Music 270a:
Fundamentals of Audio, Acoustics and Sound

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Sound

• Sound is the result of a **wave** created by vibrating objects, propagated through a medium from one location to another.

• Sound is thus a **mechanical** wave:
  – a disturbance travelling through a medium;
  – transports energy from one location to another;

• When synthesizing sound, we may synthesize:
  1. the waveform generated by a vibrating system (signal-based modeling)
  2. the vibrating system itself (acoustic modeling)
Sound Waves

• In particular, sound is the result of **travelling waves**:
  - waves propagating in one direction with negligible change in shape;
  - *longitudinal*: particle displacement is parallel to the direction of propagation;
  - *transverse*: particle displacement is perpendicular to the direction of wave propagation;
Sound Waveform

- Sound waves are *longitudinal waves*: a disturbance (source) creates an initial region of compression or high pressure.
- When the source vibrates, alternating regions of low and high pressure, *rarefactions* and *compressions*, are produced.
- The *waveform* of the sound shows the time evolution of the pressure variations.

![](image)

- **Properties of a Wave:**
  - **Amplitude**: maximum particle displacement from rest (Pa or N/m²).
  - **Wavelength**: length of one complete cycle (m).
  - **Period**: time to complete one cycle (s).
  - **Frequency**: number of cycles per second (Hz).
Properties of Sound Waves

- Speed of sound:
  - in air: 340 m/s
  - in water: 1480 m/s

- Amplitude range of hearing (humans)
  - Threshold of audibility: 0.00002 N/m²
  - Threshold of feeling (or pain!): 200 N/m²

- Frequency range of hearing
  - humans: 20 - 20 000 Hz
  - dogs: 20 - 45 000 Hz
  - beluga whale: 1000 - 123 000 Hz

- Period of lowest and highest audible frequencies
  - 1/20 Hz = 0.05 s  1/20 000 Hz = 0.05 ms

- Shortest audible wave
  - 340/20000=1.7cm

- Longest audible wave
  - 340/20=17m

¹Quantity depends on temperature: For air, the speed of sound is \( c = 20.1 \sqrt{T} \), where \( T \) is the absolute temperature found by adding 273 to the temperature on the Celsius scale.
Power and Intensity

• Waves can represent a number of time-evolving physical variables (force, velocity, acceleration, etc.).

• For *sound* waves, the physical variable represented by the amplitude of the waveform is pressure.

• Related to the sound pressure are
  1. the sound **power** emitted by the source
  2. the sound **intensity** measured some distance from the source.

• **Sound power**:
  – a **fixed** quantity, analogous to the wattage rating of a light bulb.

• **Sound intensity**:
  – a **quantity influenced** by environment surroundings, surfaces, and interference from other sources
  – analogous to the brightness of the light in a particular part of the room
Intensity

- **Intensity** is
  - the power per unit area carried by the wave,
  - measured in watts per square meter (W/m²).

- **Sound intensity** is
  - a measure of the sound power that contacts an area (e.g. eardrum, microphone).

- Sound is audible to humans when its intensity is above

\[ I_0 = 10^{-12} \text{ W/m}^2, \]

with 1 W/m² being the threshold of feeling.

- Intensity is related to pressure squared:

\[ I = \frac{p^2}{(\rho c)}, \]

where

- \( p \) is the pressure,
- \( \rho \) is the density of air (kg/m³), and
- \( c \) is the speed of sound (m/s).
Human hearing is better measured on a logarithmic scale than a linear scale.

On a linear scale, a change between two values is perceived on the basis of the difference between the values:

- e.g., a change from 1 to 2 would be perceived as the same increase as from 4 to 5.

On a logarithmic scale, a change between two values is perceived on the basis of the ratio of the two values:

- e.g., a change from 1 to 2 would be perceived as the same increase as a change from 4 to 8.

Figure 1: Moving one unit to the right increment by 1 on the linear scale and multiplies by a factor of 10 on the logarithmic scale.
Decibels

• The decibel (dB) is a unit named after Alexander Graham Bell, known as a telecommunications pioneer.

• A decibel is defined as one tenth of a bel, i.e., to convert from Bel to dB you multiply by 10:

\[ 1 \text{ B} = 10 \text{ dB} \]

• The decibel is a logarithmic scale, used to compare two quantities such as the power gain of an amplifier or the relative power of two sound sources.

• The decibel difference between two power levels \( \Delta L \) for example, is defined in terms of their power ratio \( W_2/W_1 \) and is given in decibels by:

\[ \Delta L = 10 \log \frac{W_2}{W_1} \text{ dB}. \]

• Since power is proportional to intensity, the ratio of two signals with intensities \( I_1 \) and \( I_2 \) is similarly given in decibels by

\[ \Delta L = 10 \log \frac{I_2}{I_1} \text{ dB}. \]
Sound Power and Intensity Level

- Decibels are often used as absolute measurements, with one of the quantities being a fixed reference.
- The *sound power level*

\[ L_W = 10 \log \frac{W}{W_0} \text{ dB}, \]

and *sound intensity level*

\[ L_I = 10 \log \frac{I}{I_0} \text{ dB}, \]

of a source, may be expressed using the threshold of audibility as a reference, defined by

\[ W_0 = 10^{-12} \text{ W}, \]
\[ I_0 = 10^{-12} \text{ W/m}^2. \]
Sound pressure Level

- Recall that intensity is proportional to sound pressure amplitude squared:

\[ I = \frac{p^2}{(\rho c)}. \]

- Though \( \rho \) and \( c \) are dependent on temperature, their product is often approximated by 400.

- When \( \rho c = 400 \), sound pressure level \( L_p \) (SPL) is equivalent to sound intensity level, and is expressed in dB by:

\[
L_p = 10 \log \frac{I}{I_0} \\
= 10 \log \frac{p^2}{(\rho c I_0)} \\
= 10 \log \frac{p^2}{(4 \times 10^{-10})} \\
= 10 \log \left( \frac{p}{(2 \times 10^{-5})} \right)^2 \\
= 20 \log \frac{p}{(2 \times 10^{-5})} \\
= 20 \log \frac{p}{p_0}.
\]

where \( p_0 = 2 \times 10^{-5} \) is the threshold of hearing for amplitude of pressure variations.
Increasing distance from a source

• A point source is one that radiates equally in all direction.

• When it radiates into free space,
  – the intensity decreases by \( \frac{1}{r^2} \) (as the radius \( r \) of a sphere increases, its surface area expands by \( 4\pi r^2 \), and
  – the pressure decreases by \( \frac{1}{r} \) (this follows from intensity being proportional to pressure squared),

  where \( r \) is the distance from the source.

• In actual practice, sound sources wouldn’t radiate so symmetrically as there would interference from other reflective objects.
Sound level when doubling the distance

• So how does the sound intensity level change with a doubling of distance?
• We know that the intensity will drop by $1/2^2$ and thus

$$L_I = 10 \log \left( \frac{1}{2^2} \times \frac{I}{I_0} \right)$$

$$= 10 \log \left( \frac{I}{I_0} \right) + 10 \log \left( \frac{1}{2^2} \right)$$

$$= 10 \log \left( \frac{I}{I_0} \right) + 10 \log \left( 2^{-2} \right)$$

$$= 10 \log \left( \frac{I}{I_0} \right) - 20 \log(2)$$

$$= 10 \log \left( \frac{I}{I_0} \right) - 20 (.3)$$

$$= 10 \log \left( \frac{I}{I_0} \right) - 6 \text{ dB}.$$ 

• Doubling the distance from a source causes a decrease of 6dB in the sound level.
Multiple sound sources

• When there are multiple *uncorrelated* sound sources, the total power emitted is the *sum* of the power from each source.

• **Question:** By how much would the sound level increase when two (uncorrelated) sources sound simultaneously with equal power?

• **Solution:** The sound power (at the source) would double and thus,

\[
L_W = 10 \log_{10}(2W/W_0) \\
= 10 \log_{10}(W/W_0) + 10 \log_{10}(2) \\
= 10 \log_{10}(W/W_0) + 3 \text{ dB},
\]

there would be an increase of 3 dB in the sound power level.

• Similarly, there would be a 3 dB increase in the sound intensity level measured at some distance away from the source.

• This is the case most of the time. However, there is an exception...
Multiple correlated sound sources

- In rare (or contrived) cases, if the sound sources emit waveforms that are strongly correlated, there will be interference.

- **Solution 2:** When two waves of the same frequency and amplitude $A$ reach the same point, they may interfere destructively or constructively resulting in a pressure amplitude range of
  - $0$ (complete destructive interference) to
  - $2A$ (complete constructive interference).

- In the case of a doubling of pressure, there’s an increase of $20 \log(2) = 6$ dB.

- Thus doubling the sound source can result in a sound level change of 0-6 dB (depending on interference) for correlated sounds.