Room Acoustics

CMSC 828D / Spring 2006

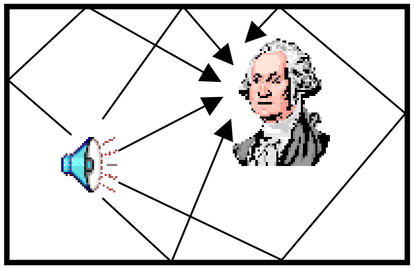
Lecture 20

Lecture Plan

- Room acoustics basics
- Structure of room impulse response
- Characterization of room acoustics
- Modeling of reverberant response

Basics

- All our life happens (mostly) not in open environments
- We hear not only the source signal but also its reflections
- Multiple propagation paths
- Reverberation
- Impulse response

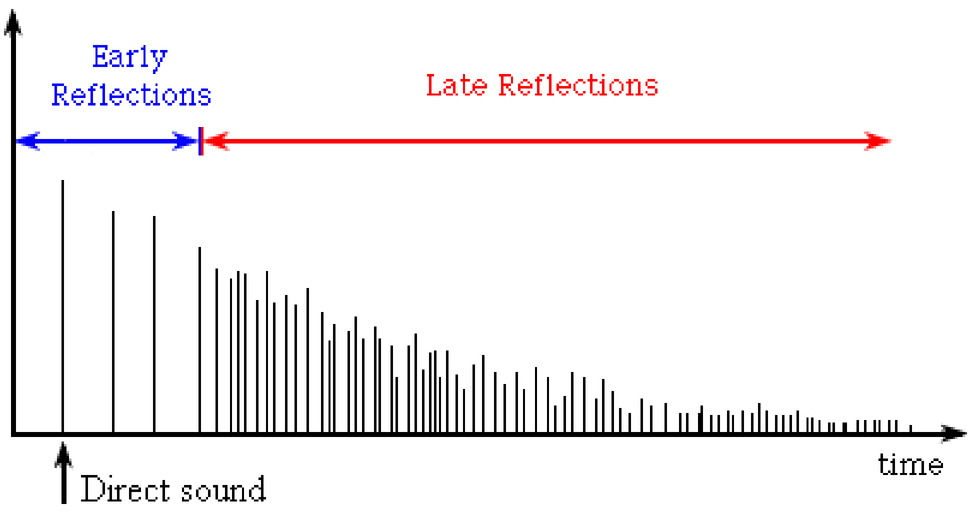


Perceptual Effects

- Pleasure of perception is influenced
  - “Reverberation”, 1900, by W. C. Sabine
  - Concert halls and theatres
- Speech quality can degrade
- Reverberation in virtual audio:
  - Crucial for externalization
  - Provides estimate of distance
  - Makes localization less accurate

Impulse Response Structure

- Pulse is produced at zero time
- Direct arrival (earliest and strongest)
- Early reflections (up to 80 ms, distinct)
- Late reflections (high density)
- Late part is a reverberation in a common sense



Early and Late Reflections

- Early reflections:
  - Strong and distinct
  - Provide spatial information
  - Should be modeled accurately
- Late reverberation:
  - Low intensity and high density of reflections
  - Provide room information
  - No longer depends on source position
  - Can be modeled statistically

Characterization

- ISO3382 standard
- All parameters can be measured
- All parameters are frequency-dependent
- Used to test room simulation software
- JND: Just Noticeable Difference
  - Smallest detectable change

Parameter	Definition	JND
T_{30}, s	Reverberation time (energy drop from –5 to –35 dB)	5%
EDT, s	Early decay time (energy drop from 0 to –10 dB)	5%
D_{50}, %	Deutlichkeit (definition), ratio of early (0-50ms) to total energy	5%
C_{80}, dB	Clarity, ratio of early (0-80ms) to late (80ms-…) energy	1 dB
TS, ms	Center time, time of the 1^{st} moment of IR	10 ms
G, dB	Sound level at 10m from the omnidirectional source, referenced to free-field level (as if no room at all)	1 dB
LF, %	Ratio of early (5-80ms) energy weighted by $\cos^2$(lateral angle) (i.e., lateral energy) to total energy	5%
LFC, %	Ratio of early (5-80ms) energy weighted by cos(lateral angle) (i.e., lateral energy) to total energy	5%
IACC	Interaural Cross Correlation Coefficient	0.2

Some Explanations

- Peak at time T_i has energy E_i and arrives from lateral angle θ_i
- Center time is then just mean T, TS = $\dfrac{\Sigma E_i T_i}{\Sigma E_i}$
- Similarly, LF = $\dfrac{\Sigma E_i \cos^2(\theta_i)}{\Sigma E_i}$
- Lateral angle is angle w.r.t. interaural axis

Importance

- T_{30}, EDT: Reverberation
  - $T_{60} = 2*T_{30}$
- D_{50}: Clarity of speech
- C_{80}: Clarity of music
- LF, LFC, IACC: Spatial impression
- Desired parameters depend on the purpose
  - Optimal T_{60} for speech: 400-600 ms
  - Optimal T_{60} for music: > 1000 ms

Sabine's Formula

- Sabine formula (1900): $T_{60} = 0.16 * V / S_e$
- V is a volume in m^3
- S_e is effective absorbing area in m^2
- $S_e = a_1 S_1 + a_2 S_2 + a_3 S_3 + \ldots$
  - a_i is the absorption coefficient $(1 - \beta)$ for area S_i
- Eyring's formula: use -ln(1-a) instead of a
- Both do not account for air absorption

Critical Distance

- As you go further from source, direct sound level drops
- In contrast, reverberant sound level stays constant everywhere in the room
- Distance at which they are equal is the critical distance D_c
- $D_c = \left[\frac{S_e}{16\pi} \right]^{½}$

Anechoic Rooms

- $T_{60} < 100$ ms
- Simulation of a free field
  - No sound sources and no reflections
- Unnatural and often unpleasant feeling
- Use of anechoic rooms:
  - Testing audio equipment
  - Performing hearing tests

Reverberant Rooms

- Large, specially-designed concert halls
- Acoustically pleasant (for each seat!)
- Even decay of the reverberant response
  - To avoid disturbing artifacts
- Good for organ music
- Horrible for speech
  - Intelligibility is impaired by late reflections
  - Try to talk in a large gym or in a pool…

Reverberation Modeling

- Necessary for:
  - Simulation of virtual auditory space
  - Design of performance spaces
  - Validation of signal processing algorithms
  - Improved spatially selective sound capture
- Various methods
  - Accuracy versus cost tradeoff (as always)

Physics

- Sound is a wave
  - Wavelength: 1.7 cm to 17 m
  - Speed: 343 m/s
  - Absorption (reflections, air)
  - Interference effects
  - Large dynamic range
- Light is also a wave
  - Six orders of magnitude shorter wavelength

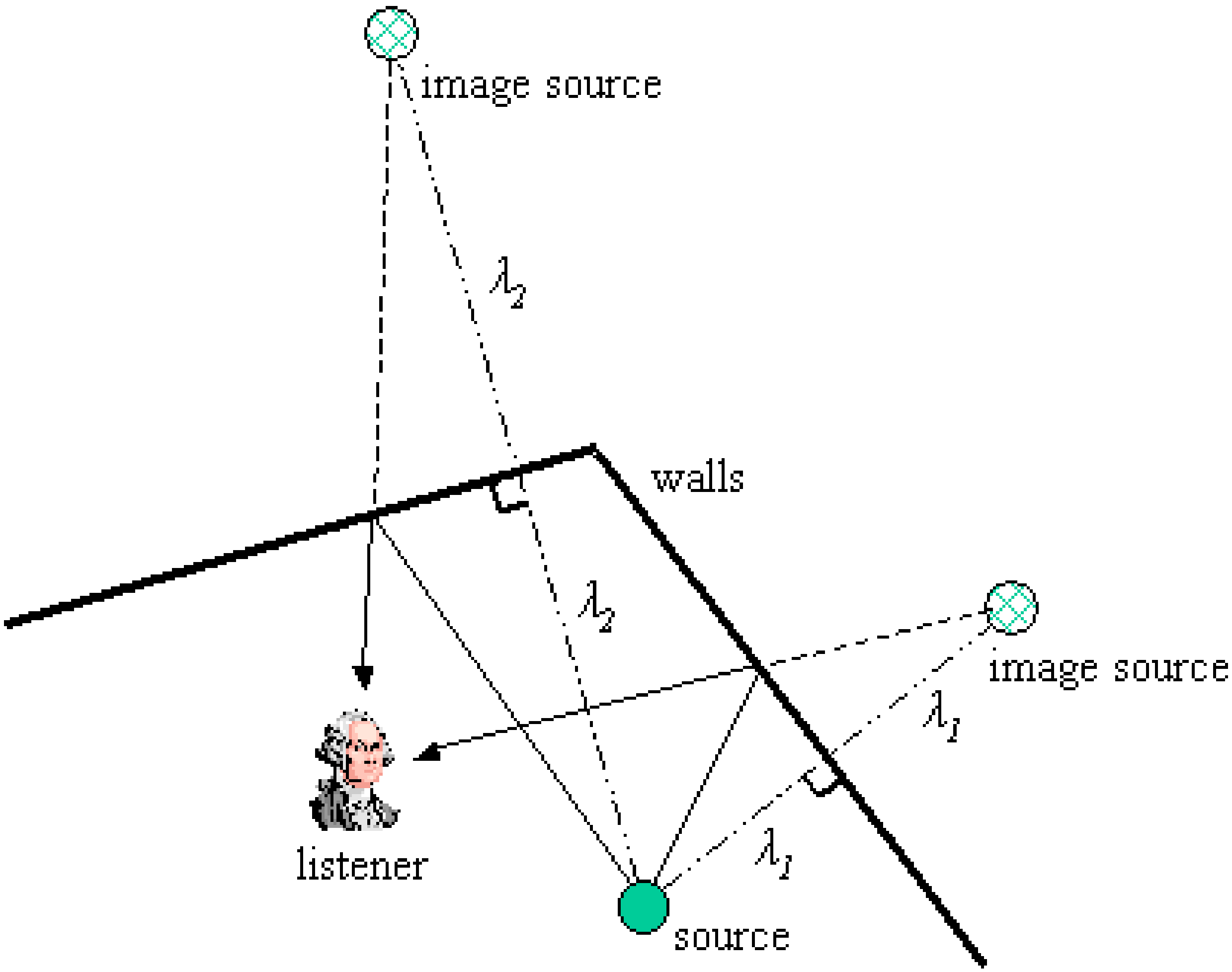
Wavelength Influence

- Wavelength << object size:
  - Specular reflection (walls)
- Wavelength >> object size:
  - No effect (coffee mug)
- Wavelength ~ object size:
  - Diffraction (table) (most complicated)

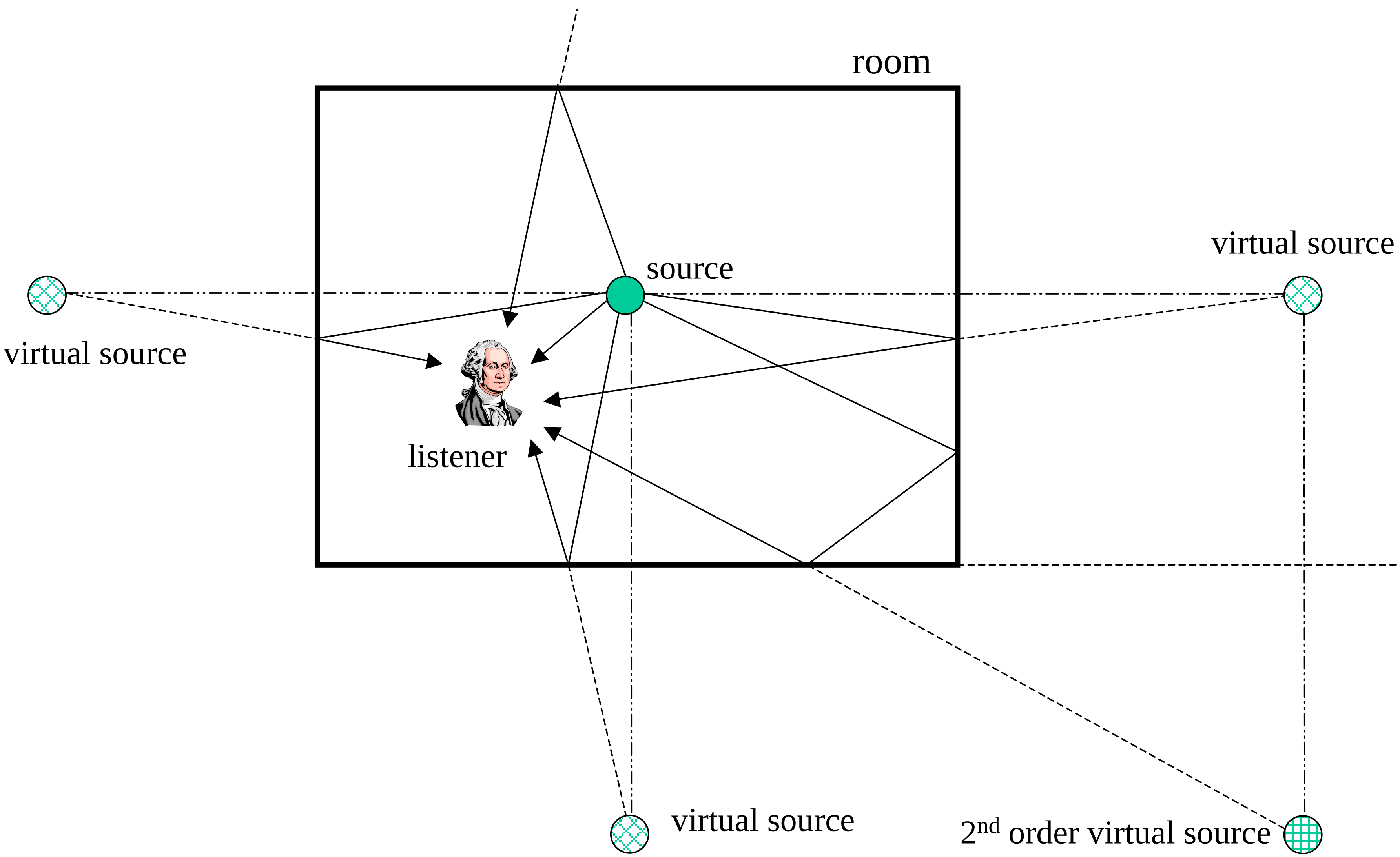
Image Model

- Assumptions:
  - Rectangular room
  - Specular sound reflections
  - Frequency-independent reflections coefficients
  - No air absorption
- Image sources
  - Reflection of the actual sound source in the wall

Image Source



Formation of Image Sources



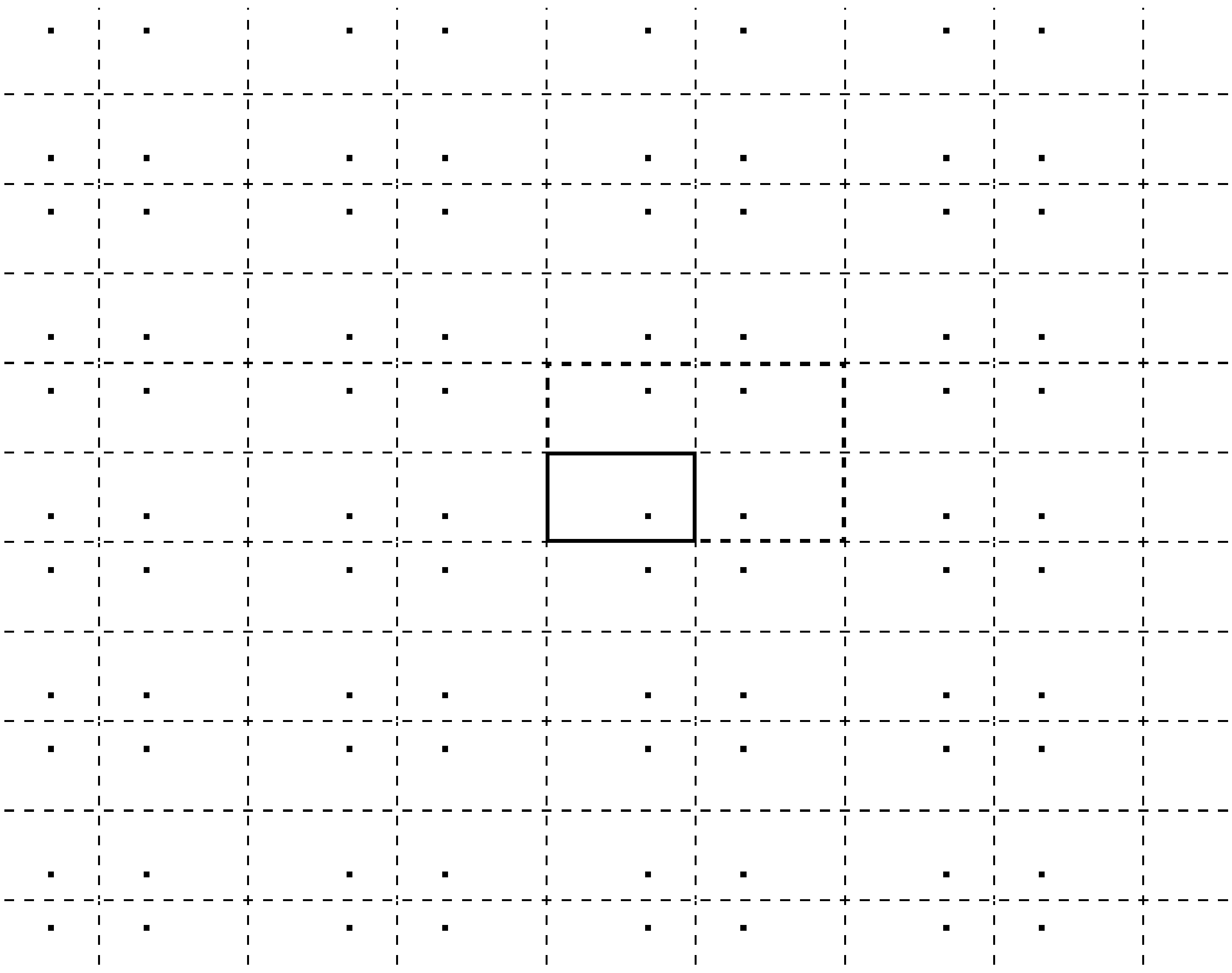
Regular Lattice of Image Sources

2-D case
for simplicity

Room is shown
by a solid line

Source is a dot
in a room

Lattice is formed
by repeating a 4-
room block shown
by thick dashed line



Source Strength

- Assume original source is unit strength
- Each wall has a reflection coefficient β_s
- Each image source has a strength Q_i
  - Upon reflection from wall *s*, the strength gets multiplied by β_s for that wall
  - So $Q_i = \prod \beta_s$, where product is taken over all walls in which the source was reflected to form that image source

Impulse Response Assembly

- $h(t) = \sum Q_i \delta(t - r_i / c) / r_i$
- Q_i is the image source strength
- r_i is the source distance
- Delta-function generates a peak in IR at arrival time r_i / c

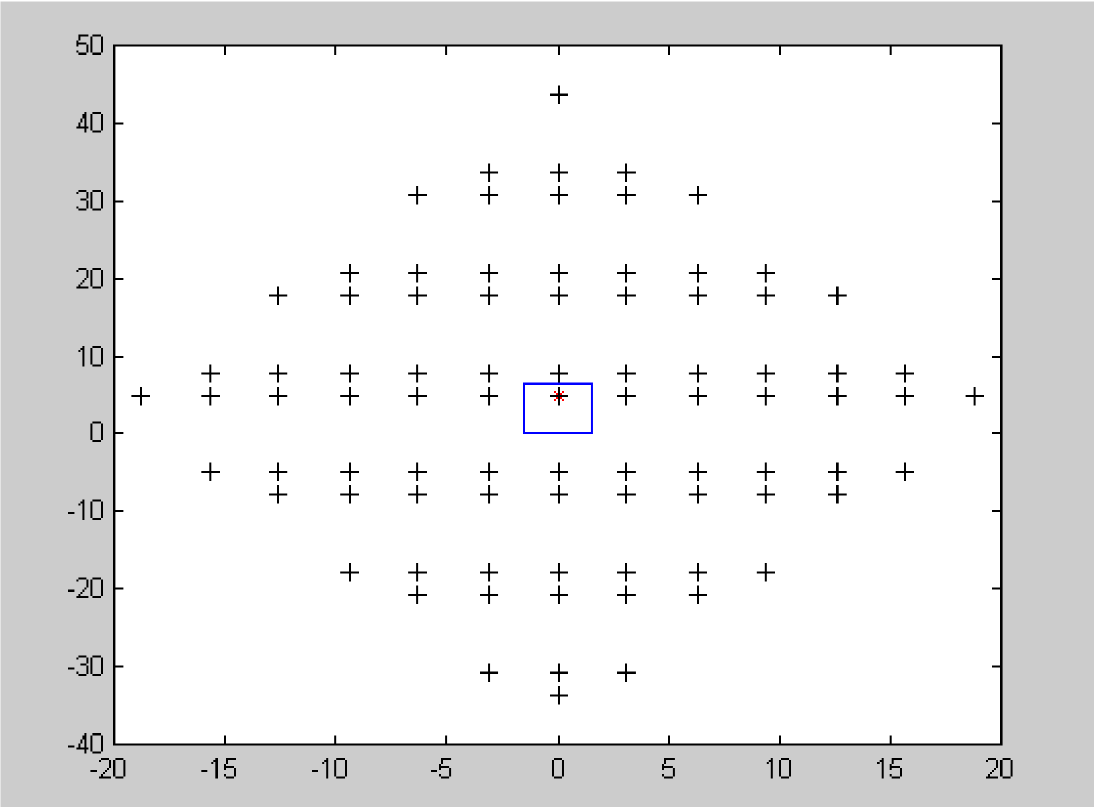
Original paper: J. B. Allen and D. A. Berkley, “Image method for efficiently simulating small-room acoustics”, Journal of the Acoustical Society of America, vol. 65(4), pp. 943-950.

Arbitrary Piecewise-planar Room

- The geometric model can be extended
- Same idea, more complicated geometry
- Need additional tests
  - Some paths are unrealizable
  - Some paths are occluded by protruding walls
- Can handle weird-shaped rooms

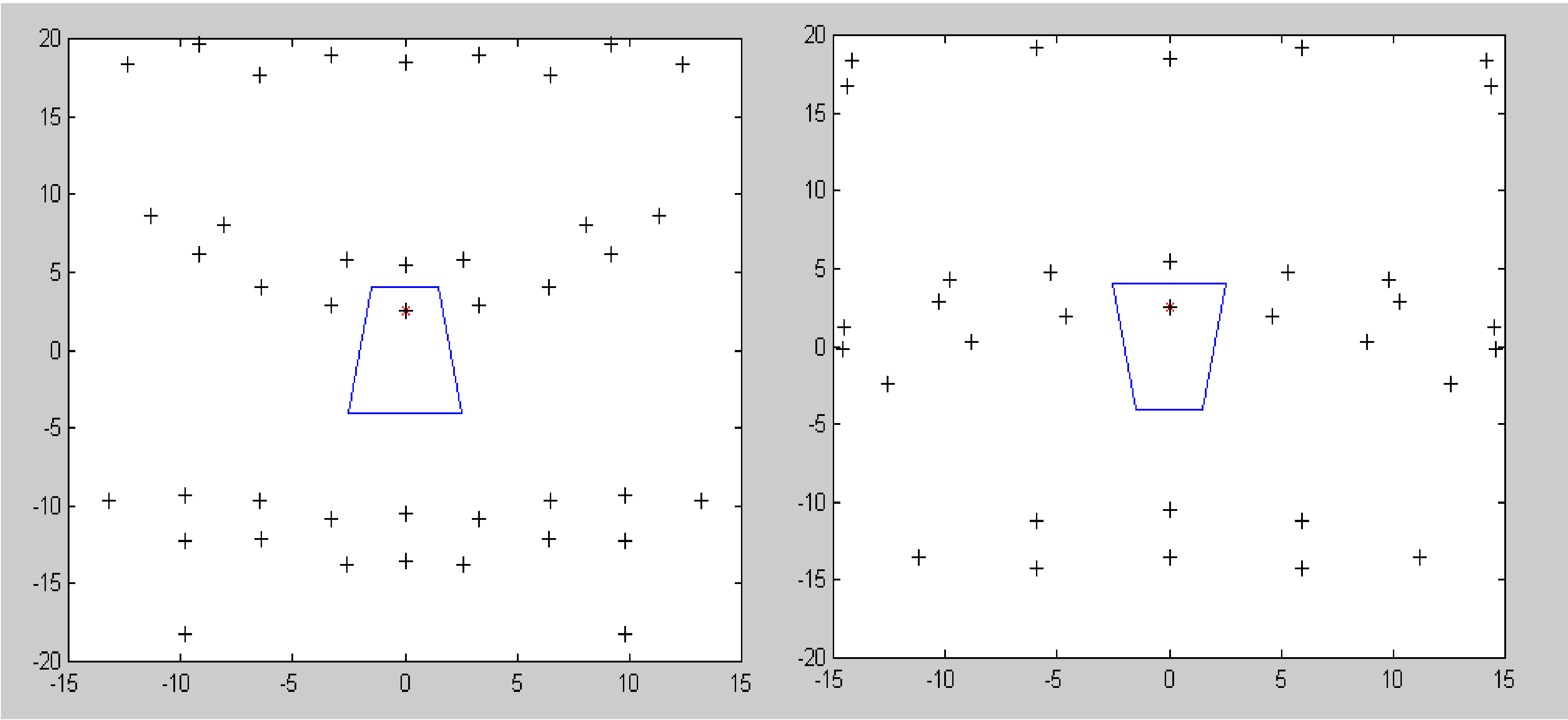
Original paper: J. Borish, "Extension of the image model to arbitrary polyhedra", Journal of the Acoustical Society of America, vol. 75(6), pp. 1827-1836.

Simulation: Rectangular Room



All sources up to 6th order of reflection are shown; blue rectangle is the room

Simulation: Fan-shaped Rooms



Lateral reflections prevail in the second case (good for perception)

Incorporation of HRTF

- Generated IR is fine if signal is recorded by an omnidirectional microphone
  - What about human listener?
  - Each image source is located at some direction
  - Must be heard from that direction
- Solution: Render all image sources keeping spatial information (via HRTF)…
  - … or at least ones constituting early reflections

Technical Details

- Two approaches
- Do each source independently
  - All sources play the same sound simultaneously
  - Their locations are determined using image model
  - For each source, filter sound with HRTF
  - Mix all results to form the playback stream
- Alternatively…

Technical Details (2)

- All sources play the same sound
- Filtering operation (convolution) is linear
- Instead of convolving the same sound with many filters and then summing the results, sum all the filters first and then convolve the sound with it
- Significantly reduced computational load

Reverberation Tail

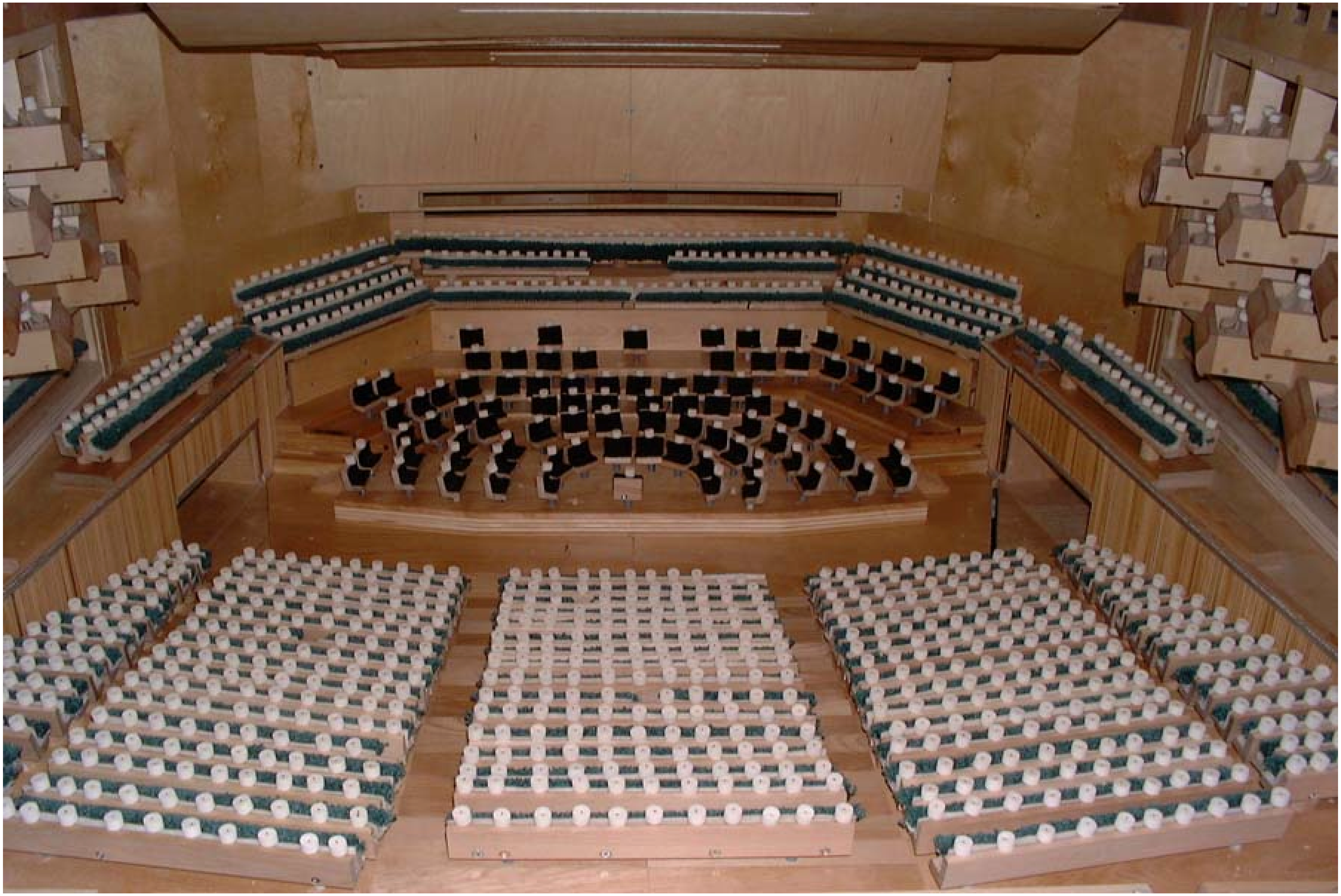
- To further reduce load, use statistical approximations of the late reverberation
  - OK 80 ms or so after the direct sound
  - No dependence on source/receiver position
  - For a given room, can compute one tail in advance and use it
  - However, tail characteristics do depend on room size and reflection coefficients
  - Feedback delay networks (FDN)

More Advanced Methods

- Ray tracing
- Beam tracing
  - Both are more efficient than the image model but still use geometric methods
- Diffraction effects
  - Model diffraction by bunch of rays
- Boundary-element methods
  - Solve wave propagation equation numerically

Scale Models

- For computationally intractable problems
  - (i.e. when it is faster to build than to compute)
- Built in 1:10 – 1:50 scale
  - Need to use ultrasound then to represent audible frequency range
- Use tiny speakers and microphones
- One can vary the design until the acoustic qualities are OK



Conclusion

- Desired room acoustical characteristics vary depending on the room purpose
- Main parameters that affect perception are reverb time and early reflections distribution
- Room acoustics can be controlled
  - Change wall material, place reflectors, diffusers…
- Room is a must for virtual audio simulation
  - Simplest model is probably OK

Some Further Reading

- W. C. Sabine (1900). “Reverberation”, in Acoustics: Historical and Philosophical Development, ed. by R. D. Lindsay, Dowden, Hutchinson, and Ross, Stroudsburg, PA (1972).
- Y. Ando (1985). “Concert Hall Acoustics”, Springer-Verlag, Berlin, Germany.
- H. Kuttruff (1991). “Room Acoustics”, 3rd edition, Elsevier Applied Science, Netherlands.
- J. A. Moorer (1979). ``About this reverberation business", Computer Music Journal, vol. 3, no. 2, pp. 13-28.