CTP 431 Music and Audio Computing

Basic Acoustics

Graduate School of Culture Technology (GSCT)
Juhan Nam

Outlines

- What is sound?
  - Generation
  - Propagation
  - Reception

- Sound properties
  - Loudness
  - Pitch
  - Timbre

What Is Sound?

- Vibration of air molecules
  - Compression and rarefaction
- Wave
  - Sound wave propagates but the air molecules stay in place
  - Transmits energy without transmitting the matter
  - Longitudinal wave
- Animation demo
  - http://www.acs.psu.edu/drussell/Demos/waves-intro/waves-intro.html

Three Stages of Sound

- Generation
  - Vibration of sound objects
- Propagation
  - Traveling of the vibration through the air
- Reception
  - Sensation of the air vibration via ears

Sound Generation

- Excitation
  - Drive force on sound objects
- Oscillation
  - Vibration by restoration force
  - Modes: complex tones
- Resonance
  - Amplify or modify the volume of oscillation

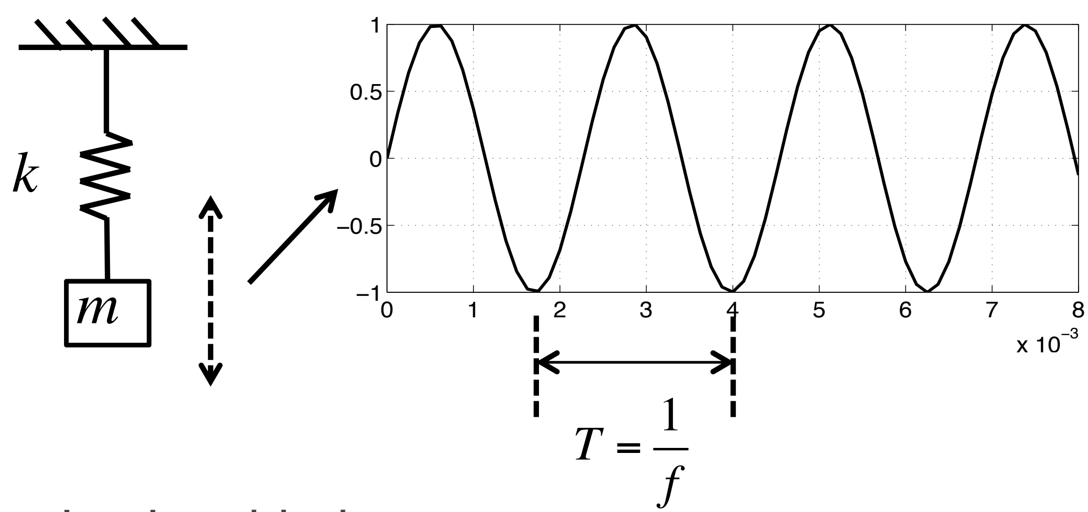
Oscillation: Simple Harmonic Motion

- A mass-spring model

Newton's second law

$$F = -kx = m\frac{d^2x}{dt^2}$$

Restoration force by Hooke's law



  - Practical model: damping is added

- Generate a sinusoid oscillation
  - Pure tone: $x = A\sin(\omega t) = A\sin(2\pi ft)$

$\omega = \sqrt{k/m}$ angular frequency

$f = \omega / 2\pi$ frequency

$T = 1/f$ period

Complex Oscillation in Musical Instruments

- Depending on the type of instruments
  - E.g. strings, air-filled pipe, membrane, bar
- Common elements
  - Excitation: initial conditions or driving force
  - Wave propagation (on the solid objects): wave equation
  - Reflection, superposition and standing wave: boundary conditions
- Generate modes
  - Each mode correspond to a sinusoidal oscillation
  - Complex tone: sinusoids are often harmonically related

Sound as Wave

- Propagation
  - Described by wave equation
- Reflection
  - Fixed-end or open-ended
- Superposition
  - Constructive or destructive sum
- Standing wave
  - Nodes and anti-nodes
- Animation demo
  - http://www.acs.psu.edu/drussell/Demos/reflect/reflect.html
  - http://www.acs.psu.edu/drussell/Demos/SWR/SWR.html

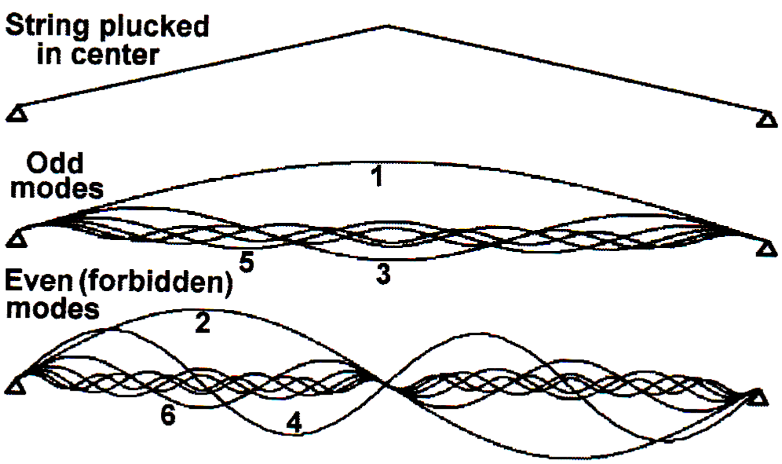
Complex Oscillation in Strings

- Excitation
  - Plucking, striking or bowing
- Modes
  - Transverse wave
  - Generate harmonic sounds
  - Pitch is determined by the distance between two ends
- Animation demo
  - https://www.youtube.com/watch?v=_X72on6CSL0

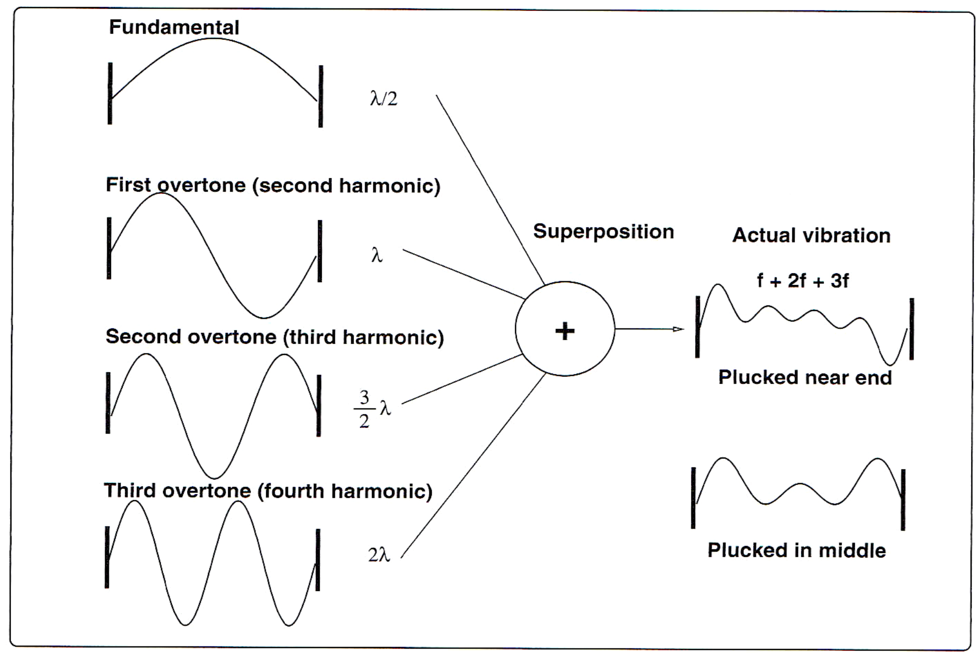
KAIST

文化CT

Modes in Strings



Plucked String (initial condition)



Plucked String (modes)

$$\lambda = 2L, L, \frac{2L}{3}, \frac{L}{2}, \ldots \longrightarrow f = \frac{c}{2L}, \frac{c}{L}, \frac{3c}{2L}, \frac{2c}{L}, \ldots$$

c speed of vibration

L Length of string

λ wavelength

Complex Oscillation in Pipes

- Excitation
  - Blowing
  - Reed: clarinet, oboe

- Modes
  - Longitudinal pressure wave that travels in air column
  - Generate harmonic sounds
    - Open-pipe (e.g. flute): full harmonics
    - Semi-open pipe (e.g. clarinet): odd-numbered harmonics

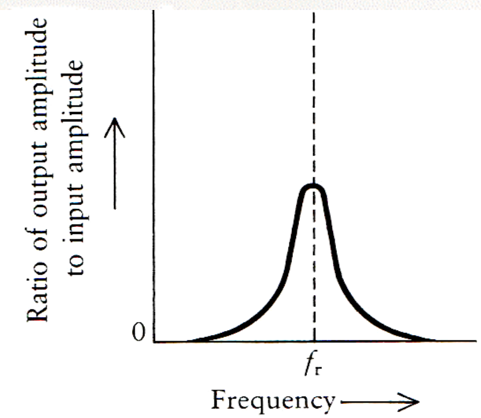
- Animation demo
  - http://newt.phys.unsw.edu.au/jw/flutes.v.clarinets.html

Complex Oscillation in Membrane

- Excitation
  - Striking
- Modes
  - Transverse wave
  - 2-D circular member or plate
  - Generate inharmonic sounds
- Animation demo
  - http://www.acs.psu.edu/drussell/Demos/MembraneCircle/Circle.html

Resonance

- Forced oscillation
  - The excitation force is continuous
  - Amplify or modify the volume of the oscillation
    - Extreme case: https://www.youtube.com/watch?v=j-zczJXSxnw
- Oscillation in pipe
  - Coupled with vibration of reed or blowing
- Oscillation in cavity
  - Guitar body
  - Tube resonators in xylophone and marimba
  - Bass reflex in woofer
  - Vocal Tract



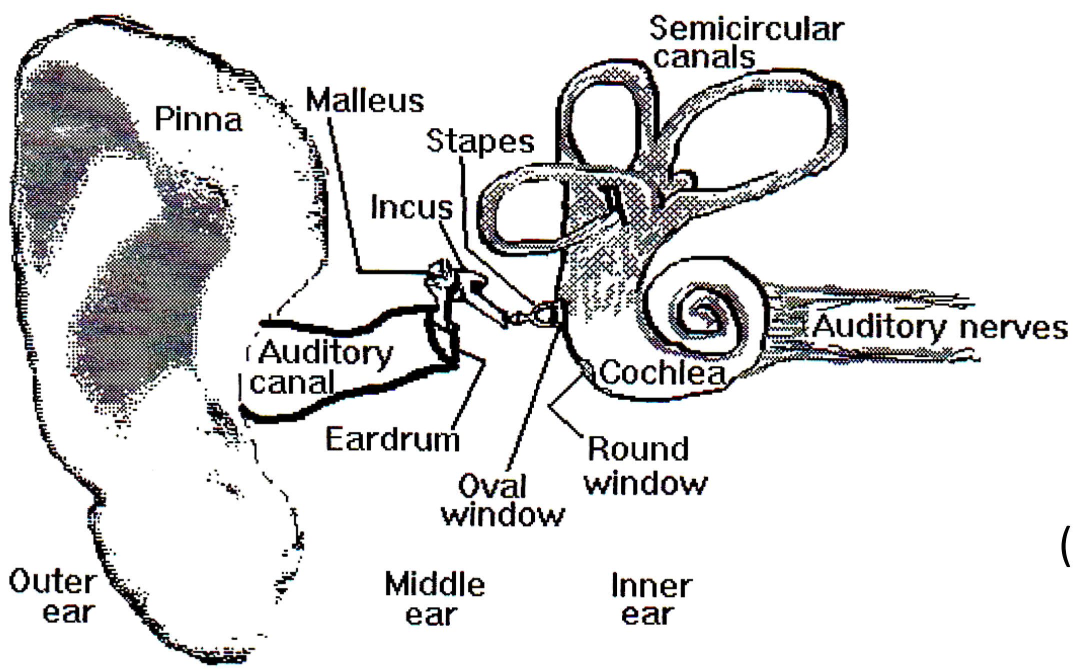
Some Interesting Videos

- Visualizing standing waves
  - http://www.nigelstanford.com/Cymatics/ (Chladni plates)

- The visual microphone
  - Capturing vibration using video: http://people.csail.mit.edu/mrub/VisualMic/

Sound Reception

- Human ear: a series of highly sensitive transducers
  - Outer to middle: air vibration to mechanical vibration
  - Middle to inner: mechanical vibration to fluid vibration
  - Inner to auditory nerve: fluid vibration to nerve firings



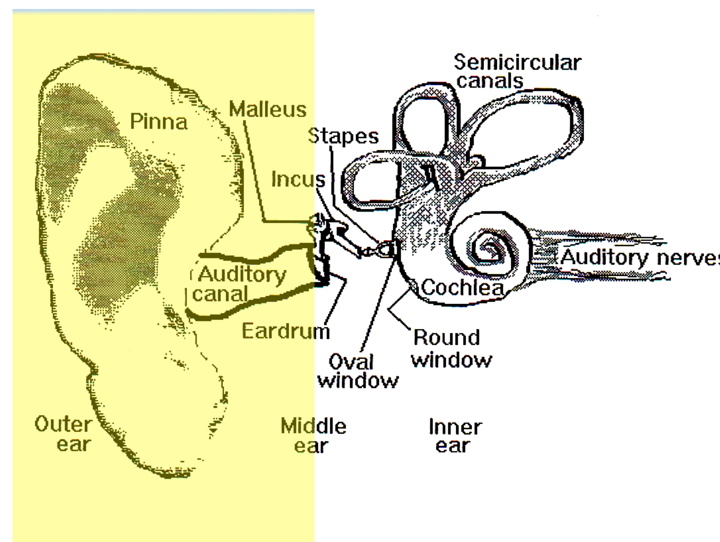
(Cook, 1999)

Outer Ear

- Pinnae
  - Collect sounds
    - http://www.douglas-self.com/MUSEUM/COMMS/ear/ear.htm
  - Related to recognize the direction of sound
    - c.f. Head-related transfer function (HRTF)

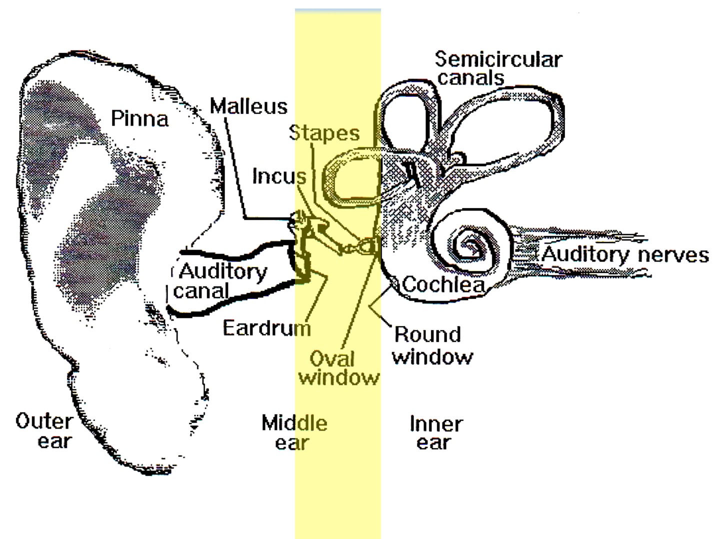
- Auditory canal
  - Protect ear drums
  - Quarter-wave resonance: boost the vibration around 3kHz by 15-20 dB

- Ear drum
  - Membrane that transduces air vibration to mechanical vibration
  - Malleus (hammer) is attached to it



Middle Ear

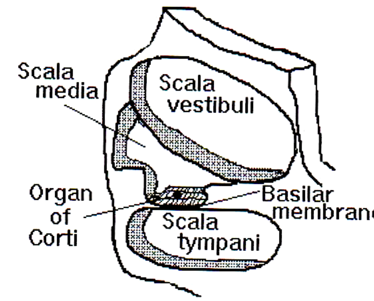
- Ossicles
  - malleus (hammer), incus (anvil) and stapes(stirrup)
  - The smallest bones in human body
  - Impedance matching: between air pressure (outer) and fluid (inner)
    - Without ossicles, only about 1/30 of the sound energy would have been transferred to inner ears
  - Amplification
    - Work as a lever: membrane size changes from the large (ear drum) to the small (oval windows)



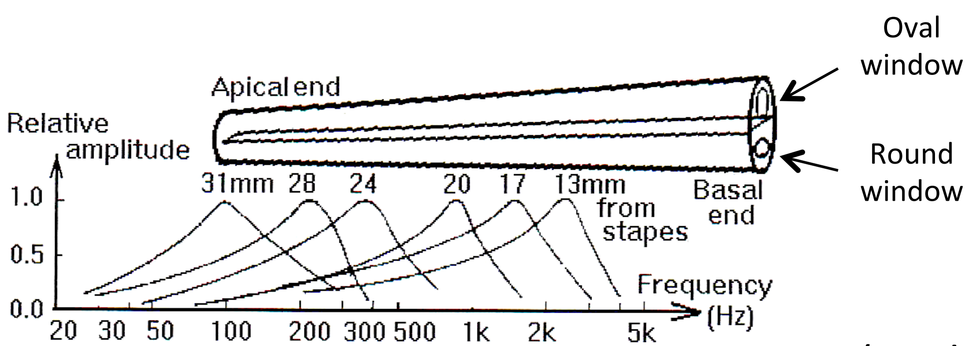
- Muscles
  - Reduce the sound transmission in response to loud sounds

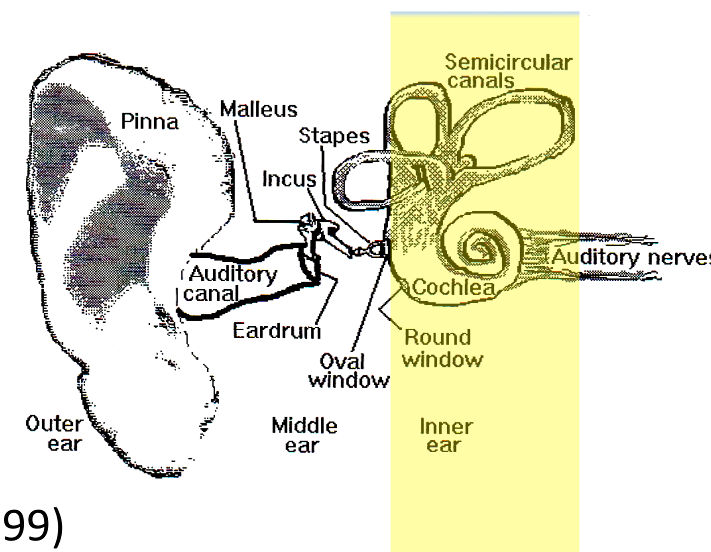
Inner ears

- Cochlea: transduces fluid vibration to nerve firing
- Basilar membrane
  - Fluctuate at different positions selectively according to the frequency of incoming vibration
    - Similar to a bank of band-pass filters
    - http://acousticslab.org/psychoacoustics/PMFiles/Module03a.htm
  - Frequency resolution becomes worse as frequency increases



- Organ of Corti
  - One row of inner hair-cell: fire neural spikes
  - Three rows of outer hair-cell: gain control





(Cook, 1999)

Auditory Transduction Video

- Auditory Transduction
  - http://www.youtube.com/watch?v=PeTriGTENoc

Sound Properties

- Loudness, Pitch, Timbre

- These are psychological (or perceptual) properties of sound
  - They are associated with various physical properties: e.g. amplitude (or pressure), fundamental frequency, spectrum, envelope and duration

Loudness

- Perceptual correlate of pressure (or amplitude)
  - Attribute of auditory sensation in terms of the order on a scale extending from quiet to loud (ANSI, 1994)
  - Based on subjective measure
  - Loudness depends on not only sound intensity but also frequency, bandwidth and duration

Sound Pressure Level

- Objective measures of sound strength
  - Sound pressure is a physically measured amplitude of sound
- Decibel scale
  - Relative quantity to a reference.
    - Sound Pressure Level (SPL): $20\log_{10}(P/P_0)$

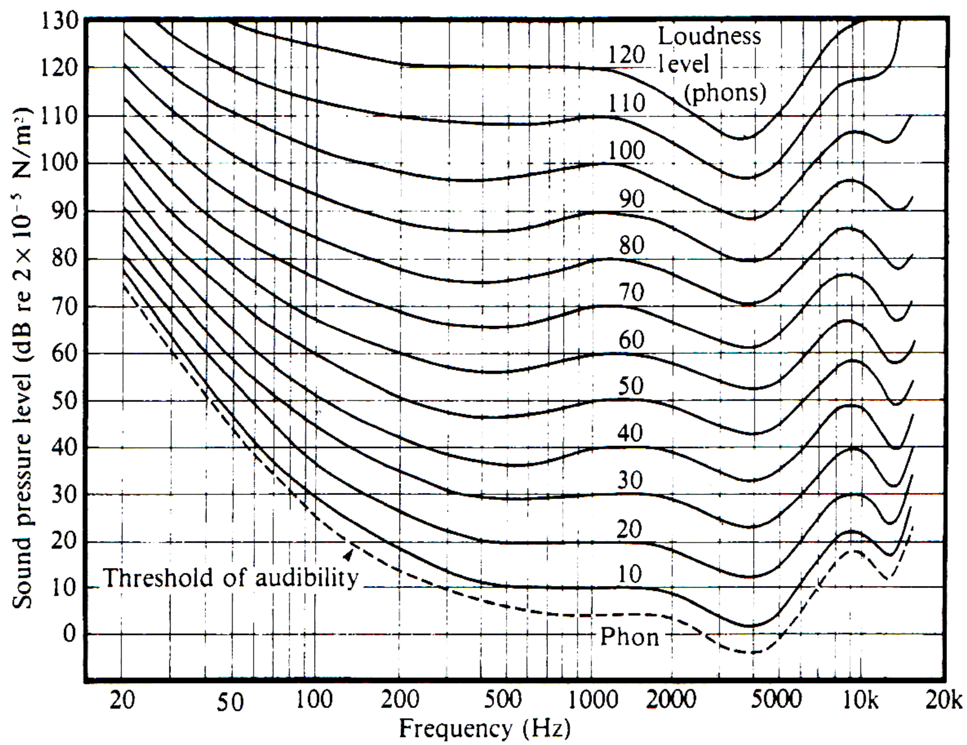
$P_0 = 20\mu\text{Pa}$: threshold of human hearing

Source: http://www.audioholics.com/home-theater-connection/basic-home-theater-setup-guide/splmeter500x332.jpg/image_view_fullscreen

SPL meter

Equal-Loudness Curve

- Loudness depends on frequency
  - 1kH is used as a reference
  - Most sensitive to 2-5KHz tones due to resonance in ears
    - EQ curve by ears is a flipped version of the equal-loudness curve?
  - See the threshold of hearing



Do your own test: http://newt.phys.unsw.edu.au/jw/hearing.html

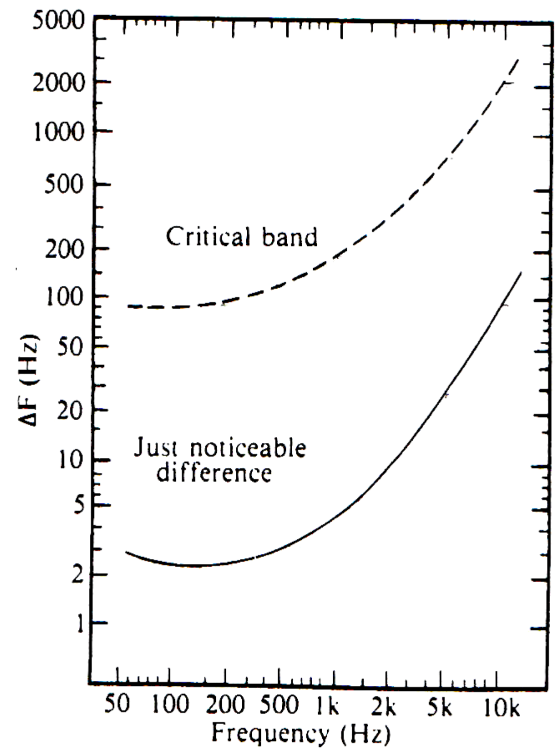
Pitch

- Perceptual correlate of fundamental frequency (F0)
  - Auditory attribute of sound according to which sounds can be ordered on a scale from low and high (ANSI, 1994)
  - Measured by subjective test
  - Pitch is mainly determined by fundamental frequency. However it also depends on pressure, spectrum, envelope and duration.

- Pitch and fundamental frequency are often exchangeable used
  - However, note that they are actually different!

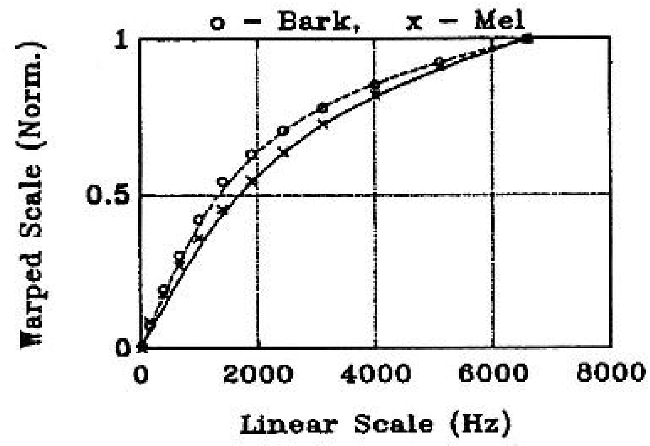
Pitch Perception

- Audible pitch range
  - 20Hz to 20kHz
  - Upper limits gradually decreases with age and also how much you are exposed to strong noises
- Pitch resolution
  - Just noticeable difference (JND) depends on the frequency, the sound level, the duration of the tone.
  - This is related to pitch scale



Pitch Scale

- Human ears are sensitive to frequency changes in a log scale
  - Mel scale: pitch ratio of tones
  - Bark scale: critical band measurement



- Musical pitch scale
  - Music note (m) and frequency (f) in Hz

$$m = 12\log_2\left(\frac{f}{440}\right) + 69, \qquad f = 440 \cdot 2^{(m-69)/12}$$

Timbre

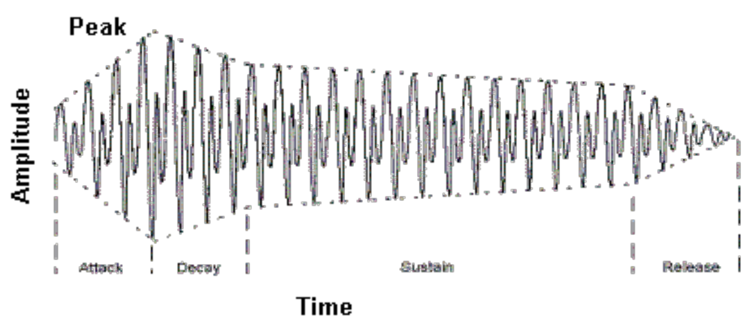
- Attribute of sensation by which a listener can judge two sounds having the same loudness and pitch are dissimilar (ANSI)

- Tone color or quality that defines a particular sound
  - Class: piano, guitar, singing voice, engine sound
  - Identity: Steinway, Fender Stratocaster, MJ, Harley Davisson

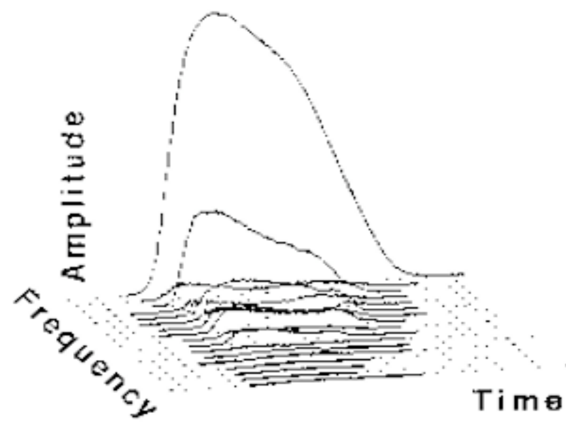
- Timbre is a very vague concept
  - There is no single quantitative scale like loudness or pitch

Timbre Perception

- Determined by multiple physical attributes
  - Harmonicity: ratio between tonal and noise-like characteristics
  - Time envelope (ADSR)
  - Spectral envelope
  - Changes of spectral envelope and fundamental frequency
  - The onset of a sound differing notably from the sustained vibration



ADSR



Changes of spectral envelope

Timbre Perception

- Determined by multiple parameters

KAIST