2018 Fall

CTP431: Music and Audio Computing

Fundamentals of Musical Acoustics

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Outlines

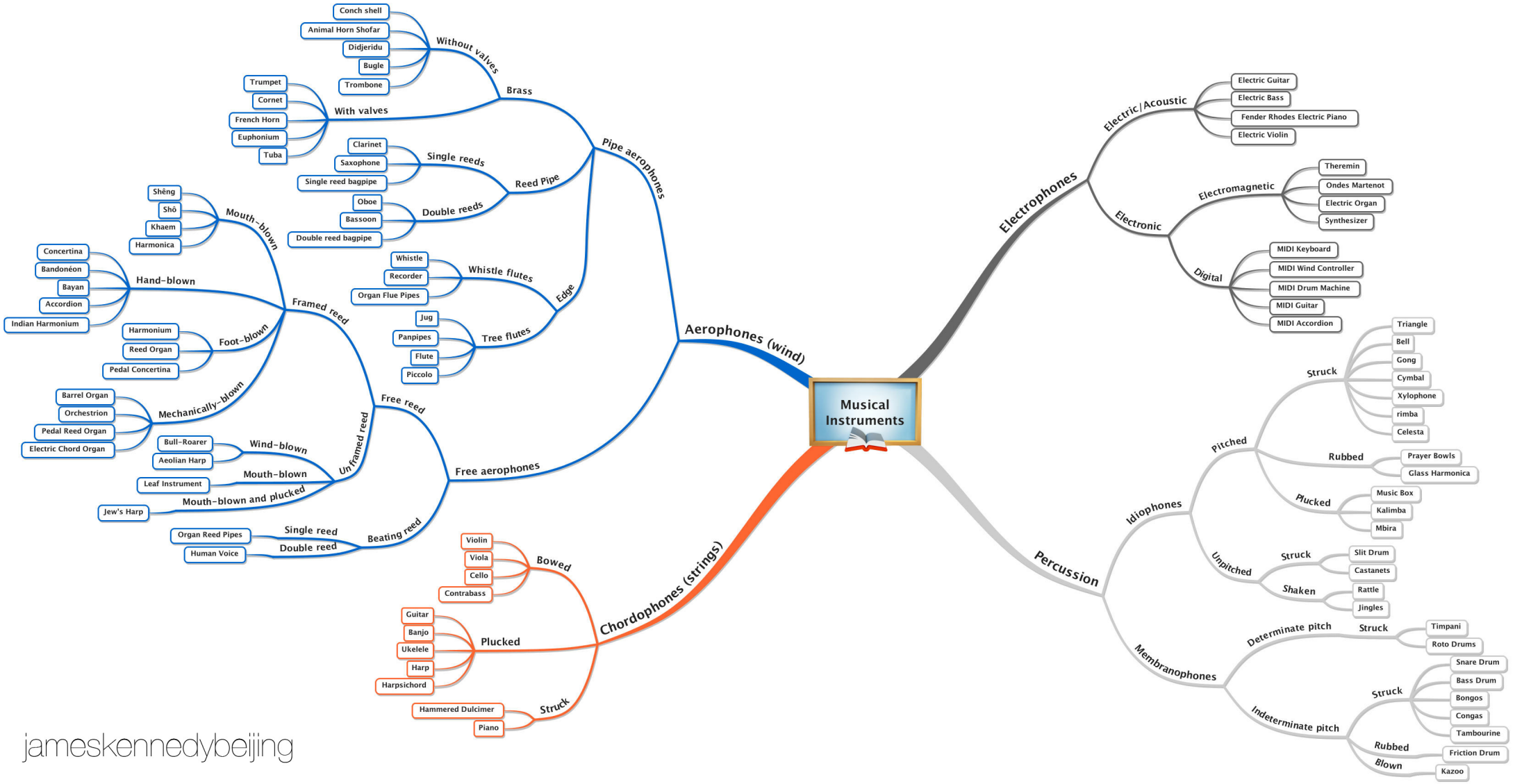
- Introduction to musical tones
- Musical tone generation
  - String
  - Pipe, Membrane
- Properties of musical tones
  - Time-domain
  - Frequency-domain
  - Time-Frequency domain
- Human perception

Introduction to Musical Tones





Taxonomy of Musical Instruments



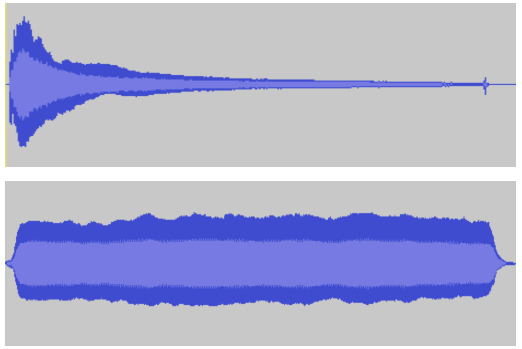
jameskennedybeijing

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

Musical Tone Generation

Excitation
(plucking, striking)

Source-driven
(bowing, blowing)

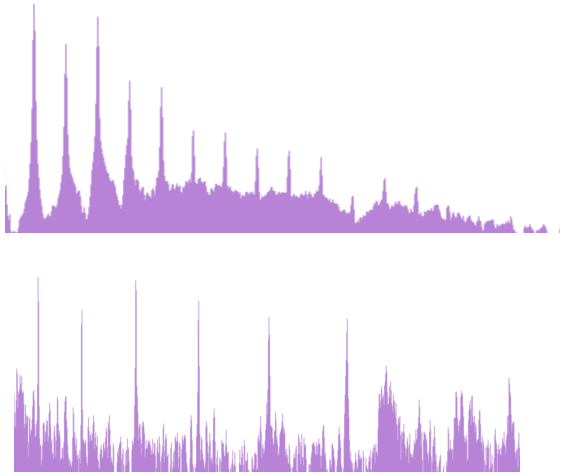


Amplitude Envelope

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

1D vibration
(string, pipe)

2D vibration
(bar, drum)

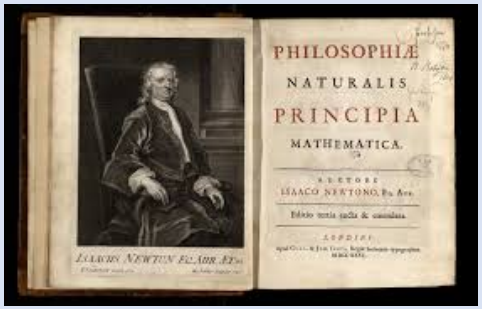


Pitch and Spectral Envelope

Musical Tone Generation

Excitation
(plucking, striking)

Source-driven
(bowing, blowing)

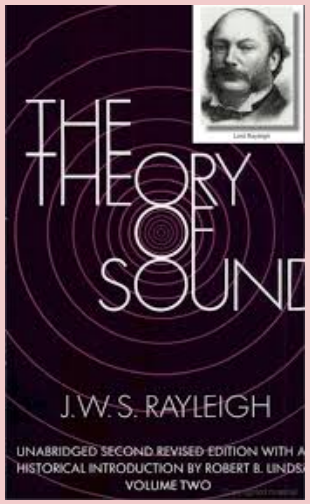


Newton
“Law of motion”

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

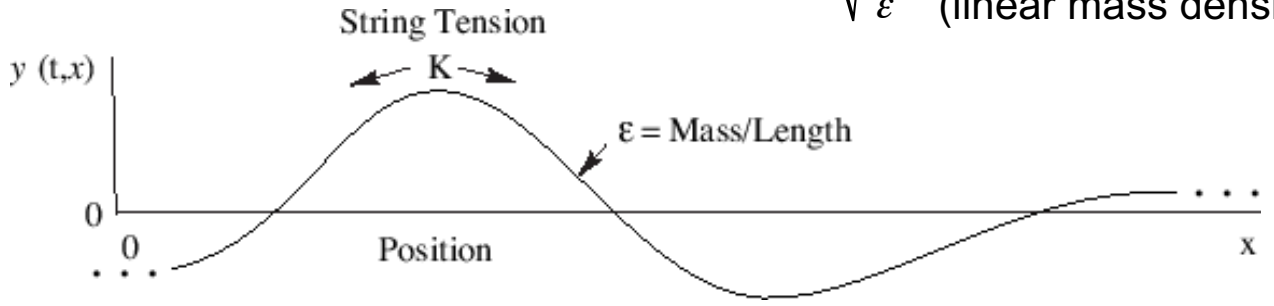
Musical Tone Generation: String

- One-dimensional ideal vibrating string

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

Wave Equation

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

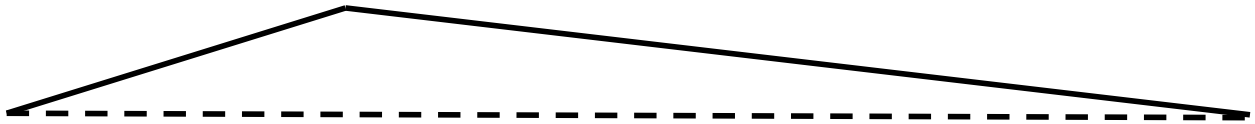


Boundary Conditions

Fixed or open ends

Initial Conditions

Action (plucking, striking)



Wave Propagation

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

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

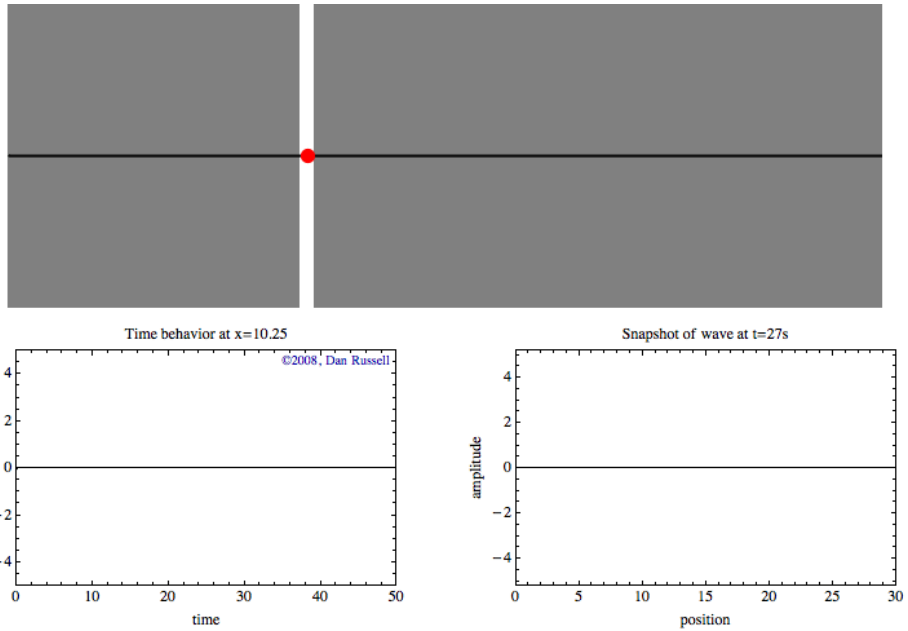
General solution

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)

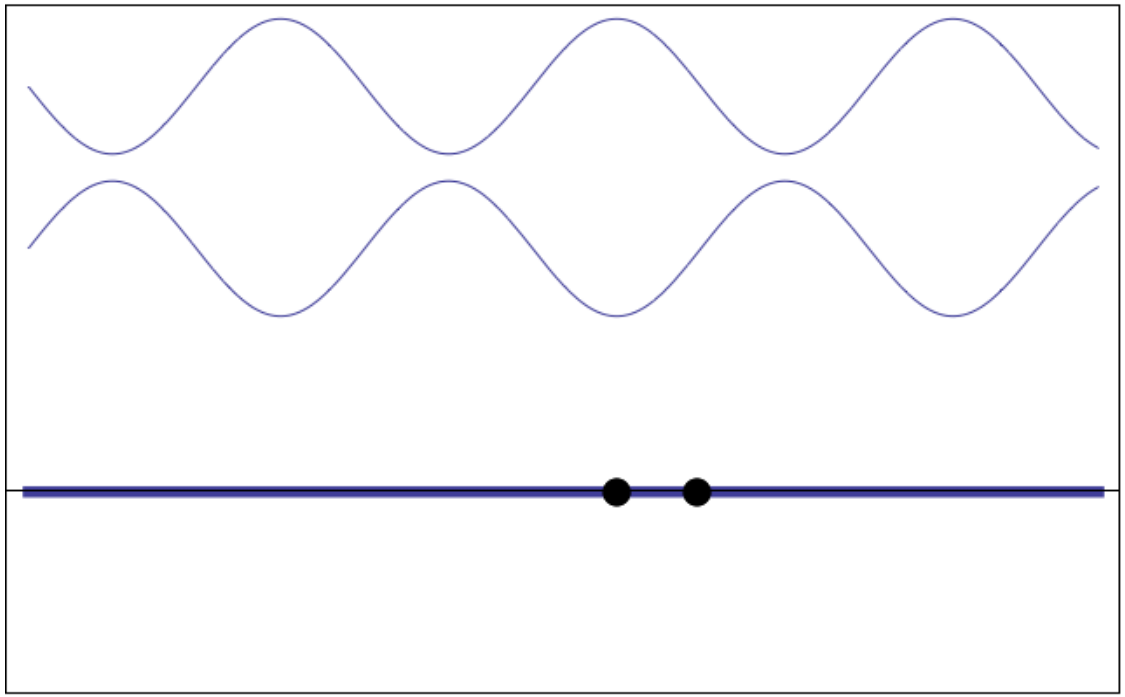
Soft Boundary

(wave is mirrored)

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

Wave Superposition and Standing Wave

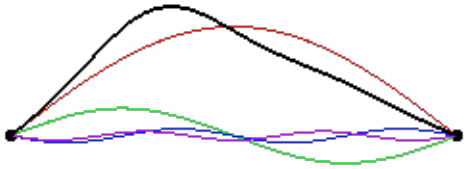
- The sum of two travelling waves in opposite directions with the same frequency cancel or reinforce each other, creating a stationary oscillation



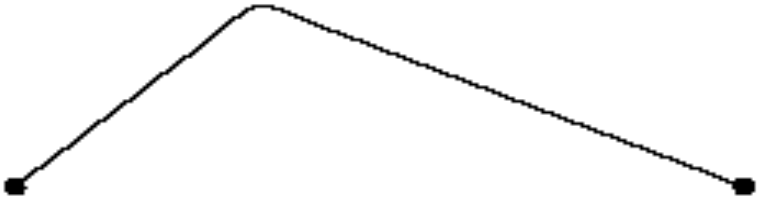
Source: http://www.acs.psu.edu/drussell/Demos/superposition/superposition.html

Complex Harmonic Oscillation

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



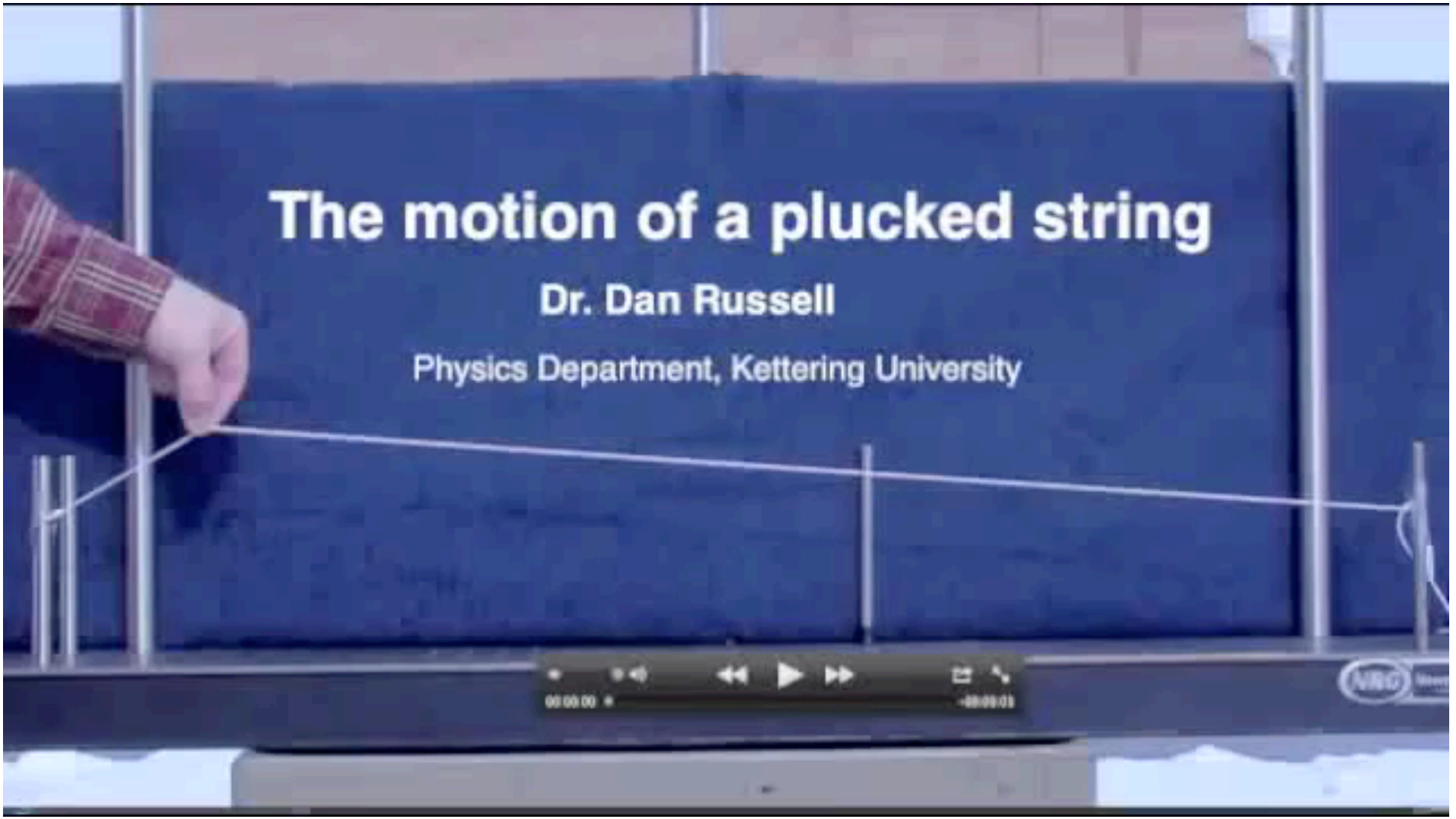
Modes



Wave Motion

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

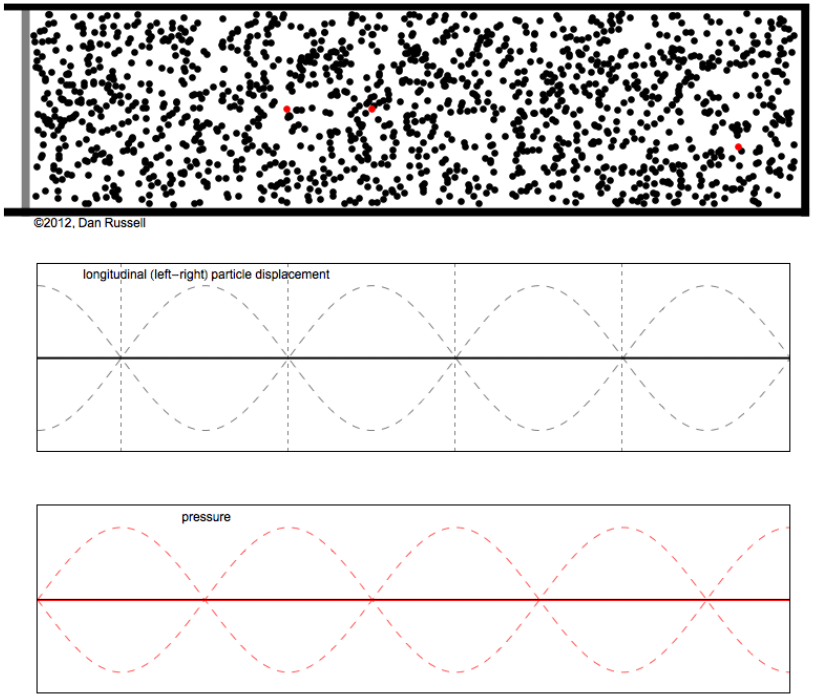
Video



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

Musical Tone Generation: Pipe

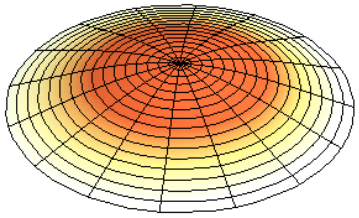
- Analogous to ideal 1D string
  - Woodwind or brass instrument: flute, clarinet, trumpet
  - Blowing: continuous excitation
  - Longitudinal pressure wave to travel in air column



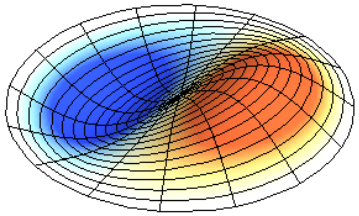
Source: https://www.acs.psu.edu/drussell/Demos/StandingWaves/StandingWaves.html

Musical Tone Generation: Membrane

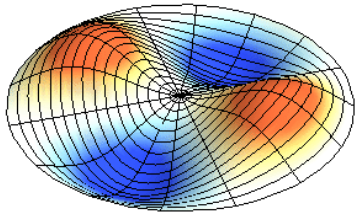
- 2D wave equation: $y(x, y, t)$
  - Drum, percussion
  - Boundary condition: by the shape of membrane
  - Circular harmonic oscillation → generate inharmonic tones



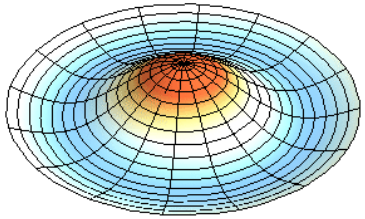
(0,1) Mode



(1,1) Mode



(2,1) Mode

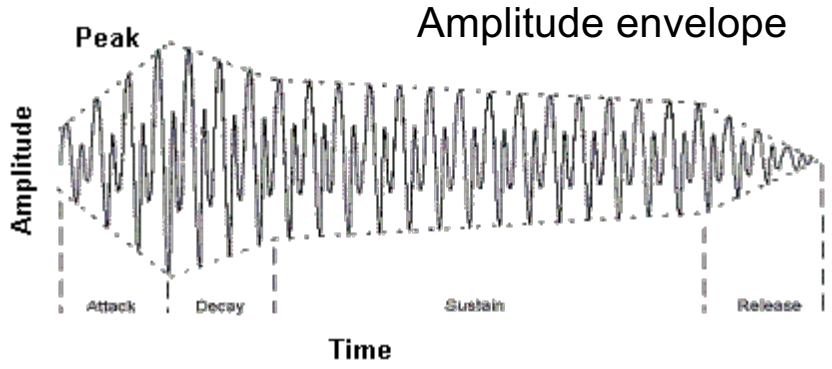


(0,2) Mode

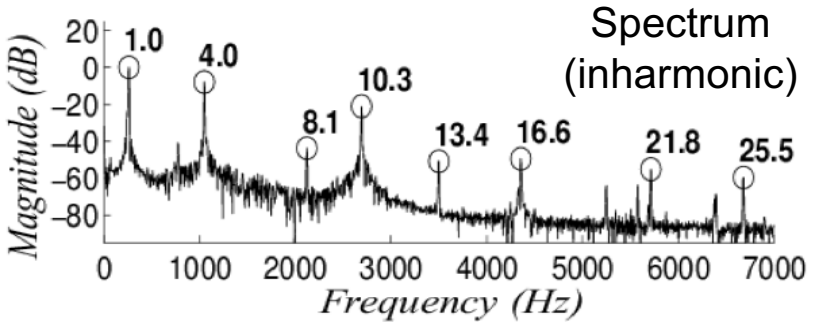
Source: https://www.acs.psu.edu/drussell/Demos/MembraneCircle/Circle.html

Properties of Musical Tones

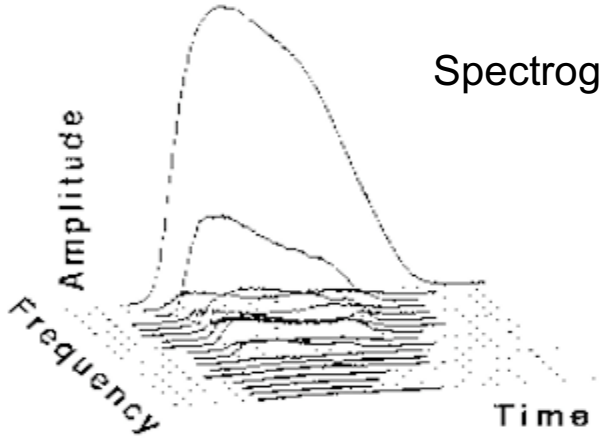
- Time domain
  - Intensity (dynamics)
  - Amplitude envelope (ADSR)



- Frequency domain
  - Pitch (fundamental frequency)
  - Spectral envelope (formant)
  - Harmonicity: ratio between tonal and noise
  - Inharmonicity



- Time-Frequency domain
  - Temporal changes of spectral envelope

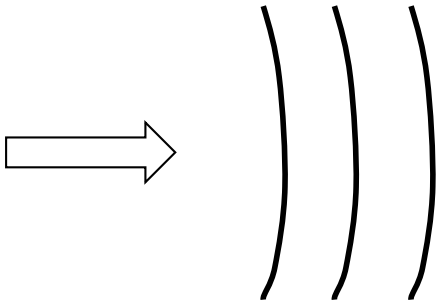


Sound Generation and Perception

Generation

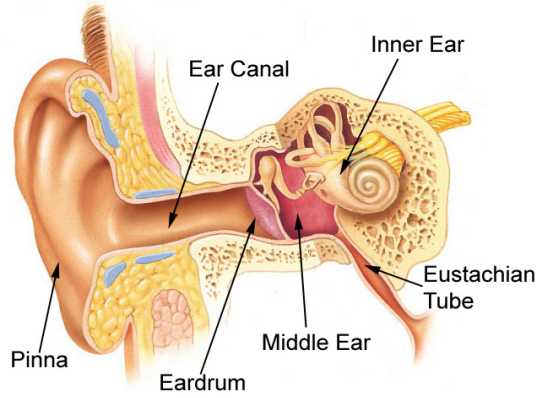
Vibration on instruments

Propagation



Traveling via the air

Perception



Sensation of the air vibration through ears

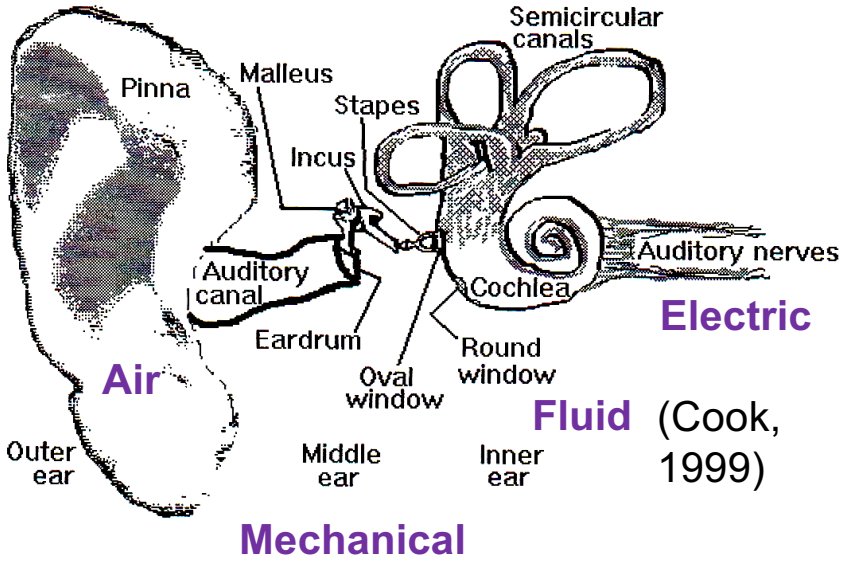
Physical

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

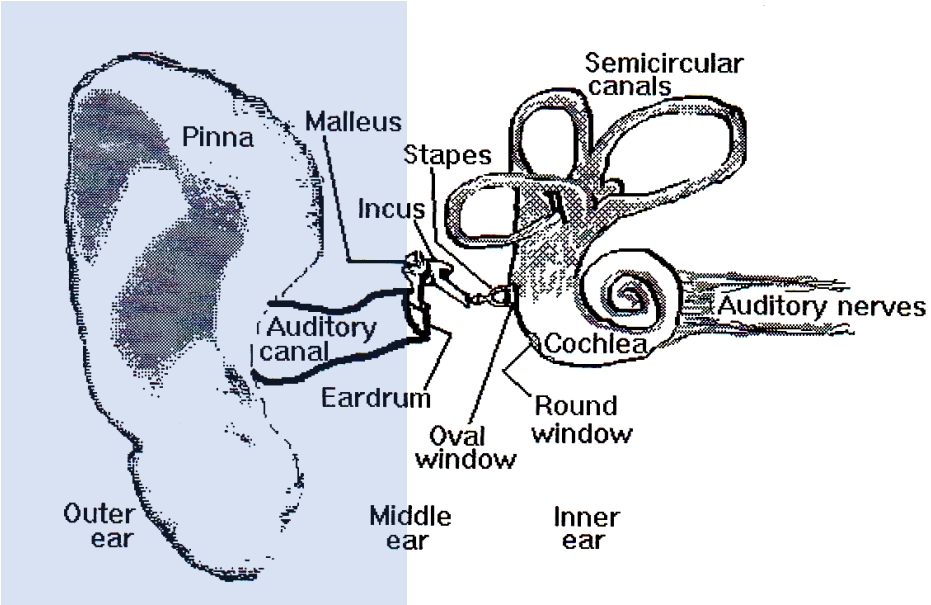


(Cook, 1999)

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

Outer Ear

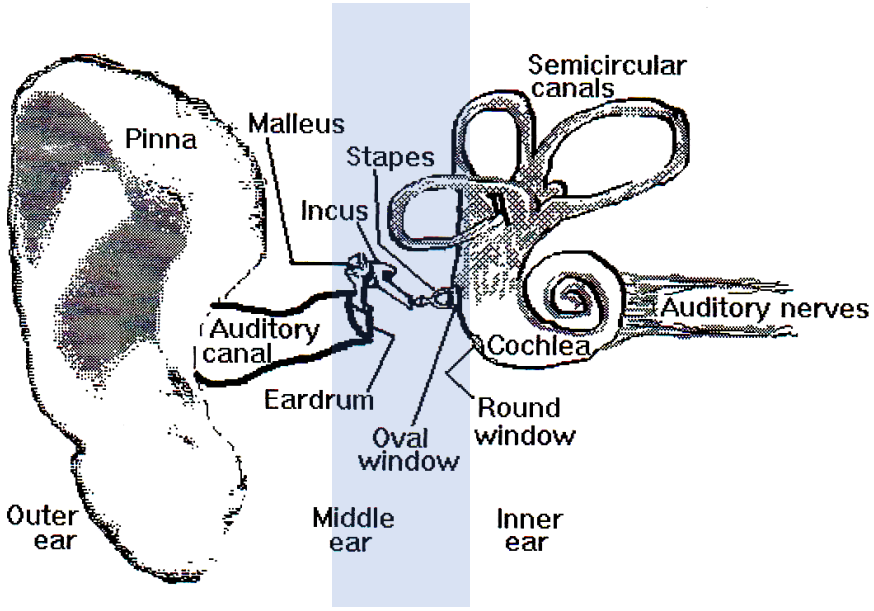
- Pinnae
  - Collect sounds: http://www.douglas-self.com/MUSEUM/COMMS/ear/ear.htm
  - Related to recognize the sound direction (spatial sound)
    - Head-related transfer function (HRTF)
- Auditory canal
  - Protect ear drums
  - Quarter-wave resonance: boost the vibration around 3kHz by 15-20 dB
- Ear drum
  - Membrane that transduces air vibration to mechanical vibration
  - Malleus (hammer) is attached to it



Middle Ear

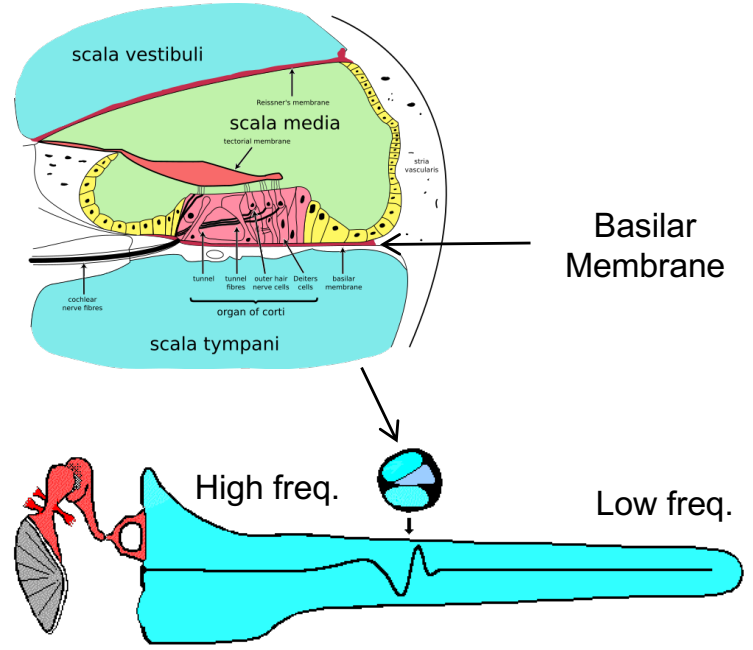
- Ossicles
  - malleus (hammer), incus (anvil) and stapes(stirrup)
  - The smallest bones in human body
  - Impedance matching: between air pressure (outer) and fluid (inner)
    - Without ossicles, only about 1/30 of the sound energy would have been transferred to inner ears
  - Amplification
    - 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

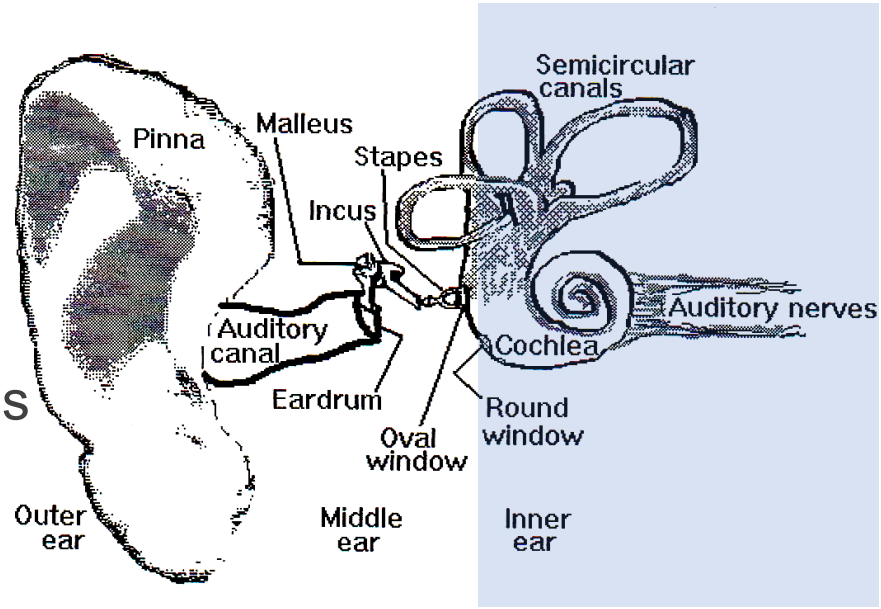


Inner ears

- Cochlear
  - 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