Auditory Localization

- How does the ear allow us to perceive where in space a sound is located?
- The location of a sound source is typically defined by its direction and distance.
- The direction is expressed in terms of
  - azimuth angle: in the horizontal plane passing through the listener’s head: $0^\circ$ directly in front, $180^\circ$ directly behind
  - angle of elevation: in a vertical plane bisecting the listener: $-90^\circ$ directly below, $+90^\circ$ directly above

Interaural Time and Intensity

- In addition to the direction-dependent filtering done by the pinnae...
- Direction is determined predominantly by differences in a sound’s arrival time and intensity between the ears:
  - Interaural time difference (ITD) is the perceived delay between the sound reaching both ears:
    - if directly in front, the sound will reach both ears at the same time (ITD = 0)
    - listeners can resolve the location to about $2^\circ$ in front and $10^\circ$ from behind.
  - Interaural intensity difference (IID) occurs due angle-dependent shadowing:
    - when source not centered, the head partially shadows the opposite ear, diminishing intensity.

ITD and IID Cues

- The degree to which these cues are effective is dependent on the frequency content of the sound.
- Both ITD and IID are ineffective at low frequencies (below 270 Hz), and thus direction of such sounds is more difficult to determine.
- ITD cues:
  - less precise behind a listener because the change in the ITD per degree in location change is smaller.
  - most effective between 270 and 500 Hz
  - little contribution above 1400 Hz
- IID cues:
  - less sensitive to sound sources behind the head,
  - very small for frequencies below 500 Hz,
  - contribute more at higher frequencies
  - dominate at (and above) about 1400 Hz
- IID and ITD are insufficient: pinnae filtering is most pronounced above 4000 Hz.
Cues for Judging Distance

- The principle cues for judging distance are:
  1. intensity of the sound: amplitude diminishes inversely with distance (though depends on familiarity with sound);
  2. ratio of reverberated to direct sound (R/D): reverb increases with distance until an audio horizon is reached and distance cannot be discerned;
  3. amount of high-frequency energy in the sound: since there is greater attenuation of propagating sound at high frequencies, there is perceivable absence of high-frequency components at long distances.

Reverberation

- The effect of reverberation on sound depends on the room or environment in which the sound is played.
- Reverberation is produced naturally by the reflection of sounds off surfaces.

![Figure 1: Example reflection paths occurring between source (S) and listener (L).](image)

- The amount and quality of reverb depends on
  - the volume and dimensions of the space,
  - the type, shape and number of surfaces the sound encounters.

- **Impulse response of a cave**

Reverberation

- Physical Measurements Affecting Reverb

- Character of reverb can be determined by the following measurements:
  1. reverb time (RT or T60):
     - time required for a sound to decrease 60 dB (how long a listener will hear a sound);
  2. frequency dependence of reverb time:
     - T60 is not uniform over audible frequency range;
  3. time delay between the arrival of the direct sound and the first reflection:
     - the more perceivable time between echos;
  4. rate at which the echo density builds:
     - after first reflection, rate at which echos reach the listener rapidly increases producing echo density.

Reflections

- Sound can take several paths from its source before reaching the listener; only one is direct.

- The listener receives many delayed images of the sound (e.g. reflections from walls, ceiling, floor...) which lengthens the time the sound is heard.

- Sound is not only delayed, but it also decays:
  - the greater the distance travelled, the more the amplitude decreases;
  - reverberation has a decaying amplitude envelope.
1. Reverb Time (RT or T60)

- **T60:**
  - time required for a sound to decay by 60 dB,
  - proportional to how long a listener hears a sound.
- **T60 depends on:**
  - **room volume:** rooms with larger volume tend to have longer T60s;
  - **number of reflective surfaces:** T60 will decrease with an increase in surface area;
  - **nature of reflective surfaces:**
    - *absorptivity:* hard, solid, nonporous surfaces reflect acoustic energy more efficiently than softer material (e.g. curtains),
    - *roughness:* if the surface is not perfectly flat, part of the sound is reflected and part is dispersed in other directions.
- **T60 also dependent on the amplitude of the original sound and the presence of other sounds.**
- **Listen to RT demo.**

2. Frequency Dependence of T60

- **T60 is not uniform over the range of audible frequencies.**
- In a well designed concert hall, the low frequencies are the last to fade:
  - absorptive materials are better reflectors of low-frequency sounds;
  - efficient reflectors (e.g. marble) reflect sounds of all frequencies with nearly equal efficiency.
- With small solid objects, efficiency and direction of reflection are both frequency dependent:
  - results in frequency-dependent dispersion which can alter the waveform of a sound.

3. Delay between Direct Sound and First Reflection

- A long delay (> 50 ms) can result in distinct echoes
- A short delay (< 5 ms) contributes to the listener’s perception that the space is small
- A delay between 10 and 20 ms is found in most good concert halls.

4. Rate Echo Density Builds

- After the initial reflection, the rate at which the echoes reach the listener begins to increase rapidly.
- A listener can distinguish differences in **echo density** up to a density of 1 echo/ms.
- Time to reach this threshold
  - influences the character of the reverberation (typically 100 ms in a good situation).
  - is roughly proportional to the square root of the volume of the room (small spaces are characterized by a rapid buildup of echo density).