LING 490 - SPECIAL TOPICS IN LINGUISTICS

Fundamentals of Digital Signal Processing

Yan Tang

Department of Linguistics, UIUC

Week 5

Last week…

- Audio formats and codecs
  - Uncompressed and compressed
  - Lossy and lossless
  - How and why MP3 works
  - Audio file size
- WAV format
  - History and usage
  - Data structure
- Python API for WAV file reading and writing

Sound level

- To quantify how strong (in terms of energy per unit) a sound signal is
- Sound intensity (SI): I
  - *Sound energy* flux in a specific direction and sense through an area perpendicular to that direction, divided by the area.
  - Measured in the direction of the sound wave propagation
- Sound pressure (SP), p
  - *Sound force* applied perpendicular to the surface of an object, divided by the area

Sound intensity, I

- *Power* per unit area (e.g. m^2) carried by a wave

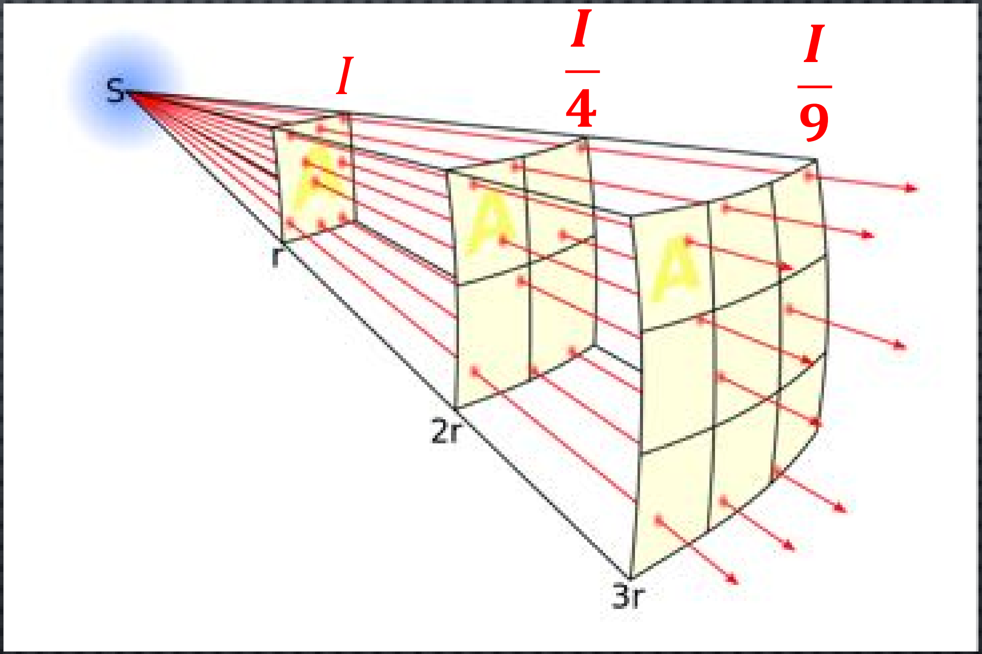
$$I = \frac{P}{A}$$

  - $\boldsymbol{P}$: power (in watts, W), the rate at which energy is transferred by the wave
  - $\boldsymbol{A}$: area in m^2

- Unit: W/m^2
  - Human ears can detect sound intensities as low as 0.000000000001 W/m^2 and up to 50 W/m^2 or more

Inverse-square law

- An "ideal" acoustic space: free field
  - free of reflection
- Sound intensity is inversely proportional to square of distance



$$I = \frac{P}{A} = \frac{P}{4\pi r^2} \quad \therefore I \propto \frac{1}{r^2}$$

https://en.wikipedia.org/wiki/Inverse-square_law

Sound pressure, p

- *Force* per unite area (e.g. m^2) carried by a wave

$$p = \frac{F}{A}$$

  - $\boldsymbol{F}$: force, interactive between the wave and ambience that cause the wave to accelerate
  - $\boldsymbol{A}$: area in m^2

- Unit: N/m^2 or *Pascal*
  - Human ears can deal with sound pressures of 0.00002 pascals up to 200 pascals

Sound intensity level (SIL) and sound pressure level (SPL)

- The range of sound level the auditory system can sense is extraordinarily wide!
  - 10^{-12} to 10^{2} for sound intensity
  - 10^{-5} to 10^{2} for sound pressure

- Idea of *decibels*: express *SIL* and *SPL* on a logarithmic scale, as a ratio of comparing to a reference

$$decibels = 10 \cdot log_{10} \frac{I}{I_{ref}} = 10 \cdot log_{10} (\frac{p}{p_{ref}})^2 = 20 \cdot log_{10} (\frac{p}{p_{ref}})$$

I_{ref}: $10^{-12}\ W/m^2$

p_{ref}: $2 \times 10^{-5}\ N/m^2$

Decibels

I_{ref}: $10^{-12}\ W/m^2$

p_{ref}: $2 \times 10^{-5}\ N/m^2$

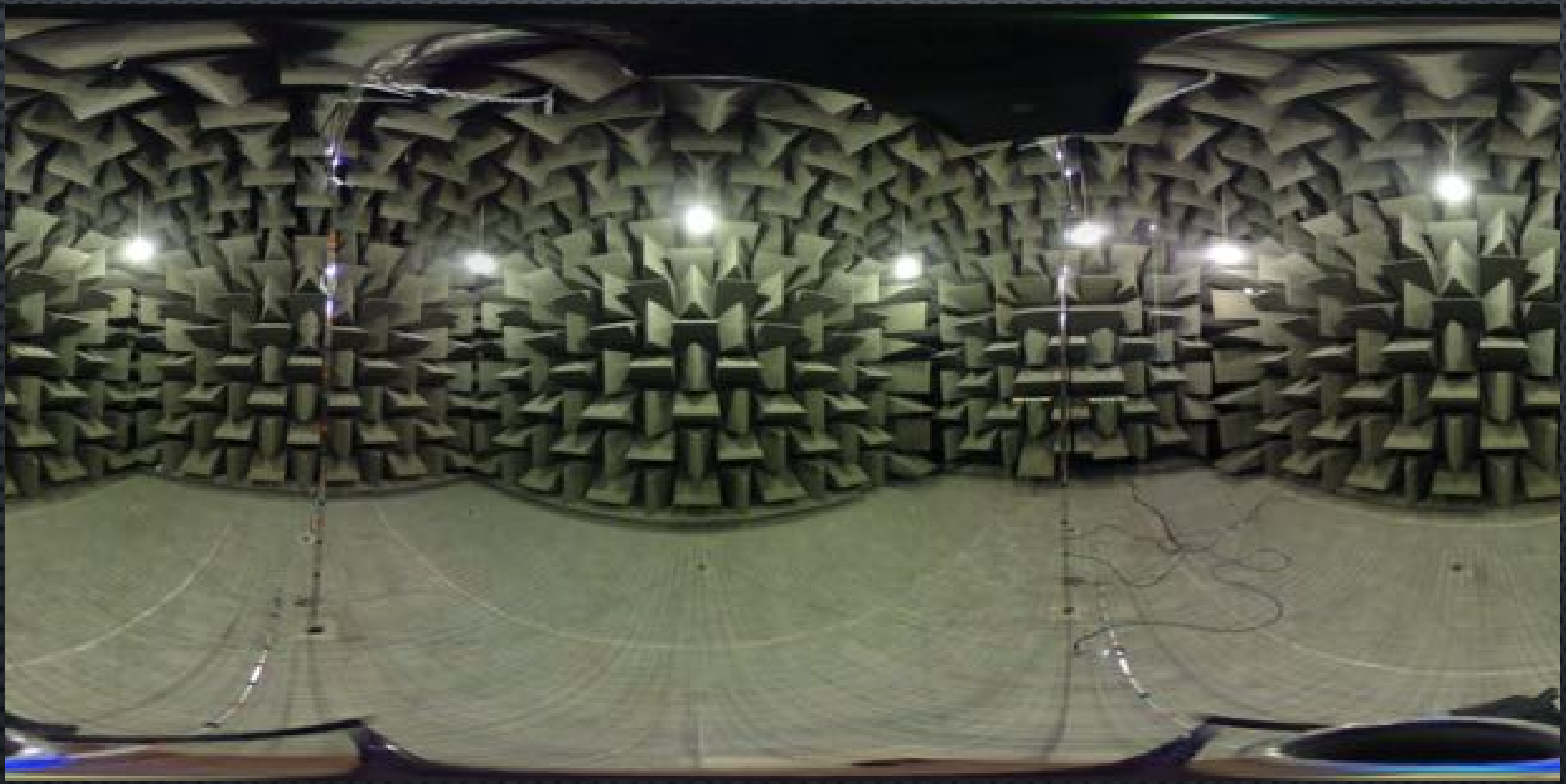
- If the intensity of a sound, I, is $10^{-10}\ W/m^2$, what is the SIL level?
- If the pressure of a sound, p, is $2 \times 10^{-4}\ N/m^2$, what is the SPL level?
- What would happen if the I (or p) were the same as the I_{ref} (or p_{ref})?
  - What is the implication?

SPL in common scenarios

Sound sources (noise) Examples with distance	Sound pressure Level L_p dB SPL	Sound pressure p N/m² = Pa Sound field quantity	Sound intensity I W/m² Sound energy quantity
Jet aircraft, 50 m away	140	200	100
Threshold of pain	130	63.2	10
Threshold of discomfort	120	20	1
Chainsaw, 1 m distance	110	6.3	0.1
Disco, 1 m from speaker	100	2	0.01
Diesel truck, 10 m away	90	0.63	0.001
Kerbside of busy road, 5 m	80	0.2	0.000 1
Vacuum cleaner, distance 1 m	70	0.063	0.000 01
Conversational speech, 1 m	60	0.02	0.000 001
Average home	50	0.006 3	0.000 000 1
Quiet library	40	0.002	0.000 000 01
Quiet bedroom at night	30	0.000 63	0.000 000 001
Background in TV studio	20	0.000 2	0.000 000 000 1
Rustling leaves in the distance	10	0.000 063	0.000 000 000 01
Hearing threshold	0	0.000 02	0.000 000 000 001

http://www.sengpielaudio.com/TableOfSoundPressureLevels.htm

SPL in common scenarios



- Anechoic chamber at the Acoustics Research Centre, University of Salford, UK
- Background noise level: -12.4 dBA

The quietest place on the earth!

- Anechoic chamber at Microsoft Research.
- Background noise level: -20.6 dBA

The relationship between I and p

$$I = \frac{p^2}{\rho \cdot c} \quad \therefore I \propto p^2$$

- $\boldsymbol{\rho}$: density of air, kg/m^3
- $\boldsymbol{c}$: sound speed in air, m/s

- Acoustic impedance:
  - $(\rho \cdot c)$, $pa \cdot s/m$
  - Both ρ are c variables to temperature
  - When T= 20 ℃, ≈ 413.3 $pa \cdot s/m$

ρ are c as functions of temperature

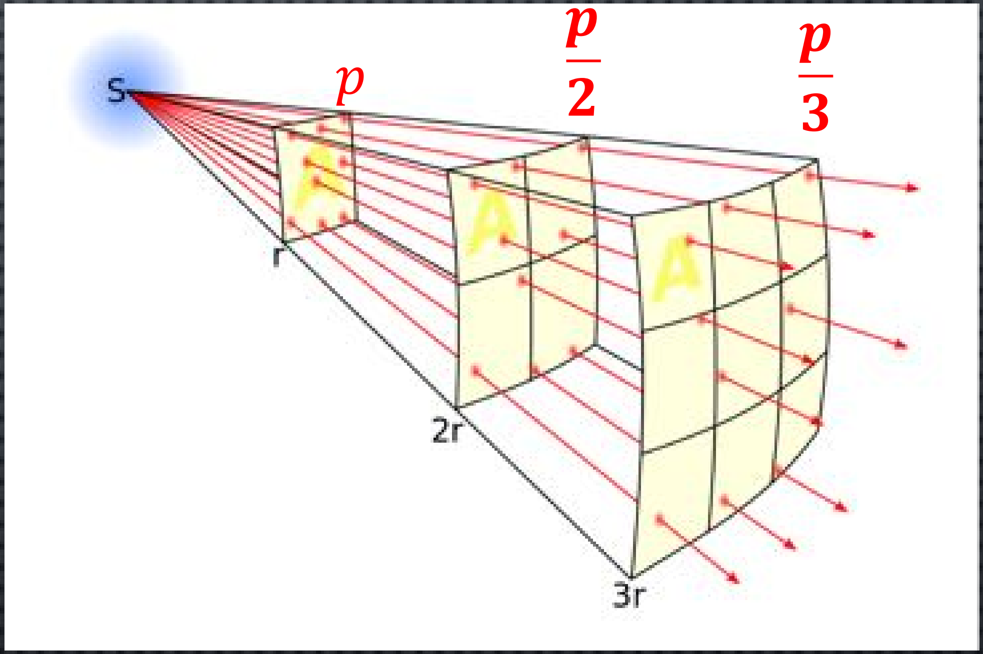
Effect of temperature on properties of air

Temperature T (°C)	Speed of sound c (m/s)	Density of air ρ (kg/m^3)	Characteristic specific acoustic impedance z_0 (Pa·s/m)
35	351.88	1.1455	403.2
30	349.02	1.1644	406.5
25	346.13	1.1839	409.4
20	343.21	1.2041	413.3
15	340.27	1.2250	416.9
10	337.31	1.2466	420.5
5	334.32	1.2690	424.3
0	331.30	1.2922	428.0
−5	328.25	1.3163	432.1
−10	325.18	1.3413	436.1
−15	322.07	1.3673	440.3
−20	318.94	1.3943	444.6
−25	315.77	1.4224	449.1

https://en.wikipedia.org/wiki/Speed_of_sound

Inverse-distance law

- Pressure is proportional to the square root of intensity
- Sound pressure is inversely proportional to distance



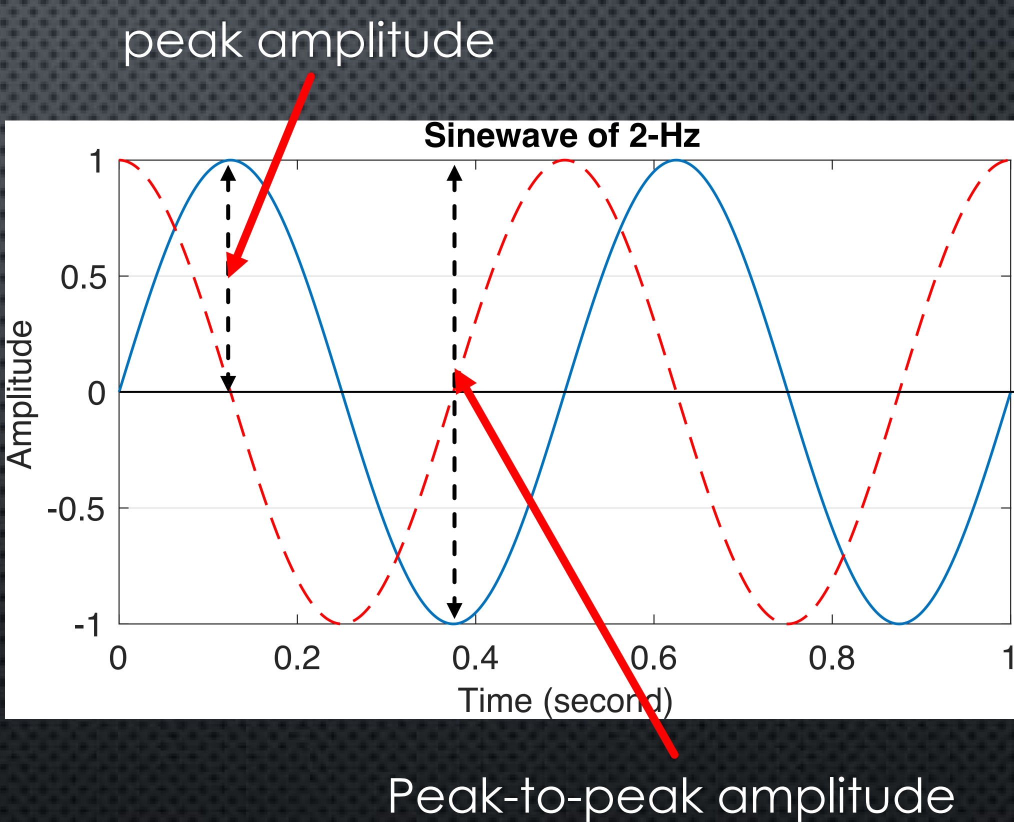
$$p = \frac{\sqrt{P\rho c\pi^{-1}}}{2r} \quad \therefore p \propto \frac{1}{r}$$

$$I = \frac{P}{A} = \frac{P}{4\pi r^2} \qquad I = \frac{p^2}{\rho \cdot c}$$

https://en.wikipedia.org/wiki/Inverse-square_law

Theoretical value of SPL

- What does amplitude of a signal represent on computer?
  - Assumption: the instant *pressure* in pascal at that time or N/m^2



Theoretical value of SPL

- Root-mean-square (RMS) amplitude

$$A_{rms} = \sqrt{\frac{\sum_{i=1}^{N} s_i^2}{N}}$$

N: number of samples

s: amplitude

  - Sound perception is a process of energy accumulation
  - RMS pressure, p_{rms} , is measured over certain duration, instead of instant pressure

$$SPL = 20 \cdot log_{10}(\frac{p_{rms}}{p_{ref}})$$

Considering the following scenario:

- Donny is going to listen to music in WAV format
- He computes average SPL of the sound in the WAV file, which turns out to be 73 dB SPL
- He is then listening to the WAV over a pair of headphones

Q: *what's the average SPL of the music Donny actually hears?*

Q: *what'll the SPL of the music Donny hears be when it is played back via a loudspeaker 2 metres away from Donny?*

Theoretical SPL vs practical SPL

- Assumes that amplitude represents sound pressure measured at the listener's position
  - Several factors may affect the sound level when reaching your ear, e.g. hardware, distance.
- In real situations, SPLs are measured using SPL meter.

Digital signal level vs SPL

- Signal level can be also quantified using the notion of dB
  - We are interested in the relative level of a signal compared to other signals
  - The intensity of signal s can be computed as an absolute value in dB, e.g.

$$I_{dB} = 10 \cdot log_{10} A_{rms}^2$$

- Therefore, 60 dB is not same to 60 dB SPL!!!

Perception of sound level

- "Sound with low intensities are perceived as '*soft*' and high intensities as '*loud*'"

- Which of the following sound is the loudest?

100 Hz

250 Hz

1k Hz

10k Hz

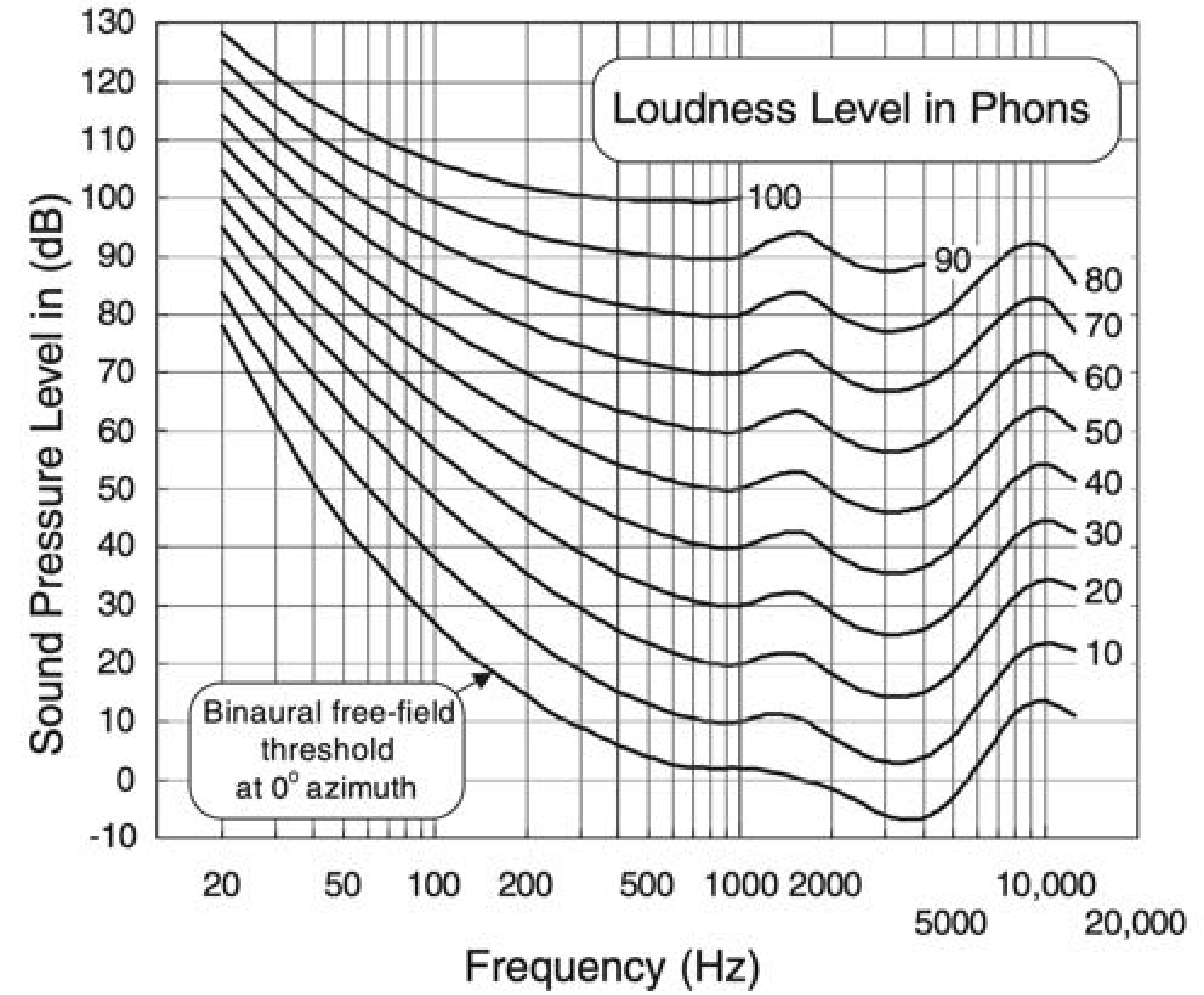
  - Sound signals at same sound level (e.g. rms=0.1) may be perceived differently loud!

Loudness

- The perception of sound level is called loudness

- Units:
  - ***Phon*** vs dB SPL
  - referenced to dB SPL at *1k* Hz.

Normal equal-loudness-level contours for pure tones



BS ISO 226:2003
ANSI S3.6-2004
ISO 389-7-2005

Loudness (≠, !=, ~=, ne) sound level!!!

- Objective measurement VS Subjective perception
  - Sound level is physical parameter of sound
  - Loudness is percept associated with the physical aspect
  - Loudness may vary across population
  - Sound level holds constant
- Relationship
  - Increasing level is associated increasing loudness
  - *Not simple one-to-one correspondence*
- Other factors
  - Frequency range (as demonstrated)