Musical acoustics

Li Su
Assistant research fellow, IIS, Academia Sinica
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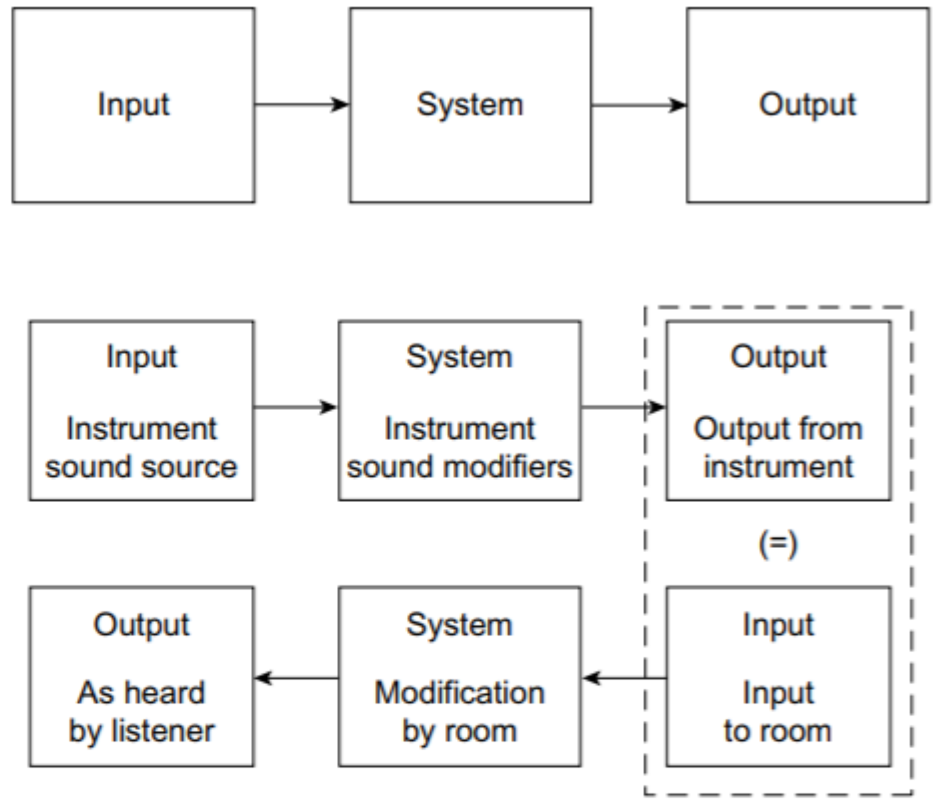
Reference

- David M. Howard and Jamie A.S. Angus, “Acoustics and Psychoacoustics,” on ScienceDirect.com, Fourth Edition, 2012

System perspective

- Instrument as a "system"
- Combination of:
  - Sound source
  - Sound modifier (filter)
- Or:
  - Oscillator
  - Resonator (filter)
  - Radiator



Instrument classes

- Hornbostel–Sachs system

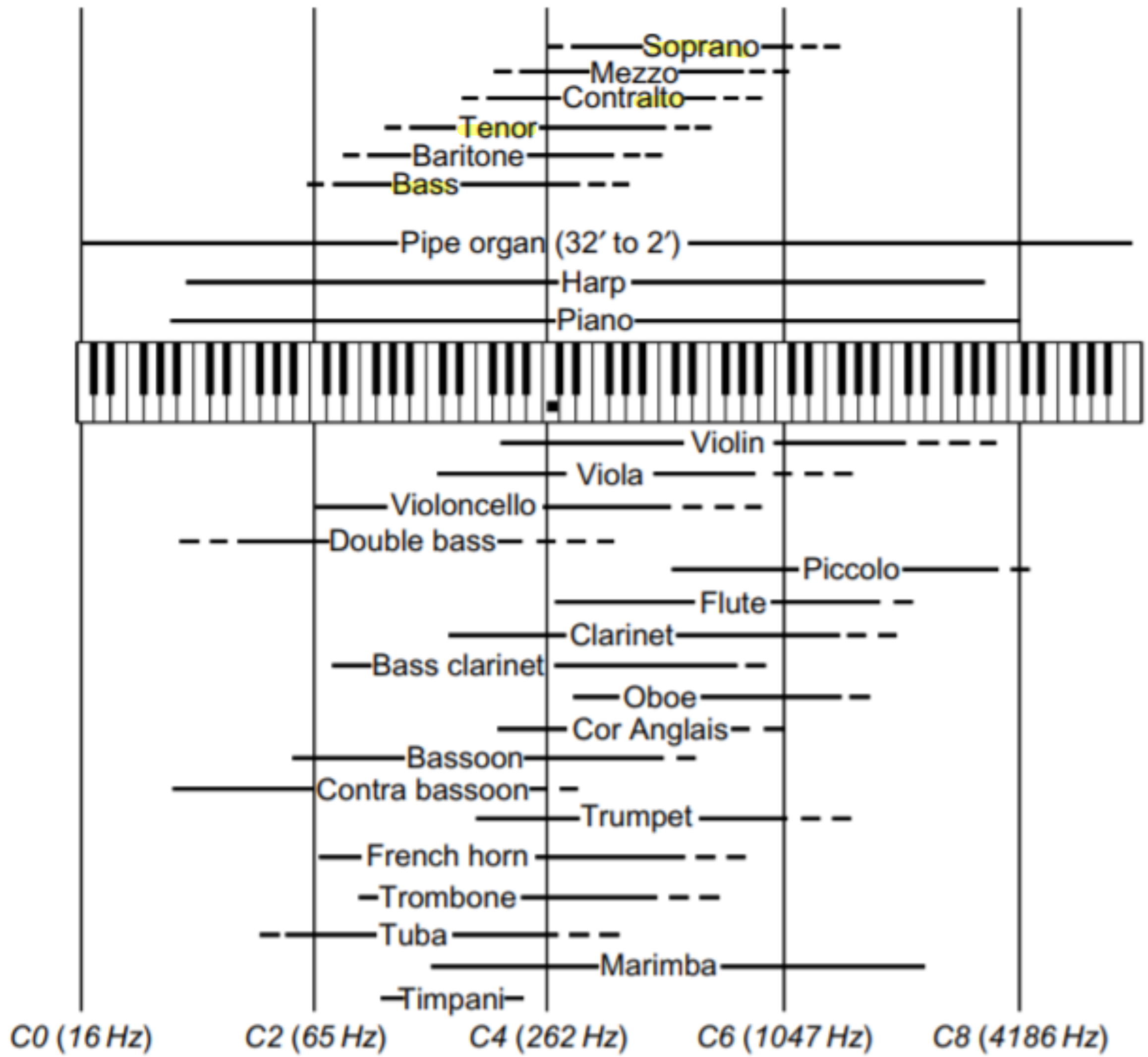
Category	Example
Idiophone	Bells, xylophones, kalimba, …
Membranophone	Timpani, kettle drums, kazoos, …
Chordophone	Violins, guitars, lutes, pianos, …
Aerophone	Brass, woodwind, …
Electrophone	Electric guitars, amplifiers, synthesizers, …





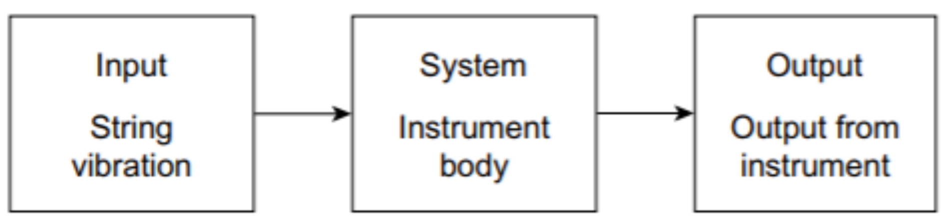
Playing ranges

- Fundamental frequency ranges



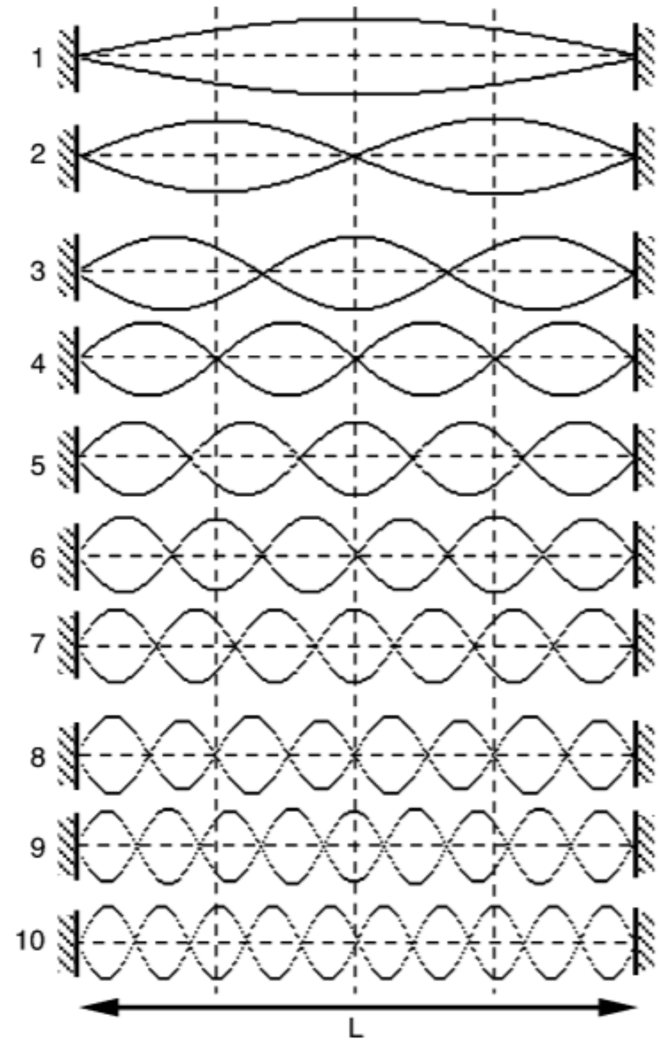
System perspective: strings

- The variable mass enables the string tension to be altered, and the length of the string can be altered by moving the right-hand bridge.



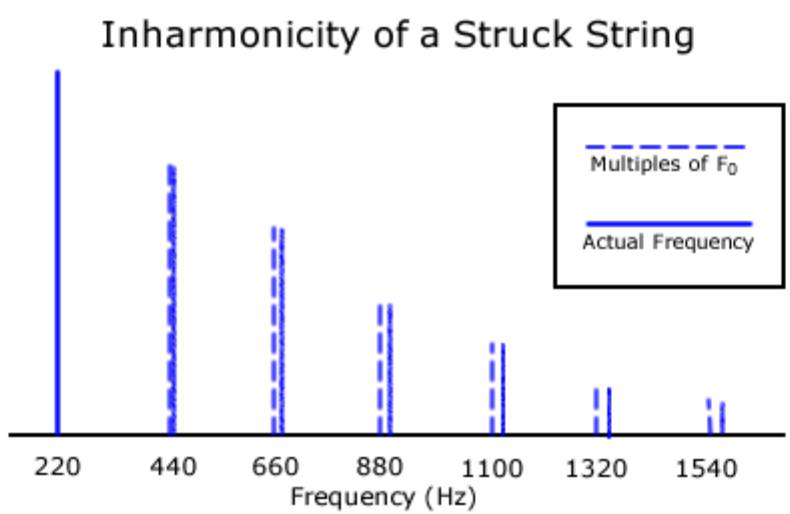
Normal modes of strings

- String as a resonator
- Ideal natural response
- The first 10 possible modes of vibration of a string of length (L) fixed at both ends



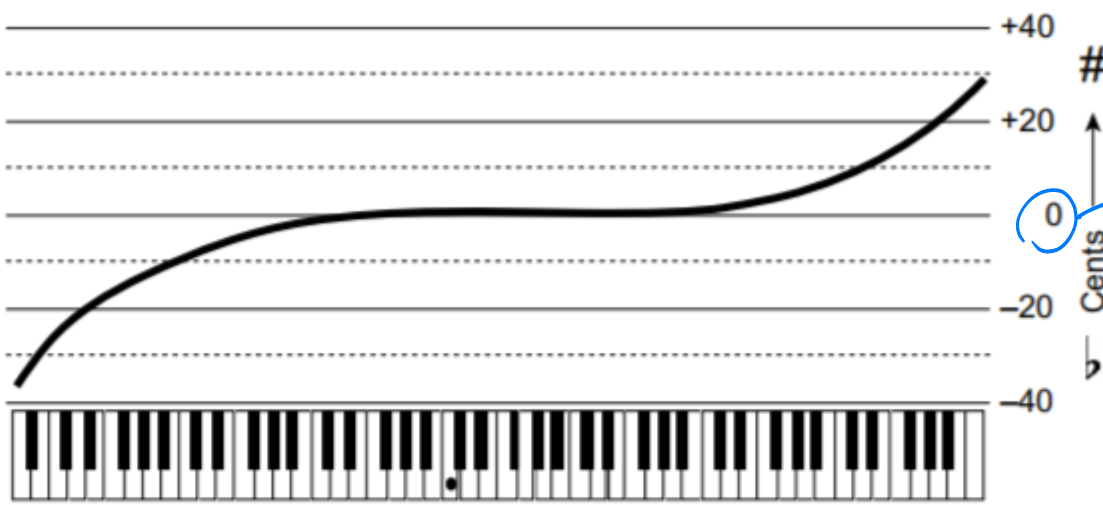
Piano: inharmonicity

- Strucked string
- Non-ideal natural response: inharmonicity caused by stiffness of strings
- Harmonic frequencies are slightly higher than the integer multiples: $f_n = f_0\sqrt{1 + \beta n^2}$



Inharmonicity and tuning

- Approximate form of the average deviations from equal temperament due to inharmonicity in a small piano. Middle C marked with a spot. (Data from Martin and Ward, 1961.)



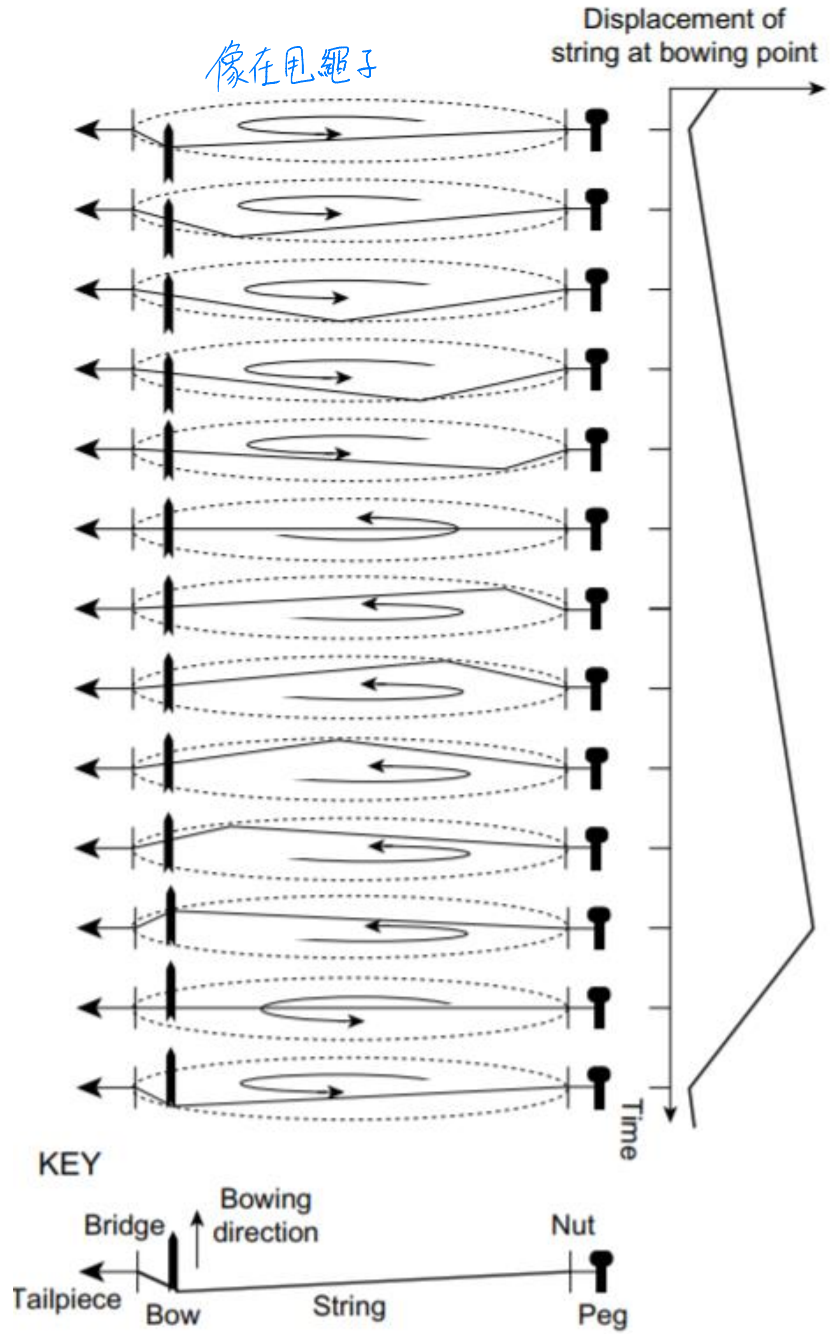
標準12平均律

Bowed string

弓

- Violin, cello, …
- One complete cycle of vibration of a bowed string and graph of string velocity at the bowing point as a function of time. (Adapted from Rossing, 2001.)
- https://www.youtube.com/watch?v=6JeyiM0YNo4

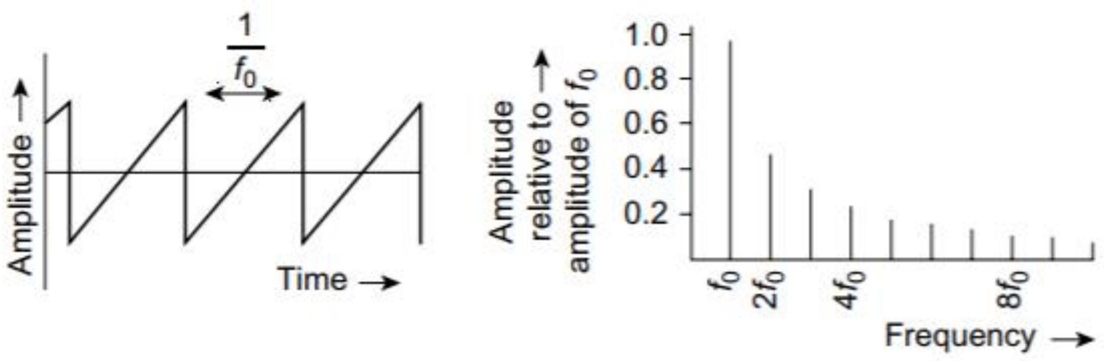
像在甩繩子



Sawtooth wave

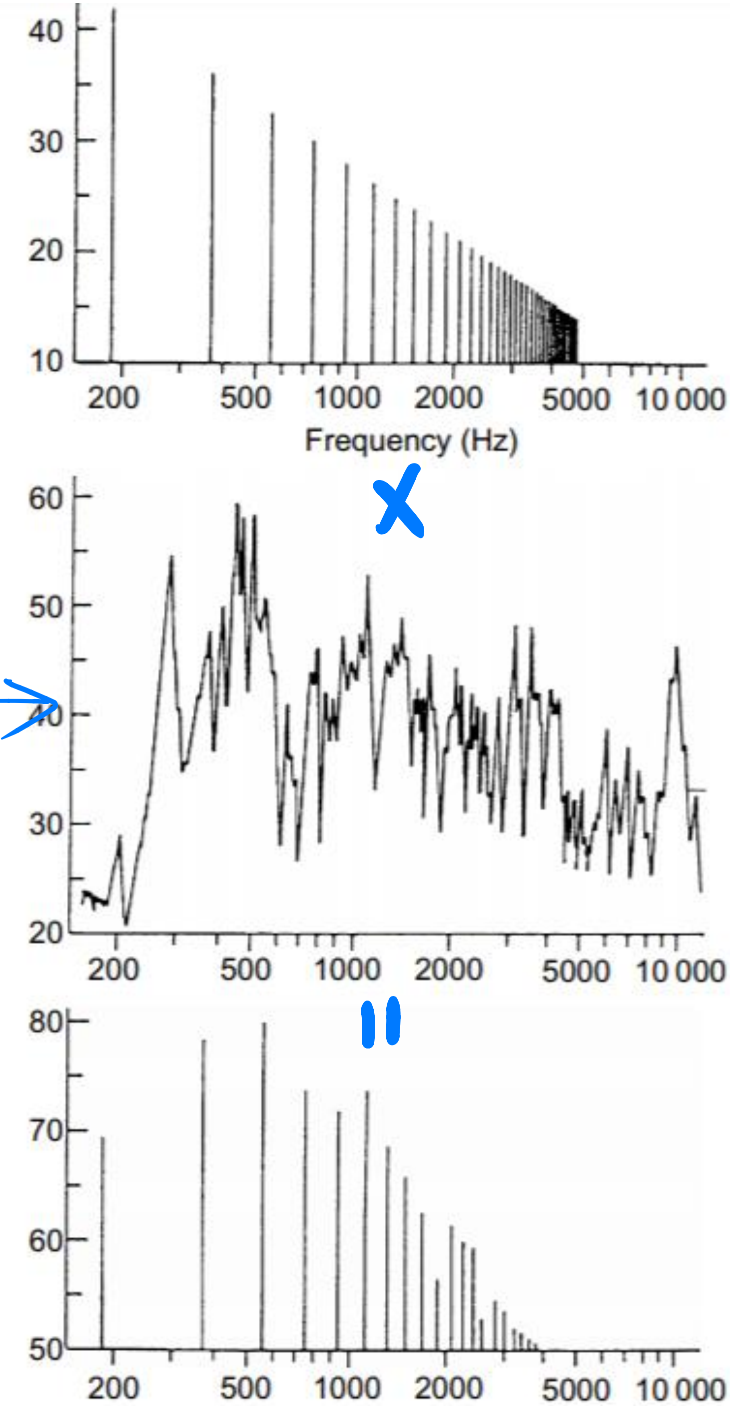
鋸齒波

- Idealized sound source sawtooth waveform and its spectrum for a bowed string



Source and modifier

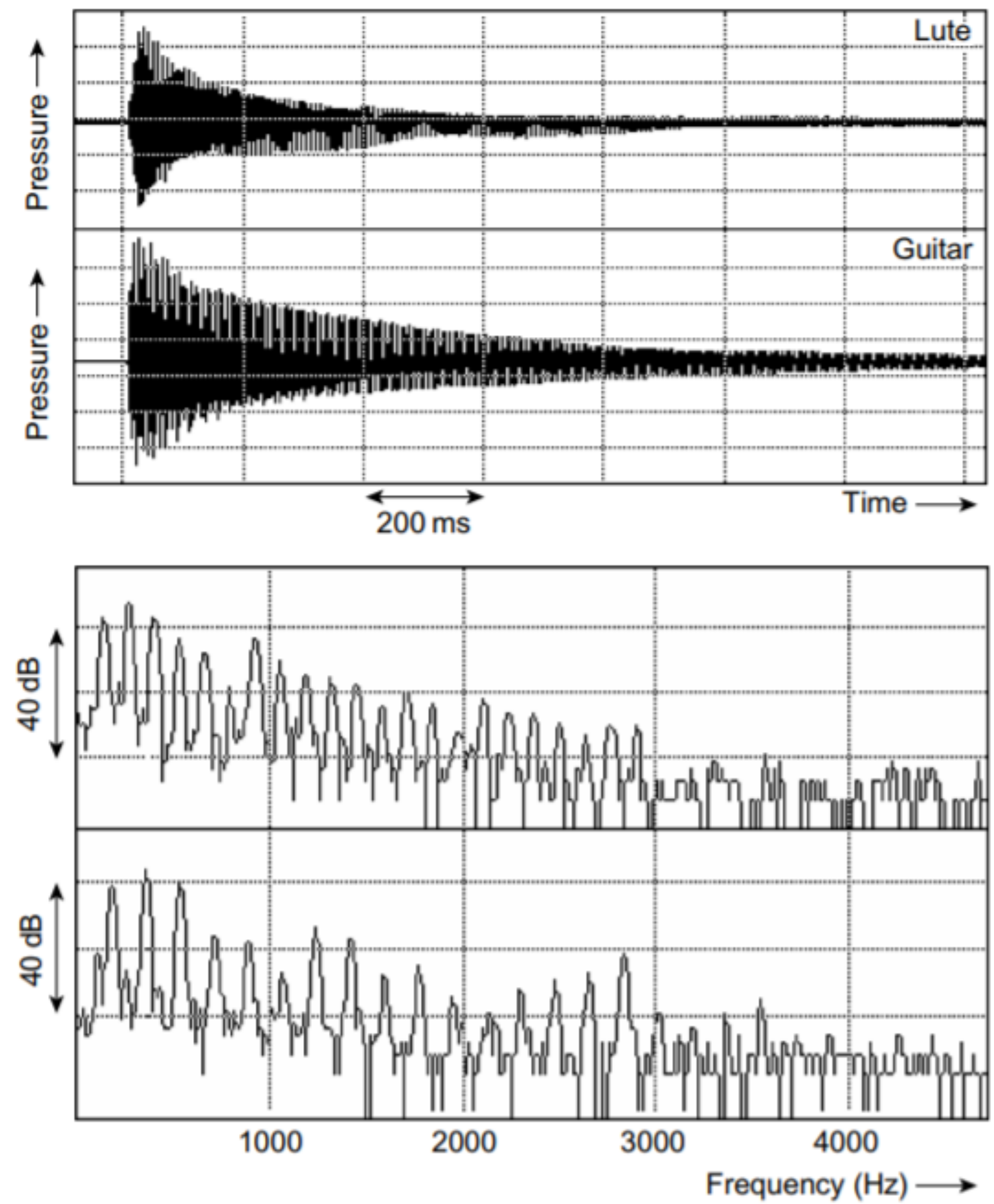
- [Violin as an example]
- https://www.youtube.com/watch?v=-A27Y4jYlPs
- "Source-filter" assumption:
  - "Pitch" and "timbre" can be separated
  - Total sound spectrum = (spectrum of source) x (spectrum of resonator)



Plucked strings

- ADSR (attack-decay-sustain-release) curve

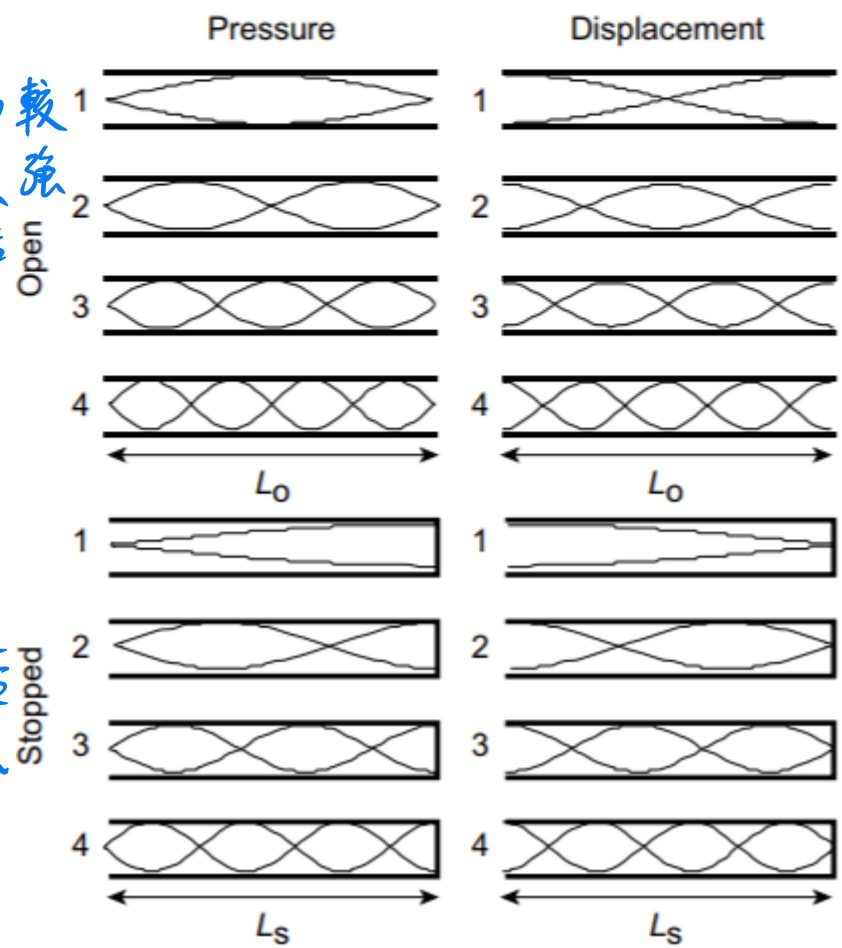
- Waveforms and spectra for C3 played on a lute and F3 played on a six-string guitar



Wind instruments

- The first four pressure and velocity modes of an open and a stopped pipe of uniform cross-section. (Note: The plots show maximum and minimum amplitudes of pressure and velocity.)

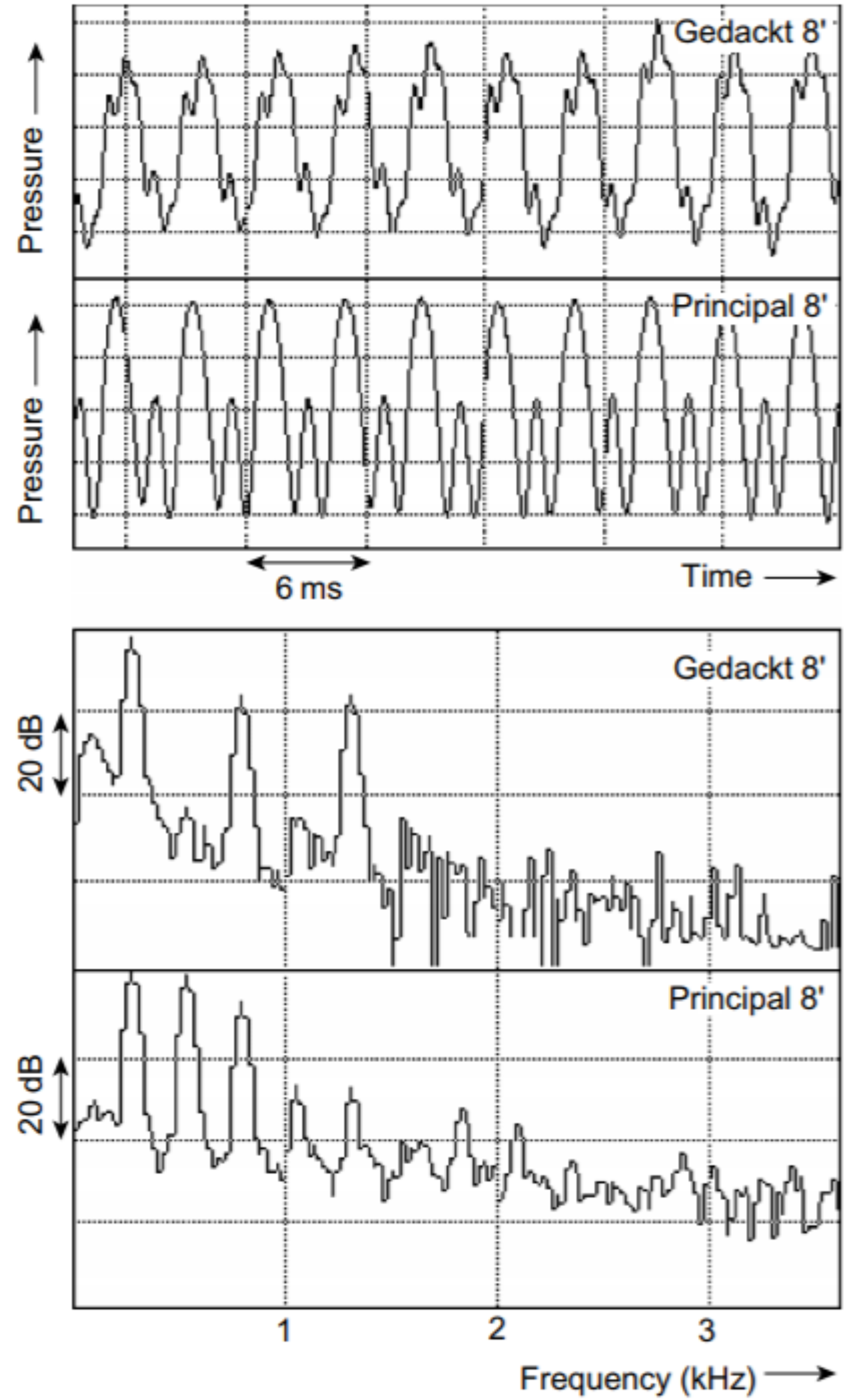
偶數倍
較強



奇數倍
較強

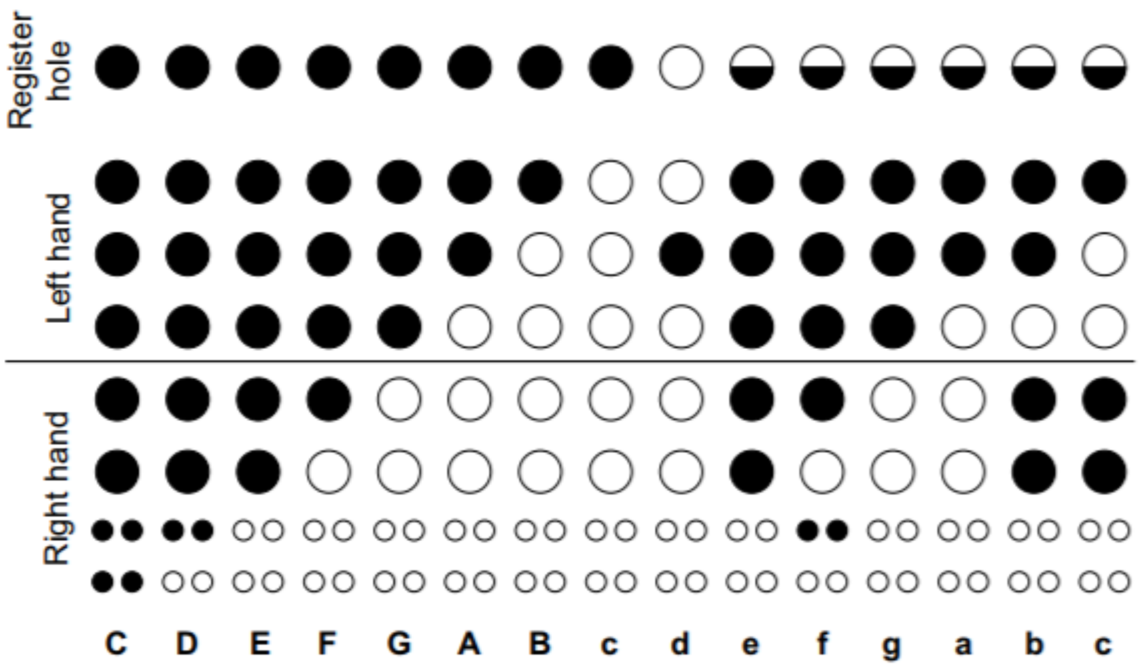
Spectra of flutes

- Waveforms and spectra for middle C (C4) played on a gedackt 8’ (stopped flute) and a principal 8’ (open flute)



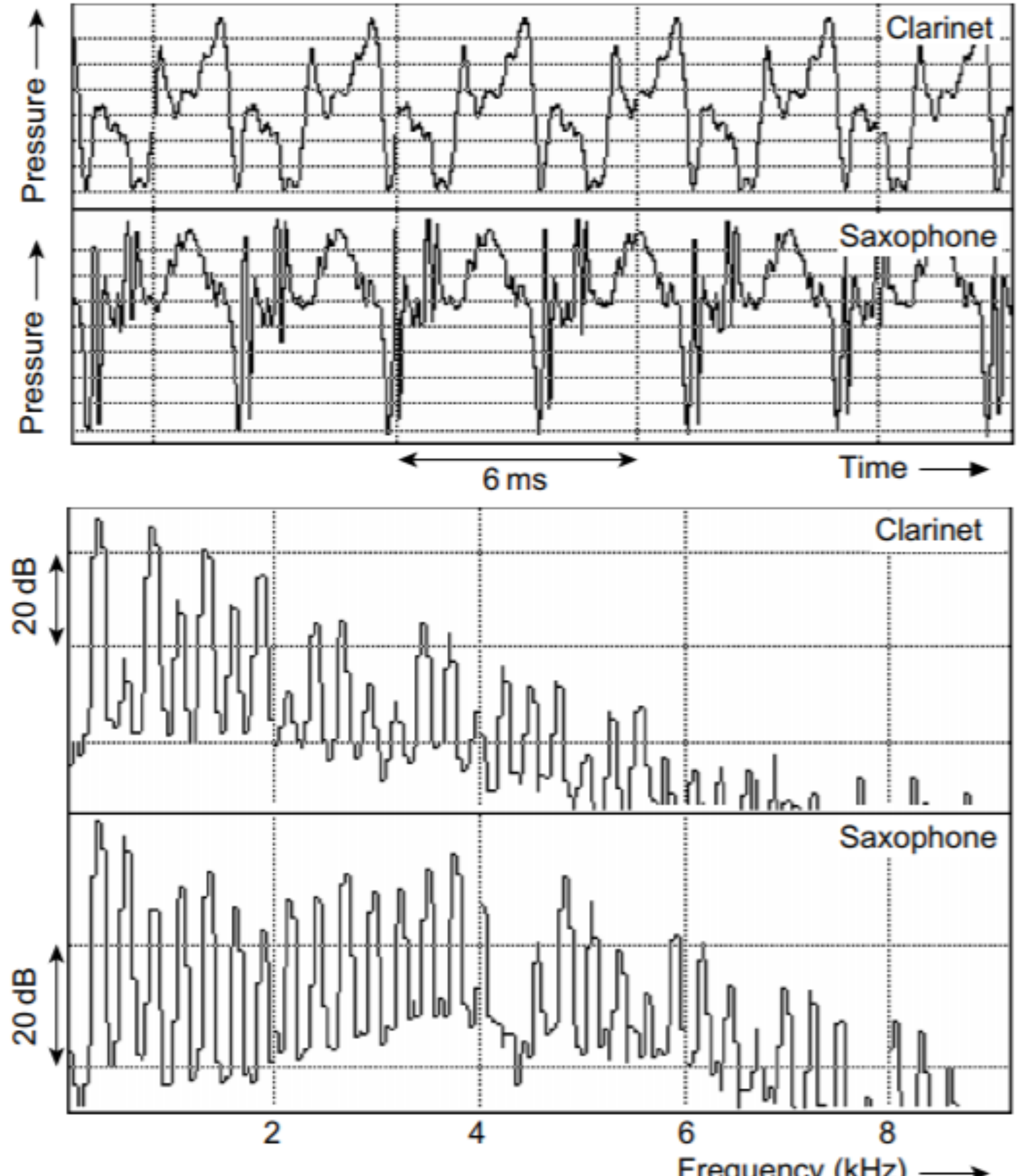
Flutes and recorders

- Fingering chart for recorders in C (descants and tenors)



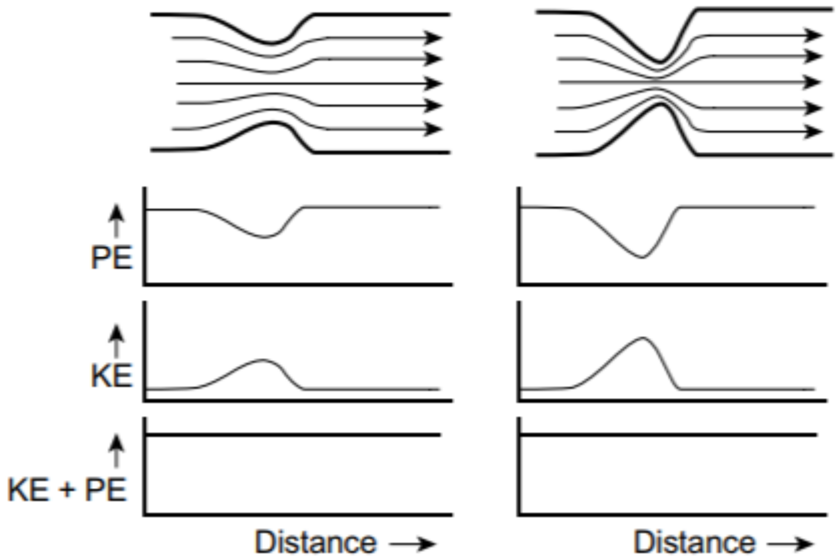
Woodwind

- Waveforms and spectra for middle C (C4) played on a clarinet and a tenor saxophone
- Single reed + pipe
- Single reed + cone



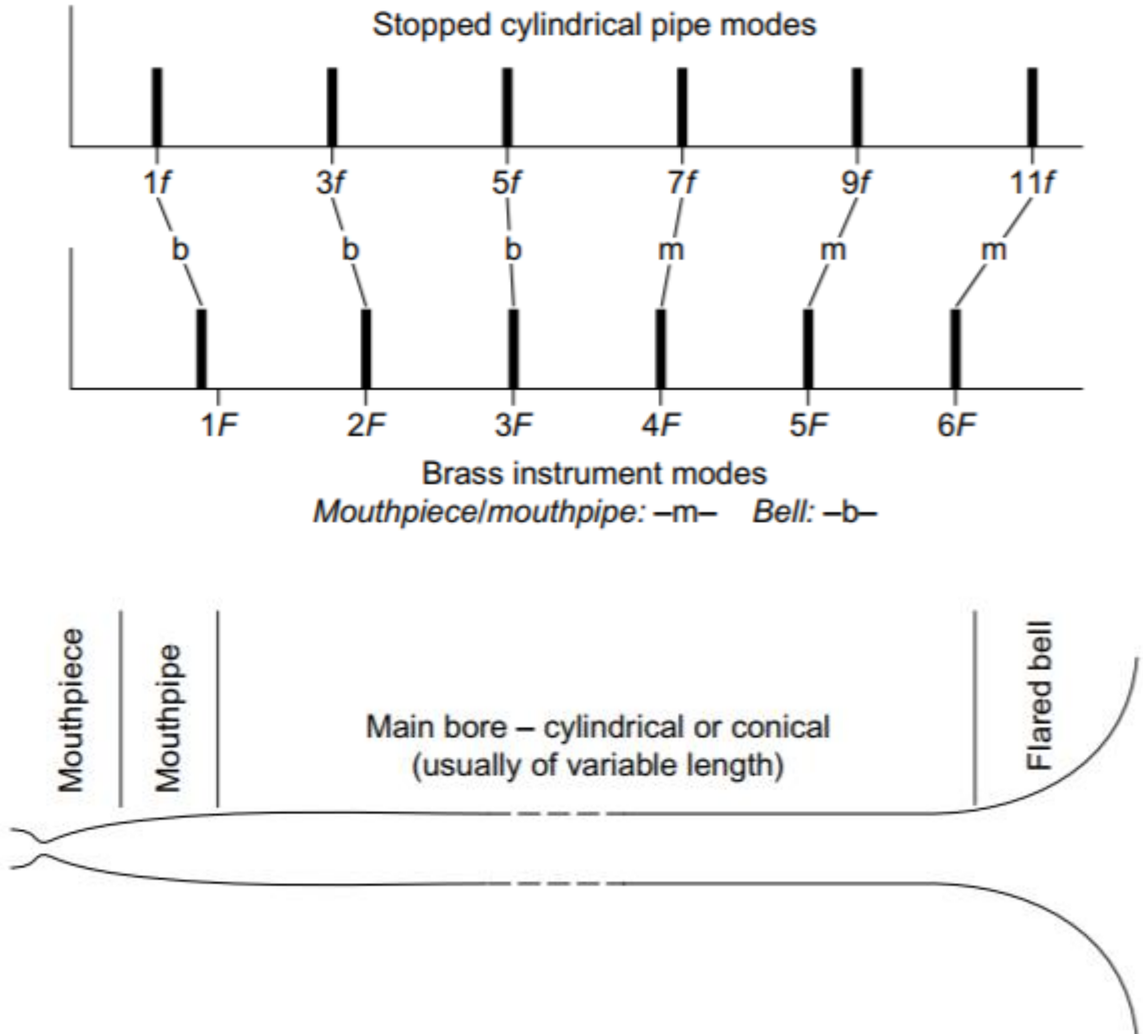
Brass: mouthpiece

- Source
- Bernoulli effect (potential energy + kinetic energy = a constant) in a tube with a constriction (PE: potential energy; KE: kinetic energy.)
- https://www.youtube.com/watch?v=A8JFz04EmvY



Brass: resonance

- Brass instrument mode frequency modification to stopped cylindrical pipe by the addition of mouthpiece/ mouthpipe and bell.



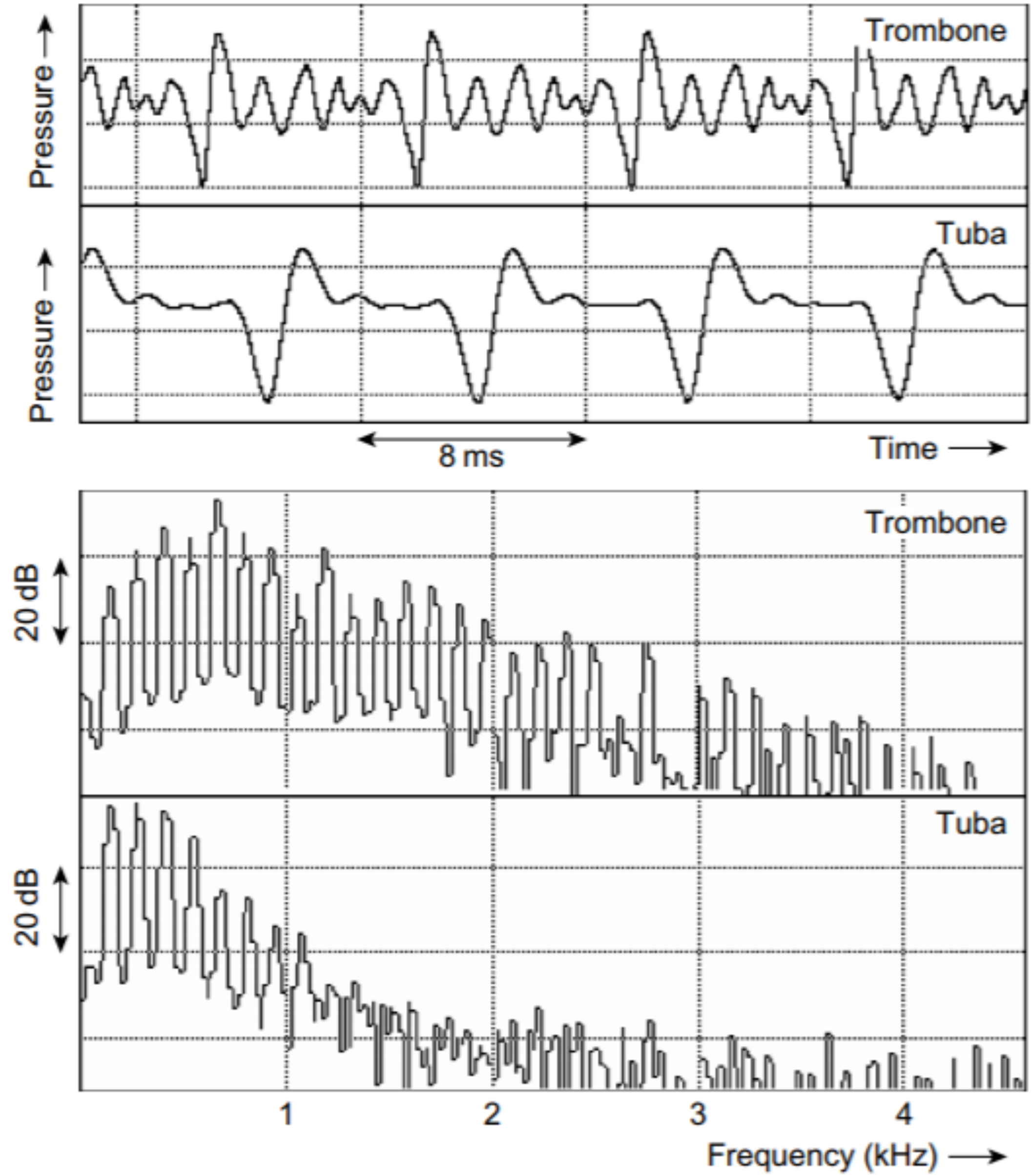
Trumpets

- Natural trumpet: can plays harmonic series only
- Baroque trumpet: holes
- Modern trumpet: valves
- Valve combinations used on a trumpet to enable 6 semitones to be fingered (Black circle: valve depressed; white circle: valve not depressed)

Semitones	–1	–2	–3	–3	–4	–5	–6
1st valve (–2 semitones)	○	●	●	○	○	●	●
2nd valve (–1 semitone)	●	○	●	○	●	○	●
3rd valve (–3 semitones)	○	○	○	●	●	●	●

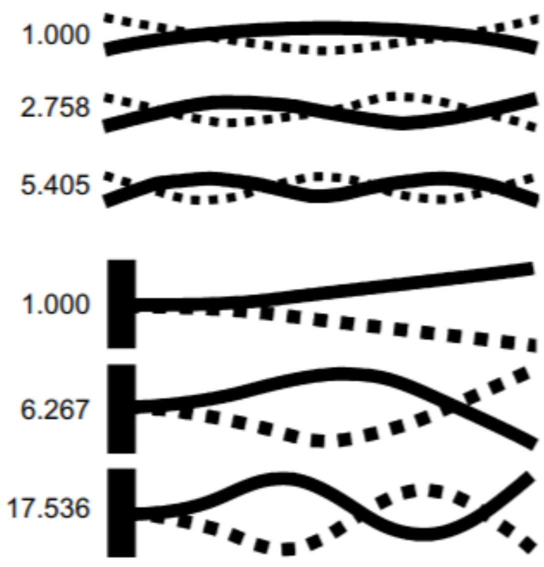
Example

- Waveforms and spectra for C3 played on a trombone and a tuba.



Percussion: bars
敲擊樂

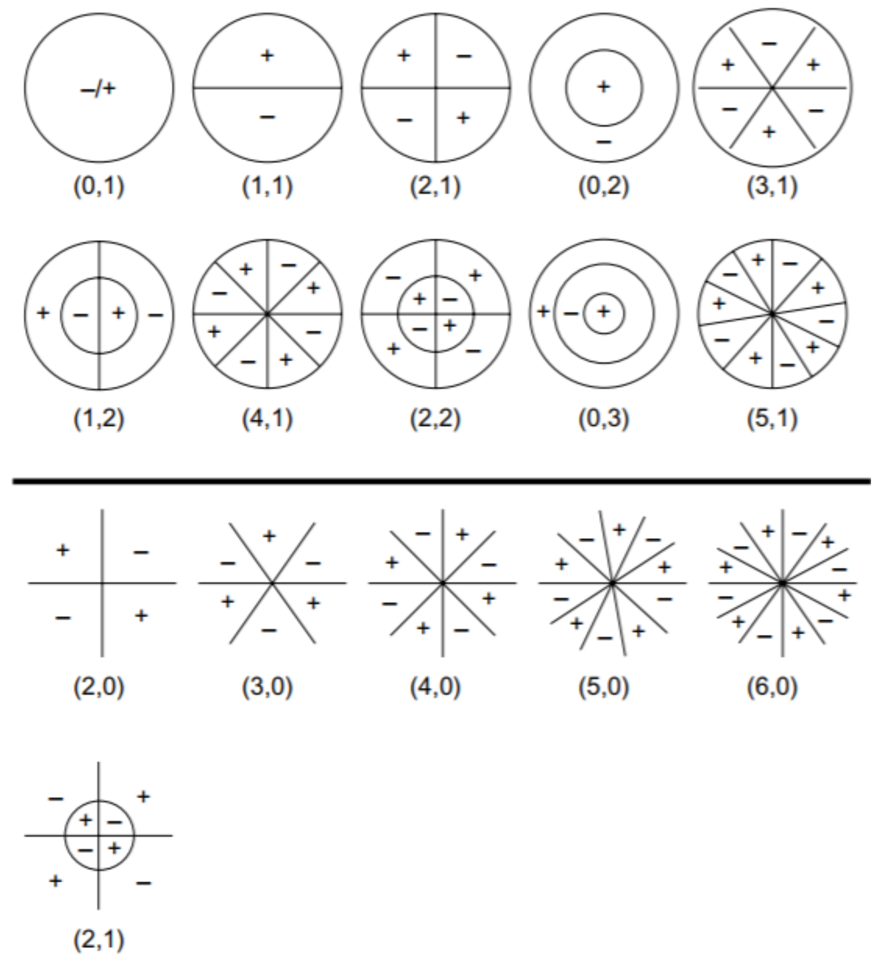
- Xylophone, glockenspiel, triangle, …
- The first three modes of a free bar (upper) and a clamped bar (lower)



Transverse mode of bar	Bar resting on supports		Bar clamped at one end	
	Ratio	Semitones	Ratio	Semitones
1 (rel. 1st mode)	1.000	0.00	1.000	0.00
2 (rel. 1st mode)	2.758	17.56	6.267	31.77
3 (rel. 1st mode)	5.405	29.21	17.536	49.58
4 (rel. 1st mode)	8.934	37.91	34.371	61.23
5 (rel. 1st mode)	13.346	44.86	56.817	69.93

Percussion: plates/membranes

- The first ten modes of a stretched drum membrane (upper) and the first six modes of a plate cymbal (lower). The mode numbers are given in brackets as (number of diametric nodes, number of circular nodes). The plus and minus signs show the relative phasing of the vibration of different parts of the structure within each mode. (Fletcher and Rossing, 1999.)



Vibration modes

- Modes and frequency ratios (from Fletcher and Rossing, 1999) as well as semitone (ST) distances between each of the first 10 theoretical modes relative to the first mode for an ideal circular membrane but without a bowl (left), a circular membrane mounted on a bowl as a timpani (center) and an ideal circular plate (right).

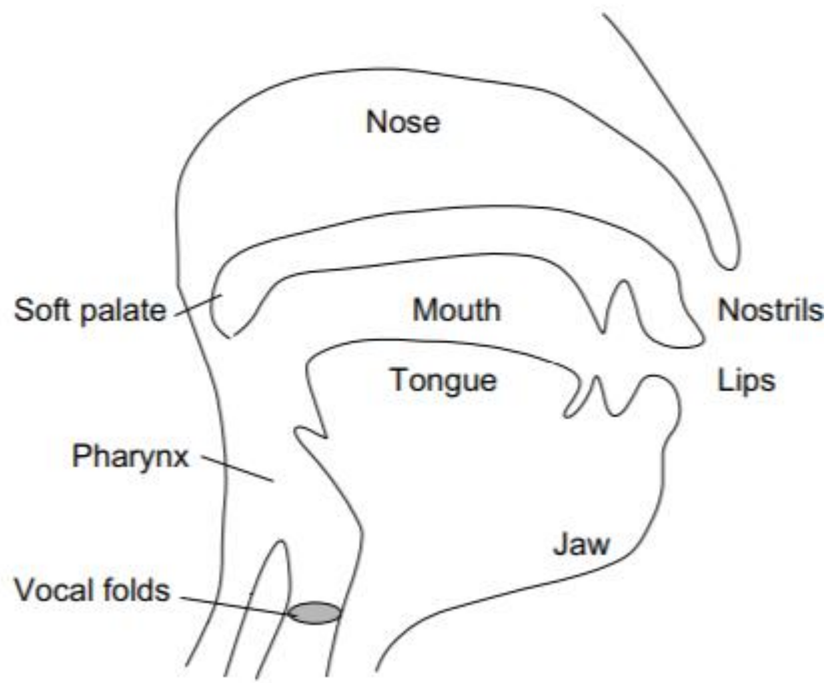
Circular membrane 膜			**Circular plate** 盤	
Mode	**Ideal ratio (ST)**	**Timpani ratio (ST)**	**Mode**	**Cymbal ratio (ST)**
(0,1)	1.000 (0.0)	1.70 (9.19)*	(2,0)	1.00 (0.0)
(1,1)	1.59 (8.1)	2.00 (12.0)	(3,0)	1.94 (11.5)
(2,1)	2.14 (13.1)	3.00 (19.0)	(4,0)	3.42 (21.3)
(0,2)	2.30 (14.4)	3.36 (21.0)*	(5,0)	5.08 (28.1)
(3,1)	2.65 (16.9)	4.00 (24.0)	(6,0)	6.90 (22.4)
(1,2)	2.92 (18.6)	4.18 (24.7)*	(2,1)	8.63 (37.3)
(4,1)	3.16 (19.9)	4.98 (27.8)	–	–
(2,2)	3.50 (21.7)	5.34 (29.0)*	–	–
(0,3)	3.60 (22.2)	5.59 (29.8)*	–	–
(5,1)	3.65 (22.4)	5.96 (30.9)	–	–

Example

- https://www.facebook.com/Mesmerizingsounds/videos/433138706880903/

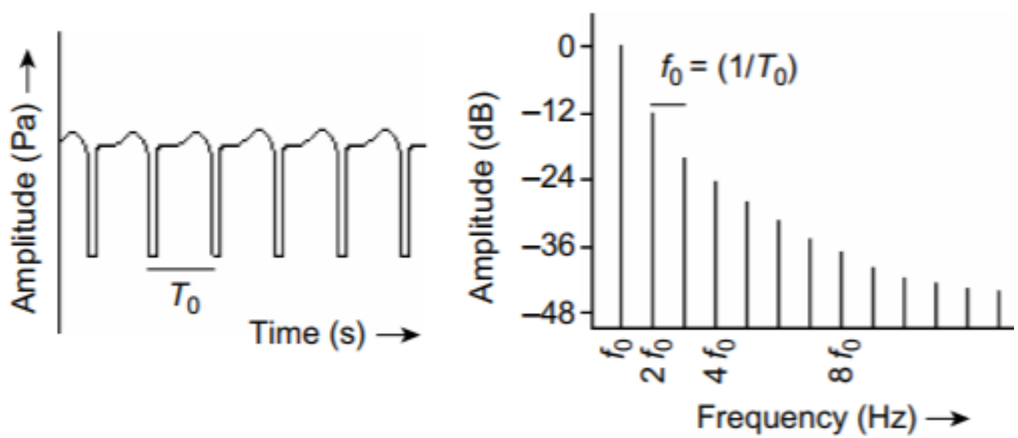
Singing voice

- Cross-section of the vocal tract



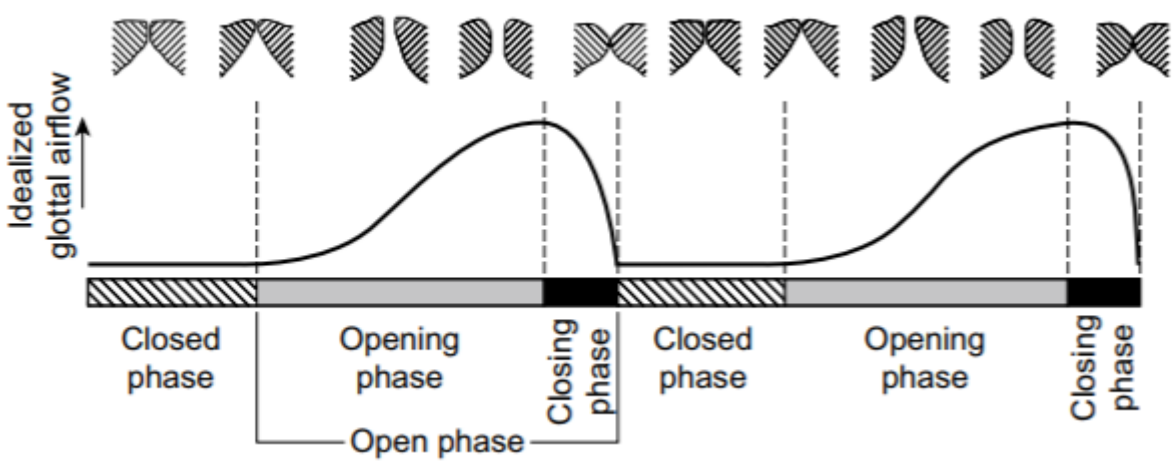
The source of voice: vocal fold

- Idealized waveform (left) and spectrum (right) of acoustic excitation due to normal vocal fold vibration. (Note that T0 indicates the period of the acoustic excitation waveform, and f0 indicates the fundamental frequency.)



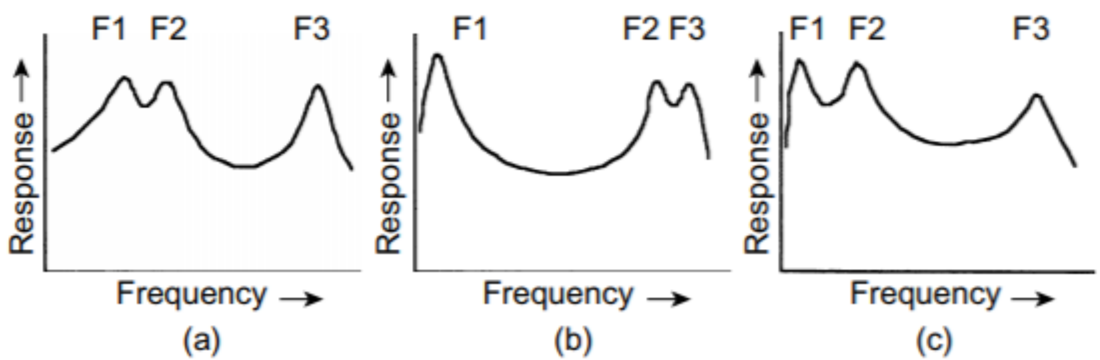
Vocal fold

- Schematic sequence for two vocal fold vibration cycles to illustrate vocal fold vibration sequence as if viewed from the front, and idealized glottal airflow waveform. Vocal fold opening, closing, open and closed phases are indicated



Formants (1)

- Source-filter modeling: assuming pitch and timbre are separable
- Idealized vocal tract response plots for the vowels in the words fast (a), feed (b), and food (c).



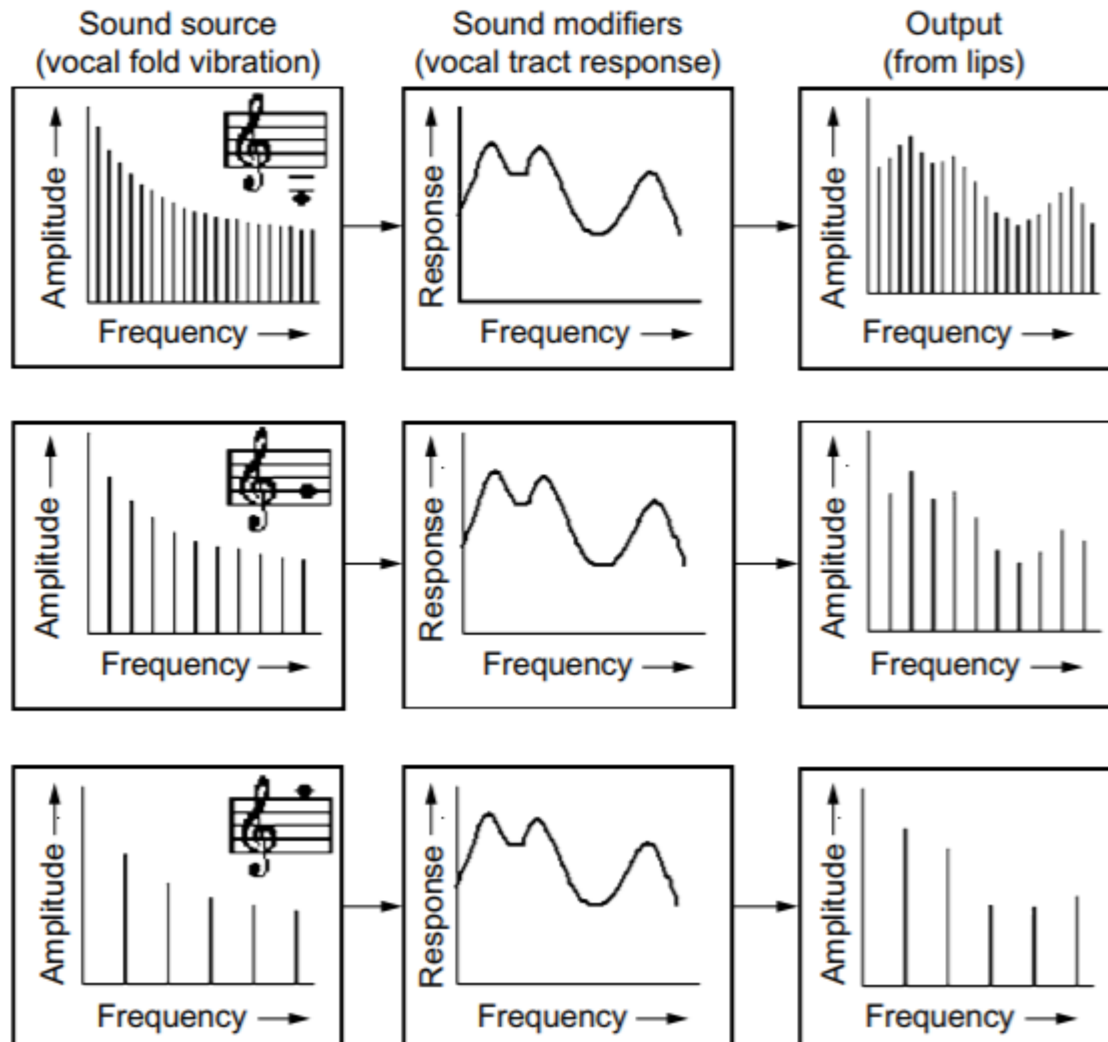
Formant (2)

- Average formant frequencies in Hz for men, women and children for a selection of vowels

Vowel in	Men			Women			Children		
	F1	F2	F3	F1	F2	F3	F1	F2	F3
beat	270	2300	3000	300	2800	3300	370	3200	3700
bit	400	2000	2550	430	2500	3100	530	2750	3600
bet	530	1850	2500	600	2350	3000	700	2600	3550
bat	660	1700	2400	860	2050	2850	1000	2300	3300
part	730	1100	2450	850	1200	2800	1030	1350	3200
pot	570	850	2400	590	900	2700	680	1050	3200
boot	440	1000	2250	470	1150	2700	560	1400	3300
book	300	850	2250	370	950	2650	430	1150	3250
but	640	1200	2400	760	1400	2800	850	1600	3350
pert	490	1350	1700	500	1650	1950	560	1650	2150

Source-filter modeling and vowels

- Singing voice input/system/ output model idealized for the vowel in fast sung on three notes an octave apart



Singing with accompaniment

- Idealized spectra: (a) a singer speaking the text of an opera aria, (b) the orchestra playing the accompaniment to the aria, (c) the aria being sung with orchestral accompaniments (Sundberg, 1987).