CMPT 468: Lecture 1
Fundamentals of Acoustics and Sound

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What is Sound?

If a tree falls in a forest and no one is there to hear it, does it make sound?

- Nearly all objects will vibrate when disturbed.
- Sound is the result of a **wave** created by vibrating objects, propagated through a medium from one location to another.
- **Acoustics** is the science that deals with the quantifiable measure of the *production*, *control*, *transmission* and *reception* of sound.
- **Psychoacoustics** is the study of the way humans perceive sounds.

Musical Acoustics

Mechanical Waves

- A disturbance travelling through a medium
- Transports energy from one location to another

Travelling waves

- Waves propagating in one direction with negligible change in shape
- Two types: *longitudinal* and *transverse*

Musical Acoustics cont.

Longitudinal Wave

Particle displacement is parallel to the direction of wave propagation.

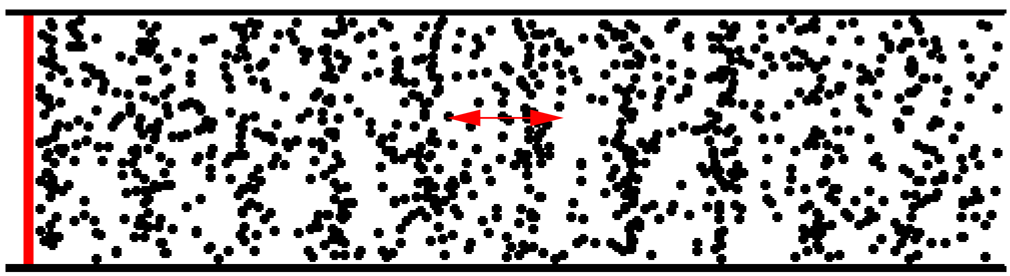

Figure 1: Longitudinal wave. Animation, courtesy of Dr. Dan Russell, Kettering University, available on class website.

Transverse Wave

Particle displacement is perpendicular to the direction of wave propagation.

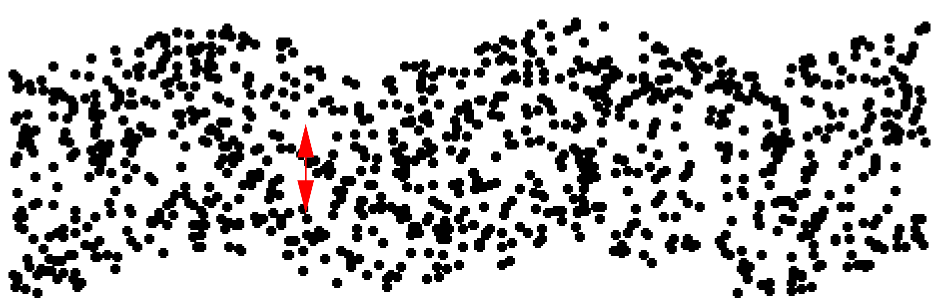

Figure 2: Transverse Wave, animation courtesy of Dr. Dan Russell, Kettering University.

Sound

- Sound waves are longitudinal waves.
- A disturbance of a source (such as vibrating objects) creates an initial region of compression or high pressure.
- When the source vibrates, alternating regions of low and high pressure are produced in the surrounding air, called *rarefactions* and *compressions* respectively.
- The alternating pressure propagates through a medium, away from the source, before reaching our ears.

Properties of a Wave

The *waveform* of the sound shows the time evolution of the pressure variations.

- **Amplitude**: maximum particle displacement from rest position (Pa or N/m^2).
- **Wavelength**: length of one complete cylce (m).
- **Period**: time to complete one cycle (s).
- **Frequency**: number of cycles per second (Hz).

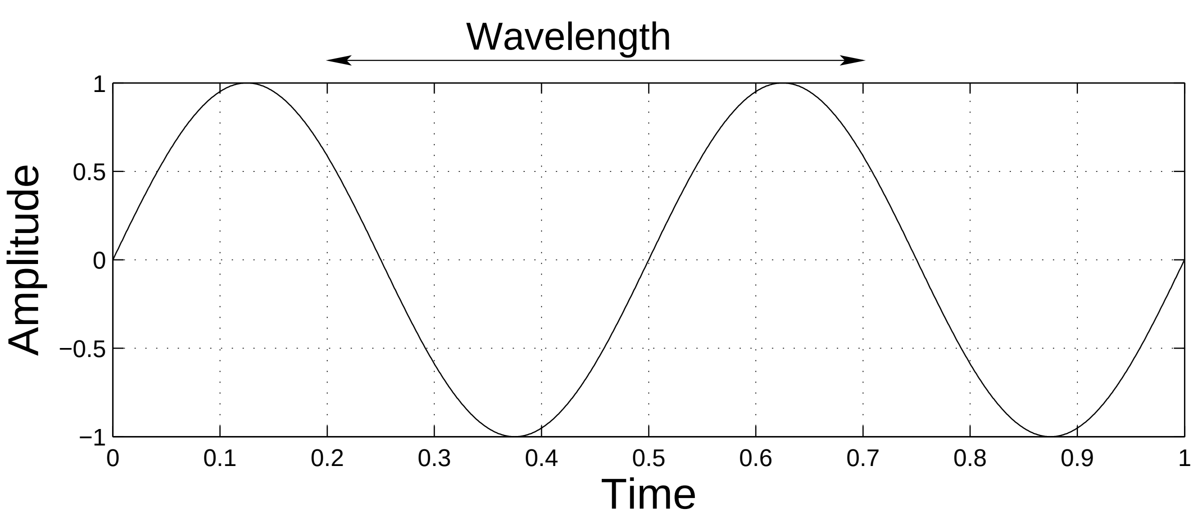

Figure 3: Sinewave.

Properties of Sound Waves

- Speed of sound[1]:
  - in air: 340 m/s
  - in water: 1480 m/s
- Amplitude range of hearing (humans)
  - Threshold of audibility: 0.00002 N/m^2
  - Threshold of feeling (or pain!): 200 N/m^2
- 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

[1] Quantity 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

- The two physical quantities for a sound wave described so far are the frequency and amplitude of pressure variations.
- 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 is analogous to the wattage rating of a light bulb—both measure a fixed quantity.
- Sound intensity is analogous to the brightness of the light in a particular part of the room—a quantity influenced by environment surroundings/surfaces and interference from other sources.

Intensity

- The intensity is the power per unit area carried by the wave, measured in watts per square meter (W/m^2)
- Sound intensity therefore, is a measure of the power in a sound that actually contacts an area, such as the eardrum.
- The range of human hearing is
  - $I_0 = 10^{-12}$ W/m^2 (threshold of audibility)
  - 1 W/m^2 (threshold of feeling)
- Intensity is related to pressure squared, with the actual relationship being

$$I = p^2/(\rho c),$$

  where p is the pressure, ρ is the density of air (kg/m^3), and c is the speed of sound (m/s).

Linear vs logarithmic scales.

- 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. Thus, for example, a change from 1 to 2 would be perceived as the same amount of 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. That is, a change from 1 to 2 (ratio of 1:2) would be perceived as the same amount of increase as a change from 4 to 8 (also a ratio of 1:2).

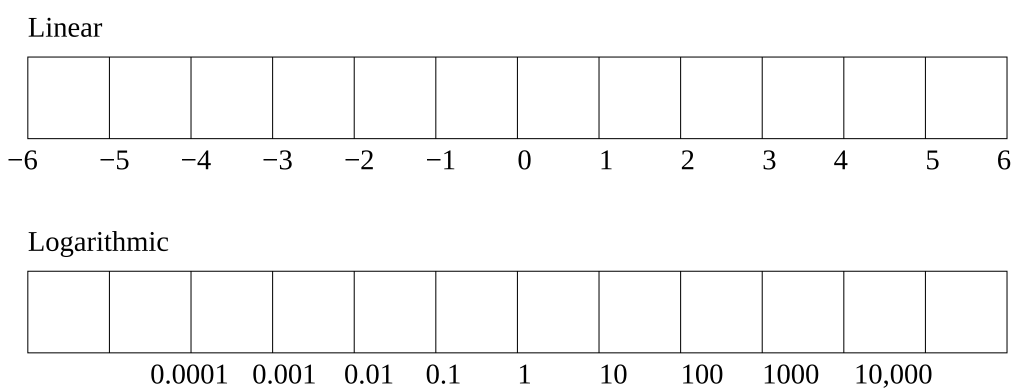

Figure 4: Moving one unit to the right increment by 1 on the linear scale and multiplies by a factor of 10 on the logarithmic scale.

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 ΔL for example, is defined in terms of their power ratio W_2/W_1 and is given in decibels by:

$$\Delta L = 10 \log W_2/W_1 \quad \text{dB.}$$

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

$$\Delta L = 10 \log I_2/I_1 \quad \text{dB.}$$

Sound Power and Intensity Level

- Though decibels are often used as absolute measurements, one of the quantities is really a fixed reference.
- The *sound power level* of a source, for instance, is expressed using the threshold of audibility $W_0 = 10^{-12}$ as a reference and is given in decibels by

$$L_W = 10 \log W/W_0.$$

- Similarly, the *sound intensity level* at some distance from the source can therefore be expressed in decibels by comparing it to a reference—usually $I_0 = 10^{-12}$ W/m^2:

$$L_I = 10 \log I/I_0.$$

Sound pressure Level

- Recall that intensity is proportional to sound pressure amplitude squared

$$I = p^2/(\rho c)$$

- Though ρ and c are dependent on temperature, their product is often approximated by 400.
- The *sound pressure level* L_p (SPL) is equivalent to sound intensity level and is expressed in dB by:

$$\begin{aligned} L_p &= 10 \log I/I_0 \\ &= 10 \log p^2/(\rho c I_0) \\ &= 10 \log p^2/(4 \times 10^{-10}) \\ &= 10 \log \left(p/(2 \times 10^{-5})\right)^2 \\ &= 20 \log p/(2 \times 10^{-5}) \\ &= 20 \log p/p_0. \end{aligned}$$

  where $p_0 = 2 \times 10^{-5}$ is the threshold of hearing for amplitude of pressure variations.
- Sound pressure level and sound intensity level are the same when $\rho c = 400$.

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 $1/r^2$ (as the radius r of a sphere increases, its surface area expands by $(4\pi r^2)$, and
  - the pressure decreases by $1/r$ (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

$$\begin{aligned} L_I &= 10\log(I/2^2 I_0) \\ &= 10\log(1/2^2) + 10\log(I/I_0) \\ &= 10\log(2^{-2}) + 10\log(I/I_0) \\ &= -20\log(2) + 10\log(I/I_0) \\ &= -20(.3) + 10\log(I/I_0) \\ &= 10\log(I/I_0) - 6 \text{ dB}. \end{aligned}$$

- Doubling the distance from a source causes a decrease of 6dB in the sound level.

Multiple sources

- Short Answer: When there are multiple sound sources, the total power emitted is the *sum* of the power from each source.
- By how much would the sound level increase when two sources sound simultaneously with equal power?
- The sound power level (at the source) would double and thus,

$$\begin{aligned} L_W &= 10 \log 10(2W/W_0) \\ &= 10 \log 10(2) + 10 \log 10(W/W_0) \\ &= 3 \text{ dB} + 10 \log 10(W/W_0), \end{aligned}$$

  yielding 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 sources exception

- In a very rare case, if the sound sources emit waveforms that are strongly *correlated*, there will be *interference*.
- When two waves of the same frequency and amplitude A reach the same point, they may interfere *destructively* or *constructively*, resulting in an overall amplitude of anywhere between 0 and $2A$, respectively.
- The resulting overall amplitude, therefore, can be anywhere from 0 (complete destructive interference) to $2A$ (complete constructive interference).
- This results in a change of anywhere between 0 dB and 6 dB.

Amplitude Envelopes

- In his work, *On the Sensations of Tone*, Hermann von Helmholtz characterized tones by the way in which their amplitudes evolved over time, that is, by their *amplitude envelope*.
- He described the envelope as having three parts:
  1. **the attack**: the time it takes the sound to rise to its peak
  2. **the sustain**: the steady state portion of the sound (where the amplitude has negligiable chane)
  3. **the decay**: the time it take for the sound to decay or fade out.

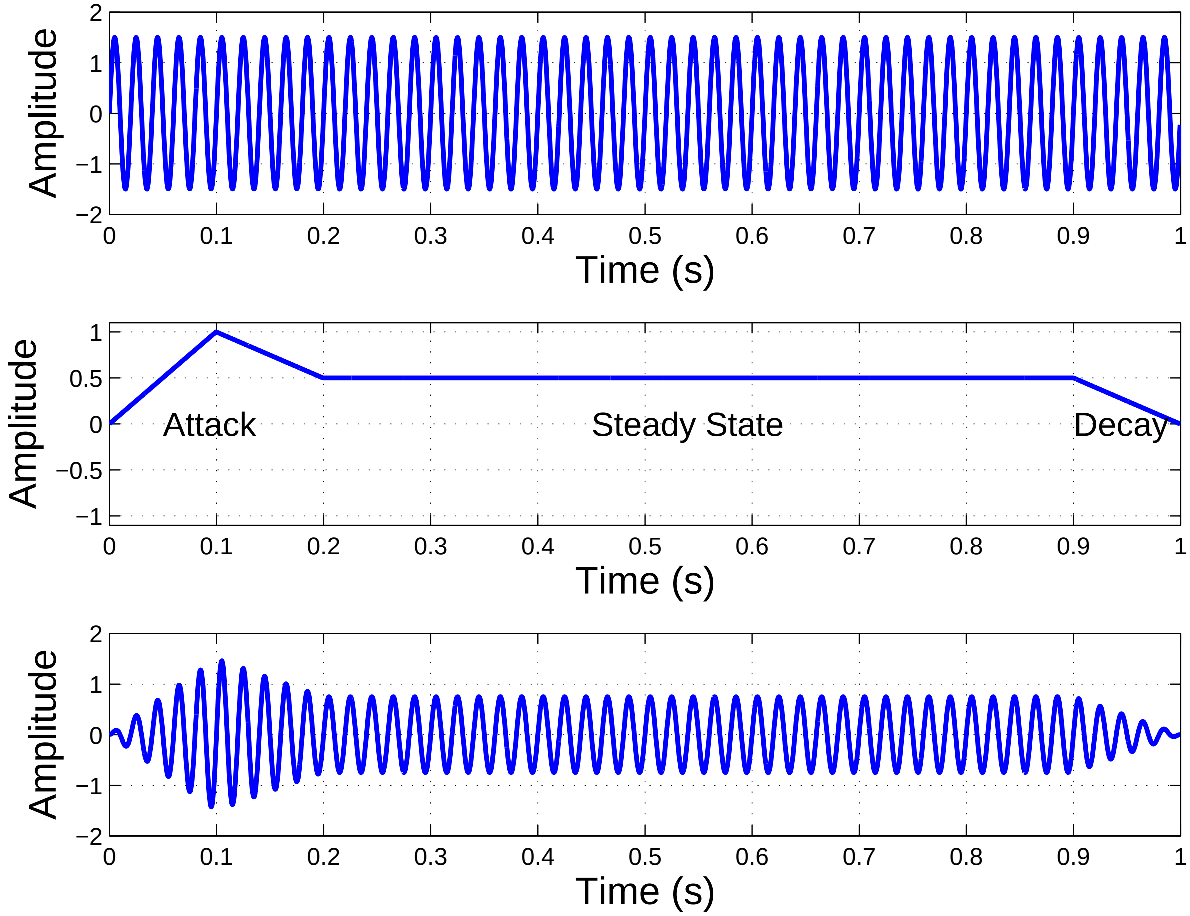

Figure 5: A sinusoid with an amplitude envelope.

ADSR Envelope

- The duration of the attack and decay greatly influence the quality of a tone: wind instruments tend to have long attacks, while percussion instruments tend to have short attacks.
- Another envelope, called ADSR, has a fourth segment inserted between the attack and the sustain.
- This envelope attempts to mimic the envelopes found in acoustic instruments.

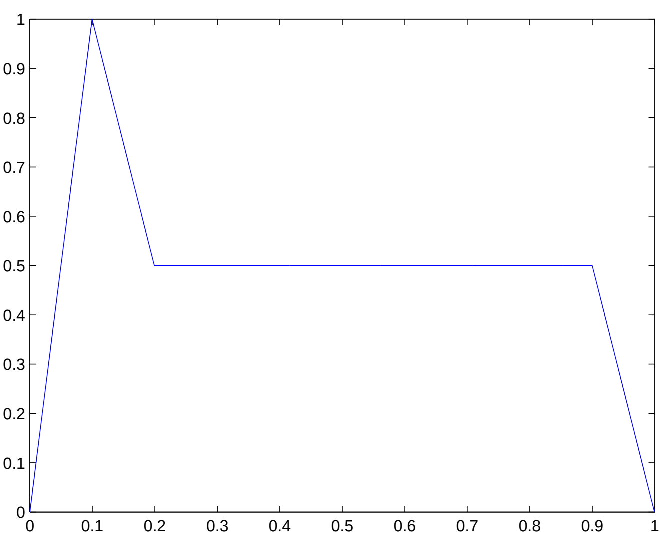

Figure 6: An ADSR envelope.