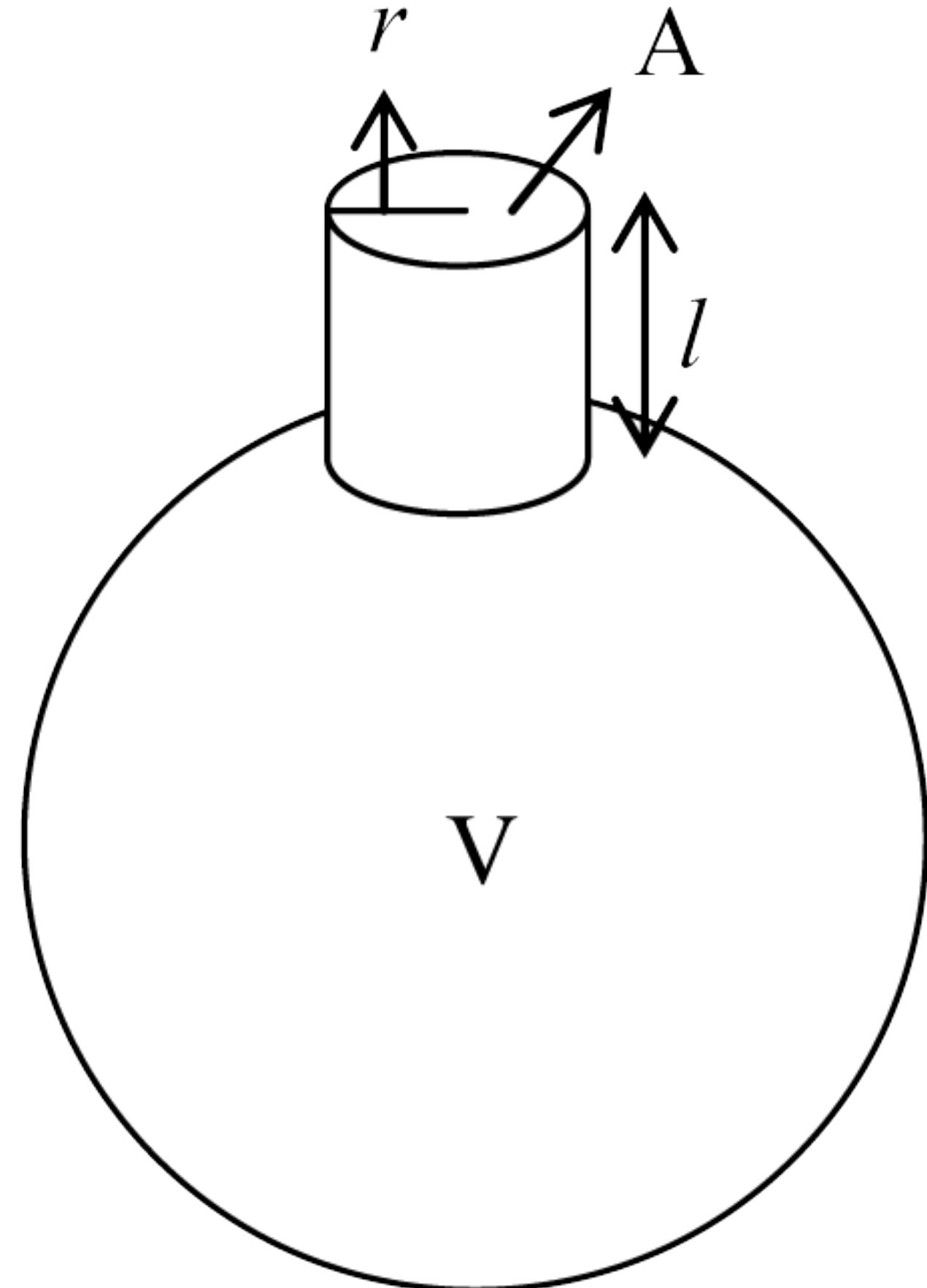


Helmholtz resonator



$$f = \frac{v}{2\pi} \sqrt{\frac{A}{l_{\text{eff}} V}}$$

- Example:

$$r = 1 \text{ cm}, l = 2.7 \text{ cm}, V = 425 \text{ mL}, v = 346 \text{ m/s}$$

$$A = \pi r^2, 1 \text{ mL} = 10^{-6} \text{ m}^3 \Rightarrow f = 239 \text{ Hz}$$

4. Fourier analysis & synthesis

Fourier's theorem

- **standing wave vibrations** are the “**building blocks**” for any complex vibration
- any complex periodic wave can be written as a **sum of harmonics**:

$$y(t) = A_1 \sin(2\pi f_1 t + \phi_1) + A_2 \sin(2\pi f_2 t + \phi_2) + \dots$$

$$f_N = Nf_1, \quad N = 1, 2, \dots$$

- **Ohm's law of hearing**: Phases have little effect on the timbre of the sound
- **Fourier analysis**: decomposing a complex periodic wave into its contributing harmonics
- **Fourier synthesis**: constructing a complex periodic wave by combining harmonics

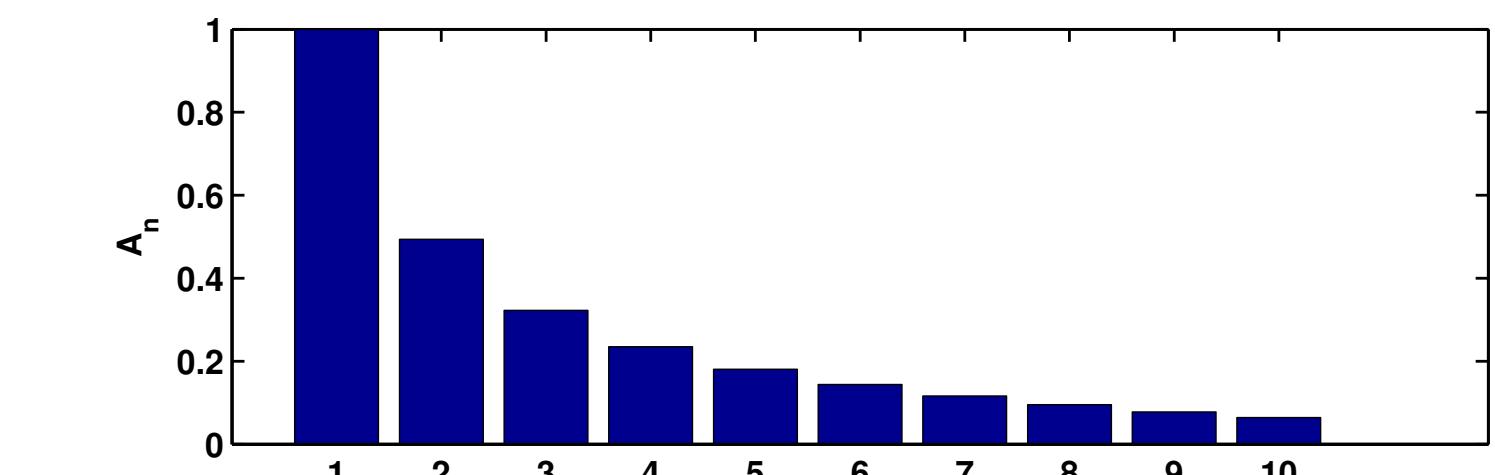
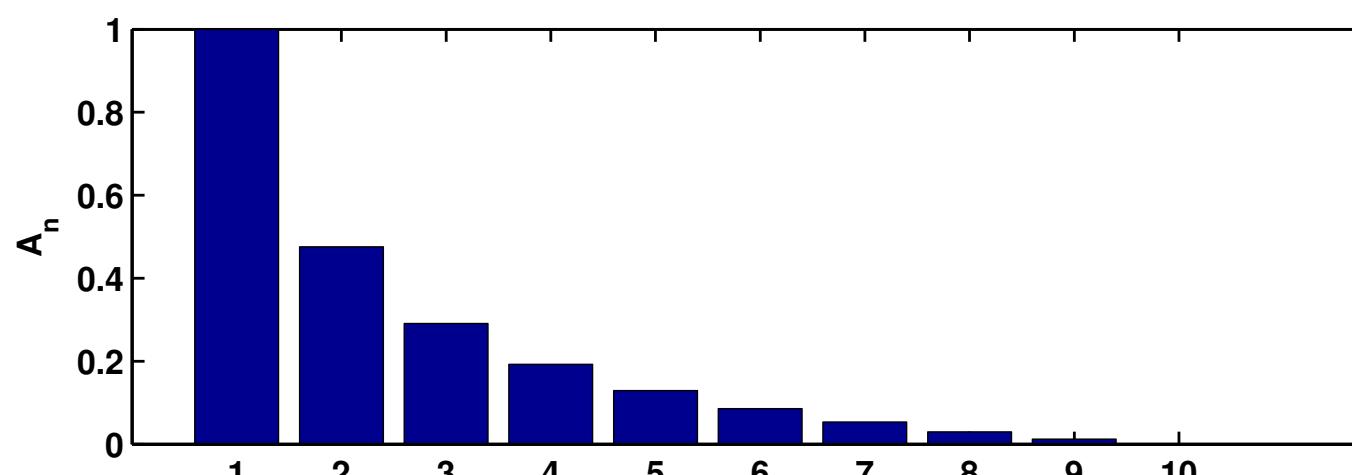
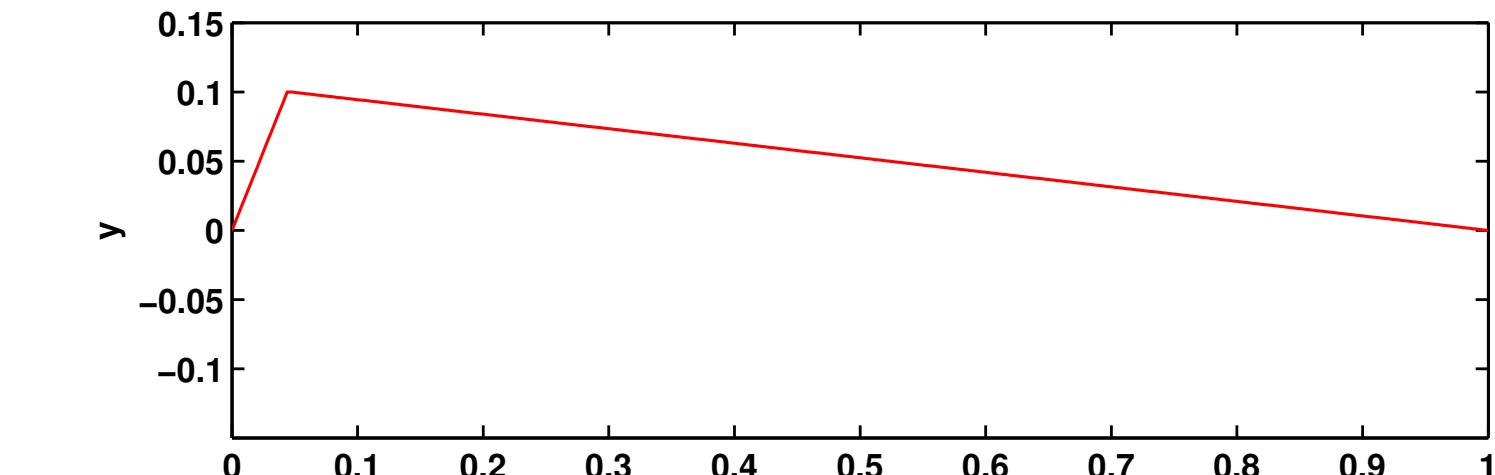
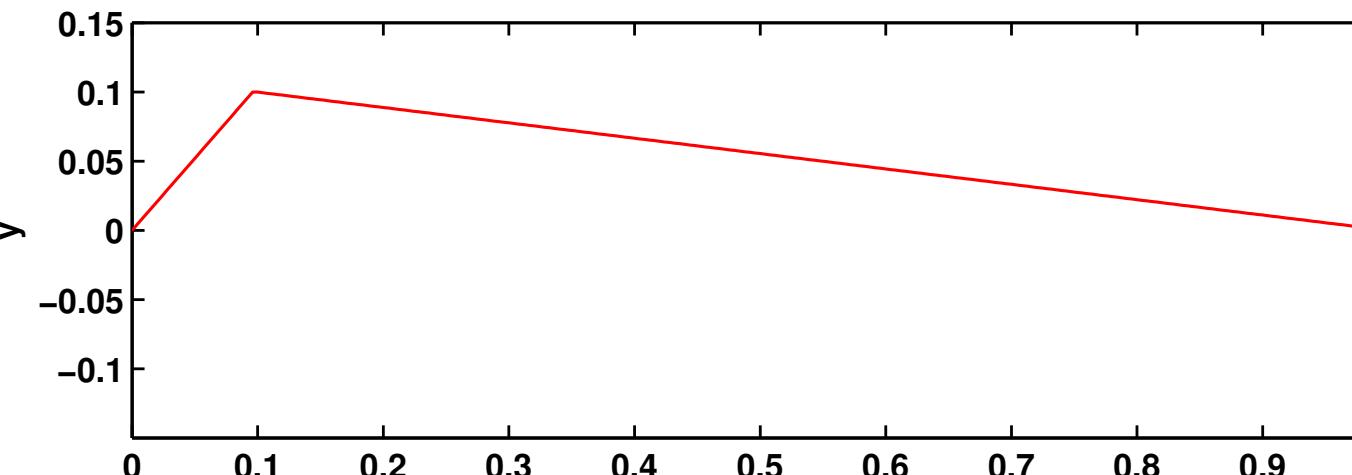
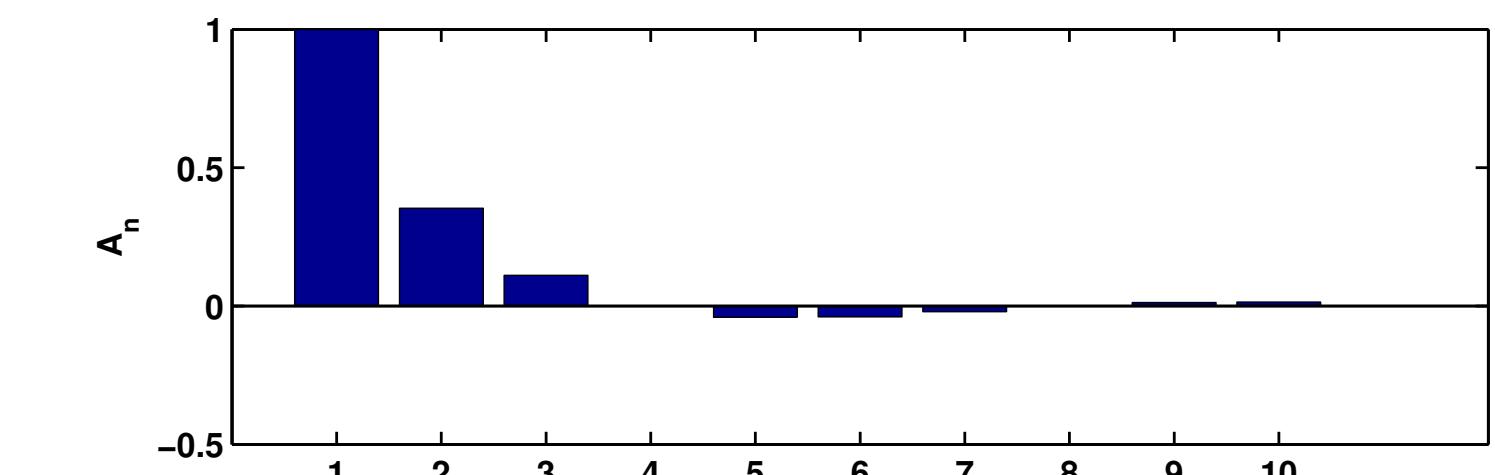
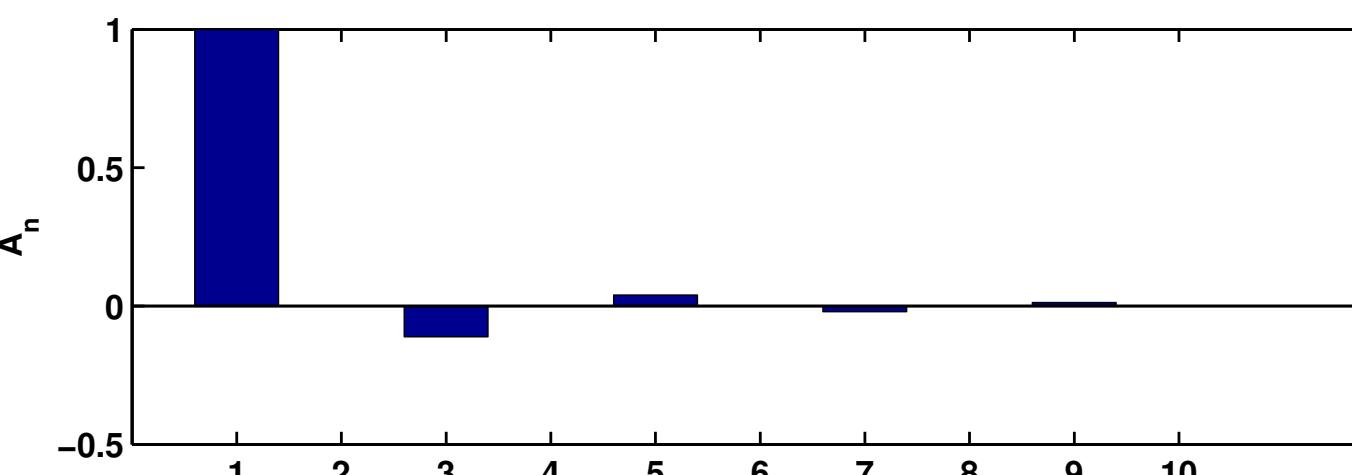
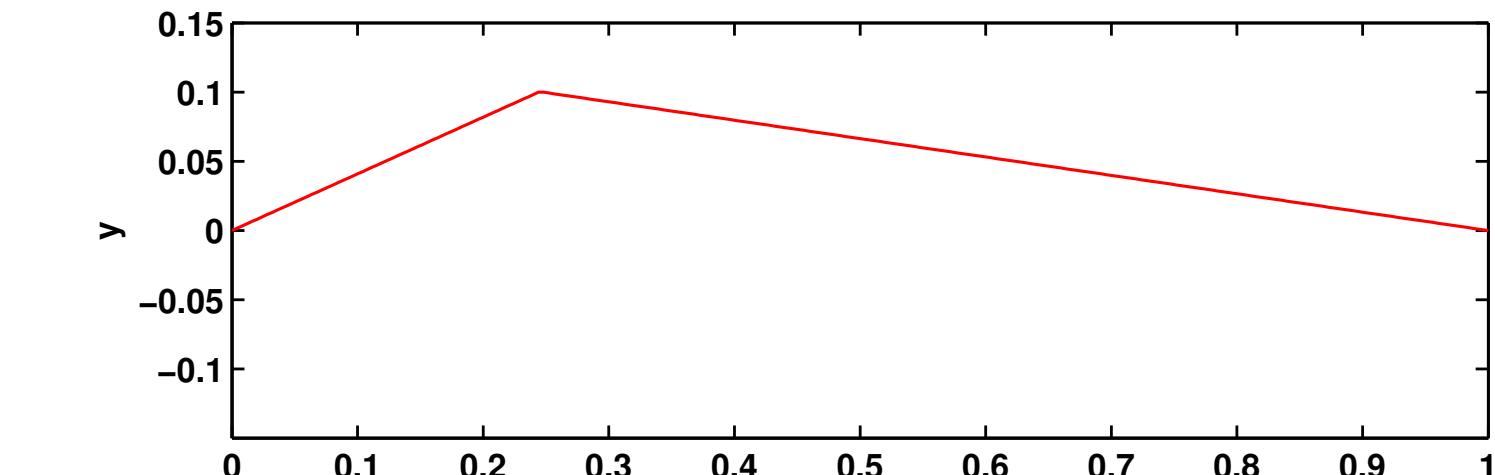
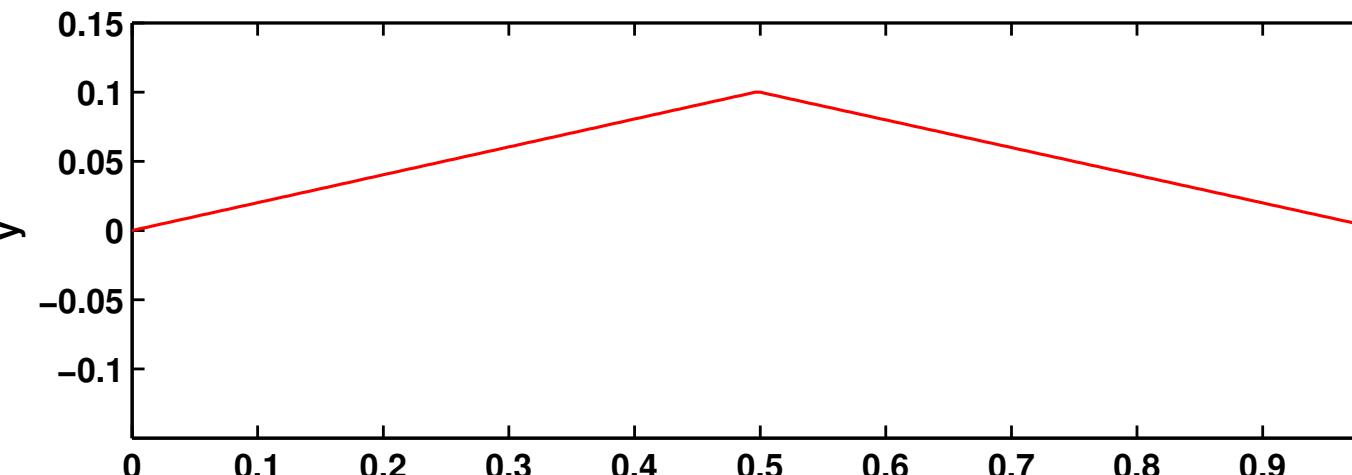
5. String instruments

Plucked versus bowed strings

- Plucked string: https://www.youtube.com/watch?v=_X72on6CSL0
- Bowed string: <https://www.youtube.com/watch?v=6JeyiM0YNo4>
- iPhone guitar video: <https://www.youtube.com/watch?v=TKF6nFzpHBU>
- NOTE: the iPhone guitar video does not show the wave pulses on the strings as they really are. Rather one sees multiple images of the same pulse shape on the string due to the “rolling shutter” effect of the iPhone camera. The actual pulses on a guitar string behave as shown in the first video.

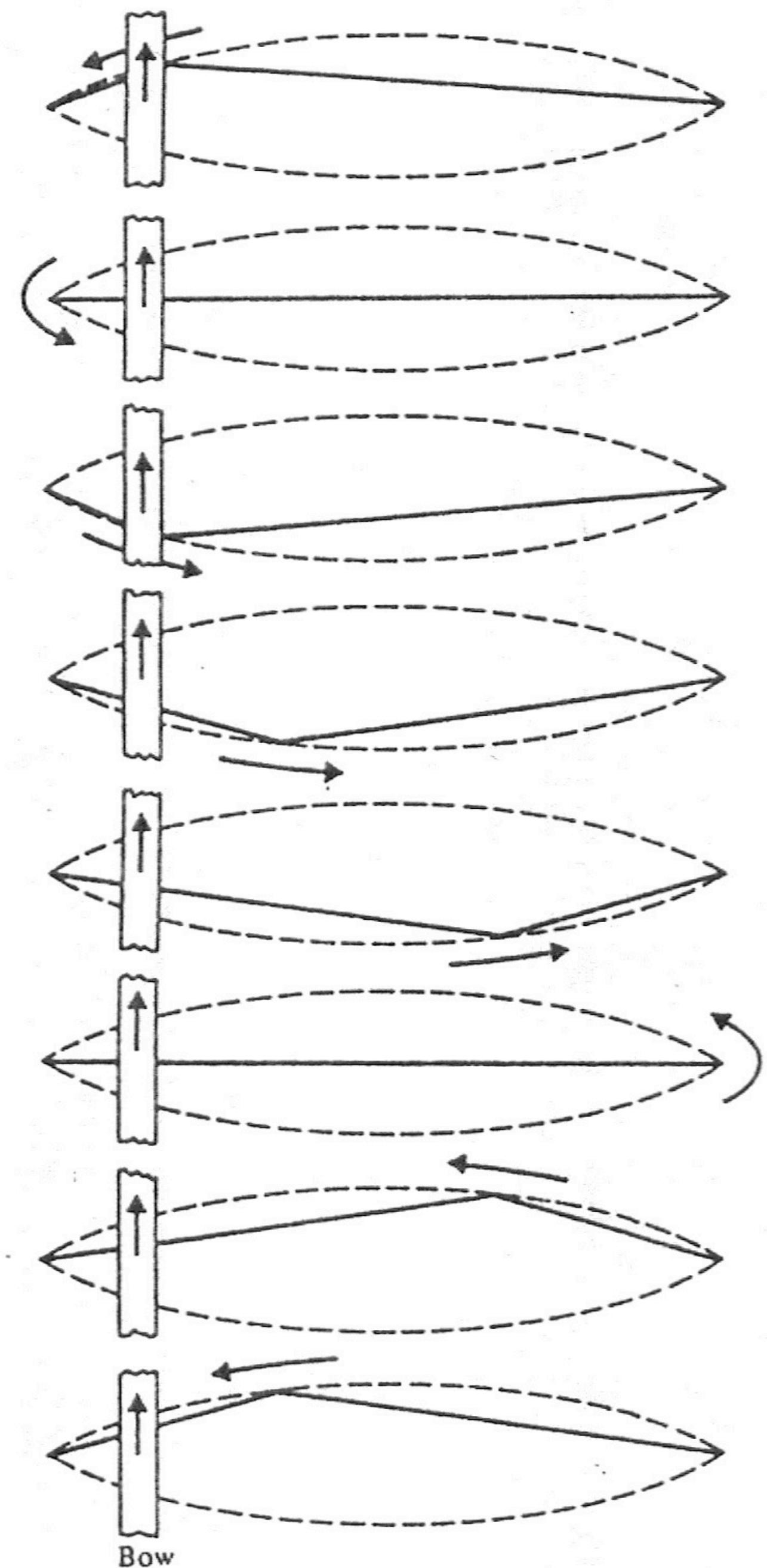
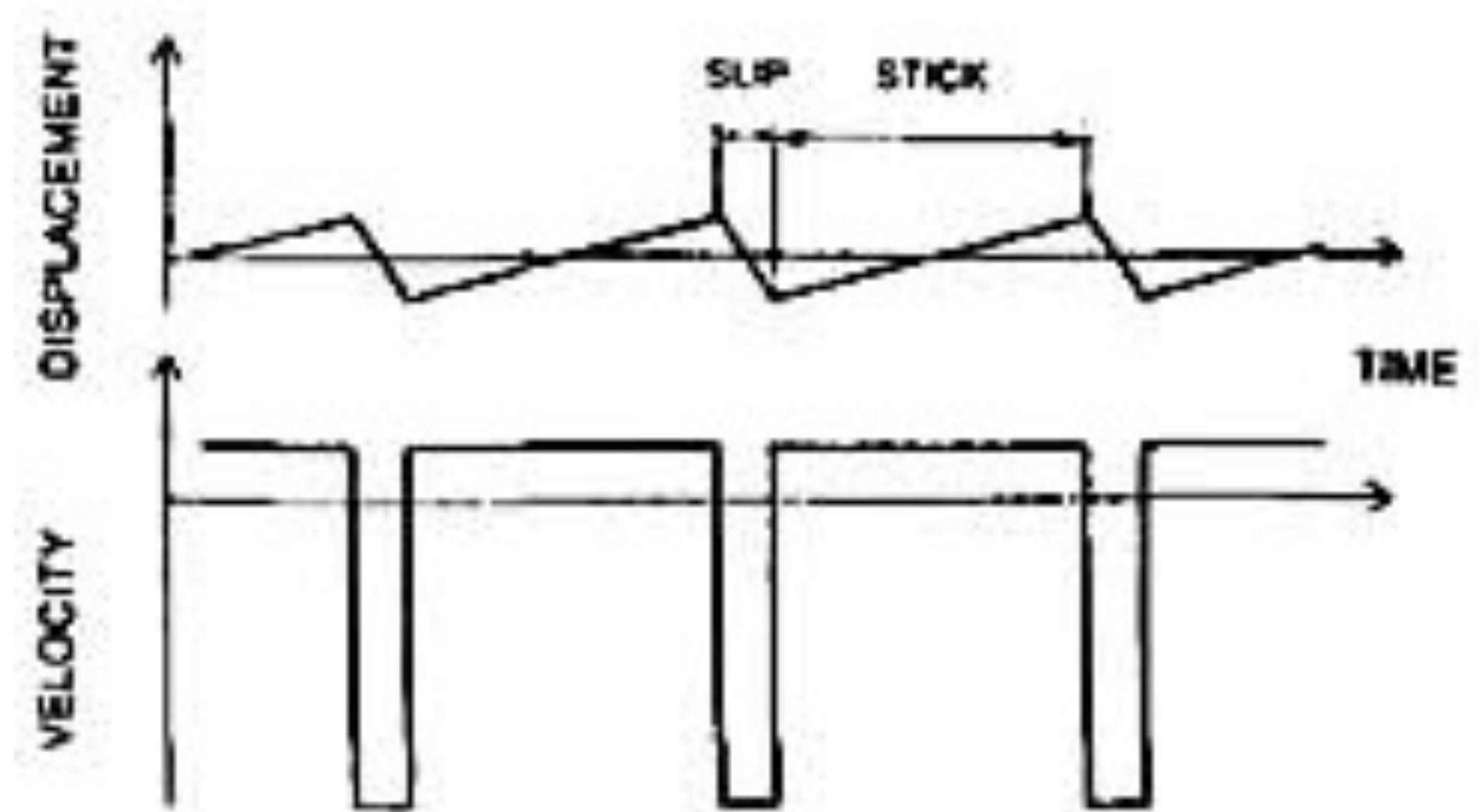
Fourier coefficients of a plucked string

- Sounds are **richer** when the string is plucked **closer to the bridge**
- If the string is plucked in the **middle**, there are **no even harmonics**



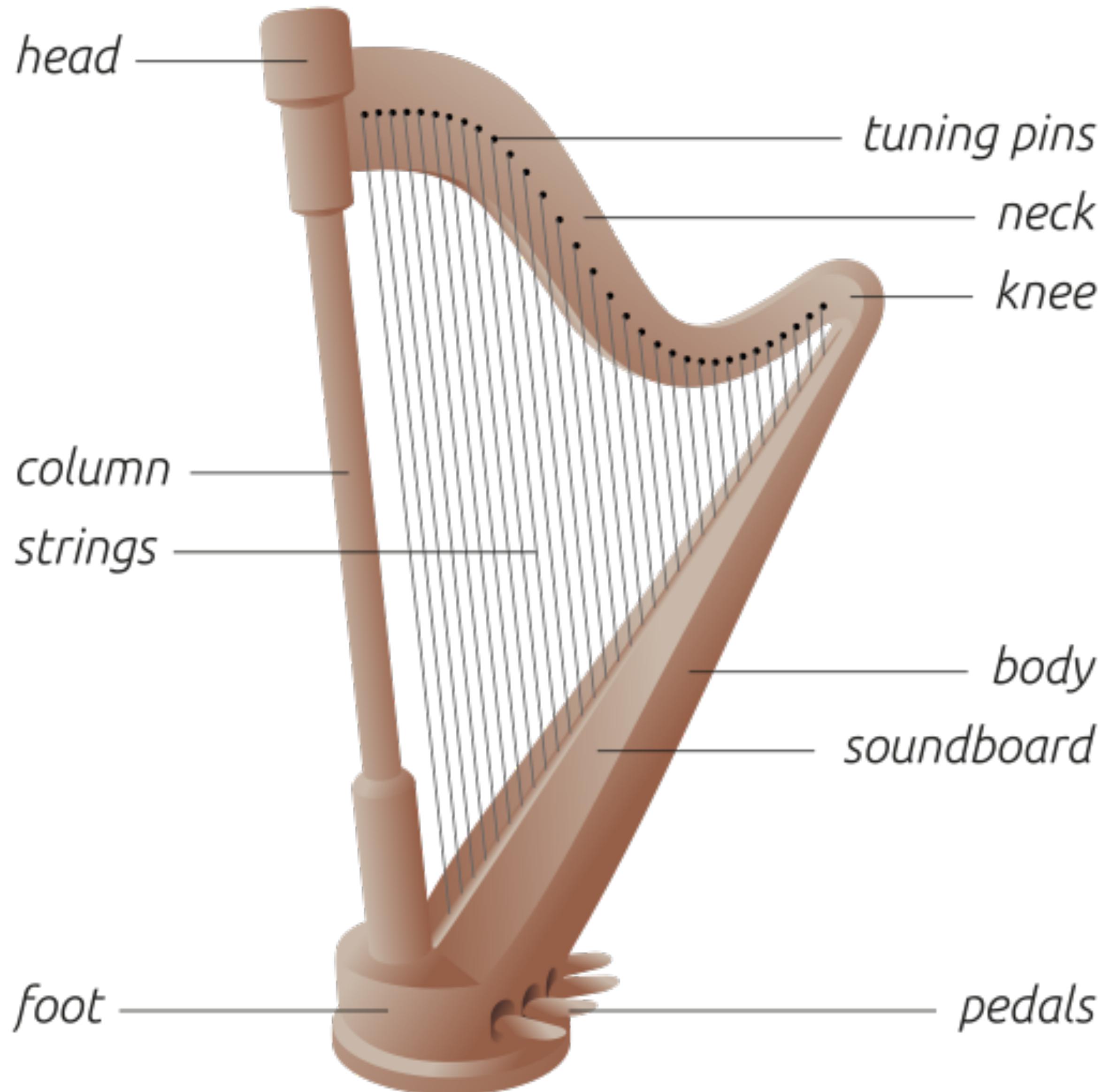
Stick-slip motion of a bowed string

- The violin string alternately “sticks” and then “slips” against the bow hundreds of times per second



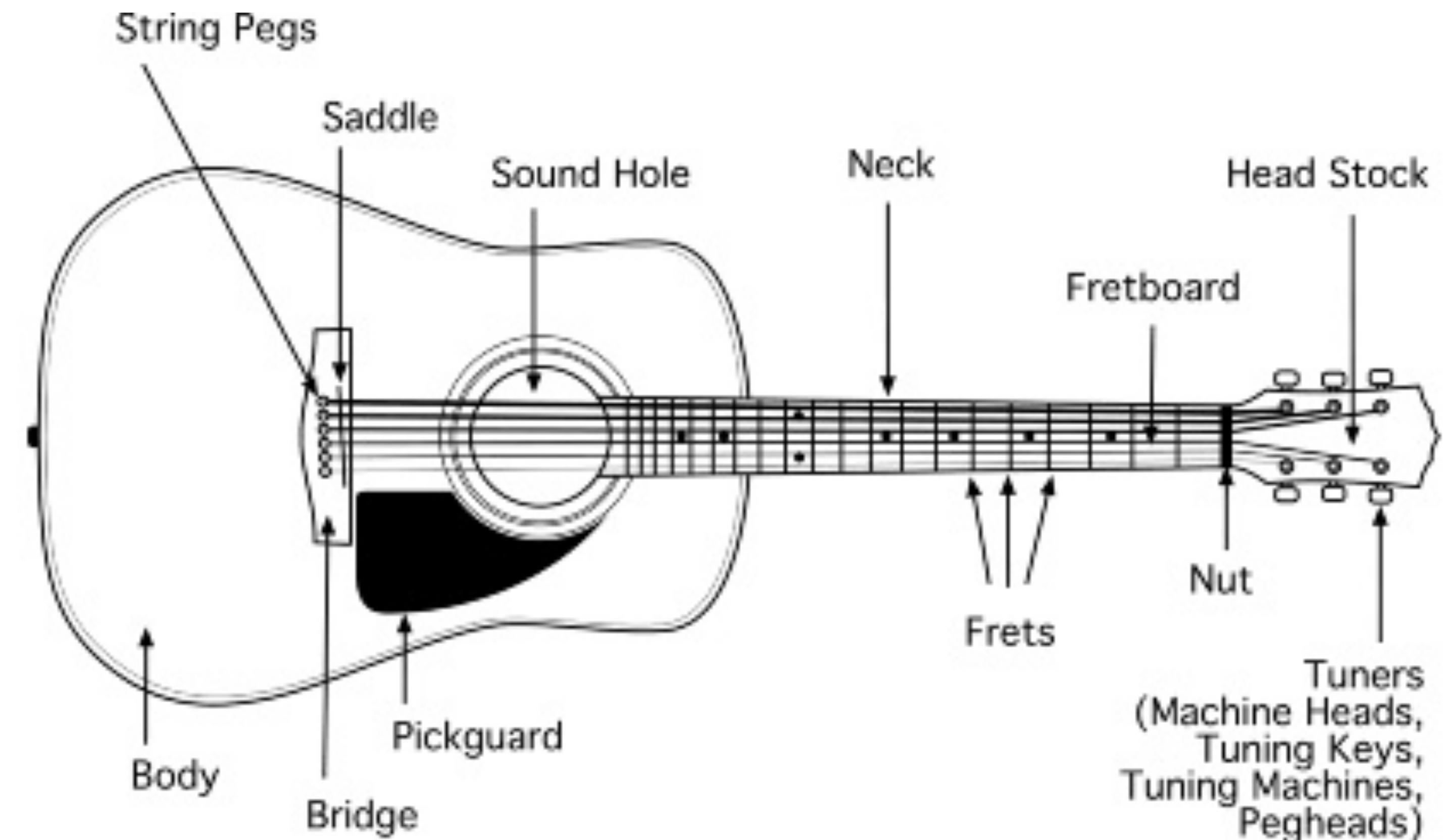
Harp

- the strings have **different fixed lengths** and are plucked
- only **one note** per string -> need lots of strings
- foot pedal can change the note, but only by **only a semitone**



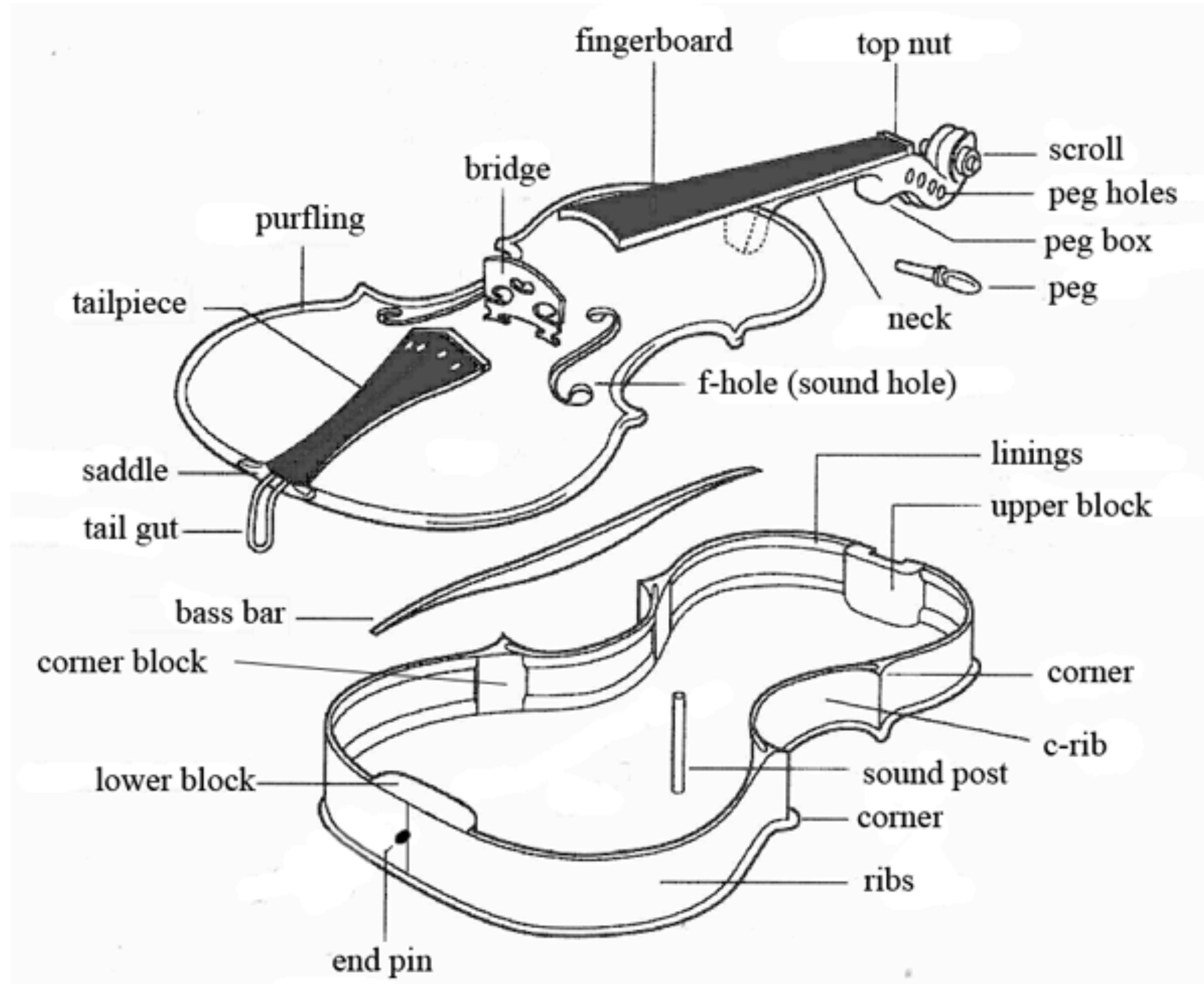
Guitar

- strings are all the **same length**, but are made of different materials and are under different tensions
- get **multiple notes** per string by pressing against a fret
- frets -> **fixed notes** (like a piano keyboard)



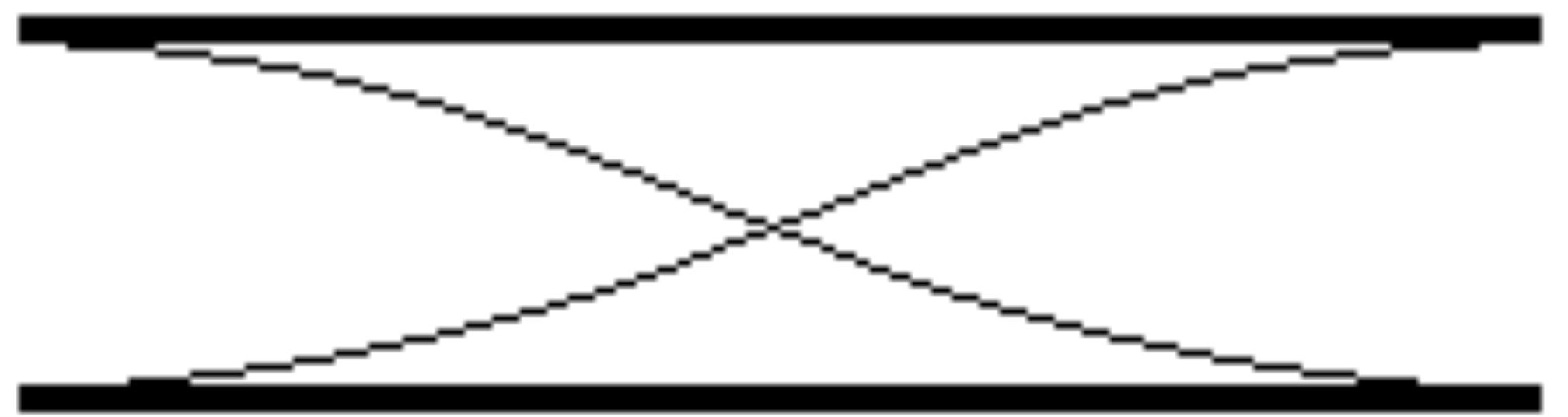
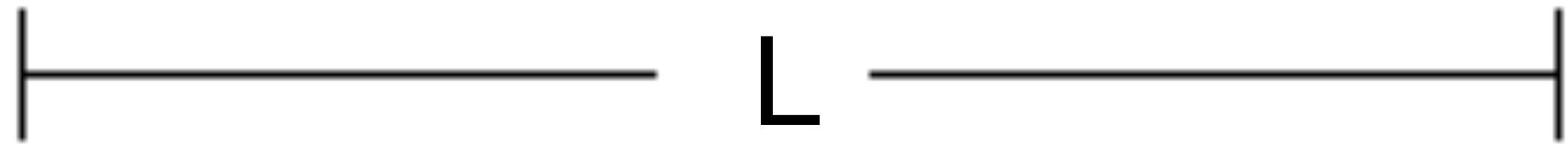
Violin

- strings are all the **same length**, but are made of different materials and are under different tensions
- get **multiple notes** per string by pressing against the neck
- no frets -> **no fixed notes**
- string vibrations are **quickly damped** if strings are plucked -> bowed instead
- can **vary tone quality** by adjusting the intensity of bowing



6. Wind instruments

Open and closed tubes (recall previous discussion)



$$\lambda_N = \frac{2L}{N} \quad f_N = Nf_1 \quad f_1 = \frac{\nu}{2L} \quad N = 1, 2, \dots$$

(both even and odd harmonics)

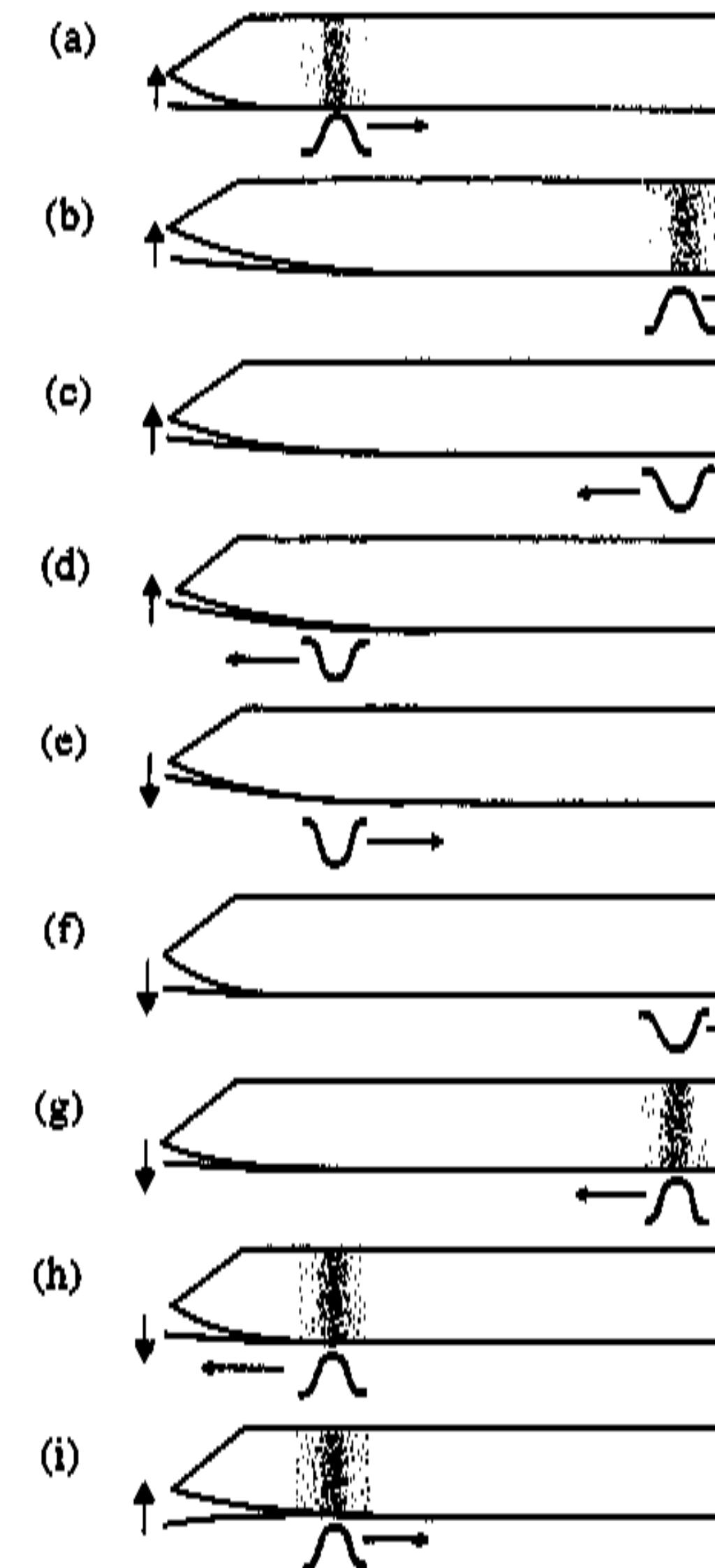
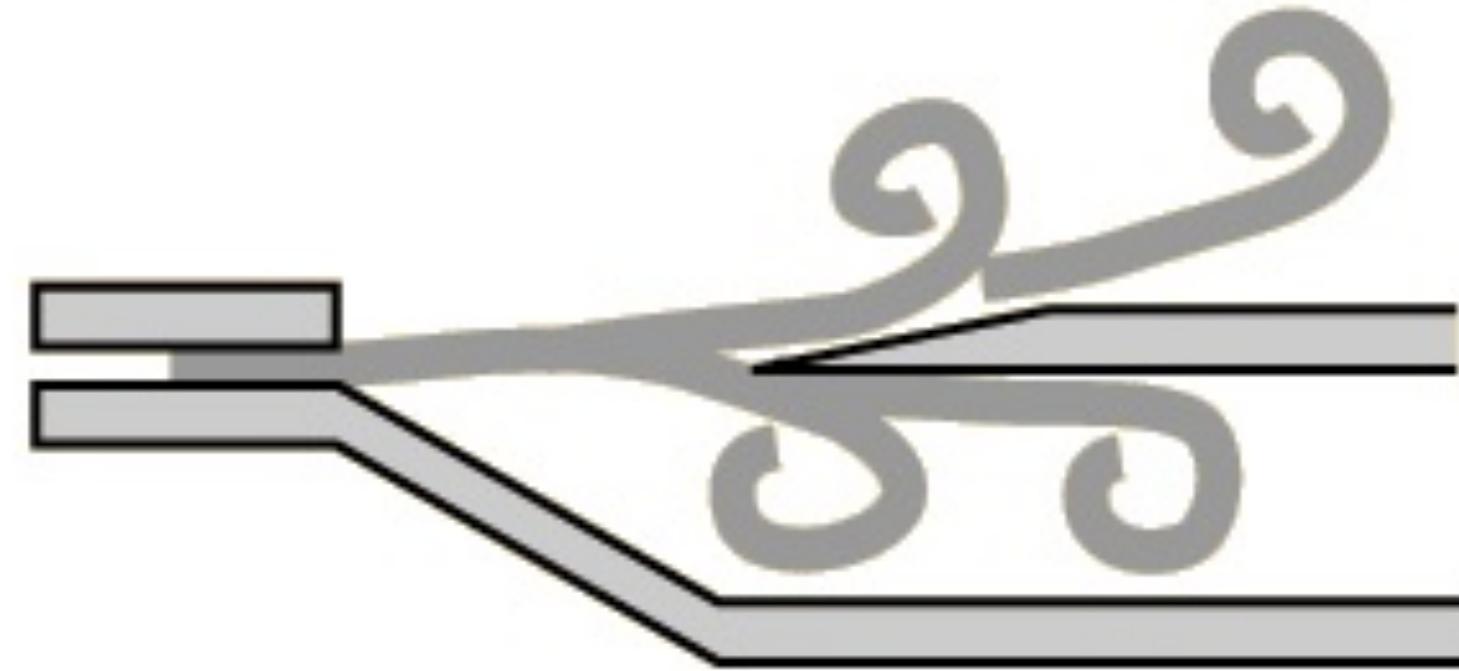


$$\lambda_N = \frac{4L}{N} \quad f_N = Nf_1 \quad f_1 = \frac{\nu}{4L} \quad N = 1, 3, 5, \dots$$

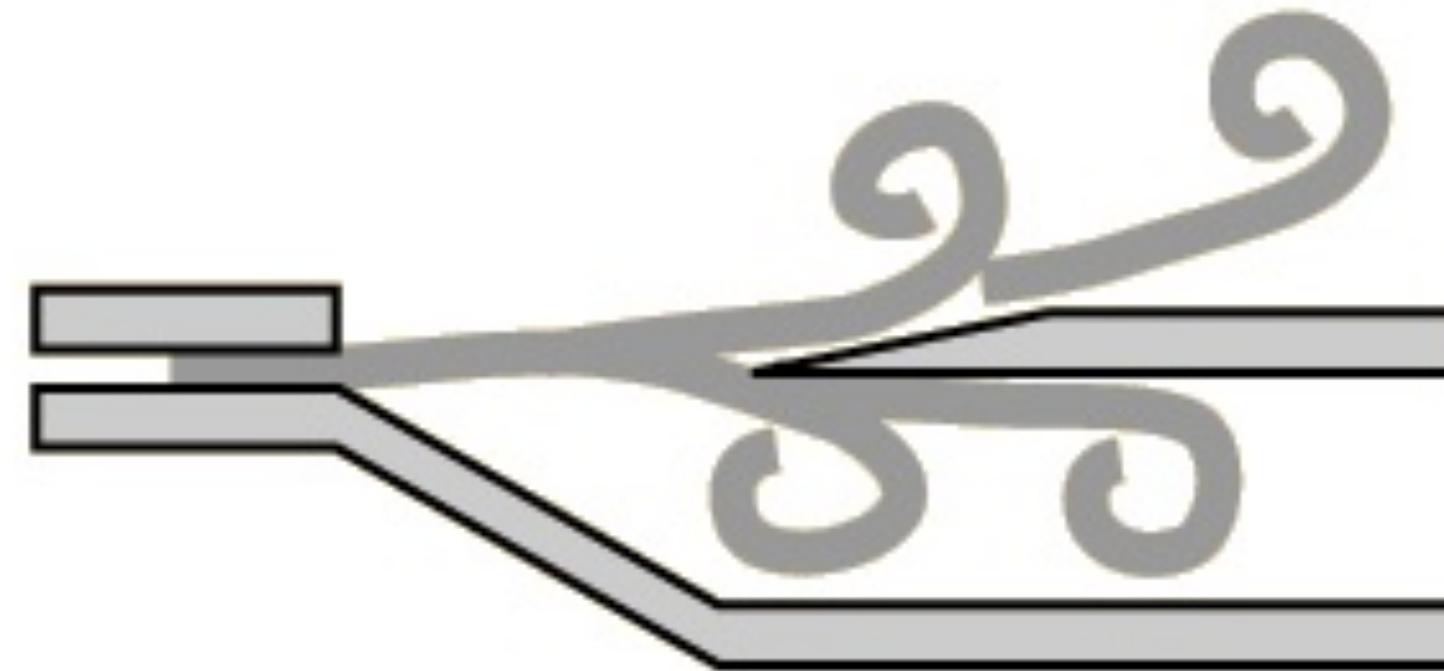
(only odd harmonics)

(air molecule displacements)

Excitations produced by an oscillating air stream or a vibrating reed



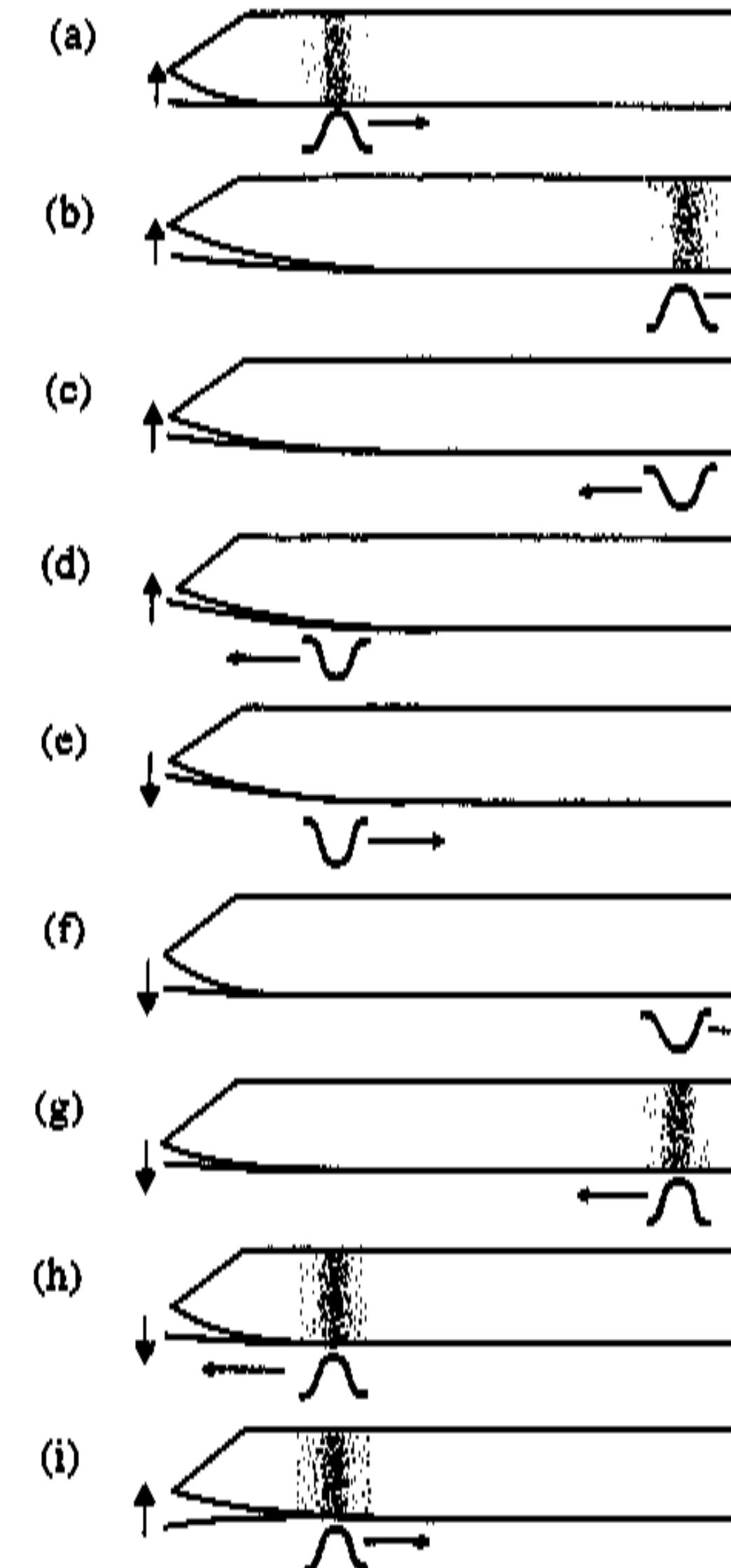
Oscillating air stream



- “**Flow-controlled**” excitation
- Used in recorders, flutes, penny whistles, etc.
- When the air stream hits the edge, it creates tiny **whirlpools** (or “vortices”) of air, which **alternate** going either into or out of the tube
- The frequency of the alternating whirlpools is determined by the **natural frequencies** of the remainder of the tube (resonance phenomena)

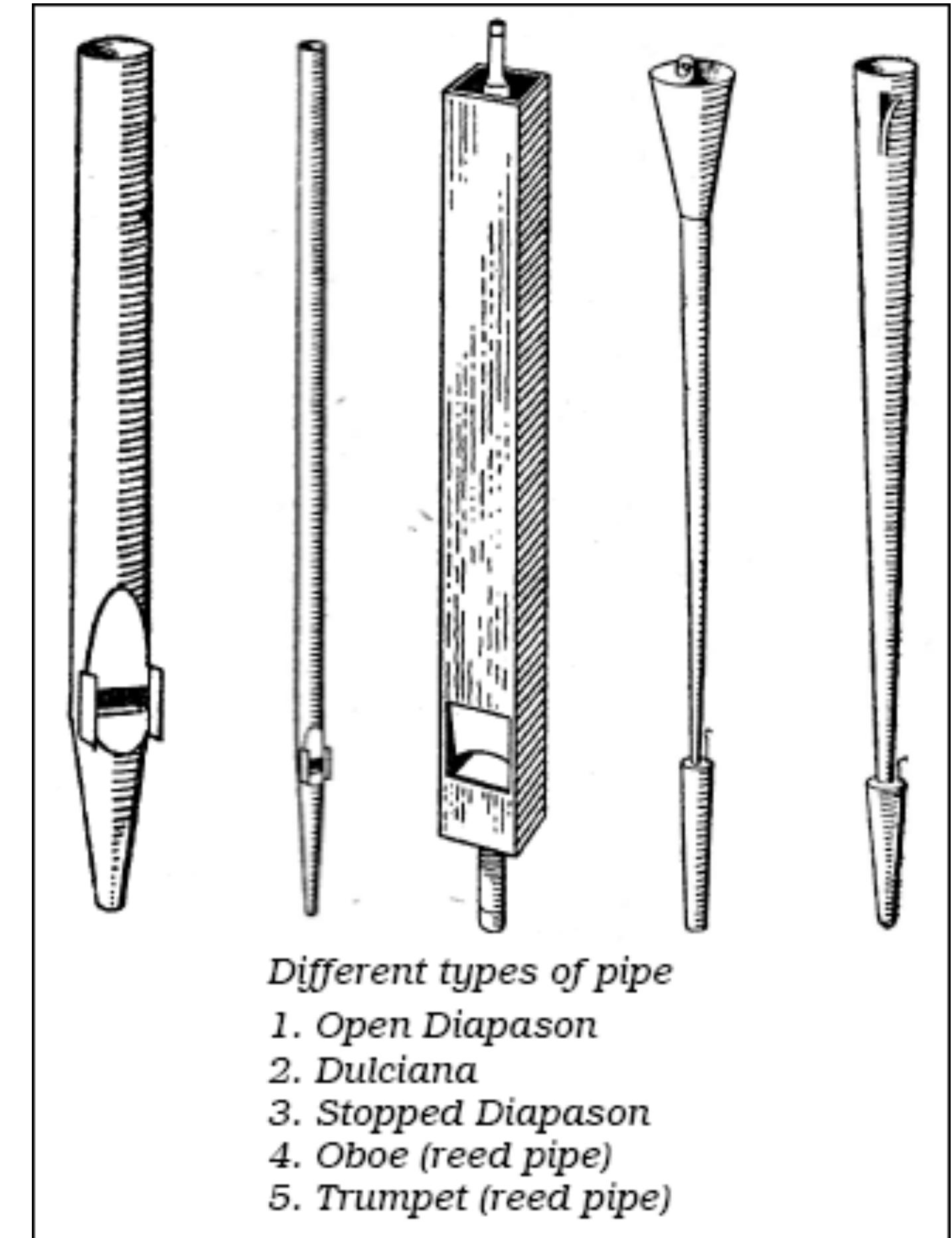
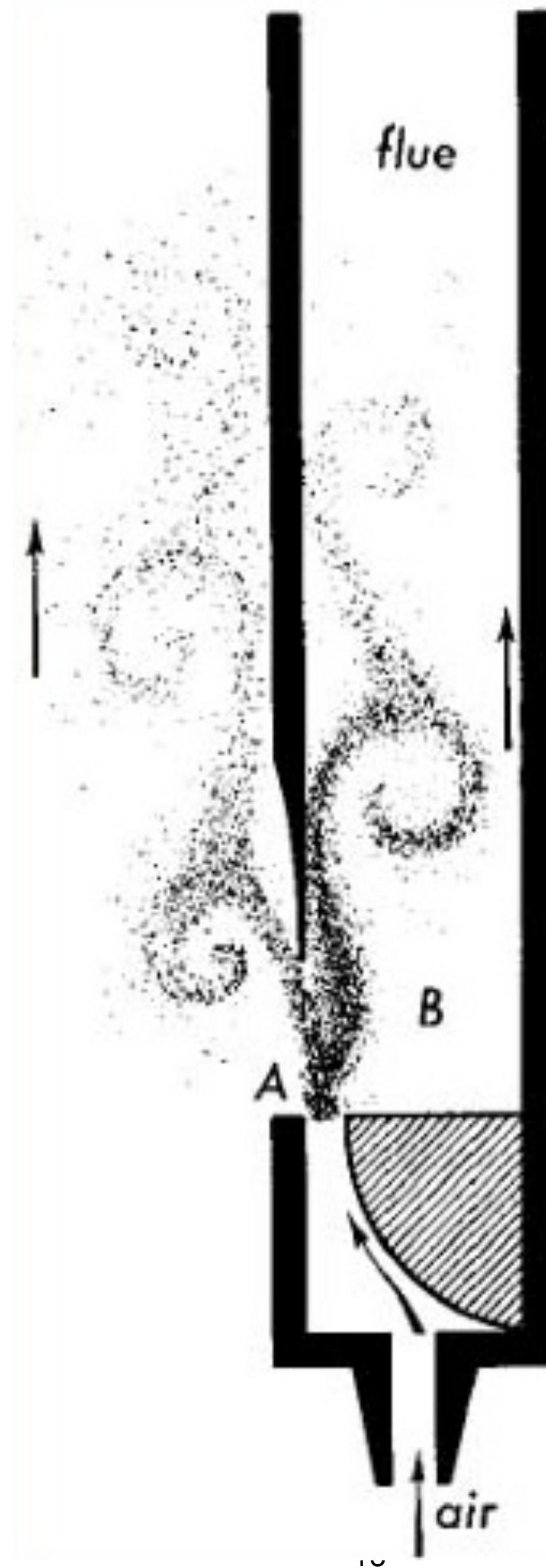
Vibrating reed

- “Pressure-controlled” excitation
- Used in clarinets, saxophones, bassoons, etc. (i.e., any instrument with a reed)
- Frequency of the opening and closing of the reed is determined by the **natural frequencies** of the remainder of the tube (resonance phenomenon)
- Also applies to the didgeridoo and brass instruments where the musicians **lips** play the role of a reed



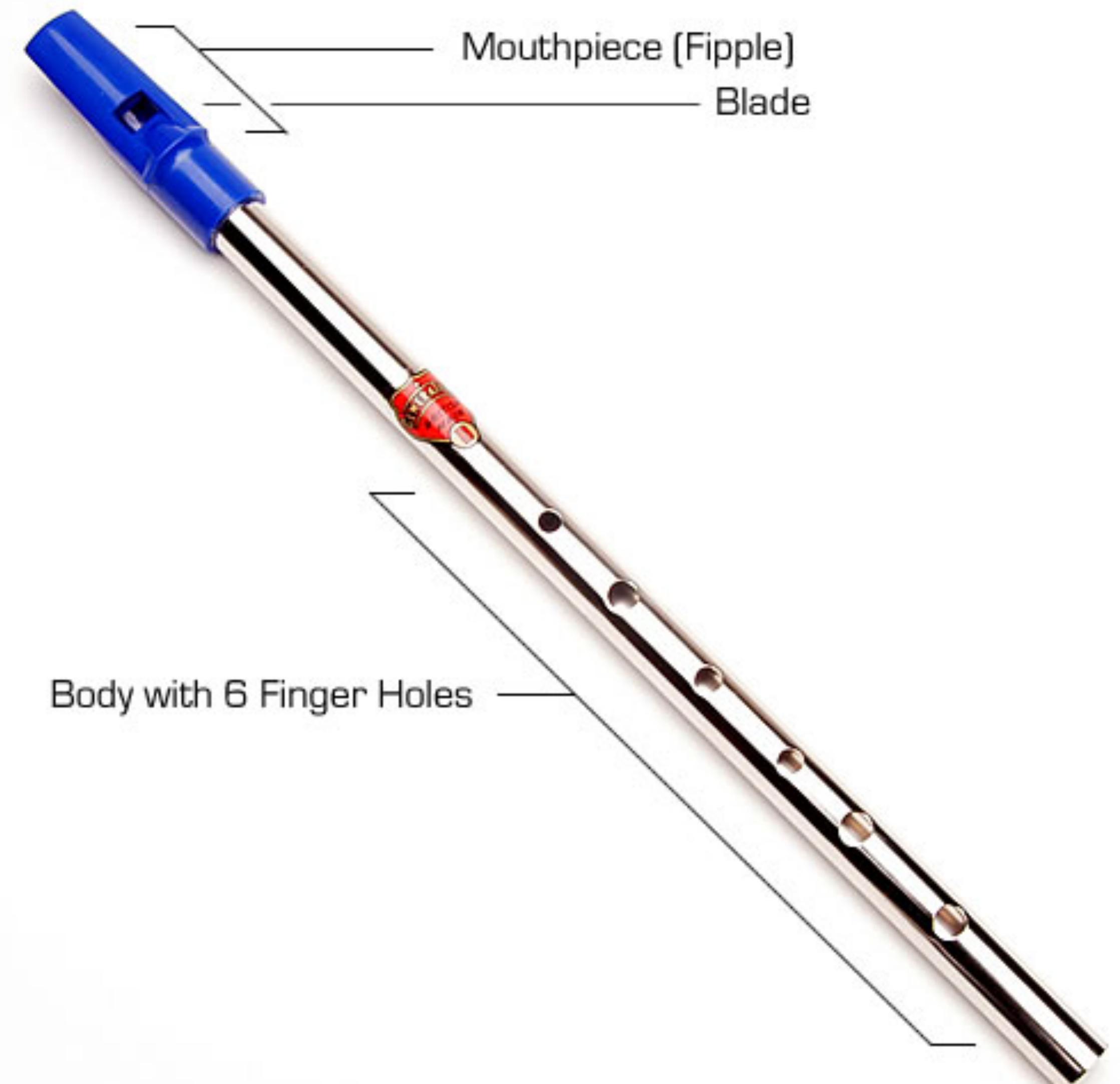
Flue-organ pipe

- Excitation can be either an oscillating air stream or a vibrating reed
- Pipe has **fixed length**
- **One note** per pipe -> need many pipes (e.g., church organ)



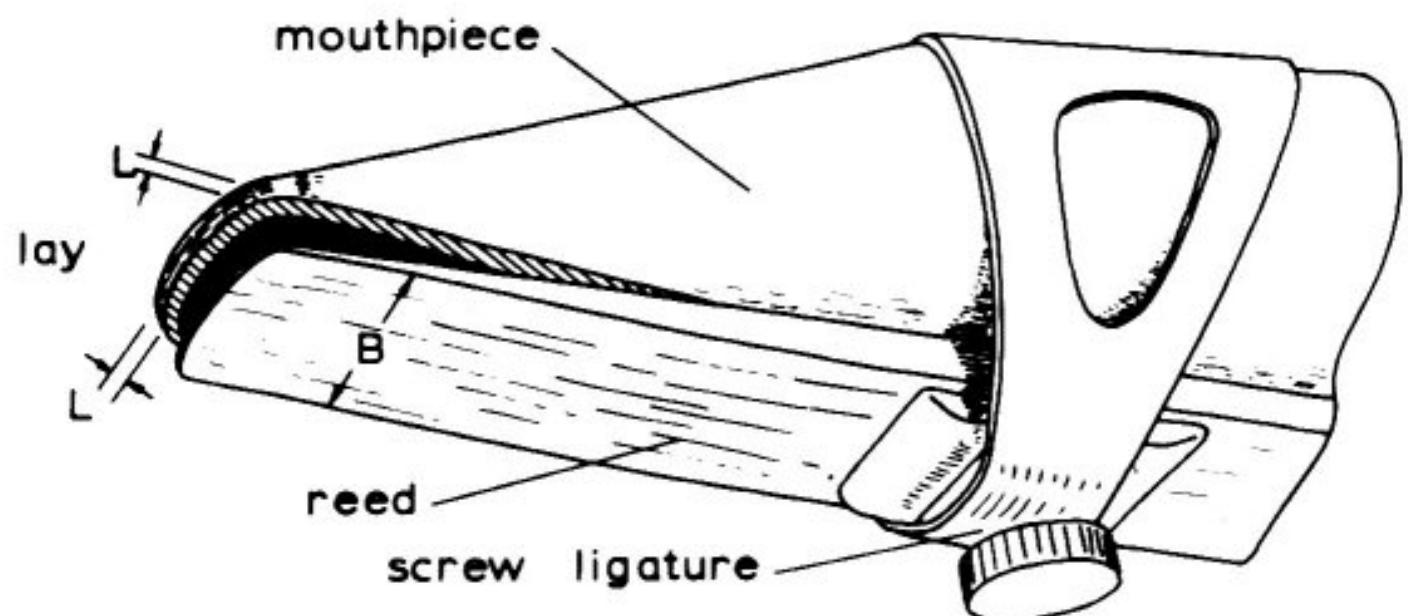
Penny whistle

- Oscillating air stream -> open at both ends
- **Tone holes** allow playing **multiple notes**



Clarinet

- Vibrating reed -> closed at one end
- Tone holes and register keys -> **multiple notes**
- Bell at end creates contribution from even harmonics



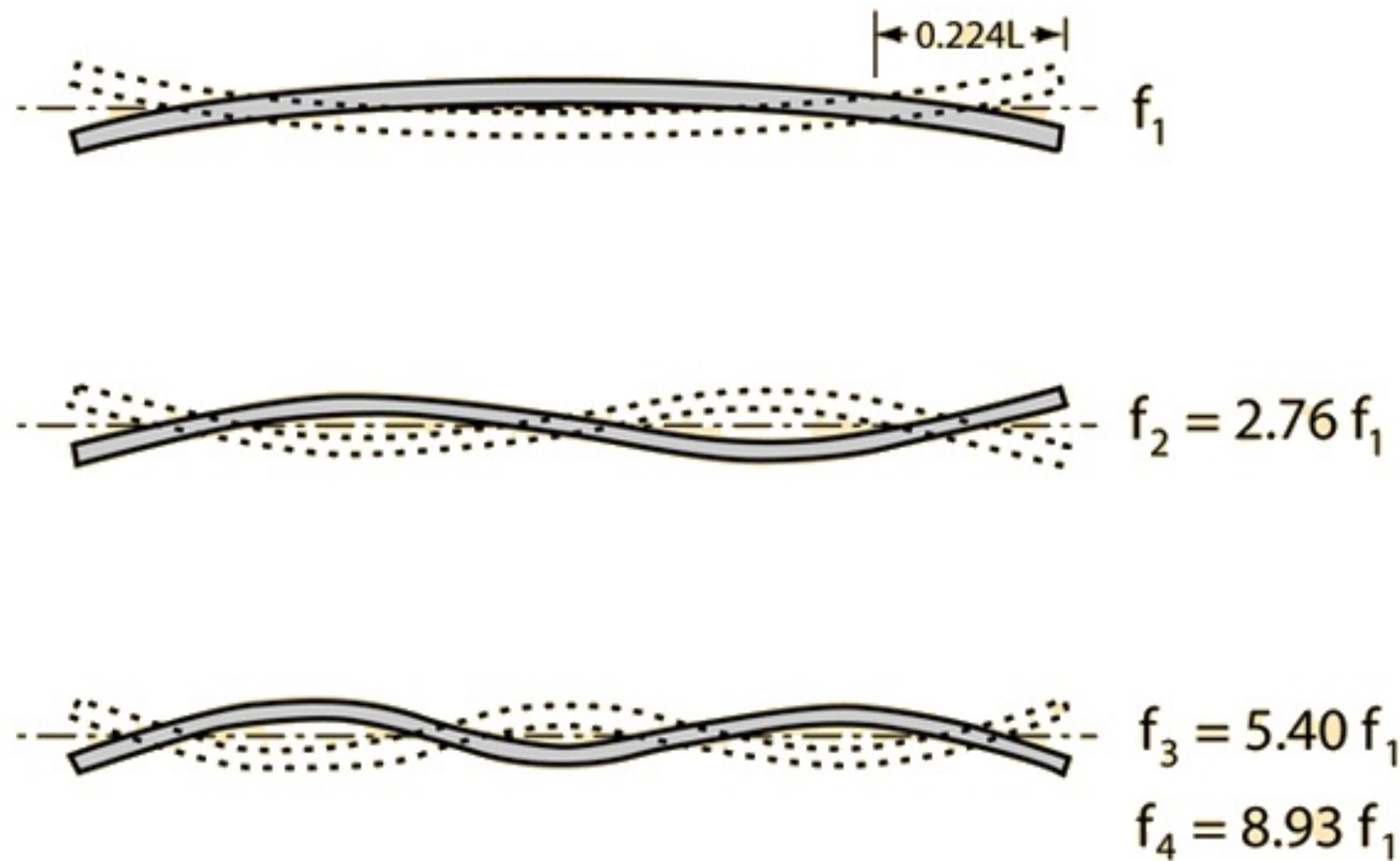
Brass instruments

<https://www.youtube.com/watch?v=Bo7VRSQLpfY>

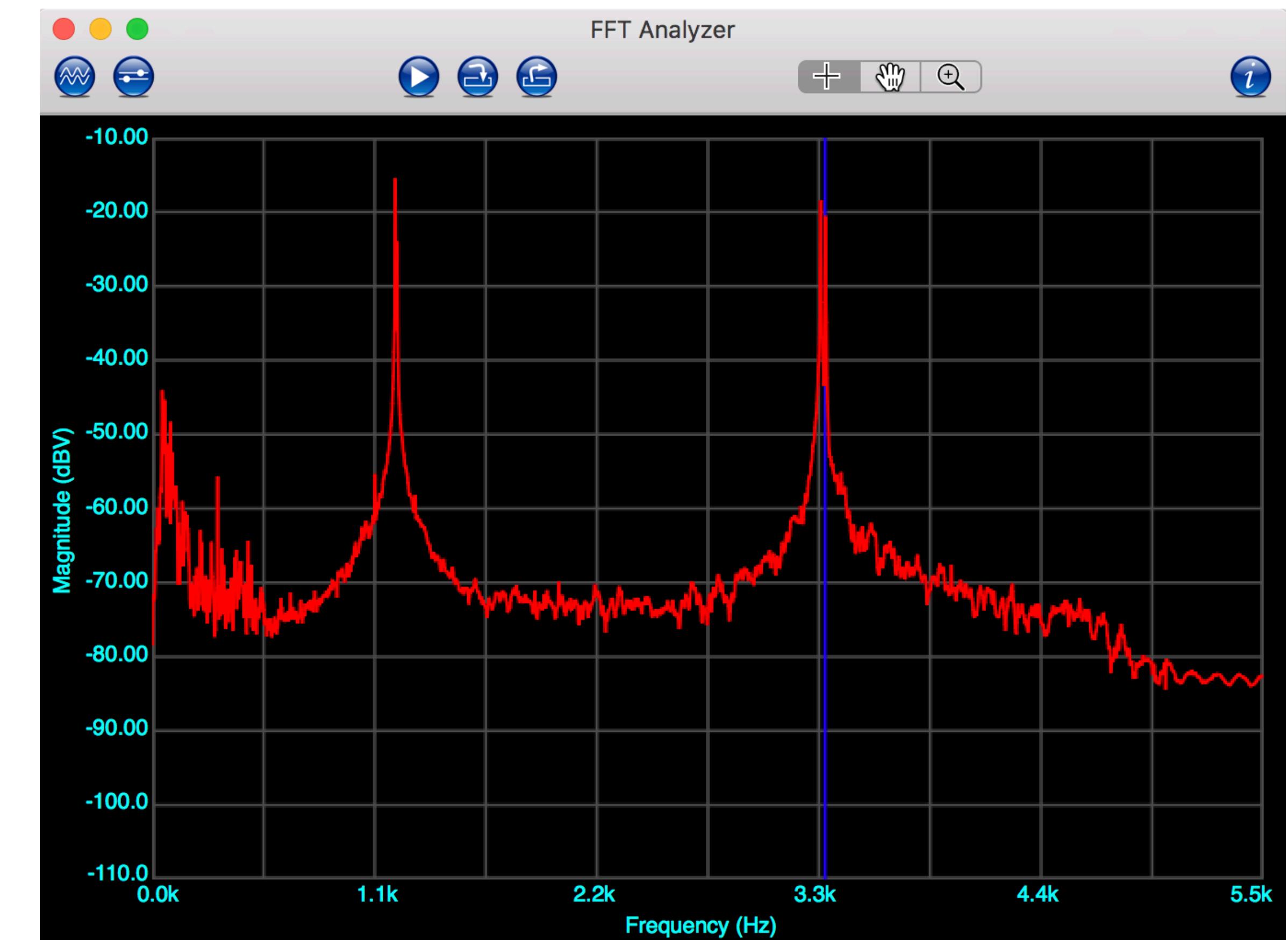
7. Percussion instruments (briefly)

Inharmonicity

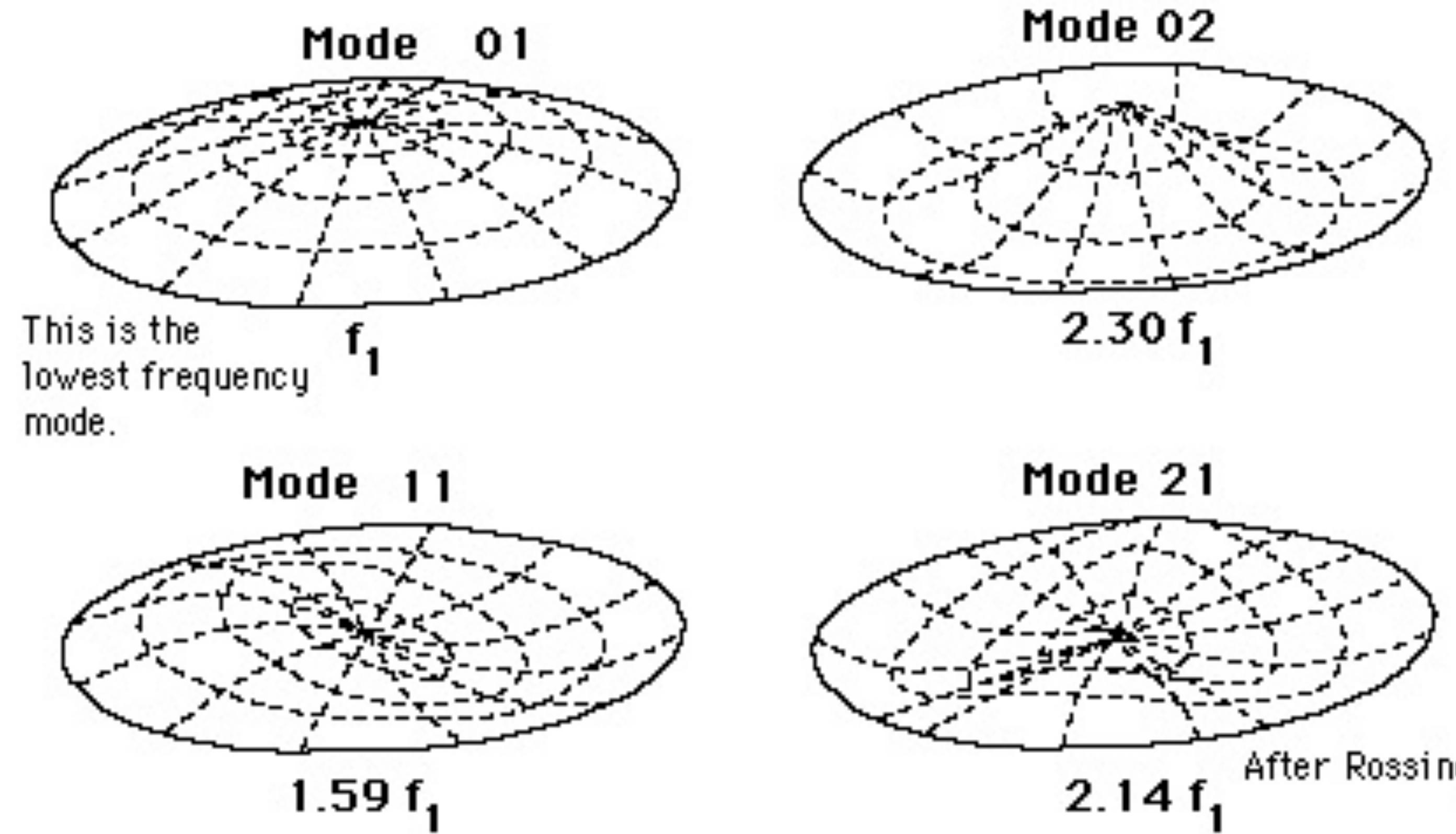
- Presence of **overtones** that are **not harmonically related** to the fundamental frequency



Example: Bell



Vibrating drum head (2-d standing waves)

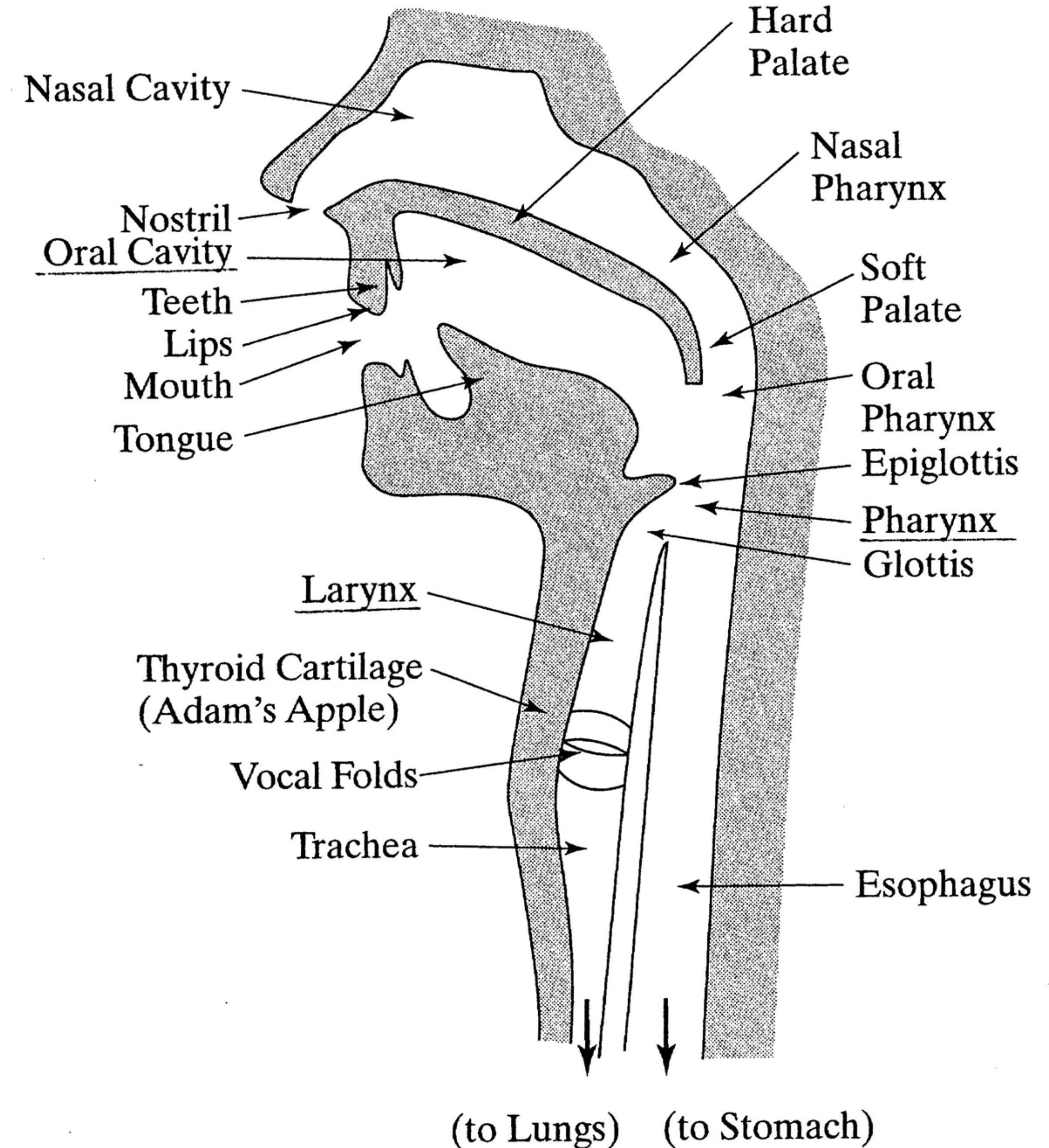


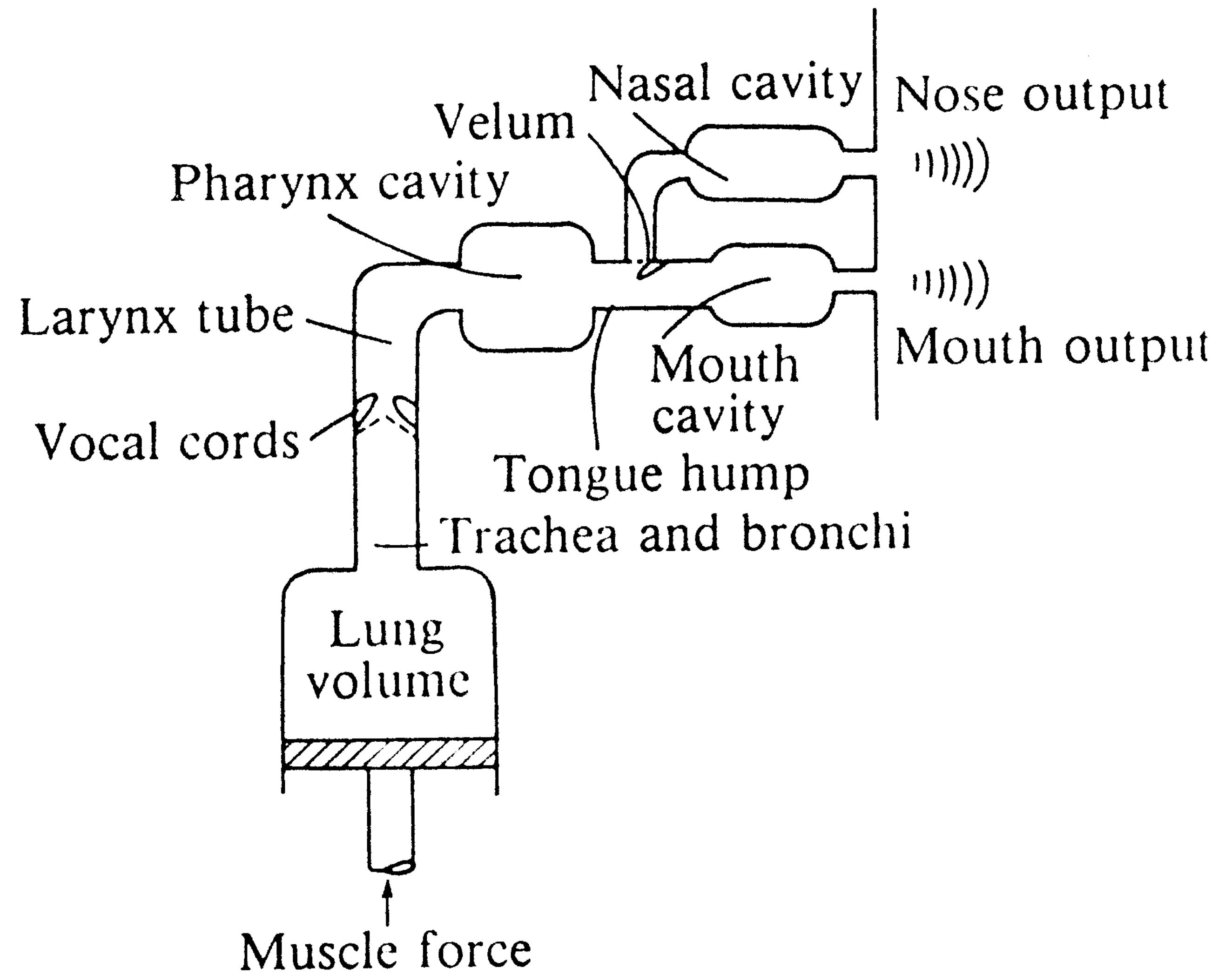
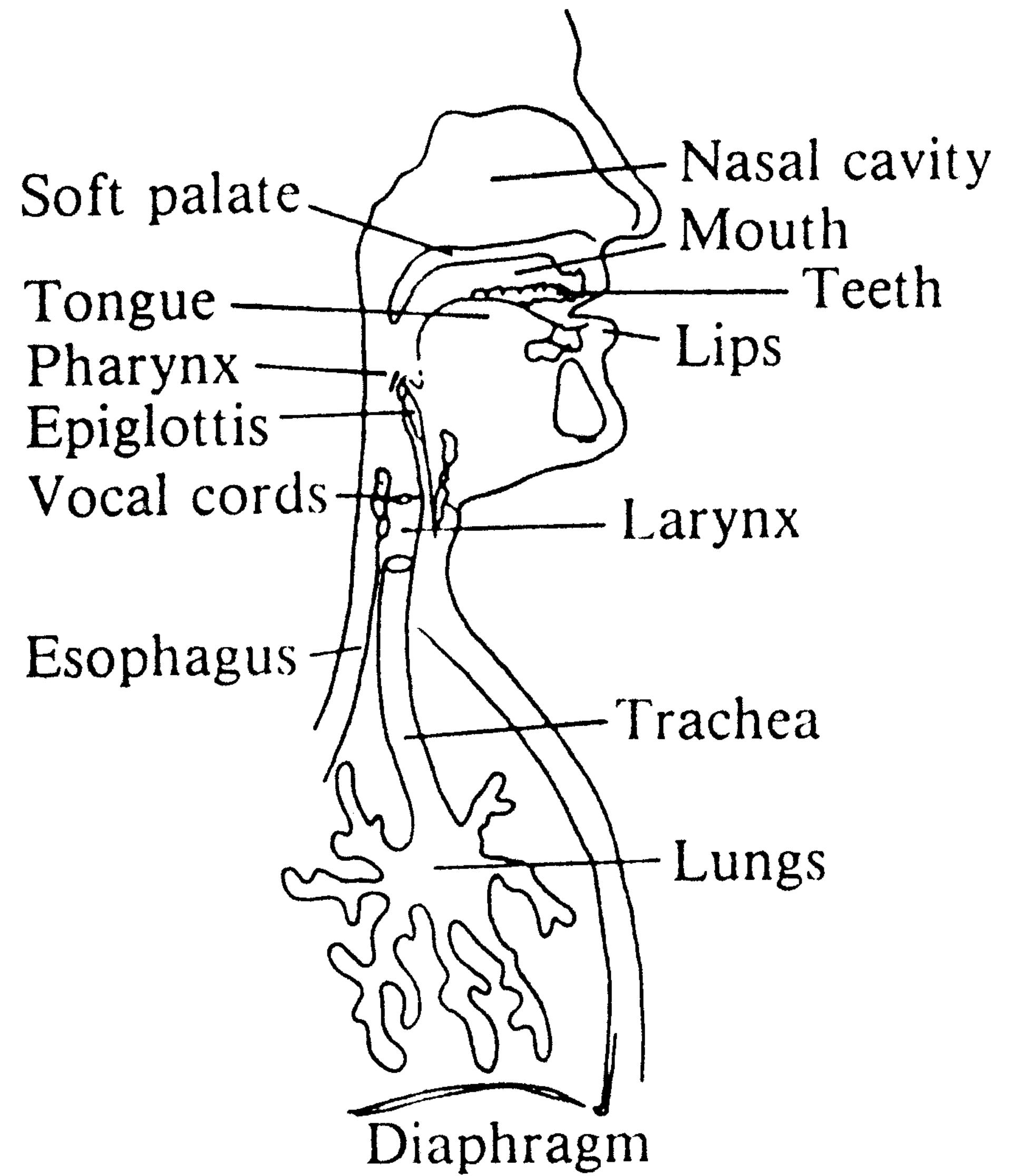
https://commons.wikimedia.org/wiki/Category:Drum_vibration_animations

https://josephromano.github.io/PHYS1406/labs/S2021/modified/Chladni_patterns.mov

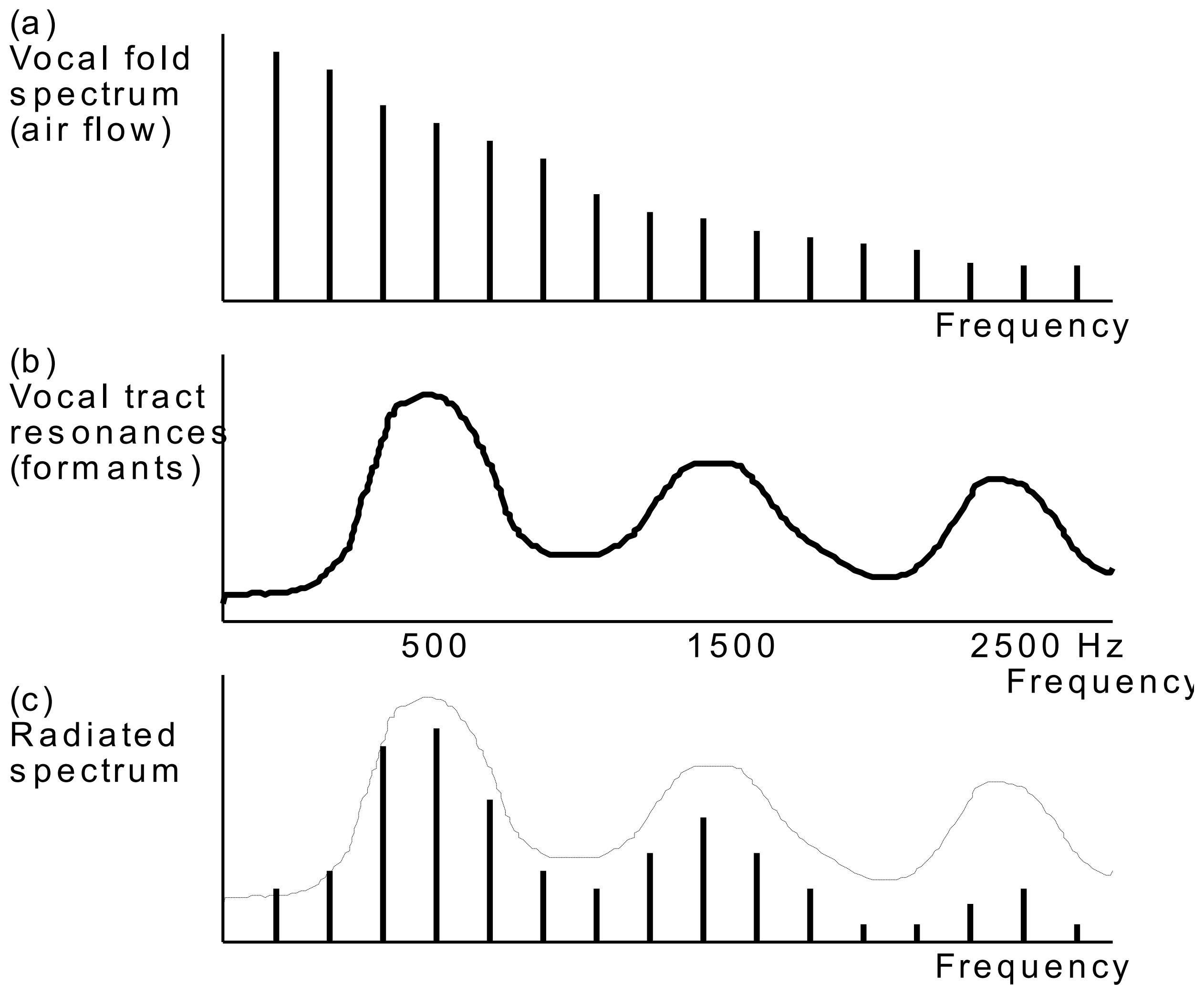
8. Voice

Vocal organs





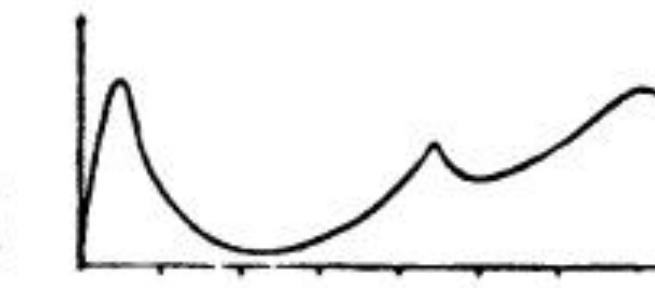
Formants



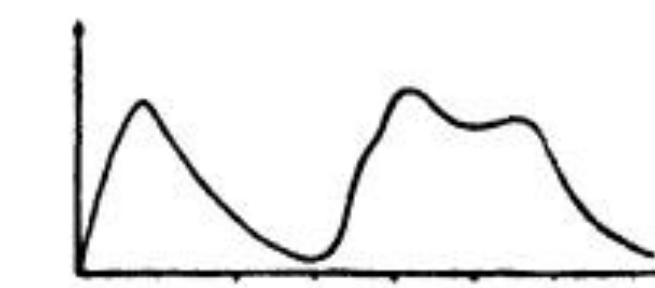
Formant regions for different vowel sounds



heed



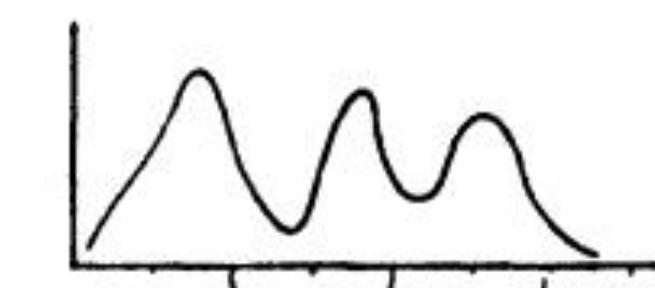
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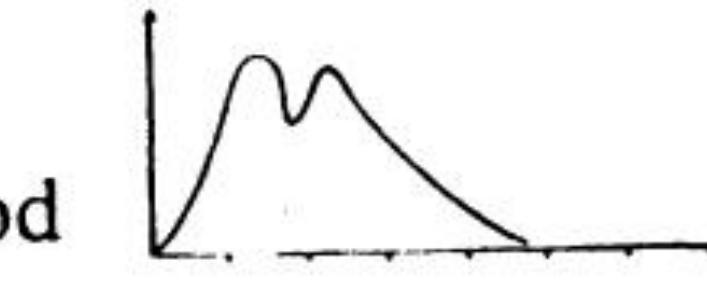
head



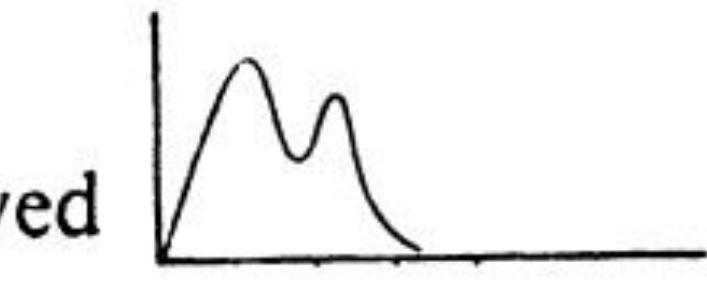
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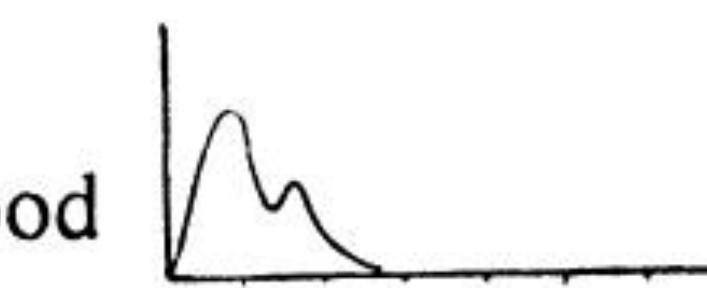
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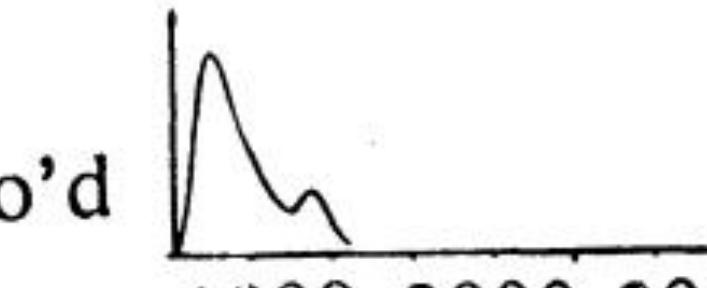
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Singing

SUNDBERG | THE ACOUSTICS OF THE SINGING VOICE

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