PHYS 536

R. J. Wilkes

Session 11

String instruments: violin, piano

Other wind instruments: Organs, Human voice

2/07/2023

Course syllabus and schedule – updated

See : http://courses.washington.edu/phys536/syllabus.htm

Session	date	Day	Readings:	K=Kinsler, H=Heller	Topic
8	26-Jan	Thu	K: Ch. 7	H: Ch. 7	Absorption losses; Pulsating spheres and simple sources; pistons and dipoles; Near field, far field; Radiation impedance; Waves in pipes ***UPDATED BELOW HERE:***
9	31-Jan	Tue	K. Ch. 8-10	H: Ch. 13	Rectangular cavities; Helmholtz resonators; Resonant bubbles; Acoustic impedance; physical acoustic filters; Doppler effect; Interference effects
10	2-Feb	Thu	K. Ch 9	H: Chs. 23-25	Musical acoustics: pitch, musical tones and frequency; timbre; beats
11	7-Feb	Tue		H: Chs. 16, 18	Musical instruments: winds and string instruments
12	9-Feb	Thu		H: Chs. 17, 19	Musical instruments: piano, human voice REPORT 1 PAPER DUE by 7 PM; REPORT 2 PROPOSED TOPIC DUE
13	14-Feb	Tue	K. Ch. 11	H: Ch. 21	Human hearing: the inner ear; pitch perception; acoustics of speech
14	16-Feb	Thu	K. Ch. 12	H: Chs. 21-22	Decibels and sound level measurements Environmental acoustics and noise criteria; industrial and community noise regulations; noise mitigation;
15	21-Feb	Tue	K. Chs. 13-14	H: Chs. 27-28; Ch. 6	Room acoustics; Transducers for use in air and water: Microphones and loudspeakers; hydrophones and pingers; Underwater acoustics: sound absorption underwater, the sonar equation
16	23-Feb	Thu	K. Ch 15		Underwater acoustics applications: acoustical positioning, seafloor imaging, sub-bottom profiling; Course wrap-up: review
17	28-Feb	Tue			Student report 2 presentations
18	2-Mar	Thu			Student report 2 presentations
19	7-Mar	Tue			Student report 2 presentations
20	9-Mar	Thu			Student report 2 presentations. TAKE-HOME FINAL EXAM ISSUED
--	17-Mar	Fri			FINAL EXAM ANSWERS DUE by 5 PM

Tonight

Class is over after you turn in your take-home exam. No in-person final exam during finals week.

Announcements

- Term paper 1 is due this Thursday
  - Submit via Canvas Assignments page by 5 pm Thursday 2/9
    - Submissions before midnight Thursday will be accepted as on-time -- after 11:59 pm you will be docked 5 pts for late papers
    - Submission portal on Canvas closes at 11:59 pm on Sunday 2/12
    - It will take at least a week for us to grade the papers – please be patient
- Don’t forget: term project 2 presentation proposal is also due this Thursday

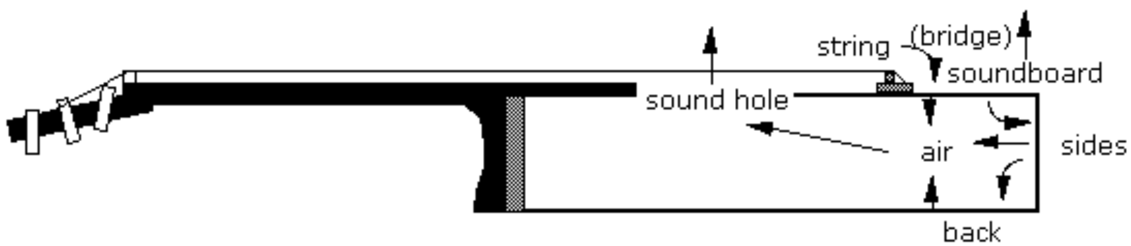
Last time

Guitar acoustics

- Body serves as Helmholtz resonator
  - Typically tuned (vary hole, body volume, bracing) to
    - A2 (55.0 Hz) for steel-string guitars
    - G#2 (103.8 Hz) for classical guitars
    - F#2 ~G2 (92.5 ~ 98.0 Hz) for Flamenco guitars

For guitar with circular hole radius r, body volume V

Helmholtz resonant freq $f_0 = \frac{c}{2\pi}\sqrt{\frac{\pi r^2}{L_{EFF} V}}, \quad L_{EFF} = 1.7r$



Vibrations at low f's

Vibrations at high f's

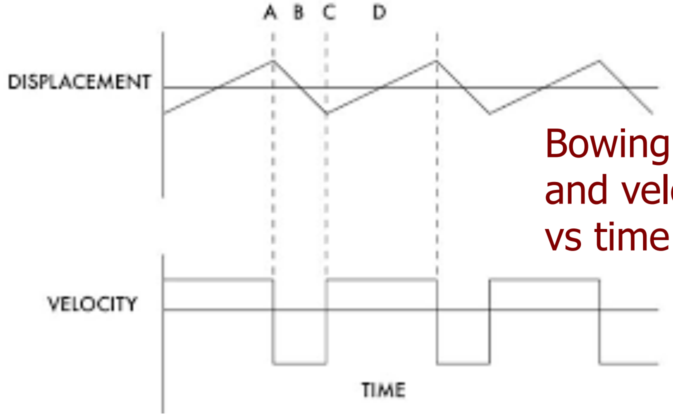
Violins

Many figs from newt.phys.unsw.edu.au/music/

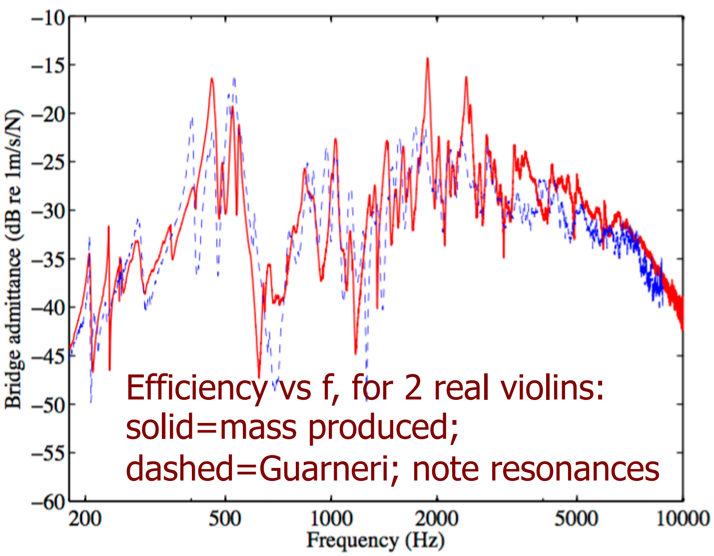
- Nomenclature

Acoustics of violins

- Bow drives strings → bridge serves as driver for body
  - Bow drags short distance, then releases: sawtooth motion
    - Constant speed of bow, then rapid return to equilibrium
    - Vibrations of bowed vs plucked string
  - Violin body = resonator to amplify the vibration of the bridge from air in body to surroundings
    - Need large surface area to push a reasonable amount of air
    - The belly and back plates have a number of resonances
      - Recall Chladni patterns of vibration
        - Shaping of plates and wood used are critical factors



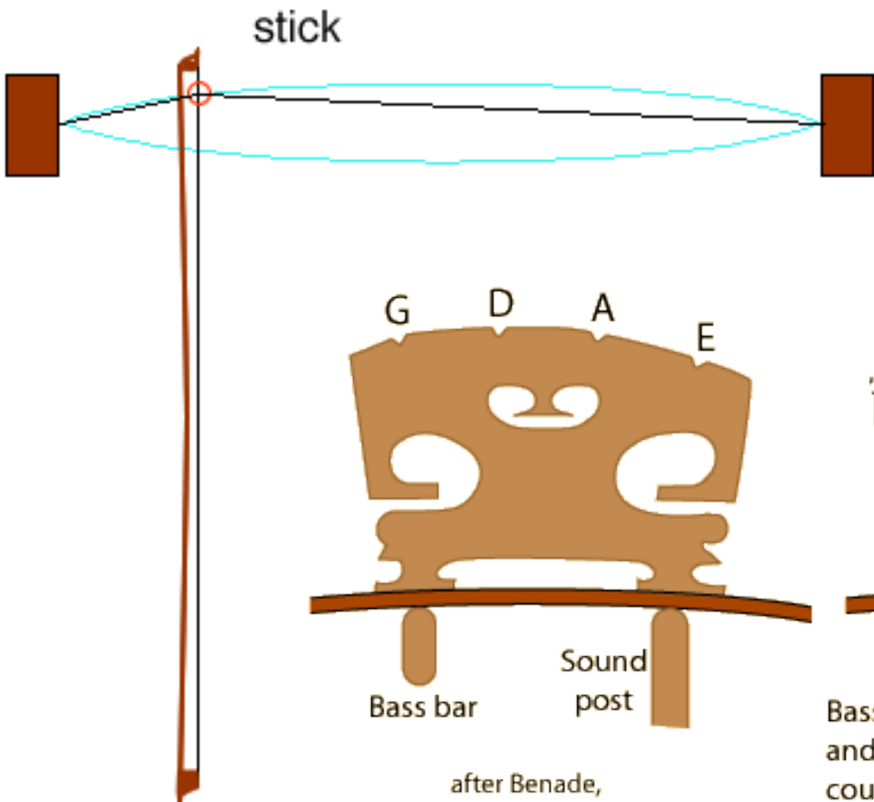
Bowing: displacement and velocity of string vs time

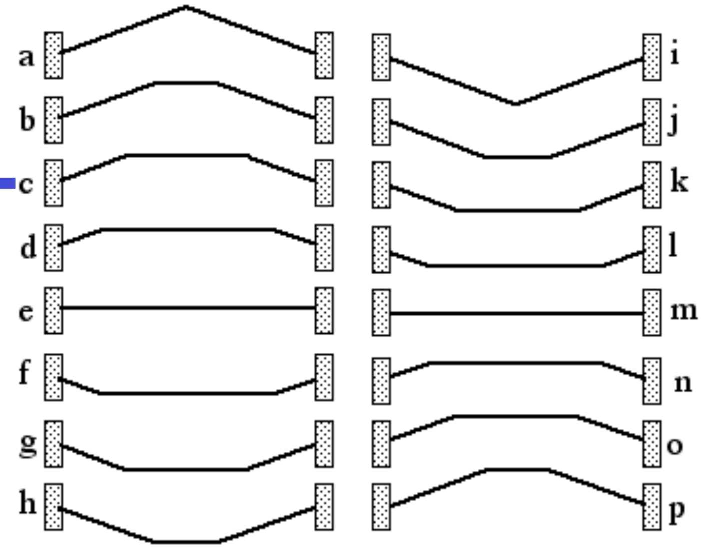


Efficiency vs f, for 2 real violins: solid=mass produced; dashed=Guarneri; note resonances

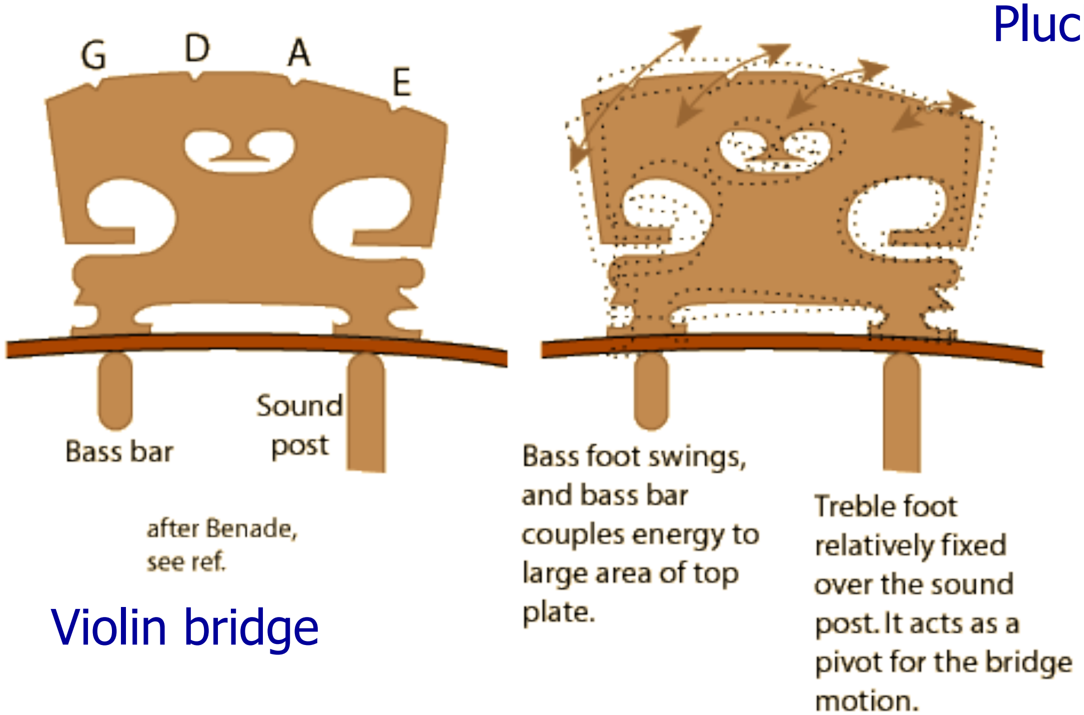
Violin components

- Bowing a string





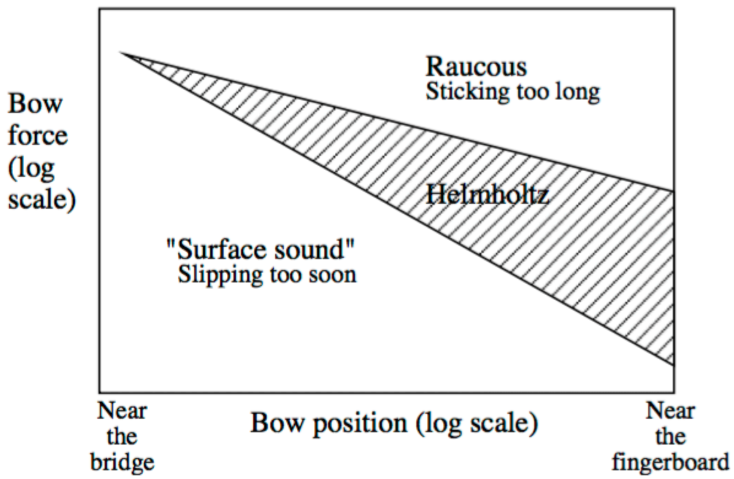
Plucked string

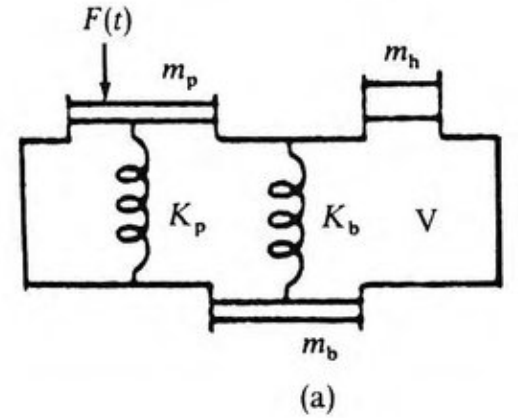


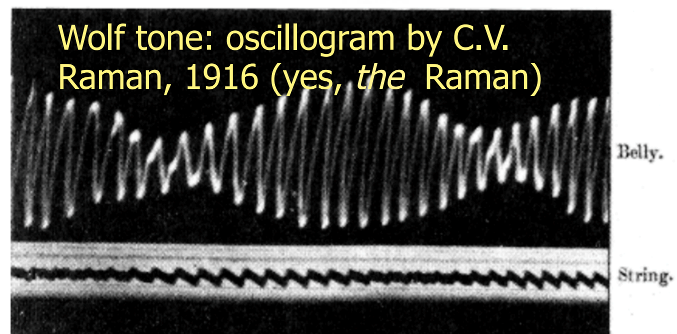
Violin bridge

Violin acoustics

- Lumped parameter model of violin body
  - h=f-holes, p=top plate, b=bottom plate
- Bow force vs position vs timbre







Wolf tone: oscillogram by C.V. Raman, 1916 (yes, *the* Raman)

- Wolf tone: https://en.wikipedia.org/wiki/File:WolfTone.ogg
  - At some point in range, the tone varies strongly and harshly, pulsating at ~5 Hz
  - Due to overlapping resonances between string and body
  - Defeat by adding mass near bridge

More string instruments: pianos and harpsichords

Types of keyboard instruments:

- Piano (strings are set into vibration by striking hammers)
- Harpsichord (strings are plucked)

(Organ: next topic)

Piano: Invented in 1709 by Bartolomeo Cristofori in Florence*

Components:

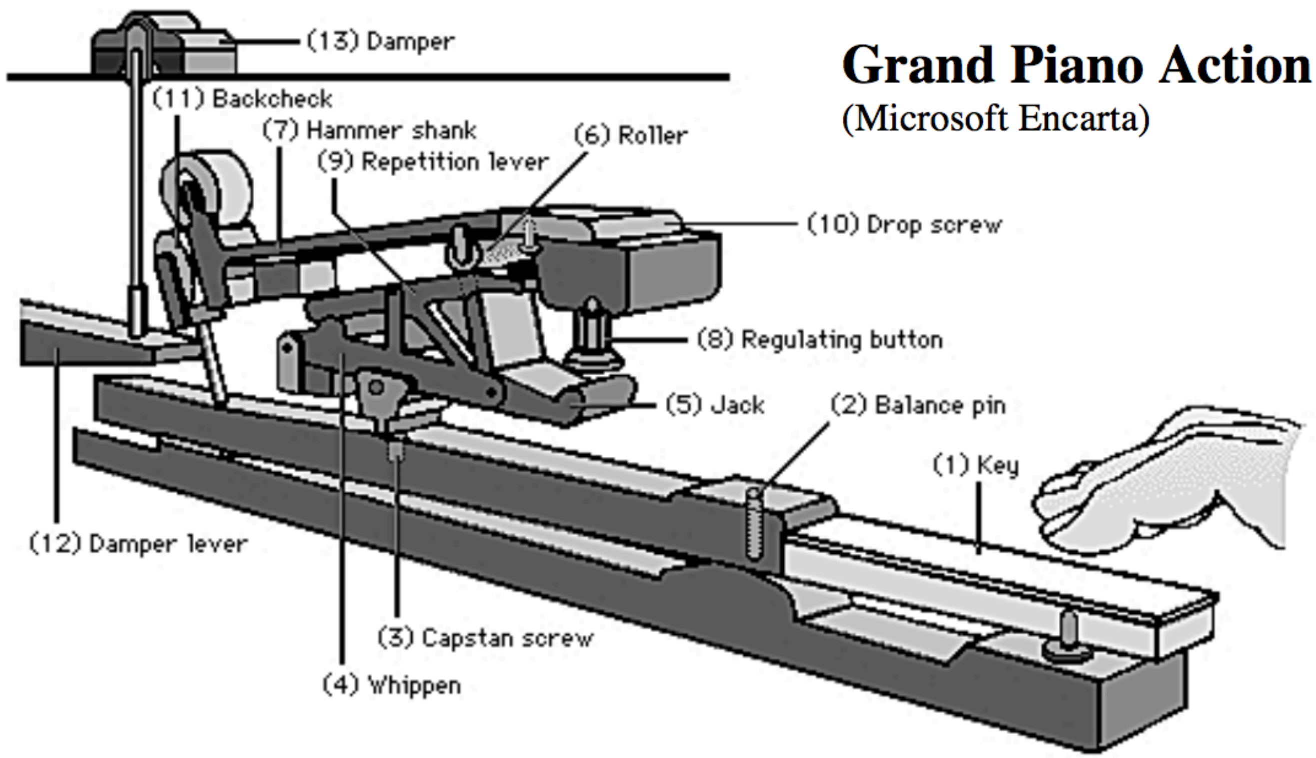
- Keyboard (>7 octaves: 88 notes, A_0 - C_8)
- Action
- Strings (more than 200)
- Bridge
- Soundboard
- Frame

www.seattlepianoco.com

* Wanted an instrument that could play "loud and soft" (= "pianoforte");
Key contribution: invention of piano "action" using a hammer to strike the strings.

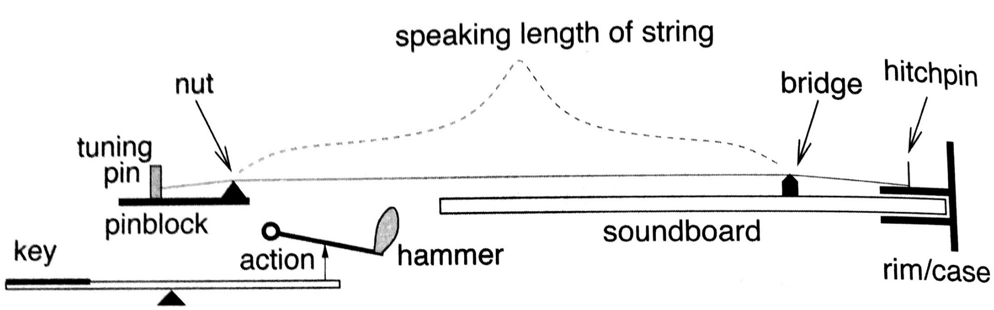
Piano action

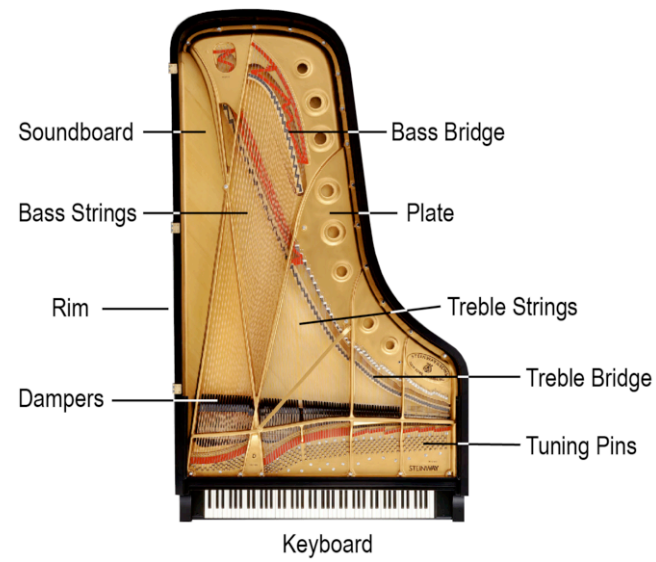
- Press key
- Damper is raised
- Hammer is thrown against string
- Rebounding hammer is caught by the back check



Hammer action

- Hammer exerts large force in small Dt
  - hammer rebounds so it does not muffle the string
- Force depends on how hard the key is pressed
  - Hammer velocity changes by factor of 100 from fortissimo to pianissimo
  - Contact time varies from <2 ms to 4 ms from ff to pp
    - 2 ms ~ half-period of 264 Hz
- String alone has poor coupling to air: need resonator – soundboard
  - Coupler = bridge





Piano strings

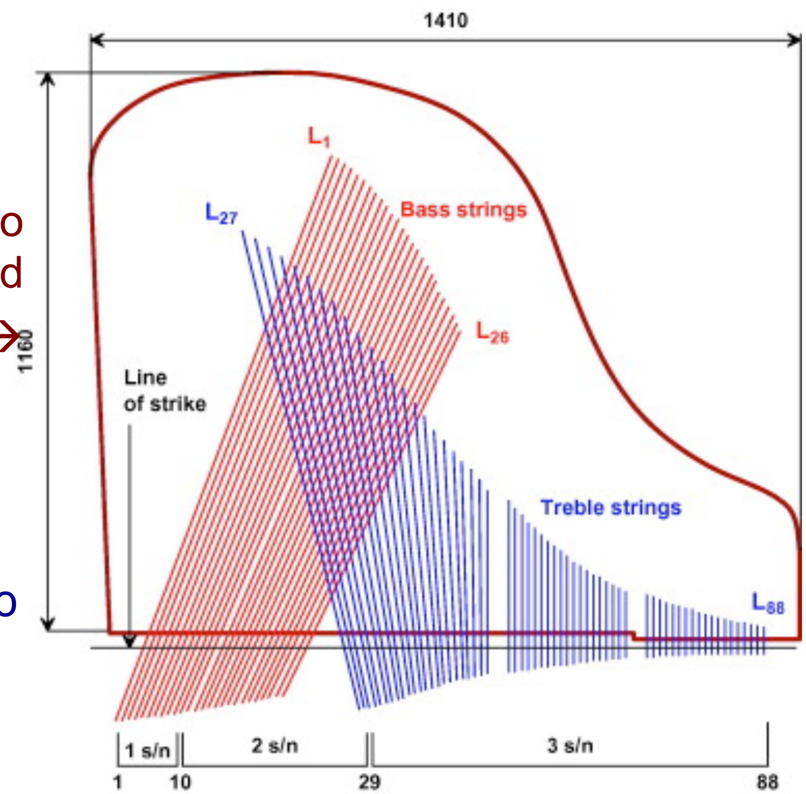
Typical concert grand piano has 243 strings:

- 8 single strings wrapped with one or two layers of wire
- 5 pairs wrapped (10)
- 7 sets of three wrapped (21)
- 68 sets of three unwrapped (204)

- String lengths from ~2m to ~5cm

Bass strings overlap the middle strings, to act nearer to the center of the sound board →

- Tensions may exceed 1000 N (220 lb)
  If a string breaks it is usually near the keyboard end, so it recoils away from the pianist!
- Total force of all strings in a concert piano > 20 tons!
  Grand pianos need frames made from cast iron



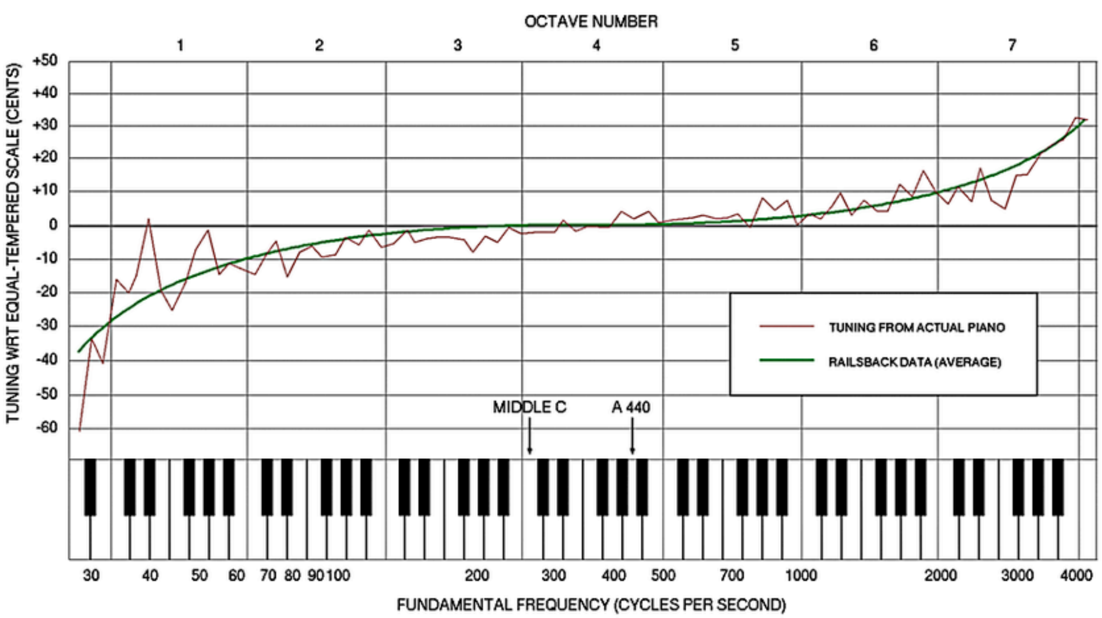
Piano strings

- Real strings resonate at frequencies off the harmonics of an ideal string, where $f_n = nf_1$
- Offset is given by $$f_n = n\,f_1\left[1+\left(n^2-1\right)\pi^3 r^4 E\Big/\left(8TL^2\right)\right]$$

("it can be shown")

Where r = string radius, T=tension, L= length, E=material modulus

  – So offset is minimal for small radius, high tension, long strings
    - For low f, strings are wire-wrapped to keep r small



Small inharmonicity is desirable :

"Inharmonicity lends color to the tone"

Deviation of note's fundamental from the equal-tempered scale, in cents =1/100 of a halftone

wikiwand.com/en/Piano_tuning

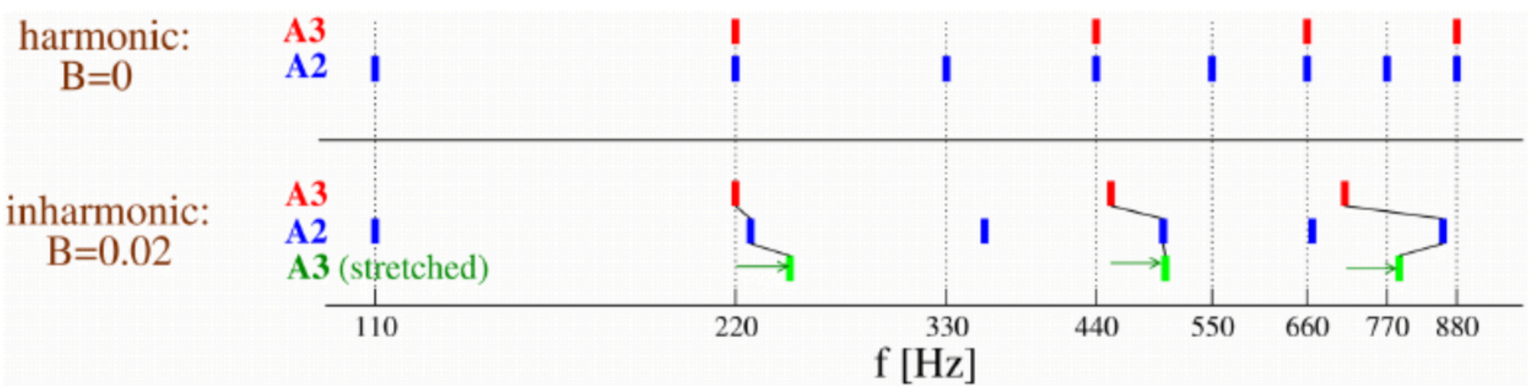
Piano tuning

To fix mismatch from inharmonicity, strings are "stretch–tuned"

- Reduce beats of a few Hertz between partials of a note and its higher octaves on the keyboard: piano tuner (by ear) tries to make beat f as low as possible
- Notes 1 octave apart (theoretically exactly 2:1 f ratio) are tuned slightly farther apart (a stretched octave)

Upper octaves are stretched up and lower are stretched down

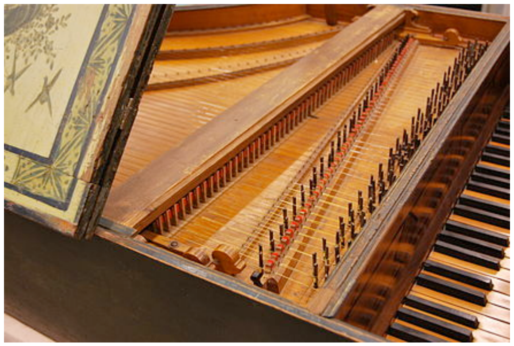
- For compressed tuning the octave is smaller than a factor of 2
- Long bass strings of large grand pianos need to be stretched less then bass strings of smaller pianos

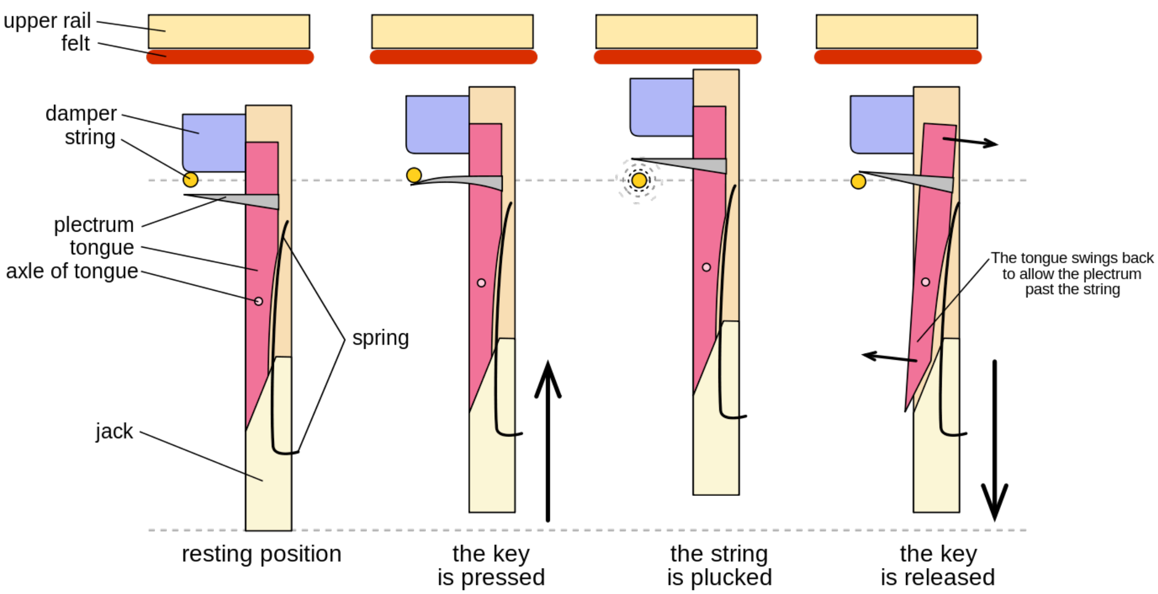


From www.researchgate.net/publication/221933427

Harpsichord: plucked string

- Strings are plucked, not hammered
- Strings have much lower tension than the piano strings
- Strings have much stronger inharmonicity than the piano strings
- Much lighter soundboard than piano – weaker sound than piano
- To vary loudness and timbre harpsichords may have additional sets (choirs) of strings





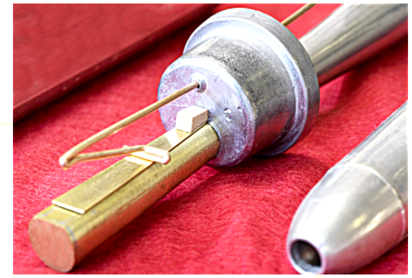
Another wind instrument: pipe organ

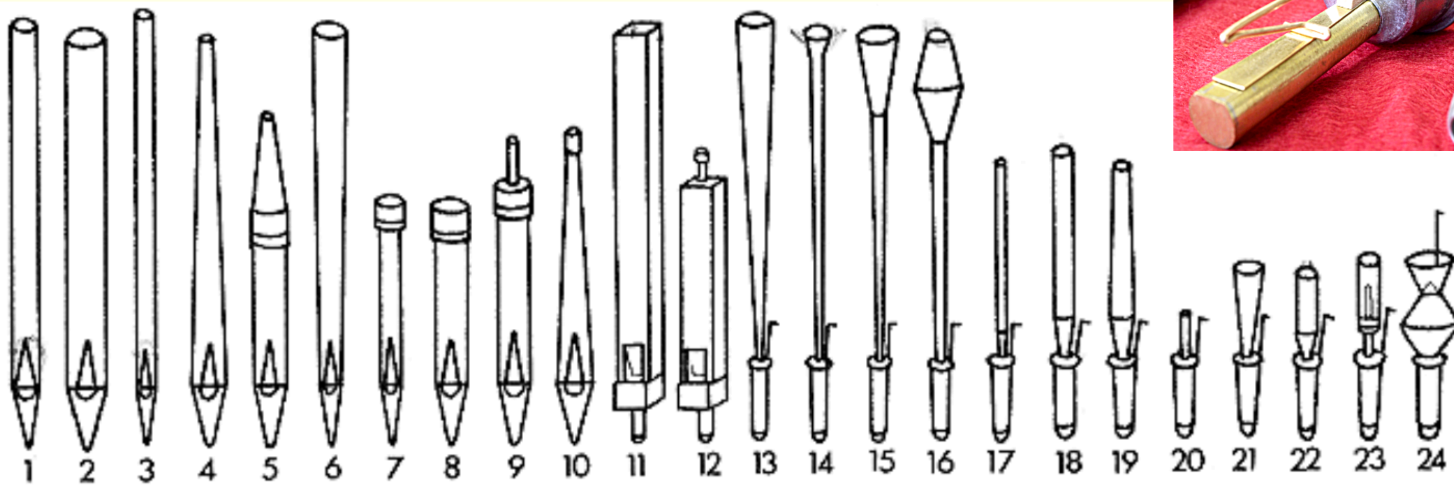
- Sound is produced by driving pressurized air through pipes
- Each pipe produces a single pitch
- Pipes are provided in sets called *ranks*
- Each rank has a common timbre
- Most organs have multiple ranks of pipes of differing timbre, pitch and loudness that the player can employ singly or in combination through the use of controls called *stops*
- An organ stop admits pressurized air (*wind*) to a set of pipes
- A pipe organ may have one or several keyboards (called *manuals*) played by the hands, and a *pedalboard* played by the feet, each of which has its own group of stops

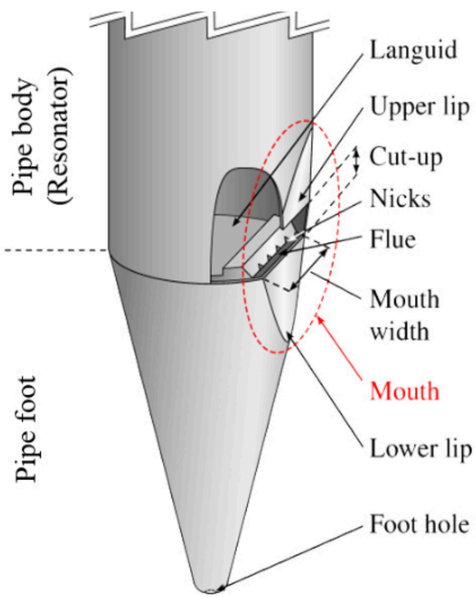
Walker-Ames Room, Kane Hall

Organ's continuous supply of wind allows notes to sustain as long as the key is held
(piano notes decay even if keys are held down)

Organ pipes





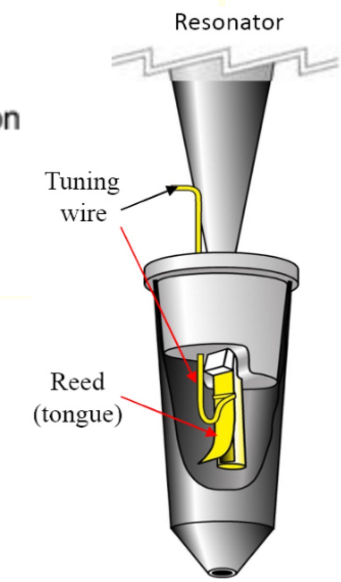


Flue pipes:

1 Principal	7 Quintaton
2 Flute	8 Gedeckt / Bourdon
3 Viole	9 Rohrflute
4 Spitzflute	10 Spitzgedeckt
5 Koppelflute	11 Open Wood
6 Trichterflute	12 Stopped Wood

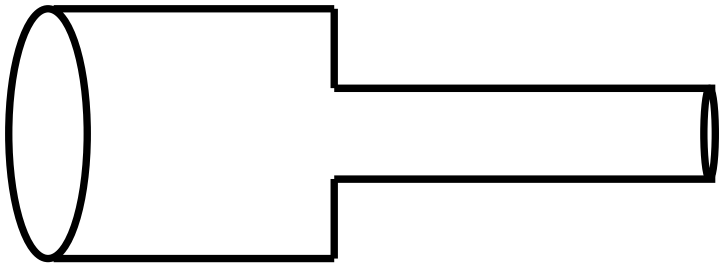
Reed pipes:

13 Trumpet	19 Musette
14 Schalmei	20 Regale
15 Oboe	21 Tricher Regale
16 English Horn	22 Vox humana
17 Krummhorn	23 Rankett
18 Dulcian	24 Baerpfeife



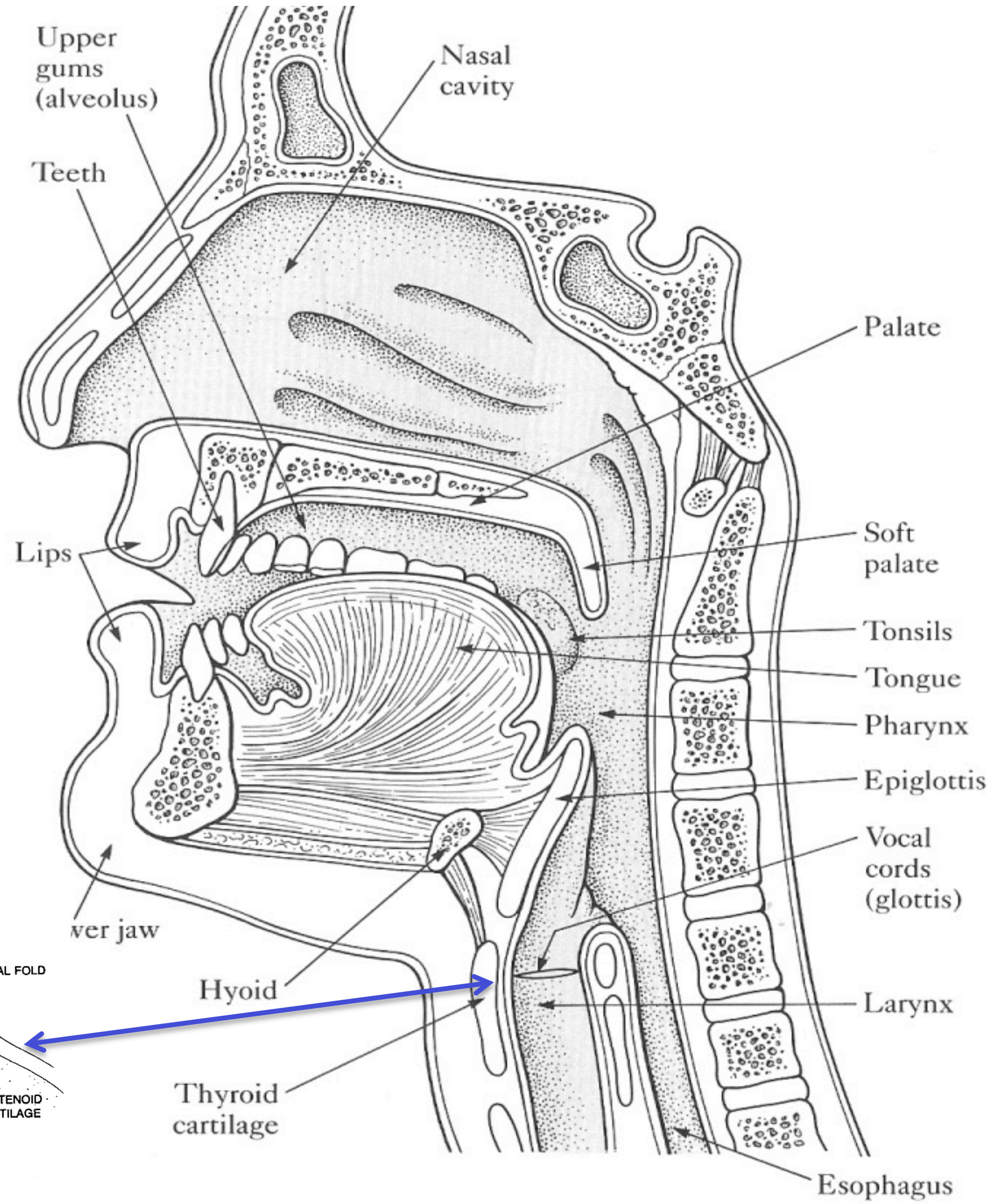
Another wind instrument: the Human Voice

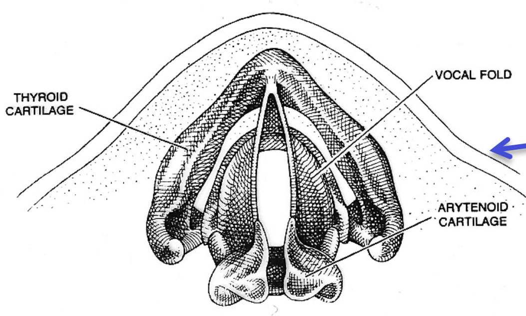
- Human voice is produced by complex system with 3 main parts:
  - Lungs
    - Air reservoir and energy source
  - Larynx
    - Air flow through vocal folds produces "buzzing" similar to lips on a brass instrument -- broad spectrum
    - Frequency is determined by thickness of folds (mass - men have lower pitch), muscle control (stiffness)
  - Cavities: pharynx, nasal, oral
    - Vocal tract acts as a resonator
      - Length is fixed (15-20 cm) – constrictions produce resonances
    - Air exits through nasal and oral cavities
- Model vocal tract as tube with variable constrictions
  - Helmholtz resonator



The vocal tract

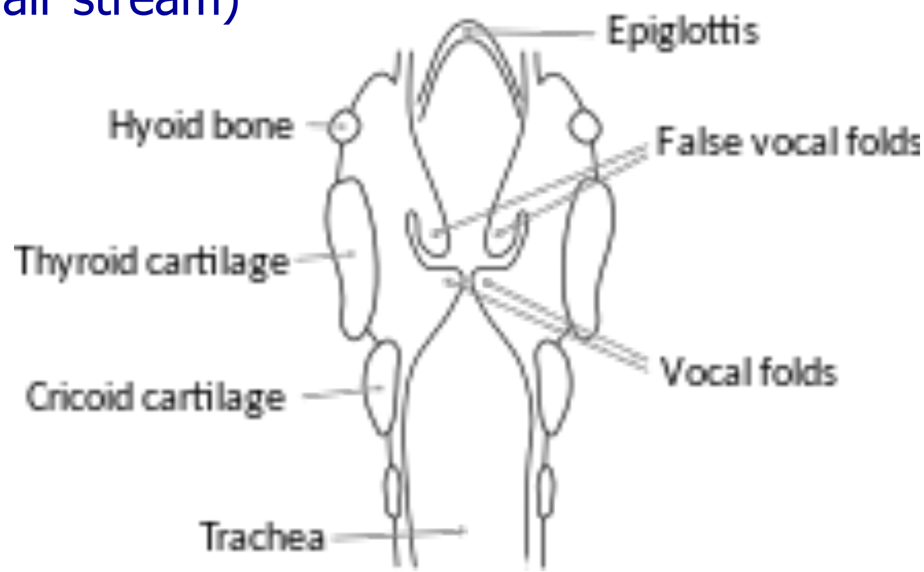
Figures from
www.cwu.edu/physics/

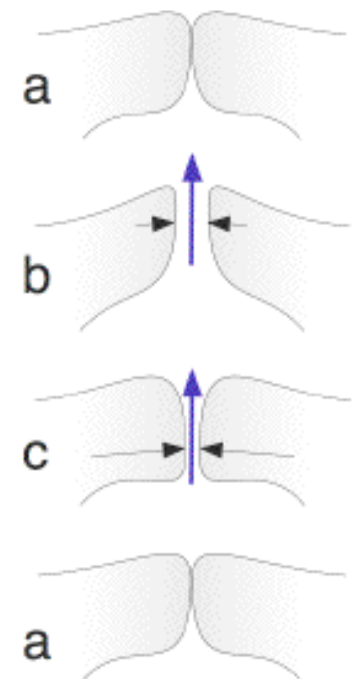




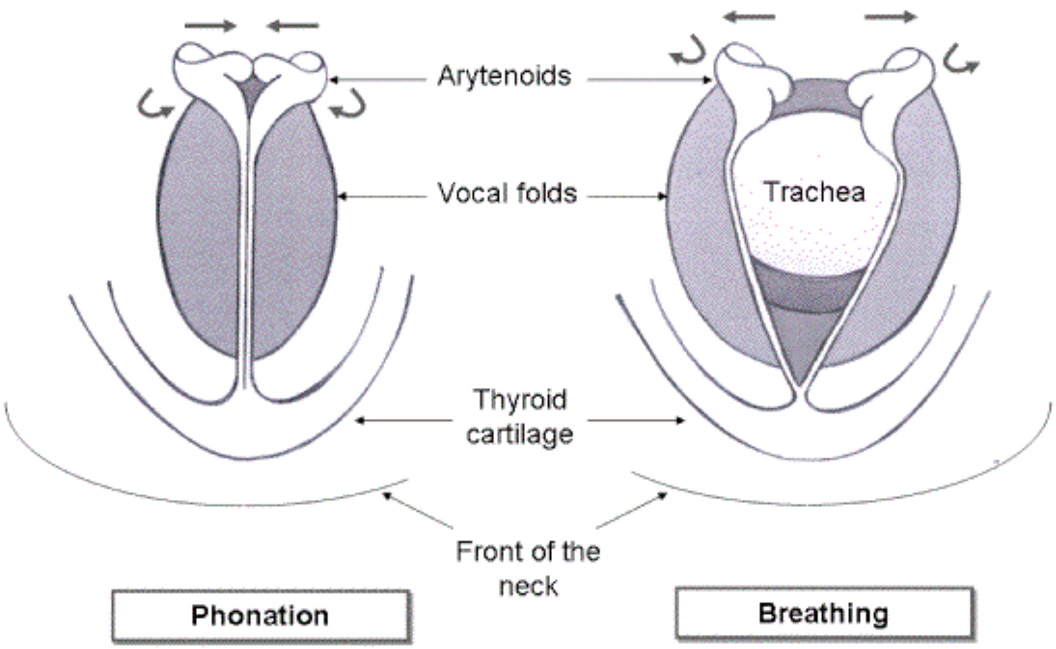
Larynx

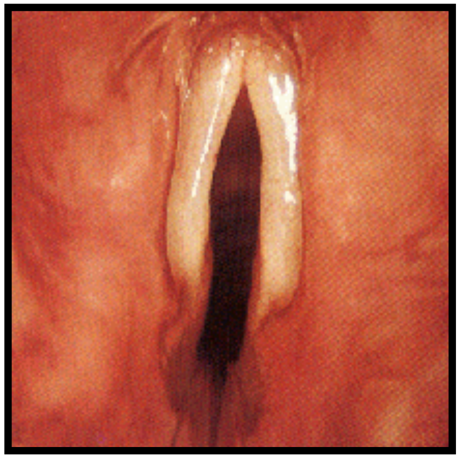
- Vocal folds (not actually "cords")
  - Vocal folds act on air stream:
    - Glottis - opening between the vocal folds
    - Completely closed (stopping air and sound)
    - Completely open (no sound—breathing)
    - Slightly open ("h" sound)
    - Rapid opening and closing (modulating the air stream)





Frequency spectrum

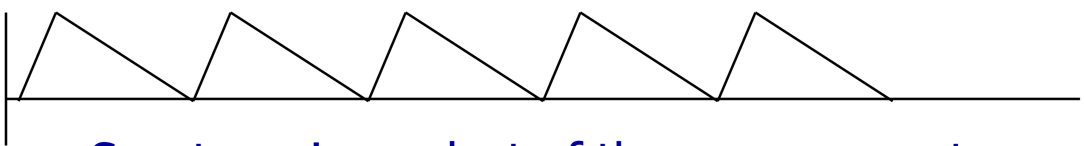


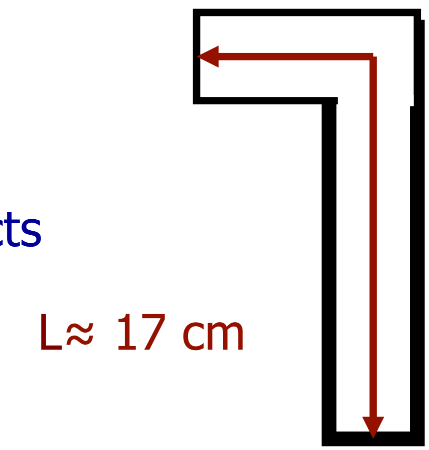


- Sound produced is similar to a pulse train (many harmonics of nearly equal amplitude)
- Like a reed, frequency of vocal folds is less influenced by feedback from resonances/impedance variation – mainly determined by muscular control

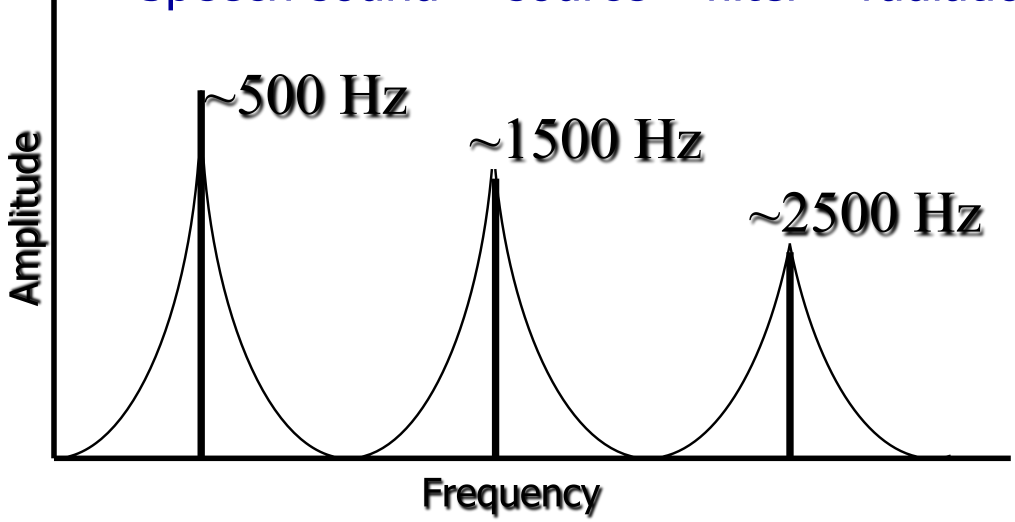
Typical Vibration Frequencies

- 110 Hz in male, 220 Hz in female, 300 Hz in child
  With wide variations between individuals
- Waveform: narrow triangle wave, ~ a pulse train
  - Buzzing sound with many harmonics of the fundamental frequency.





- Spectrum is product of three components:
- Speech sound = source * filter * radiation effects



Vocal Tract acts as a lossy stopped pipe ~17 cm long with a fundamental frequency of ~500 Hz

Vocal tract and spectrum

- From the bottom up:

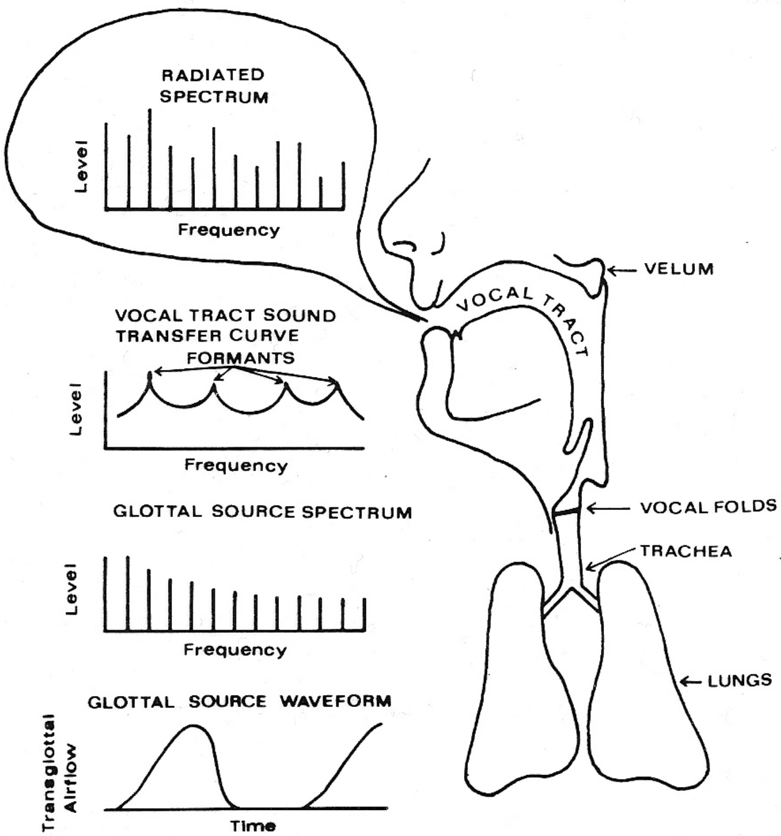
Final sound output →

Filter: vocal tract resonances

+

Effective source: pulse train

Vocal folds: buzz



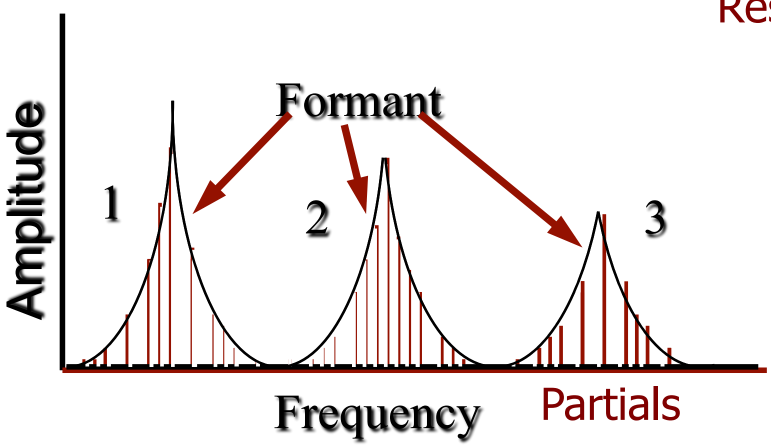
Resonances — Formants

- Formants: Peaks in sound spectra – resonances of vocal tract
  - Formants are independent of pitch

Recall:
  - Timbre of sound depends on the relative amplitude of harmonics
  - Pitch depends on the frequency of the fundamental

- Vowel sounds
  - Different vowels are essentially same pitch with different timbres
  - Resonant frequencies of vocal tract determine the spectrum

    →determine timbre
  - We determine the frequencies of formants by changing the shape of our vocal tract



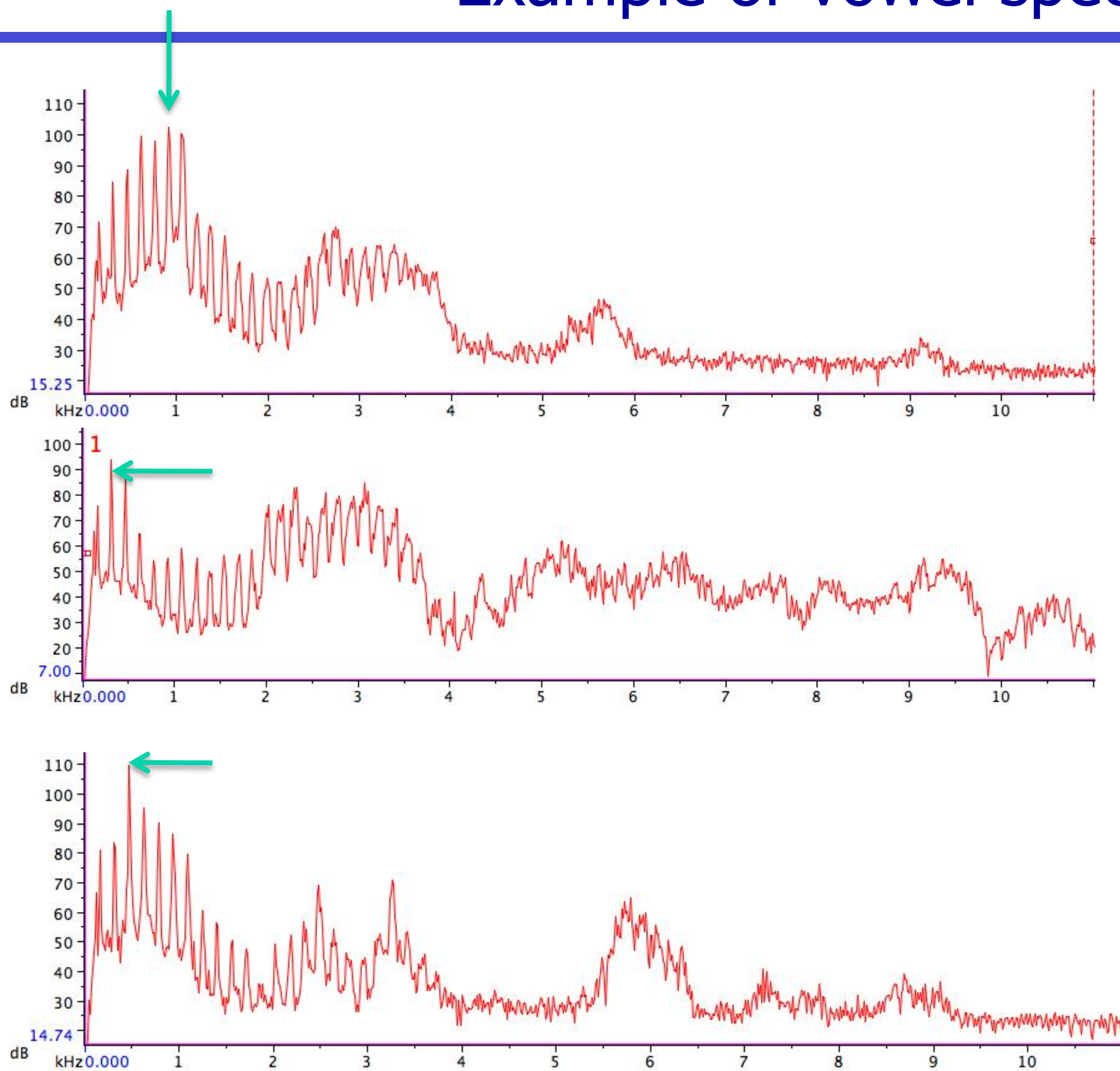
Resonant f's are ~ 500, 1500 and 2500 Hz

- First formant typically controlled by mouth opening
- Second formant typically controlled by tongue position

Partials close to the formant peaks are output with greater amplitude

Example of vowel spectra

first formant



aaa

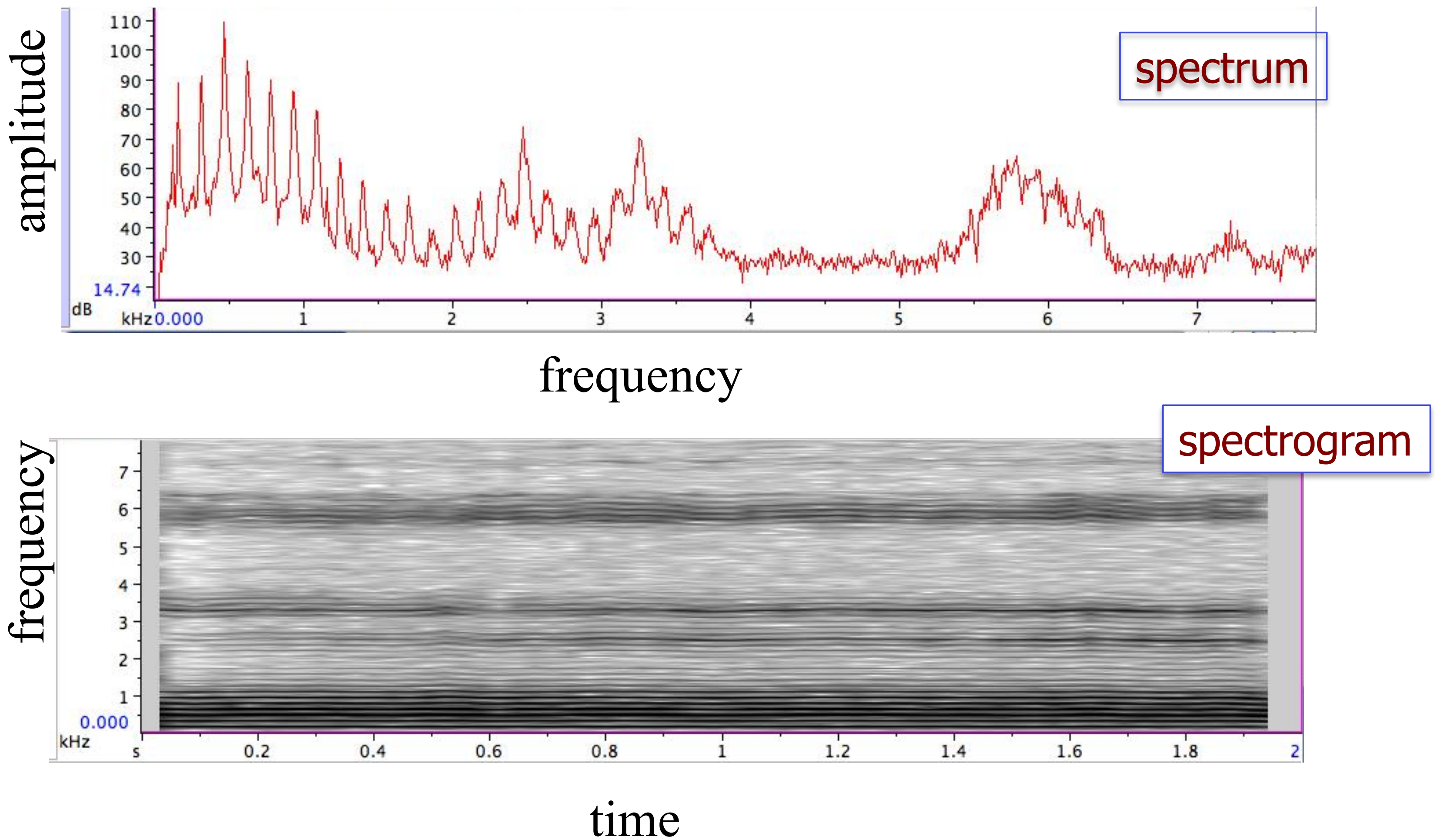
(wide open mouth)

iii

(mouth more closed)

ooo

Spectrogram: tool for analyzing voice spectra



Vocal folds' vibration mechanisms

Adapted from www.phys.unsw.edu.au/jw/voice.html -- see there for cited work

Mechanism 0 (M0) is also called 'creak' or 'vocal fry'.

- Tension of the folds is so low that the vibration is non-periodic: M0 sounds low but has no clear pitch

Mechanism 1 (M1) is usually associated with what women singers call the 'chest' register and men call their normal voice.

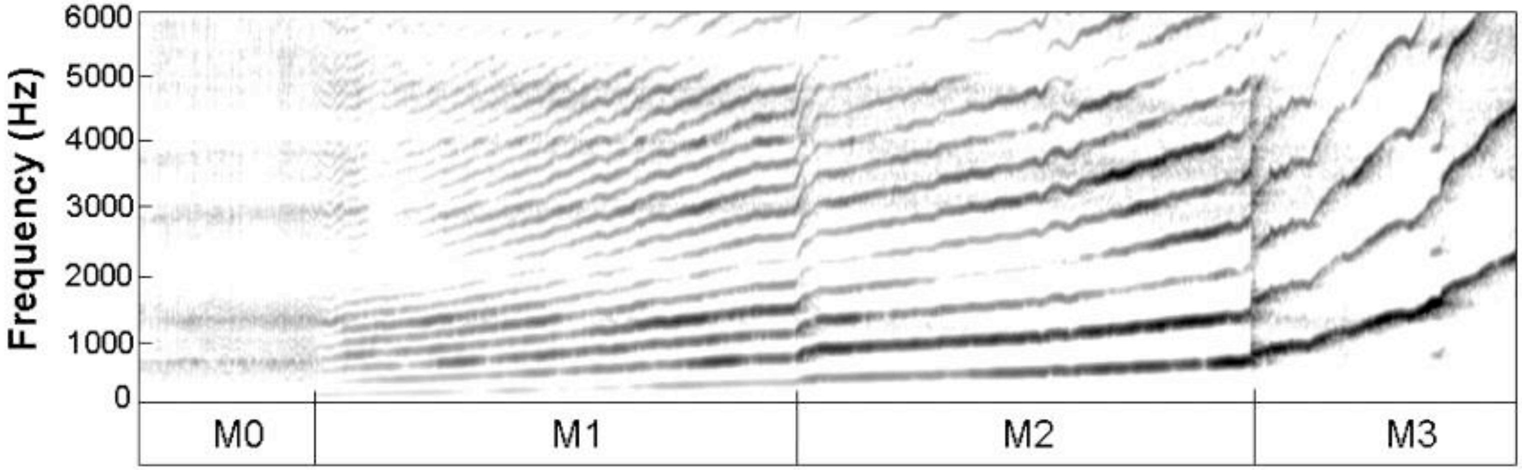
- Virtually all of the mass and length of the vocal folds vibrates (Behnke, 1880) and frequency is regulated by muscular tension (Hirano et al., 1970) but is also affected by air pressure. The glottis opens for a relatively short fraction of a vibration period (Henrich et al., 2005).

Mechanism 2 (M2) is associated with the 'head' register of women and the 'falsetto' register in men.

- A fraction of the vocal fold mass vibrates. The moving section involves about two thirds of their length, but less of the breadth. The glottis is open for a longer fraction of the vibration period (Henrich et al., 2005).

Mechanism 3 (M3) is the 'whistle' or 'flageolet' register (not to be confused with whistling) (Miller and Shutte, 1993; Garnier et al, 2010; 2012.)

Sound spectrogram vs what you hear

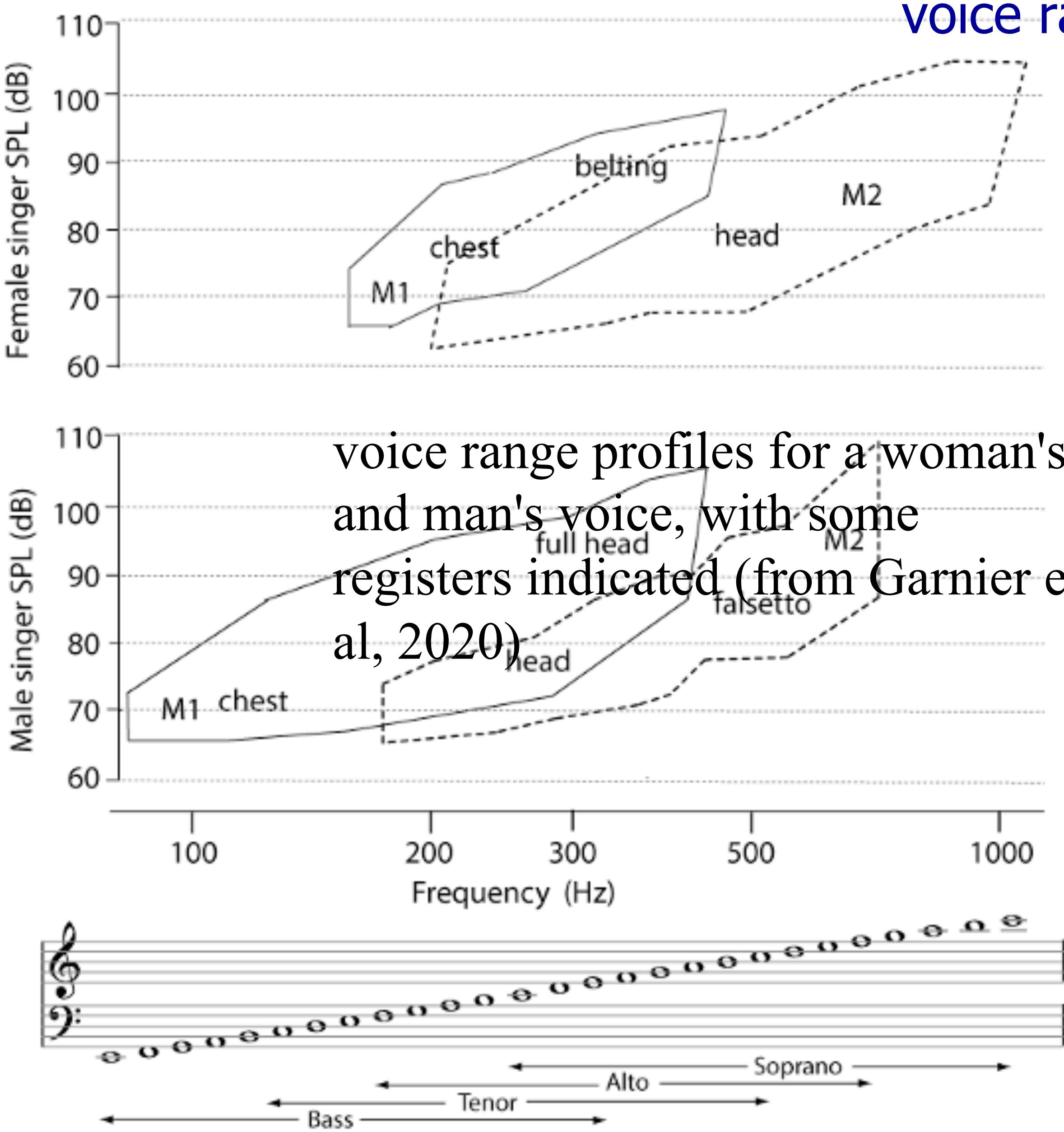


Frequency (vertical) vs time (horizontal) with sound level in grey-scale, showing the four laryngeal mechanisms on an ascending glissando sung by a soprano. The horizontal axis is time, dark represents high power.
Notice the discontinuities in frequency at the boundaries M1-M2 and M2-M3. The horizontal bands in the broad-band M0 section clearly show four broad peaks in the spectral envelope. (Four formants, one near each tract resonance.)

--audio--

From www.phys.unsw.edu.au/jw/graphics/voice7.jpg

voice range profiles



voice range profiles for a woman's and man's voice, with some registers indicated (from Garnier et al, 2020)

Voice range profiles

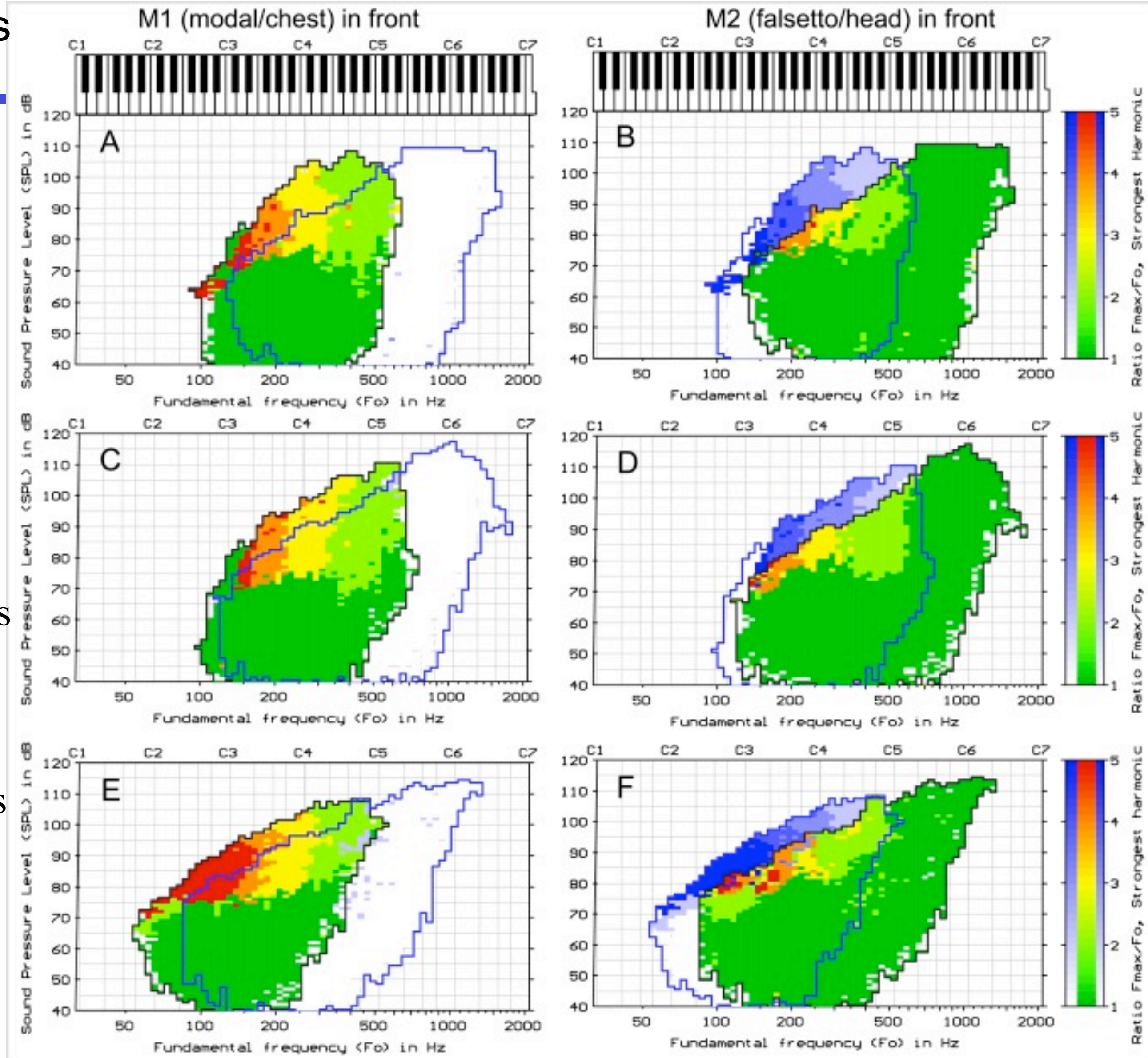
Color indicates the SPL of the strongest harmonic NHmax.

Left column: M1,
Right column: M2.
Blue: other M, for direct comparison

Panels A & B:
untrained female voices (N=16),

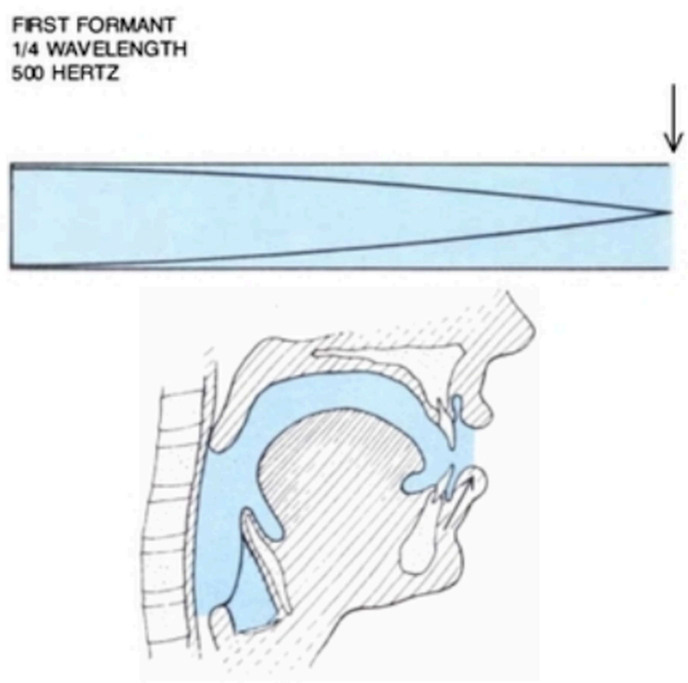
Middle panels C & D:
female singing students (N=12)

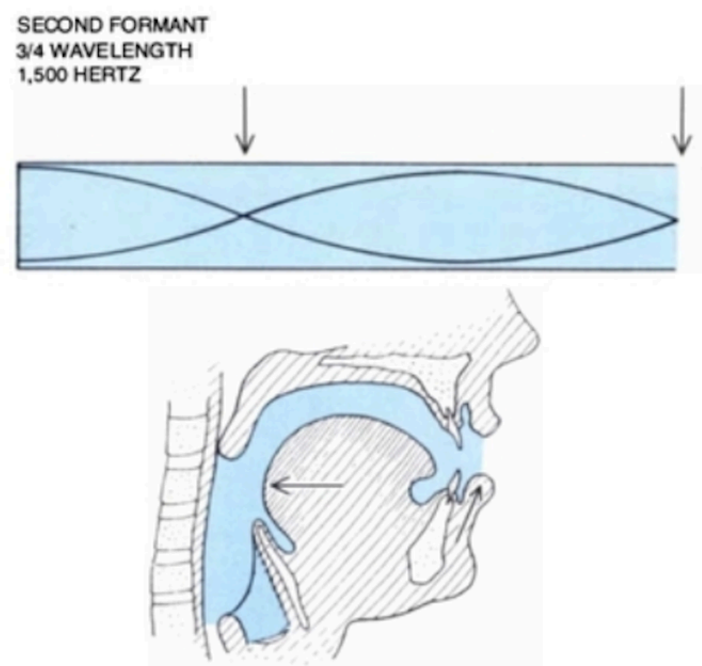
Bottom panels E & F:
male singing students (N=7).



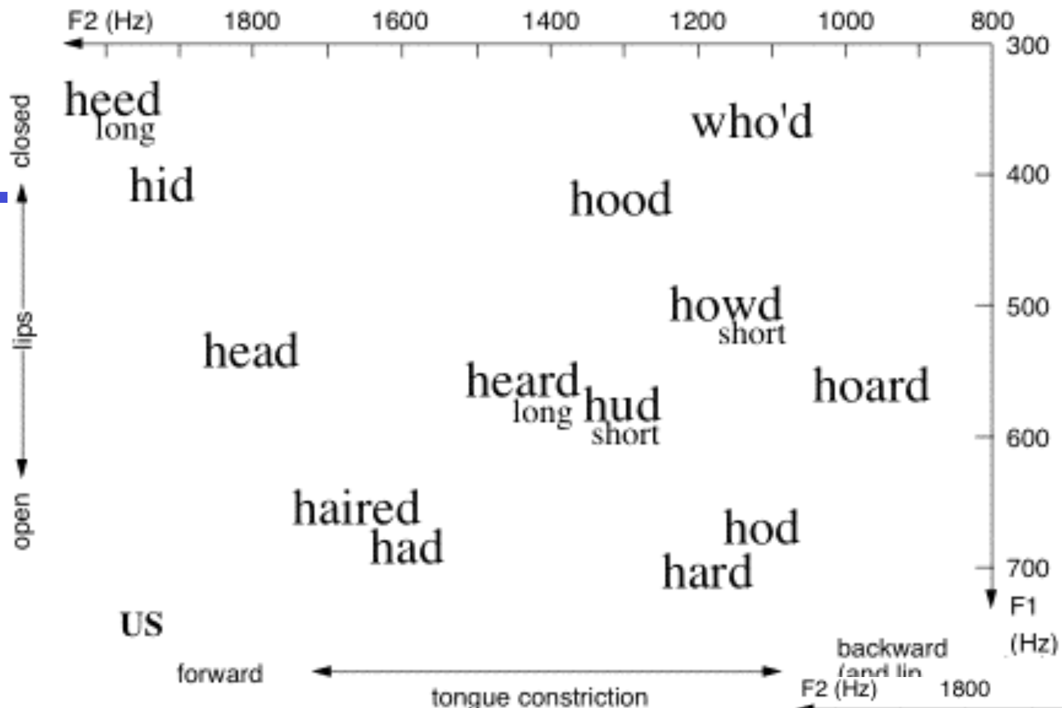
Formant tuning by singers

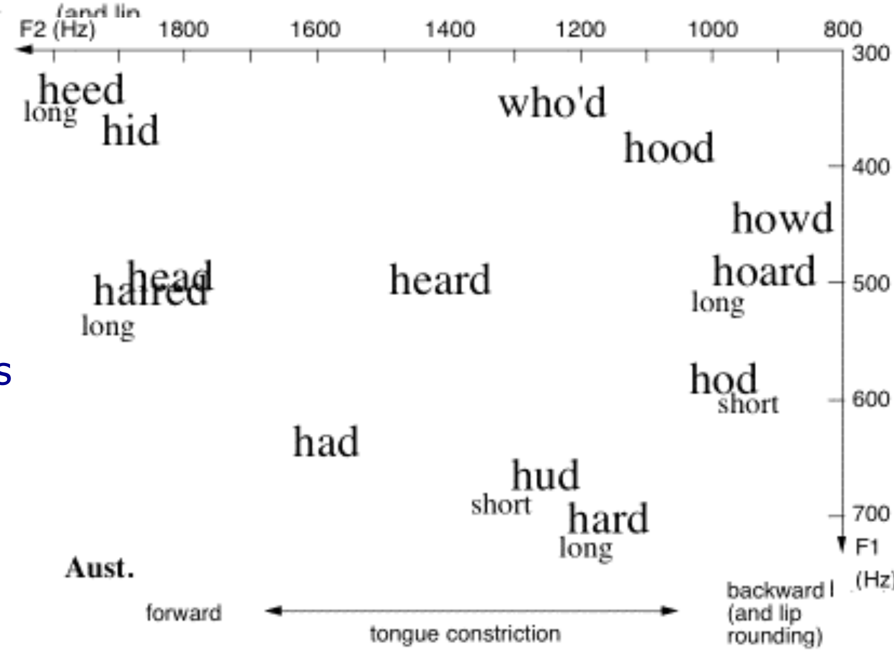
- Changing the size of the mouth opening (lips and jaw) can change the position of formants.
  - Necessary when fundamental pitch is above a formant.
  - Also used to tune formants to match harmonics of fundamental pitch.
- Creating a wider/narrower area in vocal tract at sound pressure nodes move formants higher/lower in frequency.





US vs Aussie vowel plots





First formant frequency vs second formant frequency

→ Correlated with lip and tongue positions

Overtone/Harmonic Singing

Overtone singing:

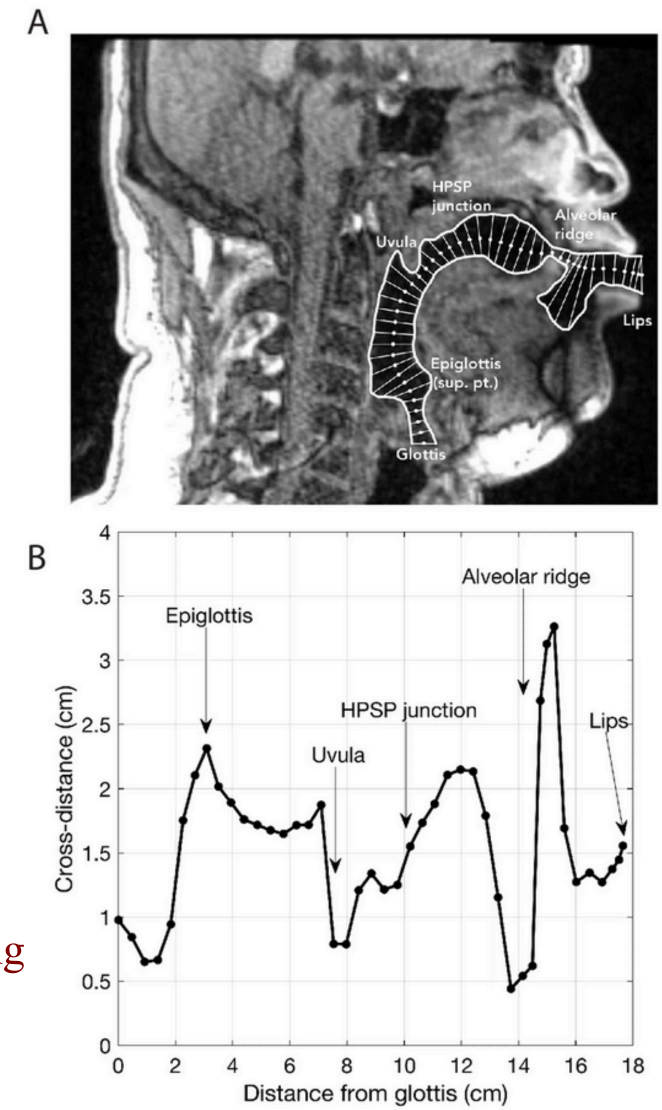
- Special type of voice production resulting in a separate high tone which can be heard over a more or less constant drone.

Overtone sound = interaction of closely-spaced formants.

1st and 2nd formants for lower overtones

2nd and 3rd formants for f > 800 Hz

- Firm, relatively long closure of the glottis is used in overtone singing
- Corresponding short open duration introduces a glottal formant that may enhance the amplitude of the intended overtone



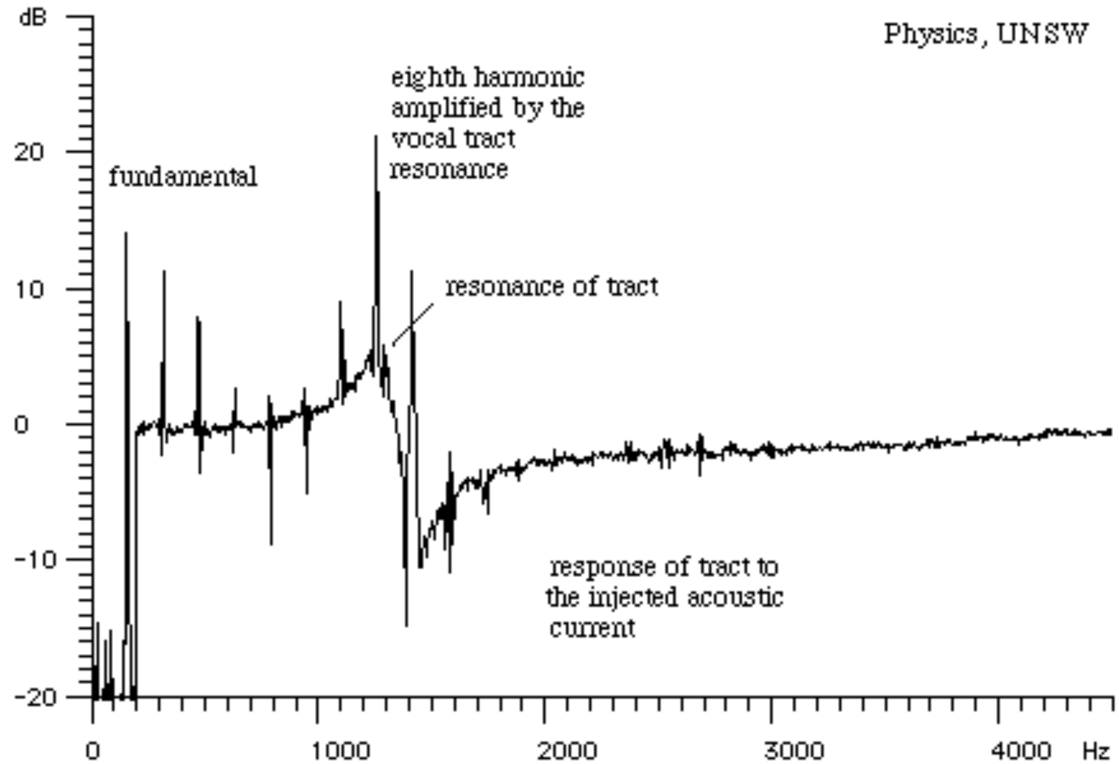
Shape of vocal tract during Khoomei throat singing*

*C. Bergevin et al, eLife Physics of Living Systems, 9:e50476 (2020)

Harmonic Singing

- One of the vocal tract resonances is made much stronger
- Makes one of the harmonics so much stronger than its neighbors that we hear it as a separate note.

Example: the 8th harmonic is amplified.
The fundamental lies in a range in which our ears are much less sensitive, so it sounds much less loud.



From newt.phys.unsw.edu.au/jw/xoomi.html

Overtone or Harmonic Singing

- Tuvan throat singing is one particular variant of overtone singing practiced by the Tuva people of southern Siberia.

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

- Overtone sound = interaction of closely-spaced formants:

1st and 2nd formants for lower overtones;
2nd and 3rd formants for f > 800 Hz

- Long glottal closure is used in overtone singing.