2018 Fall
CTP431: Music and Audio Computing

Fundamentals of Musical Acoustics

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Outlines

- Introduction to musical tones

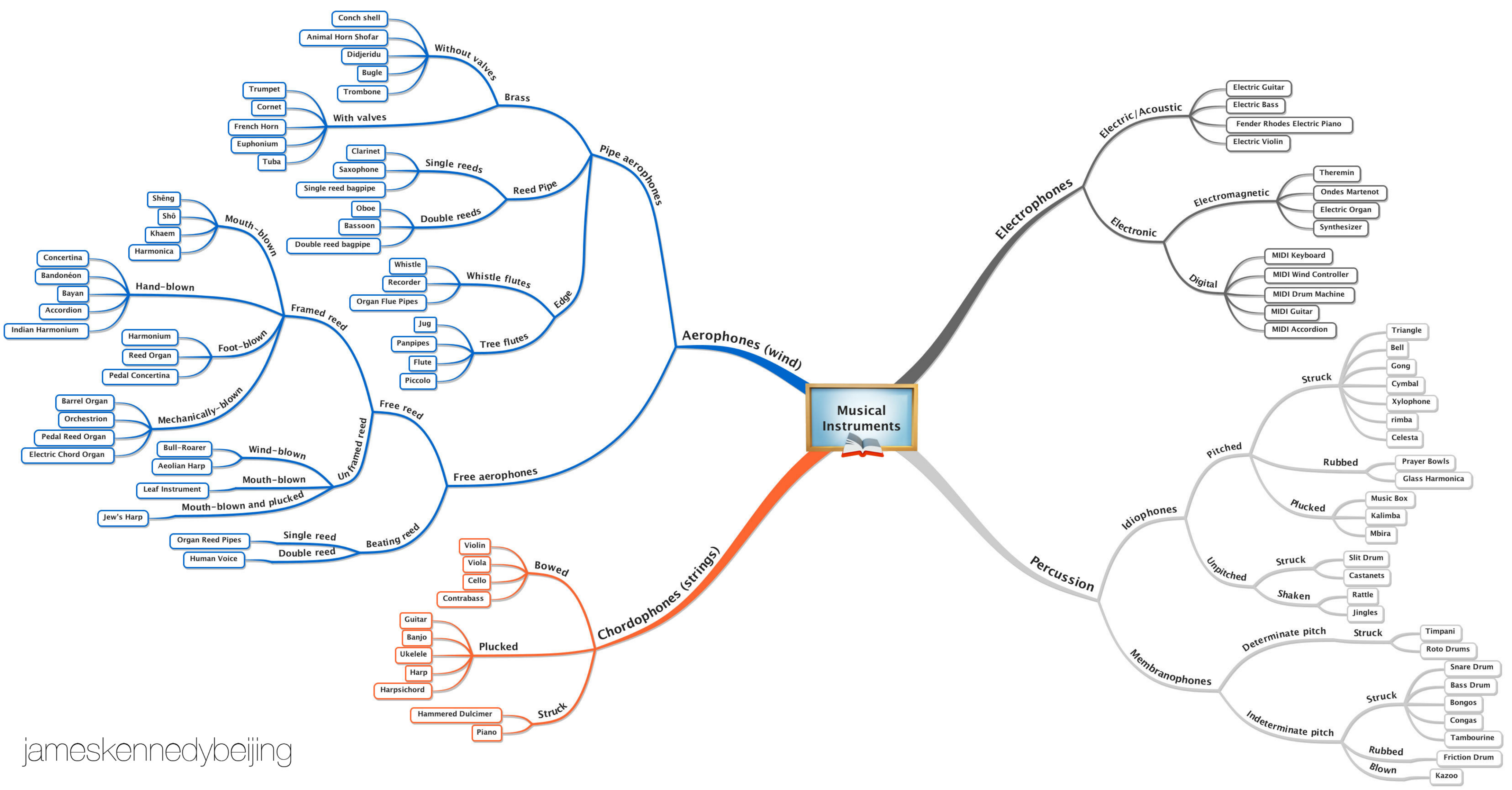
- Musical tone generation
  - String
  - Pipe, Membrane

- Properties of musical tones
  - Time-domain
  - Frequency-domain
  - Time-Frequency domain

- Human perception

Introduction to Musical Tones

Taxonomy of Musical Instruments

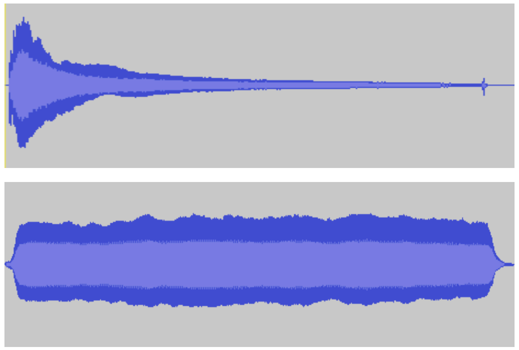


Source: https://jameskennedymonash.wordpress.com/2012/05/06/mind-map-taxonomy-of-musical-instruments/

Musical Tone Generation

Excitation
(plucking, striking)

Source-driven
(bowing, blowing)

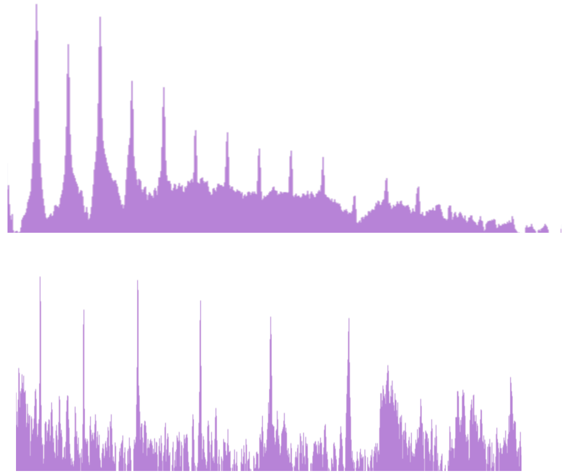


Amplitude Envelope

Action → **Musical Instrument** → **Sound**

1D vibration
(string, pipe)

2D vibration
(bar, drum)

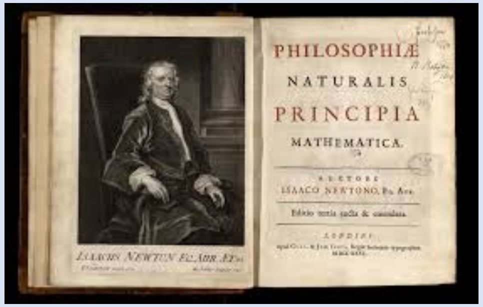


Pitch and Spectral Envelope

Musical Tone Generation

Excitation
(plucking, striking)

Source-driven
(bowing, blowing)

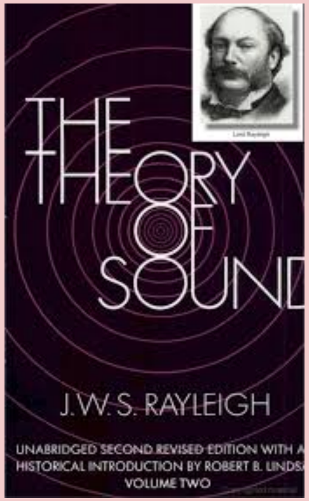


Newton
“Law of motion”

Action → **Musical Instrument** → **Sound**

1D vibration
(string, pipe)

2D vibration
(bar, drum)



Rayleigh
“Wave Properties of Sound”

Musical Tone Generation: String

1. Drive force on a sound object
2. Vibration by restoration force
3. Propagation
4. Reflection
5. Superposition
6. Standing Wave (modes)
7. Radiation

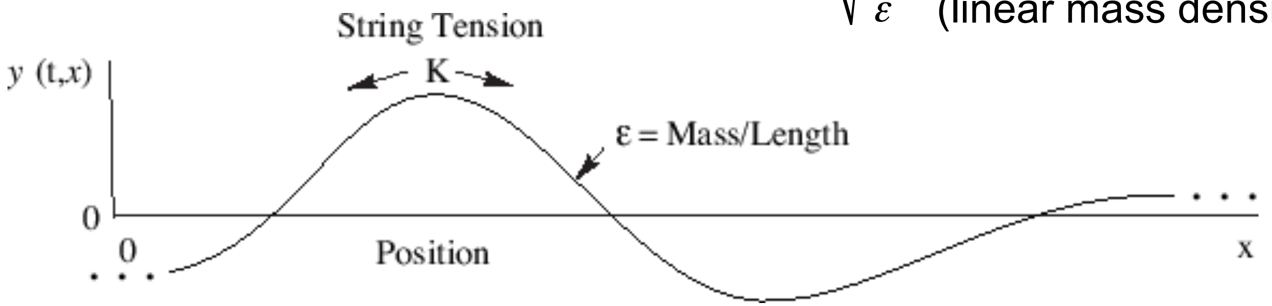
Musical Tone Generation: String

- One-dimensional ideal vibrating string

$$c = \sqrt{\frac{K}{\varepsilon}}$$ (string tension) (linear mass density)

Wave Equation

$$K\frac{\partial^2 y}{\partial x^2} = \varepsilon\frac{\partial^2 y}{\partial t^2}$$

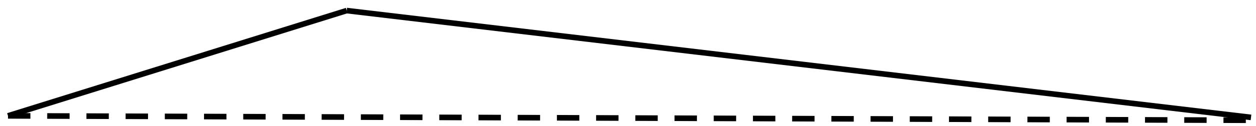


Boundary Conditions

Fixed or open ends

Initial Conditions

Action (plucking, striking)



Wave Propagation

- Explained by **wave equation** on the vibrating string

$$K\frac{\partial^2 y}{\partial x^2} = \varepsilon \frac{\partial^2 y}{\partial t^2} \longrightarrow y(x,t) = y_r(t - x/c) + y_l(t + x/c)$$

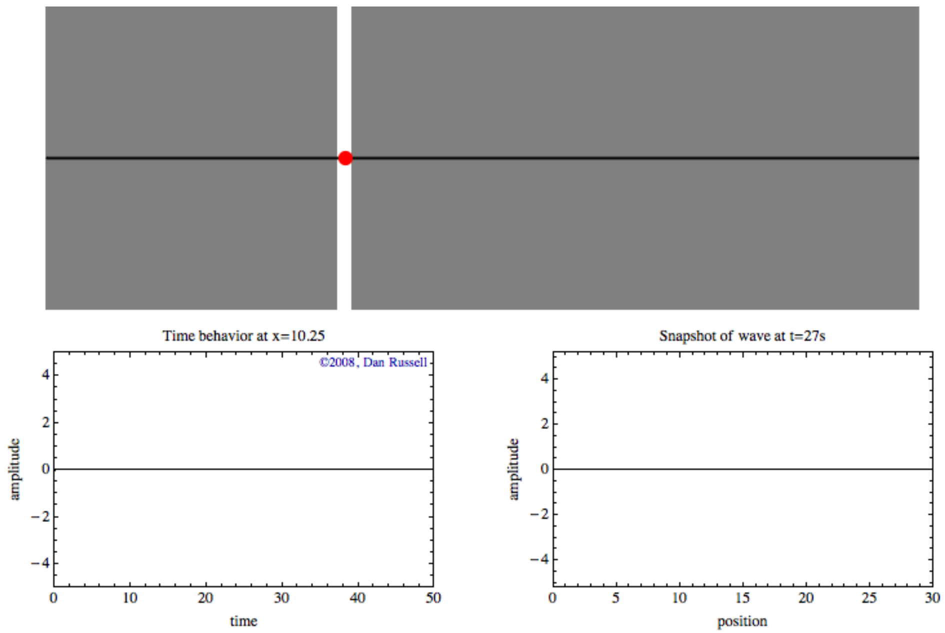
General solution

Any left-traveling wave, any right-traveling wave and the sum of the two satisfy the wave equation.

(An example of solutions)

$$y(x,t) = A \cdot \sin(\omega t + kx)$$

Note that wave is a function of time and position



Source: https://www.acs.psu.edu/drussell/Demos/wave-x-t/wave-x-t.html

Wave Reflection

- Explained by the **boundary conditions**

Hard Boundary

(wave is flipped)

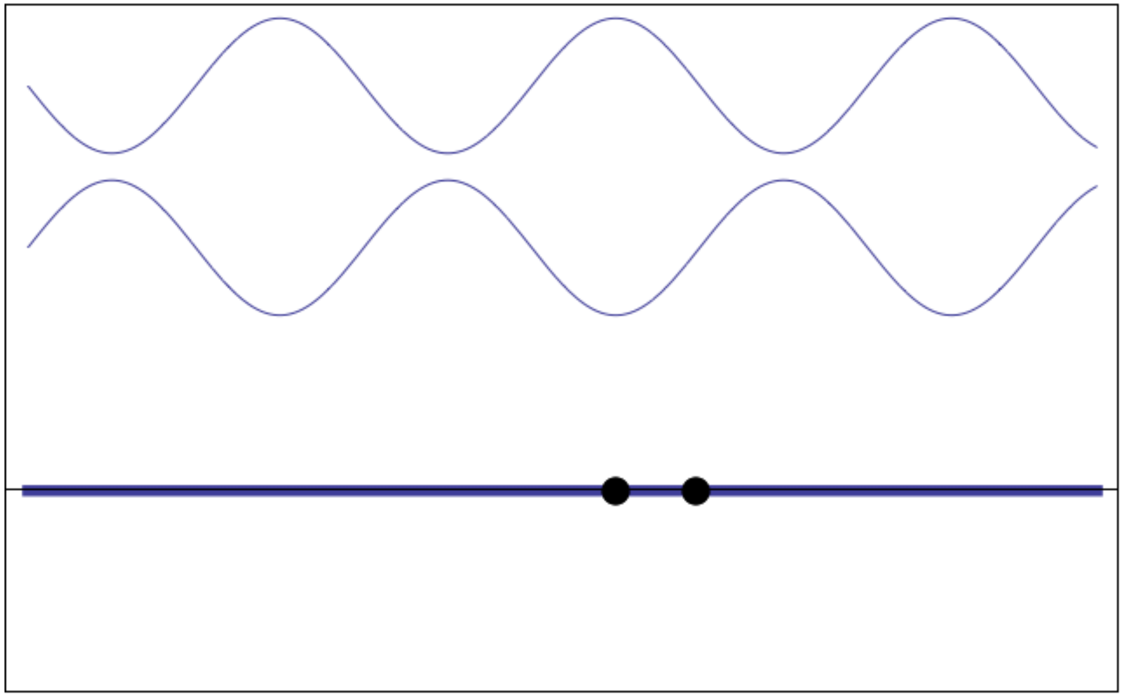
Soft Boundary

(wave is mirrored)

Source: http://www.acs.psu.edu/drussell/Demos/reflect/reflect.html

Wave Superposition and Standing Wave

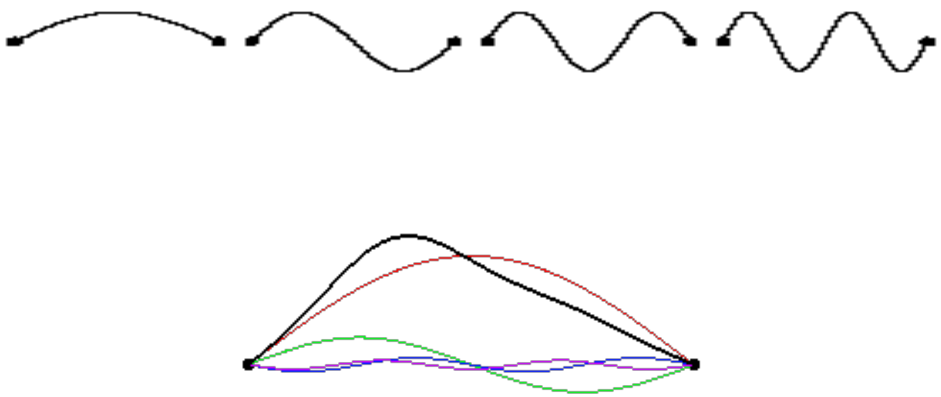
- The sum of two travelling waves in opposite directions with the same frequency cancel or reinforce each other, creating a stationary oscillation



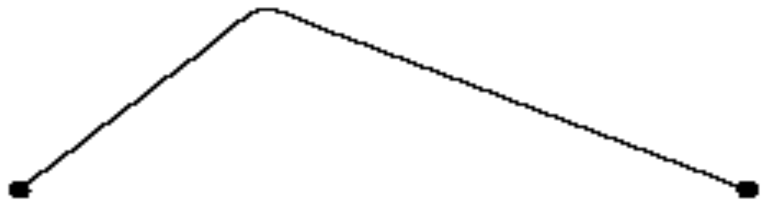
Source: http://www.acs.psu.edu/drussell/Demos/superposition/superposition.html

Complex Harmonic Oscillation

- Combination of modes are determined by the **initial conditions** (including the string length)



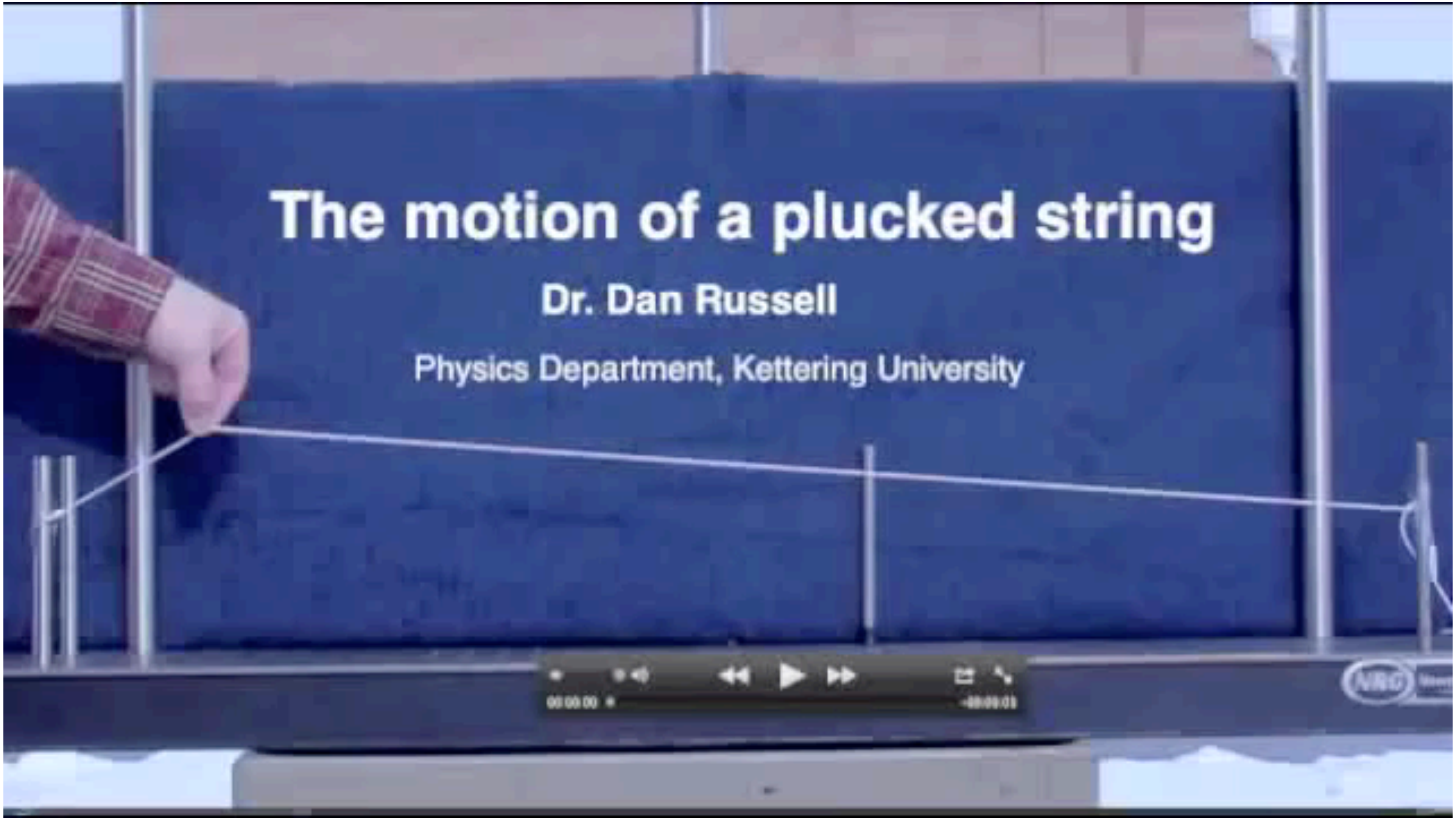
Modes



Wave Motion

Source: https://www.acs.psu.edu/drussell/Demos/string/Fixed.html

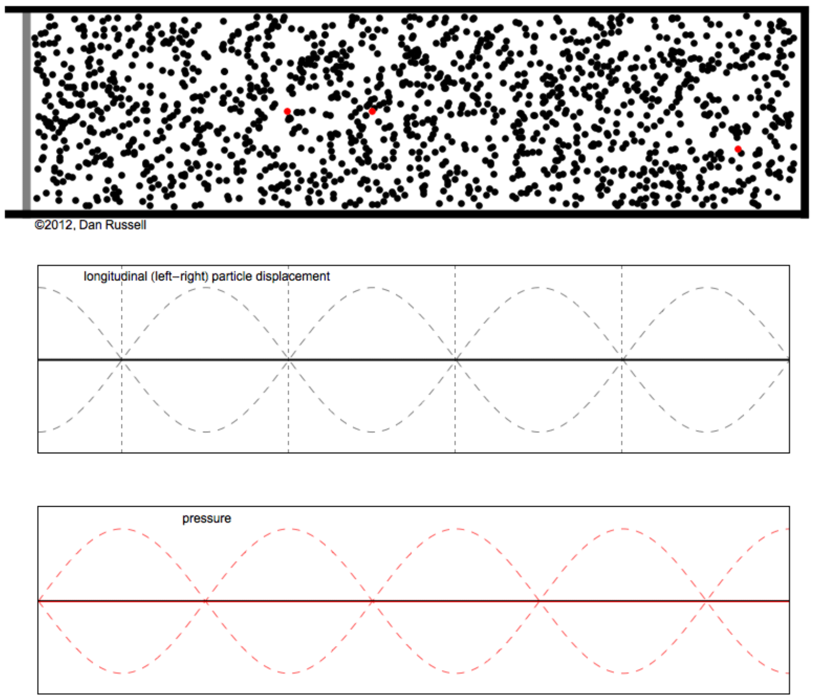
Video



https://www.youtube.com/watch?v=_X72on6CSL0

Musical Tone Generation: Pipe

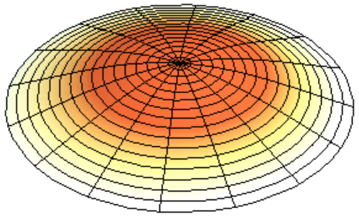
- Analogous to ideal 1D string
  - Woodwind or brass instrument: flute, clarinet, trumpet
  - Blowing: continuous excitation
  - Longitudinal pressure wave to travel in air column



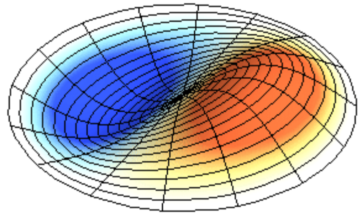
Source: https://www.acs.psu.edu/drussell/Demos/StandingWaves/StandingWaves.html

Musical Tone Generation: Membrane

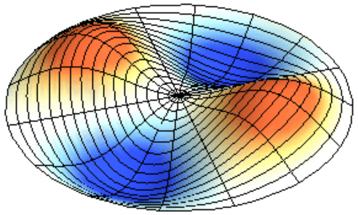
- 2D wave equation: $y(x, y, t)$
  - Drum, percussion
  - Boundary condition: by the shape of membrane
  - Circular harmonic oscillation → generate inharmonic tones



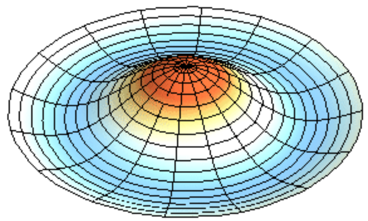
(0,1) Mode



(1,1) Mode



(2,1) Mode



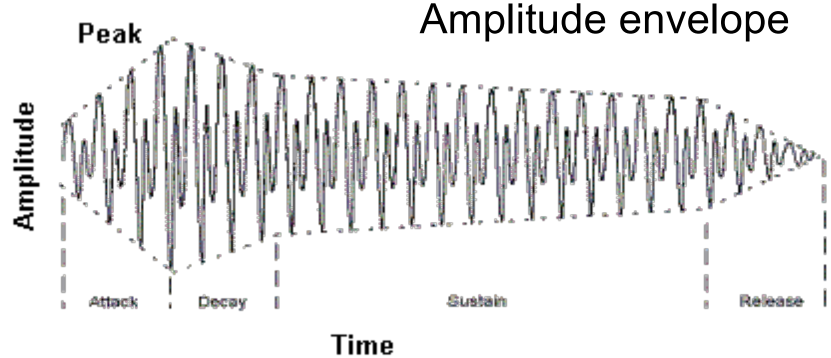
(0,2) Mode

Source: https://www.acs.psu.edu/drussell/Demos/MembraneCircle/Circle.html

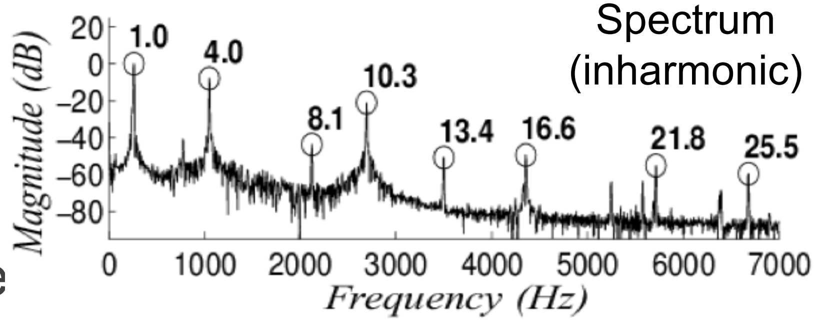
Properties of Musical Tones

- Time domain
  - Intensity (dynamics)
  - Amplitude envelope (ADSR)
- Frequency domain
  - Pitch (fundamental frequency)
  - Spectral envelope (formant)
  - Harmonicity: ratio between tonal and noise
  - Inharmonicity
- Time-Frequency domain
  - Temporal changes of spectral envelope

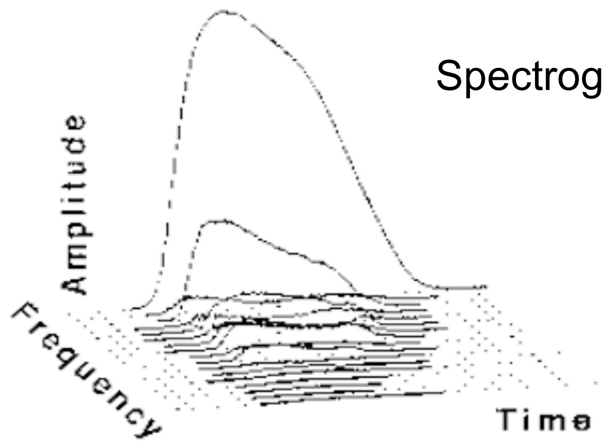
Amplitude envelope



Spectrum
(inharmonic)



Spectrogram



Sound Generation and Perception

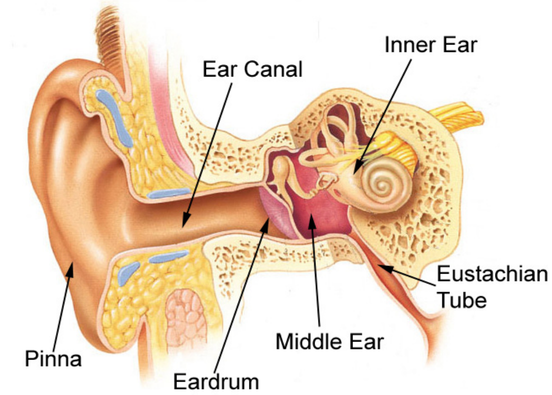
Generation

Vibration on instruments

Propagation

Traveling via the air

Perception



Sensation of the air vibration through ears

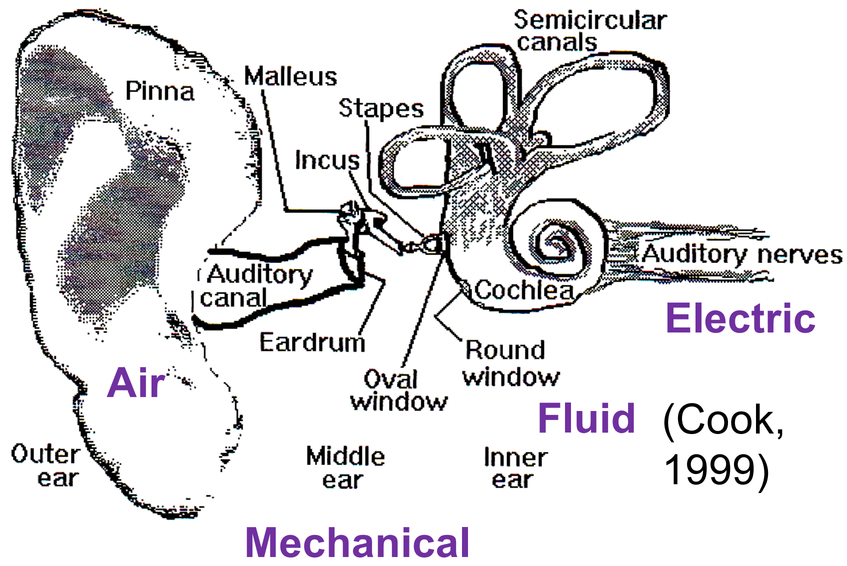
Physical

Psychological

Sound Perception

- human auditory system
  - Ears (physiological sense) and brain (cognitive sense)

- Ears
  - A series of highly sensitive transducers
  - Three parts
    - Outer, middle and inner ears
  - Transform sound into sub-band signals

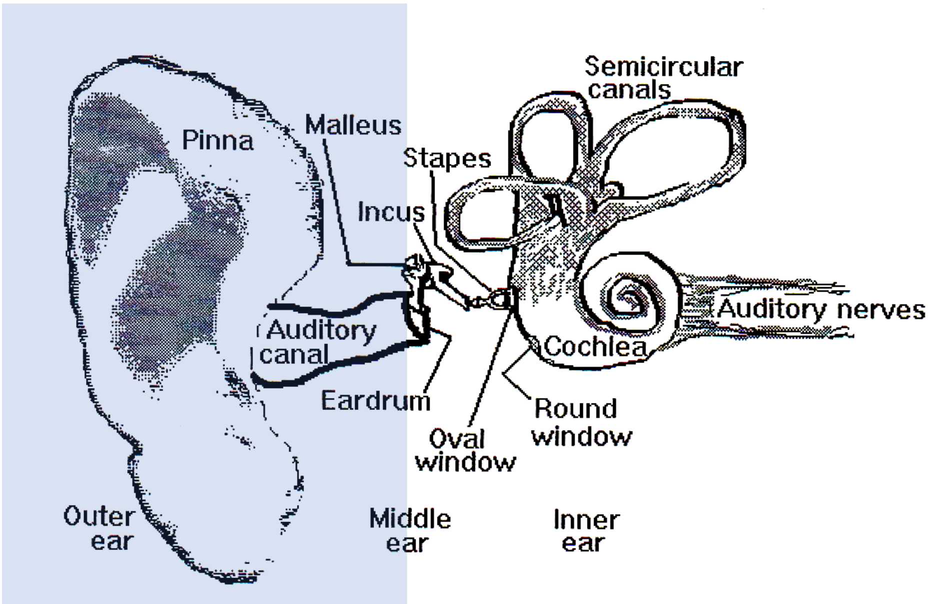


(Cook, 1999)

- Brain
  - Segregate and organize the auditory stimulus
  - Recognize loudness, pitch and timbre

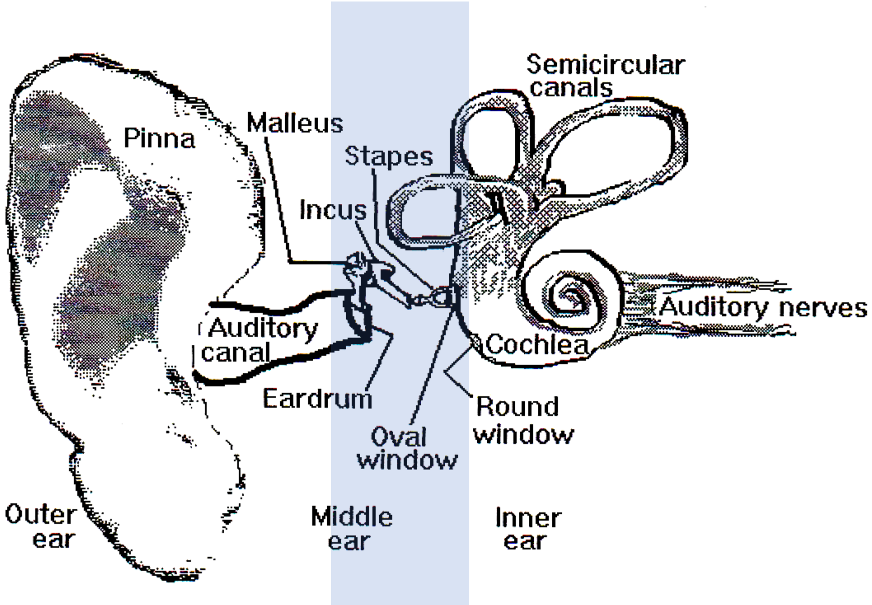
Outer Ear

- Pinnae
  - Collect sounds: http://www.douglas-self.com/MUSEUM/COMMS/ear/ear.htm
  - Related to recognize the sound direction (spatial sound)
    - 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

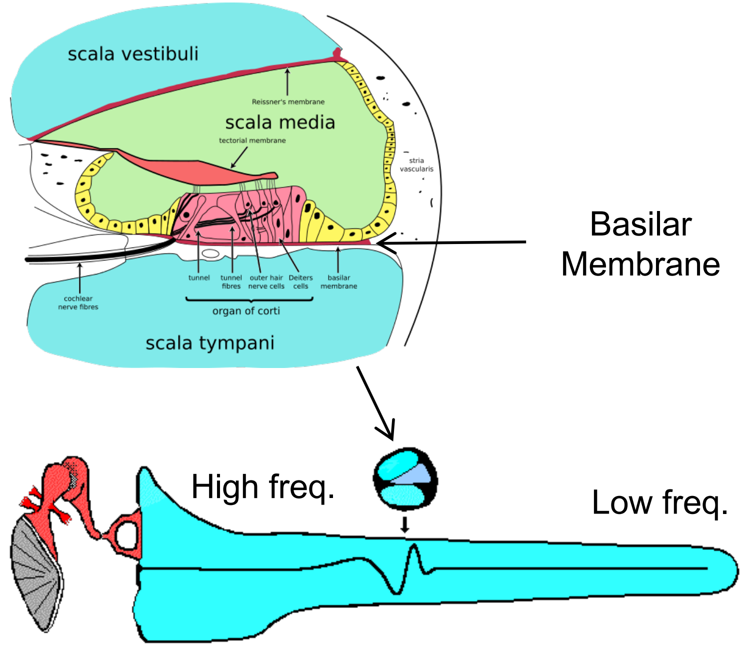
- Ossicles
  - malleus (hammer), incus (anvil) and stapes(stirrup)
  - The smallest bones in human body
  - Impedance matching: between air pressure (outer) and fluid (inner)
    - Without ossicles, only about 1/30 of the sound energy would have been transferred to inner ears
  - Amplification
    -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



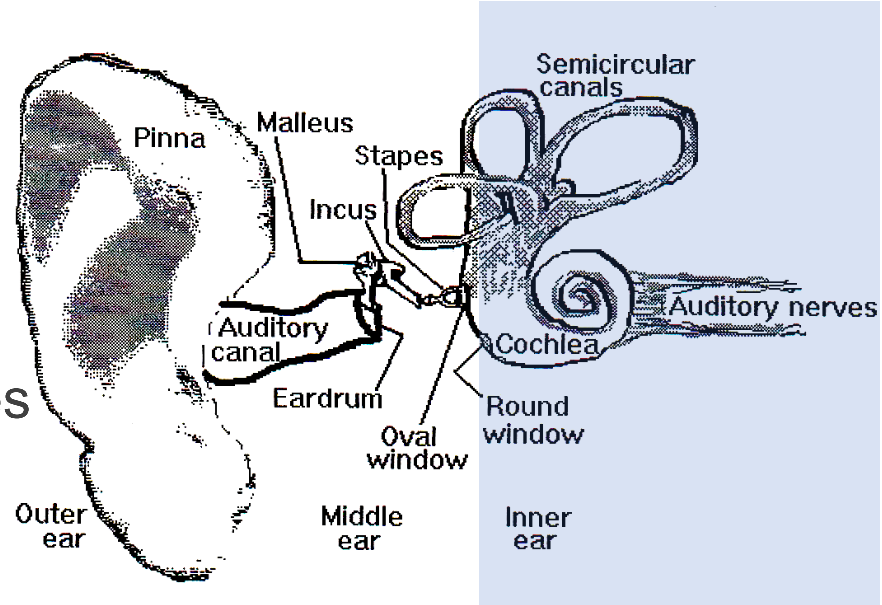
- Muscles
  - Reduce the sound transmission in response to loud sounds

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



Source: http://acousticslab.org/psychoacoustics/PMFiles/Module03a.htm



Auditory Transduction

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

References

- UNSW Music Acoustics Website
  - http://newt.phys.unsw.edu.au/music/
- Stanford Music150 (by Tom Rossing)
  - https://ccrma.stanford.edu/courses/150/
- The Science of Sound (3rd Edition)
  - Thomas D. Rossing, F. Richard Moore, and Paul A. Wheeler