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CODING PRINCIPLES FOR VIRTUAL ACOUSTIC OPENINGS

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This work was mainly done at *Media Signal Processing Research, Agere Systems, Murray Hill, NJ, USA (old Bell Labs dep.)*

http://www.acoustics.hut.fi/~aqi

Summary

- Acoustic opening: history and application ideas
- The coding problem
- Generic formulation for a coder
- Different approaches: pros and cons
- Conclusions
- Future work

Acoustic opening

- Multichannel audio communications system.
- Imitation of an open window between two rooms.
- Transducer arrays
- Macroscopic wavefield reconstruction: sweet all space, naturalness.

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- Acoustic holography
- **Wave field synthesis (WFS)** (*Berkhout (1993) et al.*)

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- **Wave field synthesis (WFS)** (*Berkhout (1993) et al.*)
- Introduced almost 70 years ago (*Snow (1934), 'Auditory Perspective',...*)

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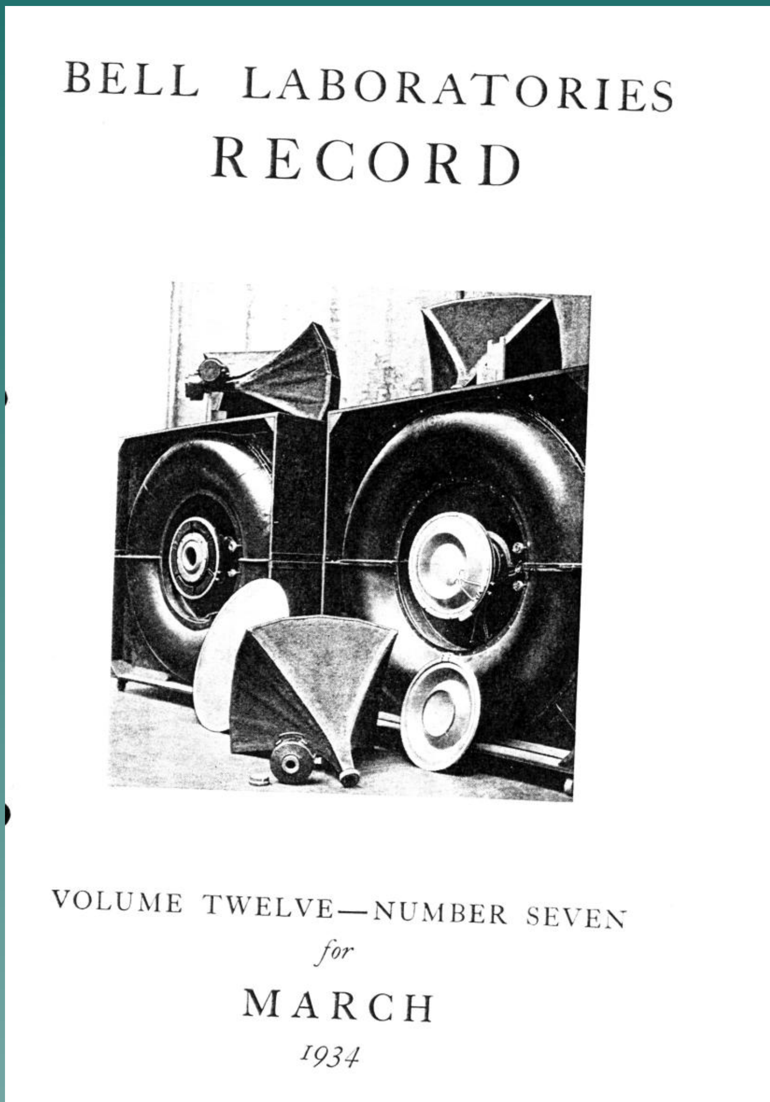


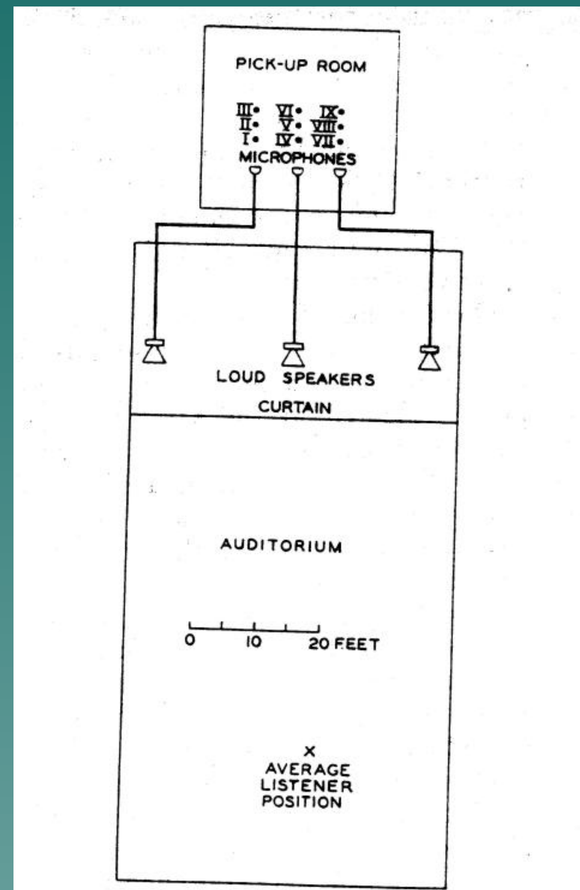
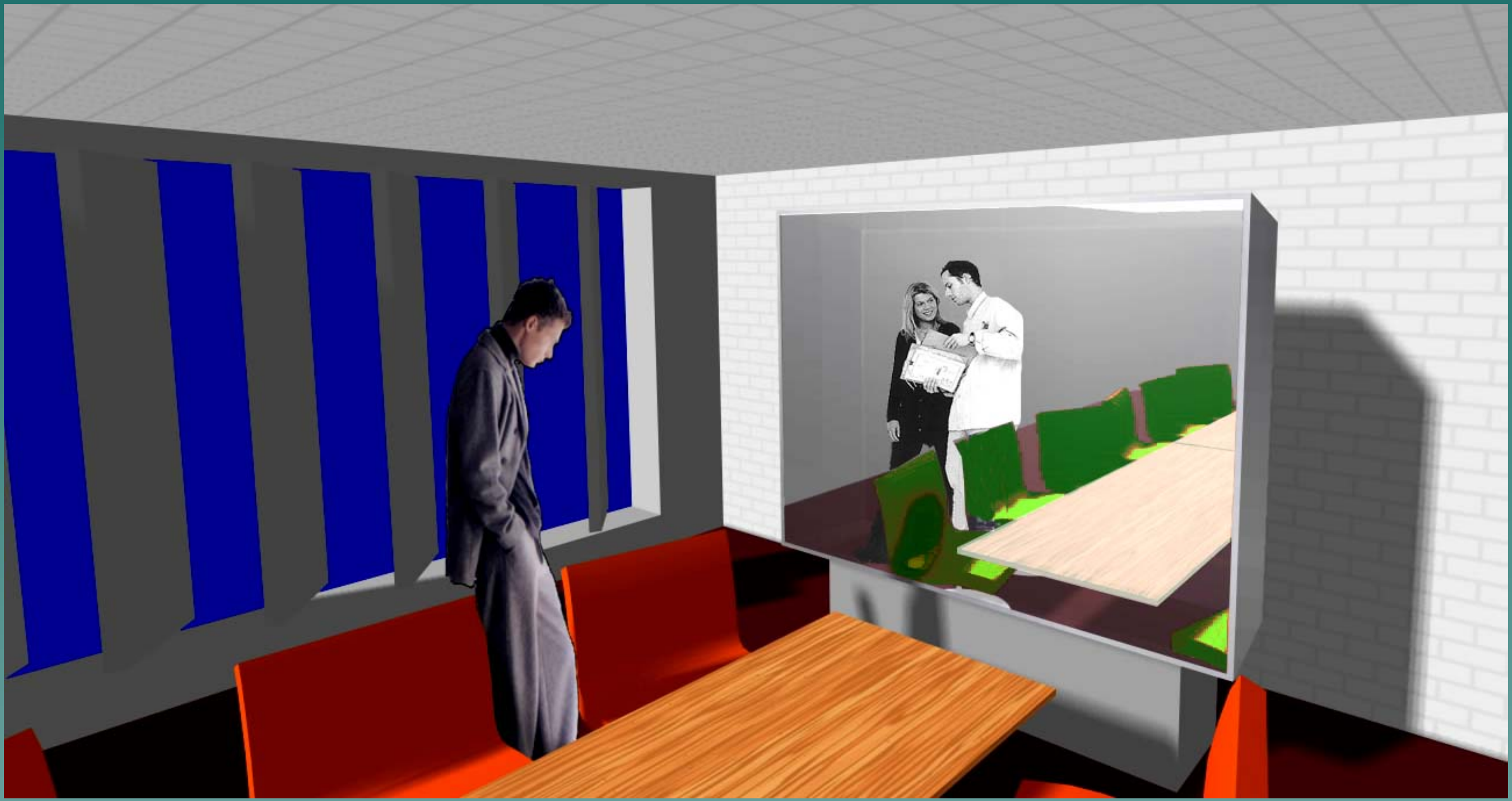


Fig. 1—For experimental purposes, pick-up microphones were mounted in a sound-proof room and connected by independent circuits to loud speakers on the stage of the auditorium

- Teleconference - communications



- Music, performing arts, remote rehearsal, artistic exhibits, interior design, entertainment, games.

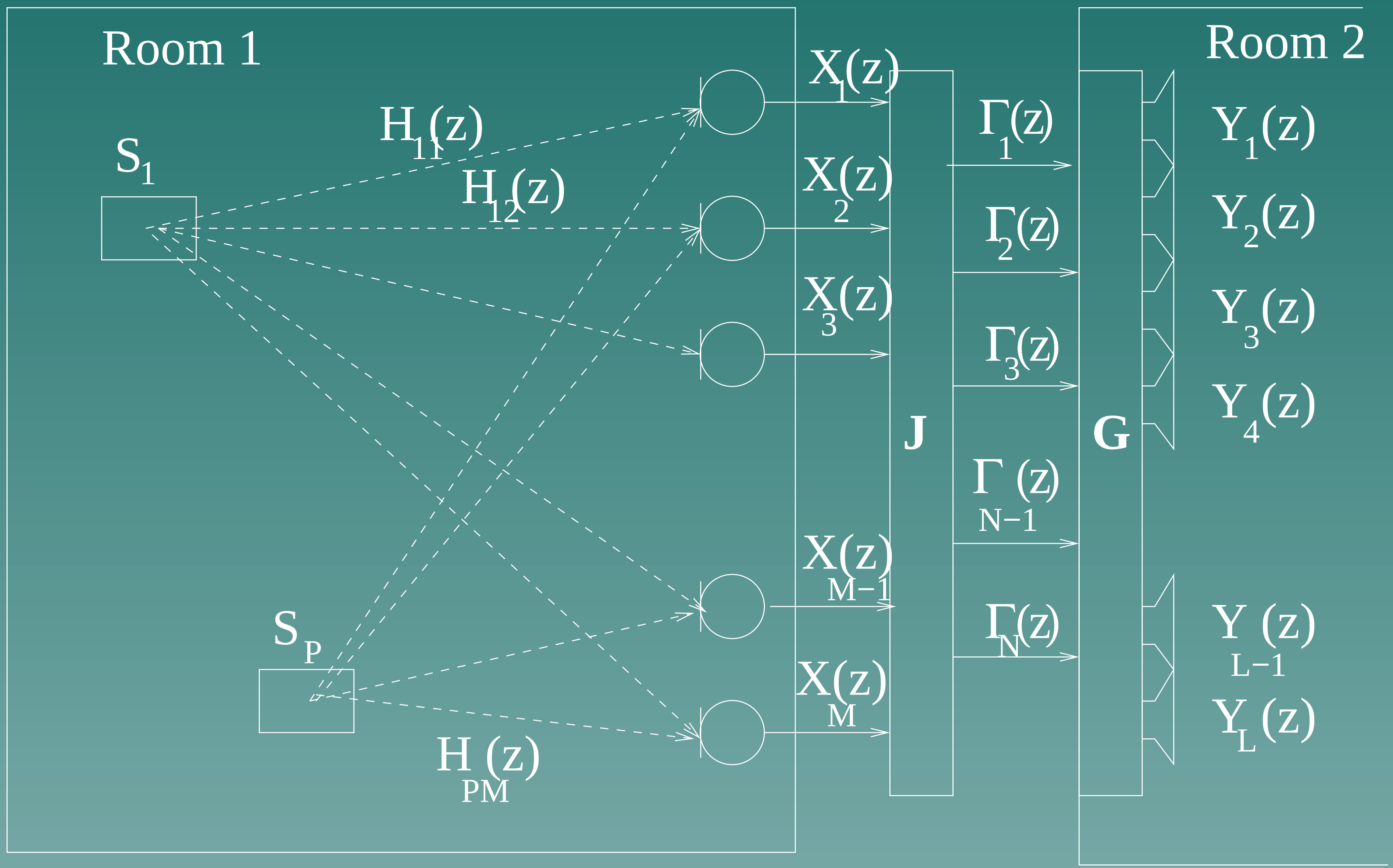
The coding problem

- *... beyond realms of possibility at present ... (Lipshitz, 1986)*
- But now,
  - ⋆ Multichannel (e.g., 48-ch) PC sound boards
  - ⋆ Cheap high-quality electret microphones
  - ⋆ New transducer technologies (DML, EMfi, etc.)

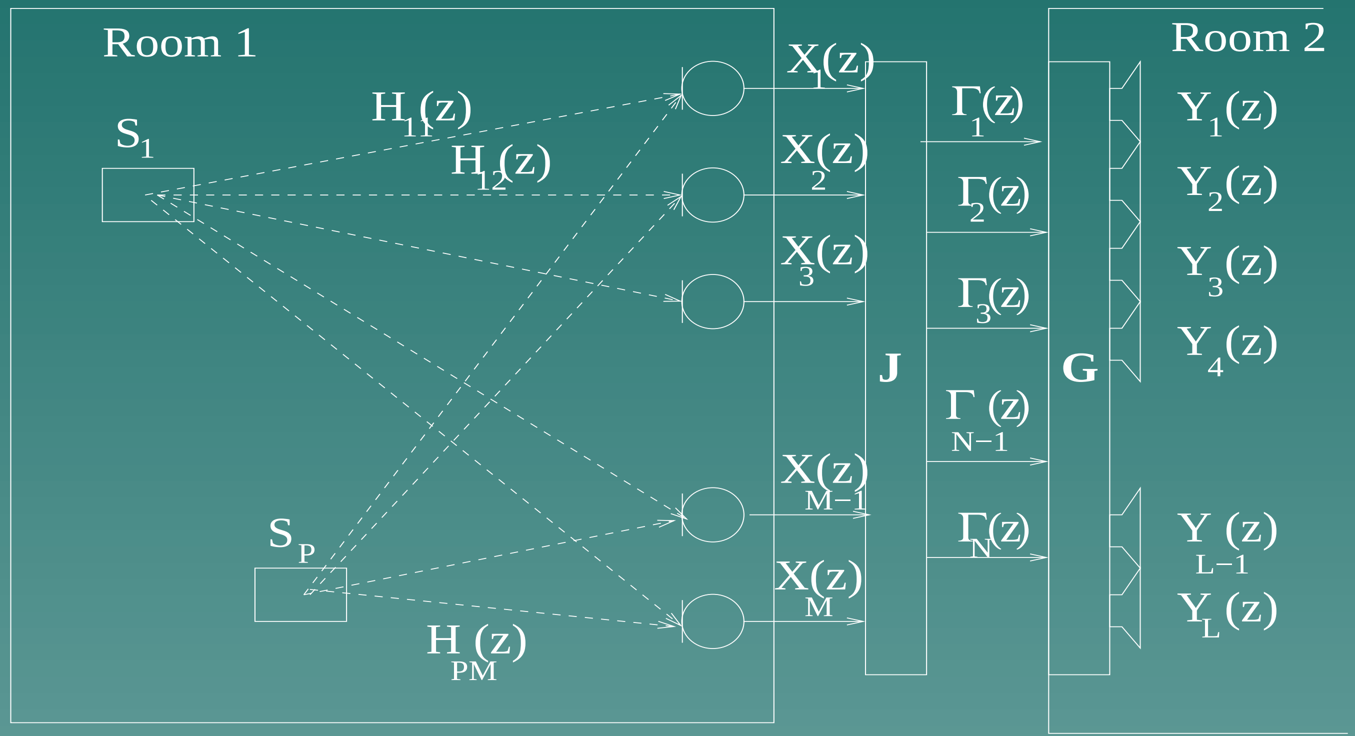
The coding problem

- *... beyond realms of possibility at present ... (Lipshitz, 1986)*
- But now,
  - ⋆ Multichannel (e.g., 48-ch) PC sound boards
  - ⋆ Cheap high-quality electret microphones
  - ⋆ New transducer technologies (DML, EMfi, etc.)
- Bitrate is still a major problem
- Large number of highly correlated nonidentical signals.
- Goal: Perceptually sufficiently accurate representation of a wavefield in an opening.

Generic formulation



Generic formulation



Encoder:

$$\mathbf{\Gamma} = \mathbf{J}\mathbf{X}$$

Decoder:

$$\mathbf{Y} = \mathbf{G}\mathbf{\Gamma}$$

- $\mathbf{\Gamma}$ - set of **generating** signals (coded and transmitted)
- $\mathbf{G}$ - **reconstruction** filters (wavefield parameters)
- **Transducer invariance**: bit-rate constant $\forall M, L$.

1. Scalar matrix $\mathbf{G}$

For example, sum-difference decoder (M/S stereo)

$$\begin{bmatrix} Y_r(z) \\ Y_l(z) \end{bmatrix} = \begin{bmatrix} G_{11} & G_{12} \\ G_{21} & G_{22} \end{bmatrix} \begin{bmatrix} \Gamma_s(z) \\ \Gamma_d(z) \end{bmatrix} = \begin{bmatrix} 1 & -1 \\ 1 & 1 \end{bmatrix} \begin{bmatrix} \Gamma_s(z) \\ \Gamma_d(z) \end{bmatrix}$$

Generalized sum-difference (Walsh-Hadamard) decoder

$$\begin{bmatrix} Y_1(z) \\ \vdots \\ Y_L(z) \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & \cdots & 1 \\ 1 & 1 & \cdots & -1 & -1 \\ & \vdots & \vdots & \vdots & \\ 1 & -1 & \cdots & 1 & -1 \end{bmatrix} \begin{vmatrix} \Gamma_1(z) \\ \vdots \\ \Gamma_L(z) \end{vmatrix}$$

Encoding $\mathbf{\Gamma} = \mathbf{J}\mathbf{X} \approx \mathbf{G}^{-1}\mathbf{X}$

Decoding $\mathbf{Y} = \mathbf{G}\mathbf{\Gamma}$

Cosine transform

$$\mathbf{G} = \left[\begin{array}{c} \text{Array of} \\ \text{Cosine basis} \\ \text{functions} \end{array} \right]$$

Karhunen-Loeve (KLT)

$$\mathbf{G} = \left[\begin{array}{c} \text{Adaptive} \\ \text{eigenfunction} \\ \text{basis} \end{array} \right]$$

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Pros

- Non-parametric (no params.)
- Transducer invariance easy
- Low complexity
- Adaptive KLT works well!

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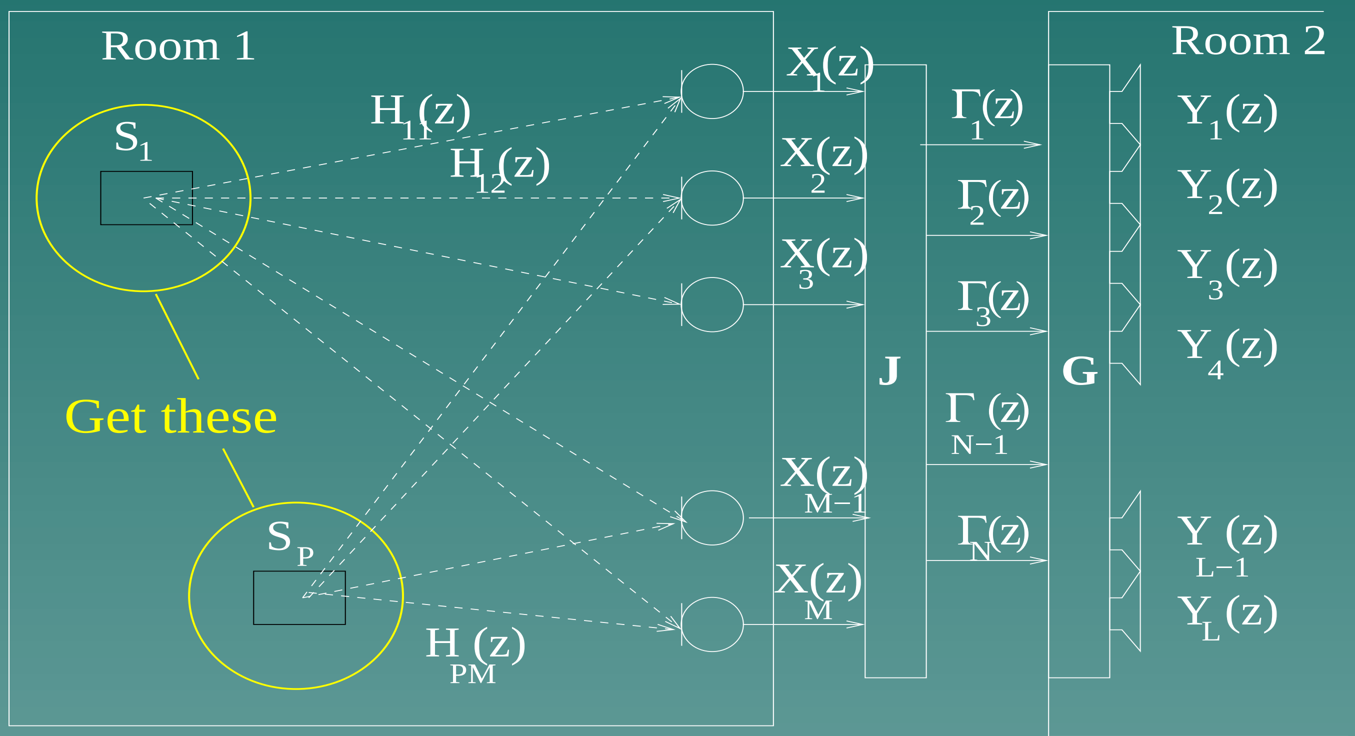
Cons

- Low coding gain
- Perceptual model?
- Blind to the problem
- Instantaneous mixture

2. Source separation approach



Signals:

$\mathbf{X} = \mathbf{HS}$

Encoder:

$\mathbf{\Gamma} = \mathbf{JHS}$

Decoder:

$\mathbf{Y} = \mathbf{G\Gamma}$

- $\mathbf{JH} = \mathbf{I} \Rightarrow \mathbf{\Gamma}$ are dry source signals!
- $\mathbf{J}$ is doing **source separation**
- $\mathbf{G}$ – Acoustics of the transmission room

Pros

- Total control over the problem
- High coding gain (?)
- Meaning of $\mathbf{G}$
- Additional functs.
- Transducer invariance
- Perceptual coding

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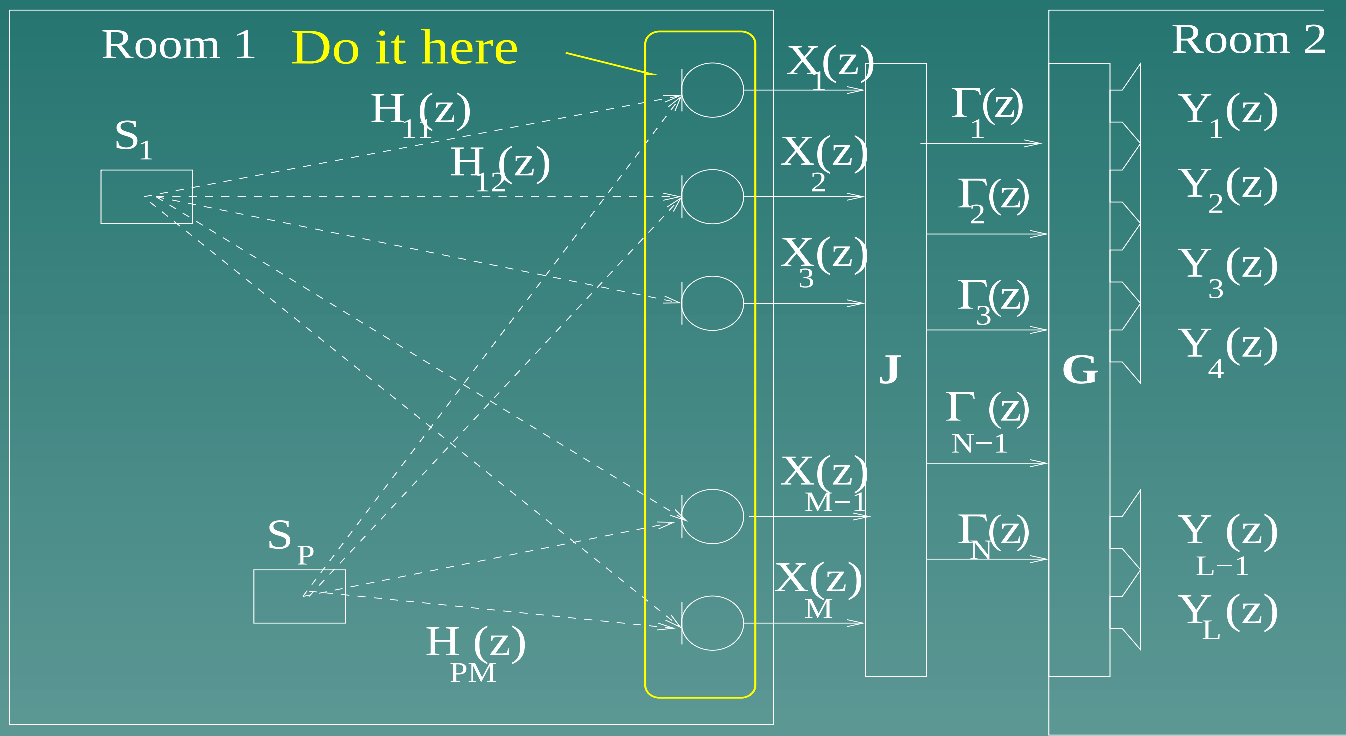
Cons

- Difficult (impossible at extreme)
- When it fails: coloration, artifacts
- Statistical Independence?
- $\mathbf{G}$ still hard to compress
- How many sources? What if $P > M$?
- If not perfect separation, what then?

3. Wavefield parametrization



Encoder:

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- Inter-channel prediction formulations
- $\mathbf{\Gamma}$ - clean microphone signals (and prediction errors)
- $\mathbf{G}$ - representation of wavefield

- In theory: one generating signal is enough!

Pros

- Simple formulations exist
- Clean generating signals
- Not making too many assumptions
- Not counting sources
- Perceptual coding

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Pros

- Simple formulations exist
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Cons

- Difficult to get high coding gain
- Non-uniqueness and stability problems for multiple Γ_n
- Not using data 'efficiently' (sources, acoustics)
- $\mathbf{G}$ is hard to compress
- Causality problems

Both approaches has many bad cons!

- Getting dry signals in source separation – difficult!
- Blind parametrization of $\mathbf{G}$ in wavefield coding – inefficient

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- Getting dry signals in source separation – difficult!
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- We need a **hybrid**:
  - ⋆ $\mathbf{\Gamma}$ – clean microphone signals
  - ⋆ $\mathbf{G}$ – parametrization based on source locations and acoustics.
  - ⋆ See article for a simple example: wavefield coder for a **single source in a free field**.

Subband formulations

NOTE: All techniques mentioned in the article can be applied separately at different subbands

- The order of problem decreases
- 'Perceptual' source separation in the (ERB/Bark) domain
- Omit irrelevant data (perceptual model)
- Scalar matrix processing makes more sense
- Tolerate spatial aliasing at high freqs.
- Localization different at low and high frequencies
- **But:** Increased algorithmic delay

Conclusions

- Acoustic opening: 70 yrs old idea
- Present hardware: standard audio stuff
- Digital audio coding: new problem, many open questions
- Generic formulation, alternative approaches
- We recommend: **hybrid subband processing**

Future work

- Prototypes being prepared
- Precedence effect (perceptual theory)
- Perceptual evaluation at large listening area (AES 21st)
- Full-duplex two-way system:
  - ⋆ Feedback and Acoustic Echo Canceling, AEC
  - ⋆ Design of a coder simplifies AEC
  - ⋆ Integrate a coder and AEC
- 1-D slit to a 2-D window
- Related activity: CARROUSO, USC (Immersive audiolab), BeingThere, etc.