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Acoustics as intangible cultural heritage

Measurement, archiving and reproduction

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Context

Early Music Research

Source

Performer

Environment

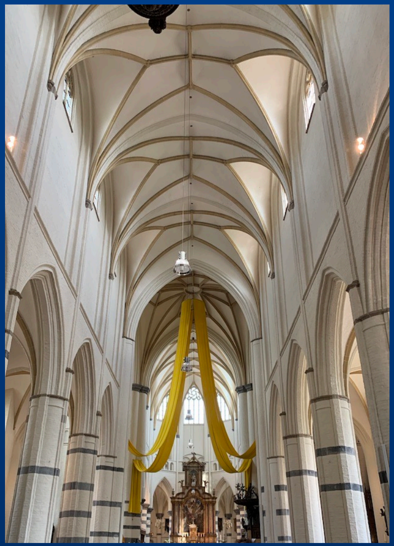

Image source: Alamire Foundation, Cappella Pratensis, TvW

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Problem statement

- **What is “acoustics” of a space?**
  - Acoustics = propagation and scattering of sound waves within a space, independent of source signal

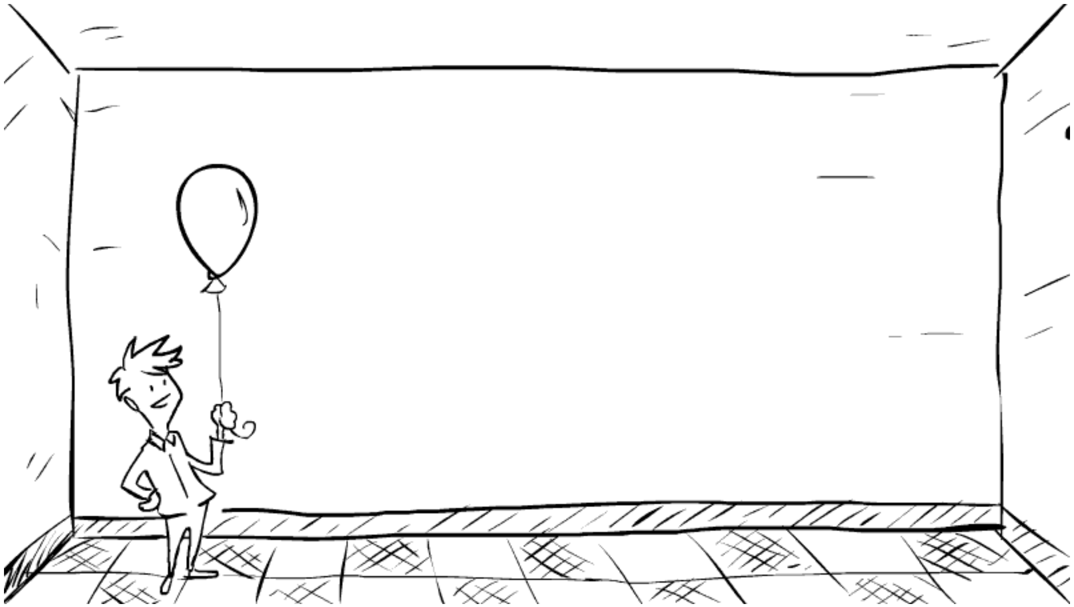

Image source: Niccolò Antonello

Problem statement

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  - Acoustics = propagation and scattering of sound waves within a space, independent of source signal

Source

Performer

Environment

source signal

acoustics

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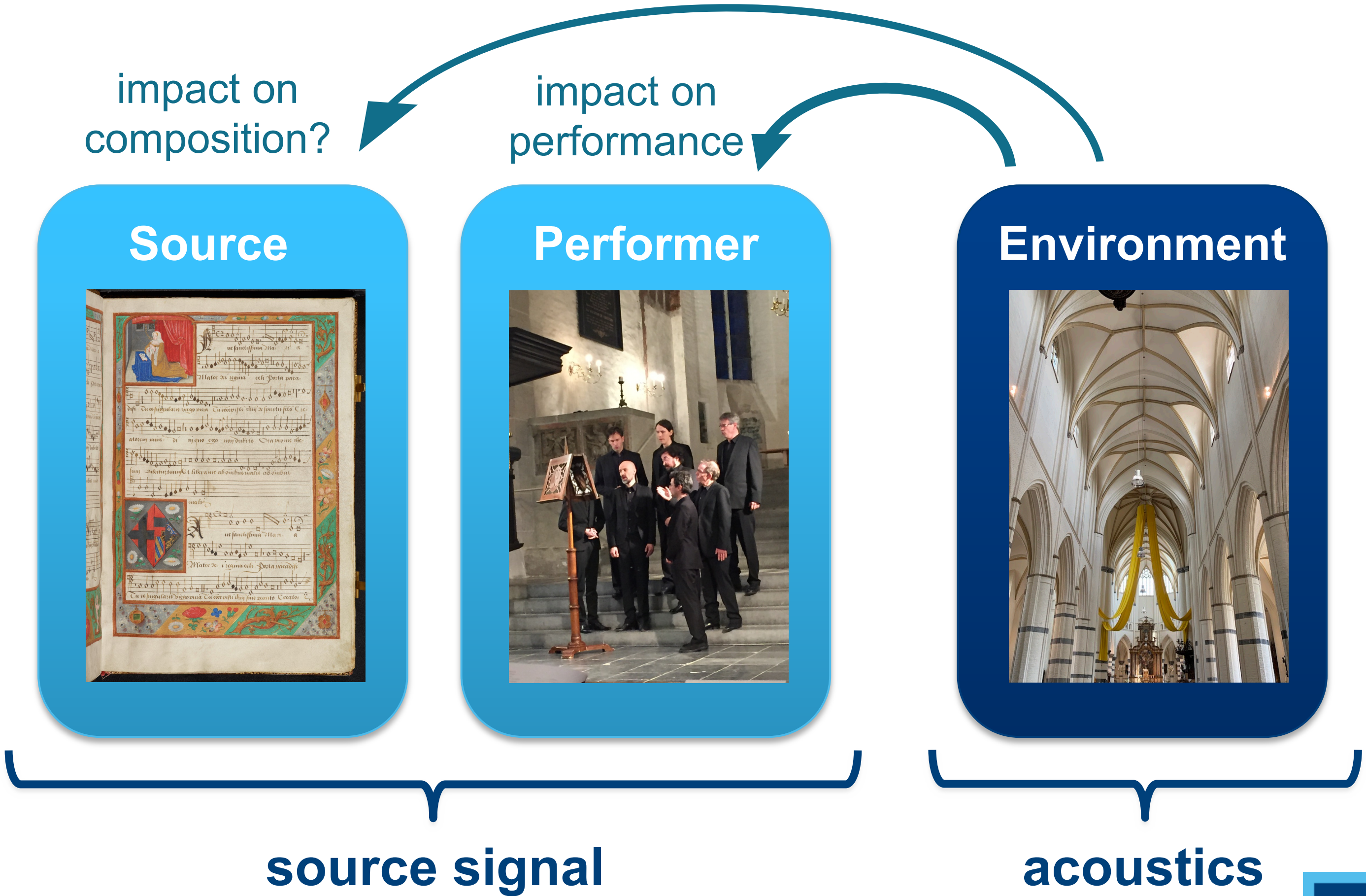
Image source: Alamire Foundation, Cappella Pratensis, TvW

Problem statement

- **What is “acoustics” of a space?**



Problem statement

- **Research question:** how can we archive the acoustics of a culturally valuable space and "reuse" it later?

2022

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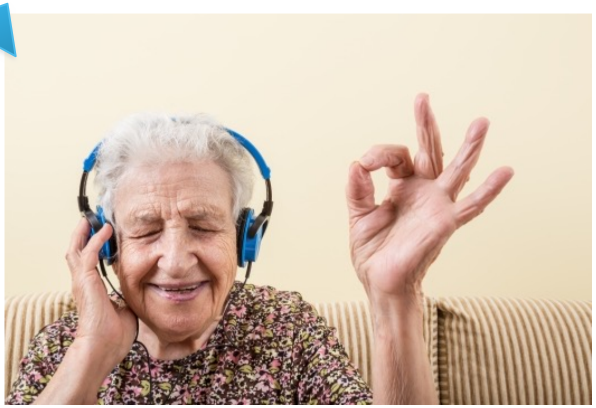


  - **Reuse** = auditory experience as if one is listening to <u>any</u> performance in the acoustics of the original space

Image source: TvW, dailynews.com

Role of AI

2022

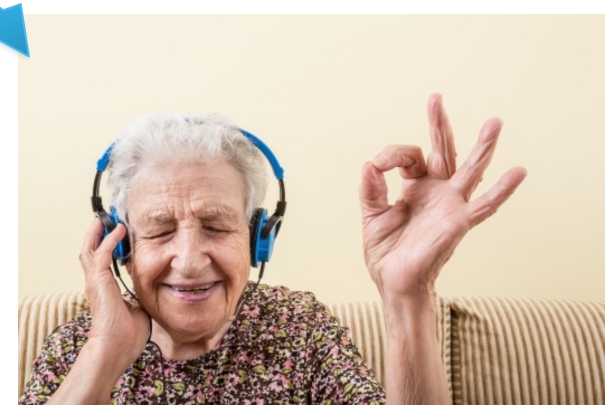
measurement

Data-driven modeling

archiving

Structured data approximation

2122



reproduction

Perceptual assessment data analysis

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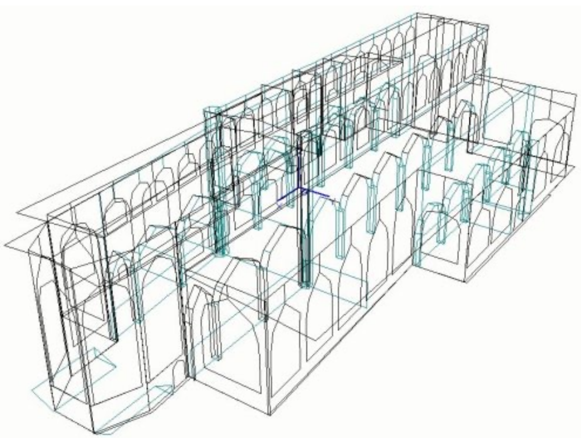
Image source: TvW, dailynews.com

Measurement: Data-driven modeling

- **How to measure the acoustics of a space?**



(1) measure geometry of space and objects inside

(2) determine sound scattering properties of walls and objects

= “descriptive” archaeoacoustics

→ tedious & time-consuming

→ reproduction?

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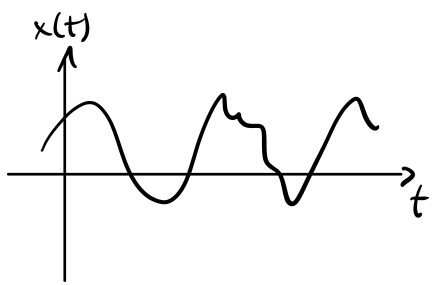
Image source: stock.adobe.com, york.ac.uk/~dtm3

Measurement: Data-driven modeling

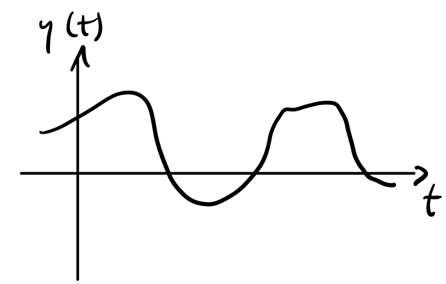
- **Data-driven modeling: “systems” view on acoustics**

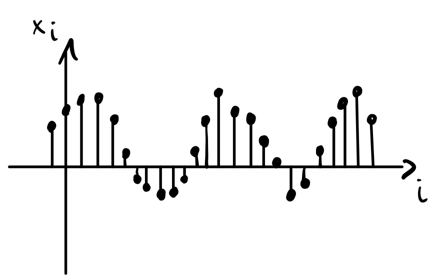
source → **acoustics** → **observed sound**

INPUT | **SYSTEM** | **OUTPUT**



continuous time:
signals = **functions**

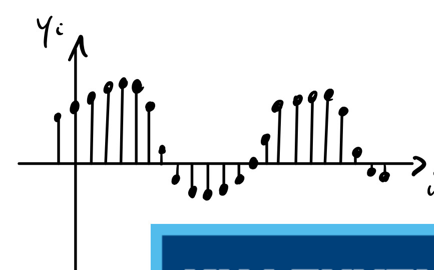




$$\mathbf{x} = \begin{bmatrix} x_1 \\ \vdots \\ x_i \\ \vdots \\ x_N \end{bmatrix}$$

discrete time:
signals = **vectors**

$$\mathbf{y} = \begin{bmatrix} y_1 \\ \vdots \\ y_i \\ \vdots \\ y_N \end{bmatrix}$$



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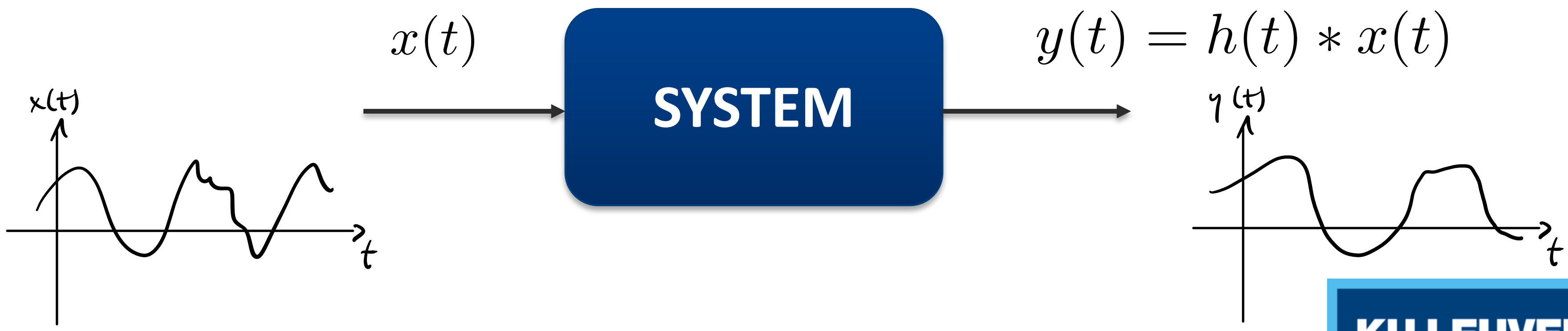
Measurement: Data-driven modeling

- **Fundamental result for linear time-invariant systems:**

  - **impulse response** contains all information on system
  - output to arbitrary input can be computed by **convolution**



Measurement: Data-driven modeling

- **Fundamental result for linear time-invariant systems:**

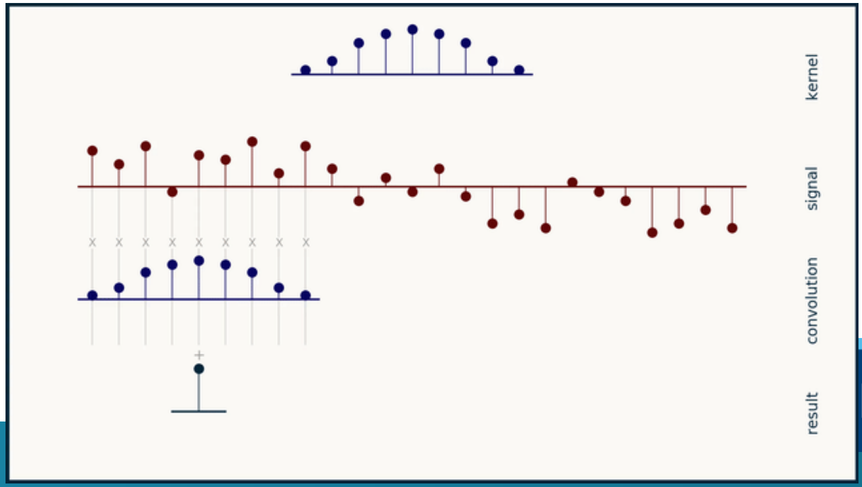
delta function

impulse response

  - **impulse response** contains all information on system
  - output to arbitrary input can be computed by **convolution**

$$\mathbf{h} = \left[h_1 \ \ldots \ h_L\right]^T$$

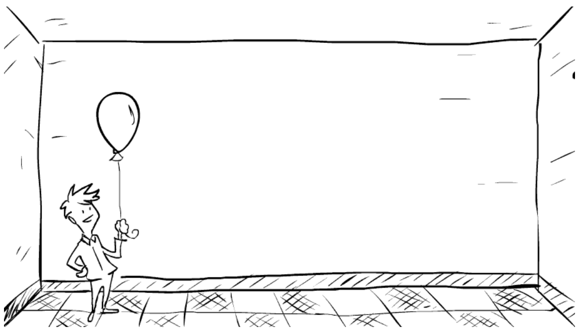
$$\mathbf{x} = \left[x_1 \quad \ldots \quad x_N\right]^T$$

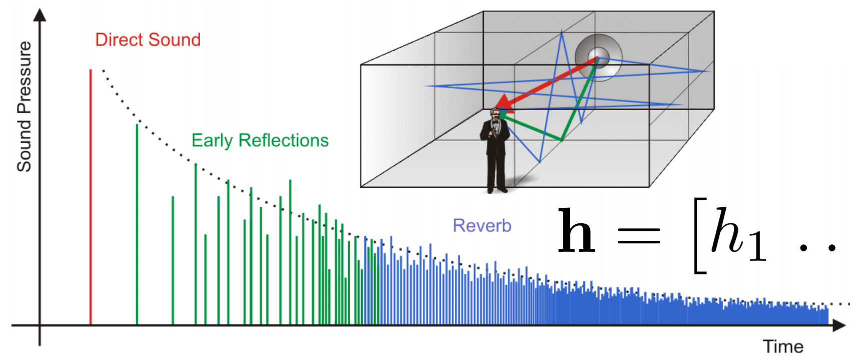


$$\mathbf{y} = \mathbf{h} * \mathbf{x}$$

Measurement: Data-driven modeling

- **Geometric interpretation of room impulse response**





$$\mathbf{h} = \left[h_1 \; \ldots \; h_L\right]^T$$

  - peaks in impulse response represent **acoustic reflections**
  - nice properties:
    - **purely data-driven model** for room acoustics
    - simple measurement protocol
  - problems:
    - dependent on source and observer positions
    - **no information on direction of arrival of reflections**
    - very long (vectors with up to 10^4 elements)

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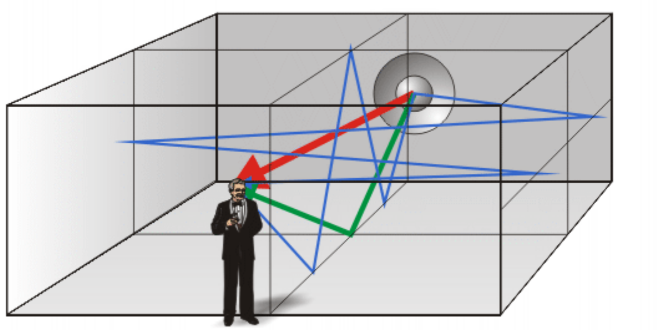
Image source: Niccolò Antonello

Measurement: Data-driven modeling

- **Spatial room impulse response**
  - include **direction of arrival information** (azimuth and elevantion angles θ,ϕ) to each peak in impulse response
  - **spatial decomposition method** [1] allows to compute spatial impulse response from set of 6 measured impulse responses

$$\begin{bmatrix} h_1^{(1)} \\ \vdots \\ h_L^{(1)} \end{bmatrix}, \begin{bmatrix} h_1^{(2)} \\ \vdots \\ h_L^{(2)} \end{bmatrix}, \ldots, \begin{bmatrix} h_1^{(6)} \\ \vdots \\ h_L^{(6)} \end{bmatrix} \rightarrow \mathbf{h}_S = \begin{bmatrix} h_1 & \theta_1 & \phi_1 \\ \vdots & \vdots & \vdots \\ h_L & \theta_L & \phi_L \end{bmatrix}$$



[1] Tervo *et al.*, "Spatial Decomposition Method for Room Impulse Responses," *J. Audio Eng. Soc.*, 61(1/2), 2013.

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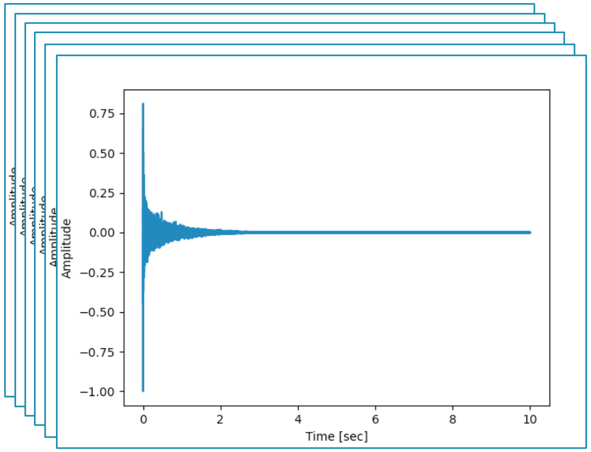
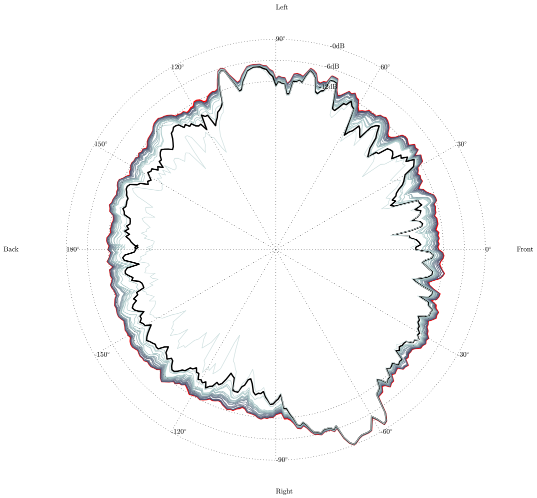
Measurement: Data-driven modeling

- **Case study: Nassau Chapel @ KBR Brussel**

Genelec 8030C

G.R.A.S. VIP 50VI-1





Role of AI

2022

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archiving

Structured data approximation

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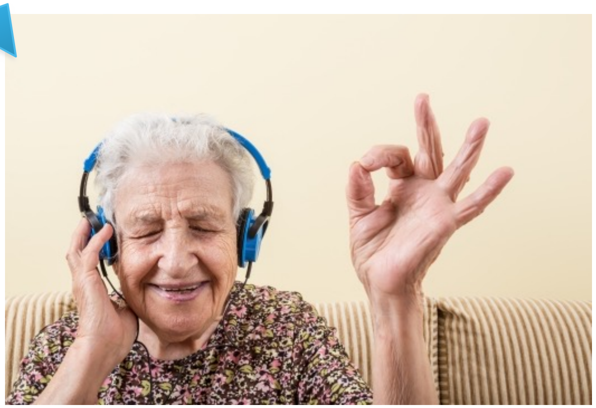

reproduction

Perceptual assessment data analysis

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Image source: TvW, dailynews.com

Archiving: Structured data approximation

- **Some simple math...**
  - impulse response contains $L \sim 10^4$ samples $\sim 10^5$ bits
  - 1 spatial impulse response = 6 impulse responses $\sim 10^6$ bits
  - plenacoustic sampling theory [2]: accurate sound field reconstruction requires spatial resolution of ~ 10 cm

    $\sim (100)^3$ source positions x $(100)^3$ observer positions

    $\sim 10^{12}$ spatial impulse responses $\sim 10^{18}$ bits ~ **100 petabyte**

[2] Ajdler *et al.*, "The Plenacoustic Function and Its Sampling," *IEEE Trans. Sig. Process.*, 54(10), 2006.

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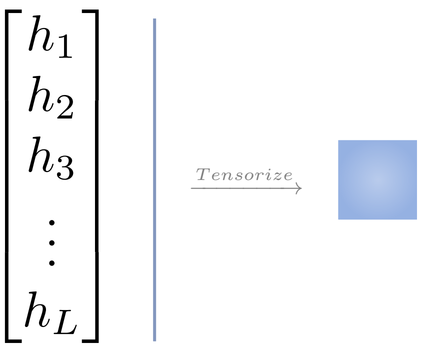
Image source: elbowroom.com.au

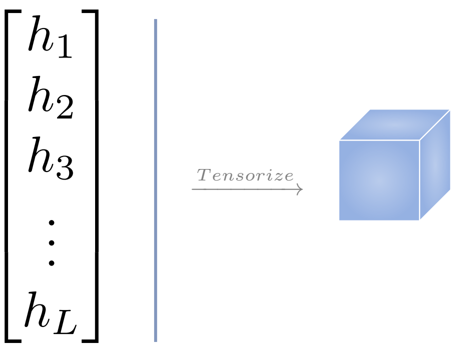
Archiving: Structured data approximation

- **Relieving curse of dimensionality using tensorization**
  – impulse response vector (= 1-D array) of length $L = 10^4$ samples can be **reshaped** into *N*-D array, e.g.
    - matrix (= 2-D array) of dimensions $\sqrt{L} \times \sqrt{L} = 100 \times 100$
    - tensor (= *N*-D array) of dimensions $\sqrt[N]{L} \times \sqrt[N]{L} \times \ldots \times \sqrt[N]{L}$

example: 2-D tensorization

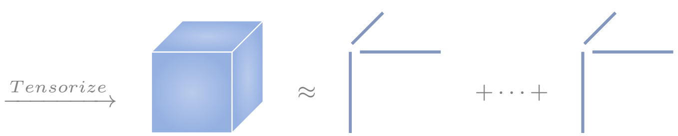


3-D tensorization



Archiving: Structured data approximation

- **Relieving curse of dimensionality using tensorization**
  - impulse response vector (= 1-D array) of length $L = 10^4$ samples can be **reshaped** into N-D array
  - N-D array can be **approximated** as sum of R rank-1 terms (canonical polyadic decomposition)
  - low-rank approximation makes sense as impulse response is linear combination of damped sinusoids (“**room modes**”) [3]
  - up to **80-90% reduction** of required archiving space [3]



[3] Jälmby, Elvander & vW, “Low-Rank Tensor Modeling of Room Impulse Responses,” *Proc. EUSIPCO*, 2021.

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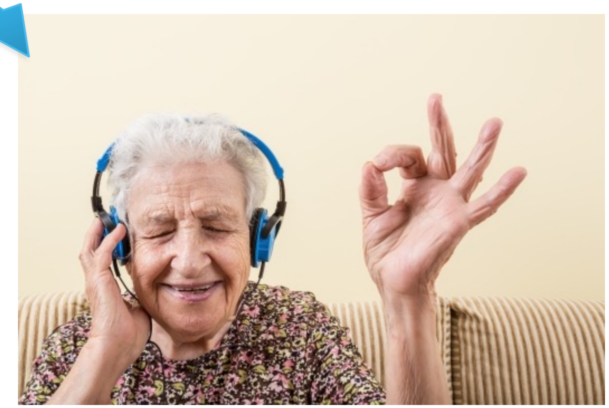
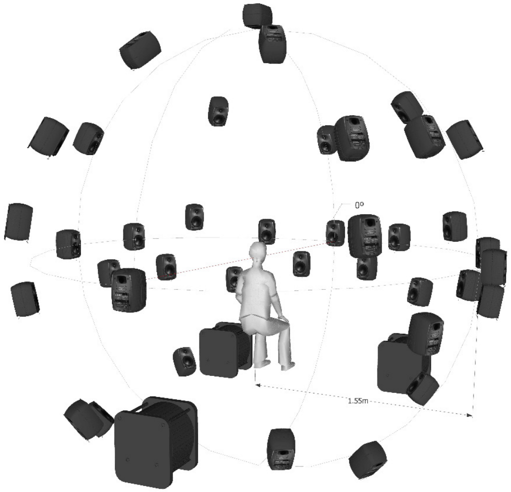


reproduction

Perceptual assessment data analysis

Reproduction: Perceptual assessment data analysis

- **Spatial room impulse response auralization**
  - 3-D loudspeaker array in (semi-)anechoic listening room: **Alamire Interactive Lab @ Library of Voices**
  - convolution of source signal with components of spatial impulse response where reflection angle ≈ loudspeaker angle



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Reproduction: Perceptual assessment data analysis

- **Perceptual assessment of room acoustics**
  - listening experiments with naive or **expert listeners**
- **Materials:** 6 virtual acoustic spaces, 4 singers, 2 pieces
  - 4 male singers from Cappella Pratensis
  - one plainchant + one polyphonic piece

Reproduction: Perceptual assessment data analysis

- **Methodology:** Flash Profile rapid sensory analysis
  - Originally developed in frame of **food tasting** experiments [4]
  - Validated for perceptual modeling of virtual acoustics **by listening** (e.g. auralization of concert halls, car cabins) [5]
  - Evaluated here for perceptual modeling of virtual acoustic **by listening while singing**

[4] Dairou and Sieffermann, “A comparison of 14 jams characterized by conventional profile and a quick original method, the flash profile”, *J. Food Sci.* 67, 2002.

[5] Kaplanis, Bech, Tervo, Pätynen, Lokki, vW, and Jensen, "A rapid sensory analysis method for perceptual assessment of automotive audio," *J. Audio Eng. Soc.*, 65(1/2), 2017.

Reproduction: Perceptual assessment data analysis

- **Methodology:** Flash Profile rapid sensory analysis
  - **1) Elicitation phase:** individual semantic definition of perceptual attributes to characterize differences between virtual spaces

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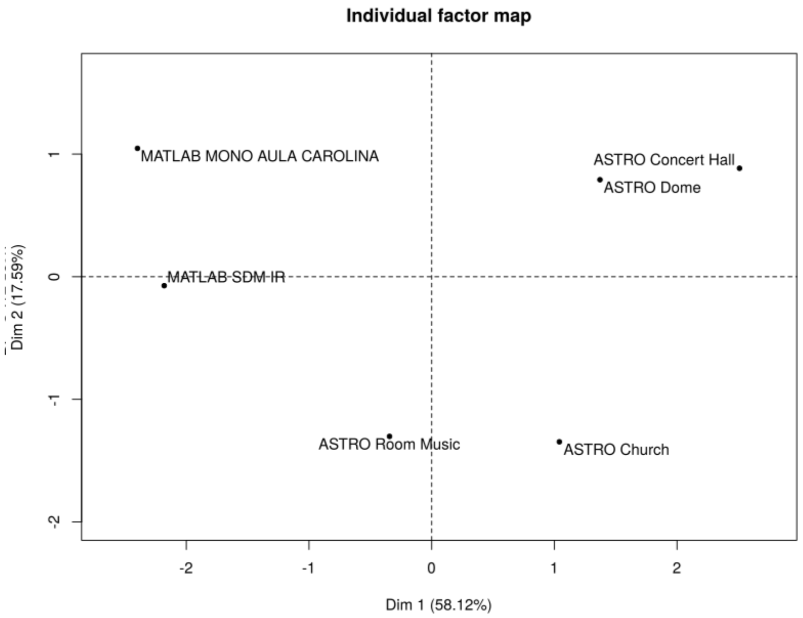
Reproduction: Perceptual assessment data analysis

- **Methodology:** Flash Profile rapid sensory analysis [4,5]
  - **2) Ranking phase:** continuous-scale (low-high) quantification of each perceptual attribute for each virtual space

Reproduction: Perceptual assessment data analysis

- **Methodology:** Flash Profile rapid sensory analysis [4,5]
  - **3) Statistical data analysis:** multi-factor principal component analysis + clustering



- 75% of perceived variance among spaces is modeled by two largest principal components
- two largest prinicipal components correlate to perceptual attributes of **spaciousness/reverberance** (Dim 1) and **spectral content** (Dim 2)
- six virtual spaces can then be mapped into this 2-D principal component subspace

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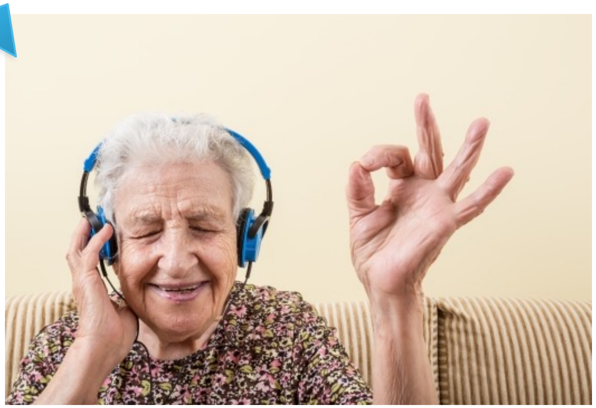

measurement → **Data-driven modeling**

archiving → **Structured data approximation**

reproduction → **Perceptual assessment data analysis**

Thank you...

- **This presentation is the result of joint work with:**
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- **The work presented here has been carried out and supported by:**

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erc

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