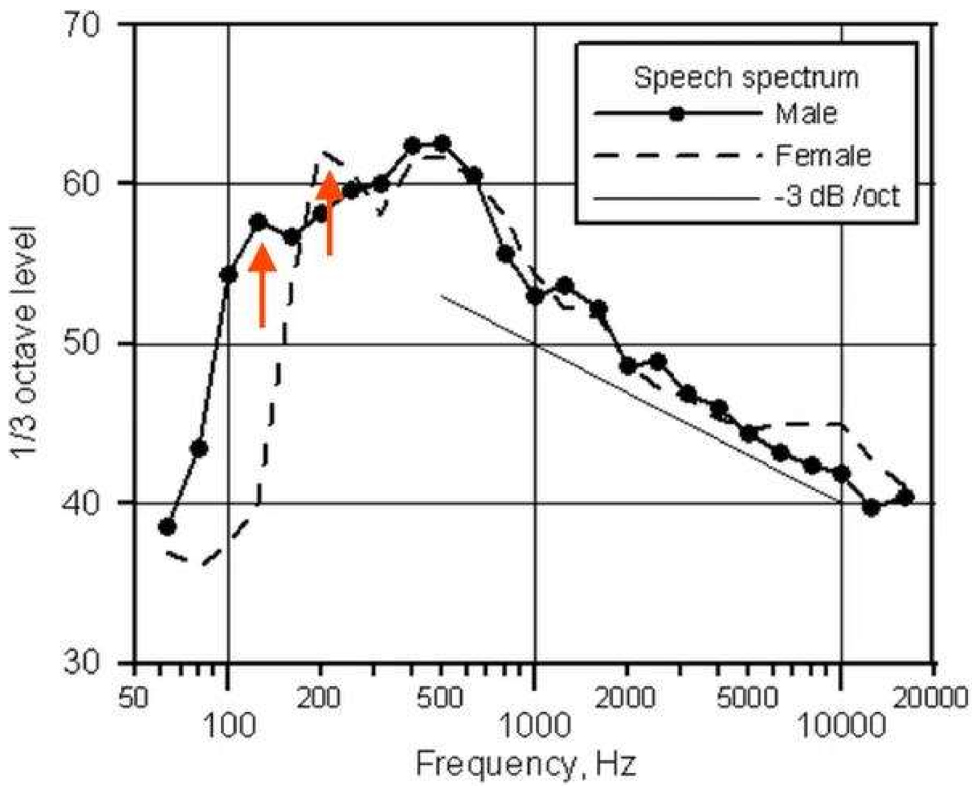


Model for frequency selectivity



Not necessary for your exam

Male and female speech spectrum



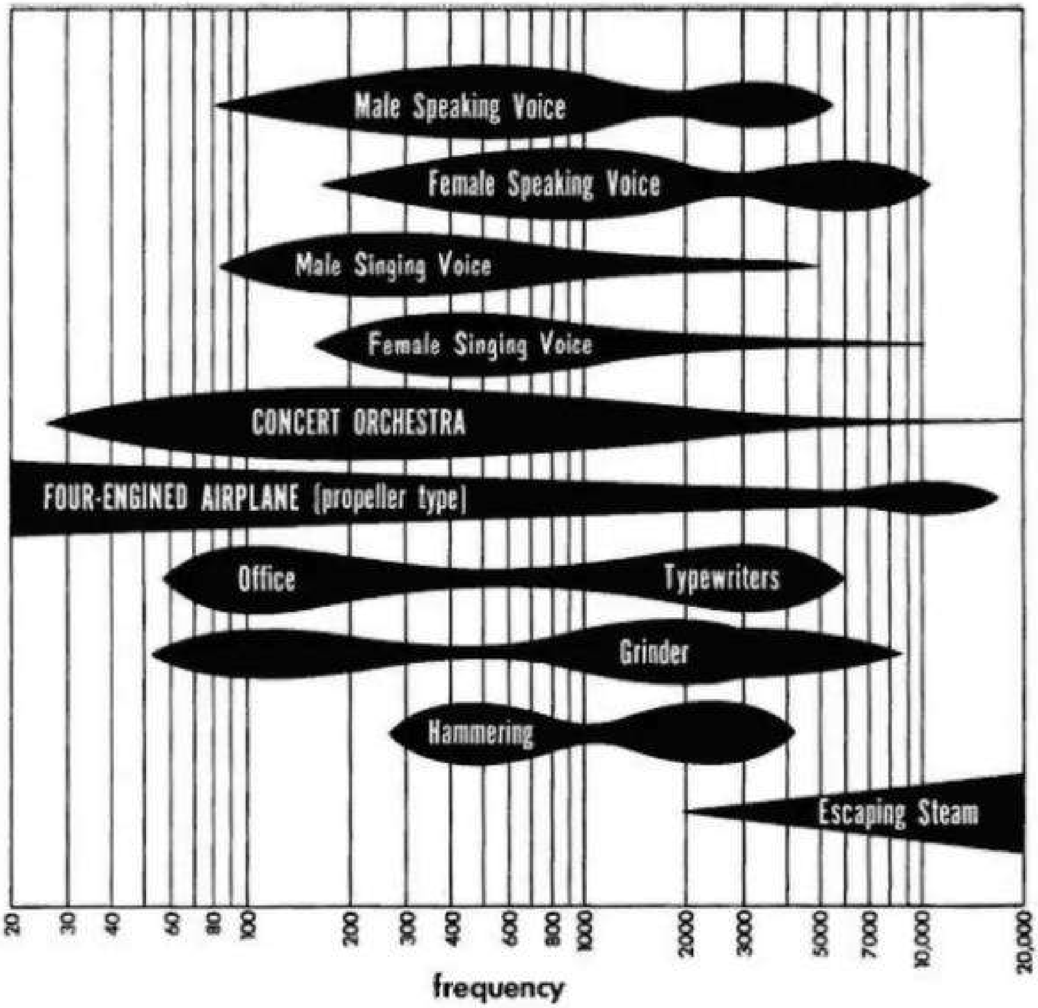
Typical fundamental frequency
- male: 125 Hz
- female: 250 Hz

Detected by different auditory filters

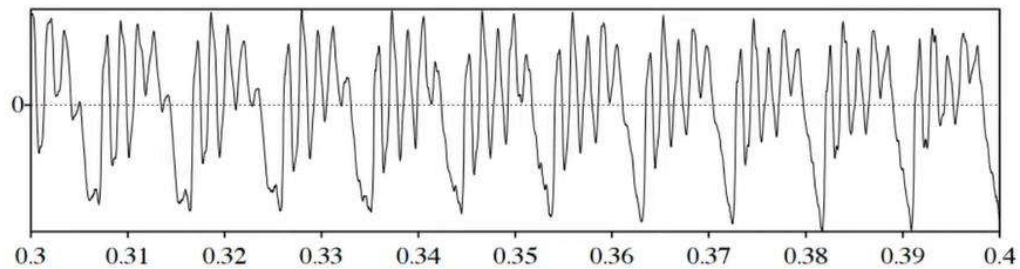
Same spectrum above the fundamental frequency

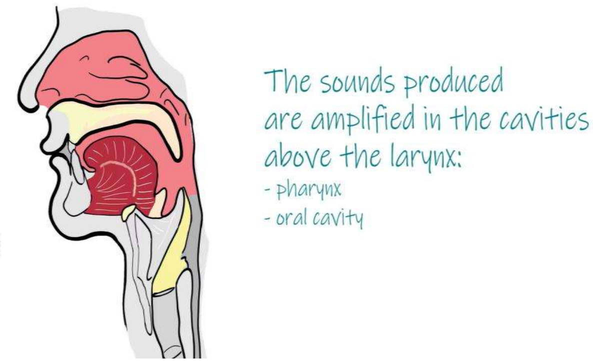
https://www.youtube.com/watch?v=NUNesRksmk4

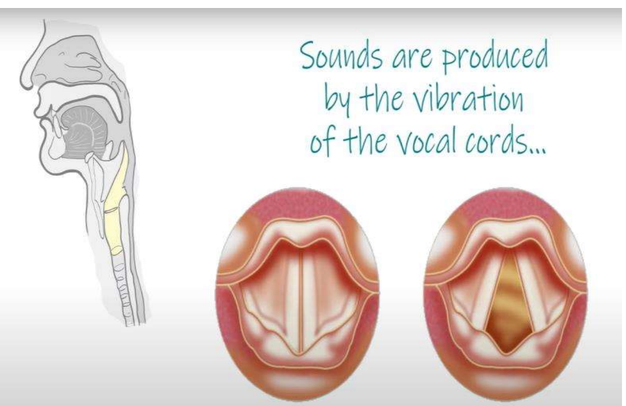
Psychoacoustics

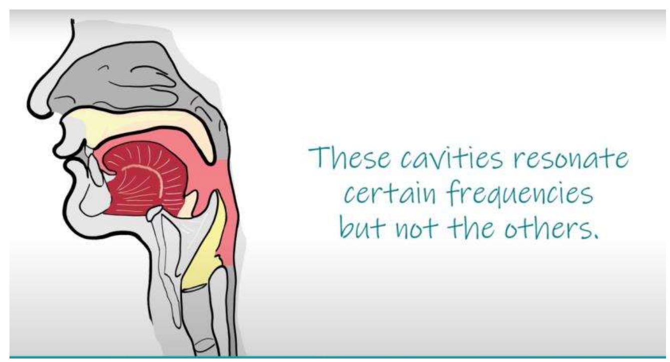


Psychoacoustics







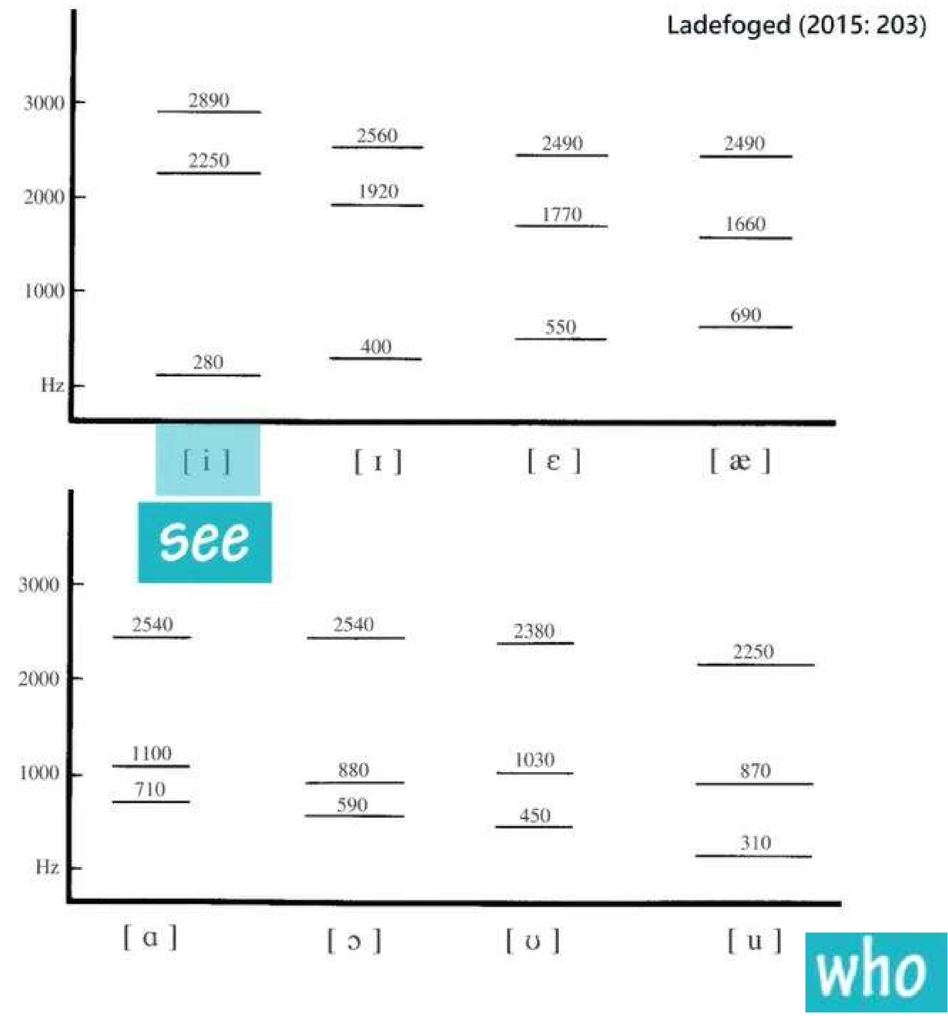


Psychoacoustics

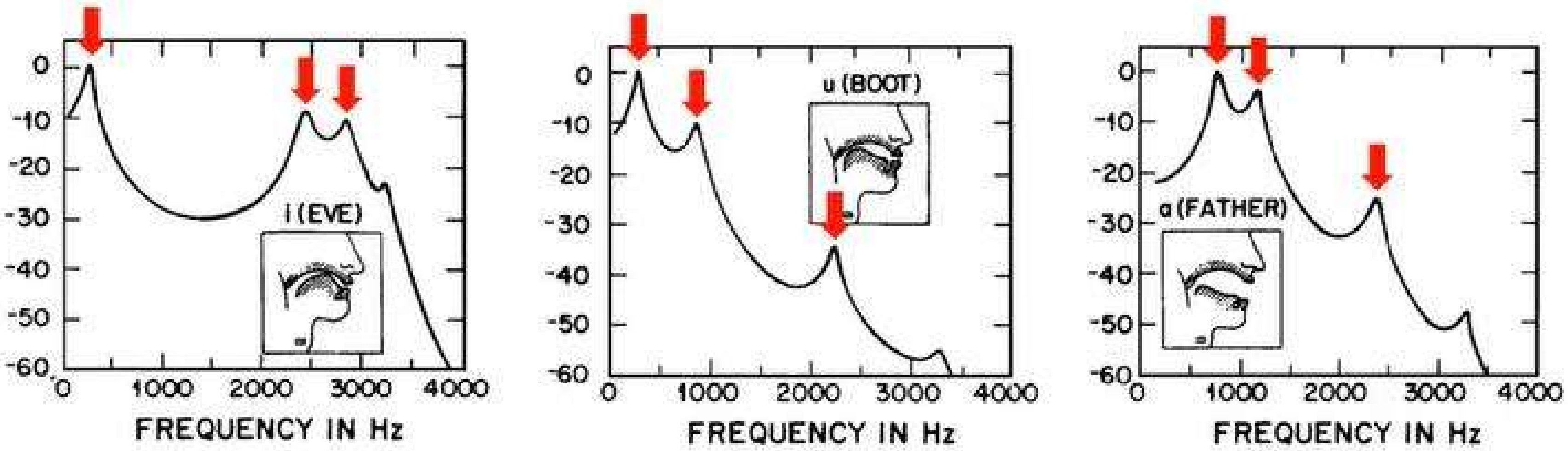
What is a formant?

Formants, or formant frequencies, are peaks or maximal points in the sound spectrum.

Ladefoged (2015: 203)



The spectrum of a vowel



Eve Boot Father

Red arrows show the formants

We use the formants to distinguish between vowels

They go into different auditory filters

https://www.youtube.com/watch?v=NUNesRksmk4

Psychoacoustics

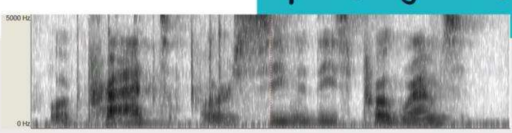
There are computer programs that can help you analyze sounds by showing you their components.

Computer programs

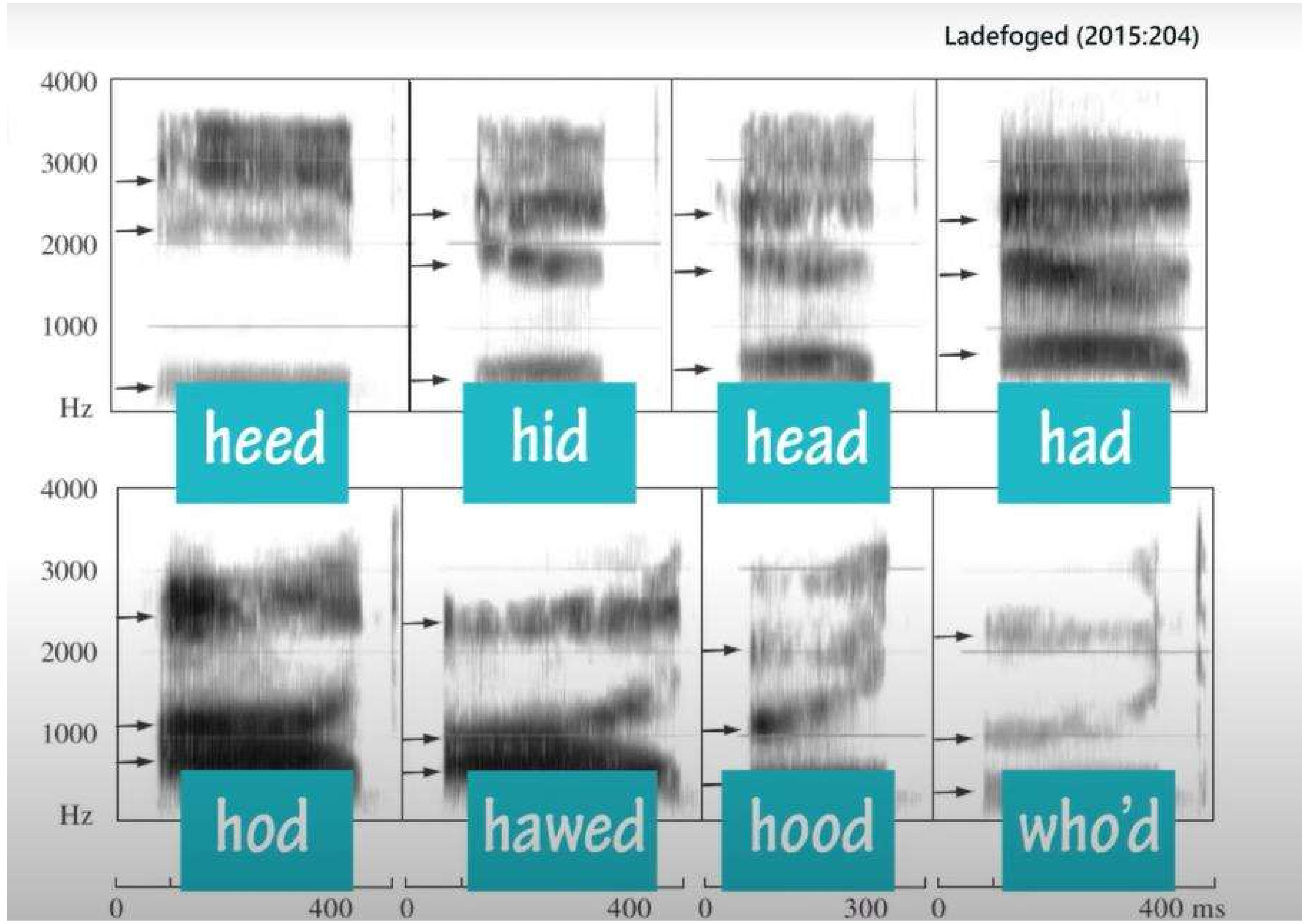
Audacity

Praat

Spectrograms

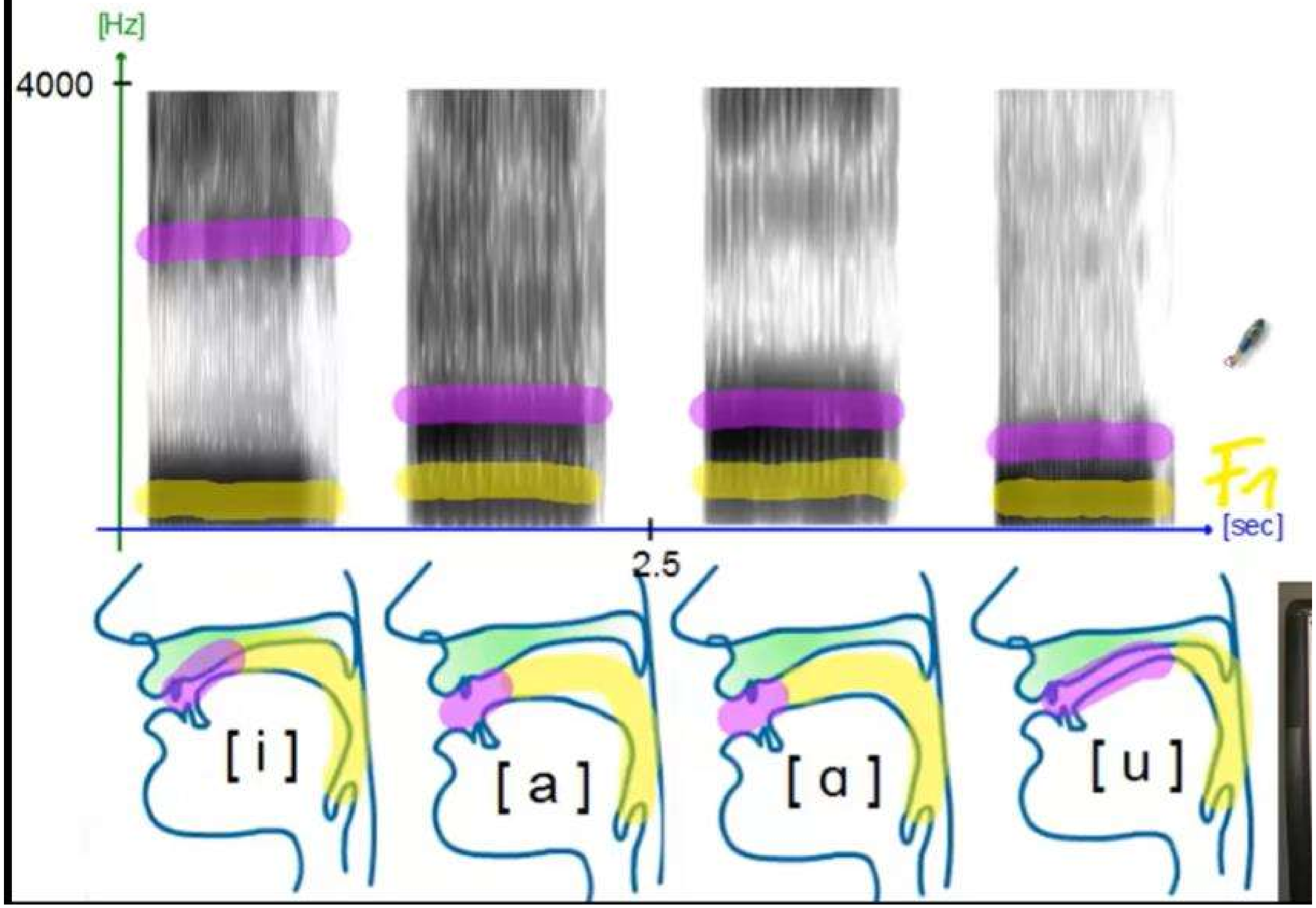


You can then analyze and interpret these spectrograms in order to understand sounds with objective numbers.



https://www.youtube.com/watch?v=NUNesRksmk4

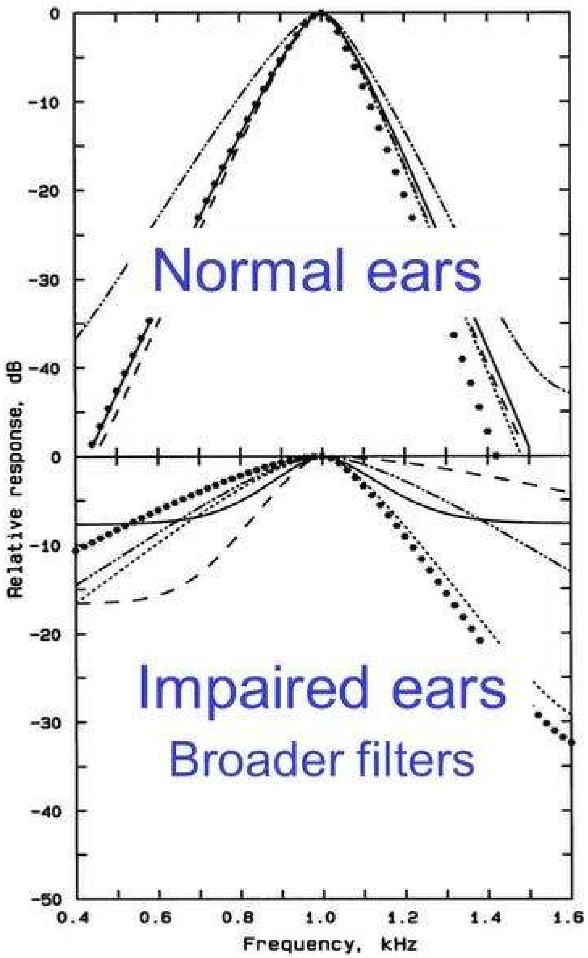
Vowels



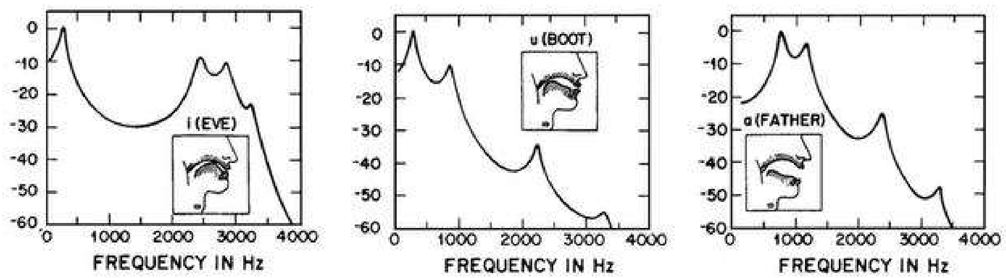
Auditory filters for hearing impaired

Some degree of hearing loss to deaf

Psychoacoustics



Auditory filters for hearing impaired



Broader auditory filters:

- ⇒ fewer filters
- ⇒ bad auditory resolution
- ⇒ difficult to separate sounds
- ⇒ bad formant separation

Not necessary to remember the spectrum

Where are the auditory filters?

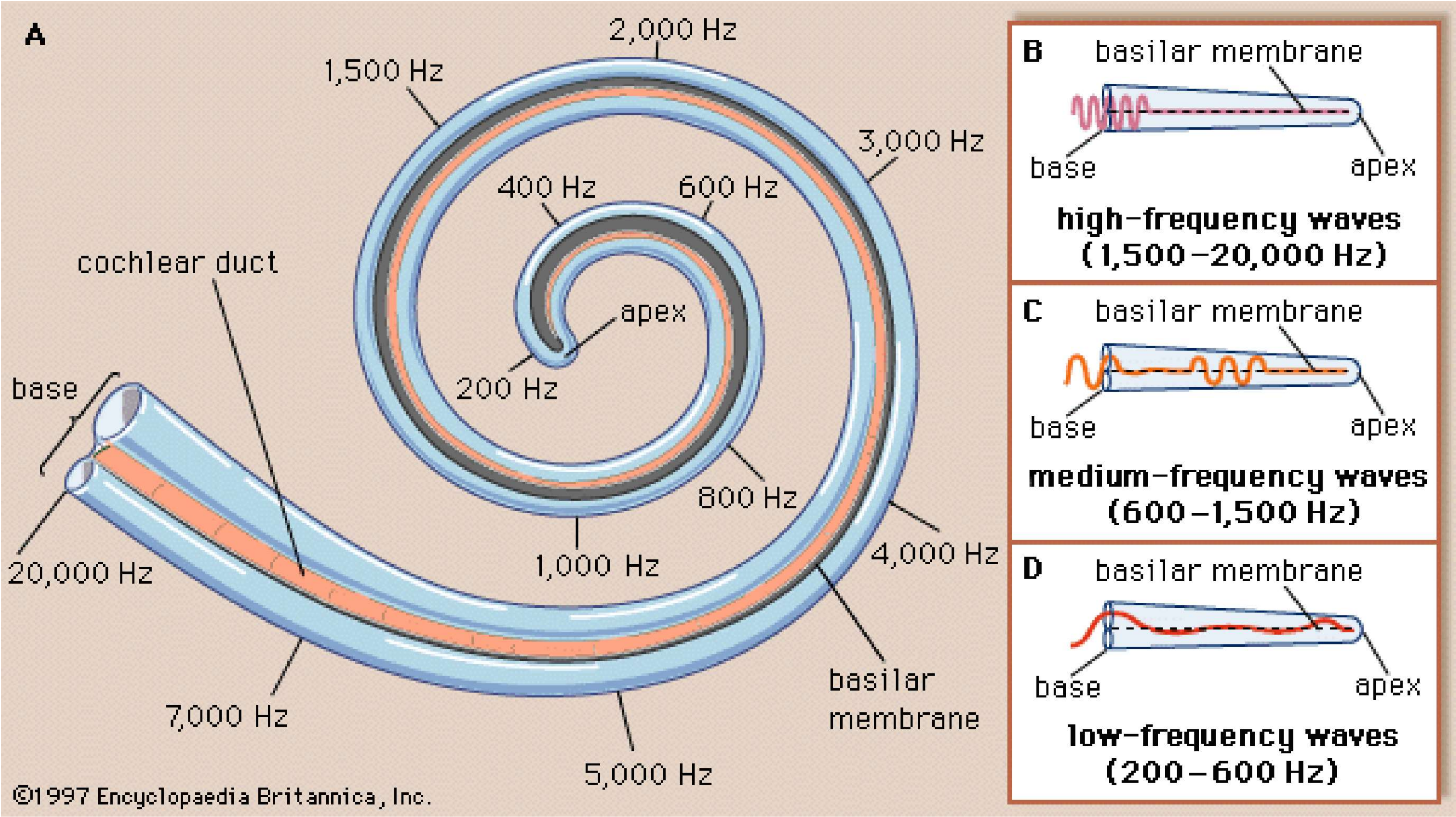
They are at the
Basilar Membrane

Example 6 kHz

High frequencies Low frequencies

The shape is partly determined by
- the BM-movement
- the feedback mechanisms in the auditory system

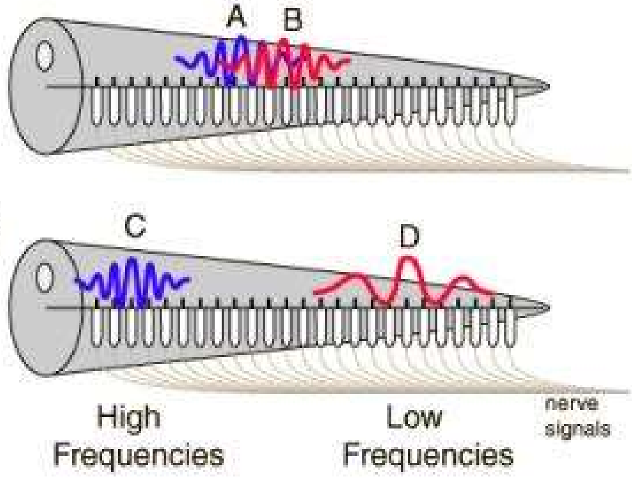
Psychoacoustics

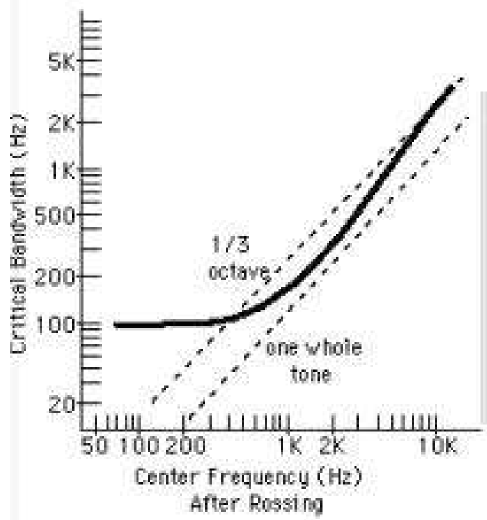


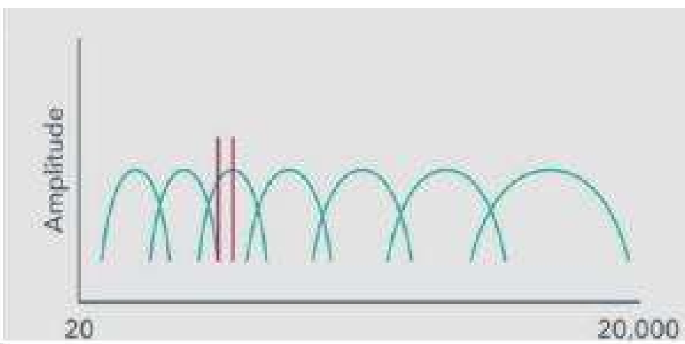
Psychoacoustics

Existence of Critical Bandwidth

Assume
A, B, C, D are of
equal loudness







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Existence of sound masking –reduces perception

If there are 2 sounds close in frequency and one of them is of very high intensity it will saturate the cilia and therefore mask the lower intensity signal

- If a set of cilia responding to one band is simultaneously excited by 2 frequencies within its bandwidth as indicated by the 2 red lines or A and B in the example on top, they will not be resolved accurately.
- Any external noise contribution within this band will also reduce the perception of the signal.
- So we will require noise cancellation to actually improve the signal detection within the same band.

https://www.youtube.com/watch?v=NaK6GrLg4cE&list=PLASEfdY-tiDrIwtPGSO7dfqeVvVyjf07o&index=3

https://www.youtube.com/watch?v=lnpbEOb1F98

https://www.youtube.com/watch?v=os_1HAyOxYI

https://www.youtube.com/watch?v=EeEspQ6-Gzk&list=PLASEfdY-tiDrIwtPGSO7dfqeVvVyjf07o&index=12

Today's Agenda

Quality or Timbre (Pronounced as "Tim Brae")

How do you distinguish a veena, violin or a clarinet playing the same note?

How do you identify the voice of the singer?

How does each person's voice/ each instrument have an unique signature?

Timbre

- Define timbre
- Identify the three main features based on which an unique timbre is identified
- Explain qualitatively the relationship between the time domain signal and frequency spectrum
- List some general applications where timbre is exploited

Timbre

- ✓ Sounds may be generally characterized by pitch, loudness, and quality.
- ✓ Sound "quality" or "timbre" describes those characteristics of sound which allow the ear to distinguish sounds which have the same pitch and loudness.
- ✓ Timbre is then a general term for the distinguishable characteristics of a tone.
- ✓ Timbre is mainly determined by the **harmonic content** of a sound and the **dynamic characteristics** of the sound such as **vibrato and the attack-decay envelope** of the sound.

Timbre

Two sounds with same loudness and same pitch but from different instruments

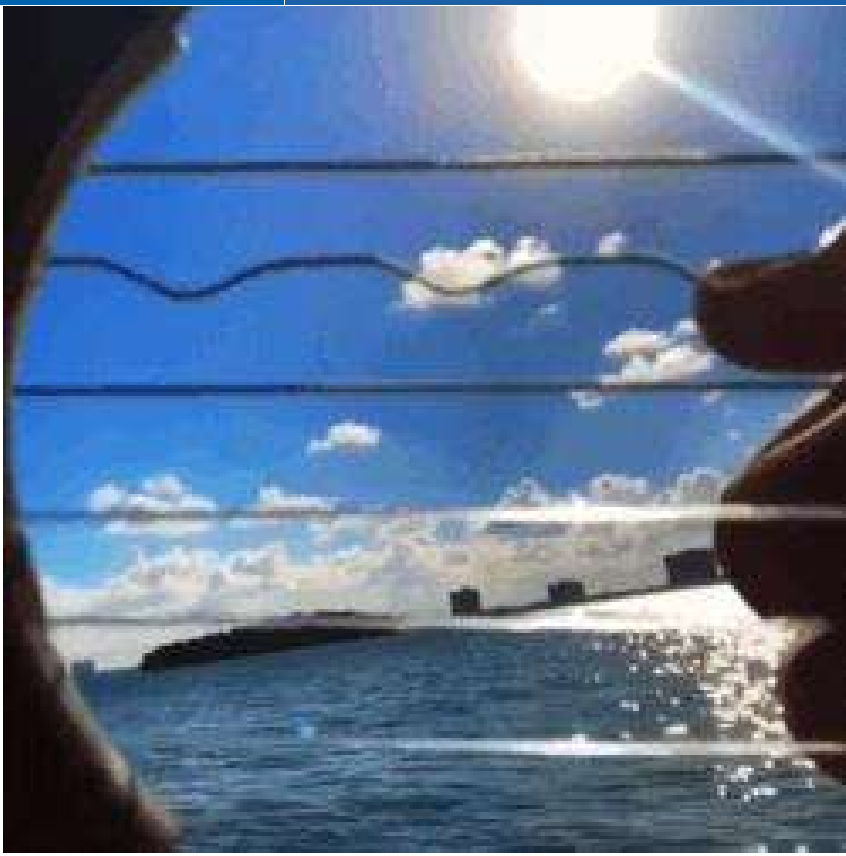
Violin and flute

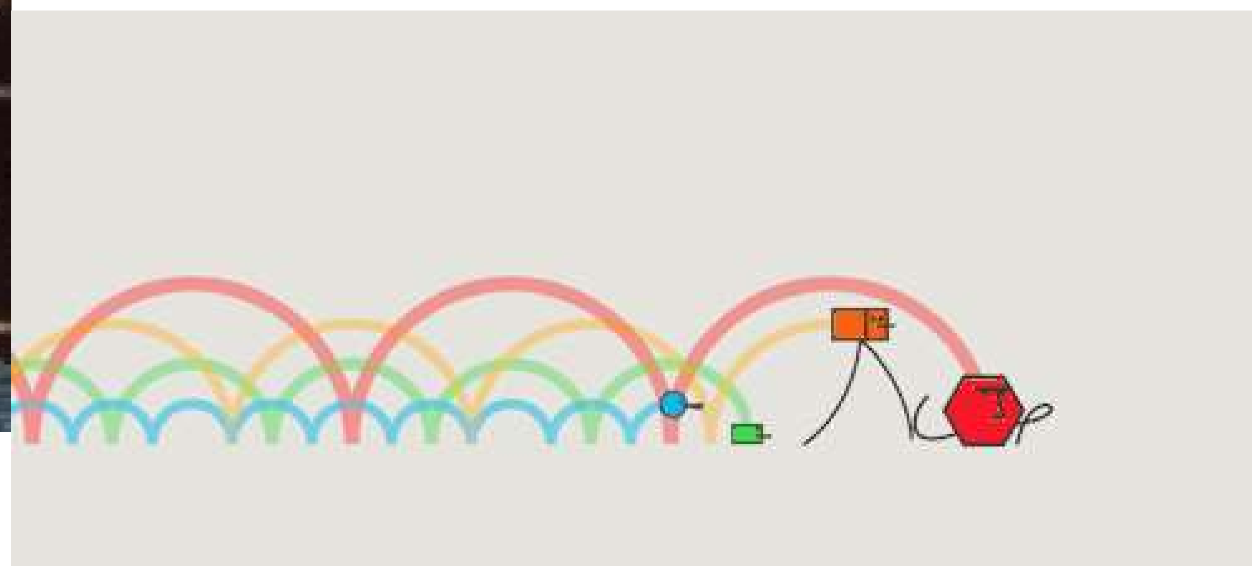
WAVEFORMS

- **Amplitude same- Same loudness**
- **Frequency same- Same pitch**
- **Waveform different**

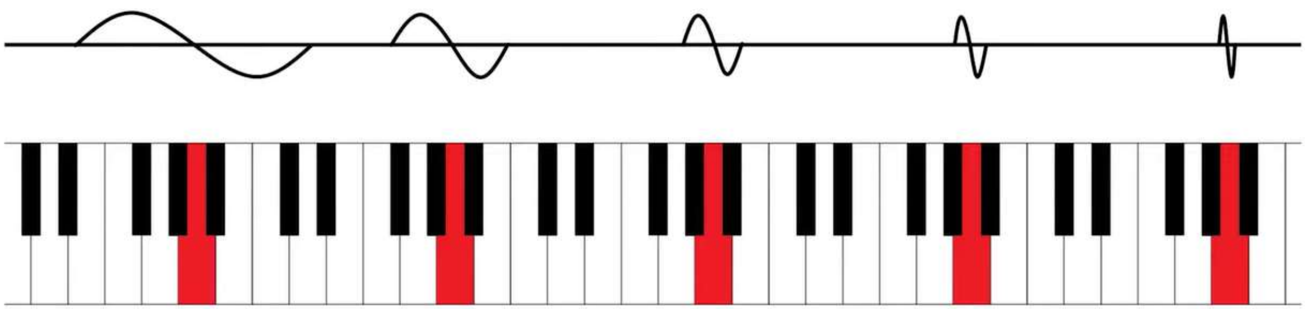
Tuning fork **Violin** **Piano**

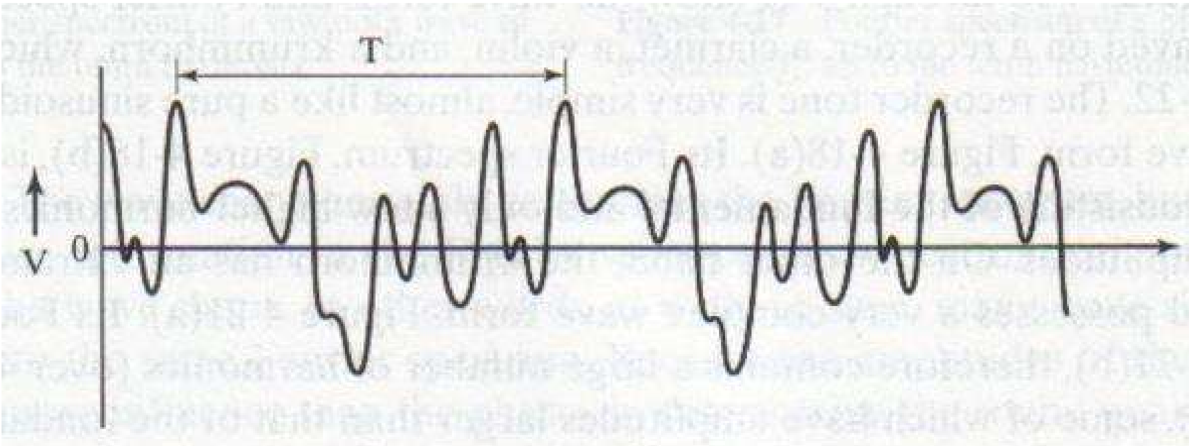
Timbre





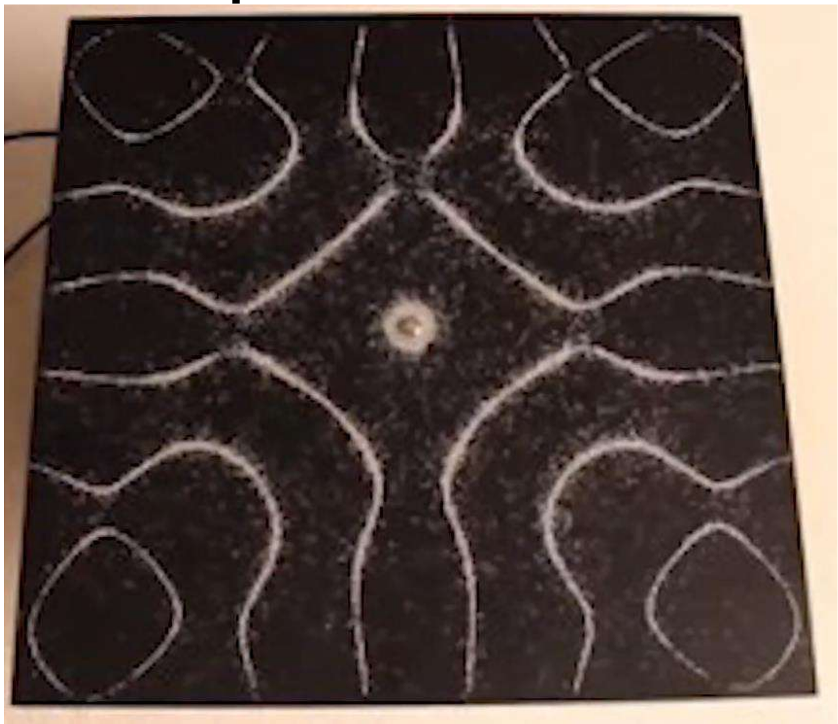
Timbre





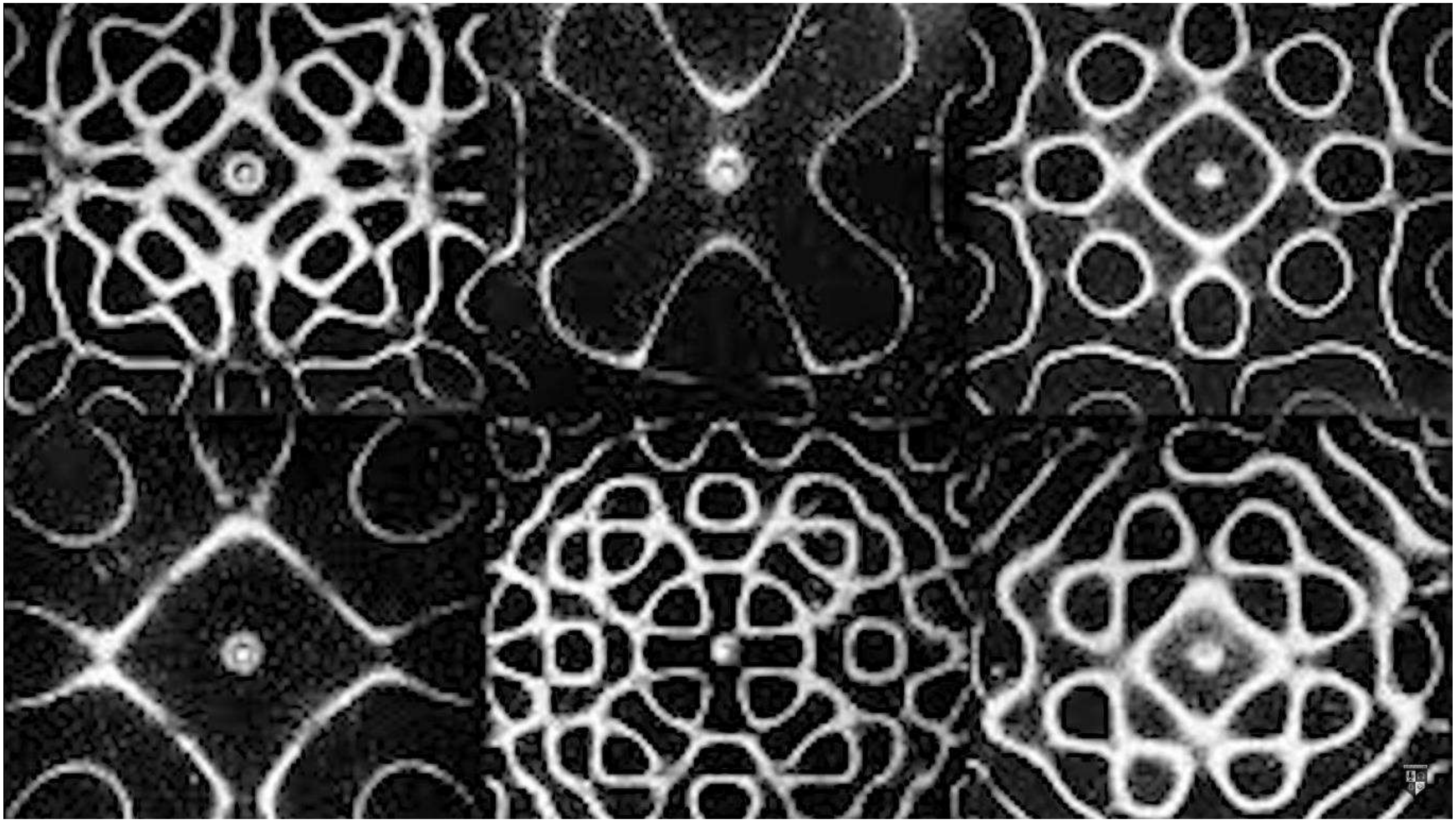
(a)

Chladni plate



Chladni plate

Chladni plate



Timbre

Our ears are very good at perceiving different sounds.

One way to do this is through the "timbre" of the sound.

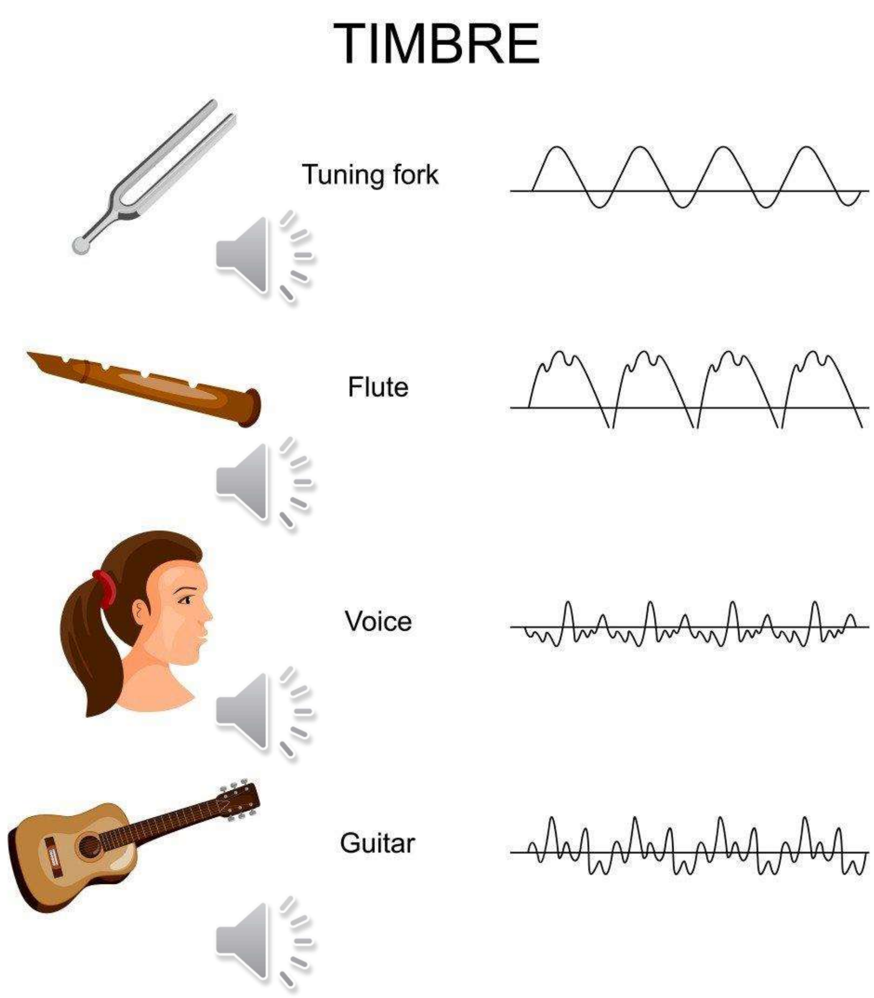
Timbre is the tonal quality or tonal color of the sound.

The timbre of the sound is determined by the overtones an harmonics the sound produces.

The amplitude and pitch change in each harmonic gives the instruments their particular timbre.

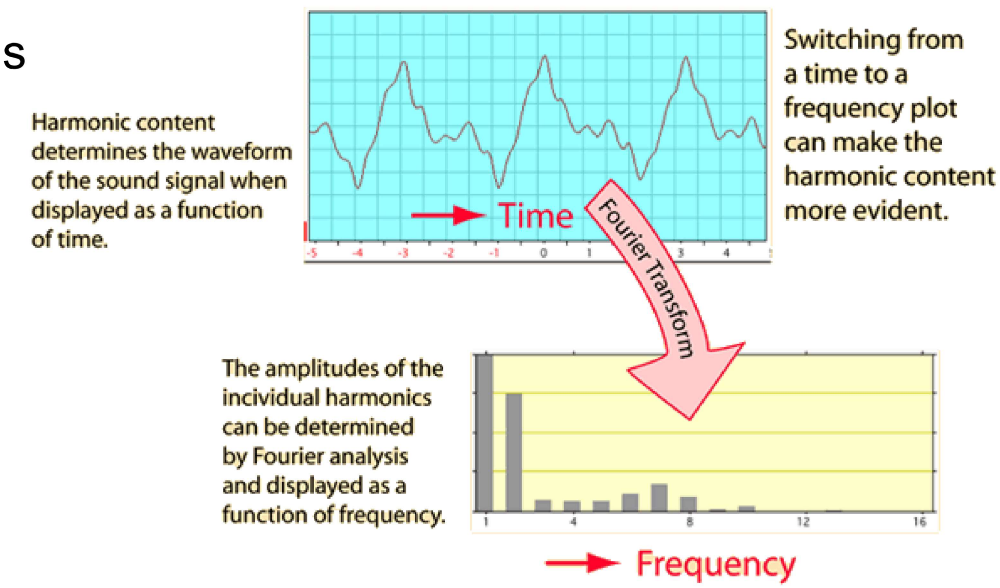
This "quality" of sound is as much a perceptual phenomenon as it is a physical one.

People can differentiate between two sound sources due to the perceptual capabilities of the ear.



Harmonic content

- ✓ The primary contributors to the quality or timbre of the sound of a musical instrument is the harmonic content, the number and relative intensity of the upper harmonics present in the sound.
- ✓ Some musical sound sources have overtones which are not harmonics of the fundamental.
- ✓ While there is some efficiency in characterizing such sources in terms of their overtones, it is always possible to characterize a periodic waveform in terms of harmonics - such an analysis is called Fourier analysis.



It is common practice to characterize a sound waveform by the spectrum of harmonics necessary to reproduce the observed waveform.

Timbre- Harmonic content

Fourier Synthesis: The process of combining harmonics to form a complex wave.

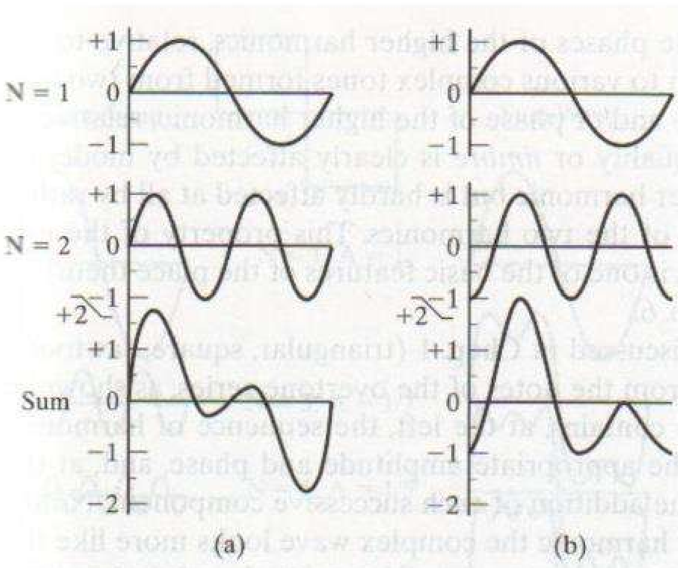


Figure 4-1 Fourier synthesis of complex waves from equal amplitudes of fundamental and second harmonic. Parts (a) and (b) differ in the phase of the second harmonic.

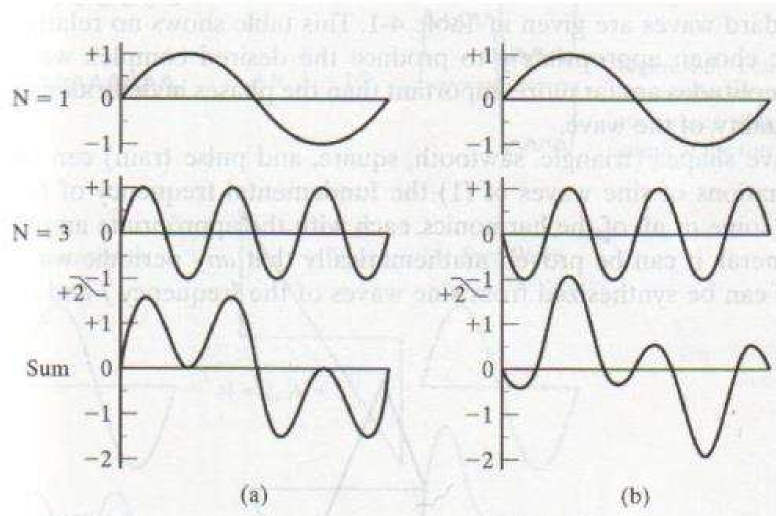


Figure 4-2 Fourier synthesis of complex waves from equal amplitudes of fundamental and third harmonic. Parts (a) and (b) differ in the phase of the third harmonic.

Timbre- Harmonic content

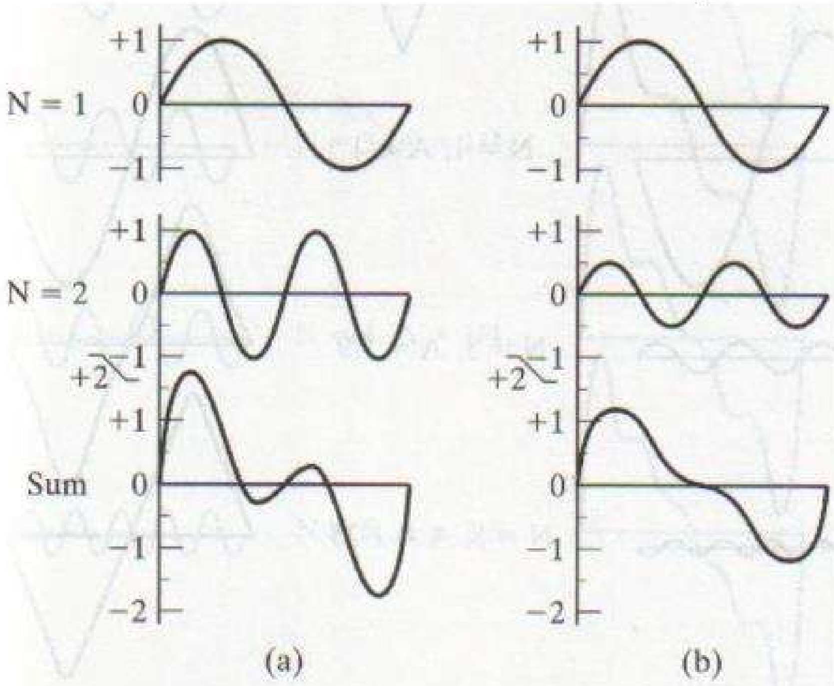


Figure 4-3 Fourier synthesis of complex waves from the fundamental and second harmonic. In part (a) amplitudes of the fundamental and second harmonic are equal; in part (b) the amplitude of the second harmonic is half that of the fundamental.

The shape of the complex wave is determined by:
(1) the number and relative amplitudes of the component harmonics.
(2) the phases of the higher harmonics, relative to the fundamental.

The tone quality or timbre is affected by moderate changes in the amplitude of the higher harmonic but is hardly affected at all by rather large changes in the relative phases of the two harmonics.

Timbre- Harmonic content

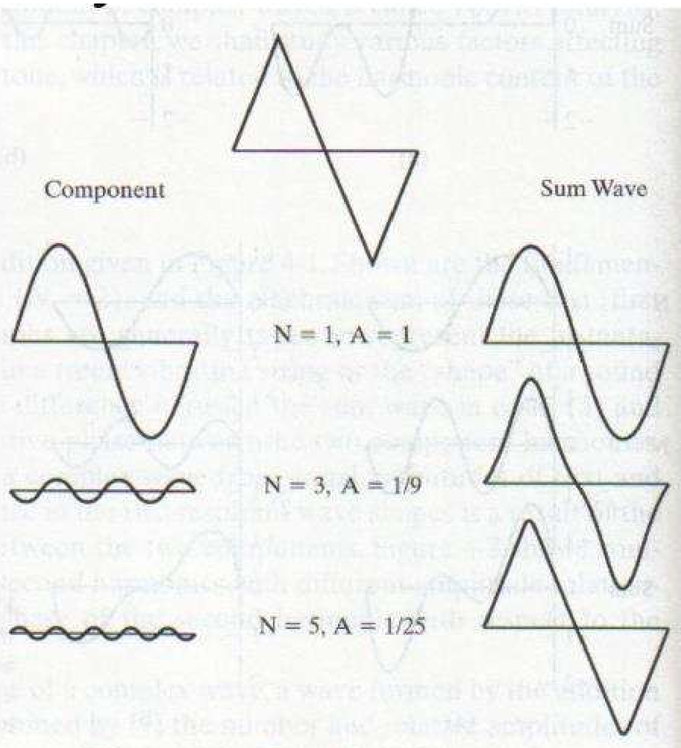


Figure 4-4 Fourier synthesis of a triangular wave. At the left are the successive harmonics; at the right are the sum waves, including each successive harmonic. The graph at the top is the wave being synthesized.

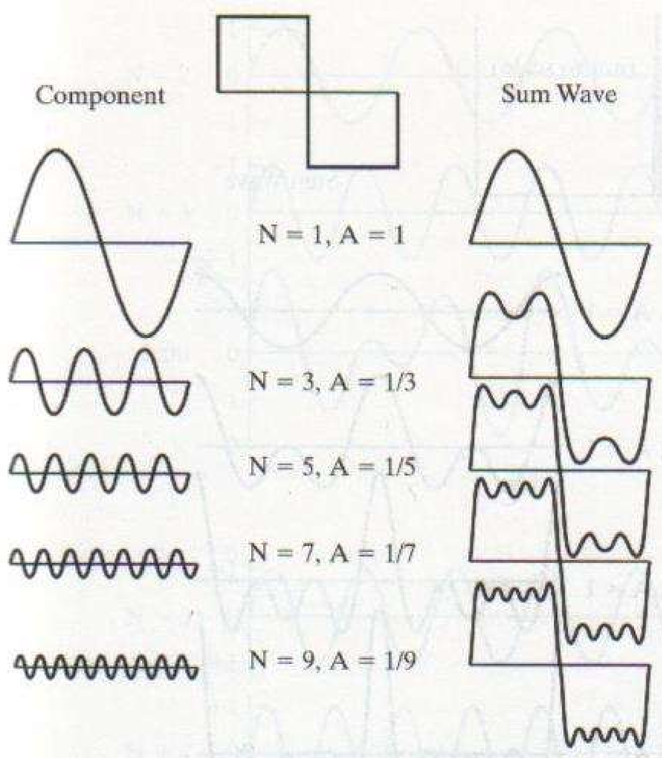


Figure 4-5 Fourier synthesis of a square wave. At the left are the successive harmonics; at the right are the sum waves, including each successive harmonic. The graph at the top is the wave being synthesized.

Timbre- Harmonic content

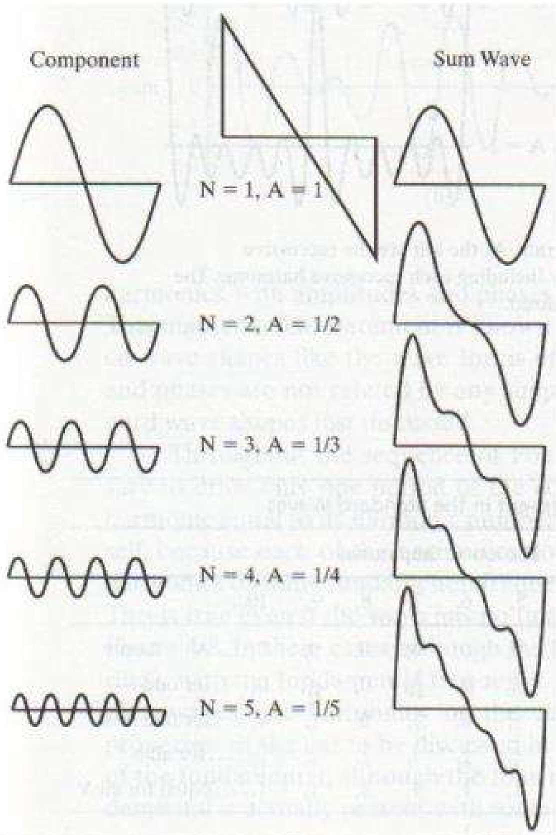


Figure 4-6 Fourier synthesis of a sawtooth wave. At the left are the successive harmonics; at the right are the sum waves, including each successive harmonic. The graph at the top is the wave being synthesized.

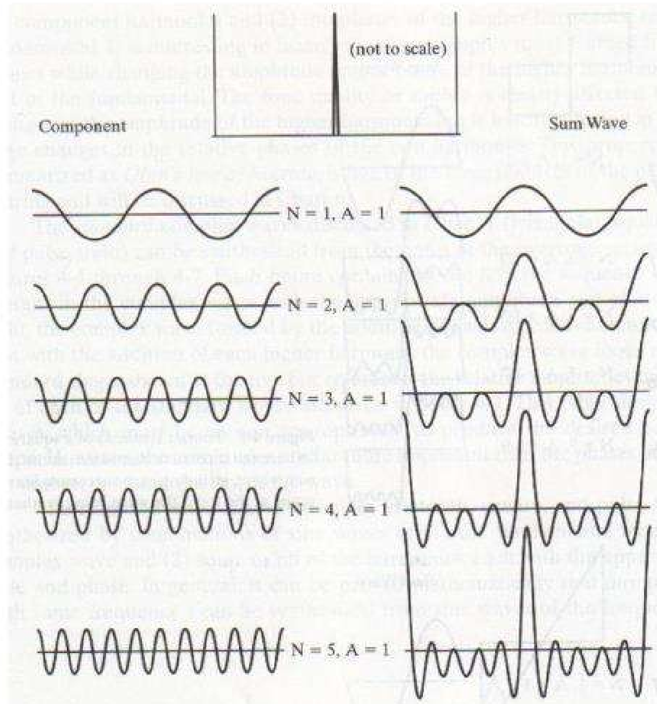
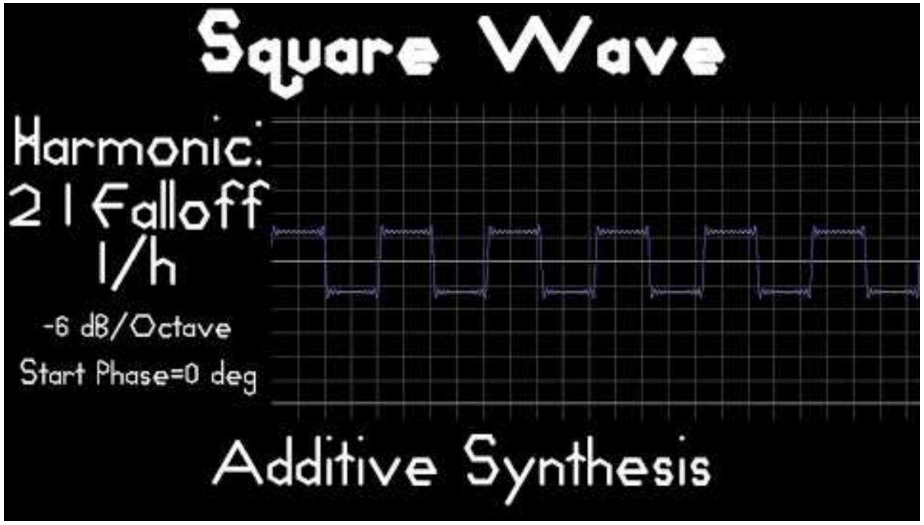


Figure 4-7 Fourier synthesis of a pulse train. At the left are the successive harmonics; at the right are the sum waves, including each successive harmonic. The graph at the top is the wave being synthesized.

Timbre- Harmonic content

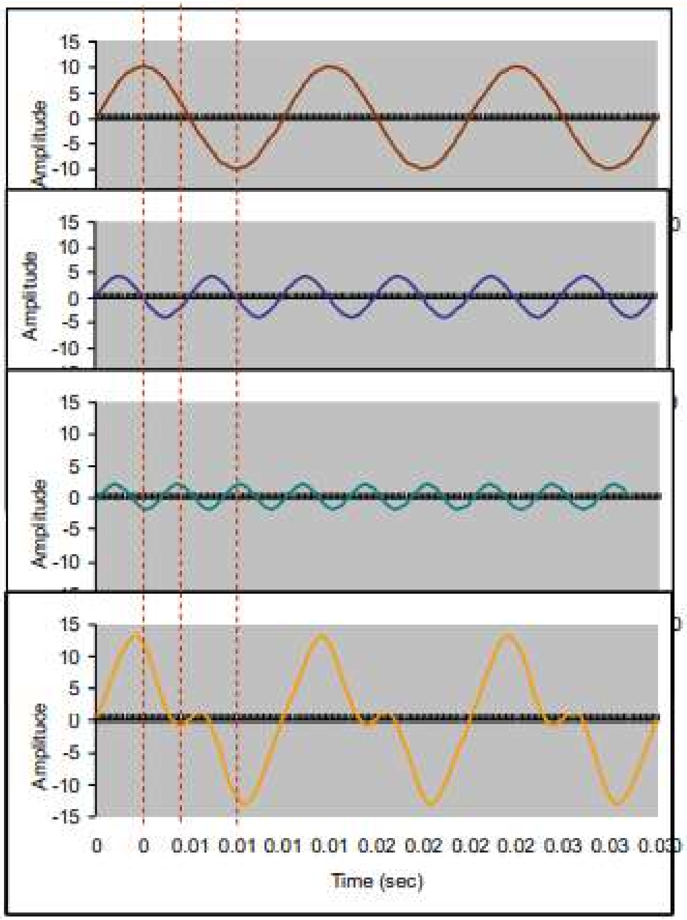
Table 4-1 Relative Amplitudes of Harmonics Present in the Standard Waves

Wave	Harmonic amplitudes									
$N =$	1,	2,	3,	4,	5,	6,	7,	8,	9,	10, ...
Sine	1,	0,	0,	0,	0,	0,	0,	0,	0,	0, . . . , $N = 1$ only
Triangle	1,	0,	$\frac{1}{9}$,	0,	$\frac{1}{25}$,	0,	$\frac{1}{49}$,	0,	$\frac{1}{81}$,	0, . . . , for odd N
Square	1,	0,	$\frac{1}{3}$,	0,	$\frac{1}{5}$,	0,	$\frac{1}{7}$,	0,	$\frac{1}{9}$,	0, . . . , for odd N
Sawtooth (ramp)	1,	$\frac{1}{2}$,	$\frac{1}{3}$,	$\frac{1}{4}$,	$\frac{1}{5}$,	$\frac{1}{6}$,	$\frac{1}{7}$,	$\frac{1}{8}$,	$\frac{1}{9}$,	$\frac{1}{10}$, . . . , for all N
Pulse train	1,	1,	1,	1,	1,	1,	1,	1,	1,	1, . . . , equal for all N


Square Wave
Harmonic:
21 Falloff
1/h
-6 dB/Octave
Start Phase=0 deg
Additive Synthesis


Sawtooth Wave
Harmonic:
11 Falloff
1/h
-6 dB/Octave
Start Phase=0 deg
Additive Synthesis

Fourier analysis



y1 = 10 sin (2π100t)

y2 = 4 sin(2π200t)

y3 = 2 sin(2π300t+180)

Superposition of y1,y2,y3

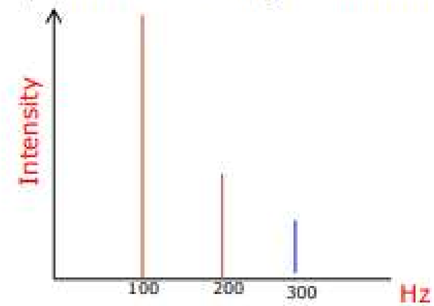
Combined output= y1+y2+y3

FT $F(\omega)=\int_{-\infty}^{\infty} f(t)e^{-i\omega t}\,dt$

IFT $f(t)=\frac{1}{2\pi}\int_{-\infty}^{\infty} F(\omega)e^{i\omega t}\,d\omega$

A simple illustration of relationship between Temporal and spectral characteristics

Spectral intensity distribution



Any time domain periodic signal can be expressed as a series of sine or cos functions.

This spectral distribution is called the fourier transform of time domain signals

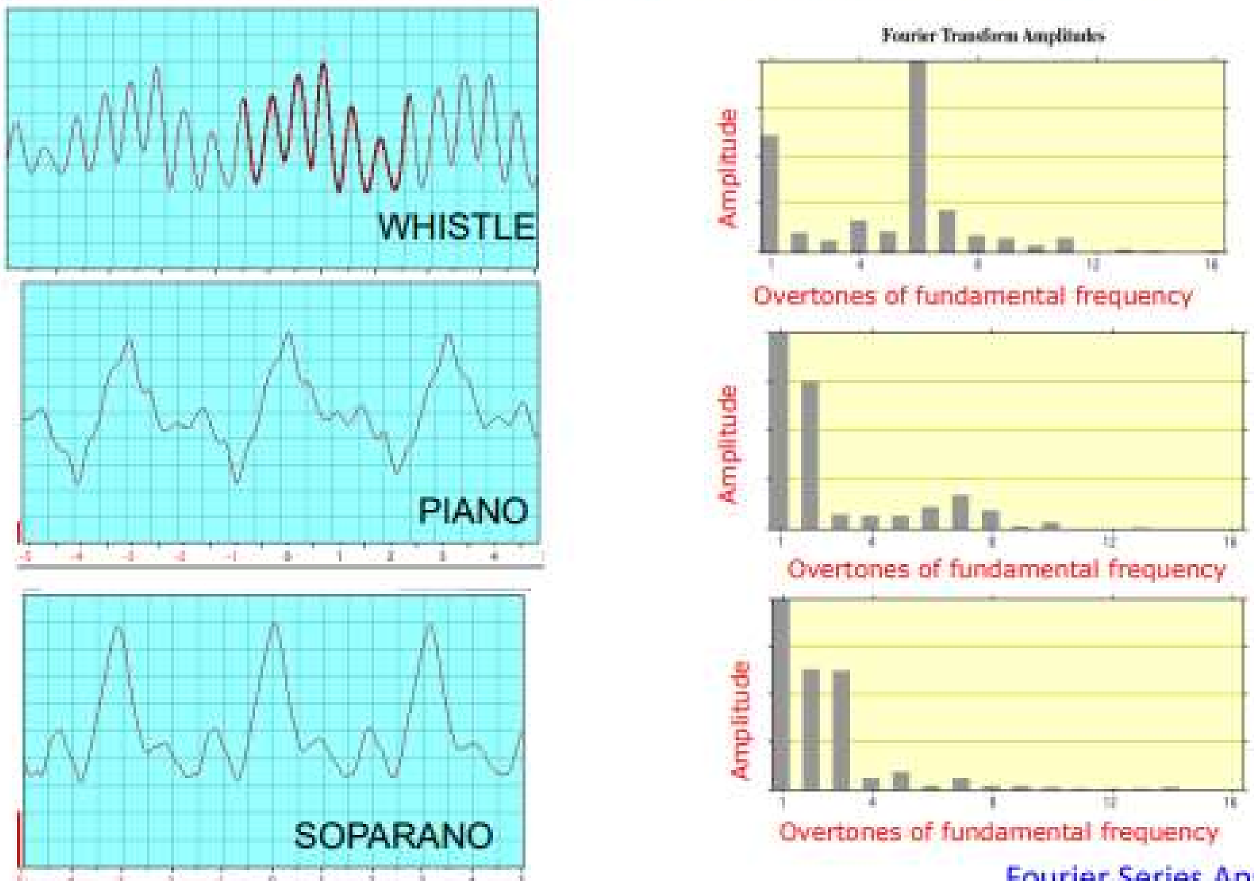
$$F(x)=a_0+\sum_{n=1}^{\infty} a_n \cos nx+\sum_{n=1}^{\infty} b_n \sin nx\,.$$

Fourier Series Applet (falstad.com)

Fourier Series Applet (falstad.com)

Fourier analysis

Fourier transforms of 3 instruments producing same fundamental frequency



Fourier Series Applet (falstad.com)

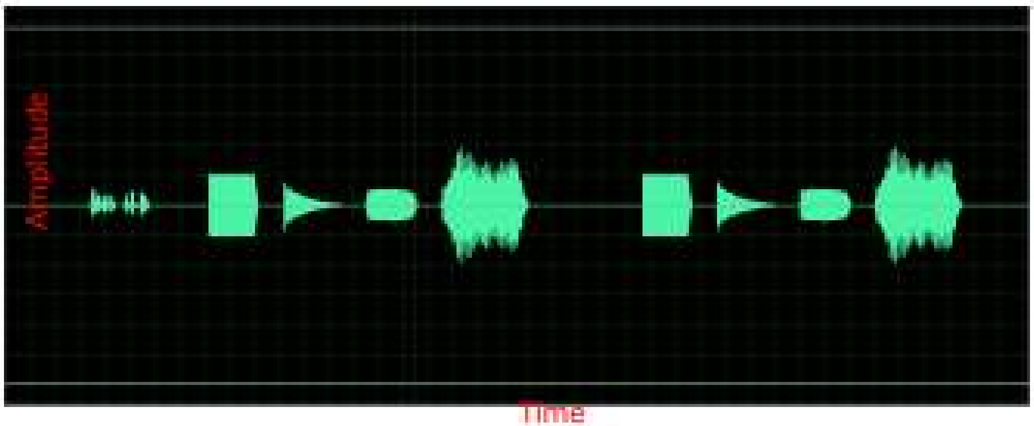
Fourier Series Applet (falstad.com)

Envelope based identification

Four complex tones are shown in the screen shot given below

One is a pure sine wave a piano, french horn, one is violin

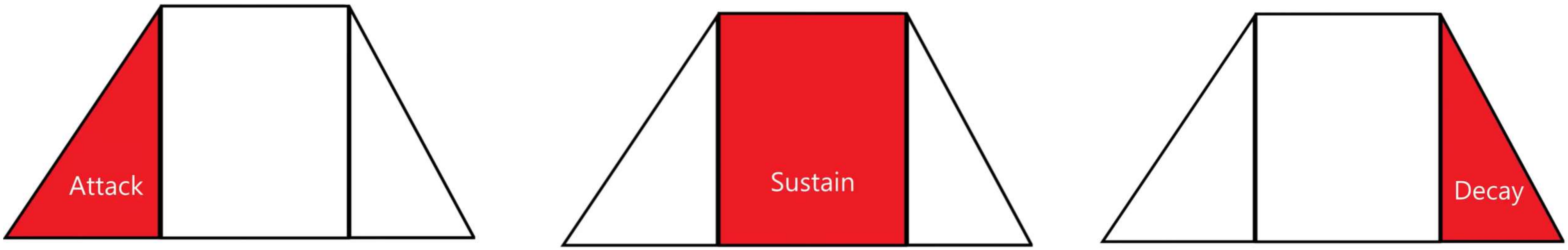
The temporal shapes (envelopes) of each are shown on the side.



Can you identify them? How ?

- Different frequency components tend to exhibit quite distinct envelopes!
- E.g., high frequencies on a piano note decay faster than low frequencies

Envelope based identification

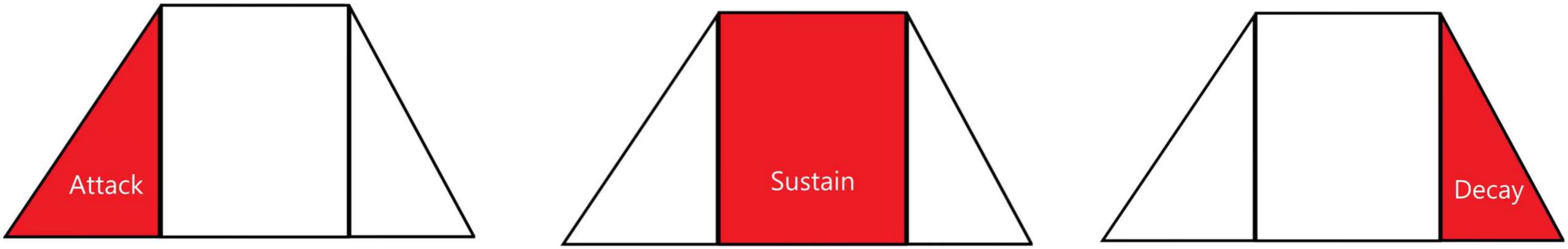


Attack time: duration a note takes to reach its maximum intensity after being played

Sustain time: duration a note steadies at a fixed intensity after being played

Decay time: duration a note takes to from its sustained value to silence

Envelope based identification



<u>**Short attack time:**</u> **Piano, pluck string (guitar)**

<u>**Long attack time:**</u> **wood wind, violin**

<u>**Short sustain time:**</u> **electric guitar**

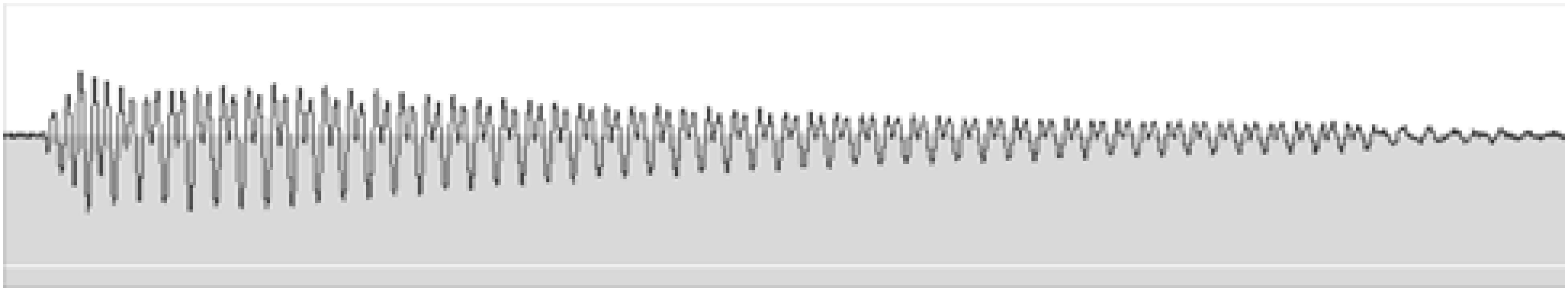
<u>**Long sustain time**</u>**: wind instruments**

<u>**Short decay time**</u>**: violin**

<u>**Long decay time**</u>**: cymbals**

Attack and decay

- ✓ Another contributors to the quality or timbre of the sound of a musical instrument is attack and decay.
- ✓ The illustration below shows the attack and decay of a plucked guitar string.
- ✓ The plucking action gives it a sudden attack characterized by a rapid rise to its peak amplitude.
- ✓ The decay is long and gradual by comparison.
- ✓ The ear is sensitive to these attack and decay rates and may be able to use them to identify the instrument producing the sound.

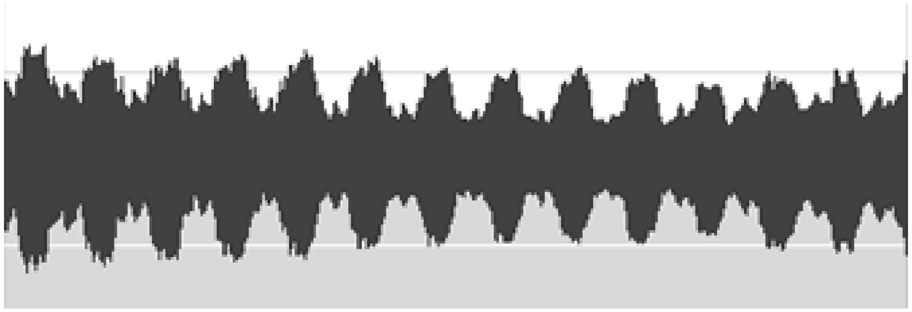


Attack and decay

- ✓ **This shows the sound envelope of striking a cymbal with a stick.**
- ✓ **The attack is almost instantaneous, but the decay envelope is very long.**
- ✓ **The time period shown is about half a second.**
- ✓ **The interval shown with the guitar string above is also about half a second, but since its frequency is much lower, you can resolve the individual periods in that sound envelope.**

Vibrato and tremolo

- ✓ The ordinary definition of vibrato is "periodic changes in the pitch of the tone", and the term tremolo is used to indicate periodic changes in the amplitude or loudness of the tone.
- ✓ So, vibrato could be called FM (frequency modulation) and tremolo could be called AM (amplitude modulation) of the tone.
- ✓ Actually, in the voice or the sound of a musical instrument both are usually present to some extent.
- ✓ Vibrato is considered to be a desirable characteristic of the human voice if it is not excessive.
- ✓ The vibrato of a singer's voice, for example, aids significantly in distinguishing the voice from other musical sounds.
- ✓ The term 'vibrato' in general use refers not only to periodic changes in pitch, but also to periodic changes in amplitude, which should more correctly be called tremolo.



Quality of sound

Quality or Timbre is ....

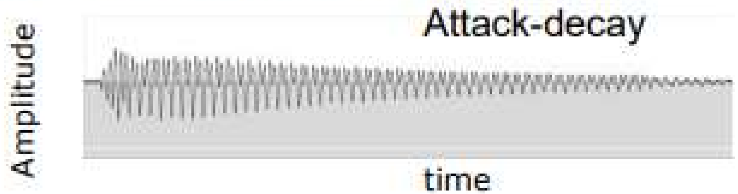
A characteristic that differentiates complex sounds of identical pitch and loudness

How does this differentiation occur?

- attack-decay - the temporal variation of the amplitude of sound (envelope) especially at the beginning and end of sound.
- vibrato / tremulo - temporal variation of frequency spectrum/amplitude of sustained sounds
- **harmonic content** - the relative intensity and phase among overtones / harmonics that accompany the fundamental frequency (i.e), spectral distribution of intensity and phase

Attack - How sound is created (Onset)

Decay- How sound terminates(Offset)



Tremulo- Amplitude modulation of sustained "ee"

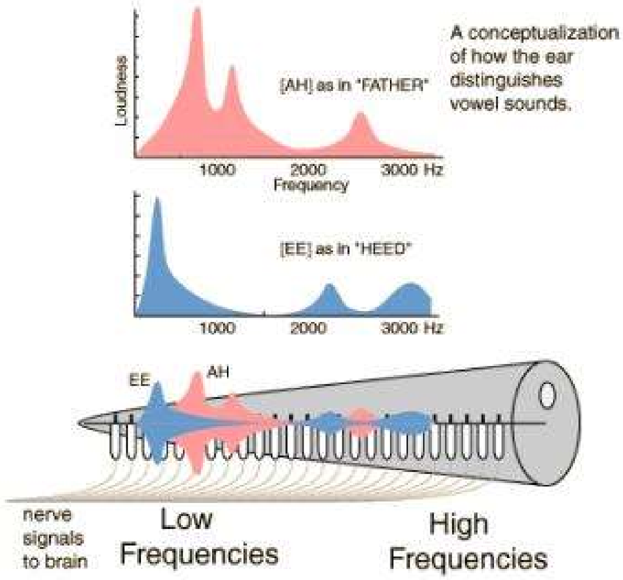
Vibrato-refers to instantaneous changes in frequency also called "chirp" in communication domain

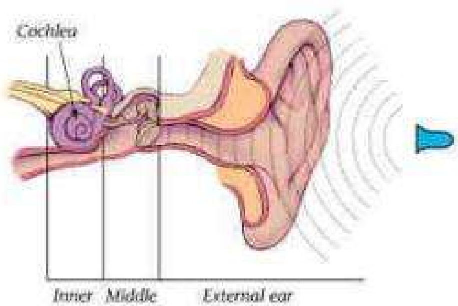
tremulo

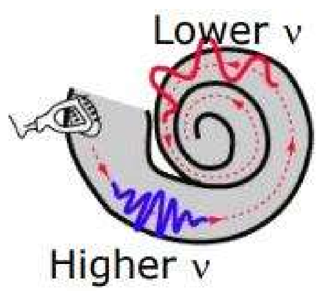
The envelope of a sound describes its amplitude profile over time

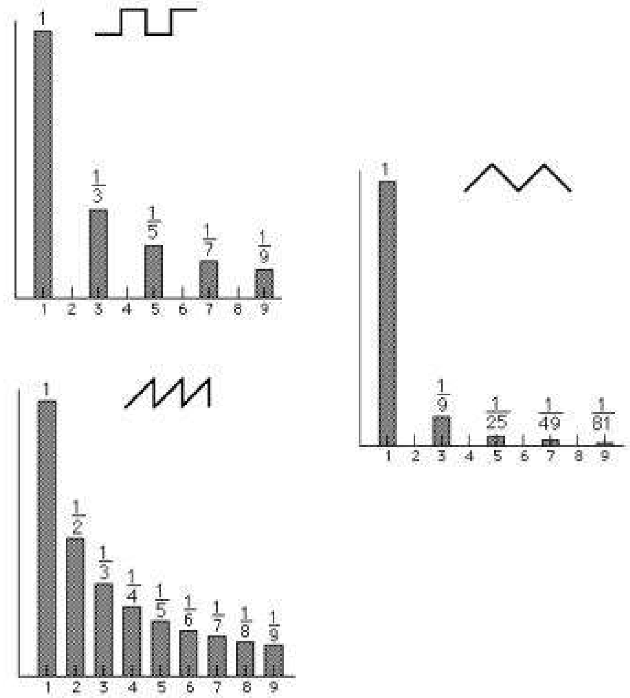
Applications of quality

Speech Analysis









Synthesis

Summary

- Timbre is a characteristic that differentiates complex sound of identical pitch and loudness produced by one source from that produced by another source.
- The differentiation is based on relative amplitudes and phases of the harmonic content accompanying the fundamental note (i.e. spectral distribution) and its temporal characteristics.

- The 3 main constituents that together determine timbre are
  - (i) spectral components and their relative intensities
  - (ii) attack-decay and
  - (iii) vibrato-tremulo (temporal variation in frequency or amplitude respectively)

- Any time domain signal can be expressed as a series of sine or cos functions. This spectral distribution is called the fourier transform of time domain signals

- It plays an important role in synthesis of signals, speech analysis, cryptography, recording, voice morphing, compressions, etc

External Resources available for Visualization as a spectrogram
3d representation: Amplitude as function of time and frequency
Shows temporal behavior of different frequency components

Great for analytical purposes: – Baudline: http://www.baudline.com/
– Sonic Visualiser: http://sonicvisualiser.org

Summary

1. Which of the following parameters characterize timbre?

   a. pitch-frequency
   b. attack-decay
   c. loudness-intensity
   d. vibrato-tremolo
   e. tone-harmonic

2. Spectral distribution is _______________ of time domain signals.

3. State if the following statement is true or false?
   Certain musical instruments can produce a pure tone.

https://www.youtube.com/watch?v=NaK6GrLg4cE&list=PLASEfdY-tiDrIwtPGSO7dfqeVvVyjf07o&index=3

https://www.youtube.com/watch?v=lnpbEOb1F98

https://www.youtube.com/watch?v=os_1HAyOxYI

https://www.youtube.com/watch?v=EeEspQ6-Gzk&list=PLASEfdY-tiDrIwtPGSO7dfqeVvVyjf07o&index=12