AI-based Audio Analysis of Music and Soundscapes

Audio Processing

Dr.-Ing. Jakob Abeßer
Fraunhofer IDMT

jakob.abesser@idmt.fraunhofer.de

Audio Processing
Sound

- Sound [Merriam-Webster]
  - “Sensation perceived by the sense of hearing”
  - “A particular auditory impression”

Audio Processing
Sound

- Sound [Merriam-Webster]
  - "Sensation perceived by the sense of hearing"
  - "A particular auditory impression"
  - "Mechanical radiant energy that is transmitted by longitudinal pressure waves in a material medium (such as air) and is the objective cause of hearing"

Audio Processing
Sound

- Mechanical vibration with contact to air
- Rapid modulation of airflow

Audio Processing
Sound Waves

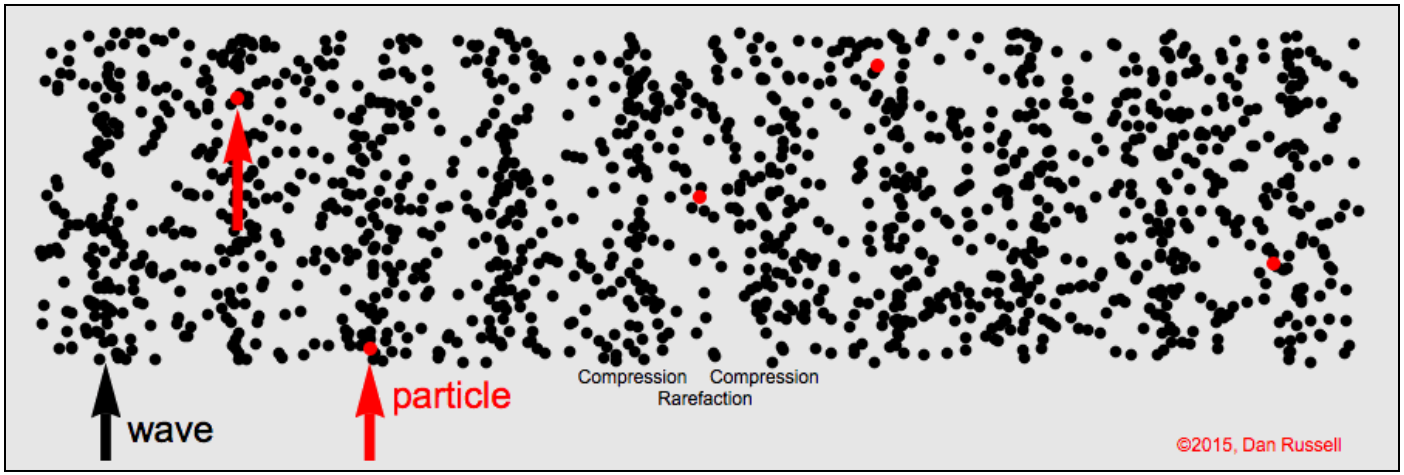


Fig. 1

Audio Processing
Sound Waves

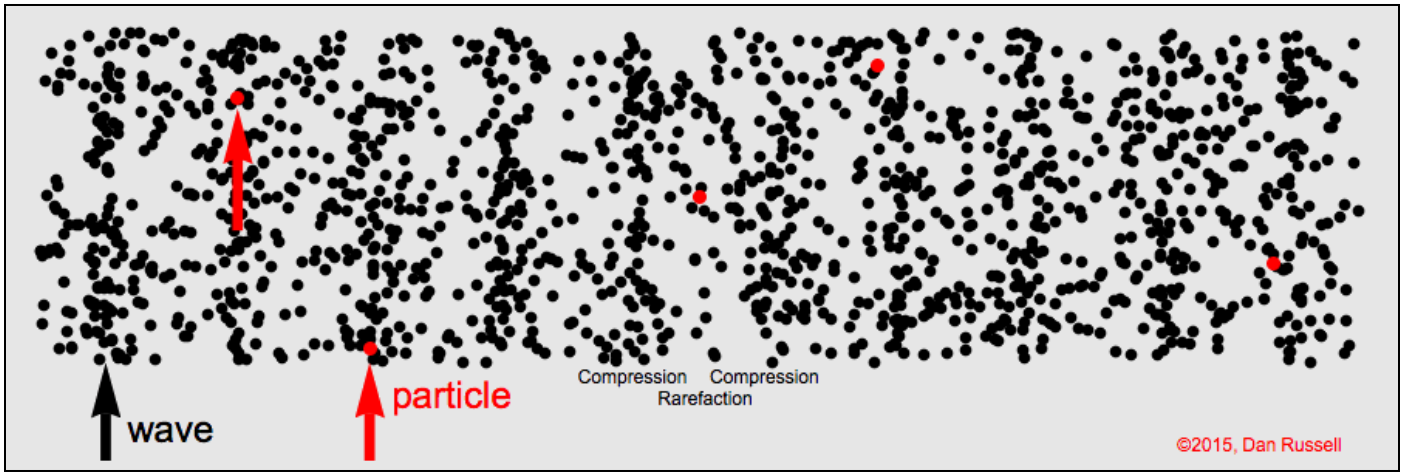
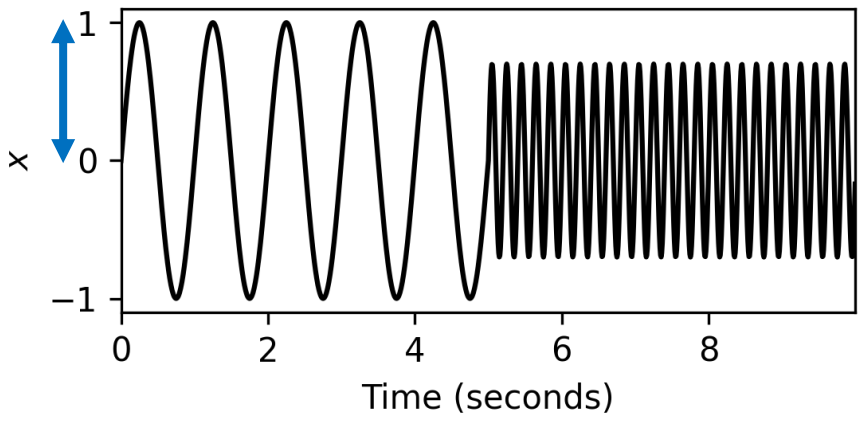


Fig. 1

- Oscillation of air pressure
- Propagate through medium (air)
- Converted into physical motion by ear / microphone

Audio Processing
Waveform

- Waveform $x(t)$
  - Amplitude (vertical displacement) of pressure vs. time

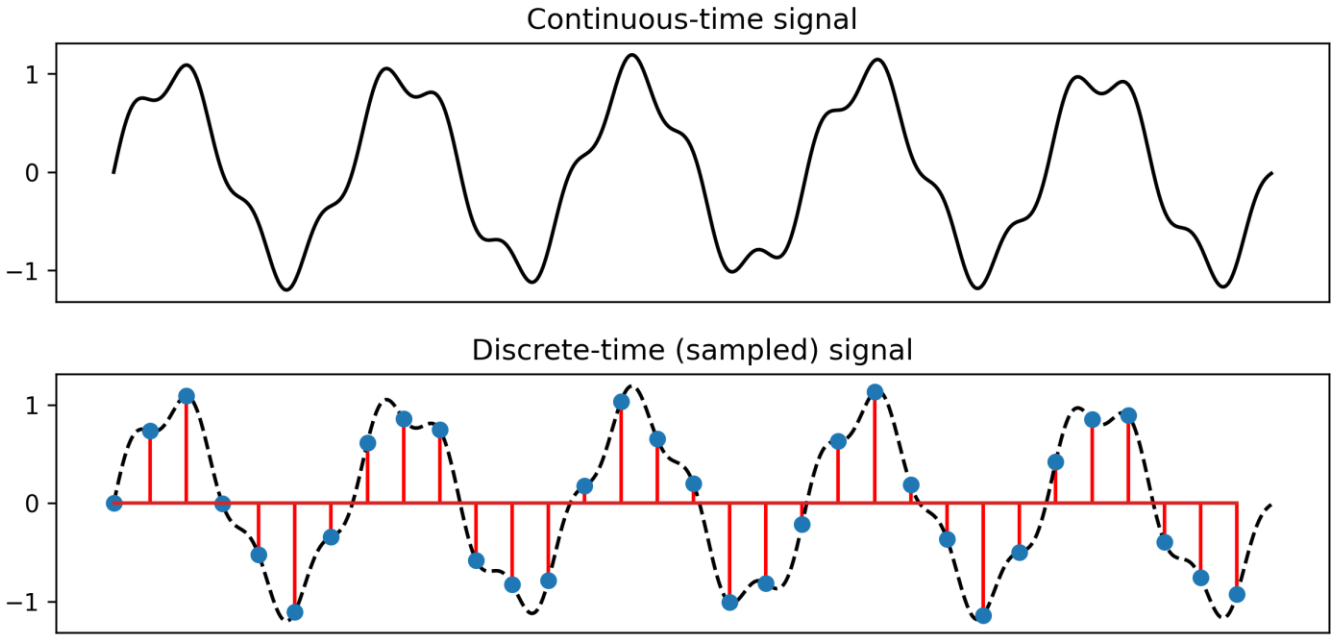


Audio Processing
Sampling

- Converting (continuous-time) analog signals into (discrete-time) digital signal

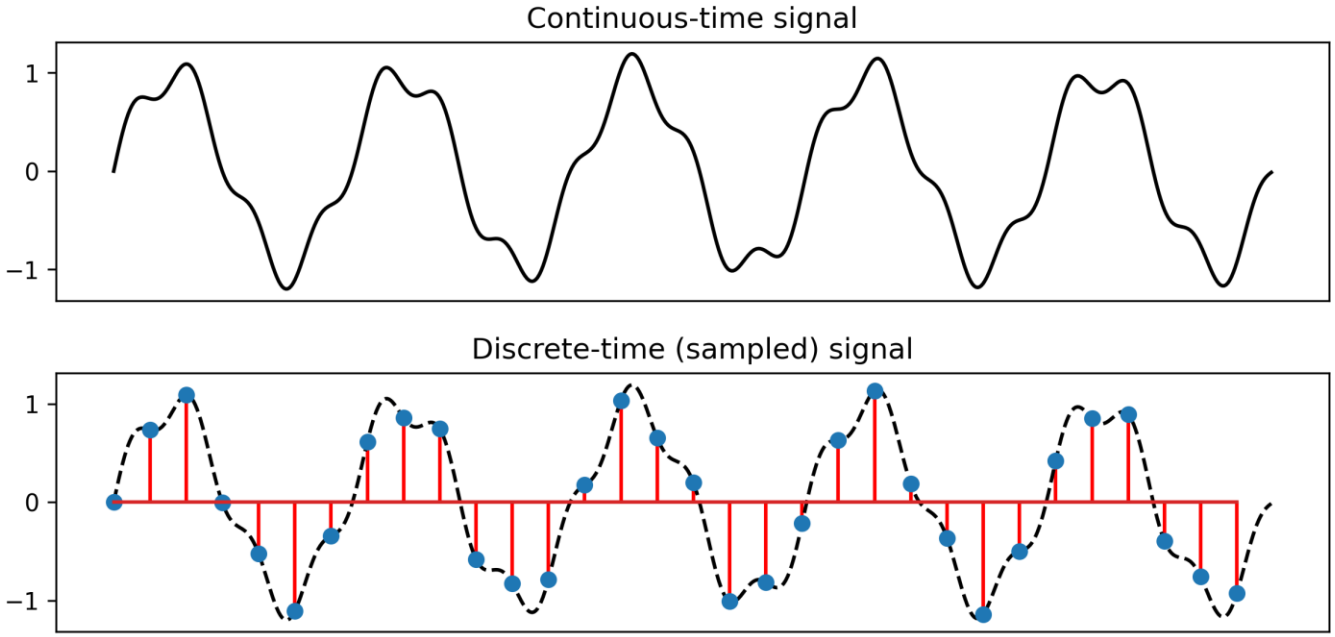
Audio Processing
Sampling

- Converting (continuous-time) analog signals into (discrete-time) digital signal



Audio Processing
Sampling

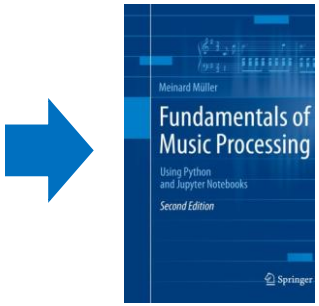
- Converting (continuous-time) analog signals into (discrete-time) digital signal



- Sampling frequency f_s: Number of samples per seconds [Hz]

Audio Processing
Sampling

- (Nyquist-Shannon) sampling theorem: $f_{\max} < f_s/2$
  - Signal must be band-limited
  - If sampling rate is too slow, aliasing occurs (higher frequencies can not be reconstructed properly



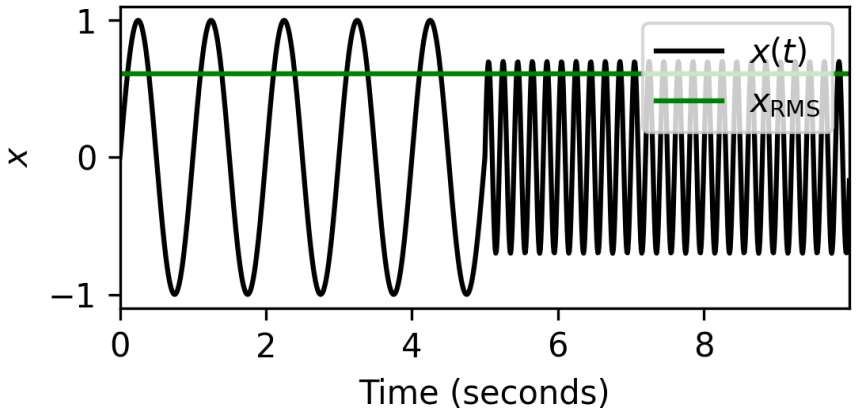
FMP Notebooks

Audio Processing
Sound Level

- Sound level [dB]
  - $L_{\mathrm{dB}} = 20 \log_{10} x_{\mathrm{RMS}}$
  - Root mean square $x_{\mathrm{RMS}} = \sqrt{\frac{1}{N} \sum_i \ {x_i}^2}$

Audio Processing
Sound Level

- Sound level [dB]
  - $L_{\mathrm{dB}} = 20 \log_{10} x_{\mathrm{RMS}}$
  - Root mean square $x_{\mathrm{RMS}} = \sqrt{\frac{1}{N}\sum_i {x_i}^2}$



Audio Processing
Sound Intensity

- Dynamics
  - Volume of a sound
- Sound power
  - Energy per time emitted by sound source (in all directions)

Audio Processing
Sound Intensity

- Dynamics
  - Volume of a sound
- Sound power
  - Energy per time emitted by sound source (in all directions)
- Sound intensity
  - Sound power per unit area
  - Minimum perceivable sound intensity = threshold of hearing
    - $I_{\mathrm{TOH}} = 10^{-12}\mathrm{W/m^2}$

Audio Processing
Sound Intensity

- Dynamics
  - Volume of a sound
- Sound power
  - Energy per time emitted by sound source (in all directions)
- Sound intensity
  - Sound power per unit area
  - Minimum perceivable sound intensity = threshold of hearing
    - $I_{\mathrm{TOH}} = 10^{-12}\mathrm{W/m^2}$
  - Intensity is computed using reference (TOH)
    - $I[dB] = 10 \cdot log_{10}\left(\frac{I}{I_{\mathrm{TOH}}}\right)$

Audio Processing
Sound Intensity

- Examples

Source	Intensity	Intensity level	× TOH
Threshold of hearing (TOH)	10^{-12}	0 dB	1
Whisper	10^{-10}	20 dB	10^{2}
Pianissimo	10^{-8}	40 dB	10^{4}
Normal conversation	10^{-6}	60 dB	10^{6}
Fortissimo	10^{-2}	100 dB	10^{10}
Threshold of pain	10	130 dB	10^{13}
Jet take-off	10^{2}	140 dB	10^{14}
Instant perforation of eardrum	10^{4}	160 dB	10^{16}

Table 1.1 from [Müller, FMP, Springer 2015]

Fig. 1.1

Audio Processing
Loudness

- Perceptual property (sort sounds from quiet to loud)
- Correlates with sound intensity
- Subjective, further depends on sound duration & frequency

Audio Processing
Loudness

- Perceptual property (sort sounds from quiet to loud)
- Correlates with sound intensity
- Subjective, further depends on sound duration & frequency

- Equal loudness curves
  - Perceived loudness [phon]

Figure 1.21 from [Müller, FMP, Springer 2015]

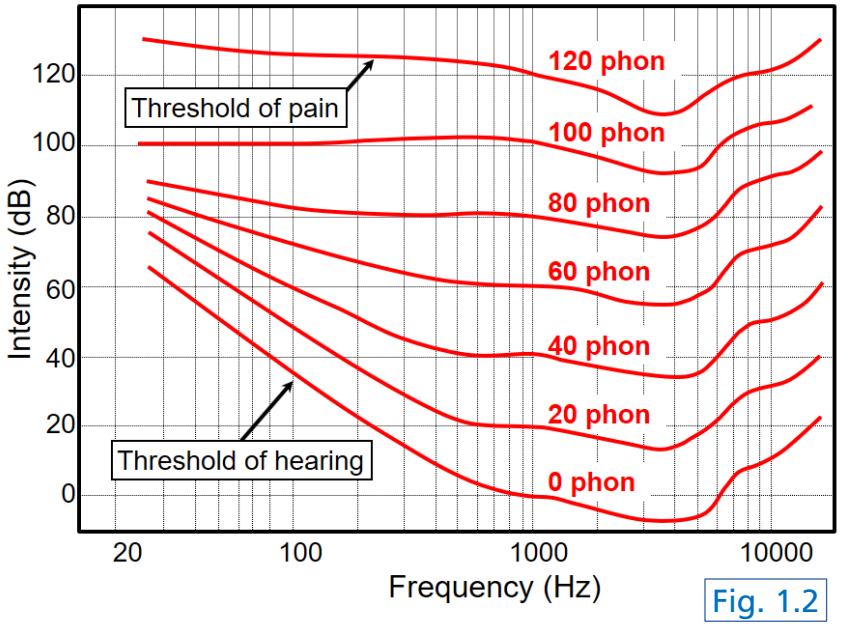


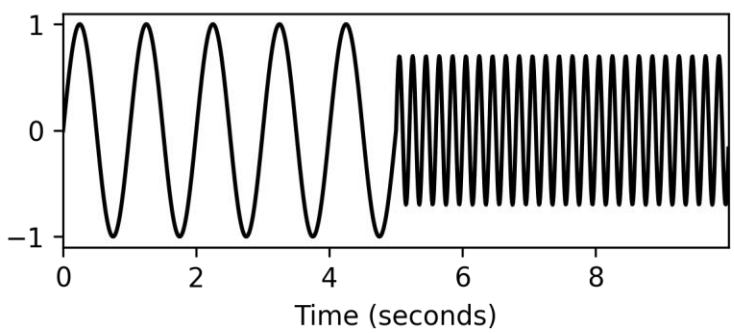
Fig. 1.2

Audio Processing
Time-Frequency Decomposition

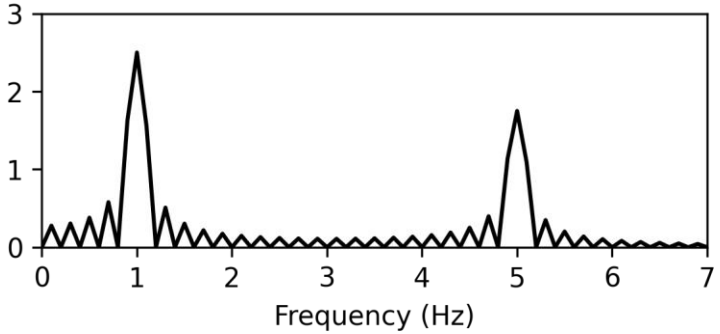
- Fourier Transform
  - Decompose signal into sum of sinusoids
    - Amplitude, frequency, phase

Audio Processing
Time-Frequency Decomposition

- Fourier Transform
  - Decompose signal into sum of sinusoids
    - Amplitude, frequency, phase



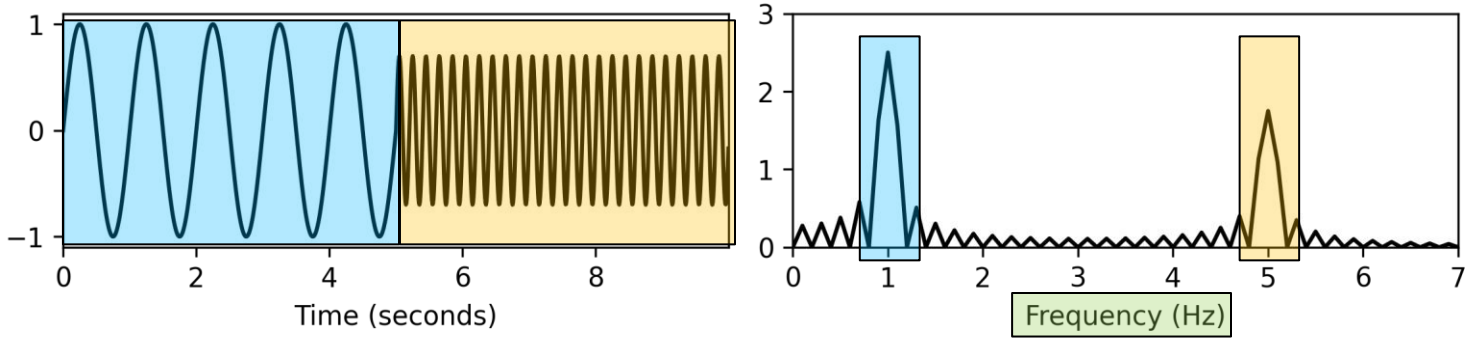
Waveform



Spectrum

Audio Processing
Time-Frequency Decomposition

- Fourier Transform
  - Decompose signal into sum of sinusoids
    - Amplitude, frequency, phase



Waveform

Spectrum

Audio Processing
Time-Frequency Decomposition

- Short-Time Fourier Transform (STFT)
  - Moving analysis window

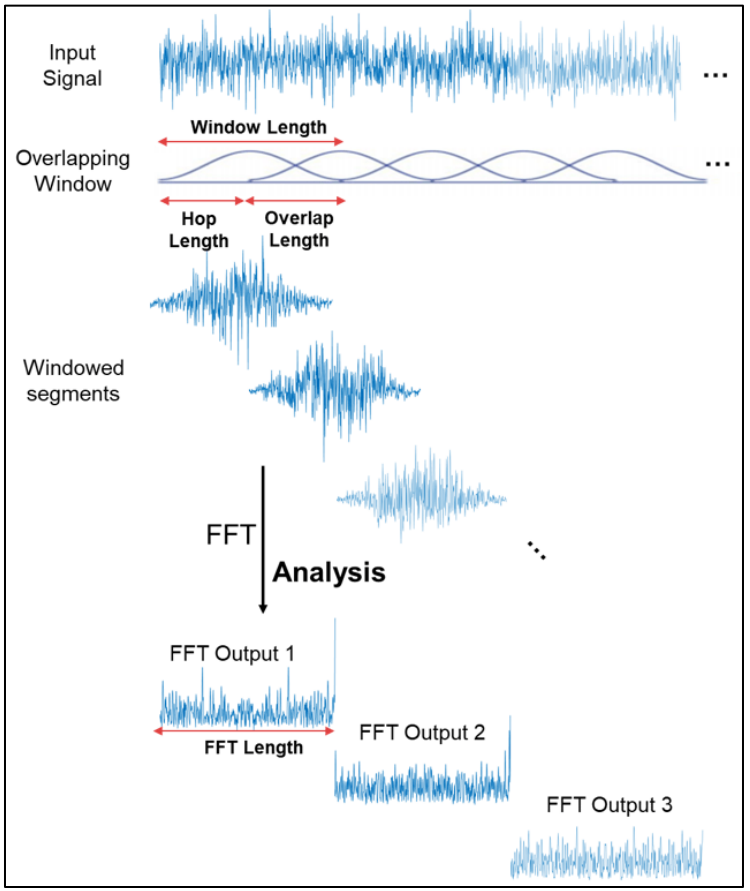


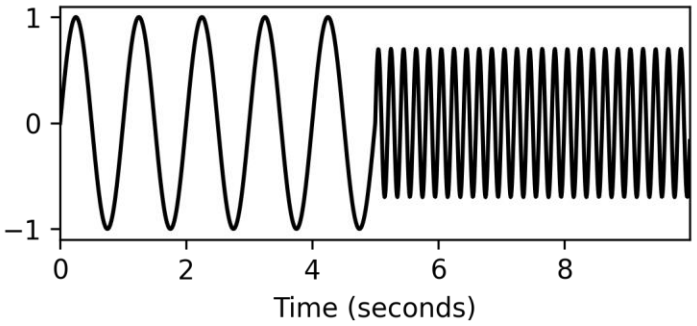
Fig. 2

Audio Processing
Time-Frequency Decomposition

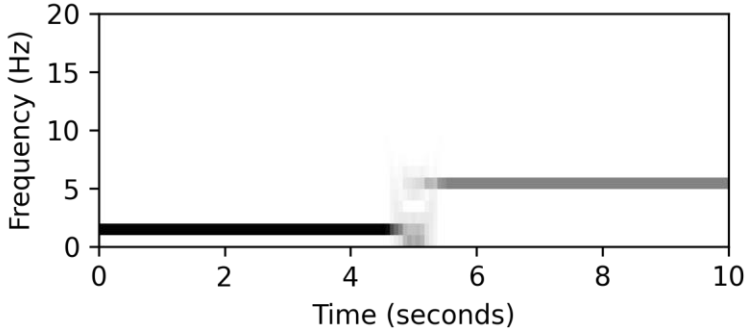
- Short-Time Fourier Transform (STFT)
  - Moving analysis window
  - Time-frequency energy distribution in audio signal

Audio Processing
Time-Frequency Decomposition

- Short-Time Fourier Transform (STFT)
  - Moving analysis window
  - Time-frequency energy distribution in audio signal



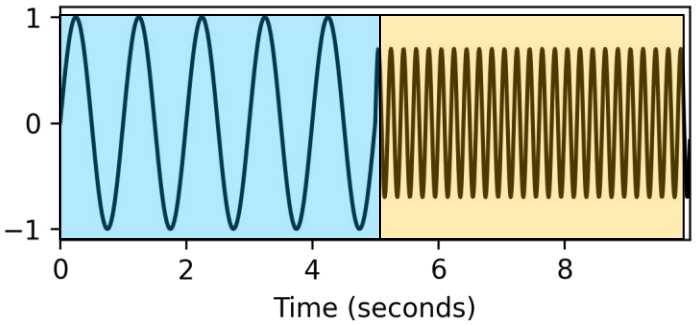
Waveform



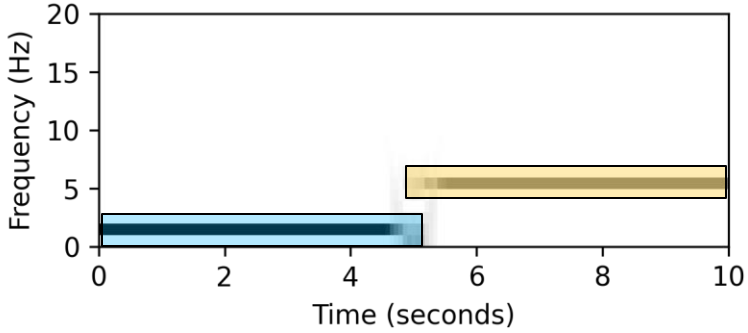
Spectrogram

Audio Processing
Time-Frequency Decomposition

- Short-Time Fourier Transform (STFT)
  - Moving analysis window
  - Time-frequency energy distribution in audio signal



Waveform



Spectrogram

Audio Processing

Programming Session #1

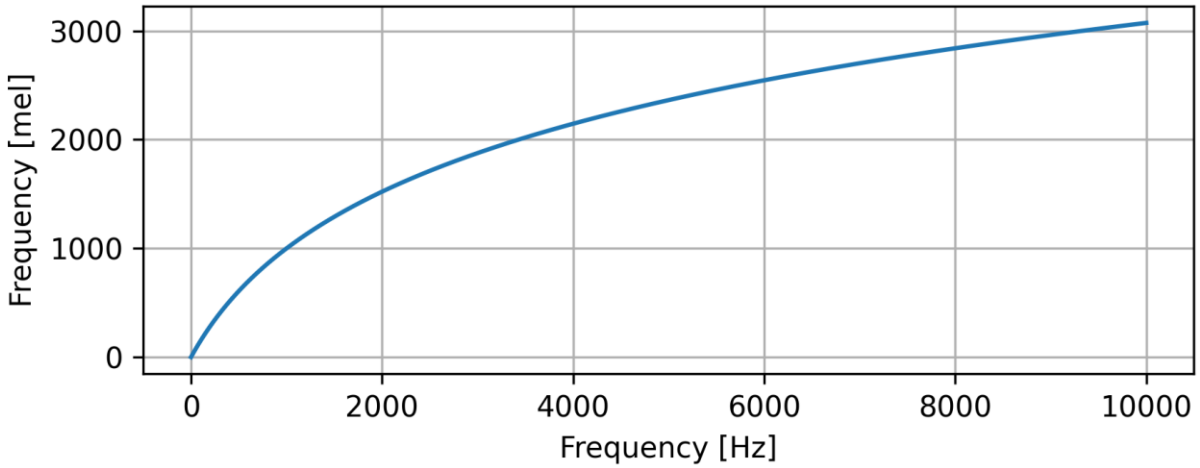
Fig. 2.1

Audio Processing
Mel Frequency Scale

- Logarithmic frequency mapping (human pitch perception)
  - $f\,[\mathrm{mel}] = 2595 \cdot \log_{10}\left(1 + \frac{f\,[\mathrm{Hz}]}{700}\right)$

Audio Processing
Mel Frequency Scale

- Logarithmic frequency mapping (human pitch perception)
  - $f\,[\text{mel}] = 2595 \cdot \log_{10}\left(1 + \frac{f\,[\text{Hz}]}{700}\right)$

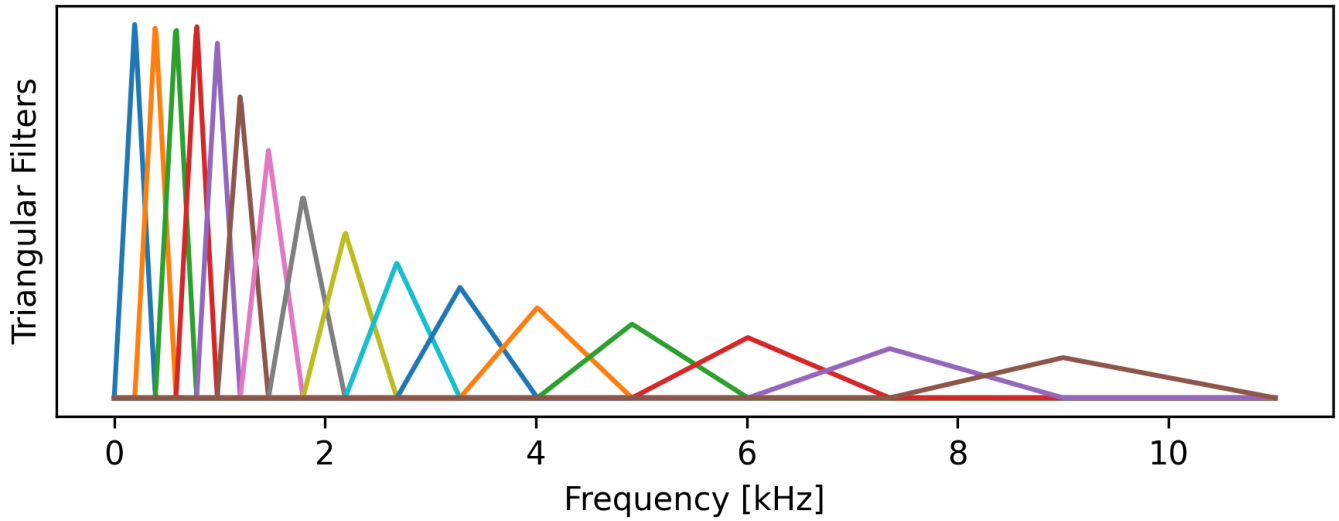


Audio Processing
Mel Spectrogram

- Mapping from STFT magnitude spectrogram to Mel spectrogram
  - Triangular filterbank + Matrix multiplication

Audio Processing
Mel Spectrogram

- Mapping from STFT magnitude spectrogram to Mel spectrogram
  - Triangular filterbank + Matrix multiplication
- Example: 16 mel bands, $f_s = 22.05\,\mathrm{kHz}$



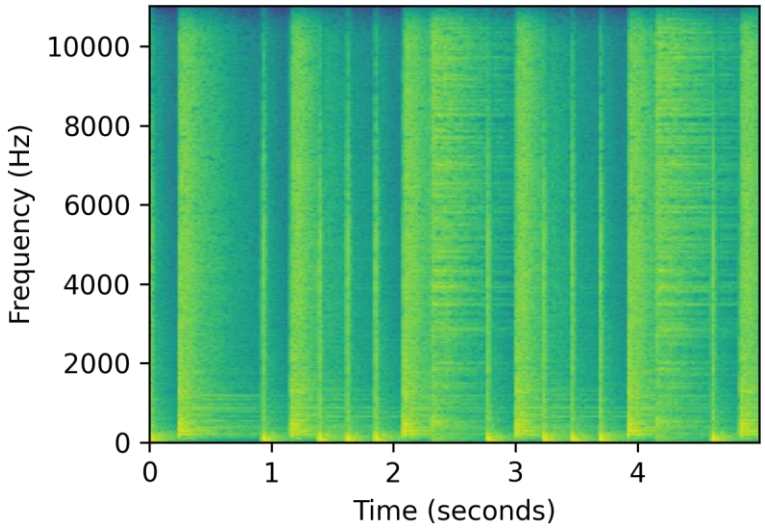
Audio Processing
Mel Spectrogram

- More efficient representation (fewer frequency bands)
- Still captures perceptually relevant information

Audio Processing
Mel Spectrogram

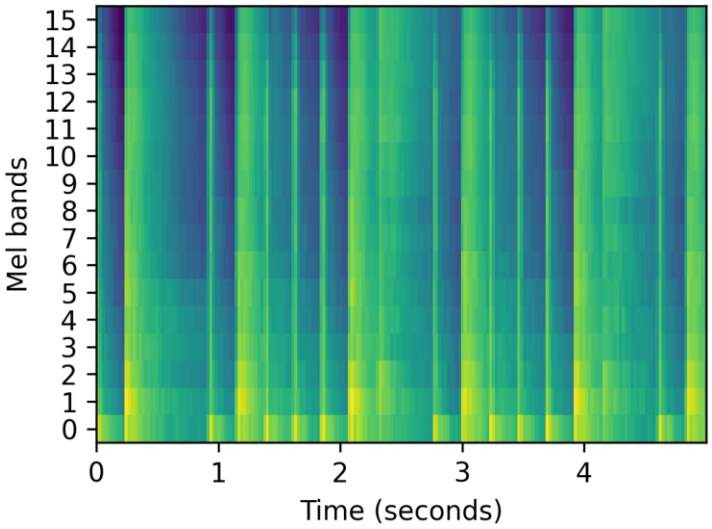
- More efficient representation (fewer frequency bands)
- Still captures perceptually relevant information

STFT



(513 frequency bands)

Mel Spectrogram

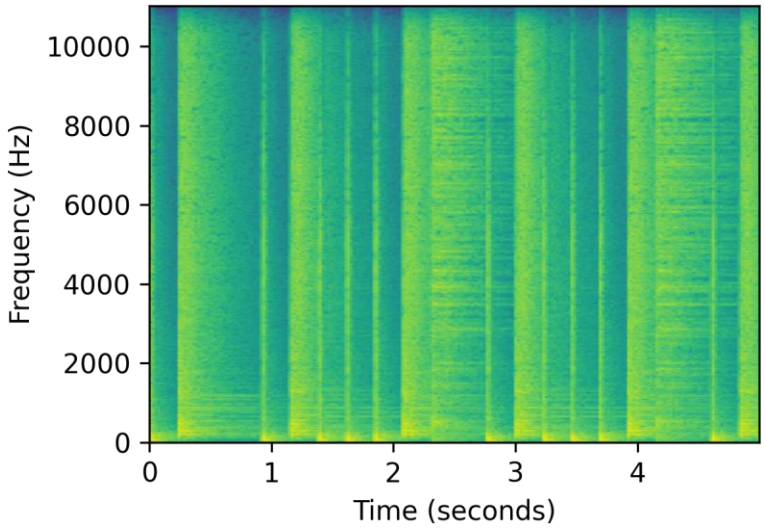


(16 Mel bands)

Audio Processing
Mel Spectrogram

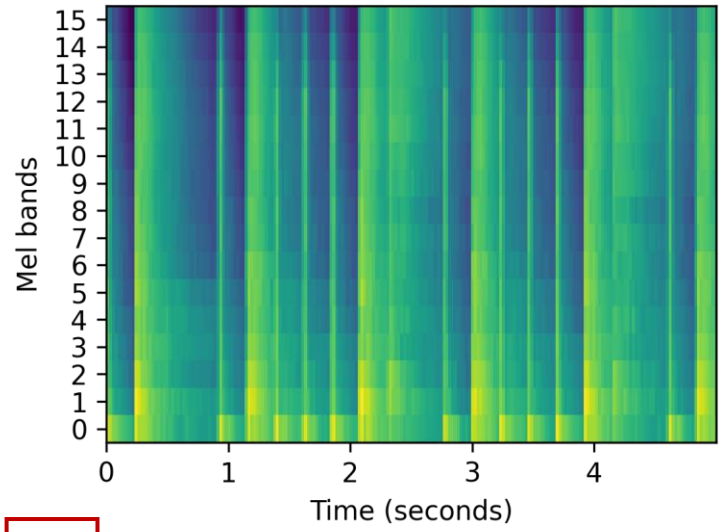
- More efficient representation (fewer frequency bands)
- Still captures perceptually relevant information

STFT



(513 frequency bands)

Mel Spectrogram

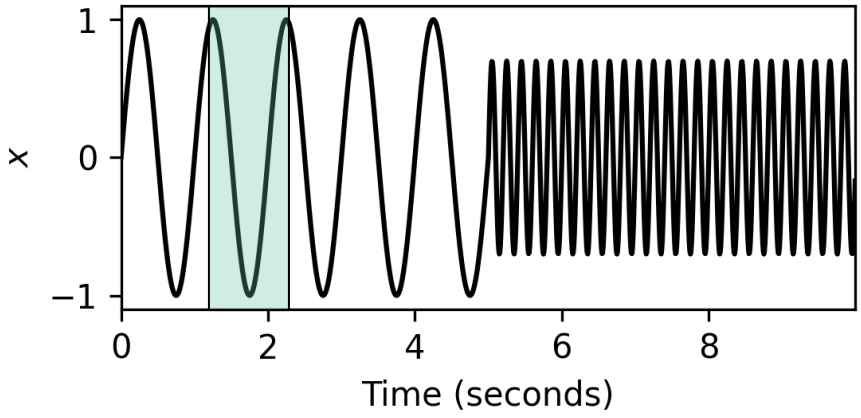


(16 Mel bands)

Compression by 96.9 %

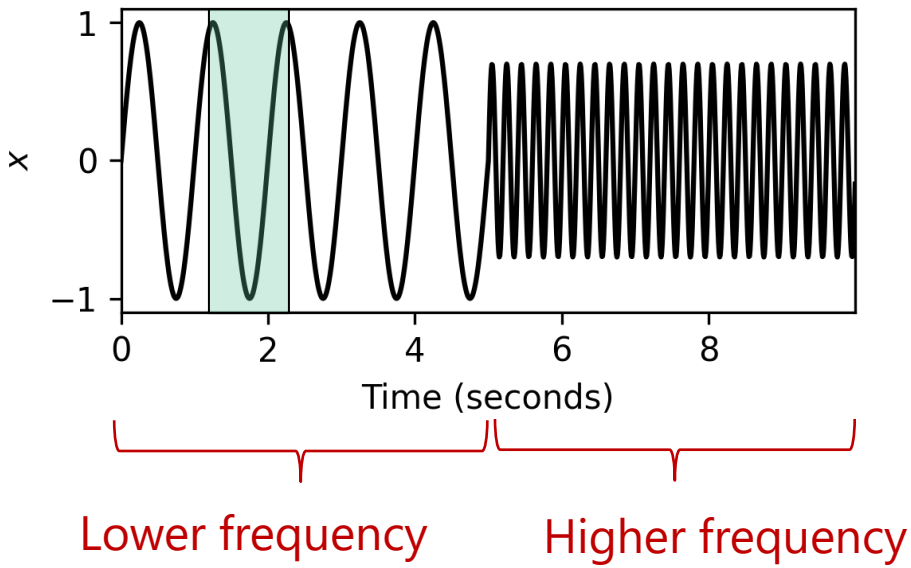
Audio Processing
Periodic Signals

- Period T $[s]$ – Duration of an elementary waveform



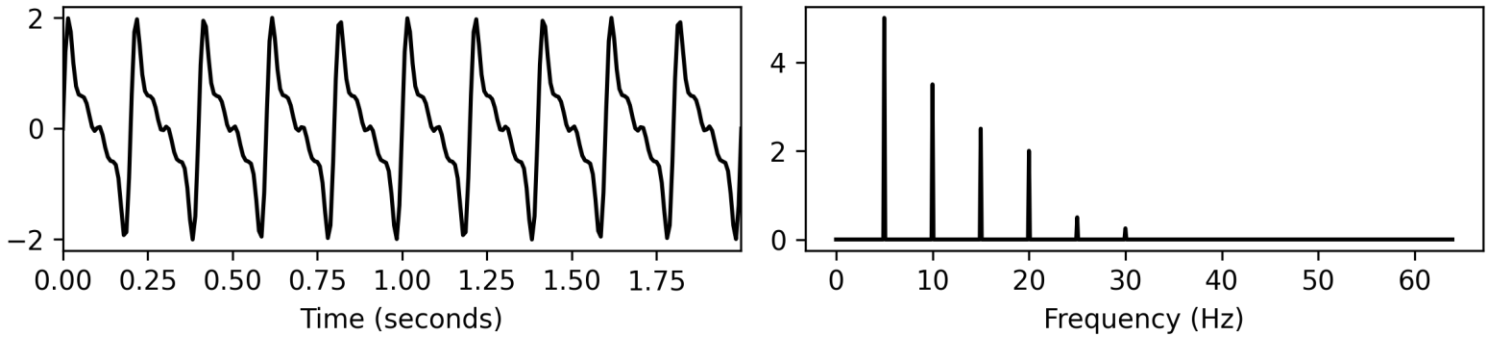
Audio Processing
Periodic Signals

- Period T $[s]$ – Duration of an elementary waveform
- Frequency f – Inverse of period ($f = \frac{1}{T}[\mathrm{Hz}]$)



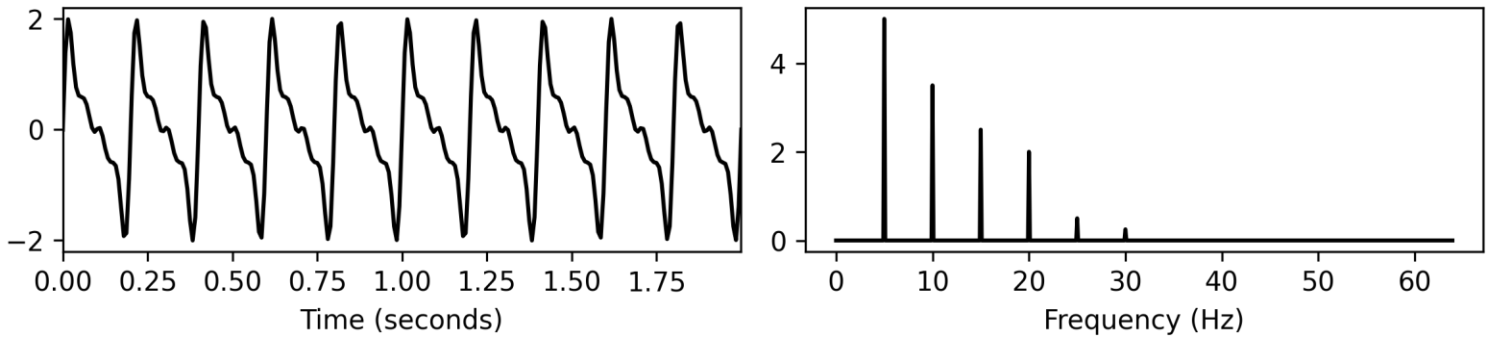
Audio Processing
Periodic Signals

- Periodic signals:
  - Sum of pure tones (partials)
    - Fundamental frequency f_0



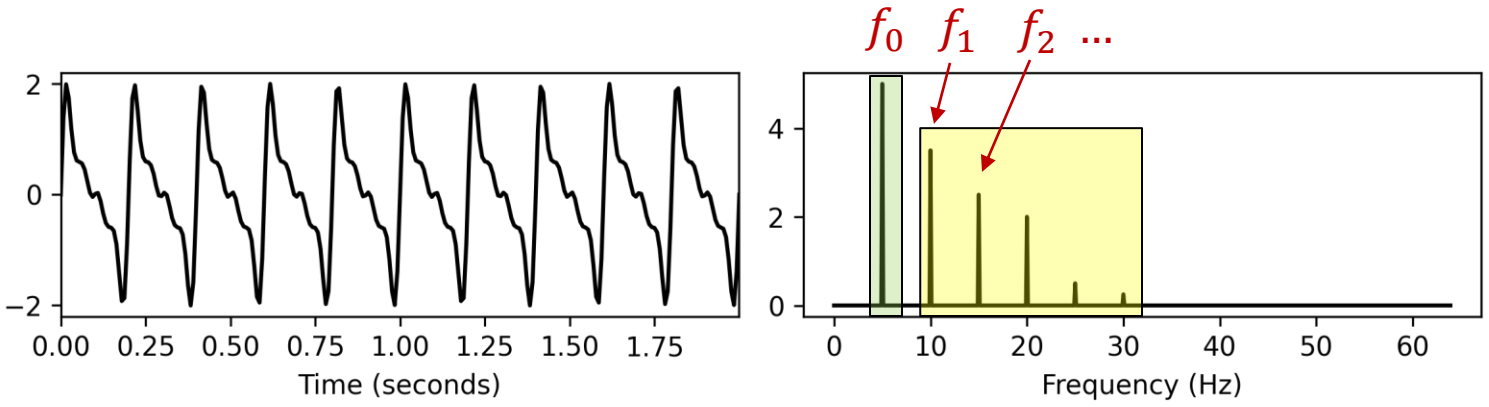
Audio Processing
Periodic Signals

- Periodic signals:
  - Sum of pure tones (partials)
    - Fundamental frequency f_0
    - Harmonics f_k (approx. integer multiples of f_0): $f_k \approx (k+1) \cdot f_0$



Audio Processing
Periodic Signals

- Periodic signals:
  - Sum of pure tones (partials)
    - Fundamental frequency f_0
    - Harmonics f_k (approx. integer multiples of f_0):
      - $f_k \approx (k+1) \cdot f_0$



Audio Processing
Pitch

- Perceptual property (sort sounds from low to high pitch)
- Closely related to frequency
  - $f = 440 \cdot 2^{\frac{p-69}{12}} [\text{Hz}]$

Audio Processing
Pitch

- Perceptual property (sort sounds from low to high pitch)
- Closely related to frequency
  - $f = 440 \cdot 2^{\frac{p-69}{12}} [\text{Hz}]$

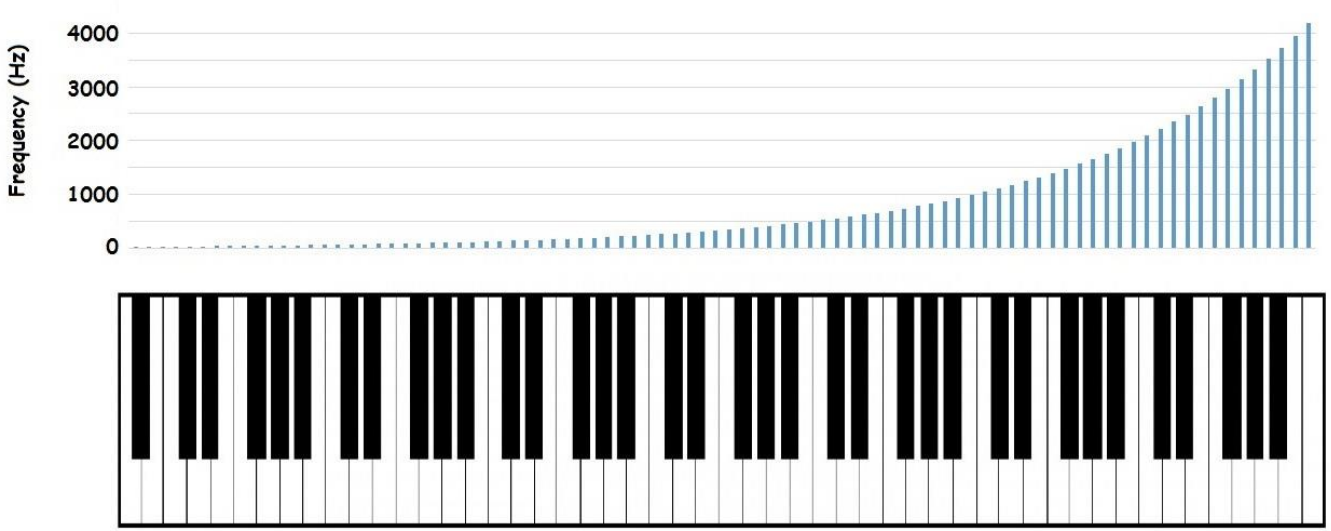


Fig. 2.5

Audio Processing
Pitch Distance (Intervals)

- Depend on ratio between pitch frequencies
- Examples

Note	Pitch p	Frequency f
A3	57	220 Hz
A4	69	440 Hz
A5	81	880 Hz

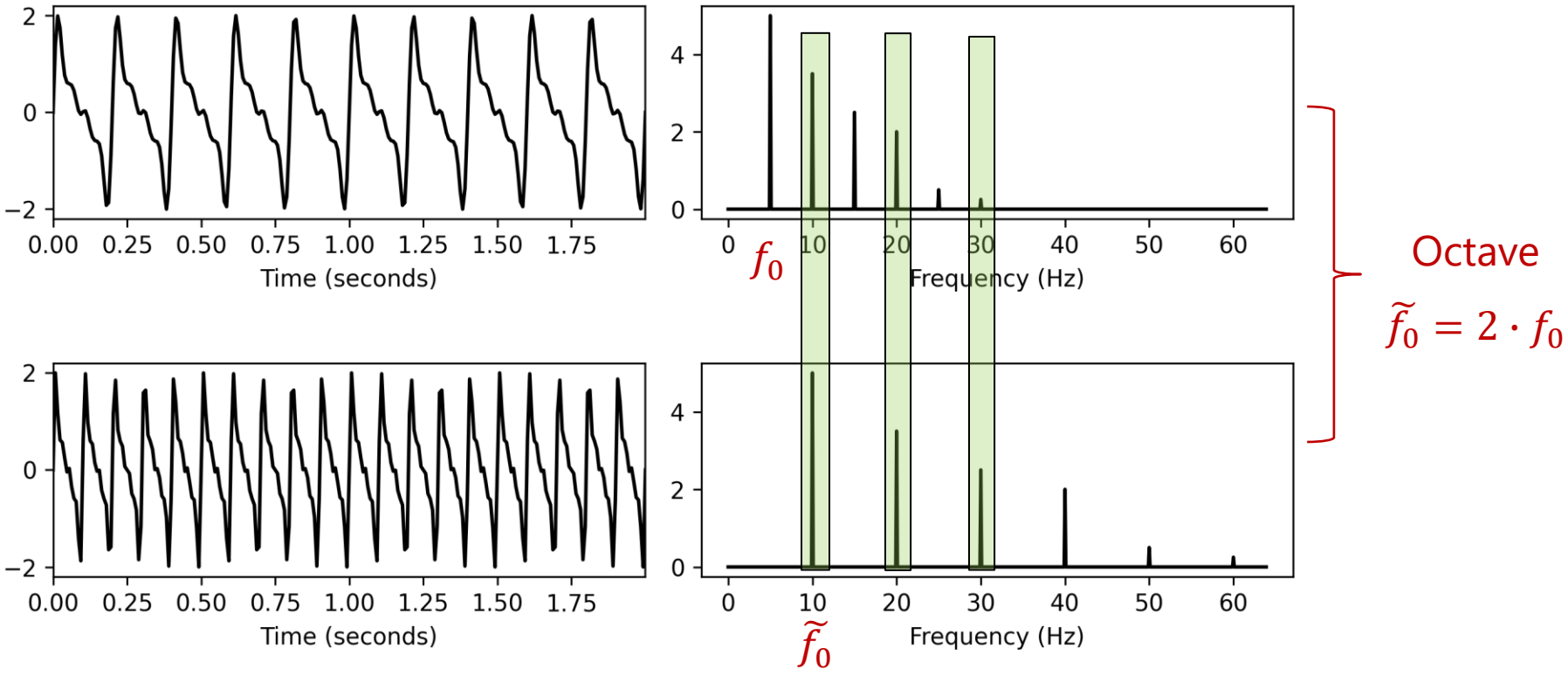
Octave intervals

$f(\mathrm{A4}) = 2 \cdot f(\mathrm{A3})$

$f(\mathrm{A5}) = 2 \cdot f(\mathrm{A4})$

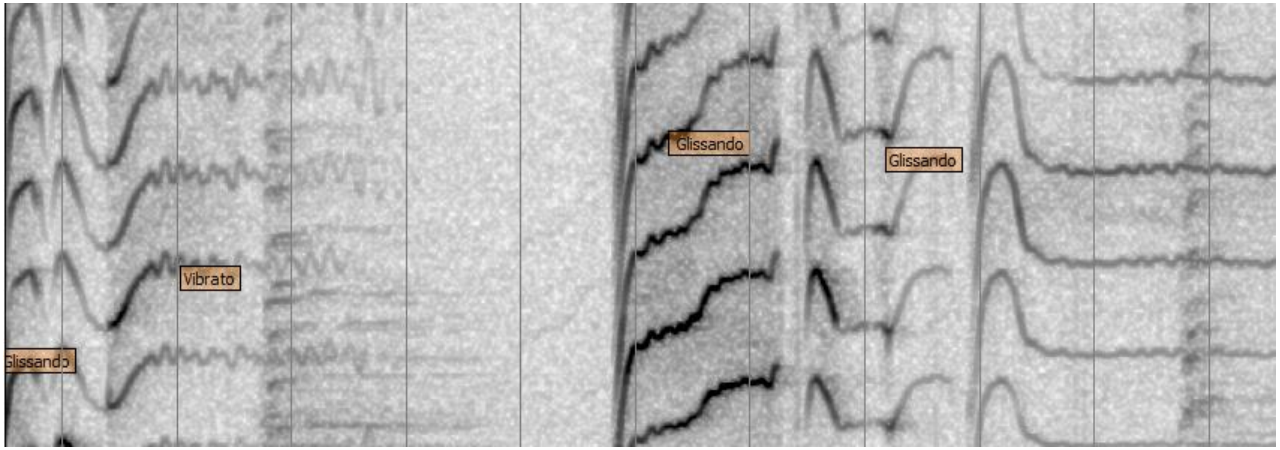
Audio Processing
Pitch Distance (Intervals)

- Note: Consonant intervals share partial frequencies



Audio Processing
Frequency Modulation

- Techniques
  - Glissando – continuous transition between note pitches
  - Vibrato – periodic frequency modulation

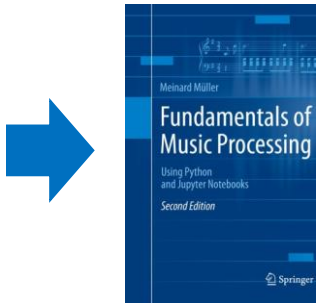


Spectrogram example (frequency x time)

Fig. 2.6

Audio Processing
Frequency Modulation

- Example: Opera singing
  - Estimation & sonification of fundamental frequency contours



FMP Notebooks

Audio Processing
Transients

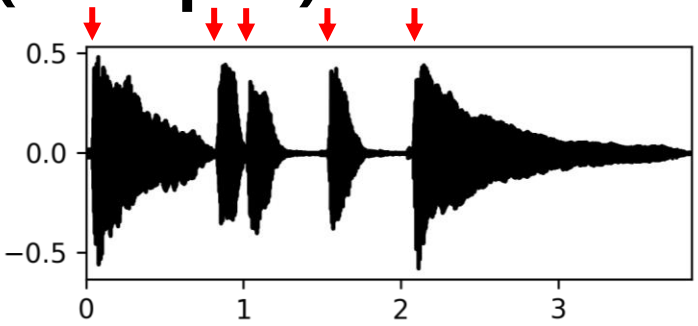
- Sound characteristics
  - High amplitude
  - Short duration
  - Wide-band signal
    - Energy distributed over large frequency range (not just a few frequencies)

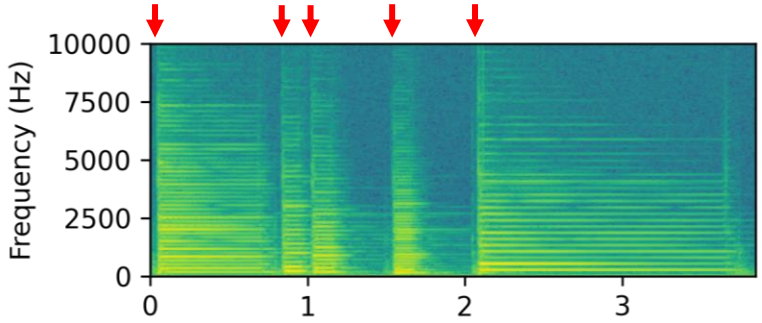
Audio Processing

Transients (Examples)

- String instruments

Audio 1





Audio Processing

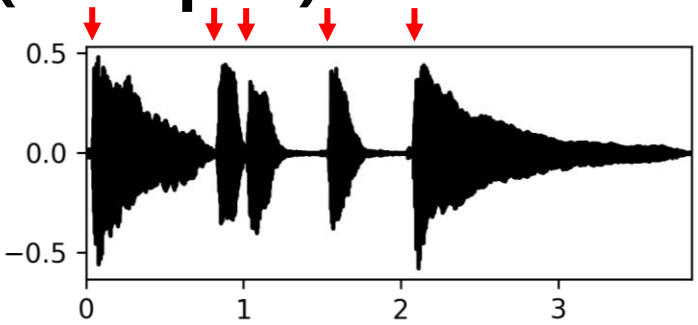
Transients (Examples)

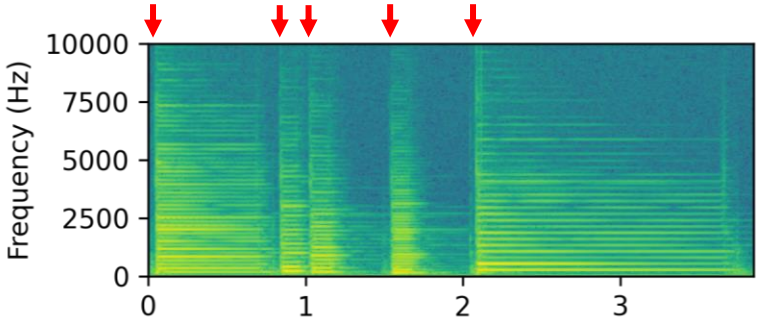
- String instruments

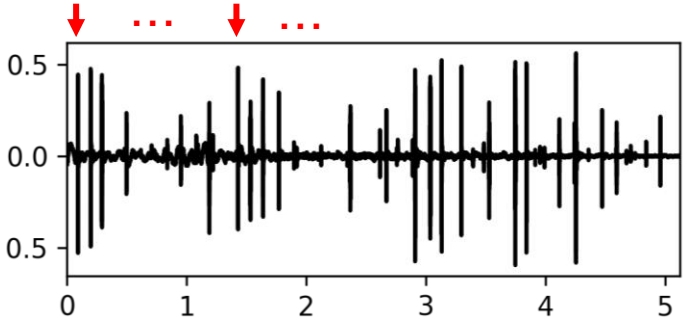
  Audio 1

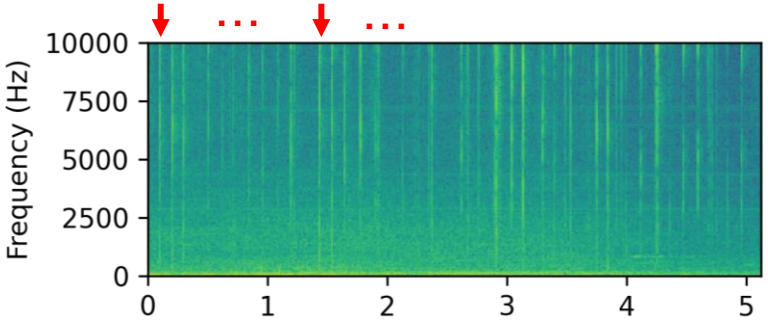
- Bat vocalizations

  Audio 2





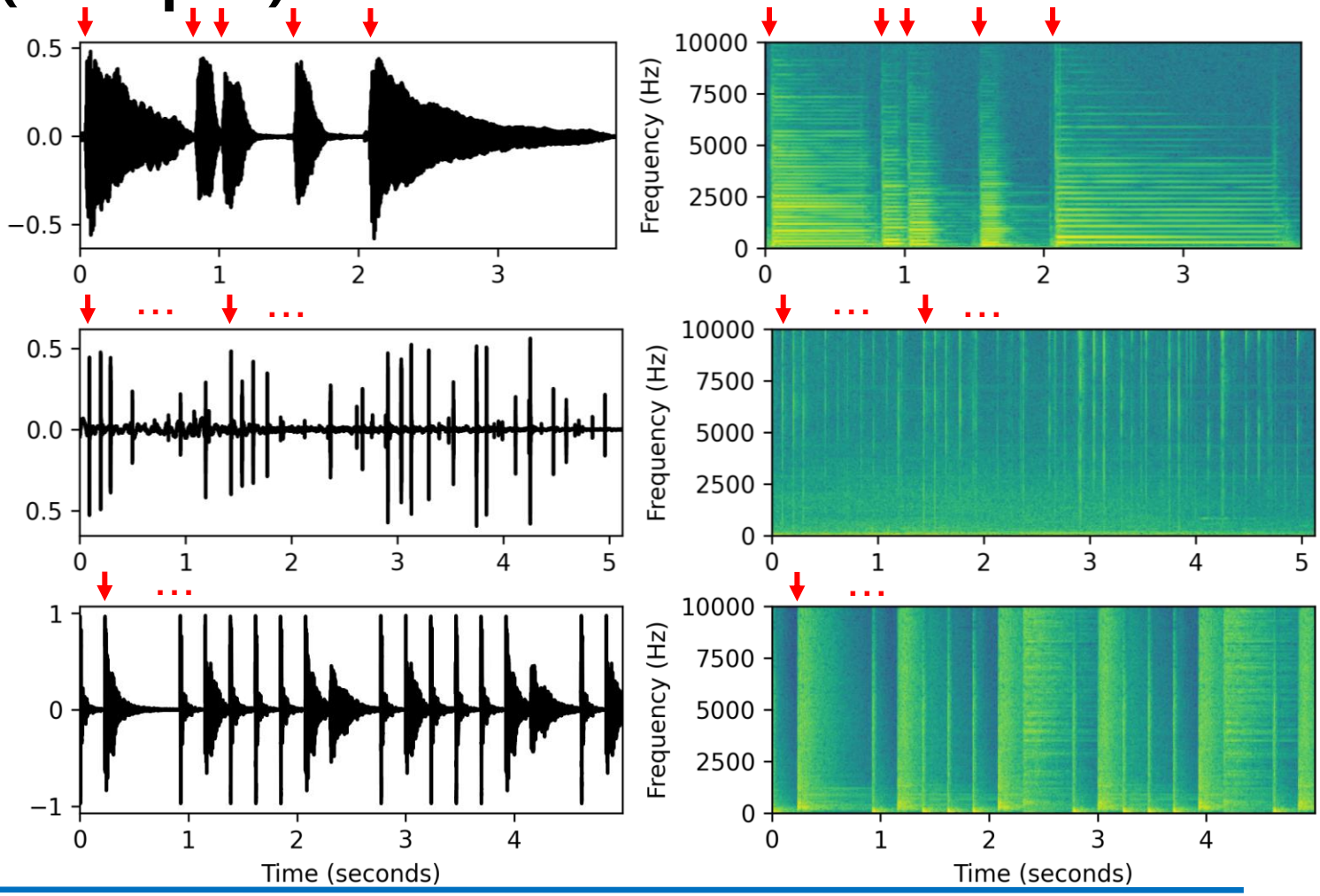




Audio Processing

Transients (Examples)

- String instruments
  Audio 1
- Bat vocalizations
  Audio 2
- Drum instruments
  Audio 3

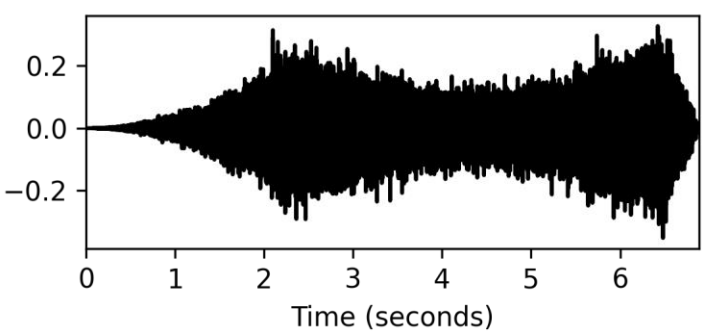


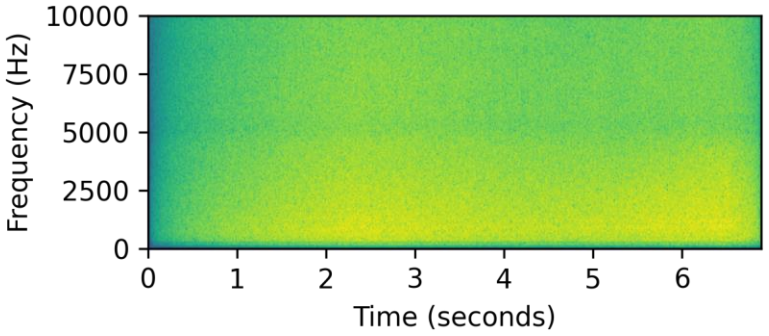
Audio Processing
Noise

- Sound characteristics
  - Non-periodic, texture-like
  - Random fluctuations of air pressure

Audio Processing
Noise

- Sound characteristics
  - Non-periodic, texture-like
  - Random fluctuations of air pressure
- Examples
  - Consonants (speech)
  - Wind (random aerodynamic turbulences)
  - Waves (ocean) Audio 4





Audio Processing
Temporal Envelope

- Smooth curve outlining the signal extreme points
- ADSR envelope model (also used for audio synthesis)
    - Attack, Decay, Sustain, Release

Audio Processing
Temporal Envelope

- Smooth curve outlining the signal extreme points
- ADSR envelope model (also used for audio synthesis)
  - Attack, Decay, Sustain, Release

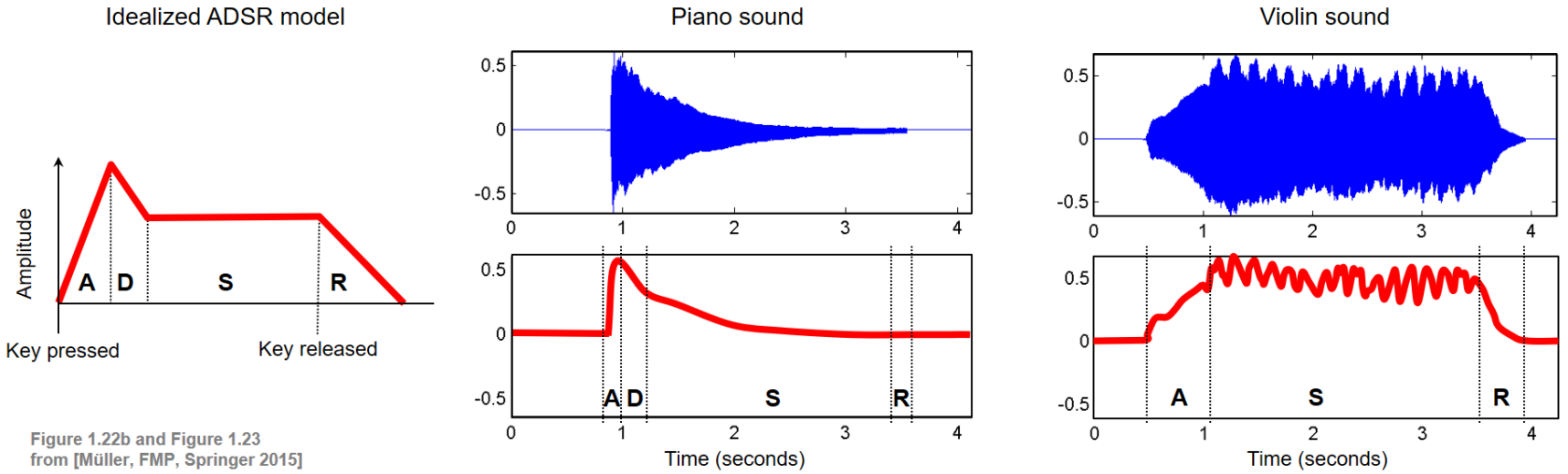
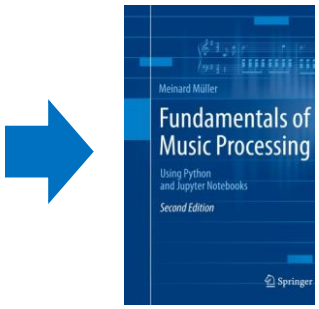


Figure 1.22b and Figure 1.23
from [Müller, FMP, Springer 2015]

Fig. 2.7

Audio Processing
Temporal Envelope

- Tremolo
  - Periodic amplitude modulation
  - Often coincides with frequency modulation (vibrato)
  - Examples: instrument sounds



FMP Notebooks

Fig. 2.7

Audio Processing
Timbre

- Perceptual attribute (complements pitch, loudness, duration)
- Difference between musical tones of same pitch & loudness

Audio Processing
Timbre

- Perceptual attribute (complements pitch, loudness, duration)
- Difference between musical tones of same pitch & loudness

- Timbre research

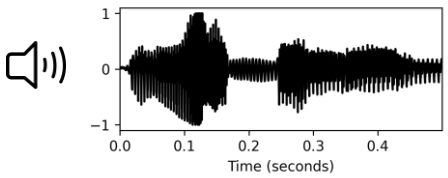
(Subjective) perceptual attributes ⟺ Correlations? ⟺ **(Objective) sound characteristics**

- Temporal / spectral envelope
- Tonal / noise-like components
- Partial (frequency) energies
- …

Audio Processing
Mel-Frequency Cepstral Coefficients (MFCC)

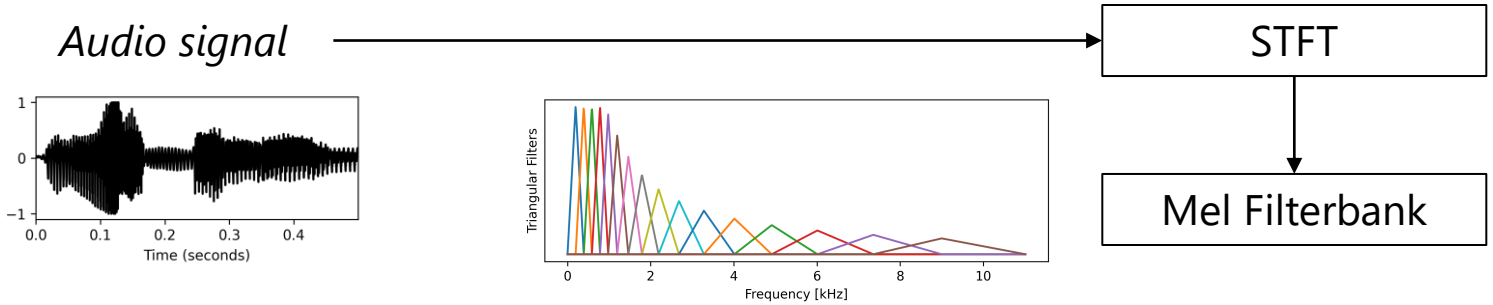
- Compact representation of spectral envelope

Audio signal



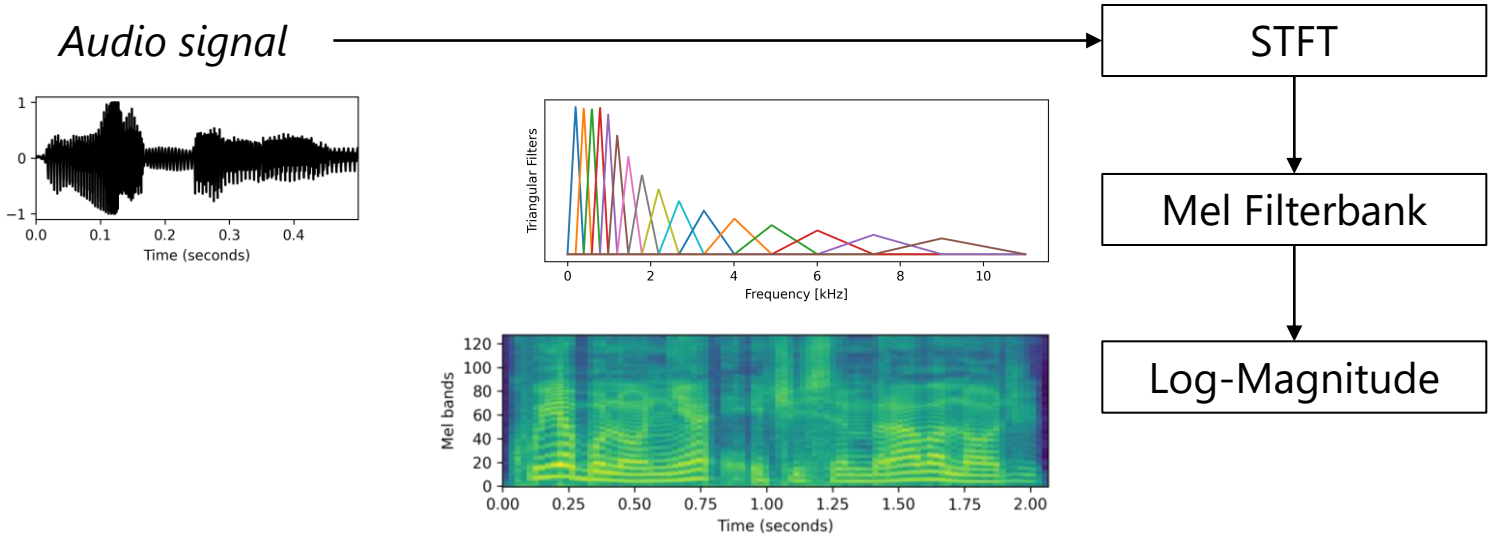
Audio Processing
Mel-Frequency Cepstral Coefficients (MFCC)

- Compact representation of spectral envelope



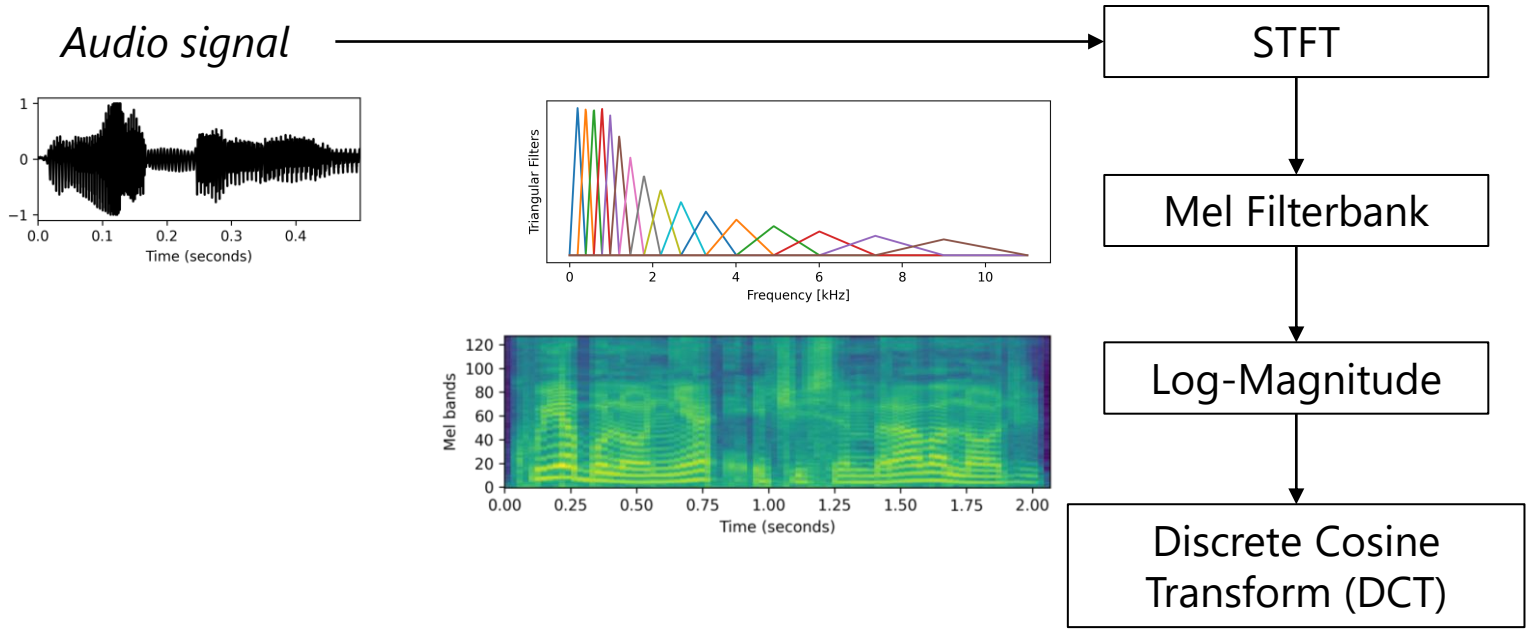
Audio Processing
Mel-Frequency Cepstral Coefficients (MFCC)

- Compact representation of spectral envelope



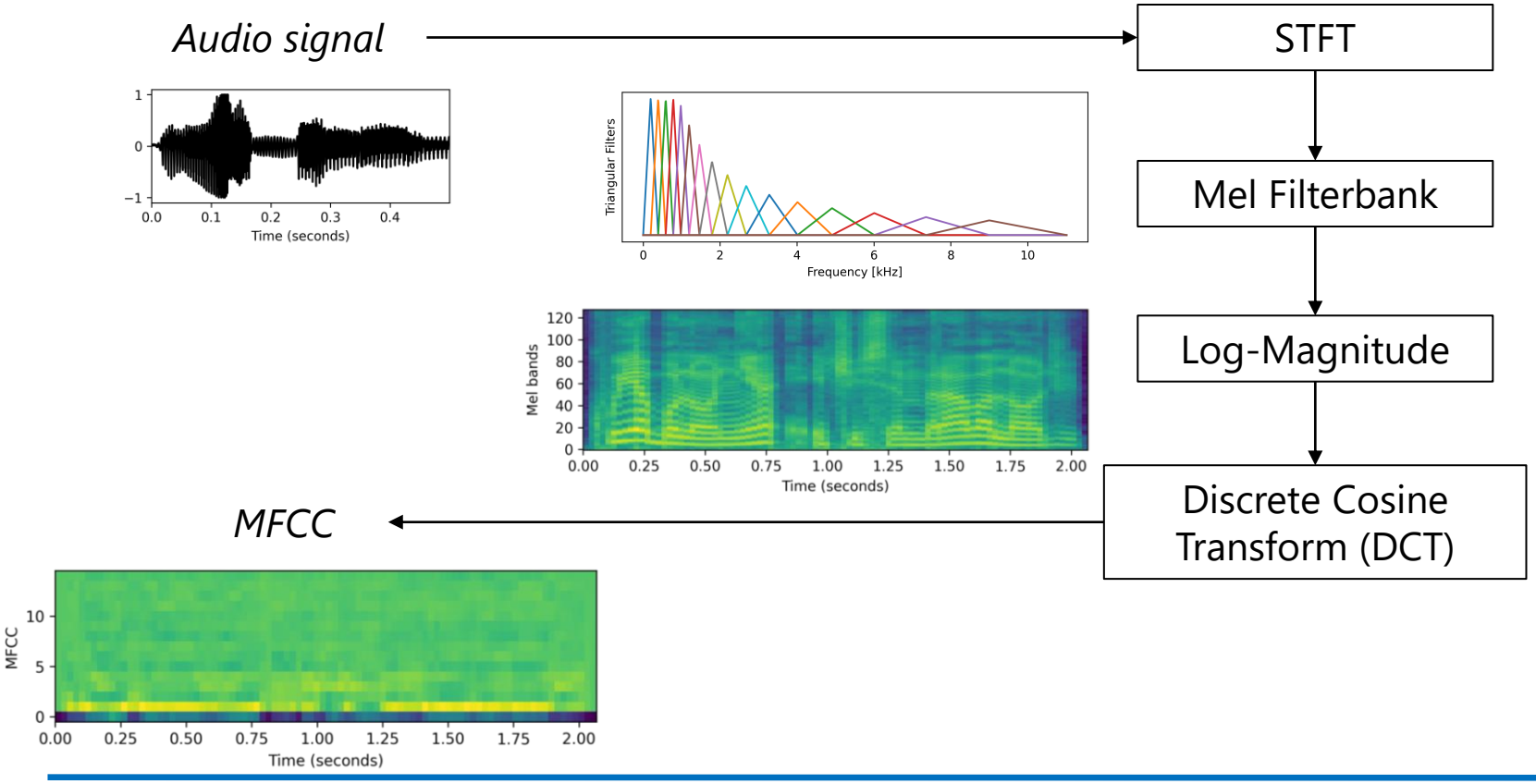
Audio Processing
Mel-Frequency Cepstral Coefficients (MFCC)

- Compact representation of spectral envelope



Audio Processing
Mel-Frequency Cepstral Coefficients (MFCC)

- Compact representation of spectral envelope



Audio Processing
Constant-Q Transform

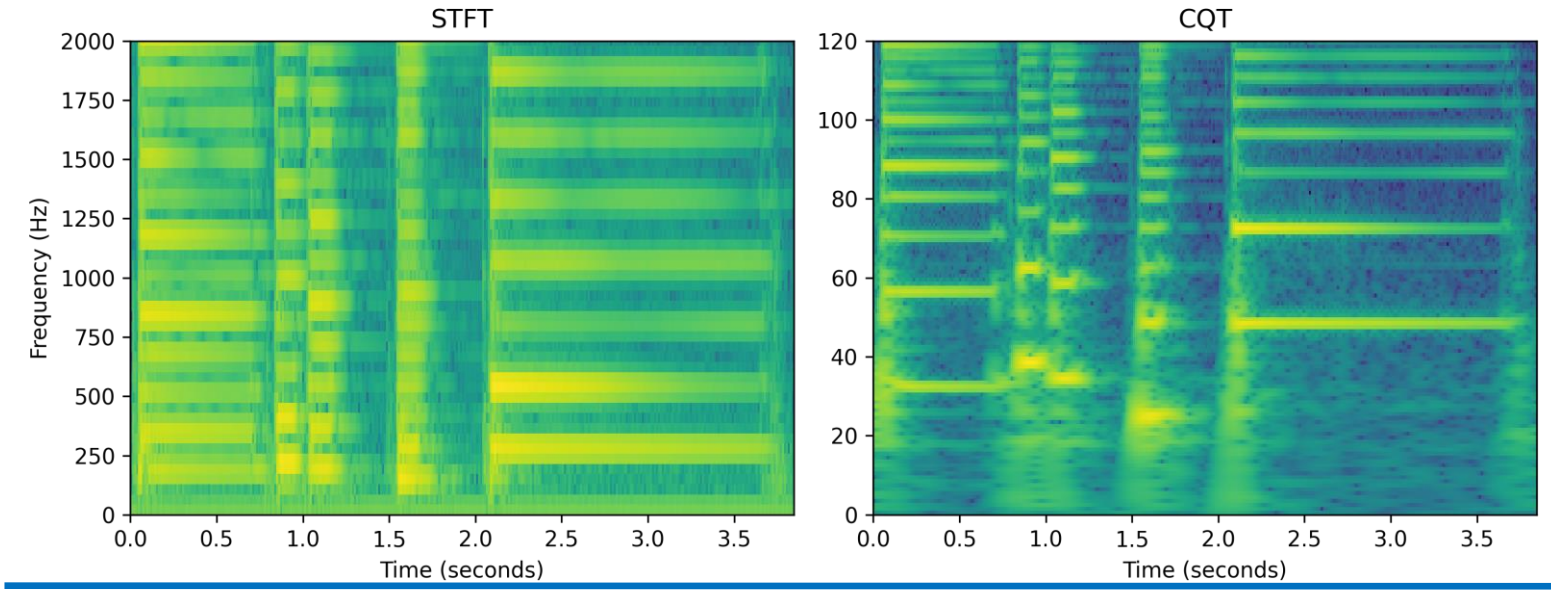
- STFT (linearly-spaced frequencies)
- CQT (logarithmically-spaced, closer to human auditory perception)

Audio Processing
Constant-Q Transform

- STFT (linearly-spaced frequencies)
- CQT (logarithmically-spaced, closer to human auditory perception)
    - Variable number of frequency bins per octave
    - Increasing time resolution towards higher frequencies

Audio Processing
Constant-Q Transform

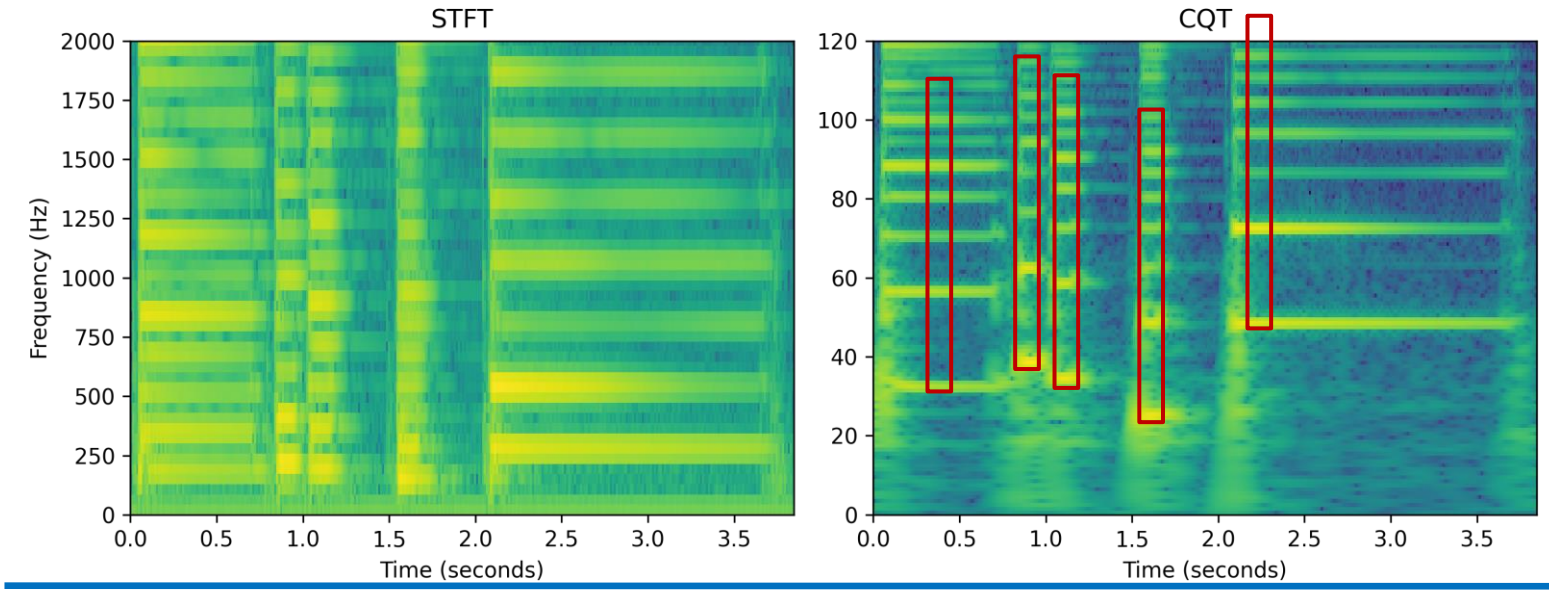
- STFT (linearly-spaced frequencies)
- CQT (logarithmically-spaced, closer to human auditory perception)
  - Variable number of frequency bins per octave
  - Increasing time resolution towards higher frequencies



Audio 1

Audio Processing
Constant-Q Transform

- Suitable for music transcription
  - Partials have a constant frequency pattern
    - Vertically shifted
    - Pitch-independent



Audio Processing
Chroma Features

- Human pitch perception is periodic
- 2 pitches one octave apart are perceived as similar
- Pitch = chroma + tone height
  - Chroma: C, C#, D, D#, …, B (12)
  - Tone height: Octave number

Figure 3.3a from [Müller, FMP, Springer 2015]

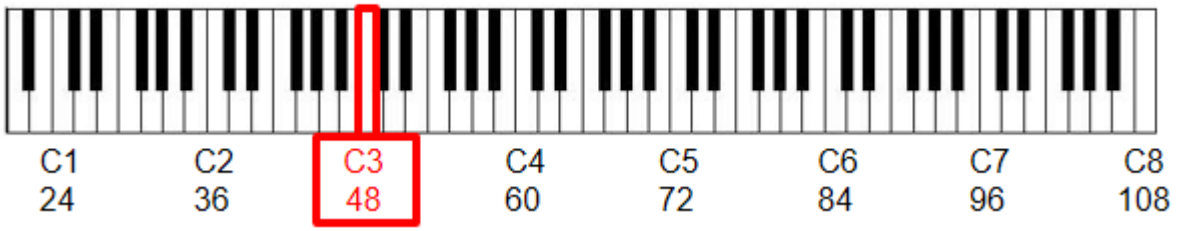
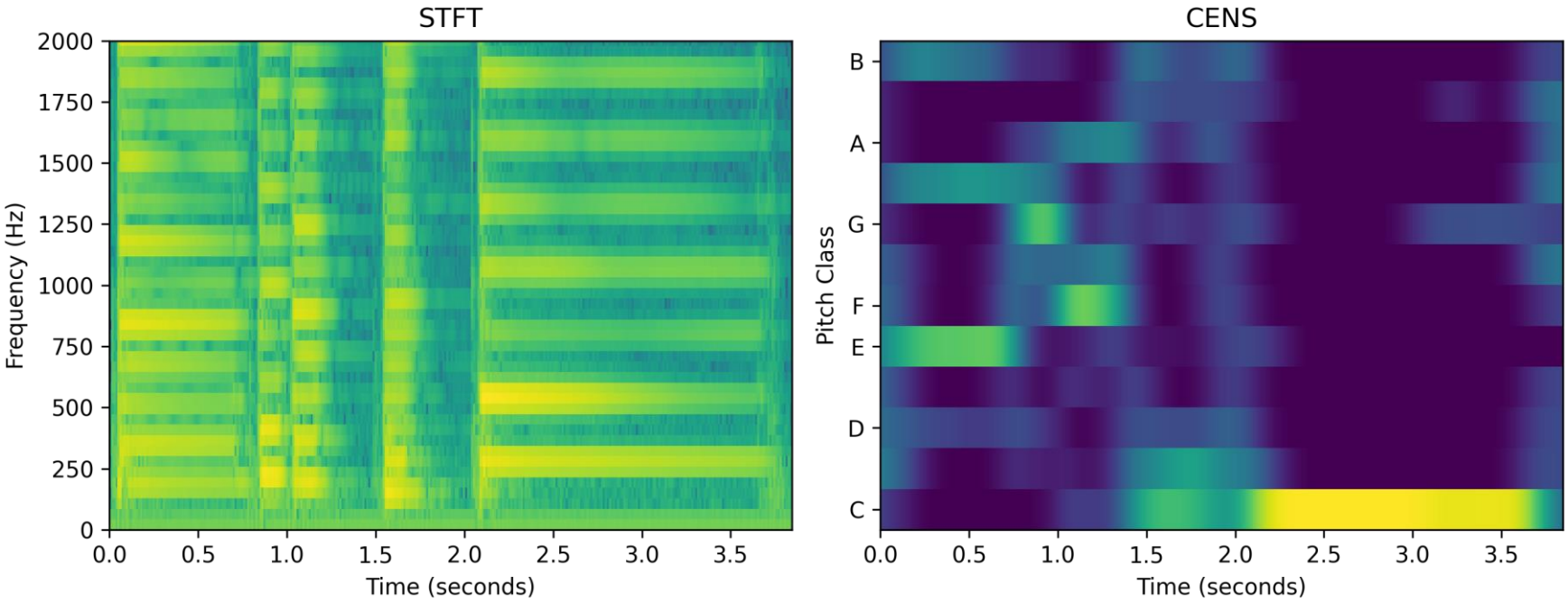


Fig. 2.8

Audio Processing
Chroma Features

- Example Audio 1



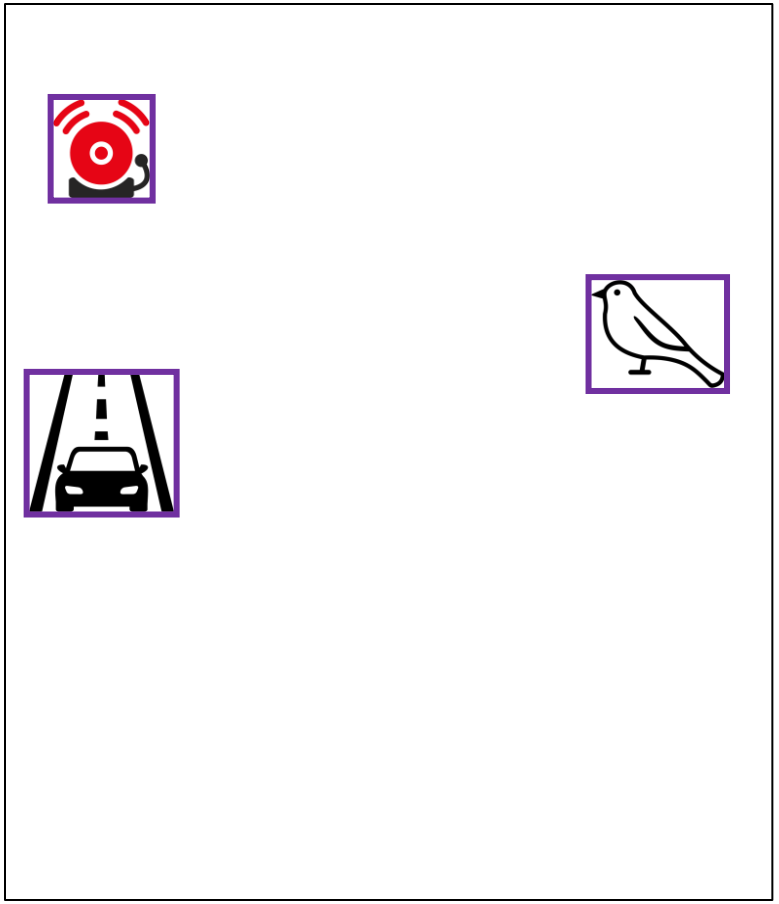
Audio Processing

Programming Session #2

Fig. 2.1

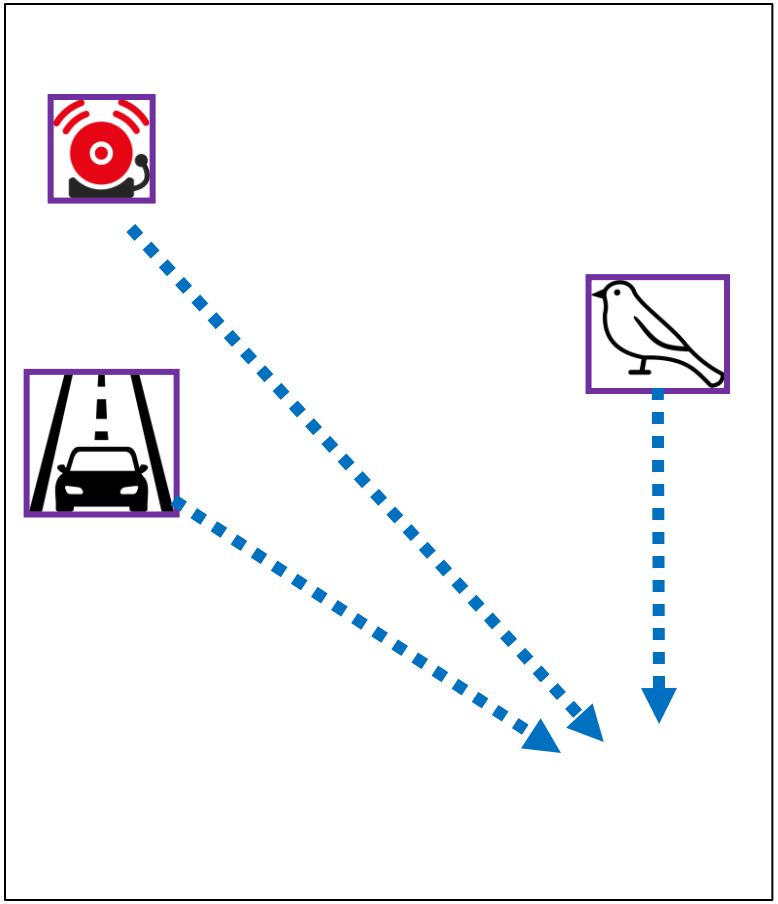
Audio Processing
Auditory Scene

- Distributed sound producing events (sound sources)



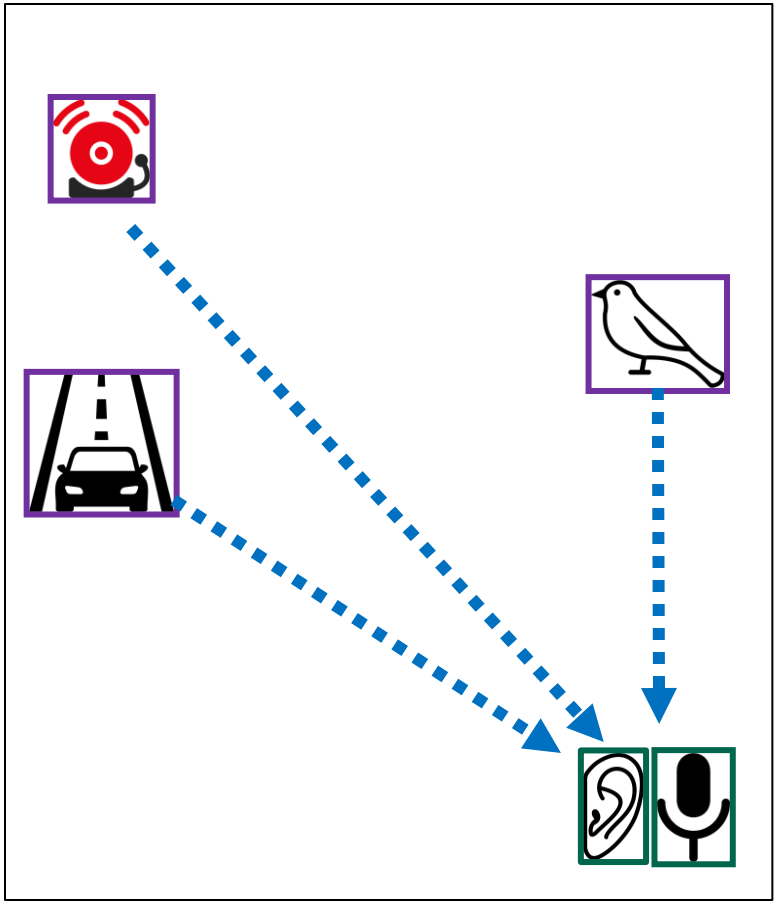
Audio Processing
Auditory Scene

- Distributed sound producing events (sound sources)
- Sound propagation through space



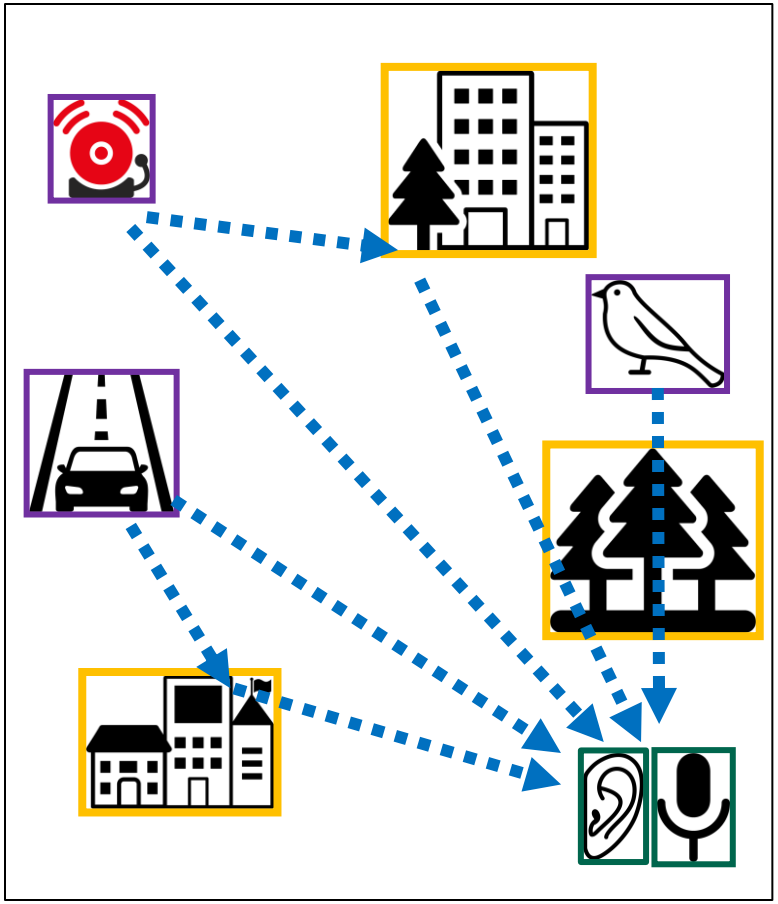
Audio Processing
Auditory Scene

- Distributed sound producing events (sound sources)
- Sound propagation through space
- Perceived (ear) or recorded (microphone)



Audio Processing
Auditory Scene

- Distributed sound producing events (sound sources)
- Sound propagation through space
- Perceived (ear) or recorded (microphone)
- Room acoustics
  - Reflection (surfaces)
  - Diffraction (objects)



Images

Fig. 1: https://www.acs.psu.edu/drussell/Demos/waves-intro/Lwave-Red-2.gif

Fig. 1.1: TODO FMP

Fig. 2: https://www.mathworks.com/help/dsp/ref/stft_output.png

Fig. 2.1: https://upload.wikimedia.org/wikipedia/commons/thumb/3/38/Jupyter_logo.svg/1200px-Jupyter_logo.svg.png

Fig. 2.5: https://pressbooks.pub/app/uploads/sites/140/2022/07/Piano_to_F.jpg

Fig. 2.6: https://www.hfm-weimar.de/popvoices/media/_glossar/BH8.png

Fig. 2.7: TODO FMP

Fig. 2.8: TODO FMP (https://www.audiolabs-erlangen.de/resources/MIR/FMP/data/C3/FMP_C3_F03a.png)

Fig. 3: https://i.makeagif.com/media/9-11-2015/6HmpFN.gif

Fig. 4: https://prezigram-assets.prezicdn.net/e53764d415cd58a530e5f66144779100cc9bdc843686bbb9ea5f5c273ef1d1784bcc63c4f75847717119716f5b62701de16797ec8a51ca9a9247981613460ebc

References

[Merriam-Webster] https://www.merriam-webster.com/dictionary/sound

Audio

[Audio 1] https://freesound.org/people/xserra/sounds/196765/

[Audio 2] https://freesound.org/people/IliasFlou/sounds/498058/ (~0:00 – 0:05)

[Audio 3] https://freesound.org/people/danlucaz/sounds/517860/ (~0:00 – 0:05)

[Audio 4] https://freesound.org/people/IENBA/sounds/489398/ (~0:00 – 0:07)