Sound waves reflect off walls in an enclosed space
  - Different paths create a series of echoes
Sound scattered by different objects in the room
Energy absorbed at walls
  - Depends on wall materials
  - Frequency dependent effects
• Simulate acoustics of a particular environment
• Causes “smearing” of signal energy

Dry speech 'airvib16'

+ reverb from hlwy16
Aside: The Precedence Effect (again)

- Reflections give misleading spatial cues

- But: Spatial impression based on 1st wavefront then ‘switches off’ for \( \sim 50 \) ms
  - even if ‘reflections’ are louder
  - leads to impression of room
Reverberation impulse response

- Room is just an LTI system
- Exponential decay of reflections:
  \[ h_{\text{room}}(t) \sim e^{-t/T} \]
- Frequency-dependent
  - greater absorption at high frequencies → faster decay
- Size-dependent
  - larger rooms → longer delays → slower decay
- Sabine’s equation (reverb time):
  \[ RT_{60} = \frac{0.049 V}{S\bar{\alpha}} \]
  - \( V = \) room volume, \( S = \) surface area, \( \bar{\alpha} = \) absorption coefficient
- Time constant based on room size, absorption
Anatomy of a reverberation impulse response

- ‘Early echos’ in room impulse response
- Actual reflection may be $h_{reflect}(t)$, not $\delta(t)$
- Echo density increases with time
  - Eventually everything looks like exponentially decaying noise (‘reverberant tail’)
Anatomy of a reverberation impulse response – example

1. Anatomy of a binaural room impulse response
   (a) Direct-path only
   (b) Early echoes only
   (c) Late reverberation only

2. Figure 2: An example utterance convolved with different parts of a binaural room impulse response. Shows the original signal, the signal convolved with the direct-path, early echoes, and late reverberation portions of the impulse response, and the full reverberated signal, in the time and spectrogram domains. Only the left ear signals are shown.

3. Straightforward. For rooms with other geometries, ray tracing can be used to calculate an impulse response using this model (Krokstad et al., 1968; Schroeder, 1970).

4. Early echoes depend on the geometry of a space, source, and listener. They are generally less sensitive to listener or source movement than the direct-path sound because of the larger source-to-listener distance. The virtual sound sources are farther away than the actual sound source, and so the same absolute motion is smaller relative to these larger source-to-listener distances. In addition, the energy of the early echoes depends less on the source-to-listener distance than that of the direct path because moving farther from one virtual source brings a listener closer to others.

5. Late reverberation
   Late reverberation arrives after the early echoes. Acoustically, it is made up of a very large number of higher order reflections and scattering off of walls and objects. It behaves somewhat like a diffuse source (Morrow, 1969; Izumi et al., 2007), generally does not contain specular reflections, and is incoherent at the two ears (Gardner, 1992). While individual reflections cannot be discerned, it is useful for its bulk properties, which include

Source: Michael Mandel’s Ph.D. dissertation, figure 2.2
Simulating reverb the easy way

- **Convolution reverb**: characterize reverb by *room impulse response*
  - 🎤 * 🎤 = 🎤
  - If spatial cues are important, can record in stereo
  - IRs of ∼1 sec → very long convolution
  - Use block-based FFT convolution (`fftfilt` in Matlab)

- Can measure impulse response directly
  - Approximate impulse: clap, gunshot, ???
  - Example impulse responses: http://www.voxengo.com/impulses/

- Simulate sound propagation in software
  - Lots of software to do this online
    - Roomsim: http://media.paisley.ac.uk/~campbell/Roomsim/
    - rir.m: http://www.2pi.us/rir.html

- Make it up
  - Exponentially decaying noise...
Simulating reverb the old fashioned way

- Reproduce perceptually salient aspects
  - early echo pattern (→ room size impression)
  - overall decay tail (→ wall materials...)
  - interaural coherence (→ spaciousness)

- Nested allpass filters [Gardner, 1992]

Schroeder allpass section

- Use $g \sim 0.7$, mutually prime $M > 50$ms
- Don’t allpass filters have flat frequency response?
Moorer Reverberator [Moorer, 79]

(a) Early echoes

(b) Reverberant tail

\(x(n)\)

\(y(n)\)

\(z^{-m_N}\)

\(m_1\)

\(m_2\)

\(m_3\)

\(a_0\)

\(a_1\)

\(a_2\)

\(a_{N-1}\)

\(a_N\)

\(C_1\)

\(C_2\)

\(C_3\)

\(C_4\)

\(C_5\)

\(C_6\)

\(A_1\)

\(z^{-d}\)
The End

Reading  *DAFX*, Section 6.5

Credits  Some slides borrowed from the *EE6280 lecture on spatial sound* by Dan Ellis and Michael Mandel