EE E6820: Speech & Audio Processing & Recognition

Lecture 8: Spatial sound

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Outline

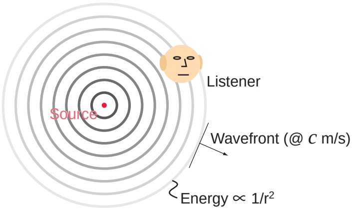
1. Spatial acoustics
2. Binaural perception
3. Synthesizing spatial audio
4. Extracting spatial sounds

Spatial acoustics

- Received sound = source + channel
  - so far, only considered ideal source waveform
- Sound carries information on its spatial origin
  - "ripples in the lake"

  - evolutionary significance
- The basis of scene analysis?
  - yes and no—try blocking an ear

Ripples in the lake

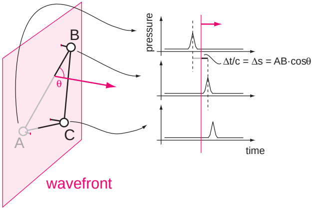


- Effect of relative position on sound
  - delay $= \frac{\Delta r}{c}$
  - energy decay $\sim \frac{1}{r^2}$
  - absorption $\sim G(f)^r$
  - direct energy plus reflections
- Give cues for recovering source position
- Describe wavefront by its normal

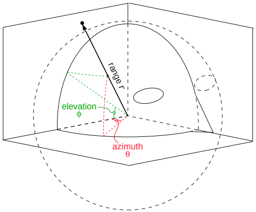
Recovering spatial information

Source direction as wavefront normal

- moving plane found from timing at 3 points



- need to solve correspondence

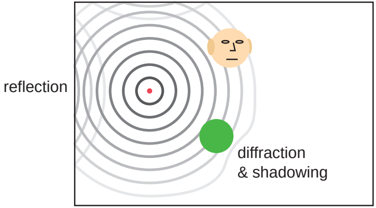


Space: need 3 parameters

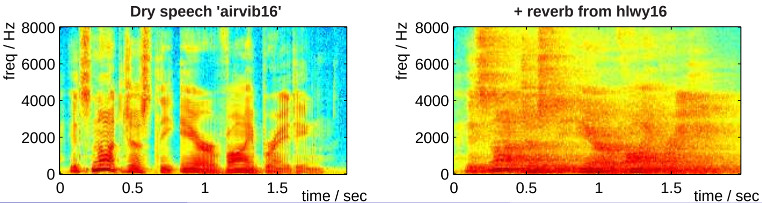
e.g. 2 angles and range

The effect of the environment

- Reflection causes additional wavefronts

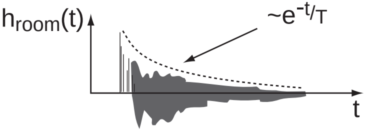


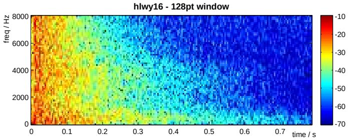
  - + scattering, absorption
  - many paths → many echoes
- Reverberant effect
  - causal 'smearing' of signal energy



Reverberation impulse response

- Exponential decay of reflections:





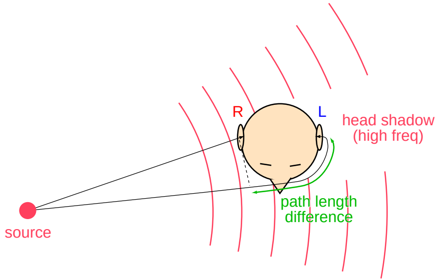
- Frequency-dependent
  - greater absorption at high frequencies → faster decay
- Size-dependent
  - larger rooms → longer delays → slower decay
- Sabine's equation:

$$RT_{60} = \frac{0.049V}{S\bar{\alpha}}$$

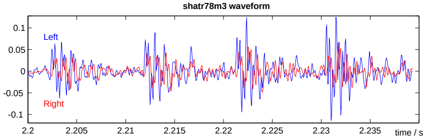
- Time constant as size, absorption

Outline

Binaural perception

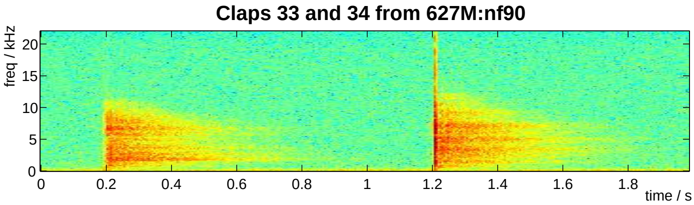


- What is the information in the 2 ear signals?
  - the sound of the source(s) (L+R)
  - the position of the source(s) (L-R)
- Example waveforms (ShATR database)



Main cues to spatial hearing

- Interaural time difference (ITD)
  - from different path lengths around head
  - dominates in low frequency (< 1.5 kHz)
  - max $\sim$750 μs $\rightarrow$ ambiguous for freqs $>$ 600 Hz
- Interaural intensity difference (IID)
  - from head shadowing of far ear
  - negligible for LF; increases with frequency
- Spectral detail (from pinna reflections) useful for elevation & range
- Direct-to-reverberant useful for range

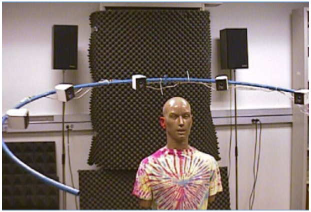


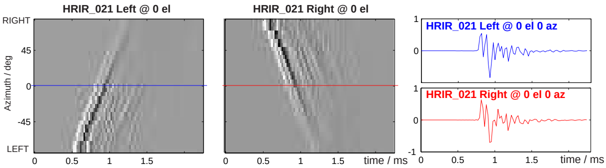
Head-Related Transfer Functions (HRTFs)

- Capture source coupling as impulse responses

$$\{\ell_{\theta,\phi,R}(t), r_{\theta,\phi,R}(t)\}$$

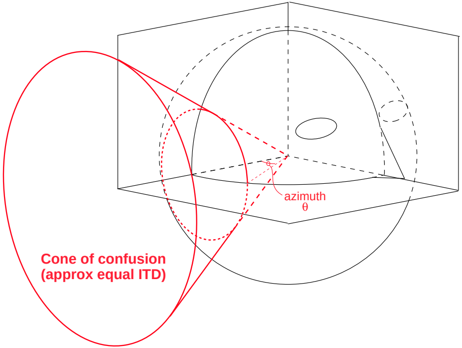
- Collection: (`http://interface.cipic.ucdavis.edu/`)





- Highly individual!

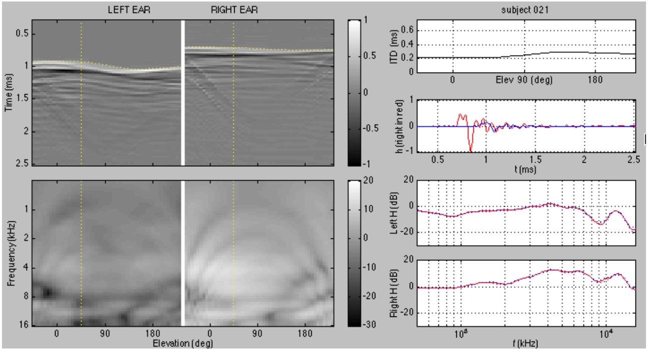
Cone of confusion



- Interaural timing cue dominates (below 1kHz)
  - from differing path lengths to two ears
- But: only resolves to a cone
  - Up/down? Front/back?

Further cues

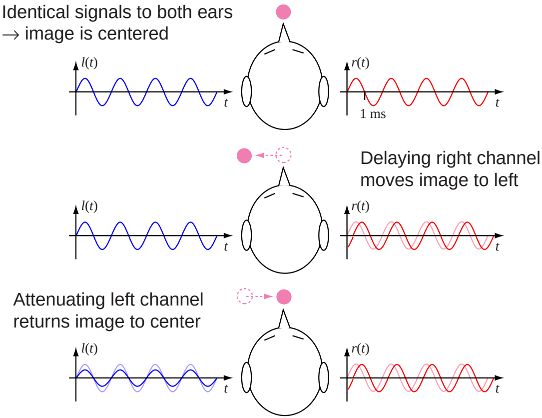
- Pinna causes elevation-dependent coloration



- Monaural perception
  - separate coloration from source spectrum?
- Head motion
  - synchronized spectral changes
  - also for ITD (front/back) etc.

Combining multiple cues

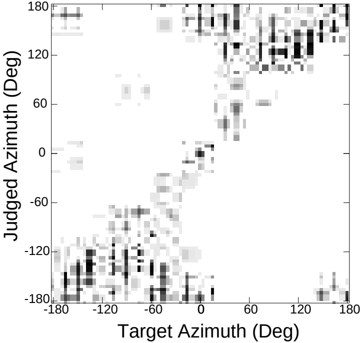
Both ITD and ILD influence azimuth;
What happens when they disagree?



- "Time-intensity trading"

Binaural position estimation

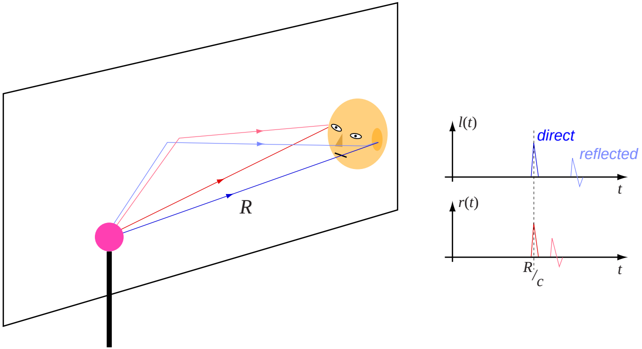
Imperfect results: (Wenzel et al., 1993)



- listening to 'wrong' HRTFs → errors
- front/back reversals stay on cone of confusion

The Precedence Effect

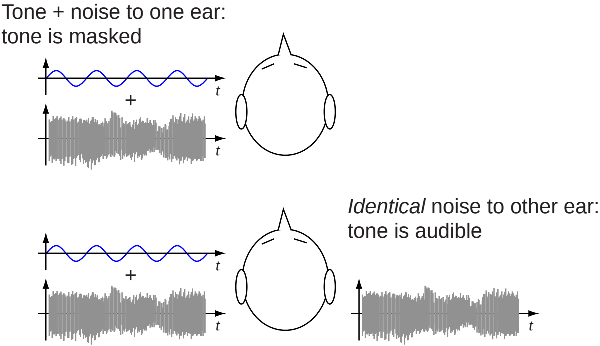
- Reflections give misleading spatial cues



- But: Spatial impression based on 1st wavefront then 'switches off' for ~50 ms
  - … even if 'reflections' are louder
  - … leads to impression of room

Binaural Masking Release

- Adding noise to reveal target



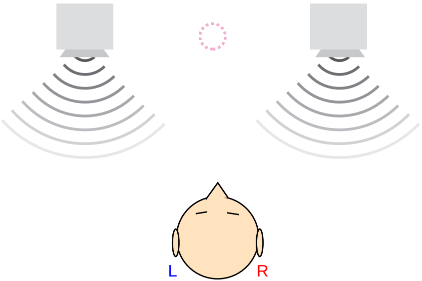
- Binaural Masking Level Difference up to 12dB
  - greatest for noise in phase, tone anti-phase

Outline

Synthesizing spatial audio

- Goal: recreate realistic soundfield
  - hi-fi experience
  - synthetic environments (VR)
- Constraints
  - resources
  - information (individual HRTFs)
  - delivery mechanism (headphones)
- Source material types
  - live recordings (actual soundfields)
  - synthetic (studio mixing, virtual environments)

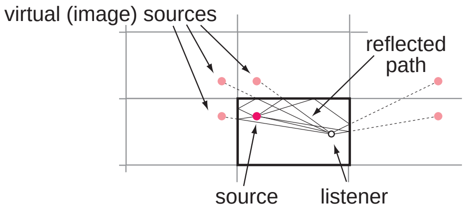
Classic stereo



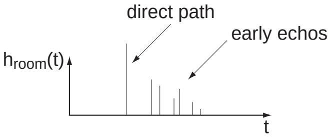
- 'Intensity panning':
  no timing modifications, just vary level $\pm$20 dB
  - works as long as listener is equidistant (ILD)
- Surround sound:
  extra channels in center, sides, ...
  - same basic effect: pan between pairs

Simulating reverberation

- Can characterize reverb by impulse response
  - spatial cues are important: record in stereo
  - IRs of $\sim$1 sec $\rightarrow$ very long convolution
- Image model: reflections as duplicate sources



- 'Early echos' in room impulse response:

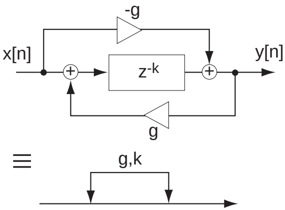


- Actual reflection may be $h_{reflect}(t)$, not $\delta(t)$

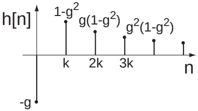
Artificial reverberation

- Reproduce perceptually salient aspects
  - early echo pattern ($\rightarrow$ room size impression)
  - overall decay tail ($\rightarrow$ wall materials. . .)
  - interaural coherence ($\rightarrow$ spaciousness)
- Nested allpass filters (Gardner, 1992)

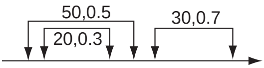
Allpass



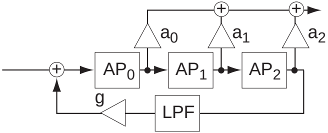
$$H(z) = \frac{z^{-k} - g}{1 - g \cdot z^{-k}}$$



Nested+Cascade Allpass



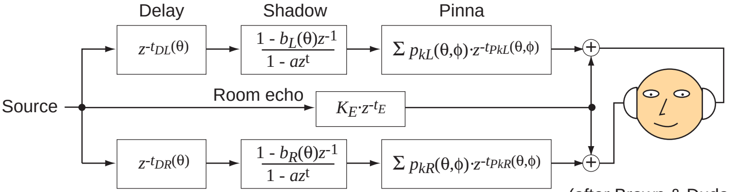
Synthetic Reverb



Synthetic binaural audio

- Source convolved with {L,R} HRTFs gives precise positioning

  . . . for headphone presentation
  - can combine multiple sources (by adding)
- Where to get HRTFs?
  - measured set, but: specific to individual, discrete
  - interpolate by linear crossfade, PCA basis set
  - or: parametric model - delay, shadow, pinna (Brown and Duda, 1998)



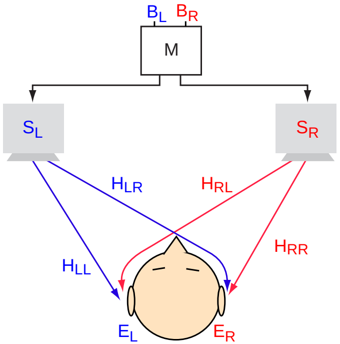
(after Brown & Duda '97)

- Head motion cues?
  - head tracking + *fast* updates

Transaural sound

- Binaural signals without headphones?
- Can cross-cancel wrap-around signals
  - speakers $S_{L,R}$, ears $E_{L,R}$, binaural signals $B_{L,R}$
  - Goal: present $B_{L,R}$ to $E_{L,R}$

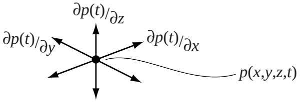
$$S_L = H_{LL}^{-1}(B_L - H_{RL} S_R)$$
$$S_R = H_{RR}^{-1}(B_R - H_{LR} S_L)$$



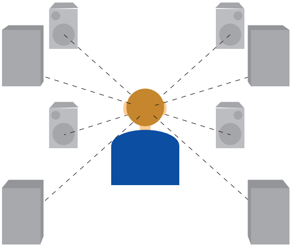
- Narrow 'sweet spot'
  - head motion?

Soundfield reconstruction

- Stop thinking about ears
  - just reconstruct pressure + spatial derivatives



  - ears in reconstructed field receive same sounds
- Complex reconstruction setup (ambisonics)



  - able to preserve head motion cues?

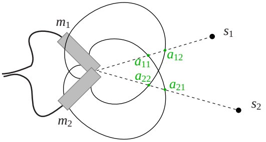
Outline

Extracting spatial sounds

- Given access to soundfield, can we recover separate components?
  - degrees of freedom: $> N$ signals from N sensors is hard
  - but: people can do it (somewhat)
- Information-theoretic approach
  - use only very general constraints
  - rely on precision measurements
- Anthropic approach
  - examine human perception
  - attempt to use same information

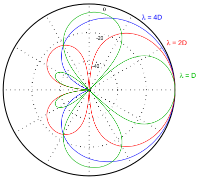
Microphone arrays

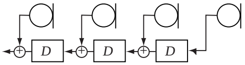
- Signals from multiple microphones can be combined to enhance/cancel certain sources
- 'Coincident' mics with different directional gains



$$\begin{bmatrix} m_1 \\ m_2 \end{bmatrix} = \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} \begin{bmatrix} s_1 \\ s_2 \end{bmatrix} \Rightarrow \begin{bmatrix} \hat{s}_1 \\ \hat{s}_2 \end{bmatrix} = \hat{A}^{-1} m$$

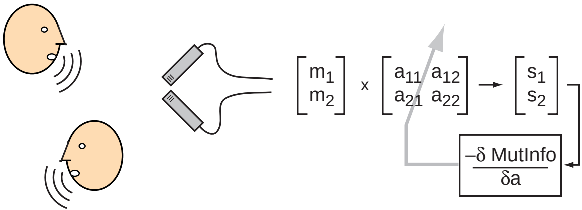
- Microphone arrays (endfire)





Adaptive Beamforming & Independent Component Analysis (ICA)

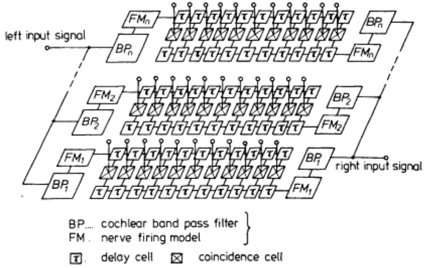
- Formulate mathematical criteria to optimize
- Beamforming: Drive interference to zero
  - cancel energy during nontarget intervals
- ICA: maximize mutual independence of outputs
  - from higher-order moments during overlap



- Limited by separation model parameter space
  - only $N \times N$?

Binaural models

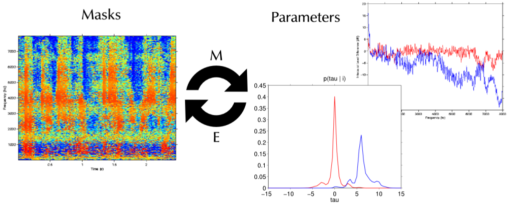
- Human listeners do better?
  - certainly given only 2 channels
- Extract ITD and IID cues?



  - cross-correlation finds timing differences
  - ‘consume’ counter-moving pulses
  - how to achieve IID, trading
  - vertical cues...

Time-frequency masking

- How to separate sounds based on direction?
  - assume one source dominates each time-frequency point
  - assign regions of spectrogram to sources based on probabilistic models
  - re-estimate model parameters based on regions selected
- Model-based EM Source Separation and Localization



  - Mandel and Ellis (2007)
  - models include IID as $\left|\frac{L_\omega}{R_\omega}\right|$ and IPD as $\arg \frac{L_\omega}{R_\omega}$
  - independent of source, but can model it separately

Summary

- Spatial sound
  - sampling at more than one point gives information on origin direction
- Binaural perception
  - time & intensity cues used between/within ears
- Sound rendering
  - conventional stereo
  - HRTF-based
- Spatial analysis
  - optimal linear techniques
  - elusive auditory models

References

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