Crash course in acoustics
Outline

• What is sound and how does it travel?
• Physical characteristics of simple sound waves
  – Amplitude, period, frequency
• Complex periodic and aperiodic waves
• Source-filter theory
Take home message

• Two types of visual representation of speech:
  – Waveforms (time by amplitude displays)
  – Spectrograms (time by frequency displays)

• Characteristics of waveforms
  – simple, complex, periodicity, frequency…

• Speech sounds
  – The source
    • vocal folds: produces a range of frequencies (harmonics)
    • Other sources, e.g. noise
  – Articulators filter this source
What is speech acoustically?

• Acoustically, speech sounds are similar to other sounds.

• What is sound?
  – Movement of particles which causes pressure fluctuation in the surrounding air.

• What happens to the air pressure?
  – **Compression**: Pressure increases so the air particles are close together
  – **Rarefaction**: Pressure decreases so the air particles are further apart

• Air pressure changes cause our eardrum and bones of the middle ear to vibrate.
How does sound travel?

- In order to even reach our ears, sound must travel from its source.
- Pressure fluctuations caused by the source propagate through elastic media:
  - there is room for molecules to move back and forth.
- In other words, sound moves in waves
  - A sound wave is a traveling pressure fluctuation
Propagation of a sound wave

From http://home.att.net/~cat4a/wave-ll.htm
See also http://entertainment.howstuffworks.com/sci-fi10.htm
The waveform as pressure changes

• Graphic representation showing changes in air pressure:

![Graph showing pressure changes over time with labeled compression and rarefaction.](image-url)
The simplest sound

- The simplest type of sound is a pure tone (e.g. the sound of a tuning fork)
  - Generated by simple harmonic motion (think pendulum)
What does this graph represent?

• We can interpret this graph as showing the movement of one air particle from its rest position.
What is a periodic wave?

- This type of wave is called periodic because the motion of the particle is repeated at regular intervals.
Frequency of a periodic wave

- **Cycle**: The completed movement of a wave
- **Period (T)**: The time it takes for each cycle in a wave to be completed
- **Frequency**: The number of cycles completed in one second
- **Hertz (or cycles per second)**: Frequency is measured in Hz and is perceived as *pitch*
- Humans can hear sounds whose frequency ranges from 20-20,000 Hz, though speech sounds essentially utilize the lowest half of this range
Frequency in more detail

• Frequency: the number of times a cycle is repeated within a time interval (in speech, the standard unit of time is 1 second)

  Frequency = 1/T (period)

• If one cycle of vocal fold vibration is completed every 1/100 of a second, then T = 0.01 and frequency is 1/0.01 = 100 cycles per second = 100 Hz (Hertz)

• Conversely, if the frequency of a sound is 200 Hz, then there are 200 cycles of the sound wave per second, and the period is 1/200 = 0.005 s = 5 ms (milliseconds)
Amplitude of a periodic wave

• The amplitude of the wave is related to the extent of particle displacement
• Roughly speaking, the greater the displacement (amplitude), the louder the sound
• NB: Amplitude and frequency are independent of one another
The independence of frequency and amplitude

Two sine waves with the same frequency but different amplitude

Two sine waves with the same amplitude but different frequency

From Ladefoged, 1996
Question

• What are the frequencies of these two sine waves? (Hint: Calculate how many cycles must be completed in one second.)
Beyond tuning forks

• If only speech were that simple. But in fact:
• Speech sounds are not pure tones
• Rather, they are made up of tones of several frequencies, and can be distinguished into two categories
  – (complex) periodic sounds
  – aperiodic sounds
Complex periodic sounds

- Complex periodic sounds are made up of two or more sine waves.
- Complex waves still have a repeating pattern.
- The component sine wave with the lowest frequency is called the fundamental frequency (F0).
A complex periodic wave

The waveform of a complex periodic sound has a complex shape that is repeated with the same periodicity as its lowest frequency component.

What is the fundamental frequency?

- 100 Hz
- 300 Hz

What is the fundamental frequency?
Waves of different frequencies (and amplitudes)

FIGURE 7.4.1 Complex wave with three sinusoidal components (100 Hz, 200 Hz, 300 Hz)

Adapted from: Ladejoged 1962, p. 35.
Further aspects of complex waves

• The waveform of a complex periodic wave is derived by adding up the amplitude of the component waves at every point in time.
• When the complex wave is known but the components aren’t, the wave can be broken down using a method called Fourier analysis.
• Vowels (and to an extent other vowel-like speech sounds, i.e. approximants) are complex periodic waves
Aperiodic waves

• Aperiodic waves have components at several frequencies, not only at frequencies that are whole number multiples of the fundamental.
• The result is an irregular non-repetitive waveform
• An example is radio static or white noise, which include components of equal amplitude at all audible frequencies
• In speech, fricatives are aperiodic.
Examples of aperiodic waves

White noise

From Denes & Pinson, 1973
Visual waveforms of speech

- One way speech can be examined is in the time domain.
- This is plotted as a time by amplitude waveform.
- No frequency information is contained in a waveform.
Limitations of waveforms

• By examining waveforms we may not be able to tell exactly which sound is shown: e.g. we can tell the sound is a stop, but we may not be able to tell whether it is a [p] or a [t]

• The difficulties are similarly great for vowels

• Frequency information is needed, in addition to time and amplitude

• **Spectrograms** are a representation that provides us with time, frequency and amplitude information
Harmonics (overtones)

- What is the difference between the tuning fork and the vocal folds in how they vibrate?
- The fork corresponds to (more or less) a simple sine wave whereas the vocal folds correspond to a complex wave.
- Components of complex waves are called harmonics.
- Harmonics are not arbitrary sine waves:
  - Rather, waves with frequencies that are whole number multiples of the fundamental frequency (F0, the lowest frequency component)
- The amplitude of each component wave is not necessarily the same.
• Spectrum is a plot of frequency against amplitude at a particular point in time

Source input (vocal folds)
Source-Filter Theory

• In the speech wave, not all harmonics have equal amplitude.
• This is because the human vocal tract acts as a filter:
  – Frequency-selective
  – Amplifies some frequencies (called formants), damps others;
• Phonation (vocal fold vibration) is the sound source that is shaped by the vocal tract
The vocal tract filter

- Different sounds have different vocal tract configurations.
- For example, consider the difference between [u], [ʊɑ], and [ɑ].

The sound source from the vocal folds always contains the same frequencies, but different vocal tract shapes will amplify some frequencies and damp others.
Frequency response for [a]: amplified frequencies (formants) at 800Hz, 1300Hz, 2500Hz (approx)
Spectrogram

X-axis is time; Y-axis is frequency; darkness is intensity
Try to find the individual phonemes of “In English” in the waveform:
Summary

• Two types of visual representation of speech:
  – Waveforms (time by amplitude displays)
  – Spectrograms (time by frequency displays)

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• Speech sounds
  – Articulators filter the source
  – Spectrum, harmonics