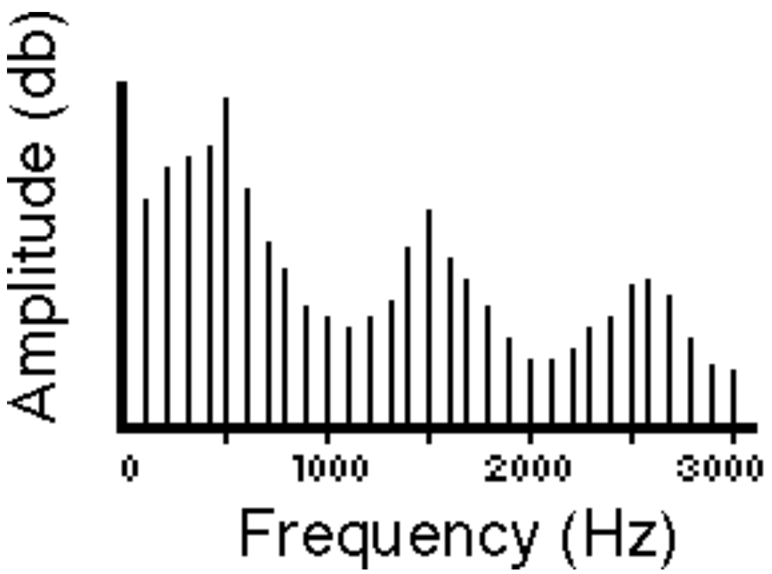
Source-Filter Theory

Speech: dual vibration system

- Larynx (source)
  - Folds vibrate in an infinite number of modes like strings
  - produces oscillations of air pressure.
  - Modes are the harmonics of the voiced source.
- Supralaryngeal tube (filter)
  - Air molecules in tube are set into vibration by air pressure fluctuations caused by larynx.
  - Air in the tube functions as another mass-spring system. Molecules vibrate in an infinite number of modes, which are the formants.
  - What determines mode frequencies?

Spectrum of a Vowel Sound (ə)

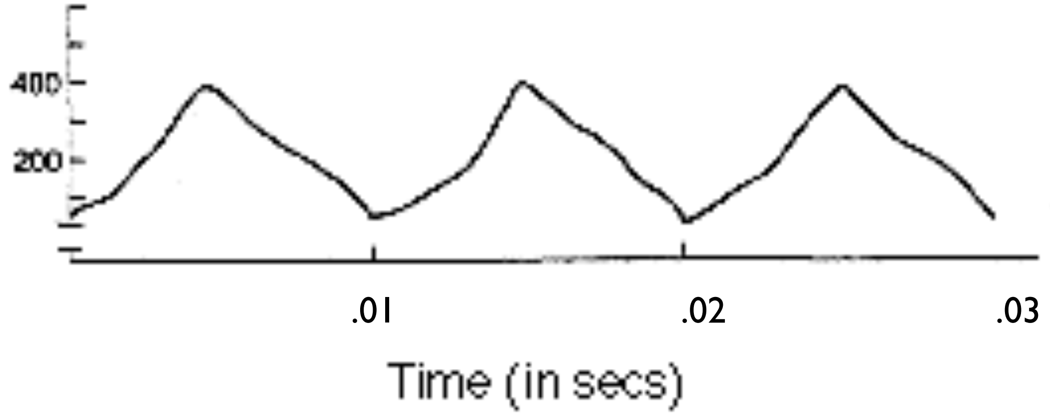
- Many harmonics
- Integer multiples of fundamental frequency (f0) = 100 Hz in this case
- The fundamental frequency, corresponds to rate of vibration of the larynx, that is, the number of opening-closing cycles of the larynx per second.
- So the frequencies of all the harmonics are determined by the rate of vibration of larynx, which we perceive as the pitch of the voice.
- Where do all the harmonics come from??



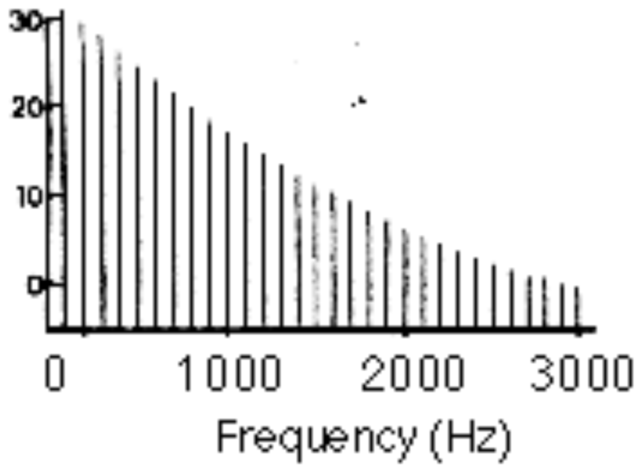
Sound Source

- sentence from siSwat'i (Southern Bantu language; Swaziland)
- electroglottograph (EGG) signal recorded from subject's larynx while sentence is being produced. (This is what it would sound like if the larynx did not have a neck and head attached to it).

Glottal Airflow



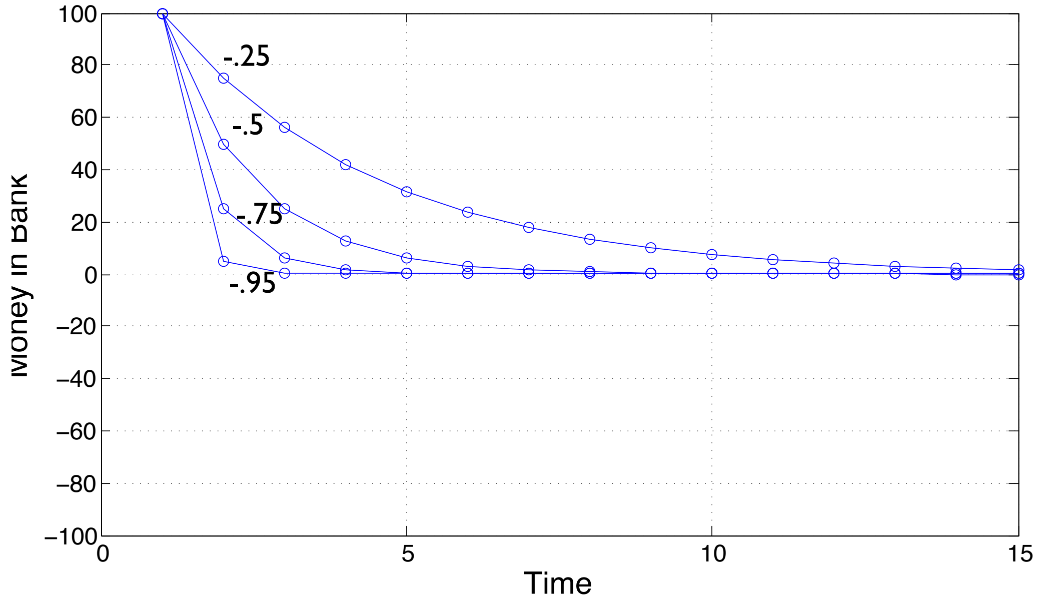
Source Spectrum



- Modulation in period of glottal wave carries intonation (pitch).
- Why is does the source spectrum look like that?

Components of (physical) dynamical systems: springs

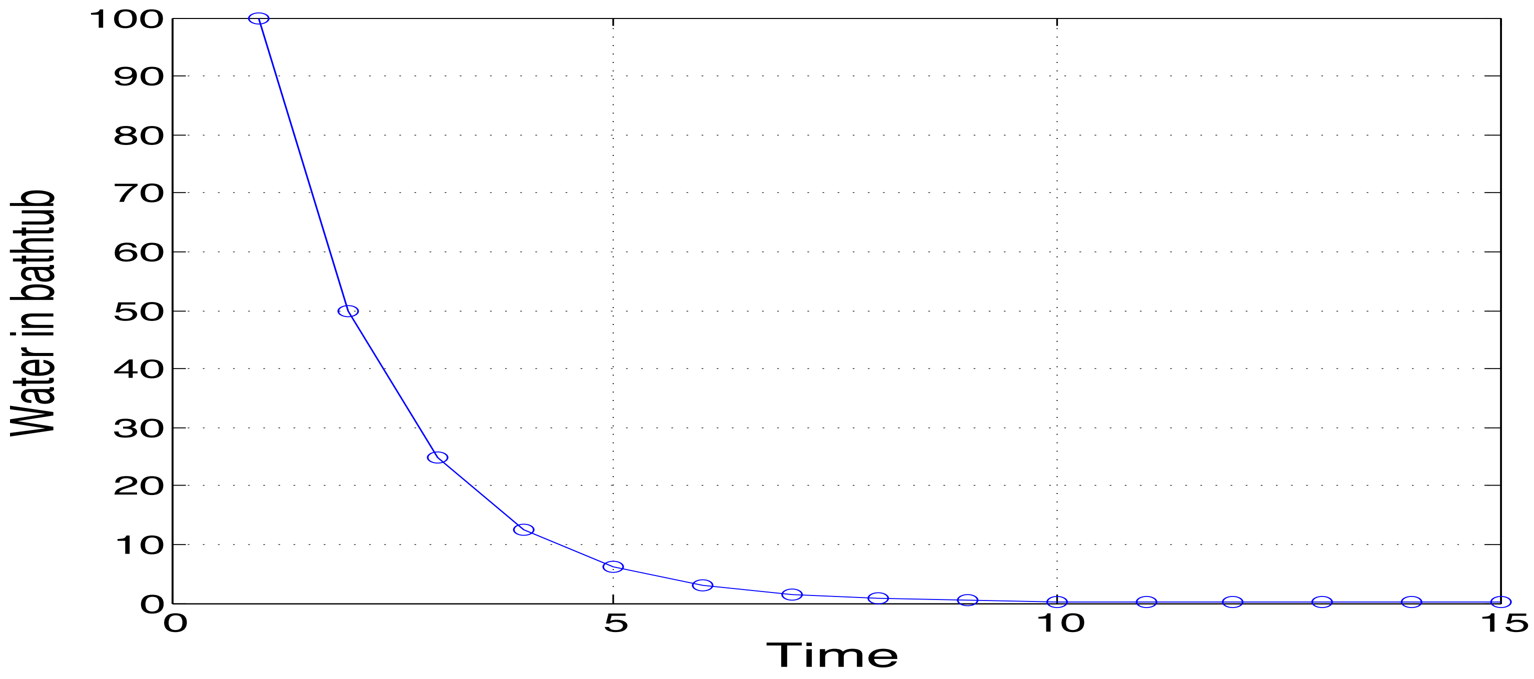
- Displace a spring from its resting position (stretch or compress) and it returns smoothly.
- *Stiffness* of spring determines how quickly it returns: slinky vs. your skin.
- Rule for change: Change in x $= -kx$
- k is related to the stiffness of the spring.



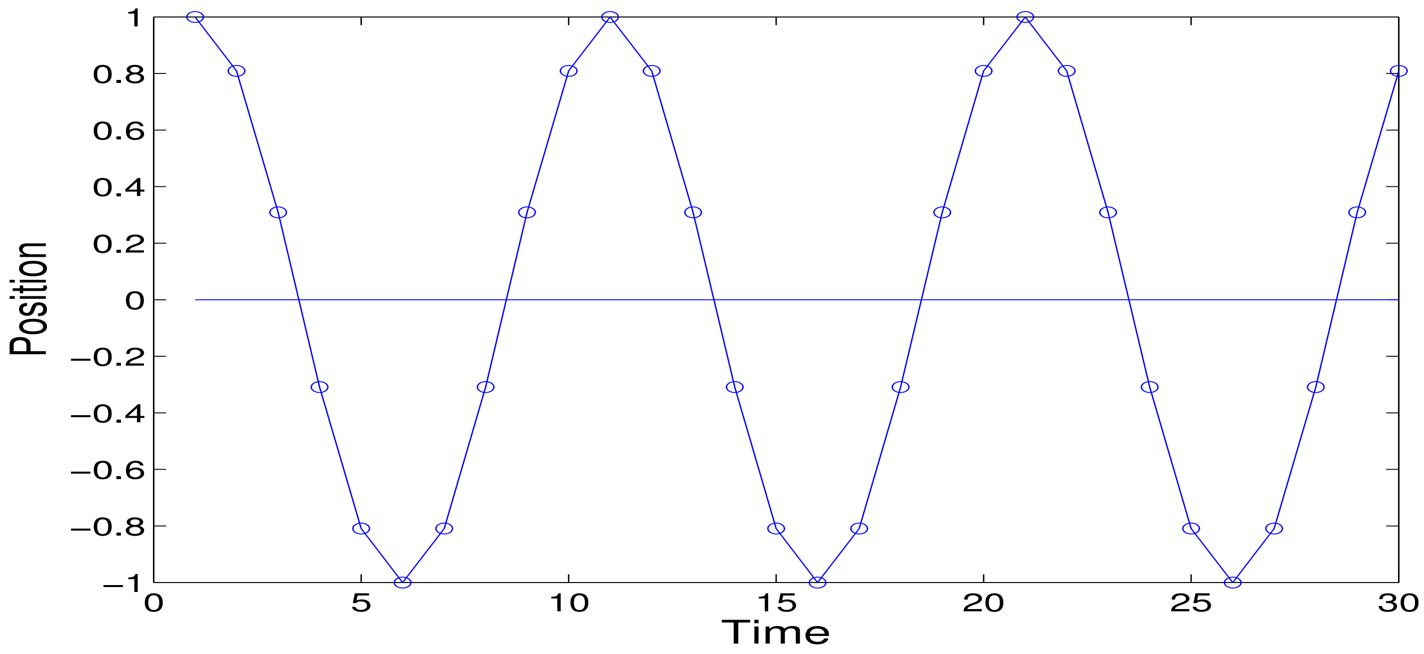
Components of (physical) dynamical systems: masses

- A mass (e.g. a book) doesnt behave like a spring
- Change its position and it stays there.
- Set it into motion and it keeps moving.
- It is characterized by a different dynamical system.
- What happens if you combine a mass and a spring?
- Pull the object at the end of the spring, and it will return to its rest position, but because the mass is in motion, it wants to stay in motion. (That is what masses do).
- Motion causes spring to compress, then the spring wants to return to its rest position again
- Result is oscillation around rest position.

Spring vs. Mass+Spring



Spring: Change in x $= -\frac{1}{2}x$

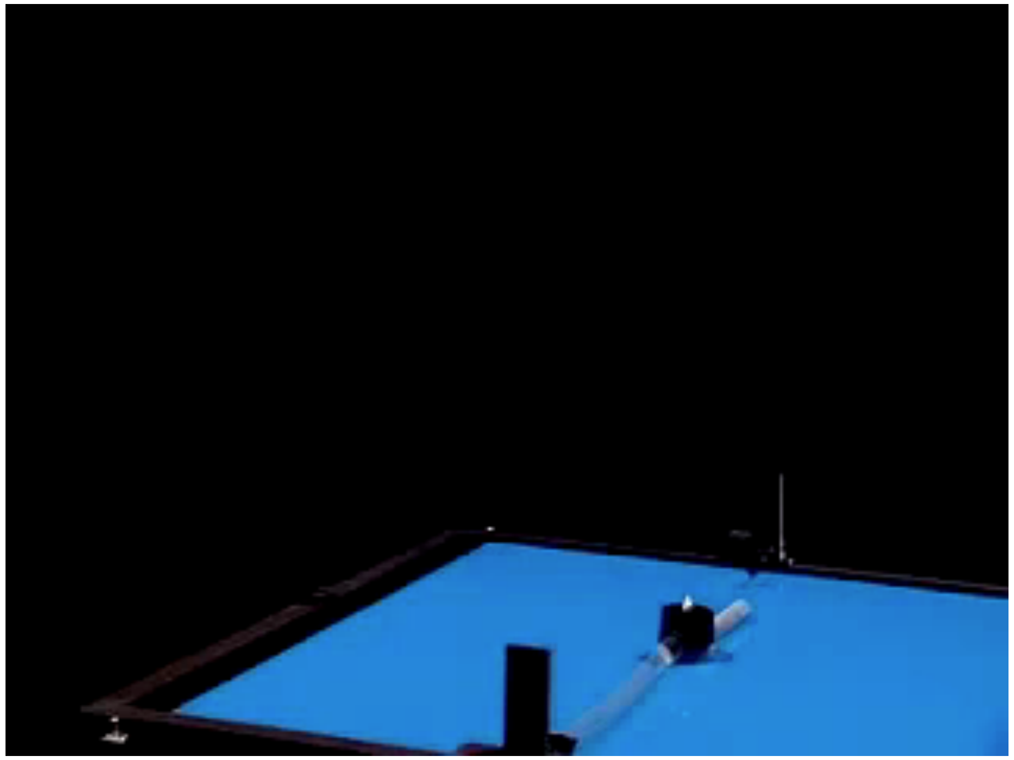


Mass+Spring

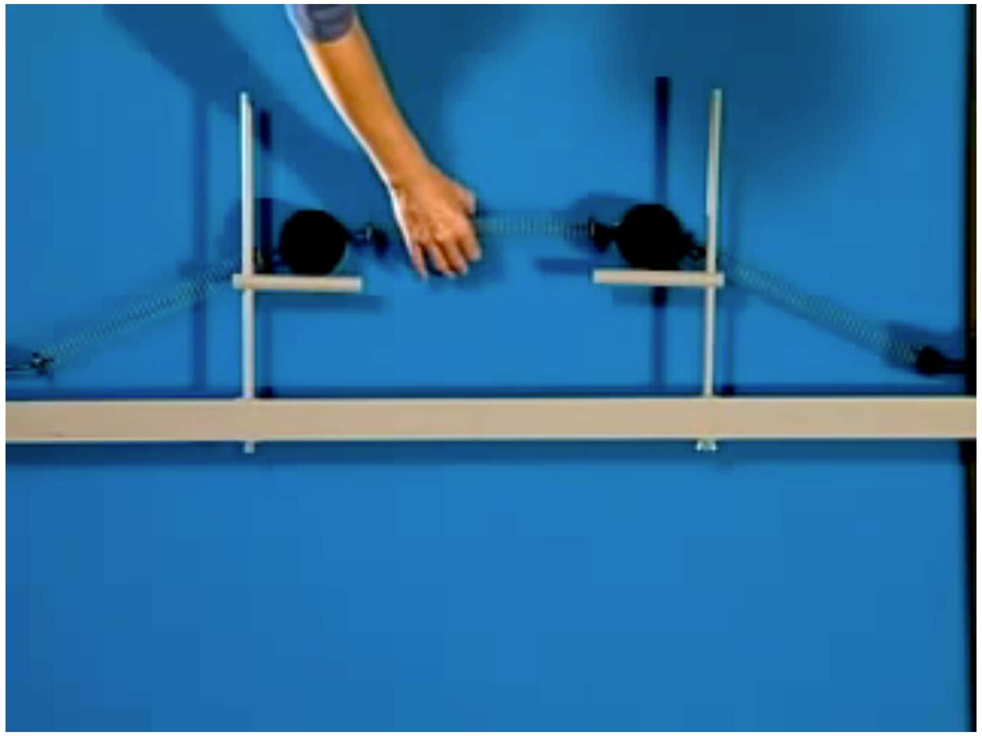
Changing Mass and Stiffness

- What is the effect of changing spring stiffness on frequency? Why?
- What is the effect of changing mass on frequency? Why?
- Demonstration:
  https://www.walter-fendt.de/html5/phen/springpendulum_en.htm

Modes of vibration: masses & springs



1 mass
1 mode



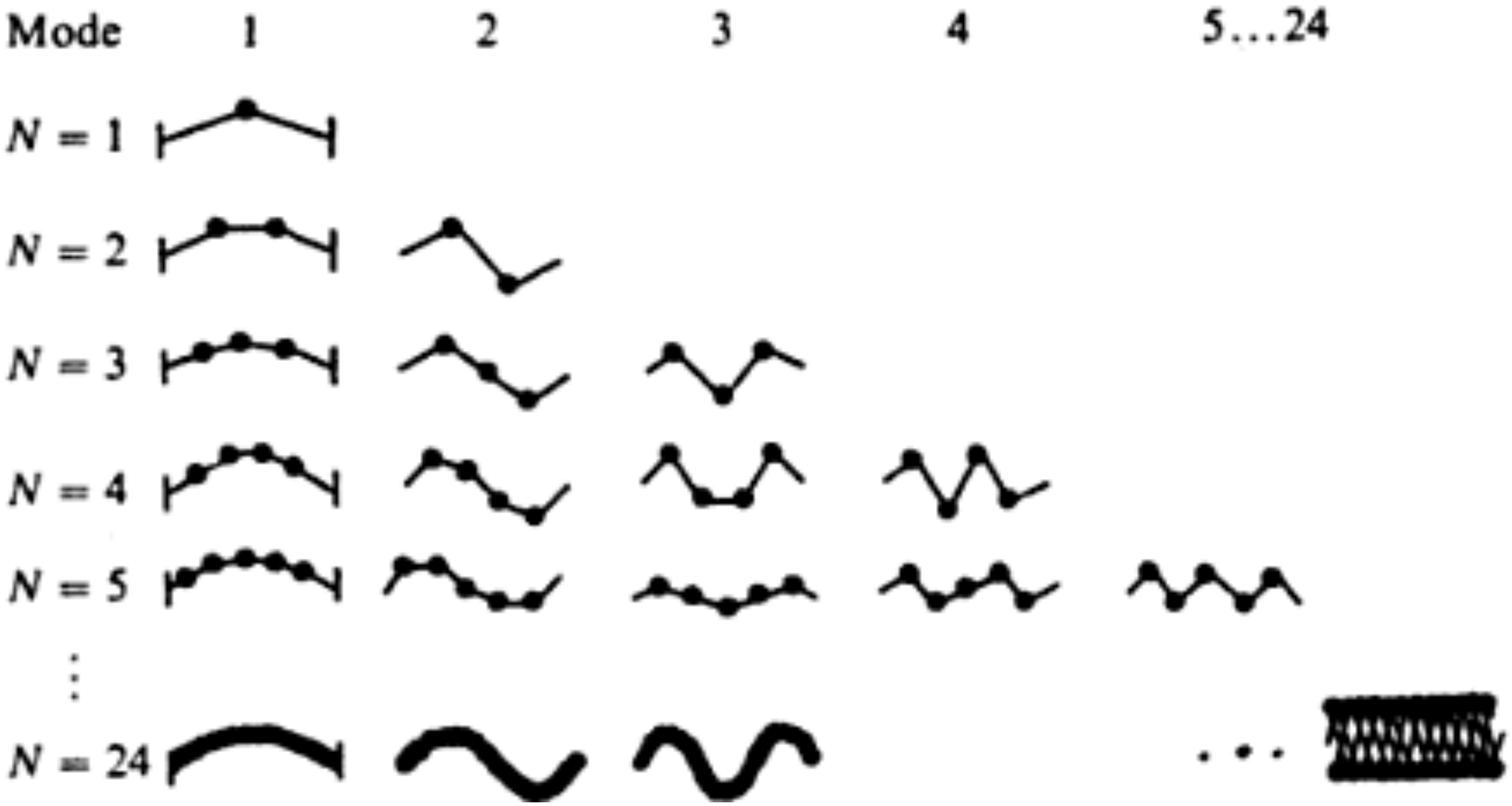
2 masses
2 modes

Why does the "anti-phase" mode have a higher frequency?

Modes

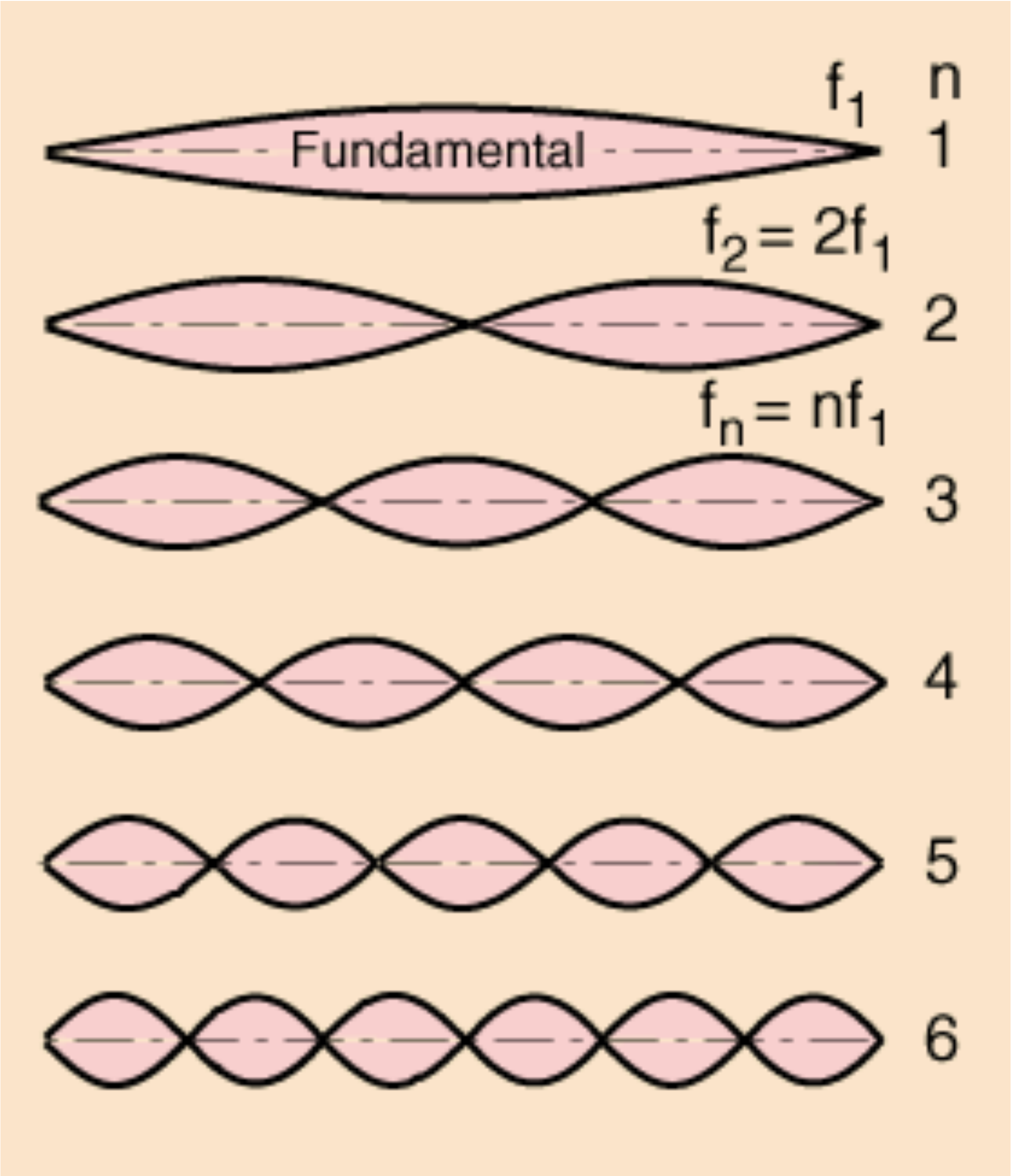
<u>Crucial Ideas:</u>

- There are as many modes as there are masses.
- In the lower modes, the system is behaving as if it has fewer masses than it actually has.
- A string can be divided into an infinite number of masses, so can oscillate at an infinite number of frequencies



Larynx as Vibrating string

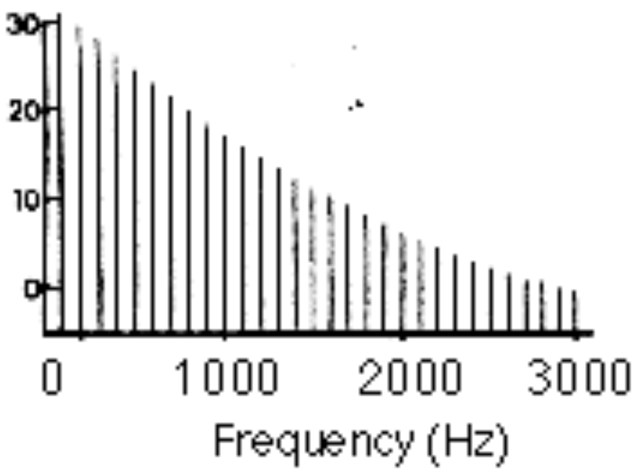
- A string attached at two ends can be thought of as composed of an an infinite number of masses connected by springs.
- Infinite number of modes.
- Each higher mode has a frequency that is an integer multiple of the lowest mode.
- Larynx is like a vibrating string (or pair of strings).



Modes of string vibrations

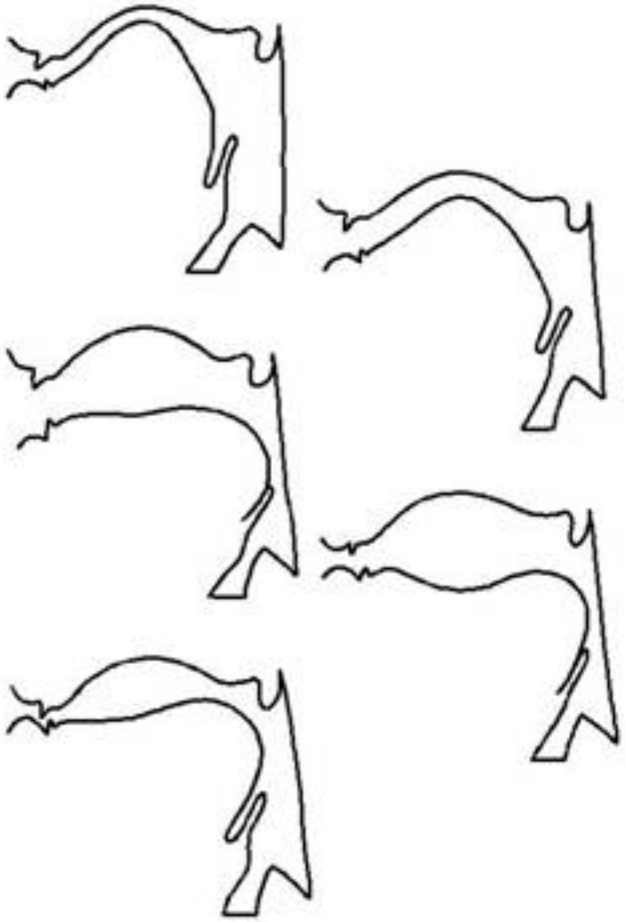
Modes of string vibrations

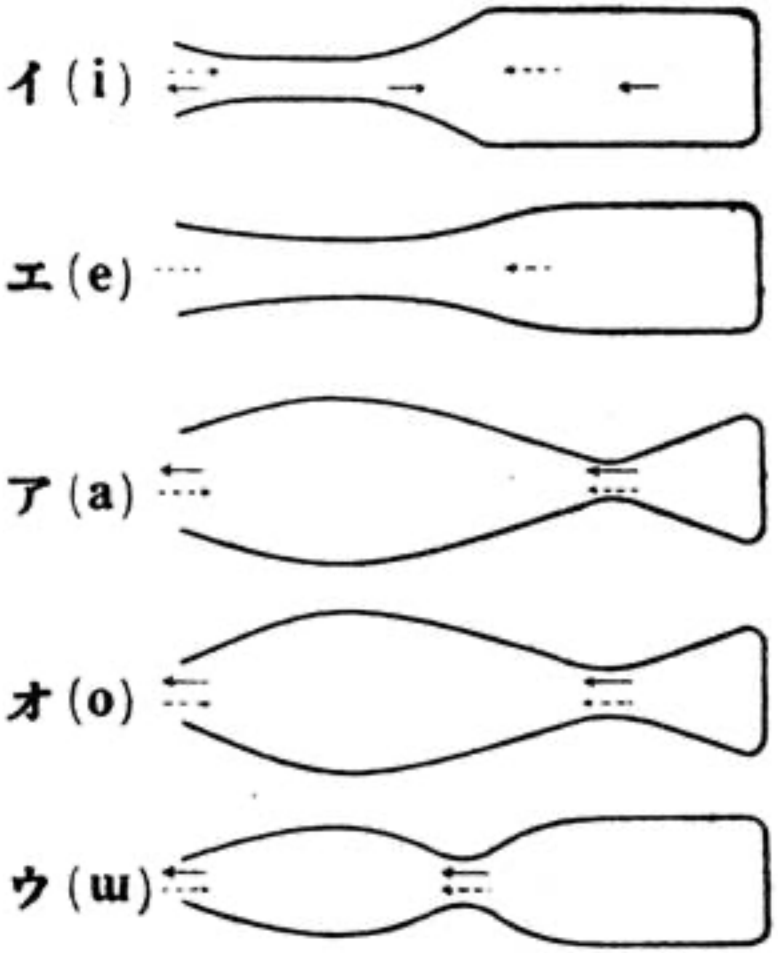
- In this example, string is set into motion by driving it at the mode frequencies, one at time.
- If we were to pluck the string, it would actually vibrate at all of the modes at the same time.
- Note that the higher the mode, the lower the amplitude (why?)
- Passing air through the larynx is like plucking a string. It vibrates at all modes at once.
- Note amplitudes of laryngeal modes (=harmonics) !


Source Spectrum

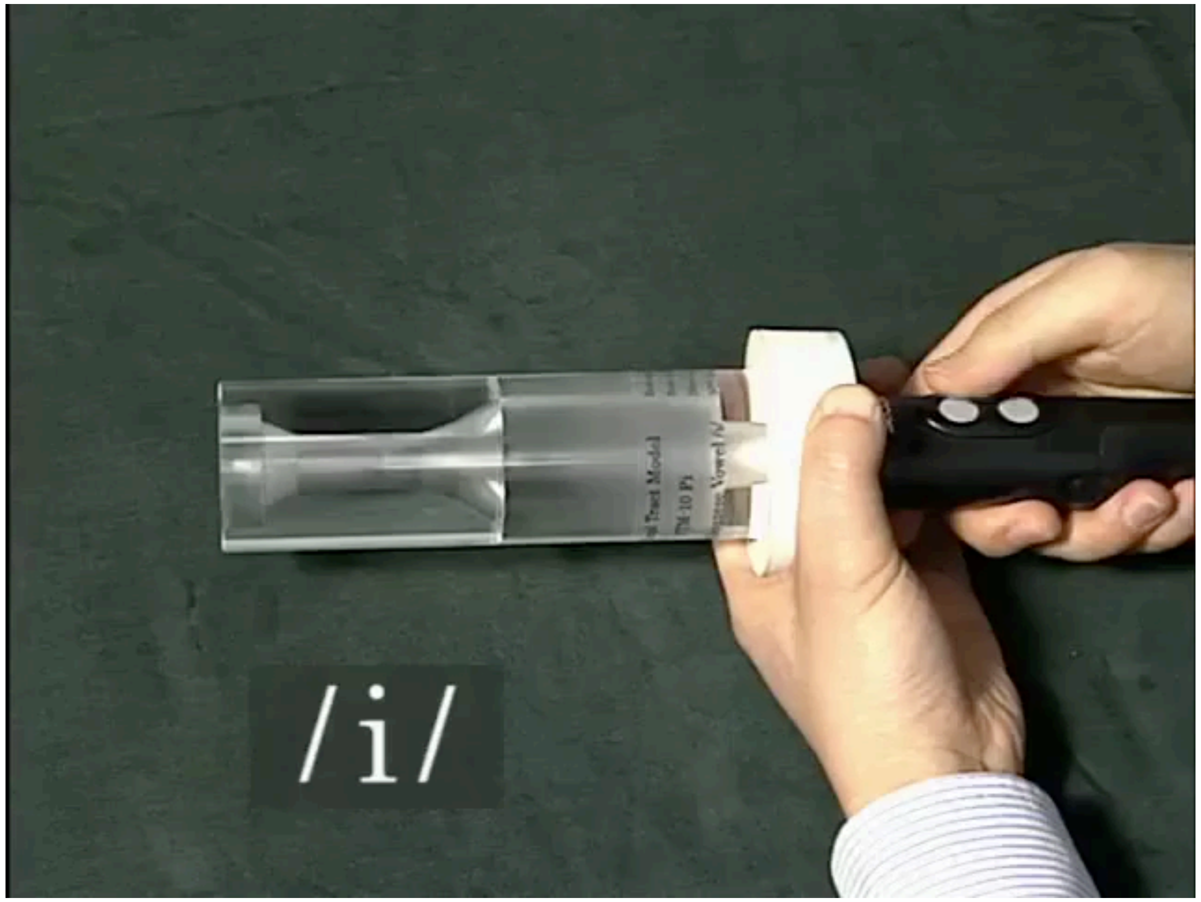
Speech: dual vibration system

- Larynx (source)
- Supralaryngeal tube (filter)
  - Air molecules in tube are set into vibration by air pressure fluctuations caused by larynx.
  - Air in the tube functions as another mass-spring system. Molecules vibrate in an infinite number of modes, which are the formants.
  - Constrictions (produced by gestures of lips, tongue tip, tongue body, and velic systems) act to change the mode frequencies.
  - Thus, the gestures leave their "signatures" in the sound that escapes the mouth.
  - Purely mechanical models can produce sounds like those produced by a human vocal tract.





Arai Laboratory



Wave Propagation

- Wave motion: Disturbance of particles in an elastic medium from equilibrium position (x_0) can propagate through to particles that are coupled to the site of the disturbance, and then to particles that are coupled to those... etc..

- Transverse Waves:

  Particle motion is at right angles to direction of wave propagation.

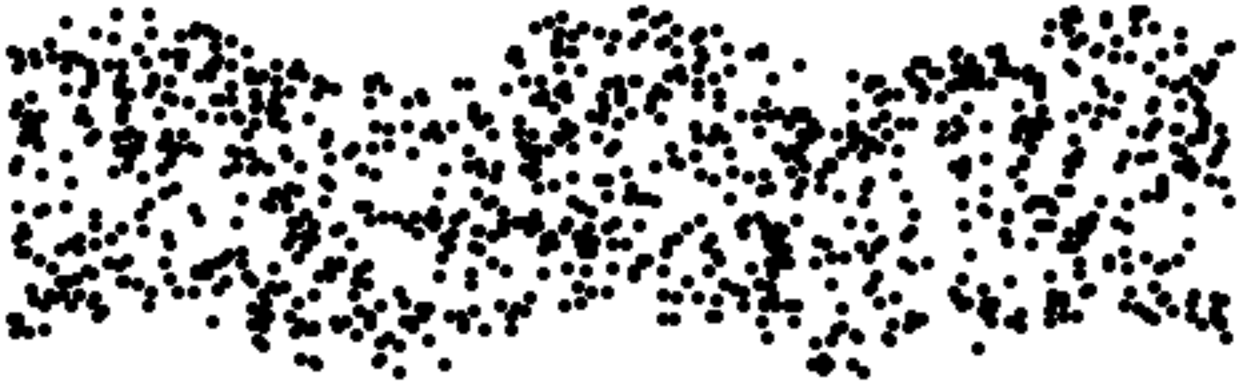
- Longitudinal Waves:

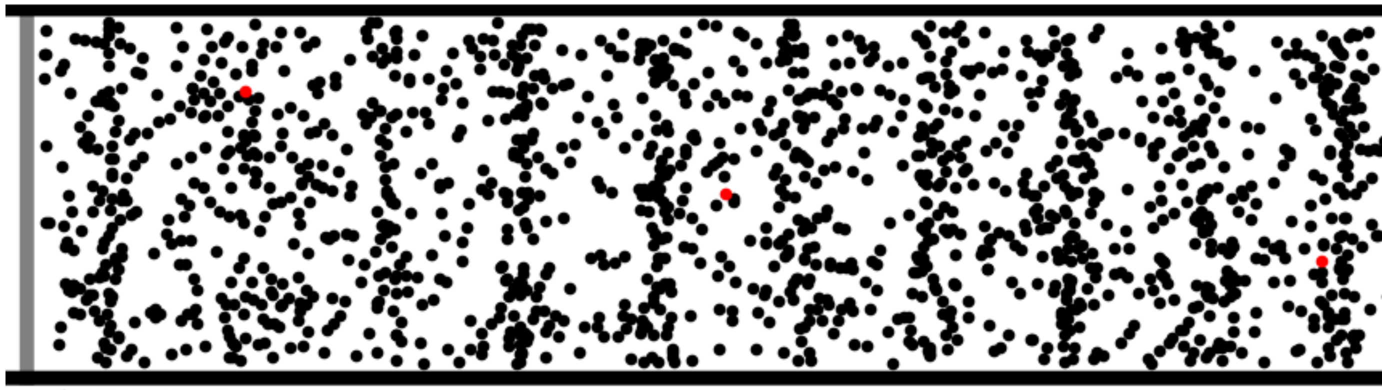
  Particle motion is along the axis of wave propagation.

Animations courtesy of Dr. Dan Russell, Kettering University

https://www.acs.psu.edu/drussell/Demos/waves/wavemotion.html

Particles oscillate over only short distances, but pattern of motion propagates over long distance





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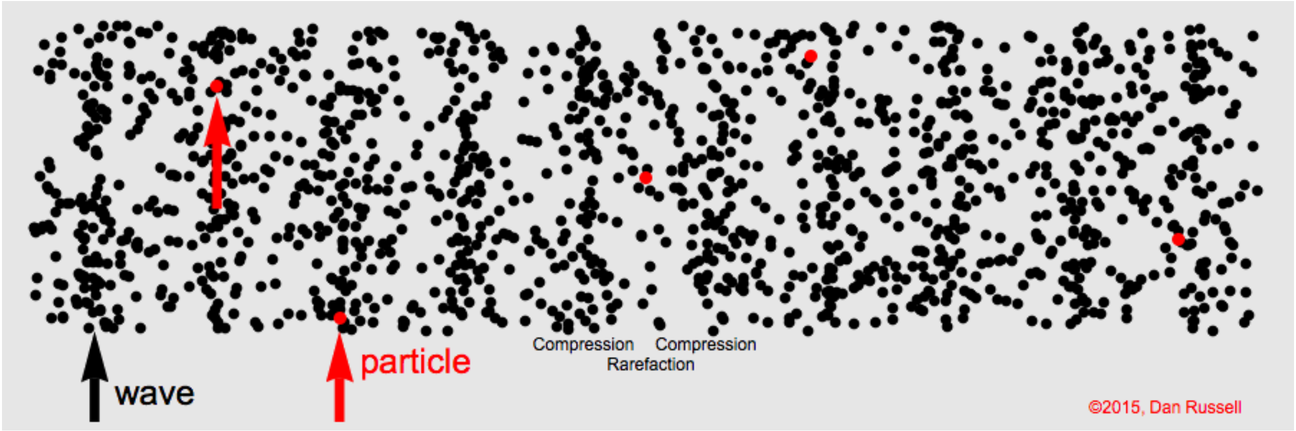
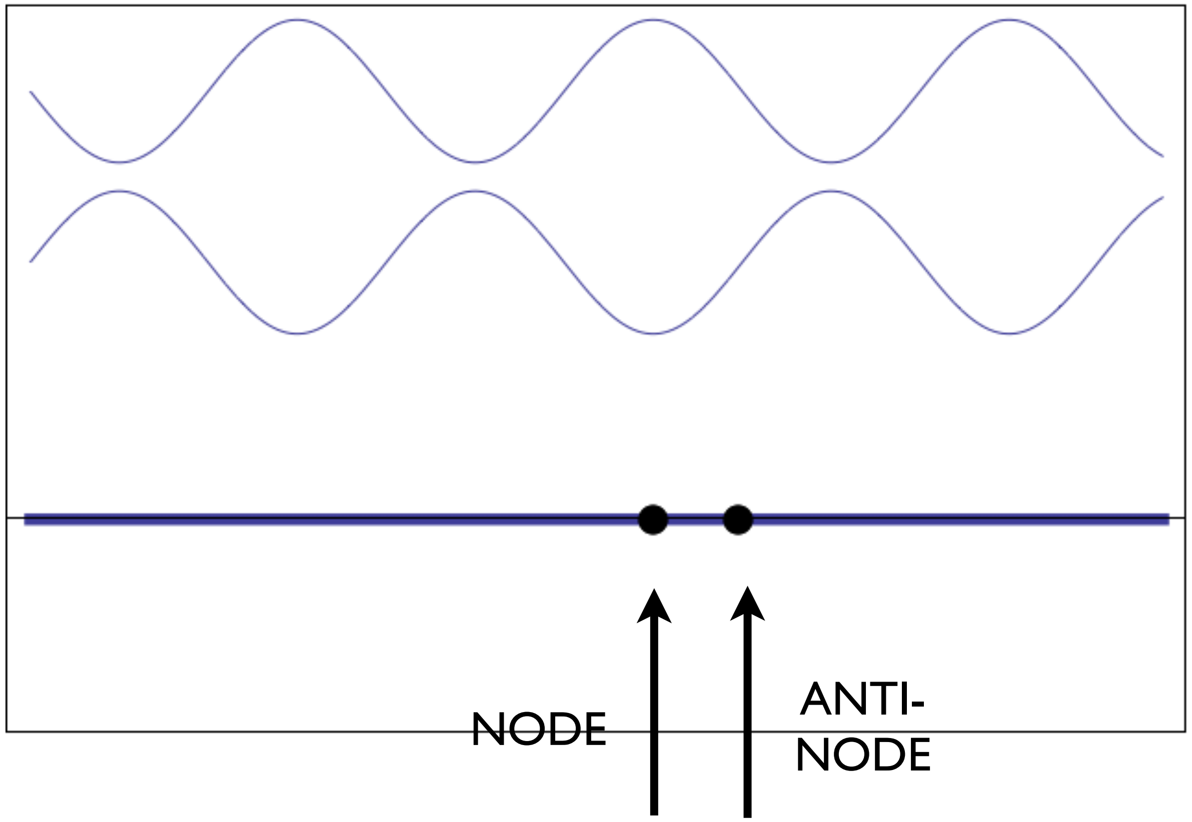


Superposition of waves

Waves traveling in opposite directions superpose when they coincide, then continue traveling.

Oscillations of the same frequency, and same amplitude form standing waves when they superpose.

- Don’t travel, only change in amplitude over time.
- Nodes: no change in position.
- Anti-nodes: maximal change in position.

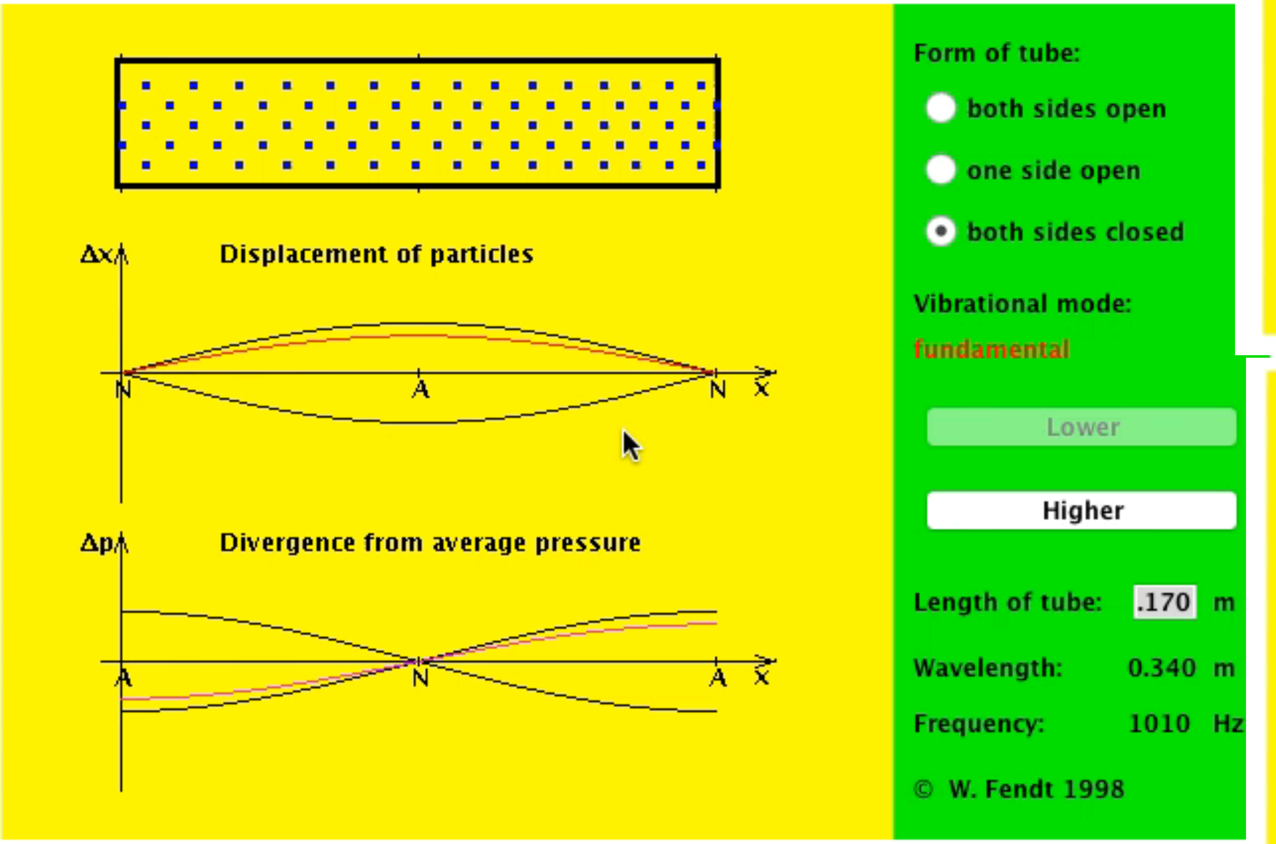


Animation courtesy of Dr. Dan Russell, Kettering University
https://www.acs.psu.edu/drussell/Demos/superposition/superposition.html

Standing waves of air in tubes

- Tube closed at both ends (like string secured at both ends)

- Standing wave is produced because the wave is reflected from off the ends



Form of tube:
○ both sides open
○ one side open
● both sides closed

Vibrational mode: fundamental

Length of tube: .170 m
Wavelength: 0.340 m
Frequency: 1010 Hz

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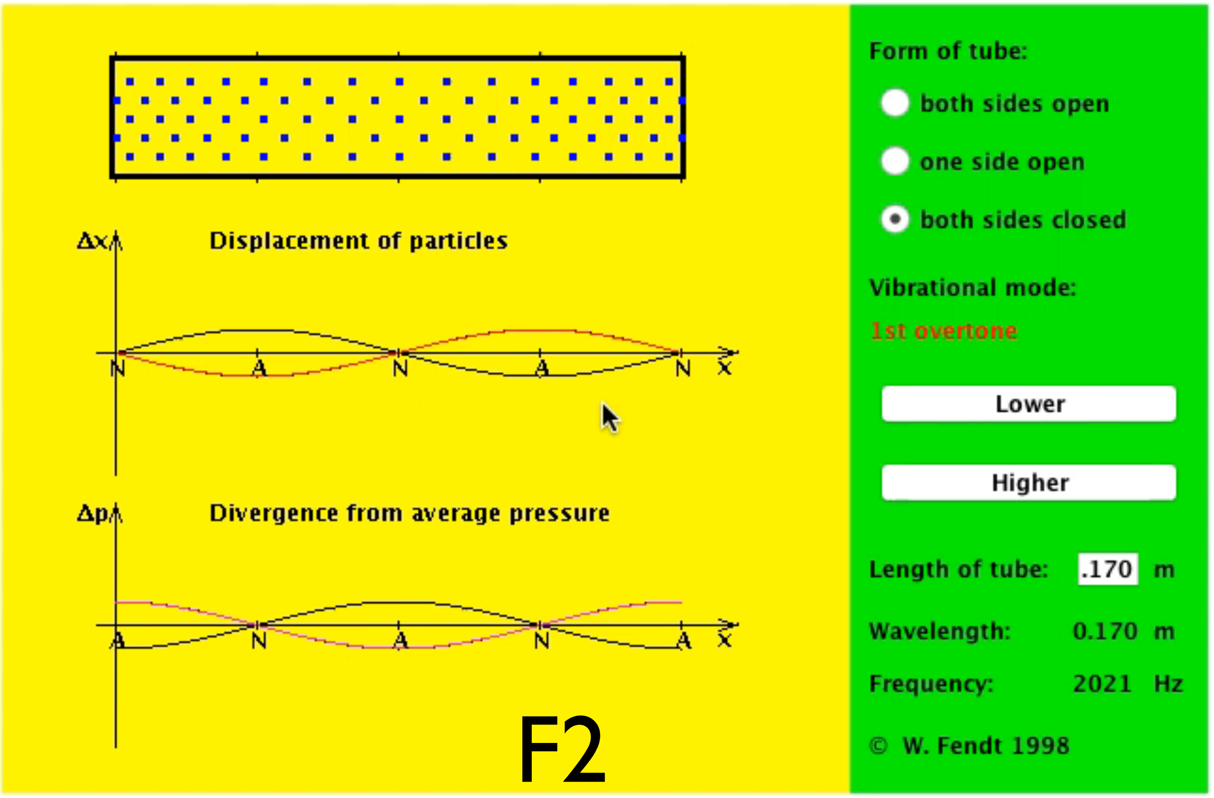
Lowest mode = F1

Modes will occur only at certain frequencies, which are determined by length of tube (L) and speed of propagation of air motion (C).



Form of tube:
○ both sides open
○ one side open
● both sides closed

Vibrational mode: 1st overtone

Length of tube: .170 m
Wavelength: 0.170 m
Frequency: 2021 Hz

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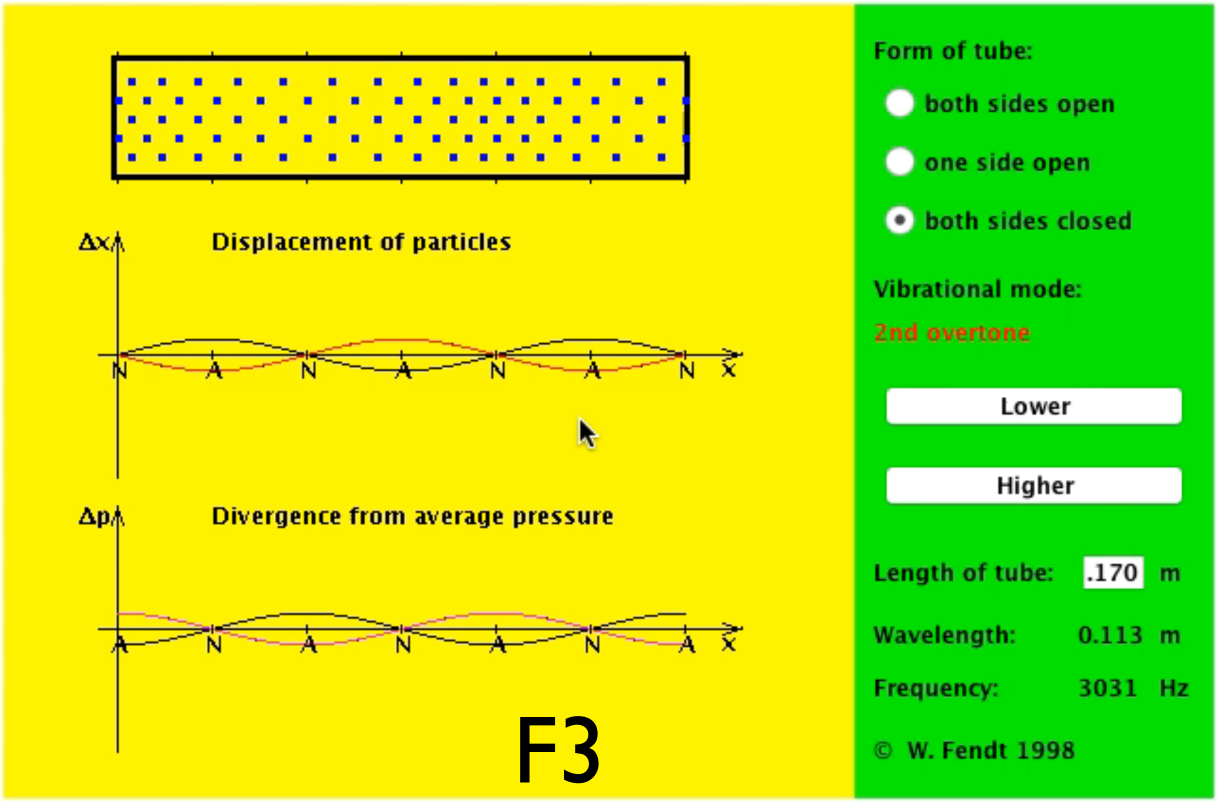
F2



Form of tube:
○ both sides open
○ one side open
● both sides closed

Vibrational mode: 2nd overtone

Length of tube: .170 m
Wavelength: 0.113 m
Frequency: 3031 Hz

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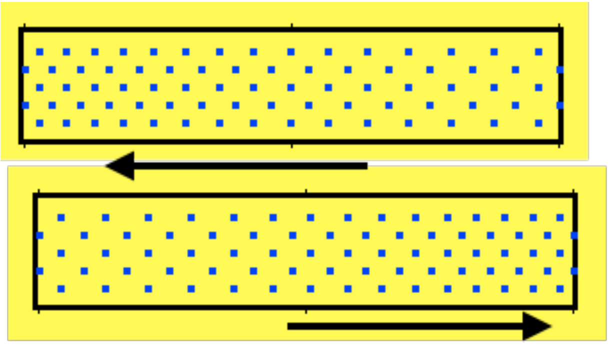
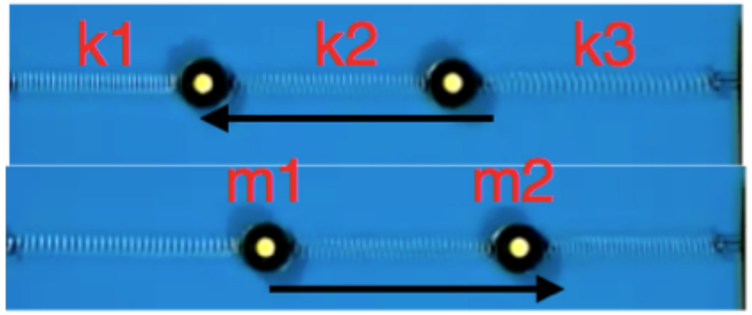
F3

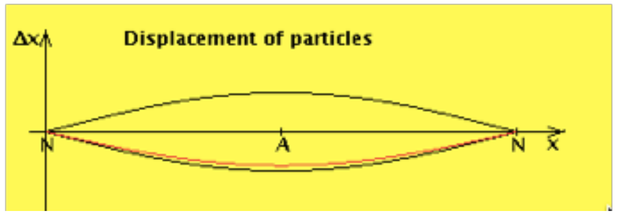
Demo: https://www.walter-fendt.de/html5/phen/standinglongitudinalwaves_en.htm

Modes of vibration of air in tubes

- Air vibrating in a tube is like many masses connected by springs.
- For visualization, first consider a tube that is closed at both ends. There will be modes of vibration like those of a string attached at both ends
- In the lowest mode, all the molecules move together (in the same direction), like our one-mass demo, and like lowest mode of the string.
- Like string, the masses near the middle moves most, the masses at the ends move less.

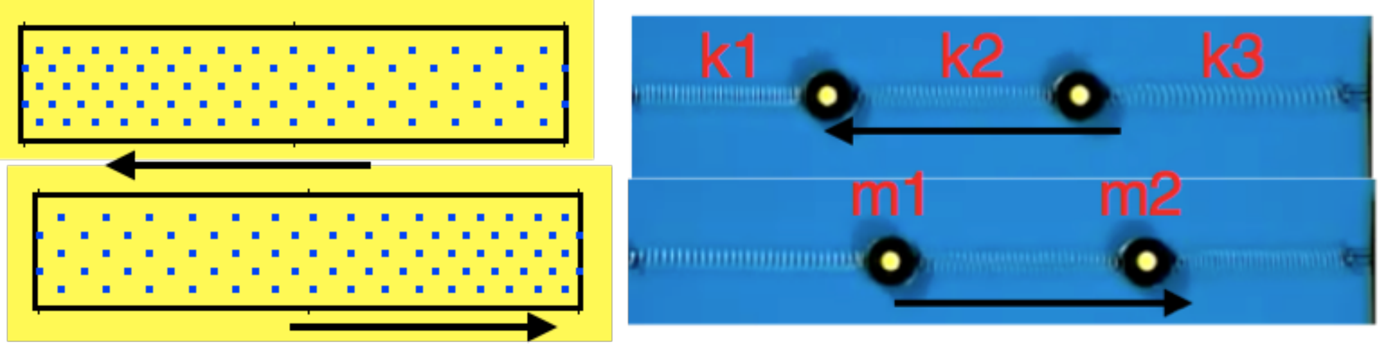


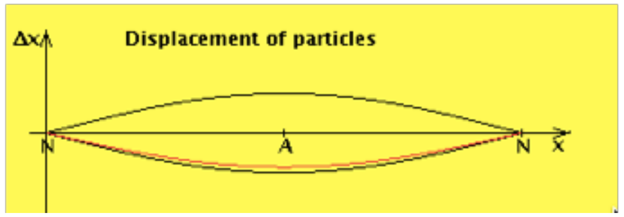




Lowest Mode

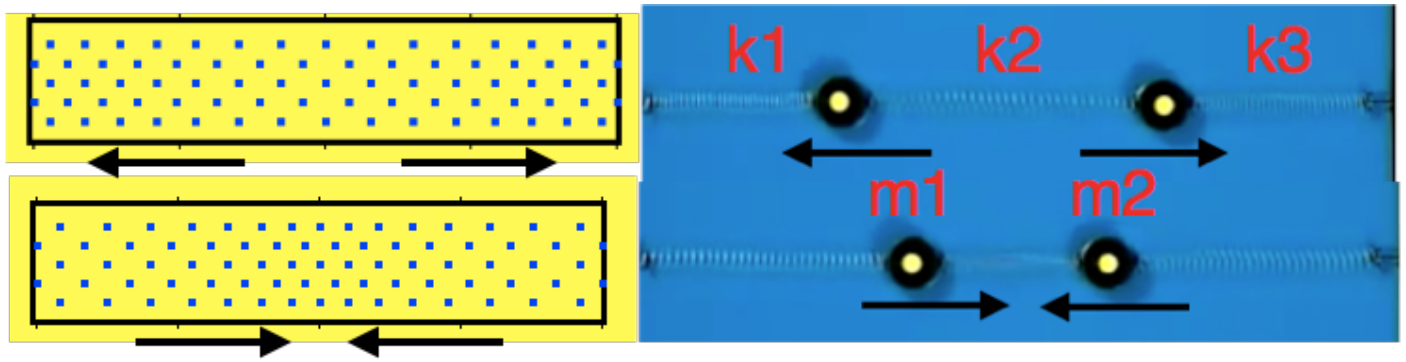
Lowest two modes of air vibration

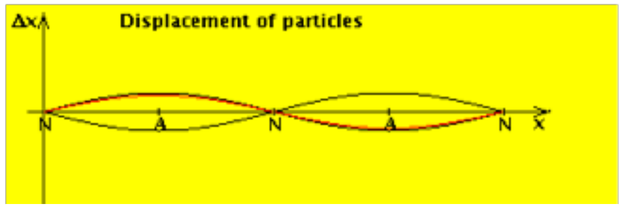




Lowest Mode

Like lowest 2 modes
of two-mass system

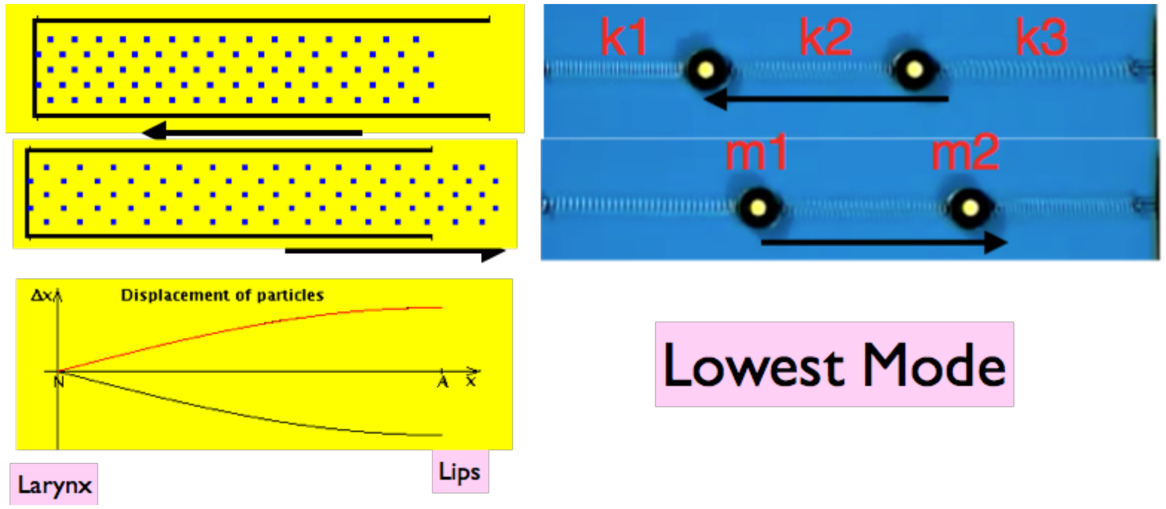




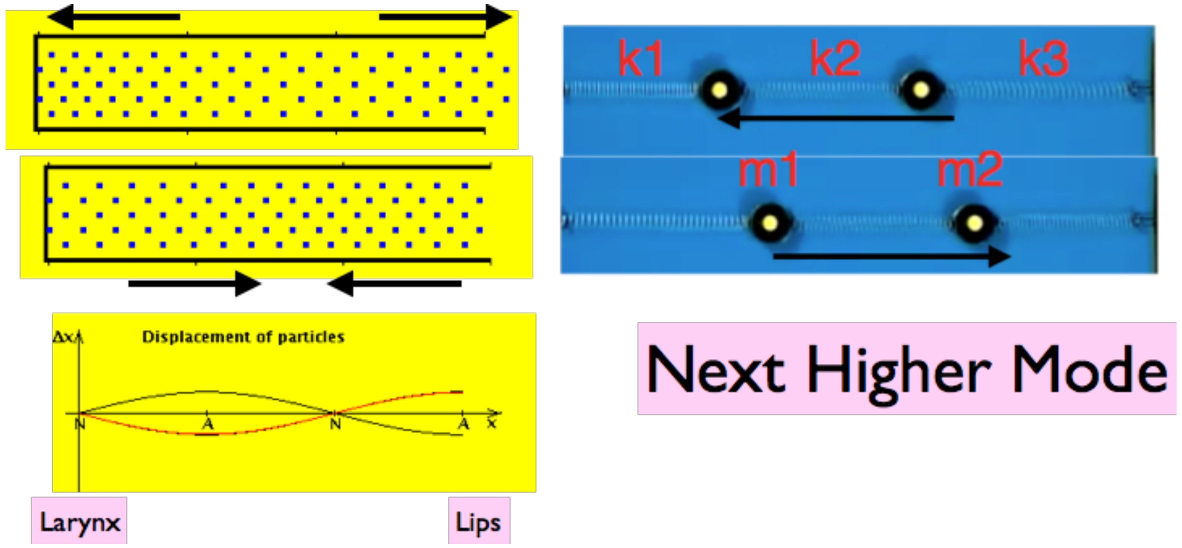
Next Higher Mode

Open Tubes

- The vocal tract is actually like a tube filled with air that is closed at one end (larynx) open at the other end (lips).
- It is like a string attached only at one end.
- Here are lowest two modes modes of air in vibration in tube with one end closed and the other open.
- These correspond to formants F1 and F2.
- But the modes are similar to closed-closed tube:
  - F1: All molecules move in same direction
  - F2: Molecules in two halves of time move in opposite directions



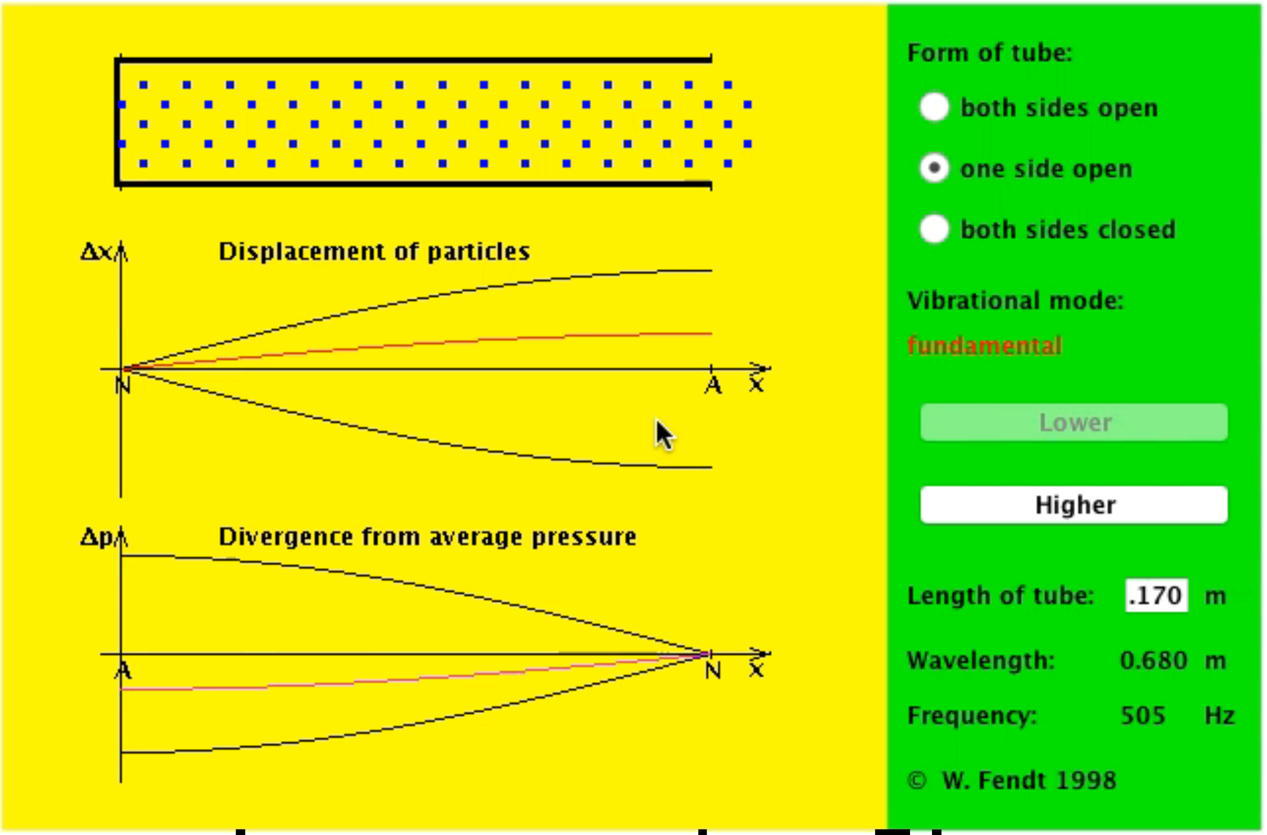
Lowest Mode



Next Higher Mode

Modes of vibration in tubes open at one end

Tube closed at one end,
open at the other.
(like vocal tract).



Form of tube:
○ both sides open
● one side open
○ both sides closed

Vibrational mode:
fundamental

Length of tube: .170 m
Wavelength: 0.680 m
Frequency: 505 Hz

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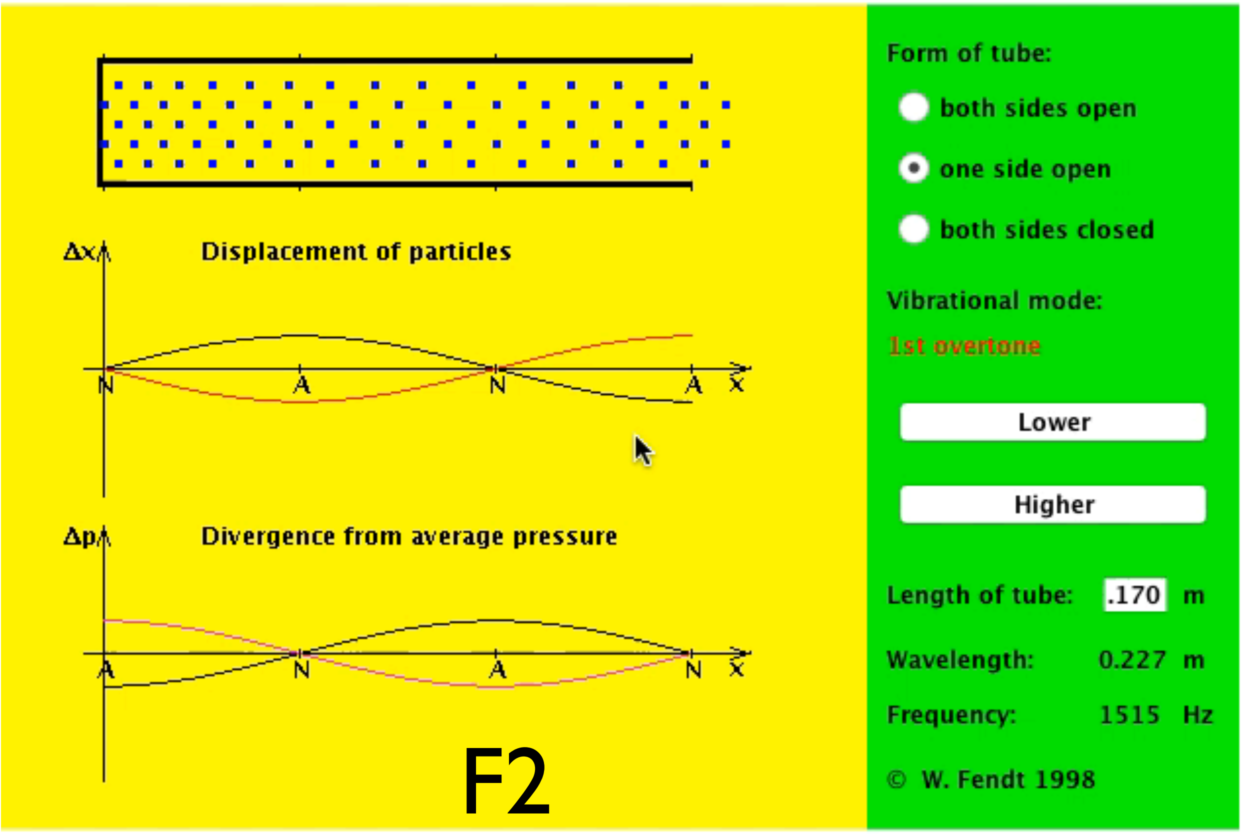
Lowest mode = F1

Modes frequencies differ for
closed-closed vs.
closed-open tube.



Form of tube:
○ both sides open
● one side open
○ both sides closed

Vibrational mode:
1st overtone

Length of tube: .170 m
Wavelength: 0.227 m
Frequency: 1515 Hz

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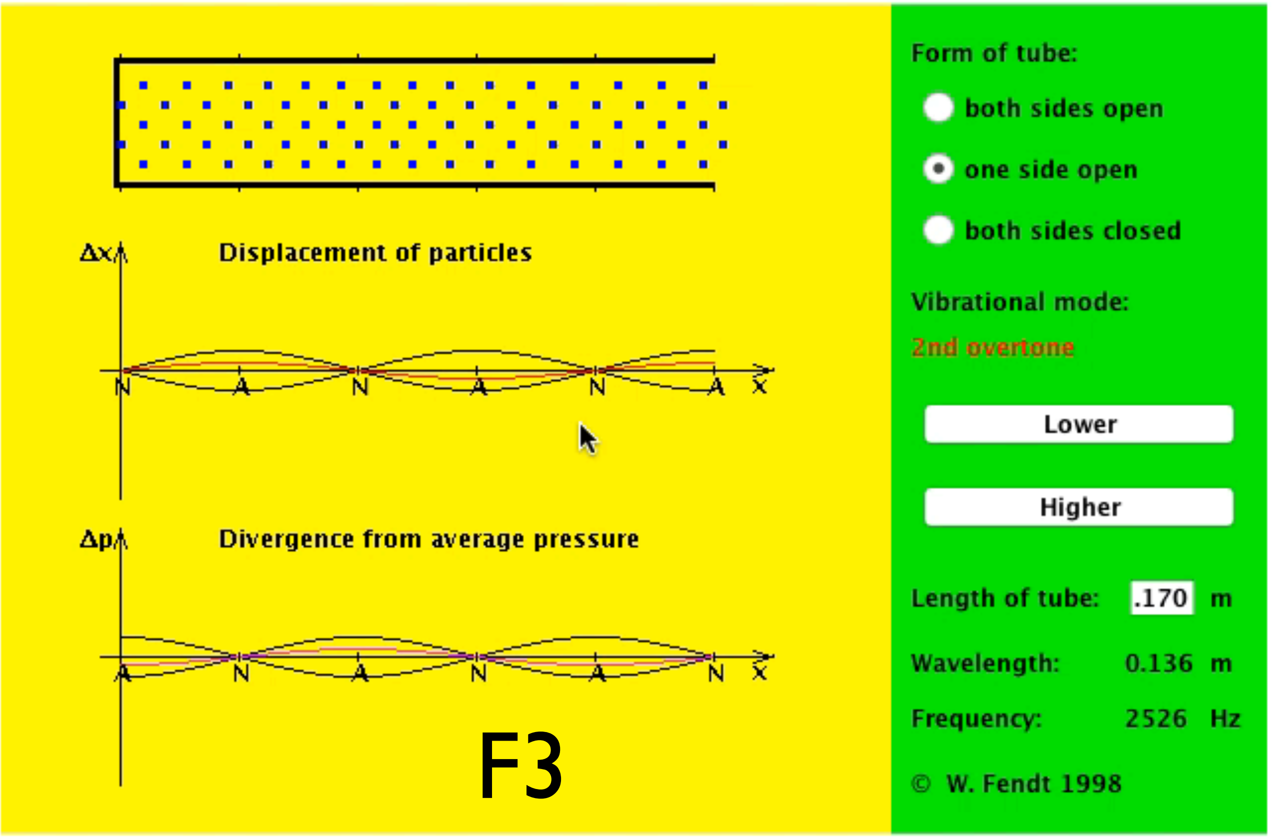
F2



Form of tube:
○ both sides open
● one side open
○ both sides closed

Vibrational mode:
2nd overtone

Length of tube: .170 m
Wavelength: 0.136 m
Frequency: 2526 Hz

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F3

Standing Waves in a Tube: What determines mode frequencies?

- In a tube with boundaries at both ends (either open or closed), only oscillations of certain frequencies will produce sustained standing waves.
- This is because reflections cause there to be a node or anti-node of velocity (closed end) or an anti-node (open end) at each end.
- Only vibrations of the certain frequencies will have the right distance between nodes (or between node and anti-node), so as the match the condition (node or anti-node) at both ends.

http://www.walter-fendt.de/ph14e/stlwaves.htm

Mode Frequencies are called Formants

- What happens to modes of air vibration when the tube is lengthened?
- They get lower. Why?
- Mammals use the formant frequencies to judge the size of con-specifics for mating purposes.
- Humans use formant frequencies to judge the size of the talker.
- What are mode frequencies of standing wave patterns in human vocal tract?

Vibration of air in vocal tract

- Modes are called formant frequencies.
- For an unconstricted vocal tract, the resonances of a 17 cm vocal tract occur at the following frequencies:

  500 Hz 1500 Hz 2500 Hz 3500 Hz ....
- The modes of vibration (formants) of an unconstricted tube or pipe are a function of the length of the tube:

$$f = \frac{nc}{4L}$$

for n = 1, 3, 5, ...

f = formant frequency in Hz
c = speed of sound 34,000 cm/s
L= length of vocal tract in cm

- So the lowest formant frequency in a 17 cm. vocal tract is:

$$f = \frac{c}{4L}$$

$= 34{,}000 / 4 * 17$
$= 500\ Hz$

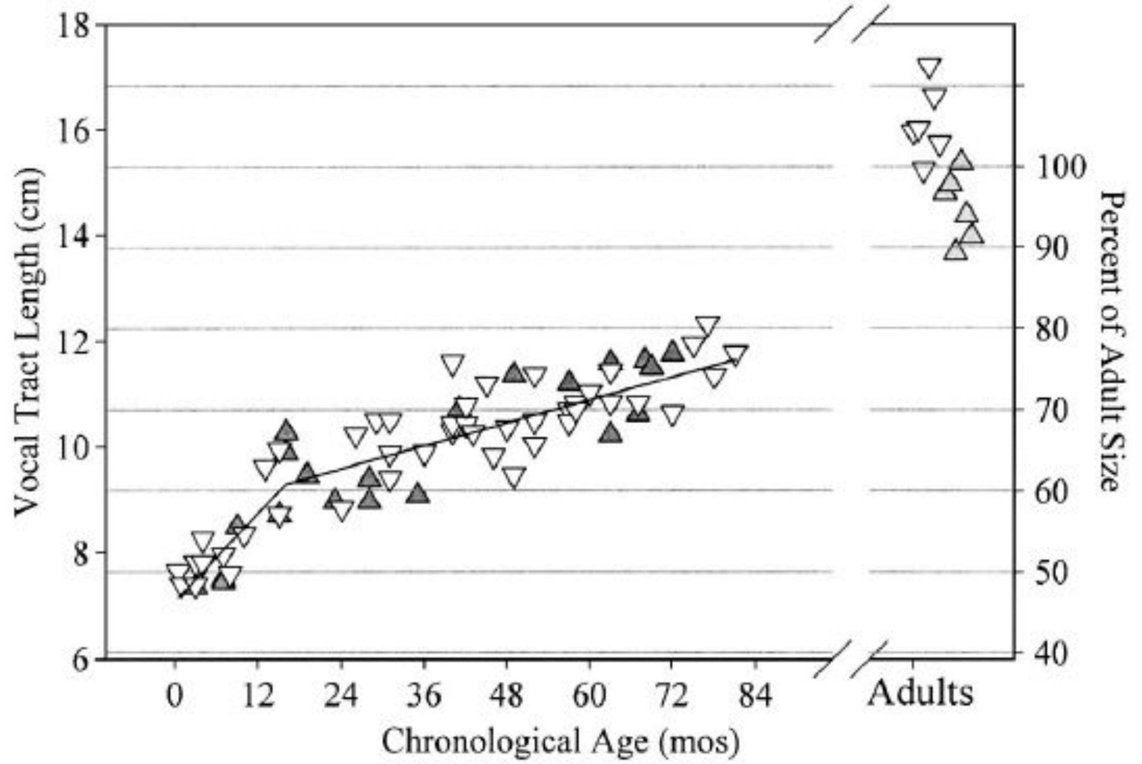
Formant Frequencies and Vocal Tract Length

- Spacing between formants:

$$\Delta f = \frac{c}{2L}$$ (always twice the lowest *f*)

= *1000 Hz* for a 17 cm vocal tract

- Formants of a young child



Voperian et al, (2005). Development of vocal tract length during early childhood: A magnetic resonance imaging study. *Journal of the Acoustical Society of America, 117*, 338–350.

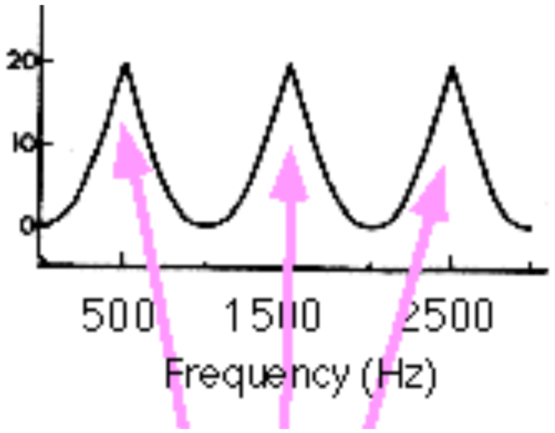
For an 8 cm vocal, the lowest resonance is:

*f = c / 4 * L*
*= 34,000 / 4 * 8*
= 1062 Hz

And spacing between resonances will be about *2120 Hz*.

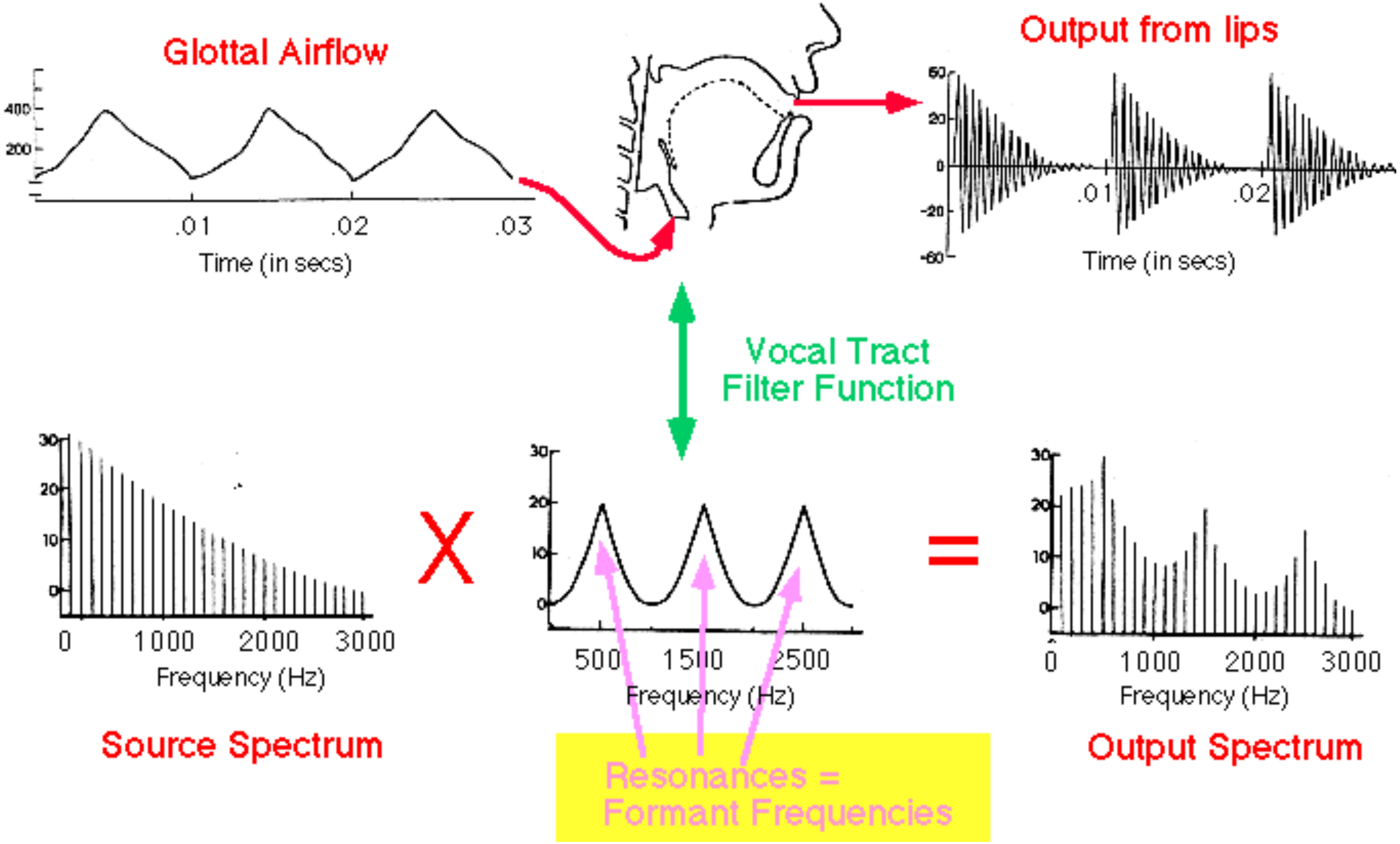
Vocal Tract as Filter

- The laryngeal vibration sets the air in the vocal tract vibrating at all frequencies of the harmonics of the laryngeal vibration.
- However, the amplitude of the vibration will depend on how close the frequency is to a mode frequency, or formant.
- The supralaryngeal vocal tract can be characterized by a filter function, which specifies (for each frequency) the relative amount of energy that is passed through the filter and out the mouth.
- The peaks in the filter function of the vocal tract are modes of the vocal tract, the formant frequencies.

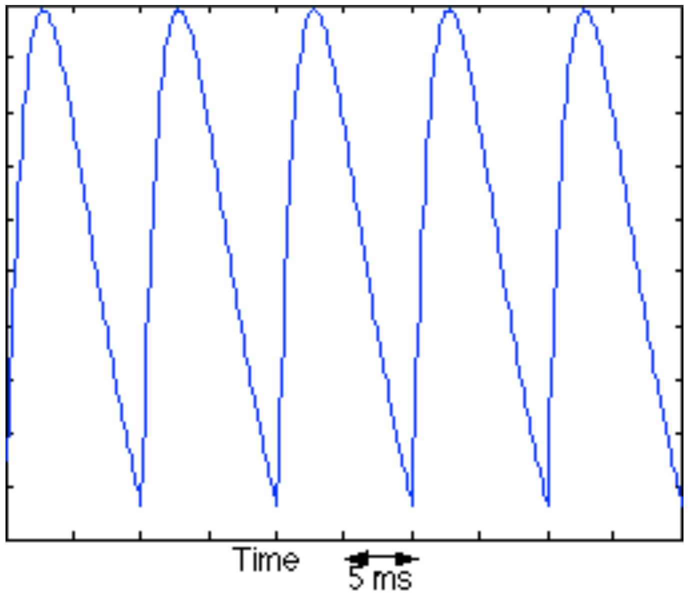


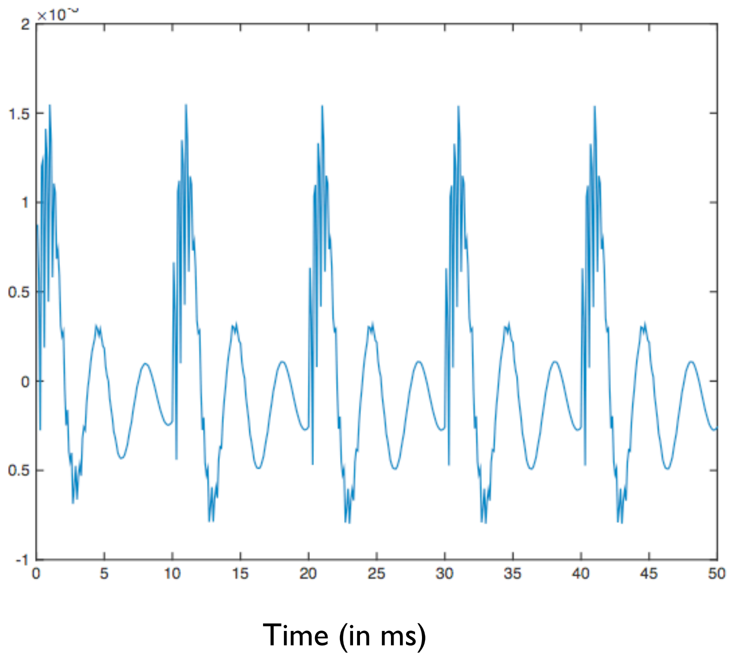
Combining Source and Filter

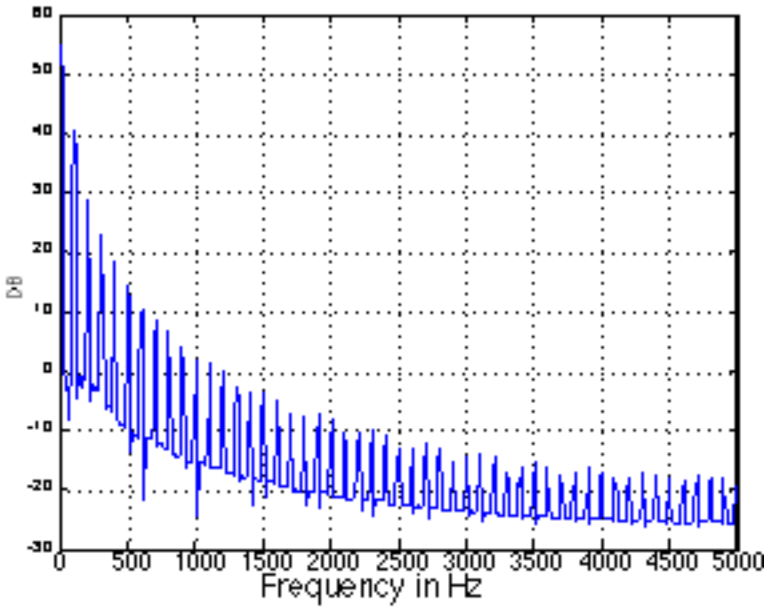
The output energy (at the mouth) for a given frequency is equal to the amplitude the source harmonic, multiplied by the magnitude of the filter function for that the frequency.

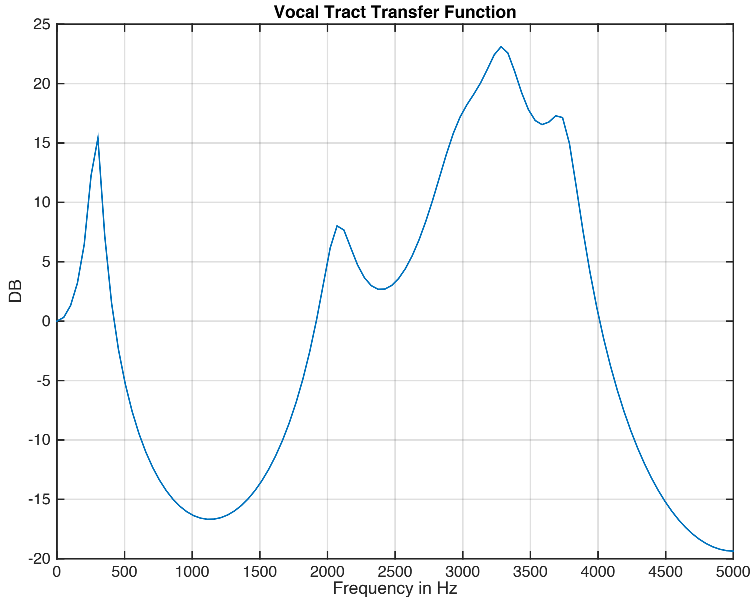


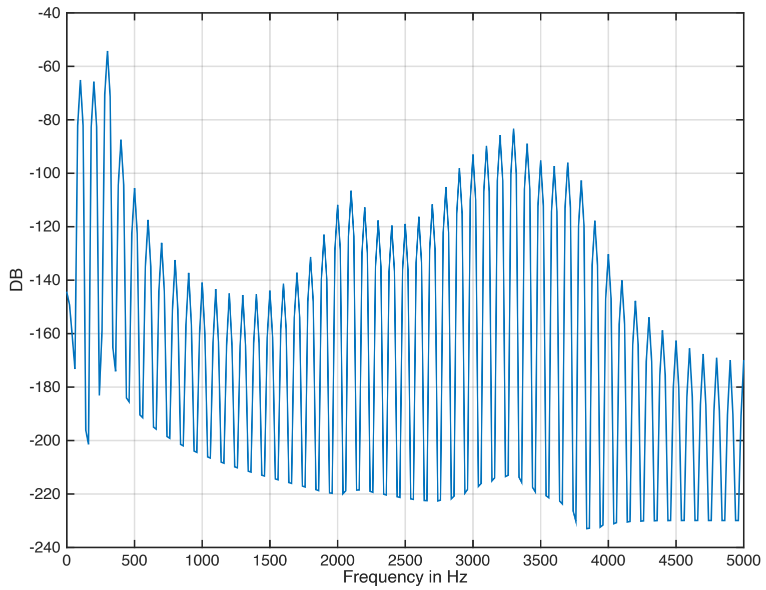
Example of Filtering: 100 Hz source



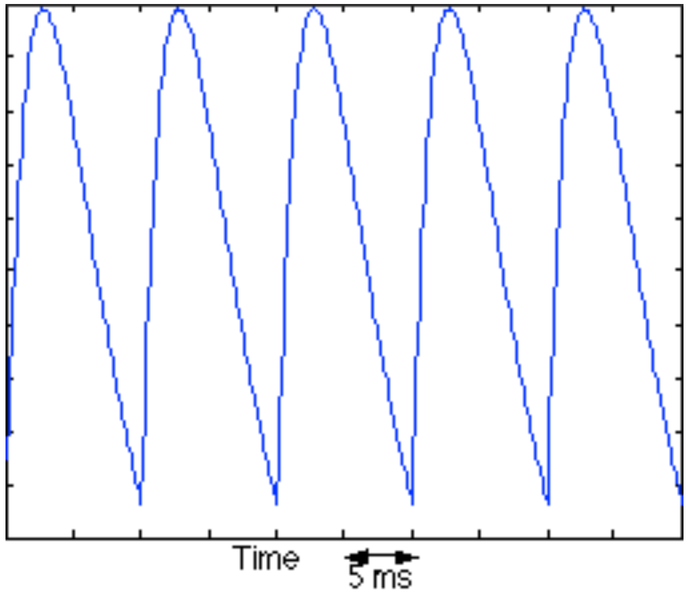


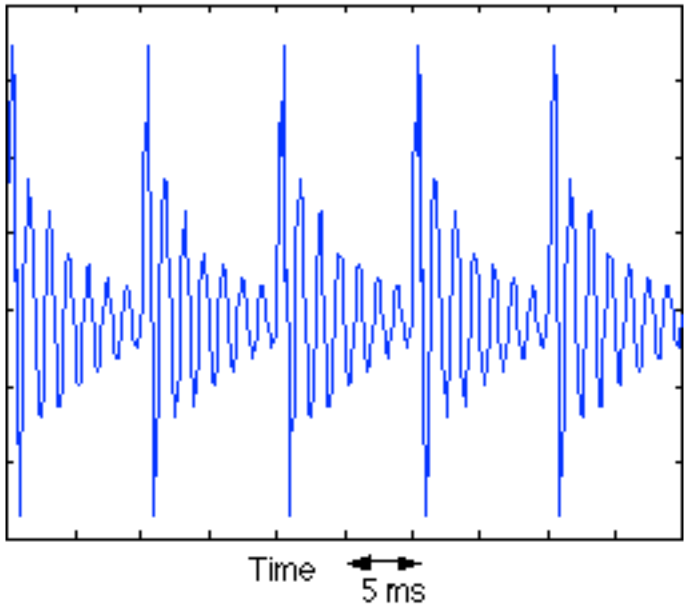


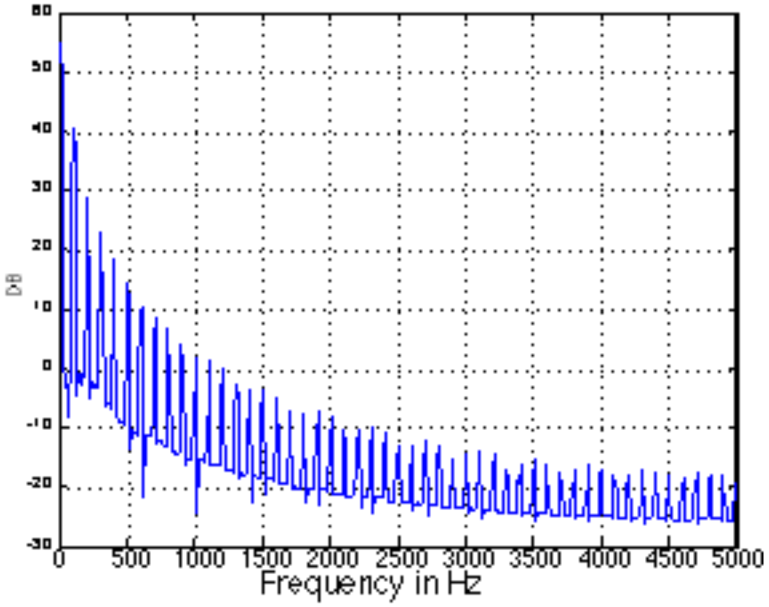


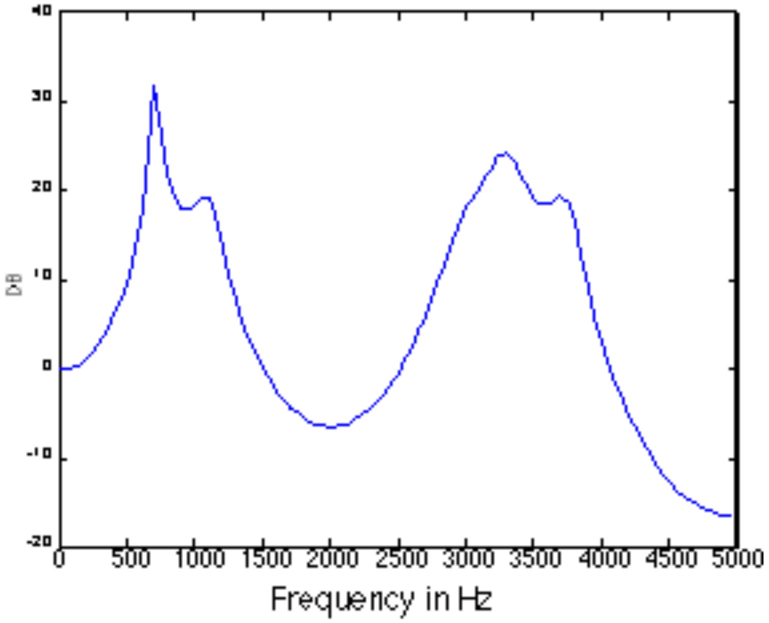


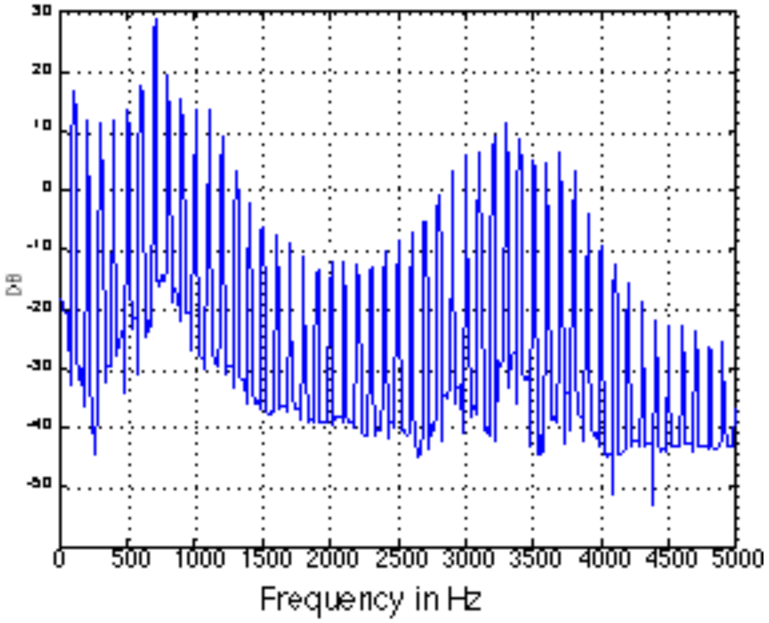
Example of Filtering: 100 Hz source



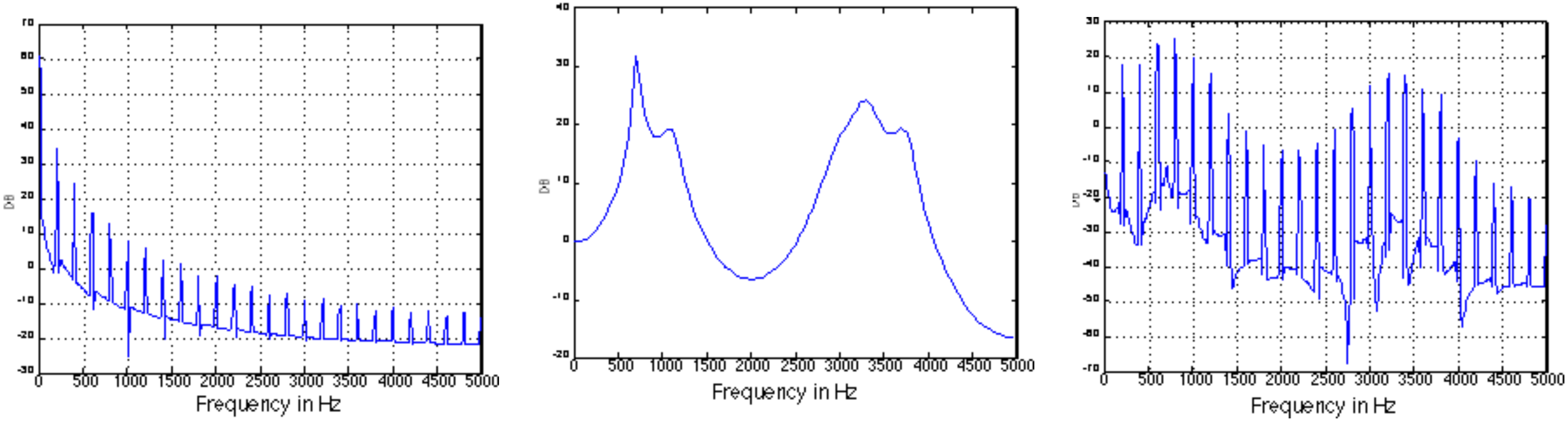








Example of Filtering: 200 Hz source

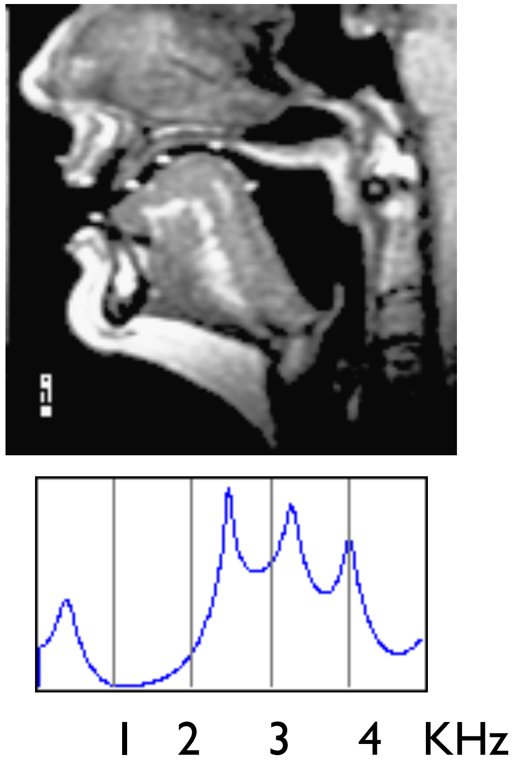


Formant Frequencies and Vocal Tract Shapes

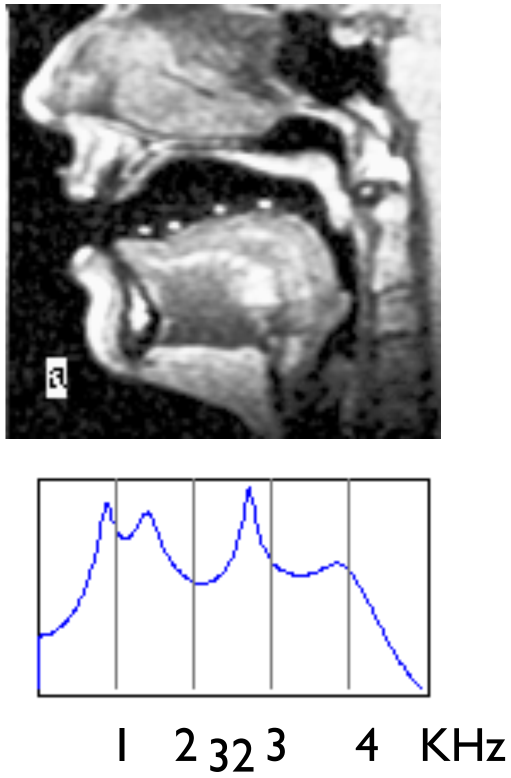
- Each vocal tract shape has a characteristic filter function that can be calculated from its size and shape.
- When the vocal tract has a constriction (produced by a gesture) resonances are no longer evenly spaced in frequency:
  - each resonance is a mode of vibration.
  - the effect of constriction on a given mode of vibration will depend on where in the tube constriction is placed.

3 basic vowels that occur in almost all languages

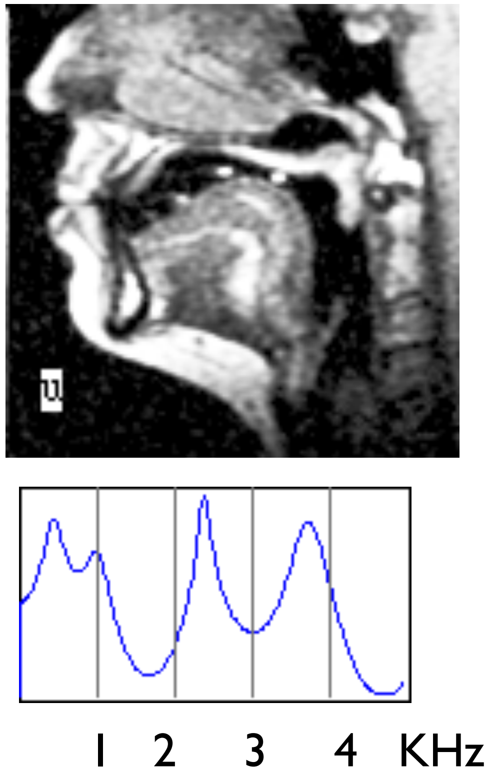
“heed”



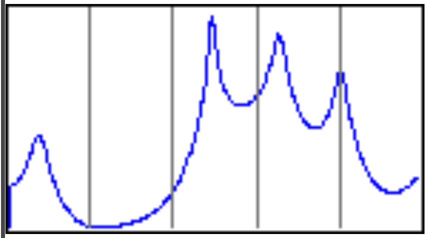
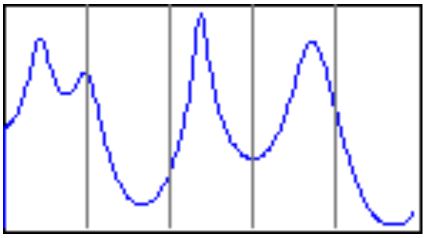
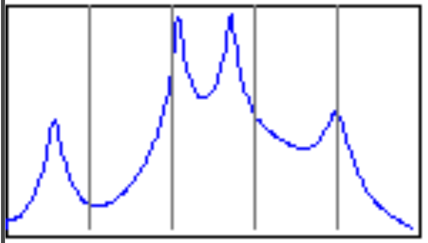
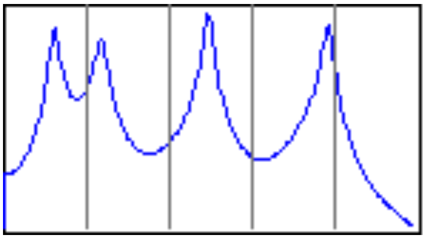
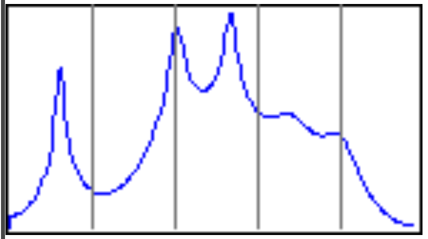
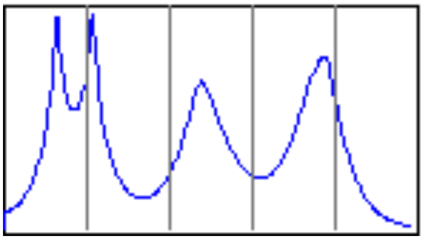
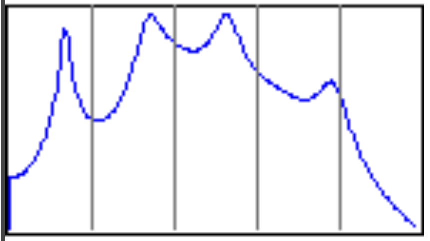
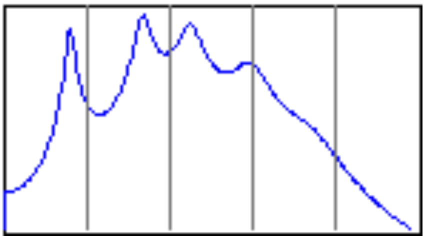
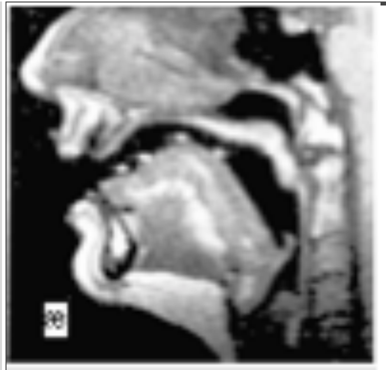
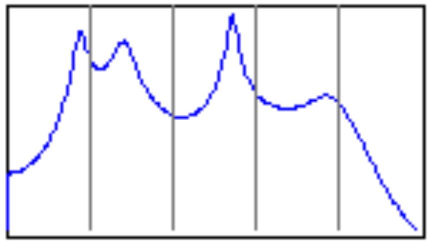
“hod”



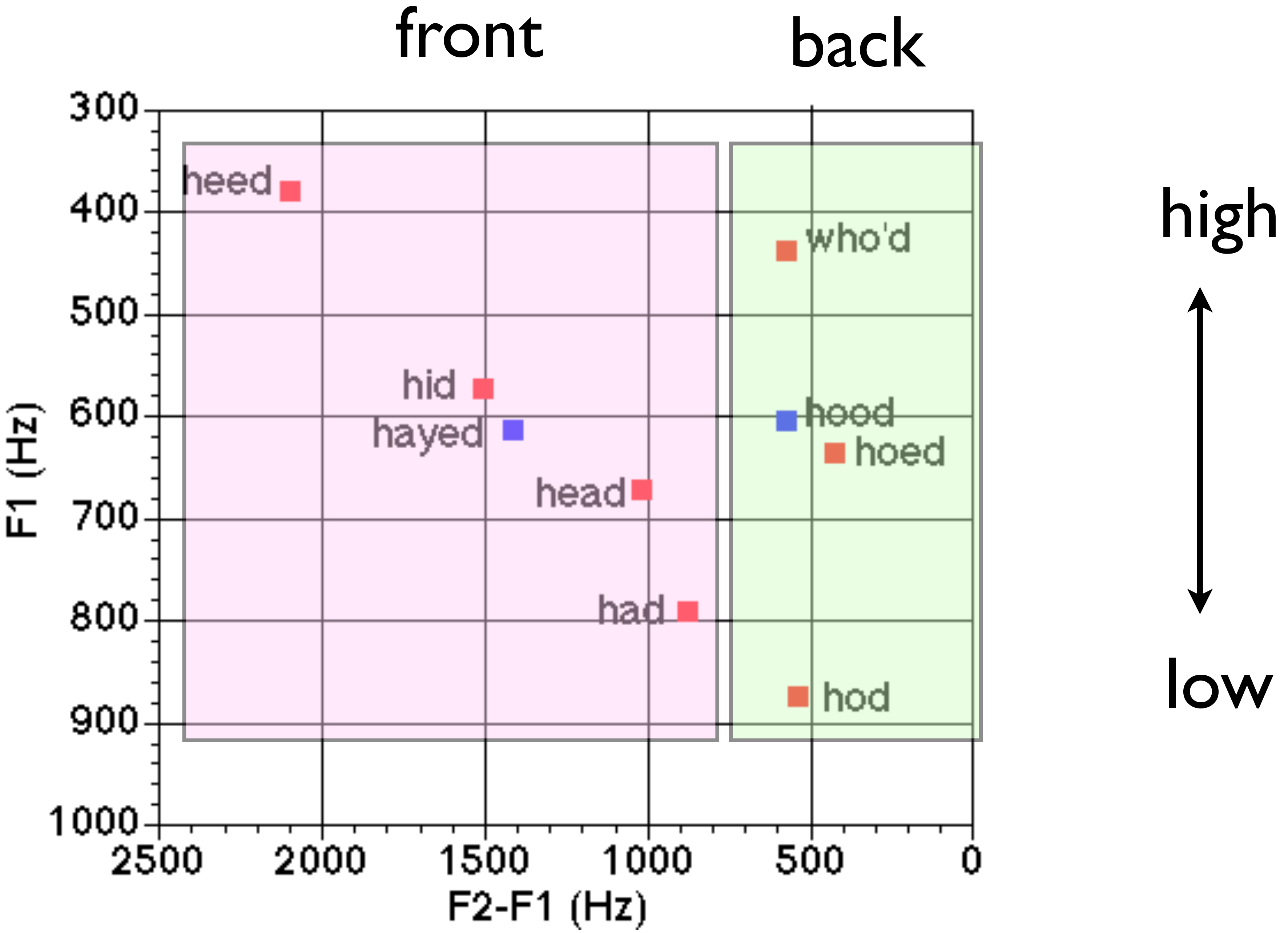
“who’d”



Source

 "heed"			 "who'd"
 "hid"			 "hood"
 "hayed"			 "hoed"
 "head"			
 "had"			 "hod"

Vowel Space


front
back
high
low
heed
hid
hayed
head
had
who'd
hood
hoed
hod
300
400
500
600
700
800
900
1000
F1 (Hz)
2500
2000
1500
1000
500
0
F2-F1 (Hz)

https://dood.al/pinktrombone/