• The source-filter model of vowel acoustics
• The glottal source
• Modeling schwa

Background reading:
• AAP Ch 2, sec 2.1 and 2.4 (review)
0. Today’s plan

• Review/check-in: Tube resonances
• Overview of the source-filter model
• The glottal-source wave
• The vocal-tract filter
• Deriving the vocal-tract filter for [ə]
• Putting source and filter together: [ə]
• Terms and abbreviations for frequencies
0. Review: Tube resonances

• Last week in class:
  How do we get from tube length to resonance frequencies?

• Lab #3:
  How do we get from resonance frequencies to tube length?
1. Overview of the source-filter model

• How do you get a trumpet to play a note?
1. Overview of the source-filter model

• To play a trumpet, you “buzz” your lips
  - This creates a **sound source** at one end of the trumpet (disturbance in the medium!)

• But what we **hear** is a trumpet note, not a buzz:
  The trumpet acts as a **filter**
  - It **changes the shape** (→ the **sound quality**) of the **complex wave** produced by the sound source
  - It does this by **suppressing** (reducing the amplitude of) some of the source wave’s **components** and **amplifying** (increasing the amplitude of) others
1. Overview of the source-filter model

• In much the same way, when we produce a **voiced speech sound** such as a **vowel**...
  - The vocal folds **buzz** (glottal-source wave)
  - The vocal-tract tube **changes the shape** of the complex wave by **suppressing** some source components and **amplifying** others

• The **source-filter model** of the vocal tract
  - **Sound source:** the **vibrating vocal folds**
  - **Filter:** the vocal tract as a **tube**
    (or a series of tubes)
2. The glottal-source wave

- What is the **glottal-source wave**?
  - Also called the **voicing wave** (form) in AAP Ch 2
  - The sound wave produced by ______
2. The glottal-source wave

• What is the glottal-source wave?
  - Also called the voicing wave (form) in AAP Ch 2
  → The sound wave produced by the vibration of the vocal folds

• To actually hear this sound wave, you would have to put a microphone right above the glottis
  - The sound waves of any speech we normally hear are further modified by passing through the vocal tract
    • That is the filter part of the model!
2. The glottal-source wave

- In the source-filter model of vowel acoustics:
  Sound **source** = vibrating vocal folds (**voicing**, also called **phonation**)
  - The **shape** of this wave is determined by the way the vocal folds open quickly and close gradually
    → More about this later in the semester
2. The glottal-source wave

• Computer-synthesized glottal-source wave: 
  [lsrc.wav] (U Delaware Speech Research Tutorials)

• Look at the waveform in Praat
  - Periodic? Simple or complex? What is $f_0$?
2. The glottal-source wave

• Computer-synthesized glottal-source wave: 
  \[\text{lsrc.wav}\] (U Delaware Speech Research Tutorials)

• Look at the waveform in Praat
  - Periodic? Simple or complex? What is $f_0$?

• Look at the spectrum (window length = 0.5 sec)
  - What is the lowest-frequency component?
  - How do the components’ \textbf{frequencies} relate?
  - How do the components’ \textbf{amplitudes} relate?
  - What is $f_0$? (should get the same answer as above!)
2. The glottal-source wave

- Characteristics of the glottal-source wave
  - **Amplitudes** of the components gradually decrease (assuming modal or ‘ordinary’ voicing)
  - **Frequencies** of the components are whole-number multiples of the lowest component

- The component frequencies thus have the *same relationship* as in a node/node system
  - Careful here: The vocal folds do not actually vibrate like a string of fixed length (they open and close to emit puffs of air)
2. The glottal-source wave

• Can the **frequencies** of the **components** of the glottal-source wave be manipulated by the speaker?
2. The glottal-source wave

• Can the frequencies of the components of the glottal-source wave be manipulated by the speaker? **Yes!**
  - Each human’s voice can produce a range of $f_0$ values (or else singing would be impossible)
  - Manipulating $f_0$ means manipulating the component frequencies
    • $f_0$ is the GCD of the component frequencies
    • So in the glottal-source wave, $f_0$ is the same as the first component frequency
2. The glottal-source wave

• If someone produces a vowel with $f_0 = 250 \text{ Hz}$, what are the frequencies of the first five components of the glottal-source wave?
2. The glottal-source wave

• If someone produces a vowel with \( f_0 = 250 \text{ Hz} \), what are the frequencies of the first five components of the glottal-source wave?

- \( f_1 \) (H1) = \( f_0 = 250 \text{ Hz} \) | don’t forget the first one!
- \( f_2 \) (H2) = 2* \( f_1 = 500 \text{ Hz} \) | whole-number multiples
- \( f_3 \) (H3) = 3* \( f_1 = 750 \text{ Hz} \)
- \( f_4 \) (H4) = 4* \( f_1 = 1000 \text{ Hz} \)
- \( f_5 \) (H5) = 5* \( f_1 = 1250 \text{ Hz} \)

• The components of the glottal-source wave are often called harmonics, abbreviated H(n)
3. The vocal-tract filter

• Much like a trumpet, the vocal tract filters the sound energy by suppressing some components of the glottal-source wave and amplifying others
  - The components amplified by the vocal tract are those close to its resonance frequencies
  - The resonance frequencies of the vocal tract depend on its length and shape
  - The vocal tract forms different shapes for different vowels (and consonants—more on this later)

• Therefore, each different vowel (such as [i] vs. [a]) corresponds to a different vocal-tract filter
3. The vocal-tract filter

- So if each different vowel corresponds to a different vocal-tract filter ...

This means that each vowel corresponds to a different set of amplified frequencies (vocal-tract resonances)
- These are known as the vowel’s formants
3. The vocal-tract filter

• Try it out: Synthesized vowels [lii.wav] | [laa.wav]
  (U Delaware Speech Research Tutorials)

• Download and open these sound files in Praat
  - What **vowels** are they? (What do you hear?)
  - Compare them to each other and to the glottal-source wave we looked at before [lsrc.wav]:
    • How do their $f_0$s compare?
    • How do their waveform **shapes** compare?
    • How do their **spectra** compare?
3. The vocal-tract filter

• Each vowel (such as [i] vs. [a]) corresponds to a different set of **resonance frequencies** (formants)

• The **shape of a complex wave** is determined by the frequencies and amplitudes of its components

  → Two different vowel categories have **differently shaped** sound waves even when they are sung on **the same pitch** (=have the same glottal-source wave)

• Waves of different shapes correspond to sounds with different **sound qualities (timbres)** — this is how different vowels differ perceptually
4. Deriving the vocal-tract filter for [ə]

- To analyze the acoustics of vowels, we need to understand why they have the resonance frequencies (formants) that they have.

- The first step: What are the resonance frequencies of the neutral vocal-tract vowel, [ə]?
  - The vocal tract is approximately a uniform tube that is closed at one end (the glottis) and open at the other end (the lips).
  - The neutral vocal-tract vowel is typically represented as [ə] (schwa), but note that it doesn’t sound exactly the same as English [ə] as in sofa.
4. Deriving the vocal-tract filter for [ə]

• The first step: What are the resonance frequencies of the neutral vocal-tract vowel, [ə]?
  - The vocal tract is approximately a uniform tube that is closed at one end (the glottis) and open at the other end (the lips)
  - What do we need to know in order to find the resonance frequencies of this vowel?
4. Deriving the vocal-tract filter for [ə]

- The first step: What are the resonance frequencies of the neutral vocal-tract vowel, [ə]?
  - The vocal tract is approximately a uniform tube that is closed at one end (the glottis) and open at the other end (the lips)
  - What do we need to know in order to find the resonance frequencies of this vowel?
    - The length of the tube (vocal tract)
    - The boundary conditions of the tube
    - The speed of sound in air (use 350 m/s)
4. Deriving the vocal-tract filter for [ə]

- We know how to calculate the resonance frequencies for a tube of this type: it is a node/antinode or quarter-wavelength system.
  - What is the distance between each pair of resonance frequencies in a system of this type?
4. Deriving the vocal-tract filter for [ə]

- We know how to calculate the resonance frequencies for a tube of this type: it is a **node/antinode** or **quarter-wavelength** system.

  - What is the distance between each pair of resonance frequencies in a system of this type?

    - Each resonance is an odd-numbered multiple of the first \( (1*f_1, 3*f_1, 5*f_1, \ldots) \)

    - So the distance between each pair of resonances is \( 2 \times \) the lowest resonance’s frequency.
4. Deriving the vocal-tract filter for [ə]

• The **precise values** for the formants of [ə], or any vowel, will differ from person to person, since people have vocal tracts of different lengths
  - However, the **relative distance between** the formants for each vowel in a language is (reasonably) consistent from speaker to speaker
4. Deriving the vocal-tract filter for [ə]

• For a vocal tract that is 17.5 cm (0.175 m) long, calculate the first three resonance frequencies
  - These values are the first three formants of [ə] for this vocal tract (use “F” for formant frequencies)
4. Deriving the vocal-tract filter for [ə]

• For a vocal tract that is 17.5cm (0.175m) long, calculate the first three resonance frequencies
  - These values are the first three formants of [ə] for this vocal tract (use “F” for formant frequencies)

1st resonance frequency (F₁):
\[
F_1 = \frac{c}{\lambda_1} \quad \lambda_1 = 4L = 4 \times 0.175m = 0.70m
\]
\[
c = 350m/s
\]
\[
F_1 = \frac{350m/s}{0.70m} = 500/s = 500Hz
\]

F₂ and F₃ are odd-numbered multiples of F₁:
\[
F_2 = 3 \times 500Hz = 1500Hz \quad | \quad F_3 = 5 \times 500Hz = 2500Hz
\]
5. Putting source and filter together: [ə]

- Synthesized [ə] [vs_x.wav] (using same glottal source) (U Delaware Speech Research Tutorials)
  - Open this sound file in Praat
  - View the waveform
  - View the spectrum (window length=0.5 sec)

- Understanding this [ə] spectrum:
  - What determines the components’ frequencies?
  - What determines their amplitudes?
5. Putting source and filter together: [ə]

- Will [ə] produced by someone with a 17.5cm vocal tract always have components at 500Hz, 1500Hz, and 2500Hz?
5. Putting source and filter together: [ə]

• Will [ə] produced by someone with a 17.5cm vocal tract always have components at 500Hz, 1500Hz, and 2500Hz?

NO!
5. Putting source and filter together: [ə]

• VERY IMPORTANT
  - The vocal-tract filter is **not** a sound source
  - The filter is **not** adding components to the complex wave at its own resonance frequencies
  - All component **frequencies** in the source-filter model are coming from the **source**
  - The **filter**’s job is only to modify **amplitudes** of the components contributed by the source
5. Putting source and filter together: [ə]

• For next time:
  See web demo “The source/filter model” (Kevin Russell, U. Manitoba)
  - The **filter** associated with [ə] (for a vocal tract of a particular length)
  - The **spectrum** of the **glottal source** (for voicing produced with a particular $f_0$)
  - The **spectrum** of the **resulting** [ə]—which is the result of **modifying** the given glottal source with the given [ə] filter
5. Putting source and filter together: [ə]

• When we put source and filter together...
  - In the spectrum of the [ə], the components (also called harmonics) of the source wave near the formants (the frequencies corresponding to amplitude peaks in the filter) are amplified the most
  - Note that the amplification effect falls off gradually from a peak; this peak marks the actual formant/resonance frequency
5. Putting source and filter together: [ə]

• When we put source and filter together...
  - The **frequencies** of the components of the resulting sound are determined by the ____
  - The **amplitudes** of the components of the resulting sound are determined by the ____
• When we put source and filter together...
  - The **frequencies** of the components of the resulting sound are determined by the **source**
  - The **amplitudes** of the components of the resulting sound are determined by the **filter**
5. Putting source and filter together: [ə]

- **ALWAYS REMEMBER:**
  
  **Formants** are related to **vocal-tract** size and shape, **NOT** to $f_0$ of phonation!

  (a) The same vowel can be sung on different pitches
  
  (b) Different vowel categories can be sung on the same pitch

- If the glottal source determined the formant frequencies, or vice-versa, (a) and (b) would be impossible
6. Terms and abbreviations for frequencies

When we are talking about **speech acoustics**:  
• The abbreviation \( f_0 \) (or \( F_0, F_0 \)) is used for the **fundamental frequency** of the **glottal source**  
• The abbreviation \( H(n) \) is often used for the \( n \)th **resonance** (\( n \)th "harmonic"=whole-number multiple) of the **glottal source**
  - The glottal source has components at whole number multiples of the lowest resonance, so the lowest resonance = \( f_0 \) (remember GCD?)  
  - Thus, for a voiced speech sound, \( f_0 = H1 \)
6. Terms and abbreviations for frequencies

When we are talking about speech acoustics:

• The abbreviation F1 is used for the first formant, that is, the first resonance frequency of the vocal-tract filter.

• F2, F3, etc. are used for the 2nd, 3rd, etc. formants, that is, subsequent resonance frequencies of the vocal-tract filter.

• Comprehension check: What is the relationship between $f_0$ (F0) and F1 in a vowel?
6. Terms and abbreviations for frequencies

When we are talking about waves in general:

- $f_0$ (sometimes F0, F₀) is used for the fundamental frequency of any wave, simple or complex

- $f_n$ is used for the $n$th resonance frequency of a standing-wave system

So:

- IF the object under analysis is a sound source,
- and IF higher resonances are all some multiple of the first one,

THEN $f_0 = f_1$