Perturbation of Modes and Vocal Tract Constrictions
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) 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 $x = -\frac{1}{2}x$
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?
Two-mass system

- In a vibratory system with 2 m and 3 k, there will be 2 modes of vibration:
  - In-phase mode: the middle spring just rides up and down with the masses.
  - Out-of-phase mode: the middle spring stretches and compresses.

Therefore: OP Mode has more effective stiffness (3 springs vs. 2) and therefore has higher frequency.
Perturbation of mass in two-mass system

- Two-mass system has two modes:
  - Increase either of the masses in the low frequency mode. What happens to frequency?
  - Increase either of the masses in the high frequency mode. What happens to frequency?

<table>
<thead>
<tr>
<th>mass</th>
<th>freq in Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>12</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
</tr>
<tr>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
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<td>5</td>
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<tr>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>10</td>
<td>3</td>
</tr>
</tbody>
</table>

Lowest frequency mode

2nd harmonic frequency mode
Perturbation of stiffness in two-mass system

- Increase the stiffness of either of the end springs (k1, k3) in the low frequency mode, what happens to frequency?

- Increase the stiffness of either of the end springs (k1, k3) in the high frequency mode, what happens to frequency?

Increasing mass decreases the frequency of both modes.
Perturbation of stiffness in two-mass system

- Now increase the stiffness of the middle spring (k2) in the low frequency mode, what happens to frequency?

- Increase the stiffness of the middle spring (k2) in the high frequency mode, what happens to frequency?

- Principle 3: effect of mass or stiffness perturbation depends on the position of the perturbation.
Principle 3: Effect of perturbation depends on the position

Applies to formant movements in speech.

synchronous

asynchronous
Perturbing lowest two modes of air in tube open at one end

Air molecules vibrating in a tube: closed-open

The vocal tract is actually like a tube filled with air that is closed at one end (larynx) open at the other end (lips).

Here are lowest two modes of air in vibration in tube with one end closed and the other open.

These correspond to formants F1 and F2.

Modes of vibration of air in a tube are like those of the vibration of a string that is fixed to a wall at one end.

Linguistics 285 (USC Linguistics)
Lecture 11: Understanding /IY/ and /AA/ Formants
October 15, 2017 11 / 14

Perturbation of a mass in a two-mass system

Two-mass system has two modes:

- Increase either of the masses in the low frequency mode.
- Increase either of the masses in the high frequency mode.

Increasing mass decreases the frequency of both modes.
Constriction in vocal tract = $m \uparrow \uparrow k \uparrow \uparrow$

- Portions of air have mass and springiness.
- Constricting a portion of air by constricting a tube:
  - Raises the mass, since packed molecules are harder to move, i.e. a constriction raises density.
  - Raises the stiffness (as in a tire), i.e., a constriction raises pressure.
  - So a constriction in a tube amounts to raising both mass and stiffness at the location of the constriction.
Effect of increasing mass and stiffness on mode frequencies

• Effect of mass and stiffness could cancel each other out.

• However, however, because of the effect of position, either mass or stiffness effects can be dominant.

• **Mass:**

• Mass has a maximal effect where the molecules are moving most (like the open end), as the movement of the masses will be slowed down.

• An increase of mass at a position where the molecules are not moving (like the closed end) will have no effect on frequency.

• **Stiffness:**

  Stiffness has a maximal effect there the molecules are moving least. Springiness of air doesn't matter where there is nothing to push against.
Effect of constricting vocal tract at different locations

<table>
<thead>
<tr>
<th>position</th>
<th>F1</th>
<th>F2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>mass ↓</td>
<td>mass ↓</td>
</tr>
<tr>
<td>2</td>
<td>stiff ↑</td>
<td>stiff ↑</td>
</tr>
<tr>
<td>3</td>
<td>stiff ↑</td>
<td>mass ↓</td>
</tr>
<tr>
<td>4</td>
<td>mass ↓</td>
<td>stiff ↑</td>
</tr>
</tbody>
</table>
Vowels: Constriction in Different Locations

<table>
<thead>
<tr>
<th>Location</th>
<th>Graphical Representation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palatal</td>
<td>![Palatal Graph]</td>
</tr>
<tr>
<td>Velar</td>
<td>![Velar Graph]</td>
</tr>
<tr>
<td>Uvular</td>
<td>![Uvular Graph]</td>
</tr>
<tr>
<td>Pharyngeal</td>
<td>![Pharyngeal Graph]</td>
</tr>
</tbody>
</table>

- Wood (1984) measured area functions from a variety of languages show constrictions limited to these four locations.
- Velar and Uvular usually accompanied by lip constrictions.
How do distinct constrictions produce distinct formant patterns?

• palatal (e.g. /i/)
  • F1 down, F2 up

• Pharyngeal (e.g. /a/)
  • F1 up, F2 down

• Velar (e.g. /u/)
  • F1 down, F2 down
Modes of air vibration in tube with one open end
Another view of modes: strings

Mode

Change in Frequency

F1  F2  F3
Constriction is like adding mass

- Adding mass where air (or string) is moving a lot, frequency of mode goes down.

- Adding mass where air (or string) is NOT moving a lot, frequency of mode goes up.
Adding mass where string is moving…

lowers freq

Mode

1

2

3

Change in Frequency

F1

F2

F3
Pharyngeal Constrictions

F1

F2

24
Velar/Uvular + Labial constrictions

F1

F2

Graphs showing the movement and sensitivity for F1 and F2 constrictions.