Source-Filter Theory
Vocal tract as sound production device

• Sound production by the vocal tract can be understood by analogy to a wind or brass instrument.
  • sound generation
  • sound shaping (or filtering)

• Sound Filtering
  • Constrictions (produced by gestures of lips, tongue tip, tongue body, and velic systems) act to change the effective lengths (or volumes) of pipe that the sound generated at the larynx must go through before it escapes through the mouth.
  • The changes in pipe length (or volume) have same kind of amplification and attenuation effects on frequencies of the source as the comparable changes do in instruments.
  • Thus, the gestures leave their "signatures" in the sound that escapes the mouth.
  • There is nothing "magic" about the biological tissue used for filtering in the case of speech.
  • Mechanical models can produce sounds like those produced by a human vocal tract.
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](image1)

![Source Spectrum](image2)

• Modulation in period of glottal wave carries intonation (pitch).

• Why is the source spectrum look like that?
Modes of vibration: masses & springs

<table>
<thead>
<tr>
<th>1 mass</th>
<th>2 masses</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 mode</td>
<td>2 modes</td>
</tr>
</tbody>
</table>
Modes

**Crucial Ideas:**
- 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 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 a 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)!
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.
  • Molecules vibrate in an infinite number of modes, which are the formants.
  • What determines mode frequencies?
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.

![Graph showing the relationship between time and money in the bank.](image)
Components of (physical) dynamical systems: masses

- A mass (e.g. a book) doesn't 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.
Mass + Spring
Spring vs. Mass+Spring

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

Water in bathtub

Position

Mass+Spring
Principle 1: Perturbation of mass+spring

- Perturb (change) spring stiffness by increasing it. What is effect on oscillation frequency?
  - Frequency will *increase*. Why?
- Perturb (change) mass by increasing it. What is effect on oscillation frequency?
  - Frequency will *decrease*. Why?

Spectrogram of one mass system
Multiple Masses

- One mass attached to two springs to walls
- will vibrate at a single frequency, depending on mass and stiffness.

- Two masses, each attached to the wall and to each other
- will oscillate at two different frequencies, depending on initial conditions. why?
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 two modes of air vibration

Like lowest 2 modes of two-mass system

Lowest Mode

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
Length of tube

• 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
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:

  \[ f = \frac{c}{4L} \]

  \[ = \frac{34,000}{4 \times 17} \]
  \[ = 500 \text{ Hz} \]
Formant Frequencies and Vocal Tract Length

- Spacing between formants:
  \[ \Delta f = \frac{c}{2L} \] (always twice the lowest \( f \))
  \[ = 1000 \text{ Hz} \] for a 17 cm vocal tract

- Formants of a young child

For an 8 cm vocal, the lowest resonance is:

\[ f = \frac{c}{4 \times L} \]
\[ = \frac{34,000}{4 \times 8} \]
\[ = 1062 \text{ Hz} \]

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 of the source harmonic, multiplied by the magnitude of the filter function for that 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
<table>
<thead>
<tr>
<th>English Vowels</th>
<th>Click on vowels to listen.</th>
<th>superimpose vowels</th>
</tr>
</thead>
<tbody>
<tr>
<td>&quot;heed&quot;</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>&quot;hid&quot;</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>&quot;hayed&quot;</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
<tr>
<td>&quot;head&quot;</td>
<td><img src="image7.png" alt="Image" /></td>
<td><img src="image8.png" alt="Image" /></td>
</tr>
<tr>
<td>&quot;who'd&quot;</td>
<td><img src="image9.png" alt="Image" /></td>
<td><img src="image10.png" alt="Image" /></td>
</tr>
<tr>
<td>&quot;hood&quot;</td>
<td><img src="image11.png" alt="Image" /></td>
<td><img src="image12.png" alt="Image" /></td>
</tr>
<tr>
<td>&quot;hoed&quot;</td>
<td><img src="image13.png" alt="Image" /></td>
<td><img src="image14.png" alt="Image" /></td>
</tr>
<tr>
<td>&quot;had&quot;</td>
<td><img src="image15.png" alt="Image" /></td>
<td><img src="image16.png" alt="Image" /></td>
</tr>
<tr>
<td>&quot;hod&quot;</td>
<td><img src="image17.png" alt="Image" /></td>
<td><img src="image18.png" alt="Image" /></td>
</tr>
</tbody>
</table>

Return to Linguistics 120 Home Page
Vowel Space

![Graph showing vowel space with labels for front and back, high and low, and examples like heed, hid, hayed, head, had, who'd, hood, hoed, hod.](image-url)