Announcements, Assignments, and Reminders

- Visit the URL links that were covered in previous lectures.
Cumulative Outstanding Reading

- Read chapters 1 and 2 in our book (Huang, Acero, Hon, "Spoken Language Processing").
We’ve covered speech production, including the mechanisms of speech production, and methods to describe the production of speech.
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Acoustic tube model leads to a simple all-pole filter (which will come up again when we talk about feature extraction)!

Speech production analyses for the purposes of speech recognition can be seen as a form of analysis by synthesis: inverse modeling problem, come up with parameters that given signal describe the generative process for that signal.
Outline of today

- Today we begin our discussion of speech perception
- Basic anatomy and physiology of the Ear
- Brief overview of Speech Perception theories
Good books (for today)

- our book (Huang, Acero, Hon, “Spoken Language Processing”)
- Goldstein, “Sensation and Perception”
- Moore, “An Intro to the psychology of hearing”
- Pickles, “An Intro to the physiology of hearing”
- Clark & Yallop, “An Intro to Phonetics and Phonology”
Some good videos to watch

- Overview animation: http://www.youtube.com/watch?v=qgdqpoPb1Q
- Interactive biology TV: http://www.interactive-biology.com/
- Ep 37: How Sound is Transferred to the Inner Ear http://youtu.be/L4F4zaRqQdk
- Ep 38: How We Hear Different Pitches http://youtu.be/Id-L0_7e9BI
- Ep 40: The Role of Hair Cells in Hearing: http://youtu.be/lDXVZ0U_f_E
The ear is of course how we hear.
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The ear is a complicated organ that itself transforms the sounds in quite significant ways, and the way it does so helps to determine the perception of speech.
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The ear itself can be described as having three parts, the outer, middle, and inner ear so we talk about each in turn.
Outer Ear

- Pinna (sound localization)
- Auditory canal - 3cm long, contains Wax
- meatus = pinna + auditory canal
- Tympanic membrane = eardrum: vibration (coupling between air pressure wave and bodily movement)
- Resonance in canal itself, between 2kHz and 5kHz, good for speech.
The Ear

Sound Perception

Speech Perception

Summary

Scratch

Outer & Middle Ears

The Outer and Middle Ears

The diagram illustrates the anatomical structures of the outer and middle ears, including the pinna, temporal bone, tympanic membrane, malleus, incus, stapes, and various nerves such as the facial nerve and cochlear nerve. It also shows the Eustachian tube and other related structures.
Middle Ear

- about 2 cm$^2$ in volume
Middle Ear

- about $2 \, \text{cm}^2$ in volume
- contains ossicles - 3 bones, couples together: 1) end of outer ear, eardrum, and 2) beginning of inner ear via "oval window"
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  - stapes (stirrup)
Why do we have middle ear?

- acoustic coupler to correct for impedance mismatch between air and relatively incompressible fluid in inner ear
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...
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Prof. Jeff Bilmes
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- is most efficient at 500-4k Hz
Middle Ear - acoustic coupler

- Malleus
- Incus
- Stapes
- Tympanic membrane (eardrum)
- Oval window
- Round window
- Auditory canal
Middle Ear - acoustic coupler

Force = \( P_1 A_1 = P_2 A_2 \)

Therefore \( \frac{P_2}{P_1} = \frac{A_1}{A_2} \)

\[ \frac{l_1}{l_2} = \frac{F_2}{F_1} = \frac{V_1}{V_2} \]
“Cochlea” = arguably, most important part of inner ear
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filled with lymphatic fluid
### Inner Ear

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- filled with lymphatic fluid
- tube coiled like snail shell - 35mm long, 2.5 turns
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tube coiled like snail shell - 35mm long, 2.5 turns
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- cochlea has a “base” and an “apex”
- stapes attaches to “scala vestibuli” via oval window, but liquid is not (very) compressible
- round window relieves pressure (like passive radiator, enclosed loudspeakers, but for liquid)
Cochlea
**Inner Ear - Organ of Corti**

- contained in cochlear partition

![Diagram of the Inner Ear - Organ of Corti](image-url)
Inner Ear - Organ of Corti

- contained in cochlear partition
- contains receptors, called “hair cells”
Inner Ear - Organ of Corti

- contained in cochlear partition
- contains receptors, called “hair cells’
- sits atop the “basilar membrane”
Inner Ear - Organ of Corti

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- contains receptors, called “hair cells"
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- covered by the “tectorial membrane”
Inner Ear - Organ of Corti

- about 30k sensory hair cells
Inner Ear - Organ of Corti

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- auditory nerve terminates at these hair cells (each nerve ending has about 40-140 hair cells)
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- hair cell vibration causes nerve firings
- There are both inner and outer hair cells
- outer cells have more nerve endings and have different response patterns
- no final consensus as to the different function of these cells (difficult to measure in a live human without disturbing the entire system)
Cilia, small hairs attached to the hair cells.
### Cilia

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- Hair cells embedded in organ of Corti.
Cilia

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Initially, people thought the were normal hairs but that are actually are microvilli (microscopic cellular membrane protrusions that increase the surface area of cells).
Cilia

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- Called “hair cells” because protruding from them are bundles of tiny protrusions called “stereocilia”.
- Initially, people thought they were normal hairs but that are actually microvilli (microscopic cellular membrane protrusions that increase the surface area of cells).
- When the basilar membrane is deflected by fluid waves in the cochlea, deflection of the stereociliary bundles produces electrical signals in their associated hair cell body.
Hair Cells - SEM picture of a mouse hair cell.

How do hair cells transmit? They bend.
How do hair cells transmit? They bend.

oval window vibration causes a vibration wave to be sent along basilar membrane
How do hair cells transmit? They bend.

- oval window vibration causes a vibration wave to be sent along basilar membrane
- entire organ of Corti vibrates
How do hair cells transmit? They bend.

Oval window vibration causes a vibration wave to be sent along basilar membrane.

Entire organ of Corti vibrates.

Roughly, hair cells "rub" against tectoral membrane at position where vibration occurs.
What is the "Q" of a filter?

- \( Q = \text{center frequency} / \text{bandwidth} \)
What is the “Q” of a filter?

- $Q = \frac{\text{center frequency}}{\text{bandwidth}}$

- history: “$Q$” stands for “quality factor”, high-quality filters are very narrow-band relative to their center frequency.
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- A filterbank is a set of band-pass filters.
What is the “Q” of a filter?

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![Graph showing different Q values](image)

- History: “Q” stands for “quality factor”, high-quality filters are very narrow-band relative to their center frequency.
- A filterbank is a set of band-pass filters.
- A constant \( Q \) filterbank is one where the bandwidth of the filter increases with center frequency. I.e. the \( Q \) of each filter is constant.
• Each position along membrane has a characteristic frequency (CF)
Basilar membrane

- Each position along membrane has a characteristic frequency (CF)
- The CF corresponds to maximum vibration for a given input sound.
Basilar membrane

- Each position along membrane has a characteristic frequency (CF)
- The CF corresponds to maximum vibration for a given input sound.
- Bandwidth is approximately constant $Q$ - bandwidth increases for increasing freq, better spectral resolution at lower frequencies
Basilar membrane vibration

- Wave generated on the basilar membrane by a 400 Hz input tone
Basilar membrane vibration

- Wave generated on the basilar membrane by a 400 Hz input tone

- Approximation, based on solution of integro-differential equation which describes the membrane motion in the linear approximation.
Basilar membrane vibration

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- Approximation, based on solution of integro-differential equation which describes the membrane motion in the linear approximation.
- Waves peak at a frequency-dependent location since: 1) each membrane segment interacts with each other through the fluid the cochlear duct and 2) membrane stiffness is graded from base to apex.
**Basilar membrane vibration**

- Wave generated on the basilar membrane by a 400 Hz input tone

![Image of basilar membrane vibration](image)

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See [http://www.youtube.com/watch?v=1JE8WduJKV4](http://www.youtube.com/watch?v=1JE8WduJKV4), [http://www.youtube.com/watch?v=qgdqpoPb1Q](http://www.youtube.com/watch?v=qgdqpoPb1Q), and for fun see [http://www.youtube.com/watch?v=dyenMluFaUw](http://www.youtube.com/watch?v=dyenMluFaUw)
Traveling Waves

- traveling wave (von Bekesy)
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- oval window vibrates - waves travel up basilar membrane
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- max amplitude of wave = point on BM where CF matches input frequency
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- max amplitude of wave = point on BM where CF matches input frequency
- high freq = at base
- low freq = at apex
Traveling Waves

- traveling wave (von Bekesy)
- oval window vibrates - waves travel up basilar membrane
- max amplitude of wave = point on BM where CF matches input frequency
- high freq = at base
- low freq = at apex
- stiffness of BM is a factor
Two views of frequency encoding

- Place Theory, von Bekesy’s traveling way (as described above)
Two views of frequency encoding

- **Place Theory**, von Bekesy’s traveling way (as described above)
- **Timing theory** (an alternative theory)
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- some disagreement here still
Timing - phase locking of nerves

Stimulus

1 2 3 4 5 6 7 8 9 10 11 12

- a
- b
- c
- d
- e

Total response
Timing - phase locking of nerves, more realistic
Two views of frequency encoding

- **Place**
Two views of frequency encoding

- **Place**
  - weak at < 1kHz since traveling wave is wide
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  - good at < 1kHz since timing can encode information (fire) at rates fast enough for these frequencies
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- **Both operate at frequencies between 1k - 5kHz (but still open question)**
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- Mel-scale frequency warping
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  - linear below 1kHz, log thereafter
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- **Mel-scale frequency warping**
  - linear below 1kHz, log thereafter
  - Used ubiquitously for speech recognition
  - similar to the place-timing view above
  - Mel-scale is the “M” in MFCCs, which we will learn about.
Sound Perception

- Thresholds - auditory system has a dynamic range
Sound Perception

- Thresholds
Sound Perception

- Thresholds
  - thresholds of hearing
Sound Perception

- Thresholds
  - thresholds of hearing
  - threshold of "annoyance"
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  - thresholds of feeling (pain)
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- Speech frequencies relative const. threshold of hearing
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- F0’s of male and females (typically)
Sound Perception

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- F0’s of male and females (typically)
  - Males: $F_0 = 50-250 \text{ Hz}$
Sound Perception

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- **Speech frequencies relative const. threshold of hearing**

- **F0’s of male and females (typically)**
  - Males: $F_0 = 50-250$ Hz
  - Females: $F_0 = 120-500$ Hz
Sound Perception

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- Speech frequencies relative const. threshold of hearing

- F0’s of male and females (typically)
  - Males: F0 = 50-250 Hz
  - Females: F0 = 120-500 Hz
  - So easier to hear females at lower volume
Fletcher & Munson Curves

- Loudness ≠ Intensity

![Graph showing Fletcher & Munson Curves](https://via.placeholder.com/150)
Units of Loudness - Phons

- 80 phons = different SPLs at different frequencies
Units of Loudness - Phons

- 80 phons = different SPLs at diff. frequencies
Masking

- perception of one sound is obscured by presence of another sound
  - raises threshold of hearing for other sound
  - “A masks B” means A makes you unable to hear B.
Masking

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- perceptual auditory coding (e.g., mpeg standards)
  - use fewer bits (more additive noise) by quantizing at a coarser scale
    where perceptual system might mask a given sound by some louder sound
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- simultaneous masking - two sounds at once, one masks the other
- temporal masking
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  - forward masking/backward masking
Masking

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  - different neurons have different characteristic frequencies, or CFs (point of lowest threshold)
Neural tuning curve - Cat
“Neural” (or really psychophysical) tuning curve - Human

- **L_m**
  - **L_p** \( \hat{=} 10 \text{ dB SL} \)
  - **T = 50 ms**
  - Subject LV

- **dB SPL**
  - 100
  - 90
  - 80
  - 70
  - 60
  - 50
  - 40
  - 30
  - 20
  - 10
  - 0
  - -10
  - -20

- **f_m**
  - 0.05
  - 0.1
  - 0.2
  - 0.5
  - 1
  - 2
  - 5
  - 10 kHz
  - 20
Two signals mixed together, the signal and the masker.
Psychophysical tuning curve - Human

- Two signals mixed together, the *signal* and the *masker*.
- Fixed level sinusoidal tone *signal* occurs in narrow-band noise *masker* having a center (masker frequency).
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- masking threshold as a function of masker frequency and masking intensity with fixed signal ⇒ CF (linearity assumption)
- there are other ways to do this as well
Speech Perception

- Much higher level in auditory cortex or brain - not well understood
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- phonemes, phones, syllables, words, phrases, sentences, etc. Is there an ideal realization?
- Difficult since acoustic cues for an object change depending on context, other perceptual modalities (McGurk effect), prior beliefs, etc.
Cues depend on context

![Graph showing frequency vs time for di and du](image-url)
Cues depend on context

- Cues for different “d” sounds are different depending on context.
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  - This is one of the reasons formants are unreliable to do phone classification
- So even considering acoustics, percept is dependent on more than just acoustic cues at the current time.
- Hence, must be more than just formants that are used to determine words. E.g., temporal patterns, long context, adaptation (time dependence, dependence on what you’ve previously been exposed too), etc.
Social Structure of Speech

- Turns “influence” each other (i.e., knowing the constituent parts of one turn allows either us, or in theory a statistical model, to make more informed predictions about aspects of another turn).
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- Current ASR systems do not fully exploit these phenomena.
200-5.5kHz most important — by filtering out spectral regions and measuring intelligibility
Spectral Regions of Speech Perception

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- Hence, ISDN: 4kHz BW, early digital speech channel, prior to coding and compression being ubiquitous
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- Hence, ISDN: 4kHz BW, early digital speech channel, prior to coding and compression being ubiquitous
- formal perceptual theories to determine intelligibility. E.g., the “Articulation Index” by Steeneken and Houtgast
Spectral Regions of Speech Perception

- Ex: filter out < 1kHz, then voicing and manner of articulation discrimination decreases (/p/ vs. /b/ vs. /v/)
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Telephone bandwidth 200-4kHz (good enough for most intelligibility)

Particularly bad are the infamous “E-set” /p/, /d/, /e/, /g/, /c/, etc. vowel energy
we are remarkably good at perceiving speech
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Recall the sine-wave speech, and the 1-bit speech from a few lectures ago.
Human Speech Perception

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- face recognition, when do we see a face?
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face recognition, when do we see a face?

therefore, hard to identify most important cues, since they all could potentially be used depending on context
Human Speech Perception

- Speech contains much redundant information, much can be removed w/o impacting intelligibility – E.g., checkerboard speech
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- Spectral transitions, derivatives might be key?
- Gaussian Scaled Speech (example)
- Apparently, no particular location in time/frequency that contains the crucial information (we can infer what is missing from the other bits)
- Redundancy allows us to perceive speech in many different acoustic situations — e.g., background noise, cocktail party effect
Complicated tube analysis gives us LPC.
Summary

- Complicated tube analysis gives us LPC.
- Perhaps we can hence start with LPC analysis of speech and use that.