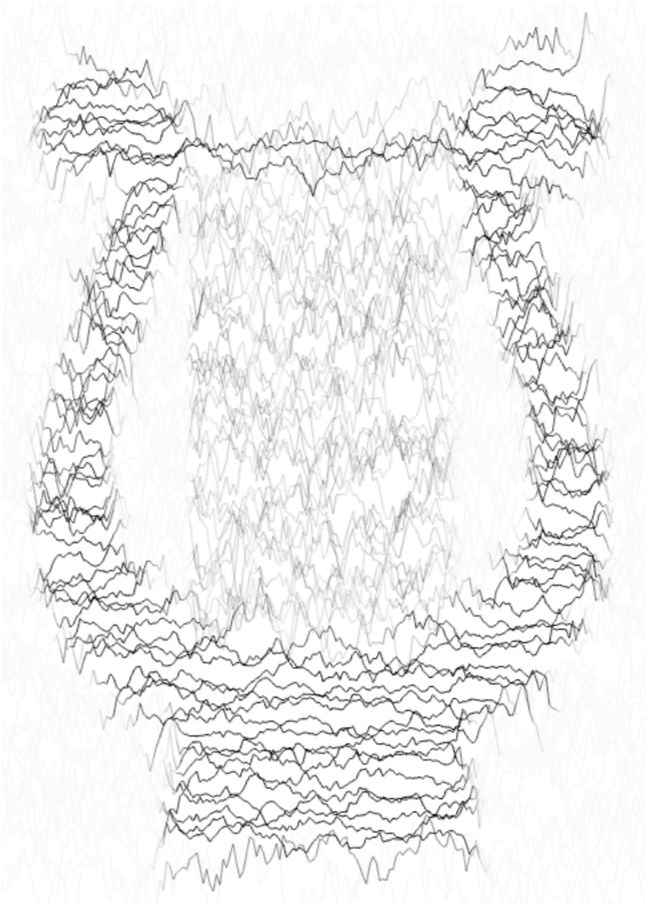

CS 498PS – Audio Computing Lab

3D and Virtual Sound

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Overview

- Human perception of sound and space
  - ITD, IID, HRTFs, and all that
- 3D audio
  - Measuring HRTFs
  - Synthesizing 3D audio
- Virtual audio
  - Synthesizing virtual audio

What is 3D audio?

- Fooling a listener that a sound is coming from a specific location around them

- Two ways to get it:
  - Easy: Using headphones
  - Hard: Using speakers

What is virtual audio?

- Modeling the effects of being in a virtual environment
  - Includes 3D audio effects
  - Also includes room effects
  - Also includes additional environmental effects

Why bother?

- Entertainment
  - Immersive gaming, 3D movies, virtual worlds, …
- Practical
  - Help listeners parse more audio streams simultaneously
  - Help users localize multiple sources
    - e.g. pilot discussions in place cockpits
  - For grabbing people's attention
    - E.g. in auditory display interfaces

A bit of hearing theory

- In order to synthesize 3D audio we need to know how to fool the human ear
- What are the cues that we need to use?
  - And how do we implement them?
- Lots of levels of complexity

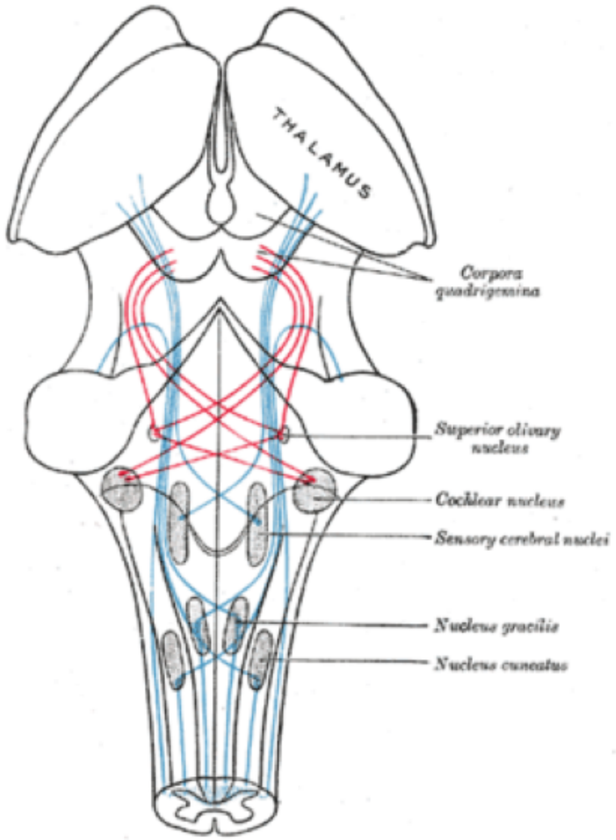
On having two ears

- Why are our ears on the sides of our head?
  - Why not one on the chin and one on the forehead?

Fundamentally different than vision

- Unlike our eyes that directly perceive 3D, our ears have to get that "computed" in the brain

- Special neural circuits in the Superior Olivary Complex (SOC) compare signals from both ears

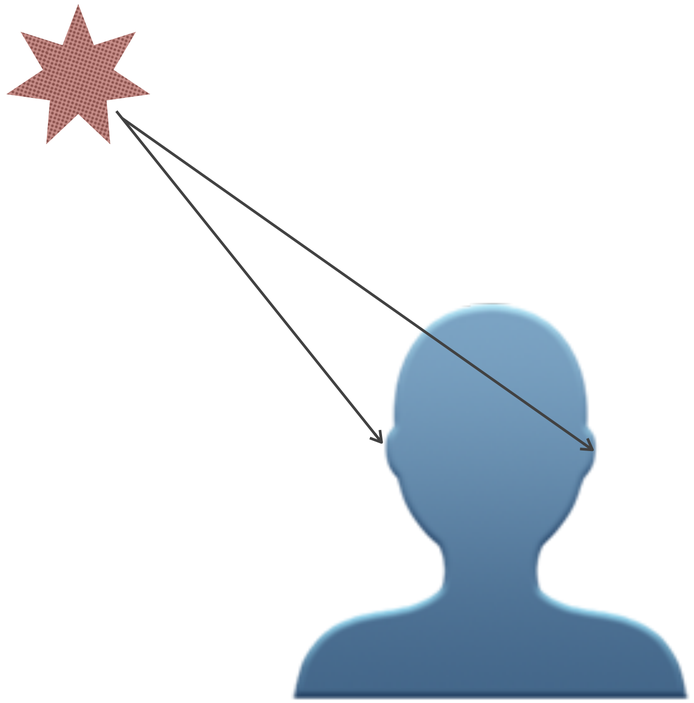


The Duplex Theory

- Formulated by Lord Raleigh (1907)
- A listener's ears receive a sound with some minor differences which act as localization cues
- The two main cues
  - Interaural Time Differences (ITD)
  - Interaural Intensity/Level Differences (IID, or ILD)

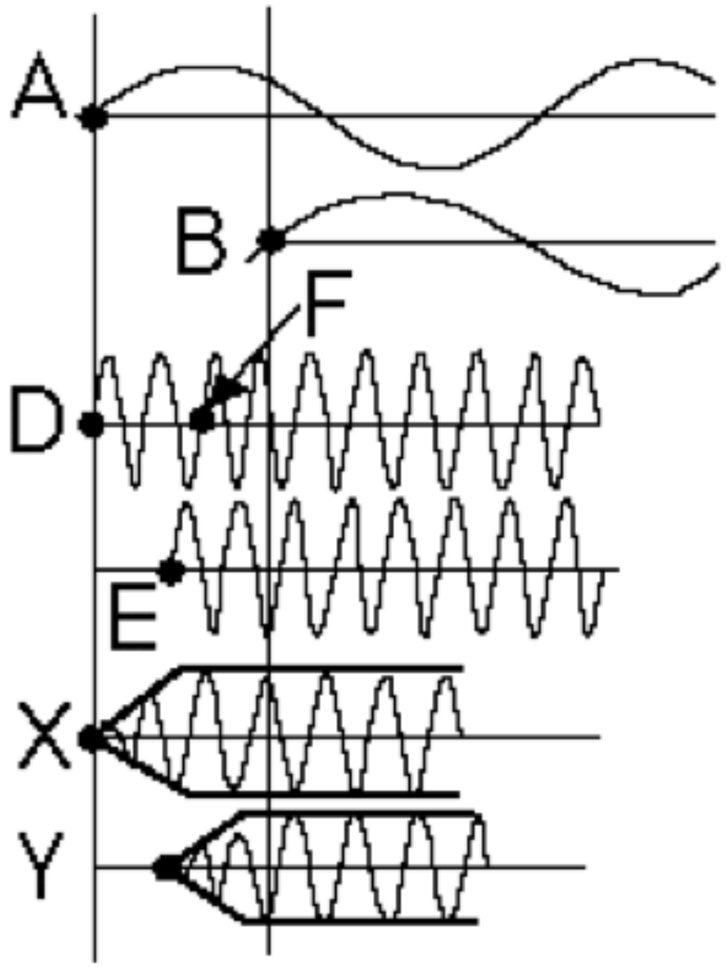
Interaural Time Differences (ITD)

- Simplest possible cue
  - Relative time difference between a sound reaching our ears
    - Sounds familiar?



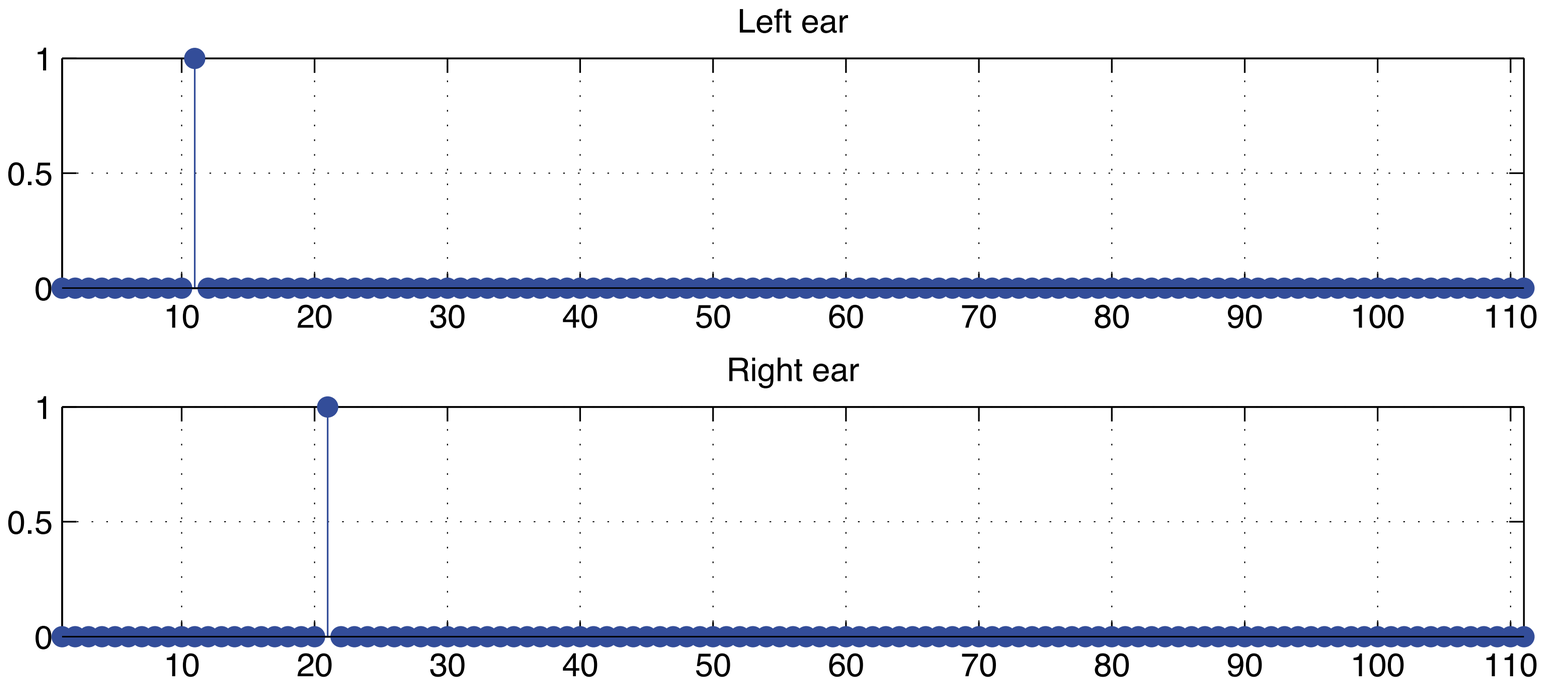
ITD tradeoffs

- Perceiving ITDs is increasingly more unreliable with higher frequencies
  - Historically the cutoff was set to 1.5kHz (any guess why?)
- But we also perform ITD with the envelopes of sounds that we hear
  - So we use higher frequencies as well



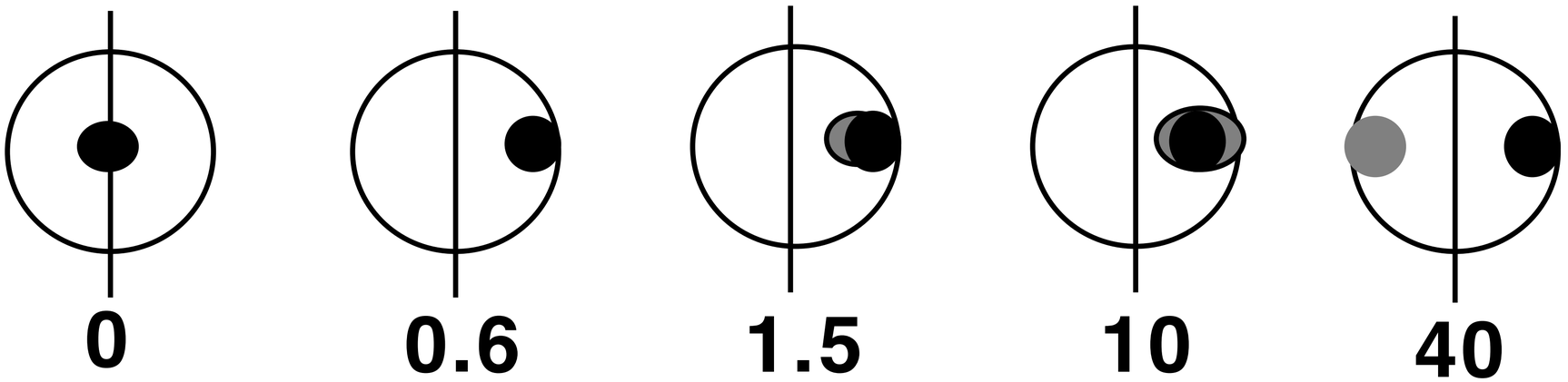
How we will model it

- We can simulate ITDs with delays
  - Similar idea to the mic array steering vector
- There will be an upper limit to the delay
  - What is it?



One more thing

- The precedence effect (a.k.a. Haas effect)
- Up to 40msec delays register as an ITD
  - More than that and we form echo percepts



Interaural Intensity Differences (IID)

- For wavelengths smaller than the listener's head we observe sound absorption
  - High frequencies get attenuated
  - Low frequencies pass mostly unharmed
- Level differences in high frequencies are a very strong cue to help us localize sounds
  - They are called IIDs, or ILDs
    - For intensity or level

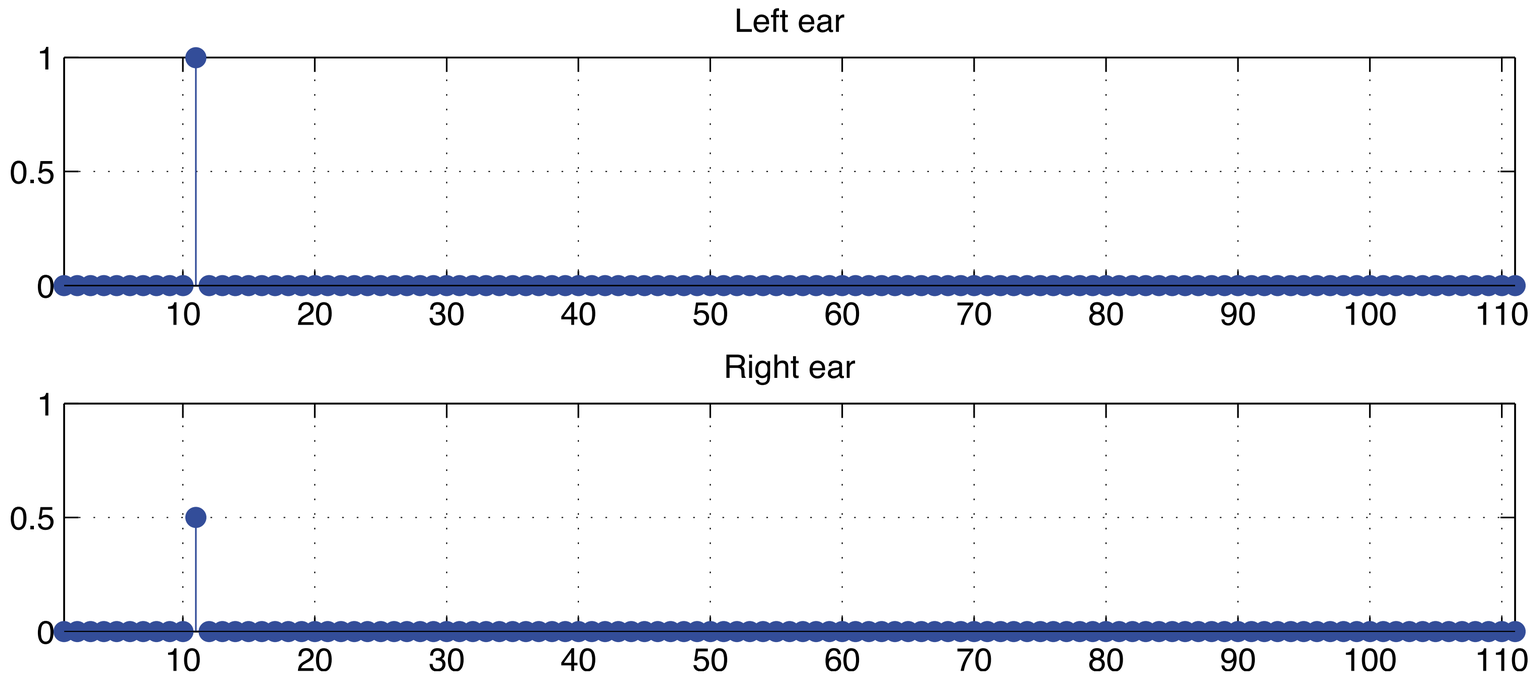
IID tradeoffs

- IIDs mostly apply to wavelengths shorter than the head of the listener
  - About a 1.5kHz cutoff
  - Lower frequencies diffract around the head

- IIDs work better when the sound source is off the plane between the two ears
  - Otherwise there is no relative head shadowing
    - What's an example location?

How can we model it?

- Easy to model using gain between ears
  - The “panpot” model
    - Ignores frequency dependencies (more later)
- Can be implemented as a filter



“Lateralization”

- ITDs and IIDs tend to produce lateralization
  - The percept of a sound on the axis between ears
  - “Inside the head” effect

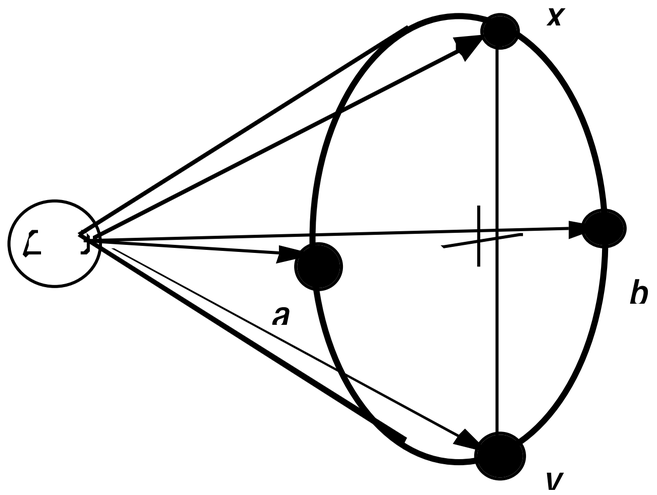
- Useful for studying perception
  - But not quite 3D sound

Combining ITDs and IIDs

- We can very simply combine both cues
  - This will give us a rudimentary 3D system
- Each ear gets a filter
  - Filter imposes a time delay for ITD
  - And a gain factor for the ILD
- Demo!

Cones of confusion

- There are parts of space that will result in the same ITD and IID values
  - We cannot distinguish sounds from these locations
    - At least not well
    - In real-life we resolve that by moving our heads



Zoological intermission

- The Barn Owl
  - Hunts through hearing in the dark
- Can shape its face to funnel sound towards its ears
- Has asymmetrical ears
  - Can use ITDs for horizontal, and IIDs for vertical localization

Entomological intermission

- The Ormia Ochracea
  - Finds host crickets through hearing
  - Very good at localization!
- Ears are 0.5mm close
  - How does it use ITD/IID?
- Coupled eardrums create new cues
  - Currently used as model for new mics

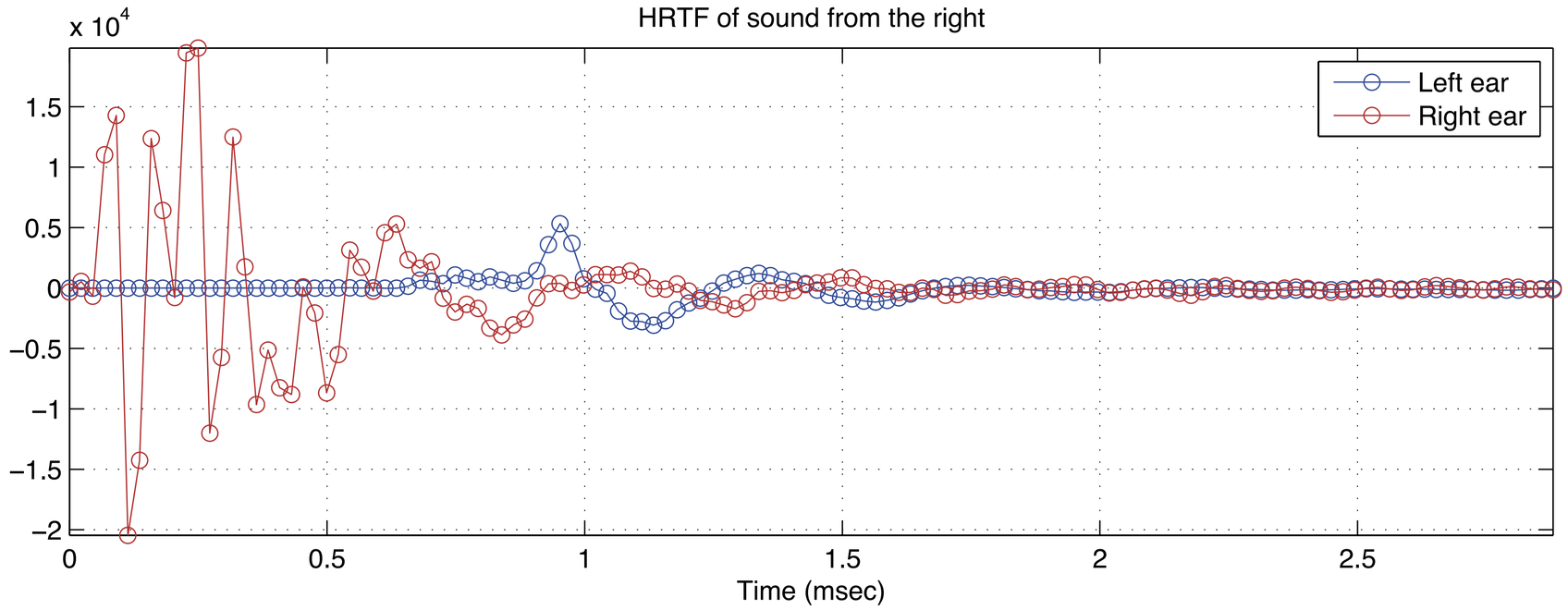
One cue to rule them all!

- ITDs and ILDs can be insufficient
  - Very simple model of environment
  - Our ears adapt to localize and are in fact a lot smarter

- Head Related Transfer Functions (HRTFs)
  - Incorporating more, and finer cues for localization

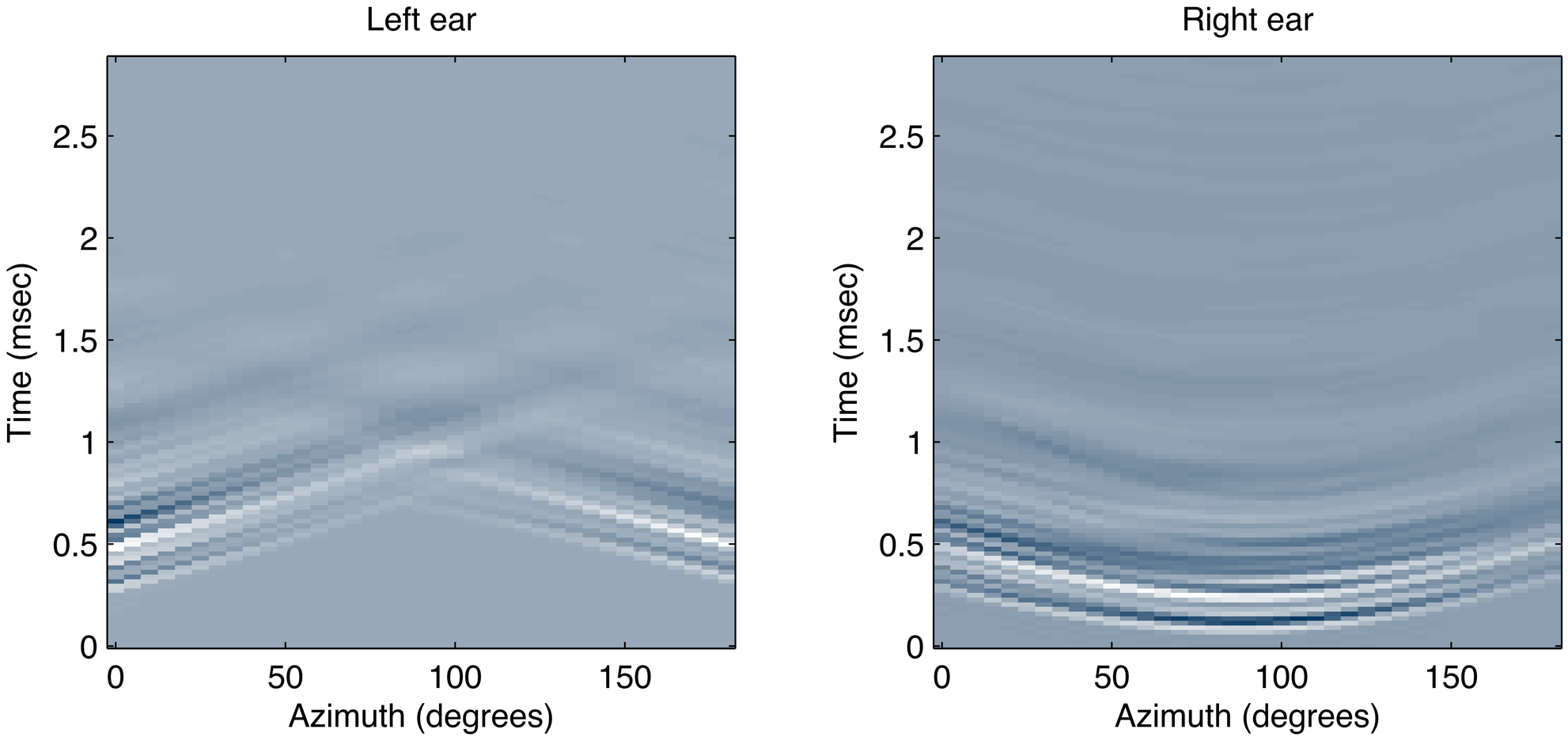
What to HRTFs capture?

- Many effects relating to our body
  - Funneling by the ears, reflections off our shoulders, sound absorption from head, effects from hair, …
  - They also incorporate ITDs and ILDs



How do they look like?

- Sweep from front to back (right side)



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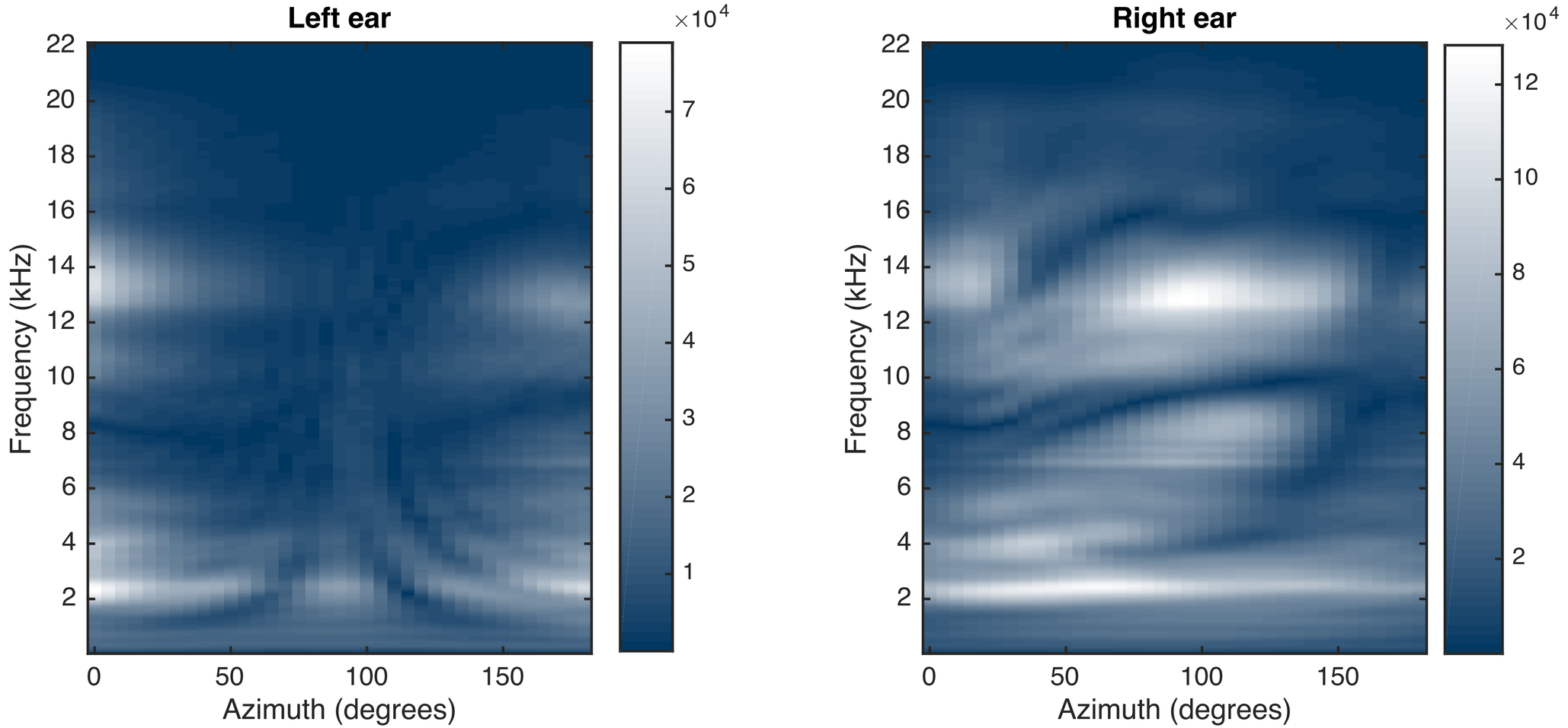
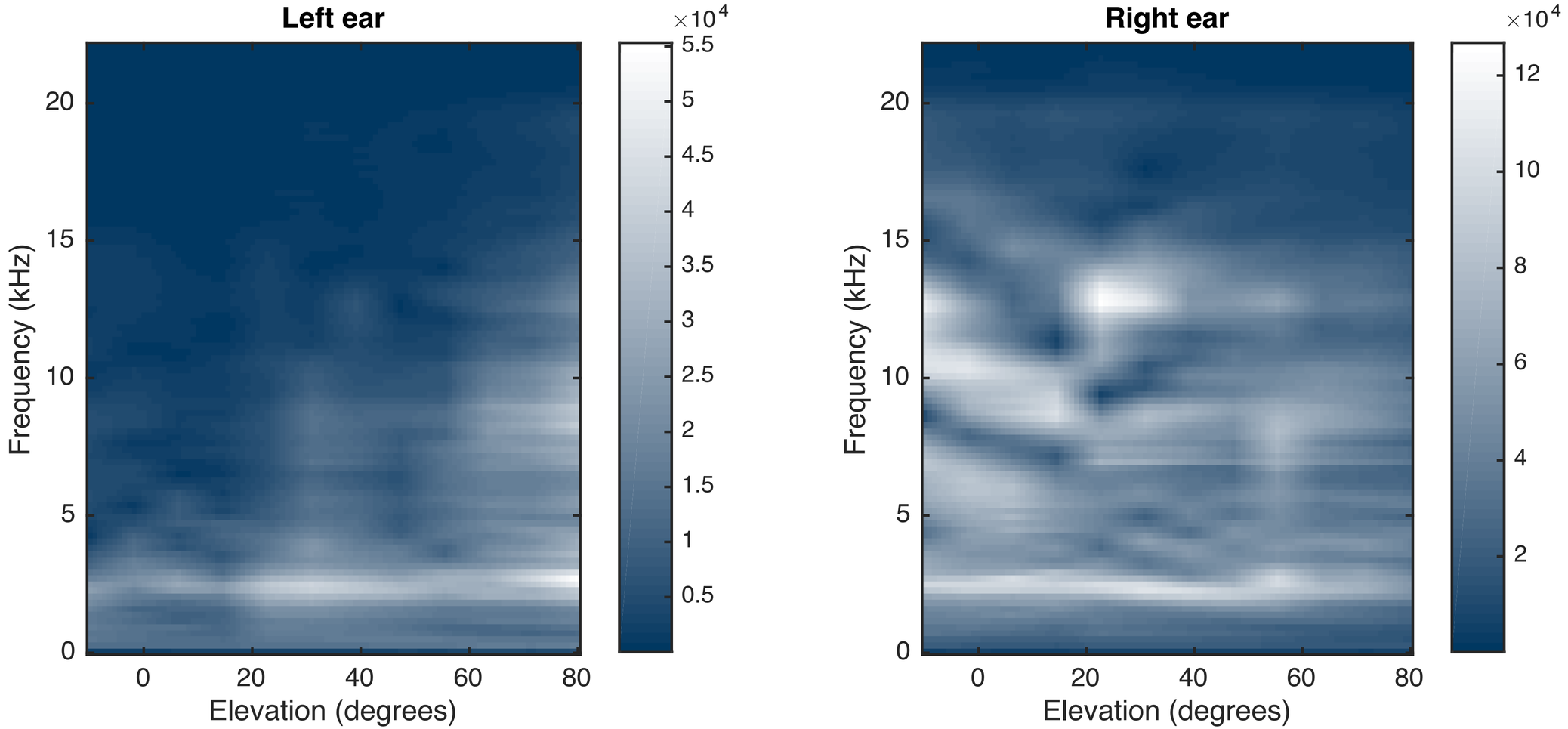


How do they look like?

- Sweep from down to up on the right



How good are HRTFs?

- Each person has a different head/torso shape
  - We often just use average HRTFs
    - They won't work for everyone
    - Being average helps in this case!

- But how to we get HRTFs?

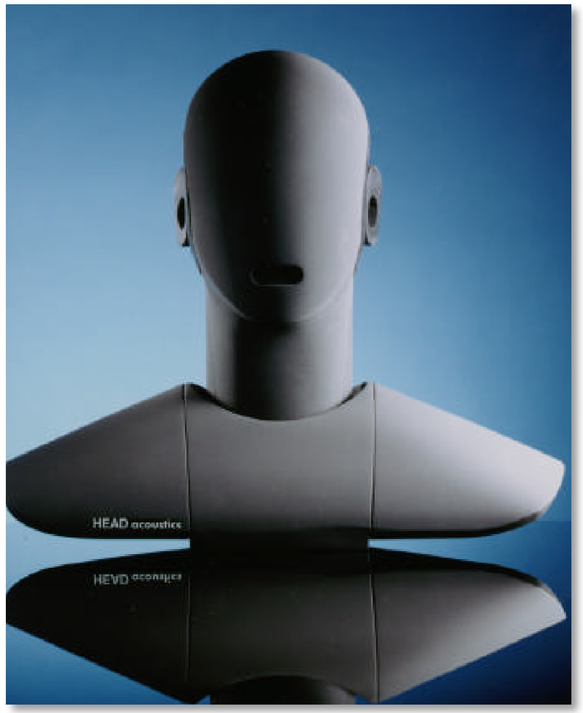
Solution 1: Binaural recordings

- Use a dummy head to make 3D recordings
- Or stick microphones in your ears
  - (but please don't stick anything in your ears!!)

Solution 2: Measure real HRTFs

- If we measure real HRTFs we can then use them on arbitrary sounds to make 3D audio
  - Just apply them as filters to generate left/right/signals

- Two ways to measure HRTFs
  - Measure a dummy head's HRTF
    - Should be an "average" set
  - Measure your own HRTFs
    - You then have a personalized copy



How do we measure HRTFs?

- Same process as measuring room responses
  - Setup microphones in dummy of human subject
  - Play MLS from different locations
  - For each location measure the transfer function
    - You should remove the speaker/mic functions though

- Pro tip
  - You should do that in an anechoic chamber
    - Why?

In math

- We record:

$$y_{\theta,\phi}[t] = h_{\theta,\phi}[t] * x[t]$$

$$Y_{\theta,\phi}[\omega] = H_{\theta,\phi}[\omega] X[\omega]$$

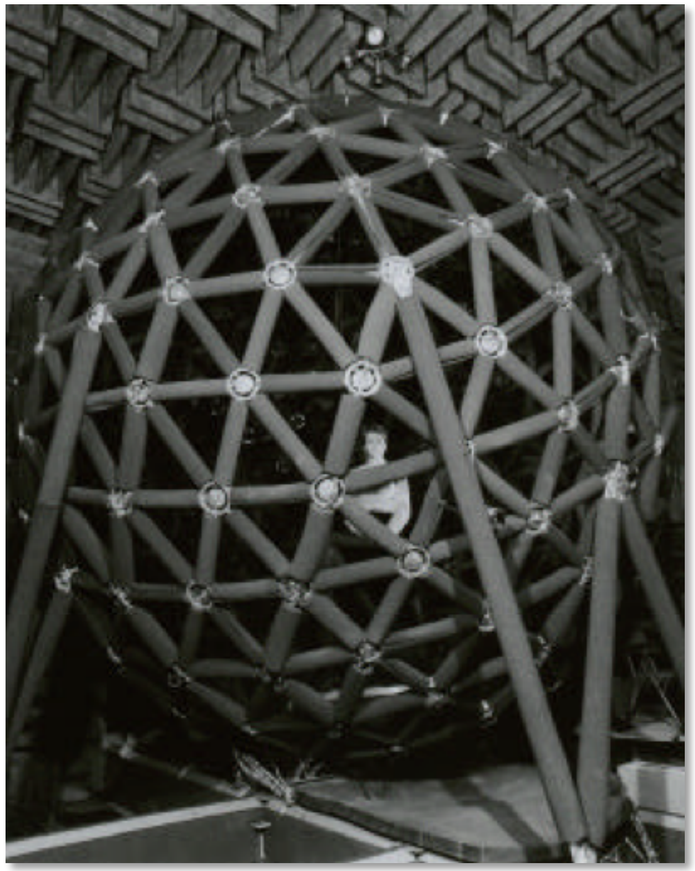
- We deconvolve with:

$$H_{\theta,\phi}[\omega] = X^{*}[\omega] Y_{\theta,\phi}[\omega]$$

- We remove speaker/mic responses
  - Use inverse filters of these responses
    - How do we measure these?

One complication

- This requires some serious lab space



One more complication

- We measure the transfer function from the source location to inside the ear

- What will convolution with an HRTF give us?
  - How do we reproduce it to sound as being 3D?

Synthesizing 3D audio

- Pick a location to position a source
  - Usually azimuth/elevation
- Select appropriate filters from HRTF set
  - Note that there is left.right symmetry so there is no need to keep all of the HRTFs
- Filter sound to model 3D effects
  - What about moving sounds?

Fast convolution reminder

- Convolution can be sped up significantly using the FFT
  - Perform convolution in the frequency domain
  - Complexity drops to $2N \log_2 N$

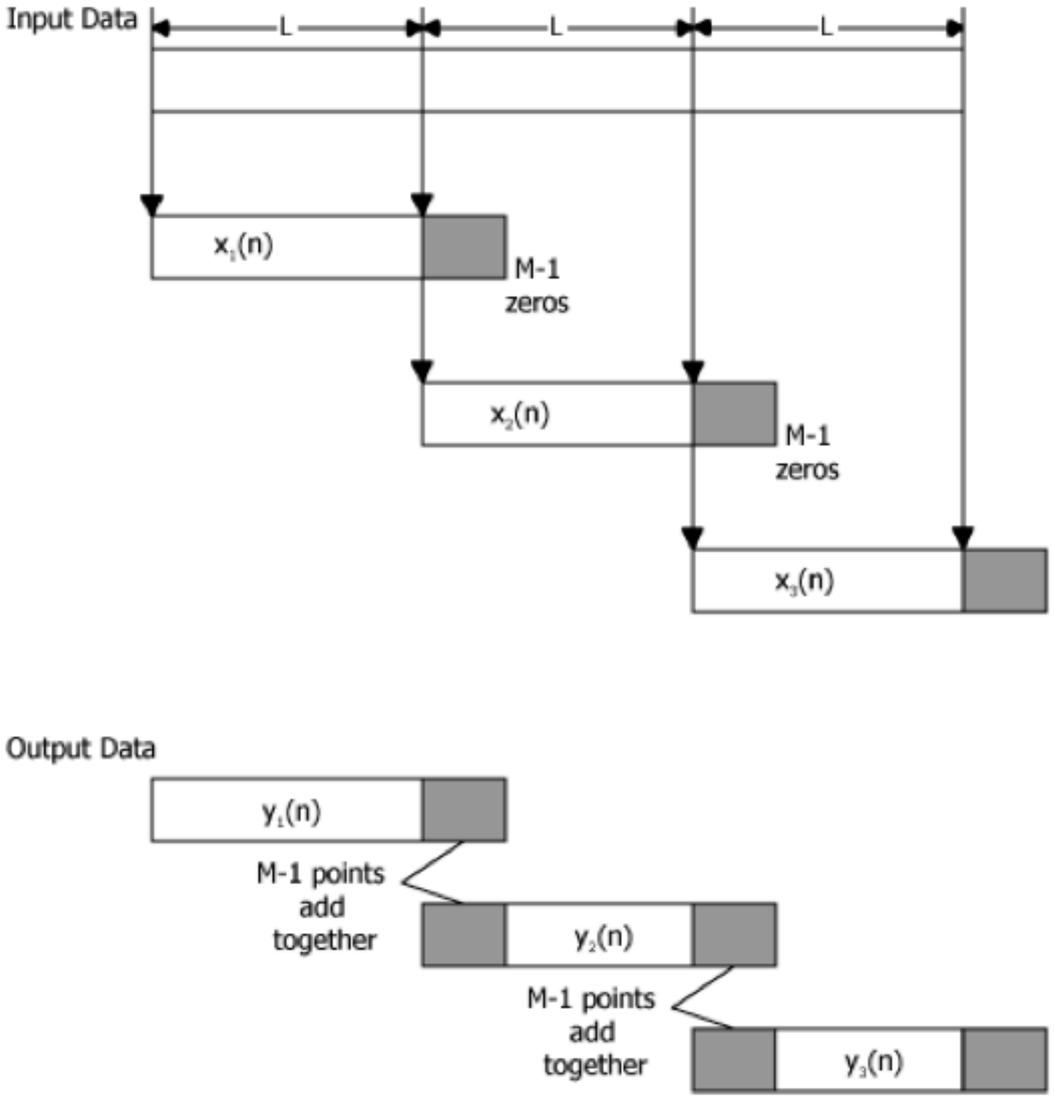
$$z = x * y \Leftrightarrow \mathrm{DFT}\left(z\right) = \mathrm{DFT}\left(x\right) \odot \mathrm{DFT}\left(y\right)$$

  - But is this useful for out case?
    - No, results in very large FFTs, doesn't allow for changing filters

- Using the STFT for convolution instead
  - Convolve each STFT frame with the desired filter at that time

Overlap-add fast convolution

- Similar to spectrograms
  - Step 1: Make frames
    - Zero pad to accommodate convolution's output length
    - Hop size == frame size
    - Do not window
  - Step 2: Convolve frames using FFTs
    - i.e. multiply complex spectra
      - Multiply each STFT frame with the DFT of the desired filter
  - Step 3: Invert back to time
    - Use overlap and add!
    - Do not window



Usual problems

- Response mismatch
  - People with funny head shapes
  - Poor reproduction (e.g. bad headphones, MP3s)
- Front/back confusion
  - Really prominent for many people
- Head movements
  - Chance the relative angle of a source

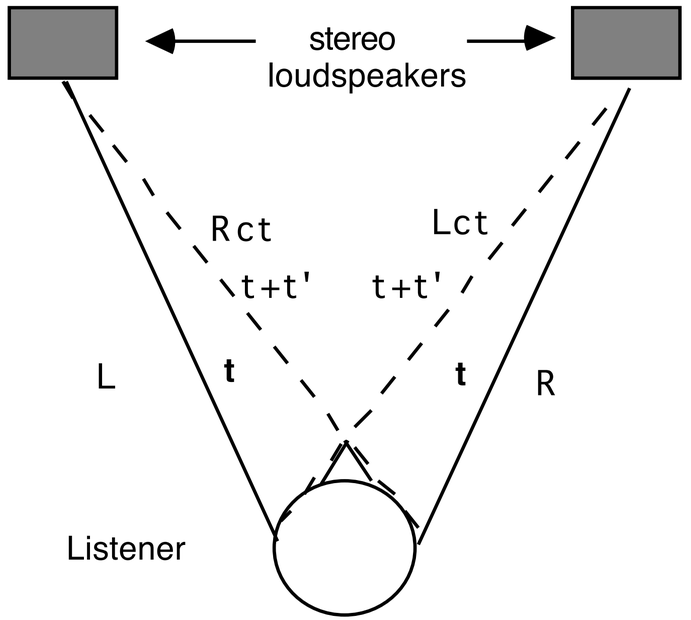
Compensating for head movement

- We can track the listener's head movements
  - Using a simple sensor on the headphones
  - Or using computer vision to measure head pose

- This allows us to find the angle between the virtual source and the rotated use head
  - One drawback: Time lag
  - One advantage: We can resolve localization ambiguities
    - We use head movements to deal with ambiguities

What about speakers

- We need to perform crosstalk cancellation
  - Use “negative” signals to construct HRTF filtering



- What are the complications here?

Complications with speaker systems

- Head movements
  - We need to compensate for moving ears!
  - Not trivial to cater to multiple people simultaneously
    - E.g. you won't get 3D sound in a movie theater

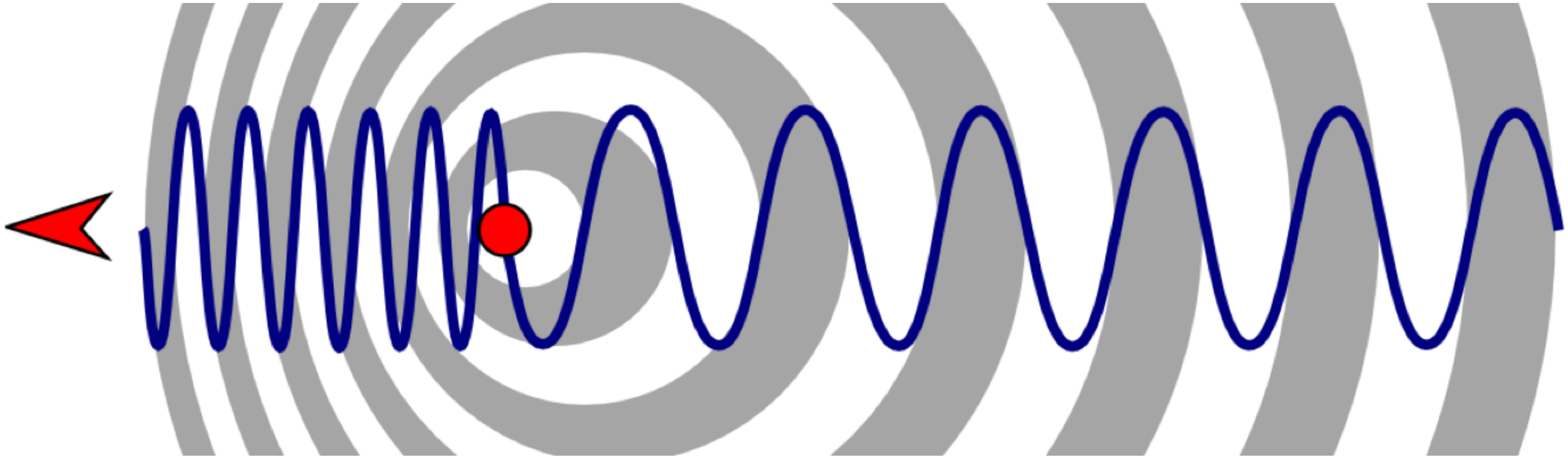
- Room effects
  - Speaker output gets convolves with room
    - and speakers …
  - Difficult to compensate for all that

Moving towards virtual sound

- 3D sound models source-to-ear effects
  - Created 3D percept, but this is not the whole story
- There are more cues that we use to localize
  - Movement cues, distance cues, context cues, …
- Proper virtual audio also models these cues

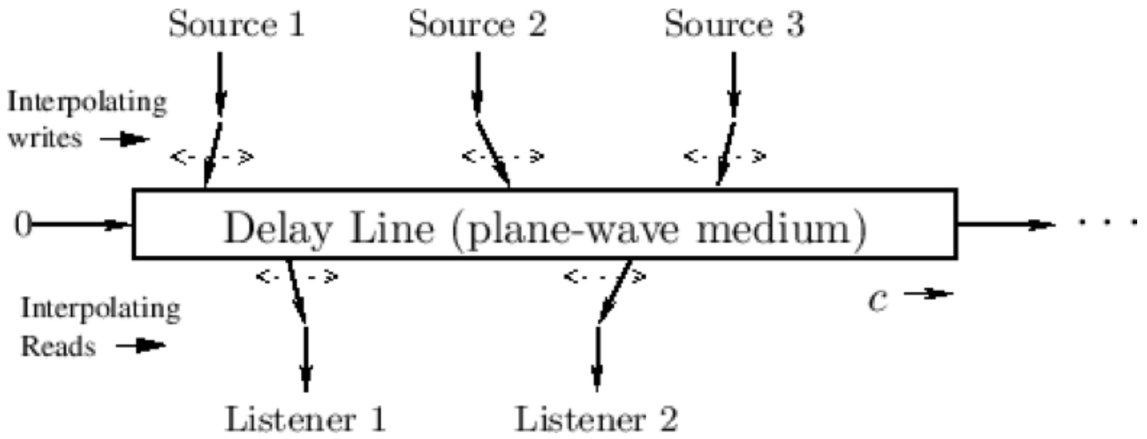
Movement cues

- Moving sources exhibit an additional important cue for localization
  - The Doppler effect



Modeling the doppler effect

- Variable delay lines
  - We can read off a delay line with interpolation
    - Sort of like changing the sample rate



  - Tricky to get good interpolation
    - More later in the semester

Distance cues

- We can also perceive how far a sound is
- Static cues
  - Level, amount of reverberation
- Dynamic cues
  - Change of source angle by head translation

And some more context cues

- Room acoustics
  - Sounds in different parts of a room sound different
- We can use HRTF filter on all the reflections
  - Overkill, but makes a difference
- And we know how to do that now! :)

Virtual sound can be complicated

- Lots effects that combine
  - Not completely clear which are necessary
    - Depends on usage scenario
  - Also not fully clear how they all interact

- Still an open problem
  - But sounds pretty good as is

Surround sound

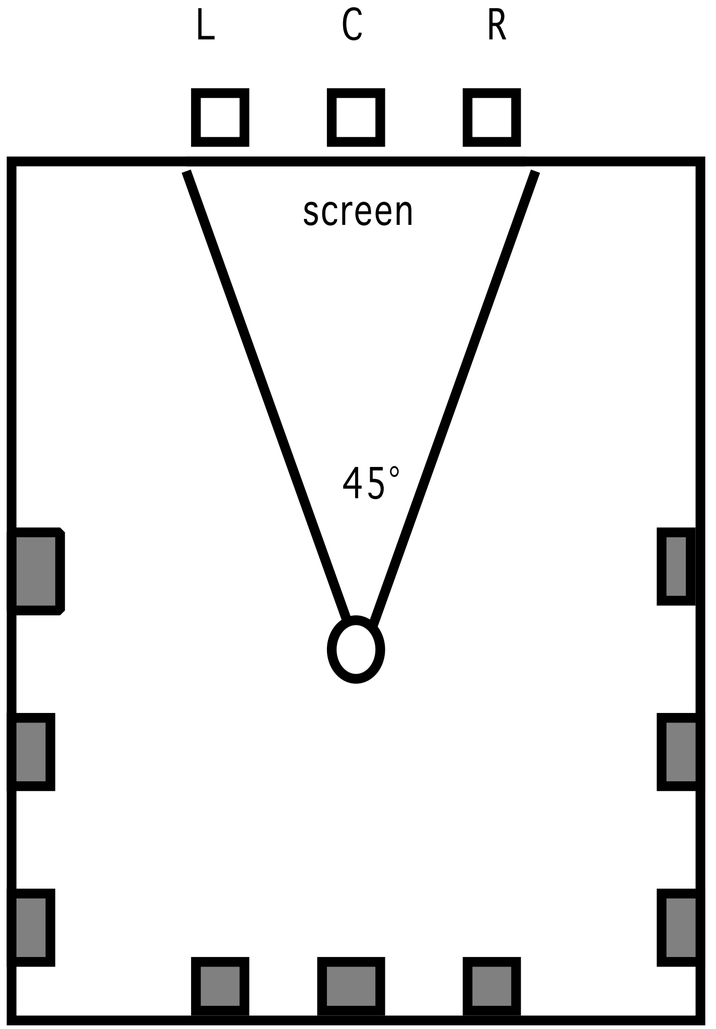
- Potentially simpler approach
  - Localization takes place using multiple speakers
  - Optionally one can use sophisticated filtering

- Common setups
  - 5.1 /7.1 sets
  - Stereo “surround”
    - Avoid like the plague!
    - Ruins stereo imaging

A virtual acoustic room setup

Theater surround sound

- Front channel for dialog
  - Ensures consistent localization
- Side and rear channels for FX
  - Also ambience sounds
- One of Dolby's claims to fame



Recap

- Some of the basics of 3D perception
- HRTFs
  - How to measure them
  - How to use them
- Additional ties for virtual audio
- Surround sound

Reading material

- 3D Sound for Virtual Reality and Multimedia
  - http://human-factors.arc.nasa.gov/publications/Begault_2000_3d_Sound_Multimedia.pdf

Next lab

- Let’s make some 3D sounds!
  - Remember to bring your headphones/earphones
    - You won’t be able to hear the results otherwise