# AI-based Audio Analysis of Music and Soundscapes

## Audio Processing

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# Audio Processing
## Outline

- Part 1
  - Sound, Sound Waves
  - Waveform, Sampling
  - Sound Level, Intensity, Loudness
  - Time-Frequency Decomposition
  - Auditory Scene
- Programming Session 1

Fig. 2.1

# Audio Processing
## Outline

- Part 2
  - Mel Spectrogram
  - Periodic Signals, Pitch, Frequency Modulation
  - Transients
  - Noise
  - Temporal Envelope
  - Timbre, Mel-Frequency Cepstral Coefficients (MFCC)
  - Constant-Q Transform
  - Chroma Features
- Programming Session 2

Fig. 2.1

# Audio Processing
## Sound

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

# Audio Processing
## Sound Waves

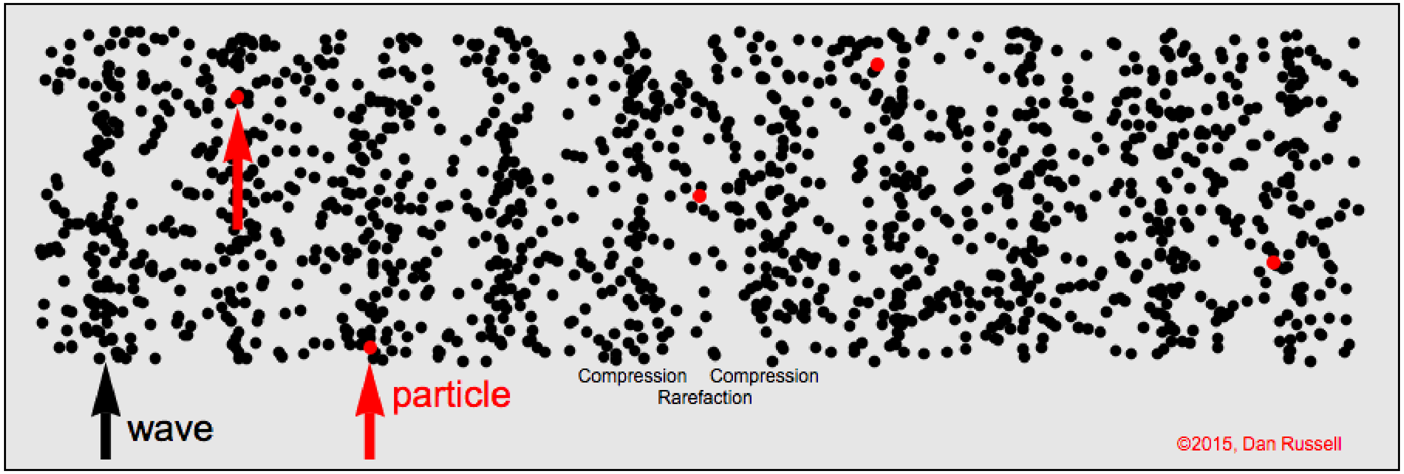
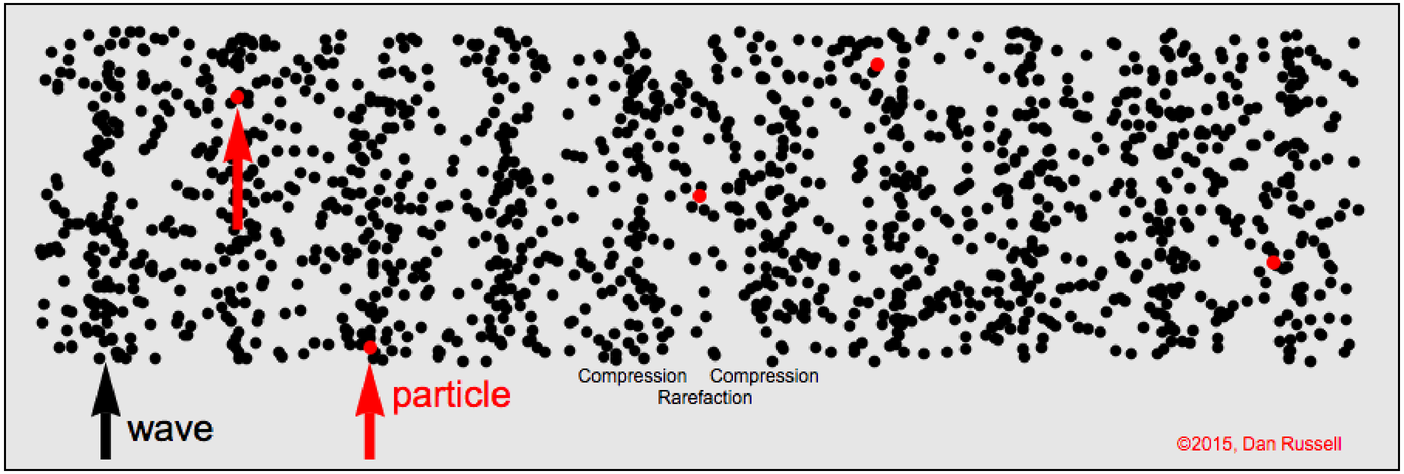



Fig. 1

# Audio Processing
## Sound Waves



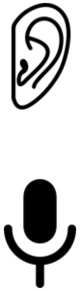
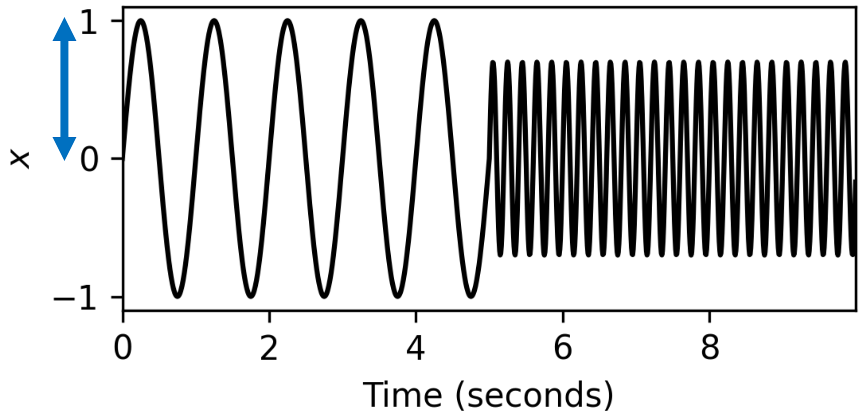



Fig. 1

- 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

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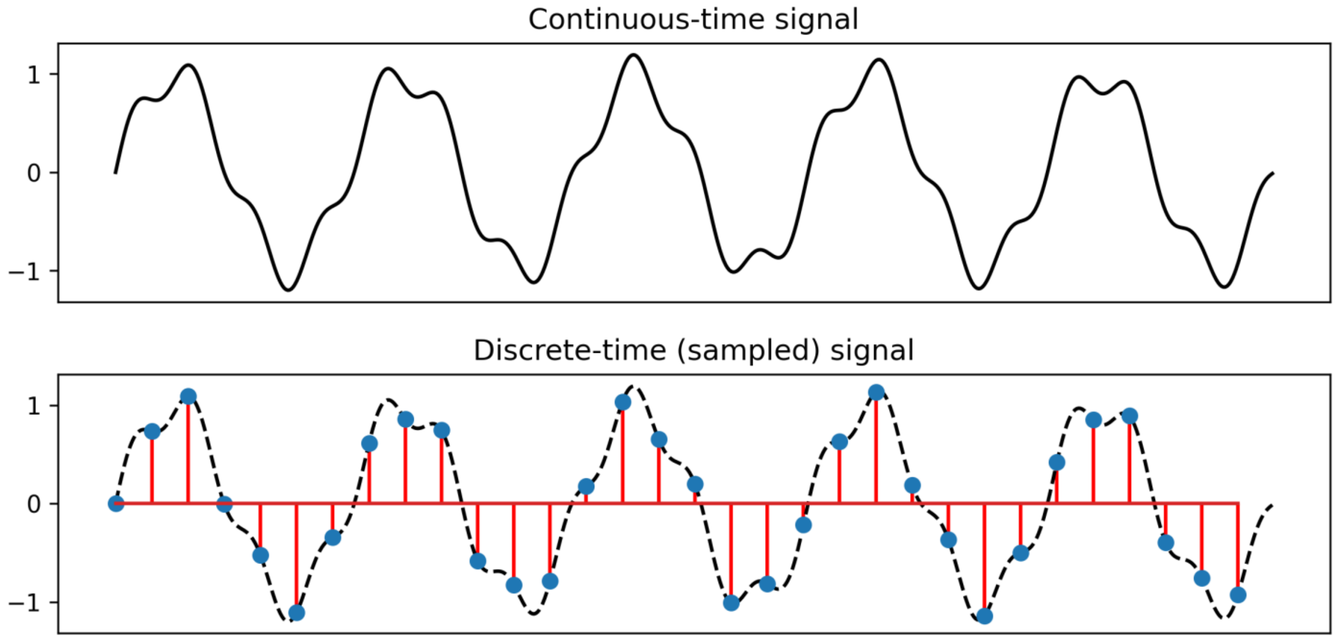

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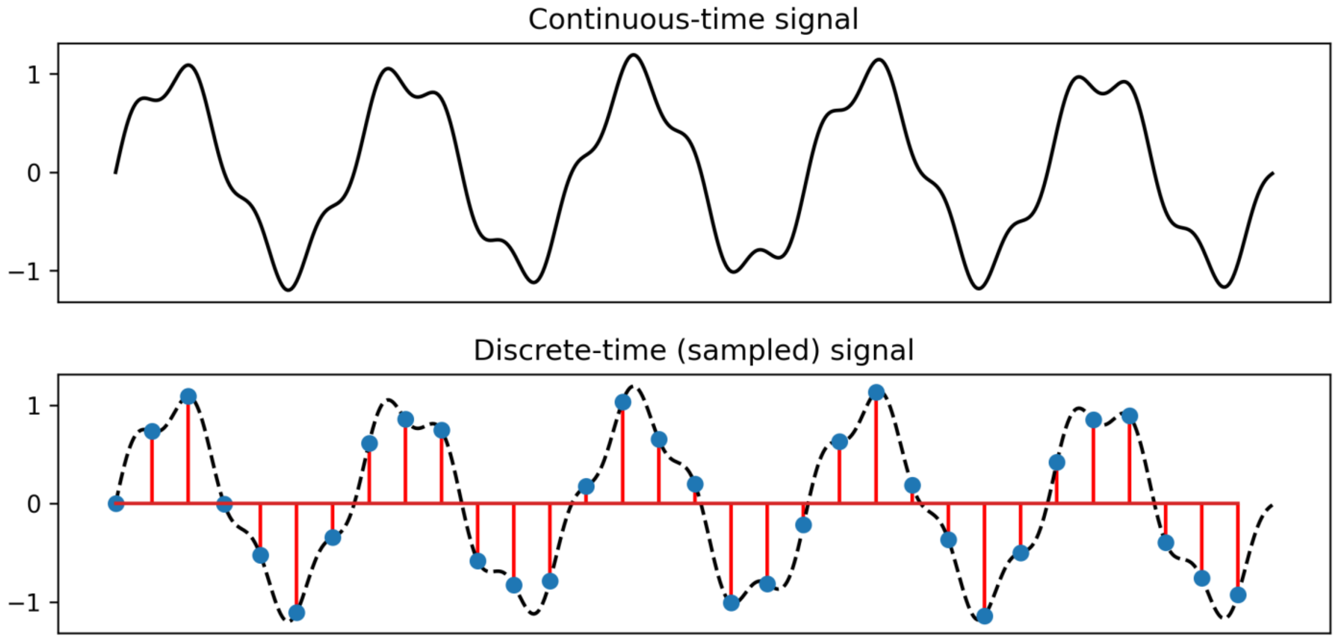
## Sampling

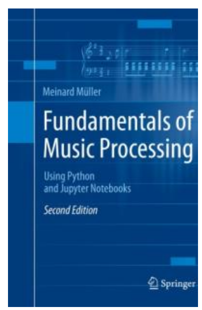
- Converting (continuous-time) analog signals into (discrete-time) digital signal




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

# Audio Processing
## Sampling

- (Nyquist-Shannon) sampling theorem: $f_{\mathrm{max}} < f_{\mathrm{s}}/2$
    - 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 $x_{\mathrm{RMS}} = \sqrt{\frac{1}{N} \sum_i \ x_i{}^2}$

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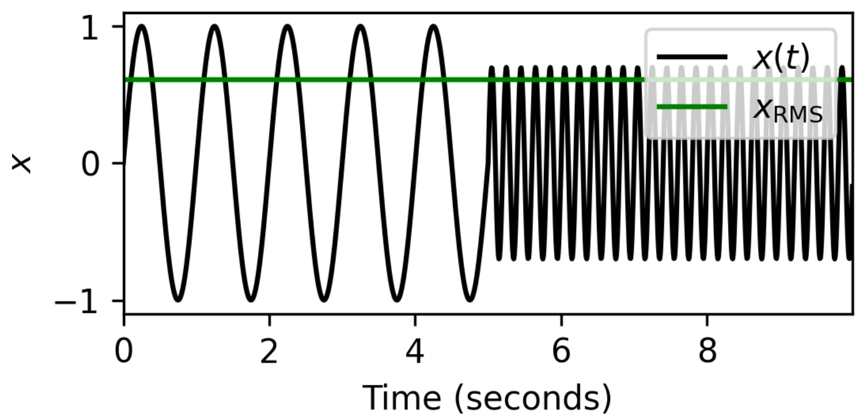

# Audio Processing
## Sound Intensity

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

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- Dynamics
  - Volume of a sound
- Sound power
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- Sound intensity
  - Sound power per unit area
  - Minimum perceivable sound intensity = threshold of hearing
    - $I_{\mathrm{TOH}} = 10^{-12} \mathrm{W/m^2}$

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## Sound Intensity

- Dynamics
  - Volume of a sound
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- 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

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

- Equal loudness curves
  - Perceived loudness [phon]

Figure 1.21 from [Müller, FMP, Springer 2015]

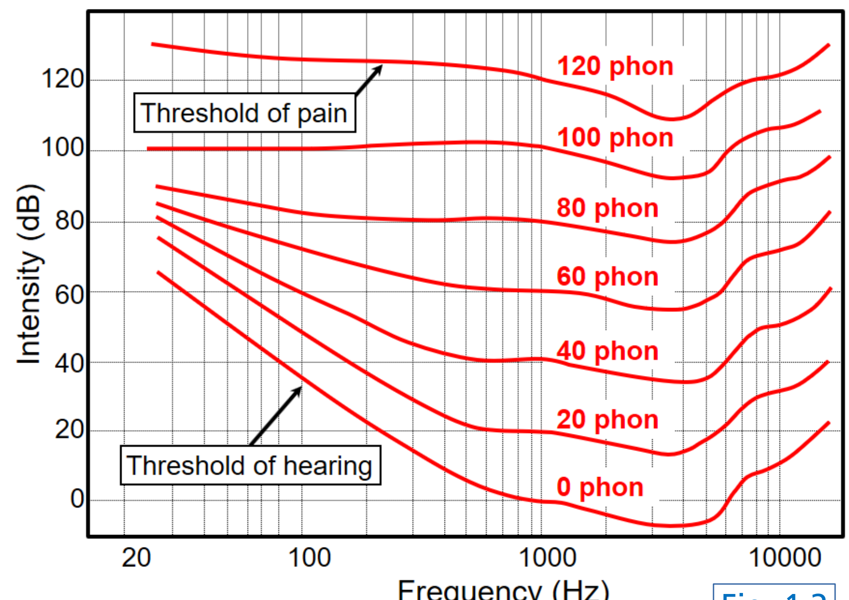


Fig. 1.2

# Audio Processing
## Time-Frequency Decomposition

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

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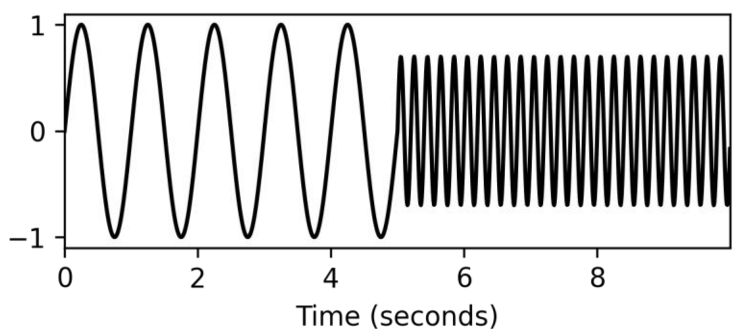
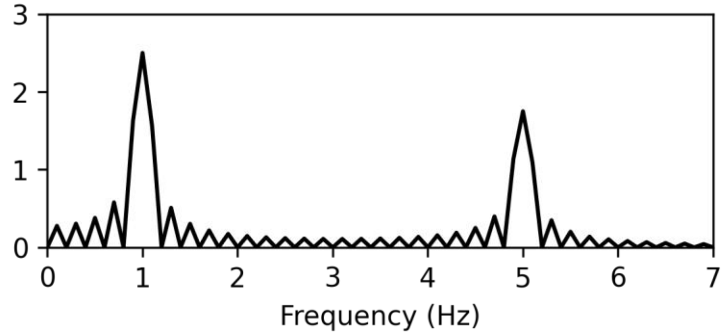


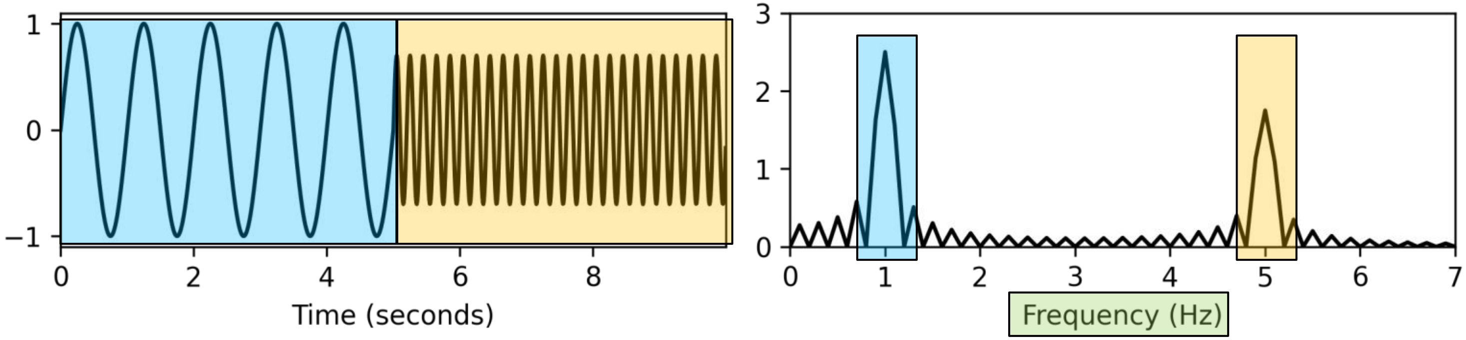

Waveform




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

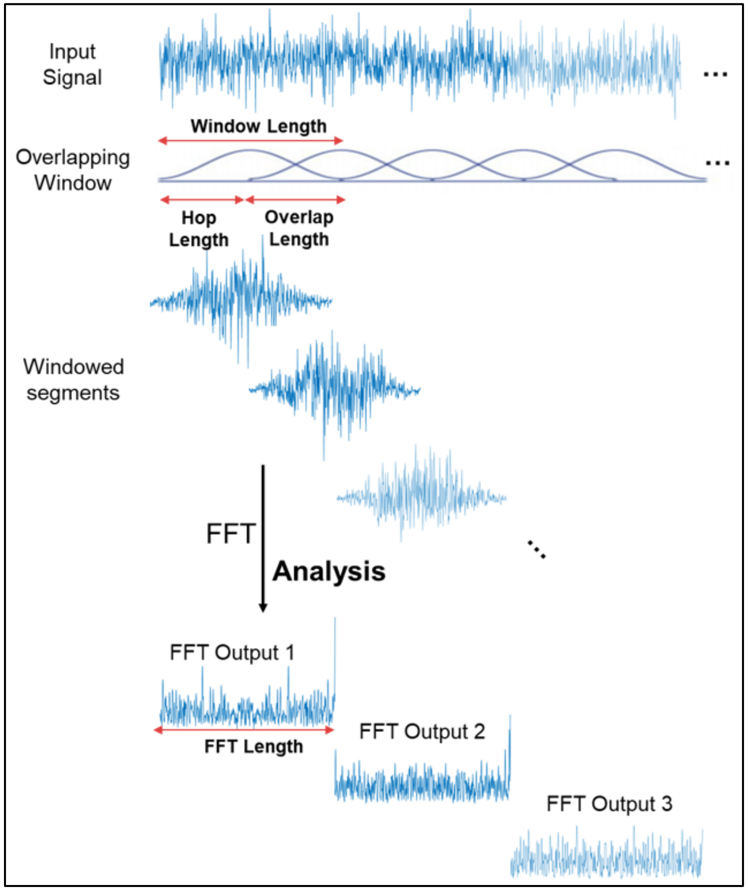



Fig. 2

# Audio Processing
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    - Time-frequency energy distribution in audio signal

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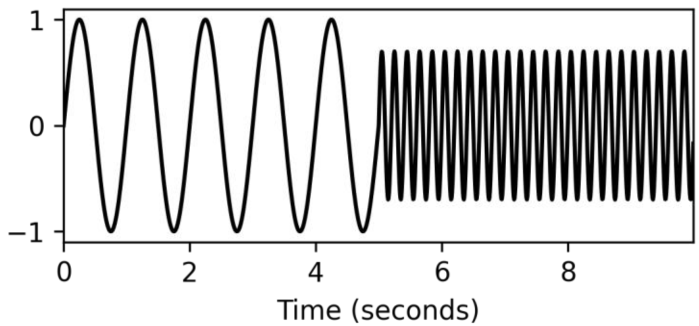
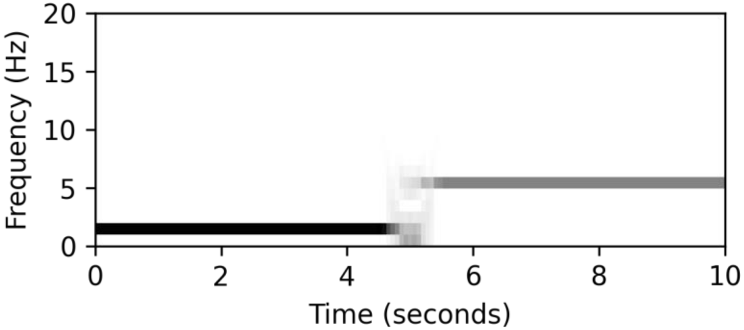



Waveform




Spectrogram

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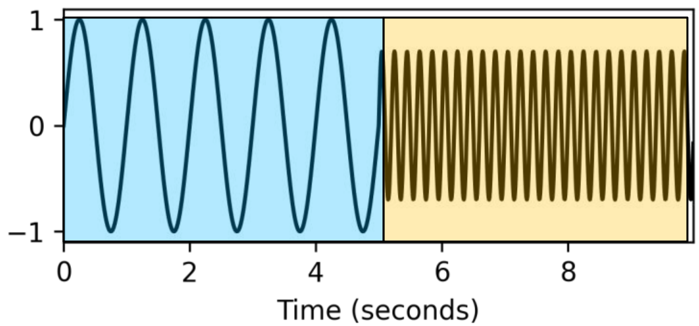


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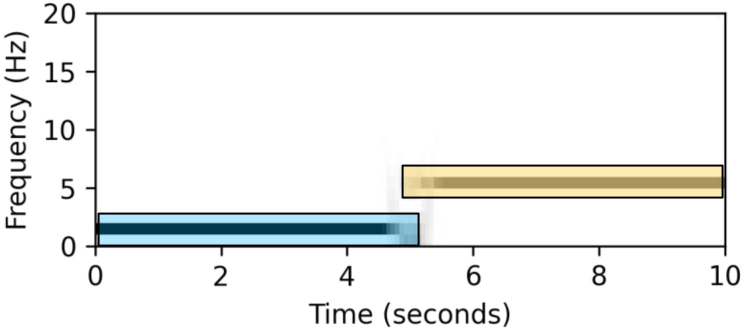
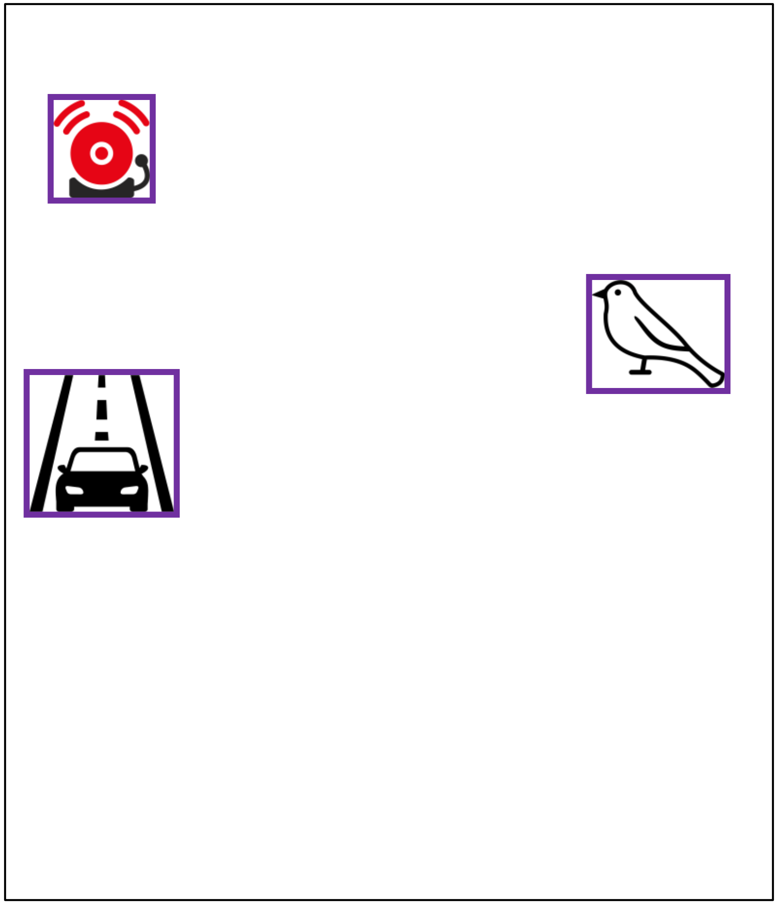



Spectrogram

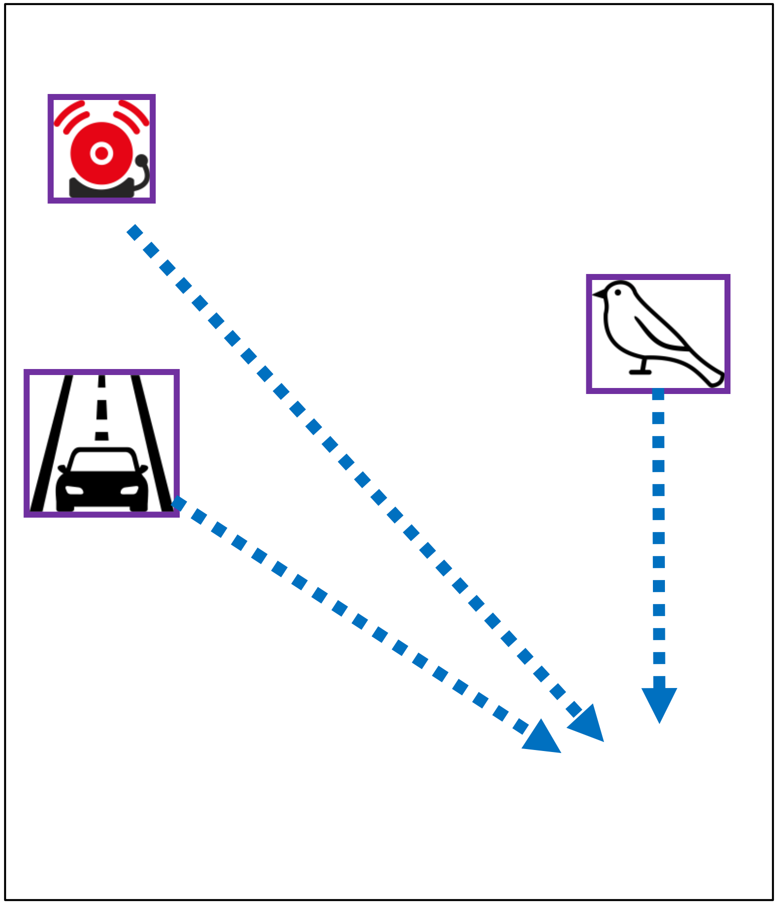
# Audio Processing
## Auditory Scene

- Distributed sound producing events (sound sources)



# Audio Processing
## Auditory Scene

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



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## Auditory Scene

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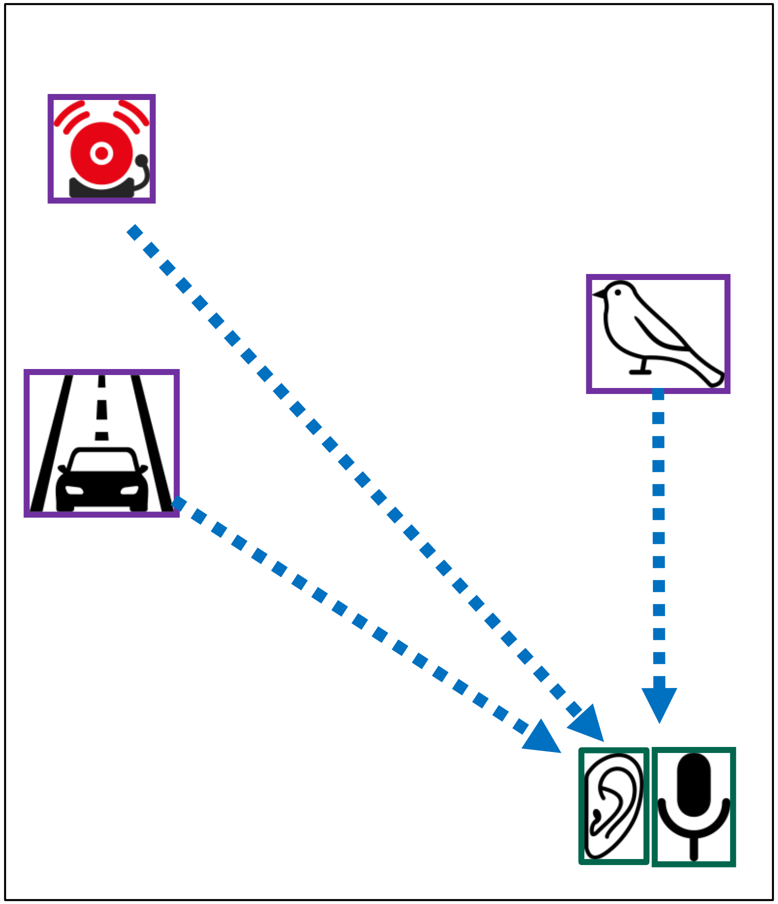
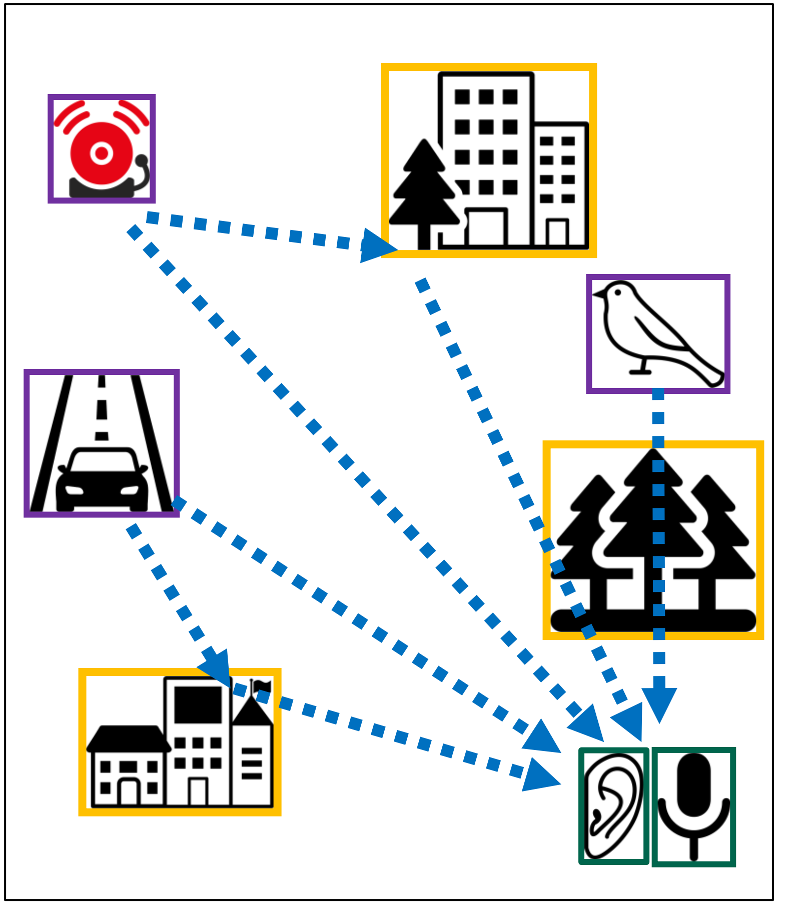


# Audio Processing
## Auditory Scene

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



# Audio Processing

## Programming Session #1

Fig. 2.1

# Audio Processing
## Mel Frequency Scale

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

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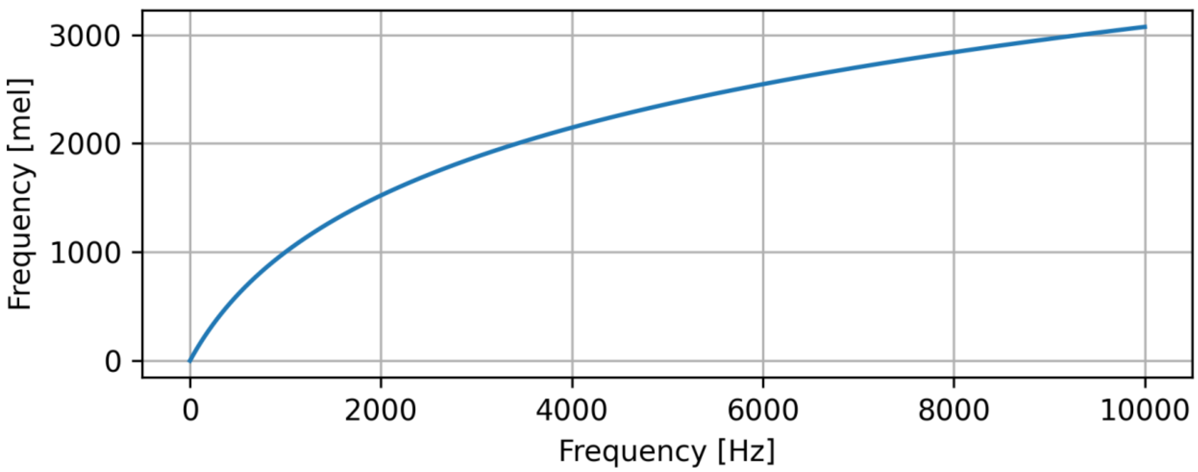

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## Mel Spectrogram

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

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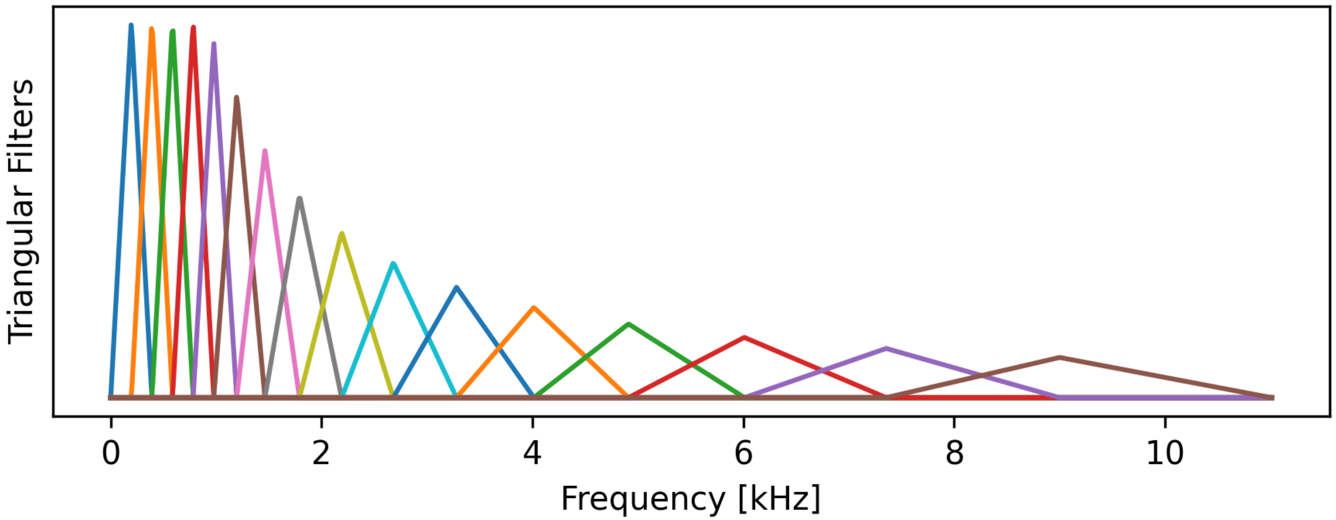
  - Triangular filterbank + Matrix multiplication
- Example: 16 mel bands, $f_s = 22.05\ \mathrm{kHz}$



# Audio Processing
## Mel Spectrogram

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

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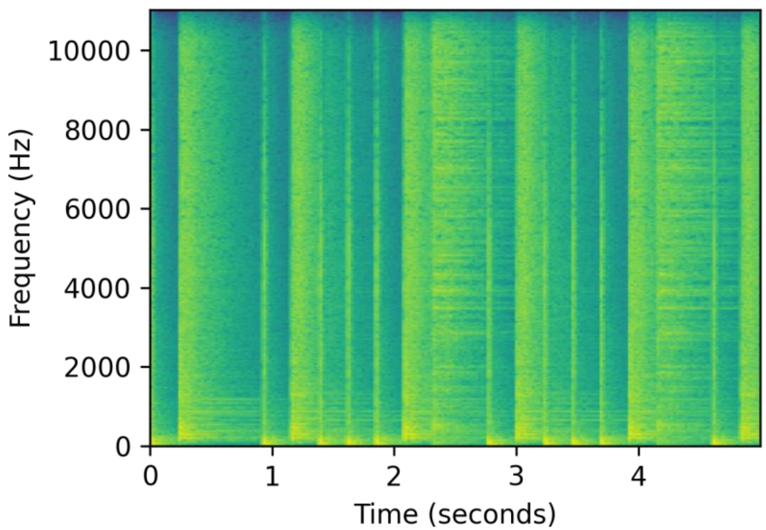
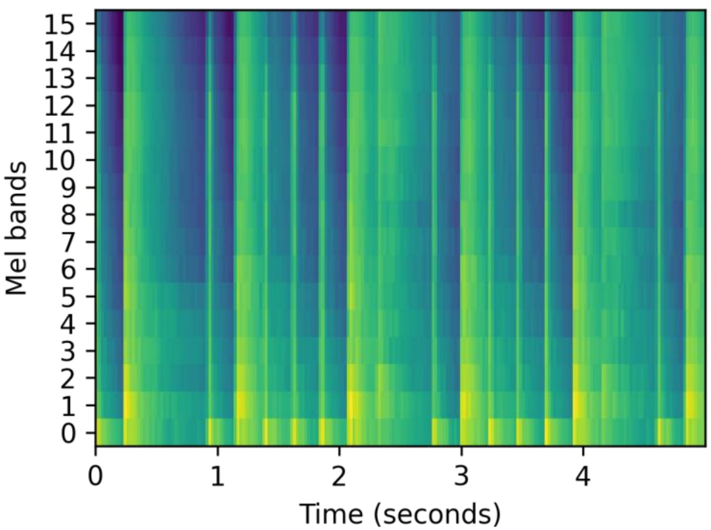
STFT




(513 frequency bands)

Mel Spectrogram

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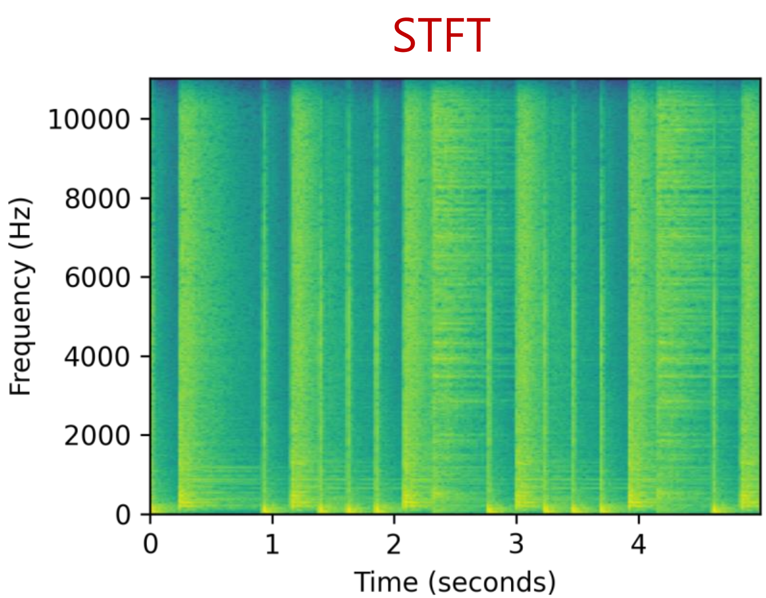


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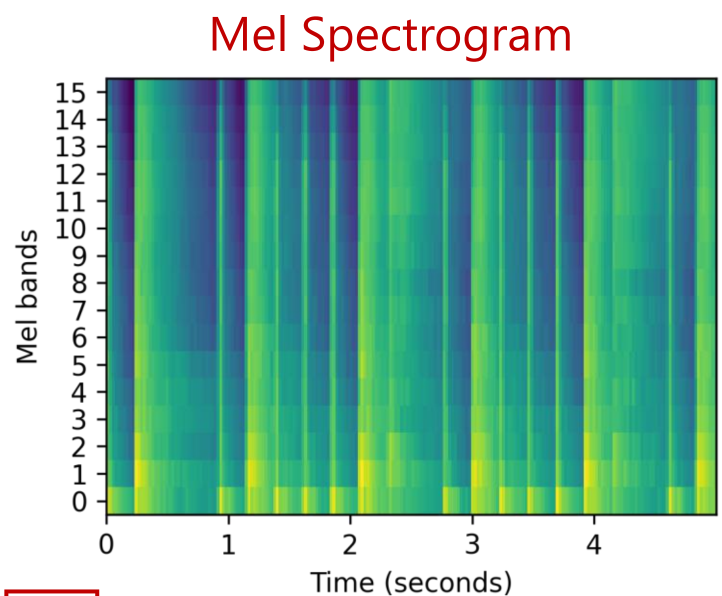
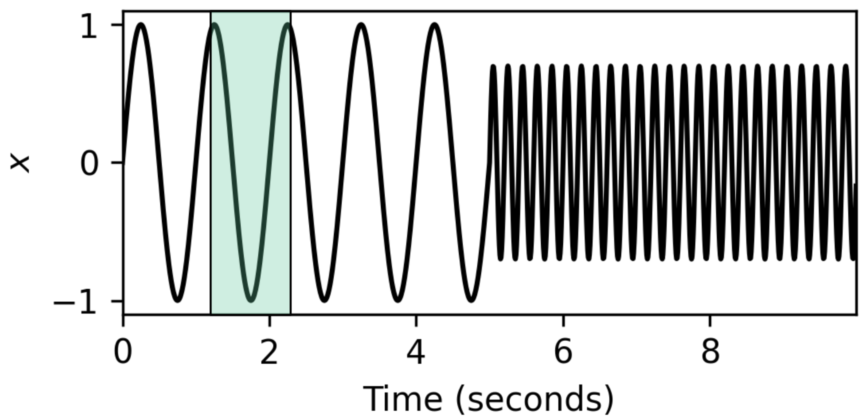



(16 Mel bands)

**Compression by 96.9 %**

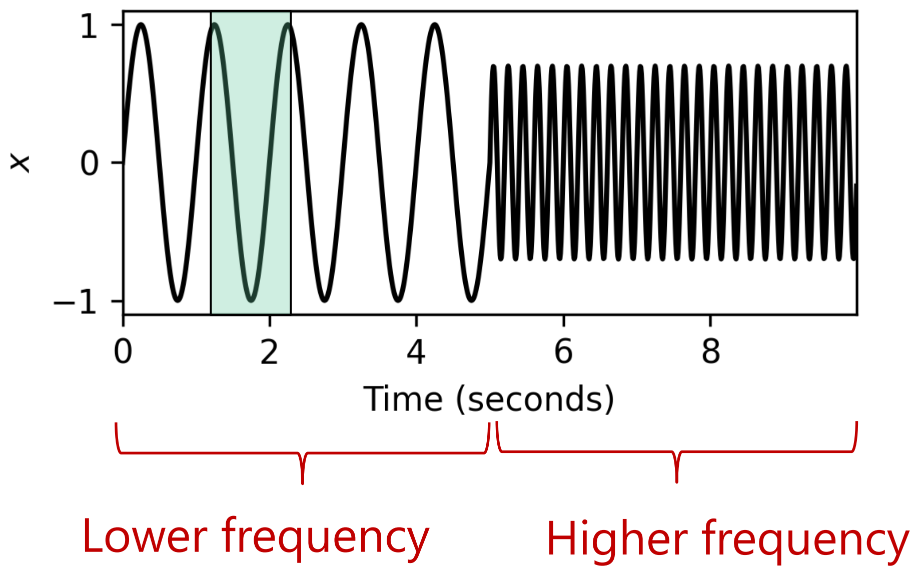
# Audio Processing
## Periodic Signals

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



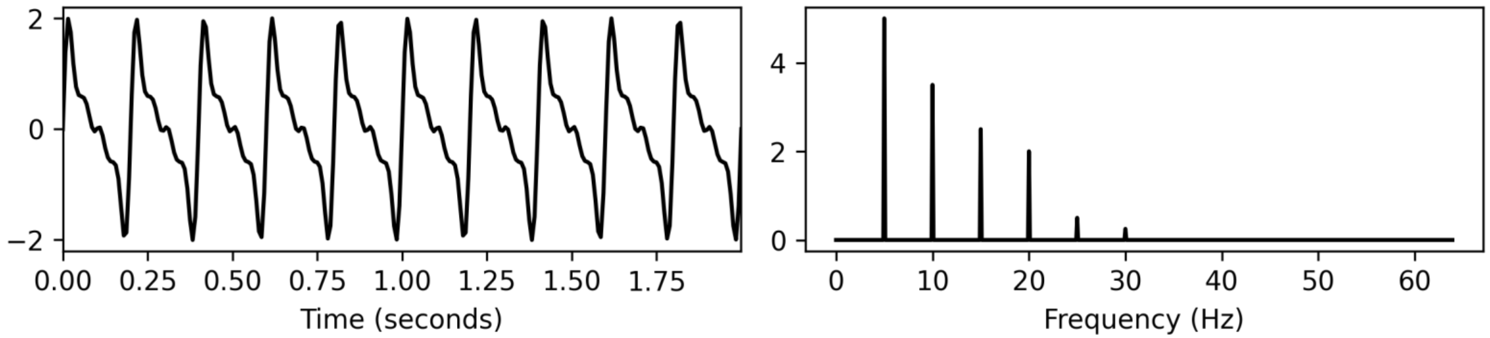
# Audio Processing
## Periodic Signals

- 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:
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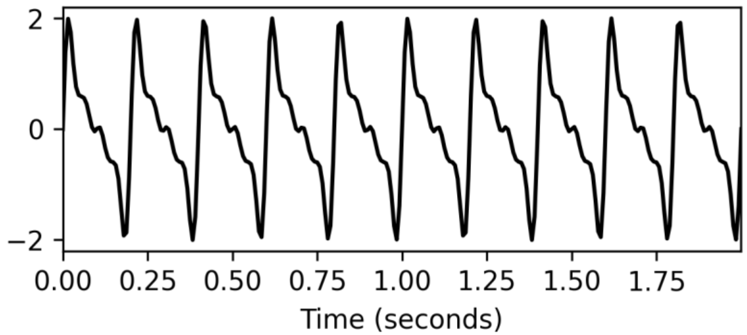
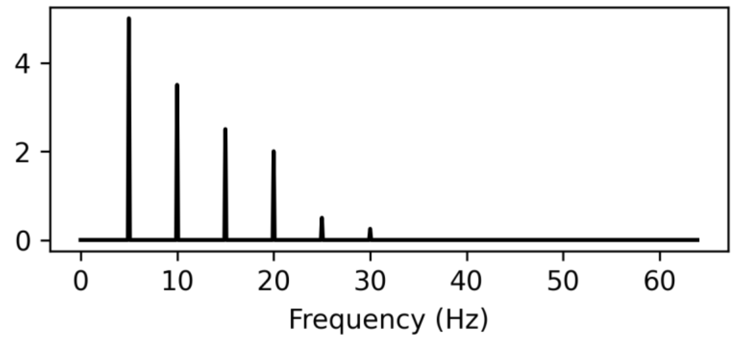
    - Fundamental frequency $f_0$
    - Harmonics $f_k$ (approx. integer multiples of $f_0$):
      - $f_k \approx (k+1) \cdot f_0$



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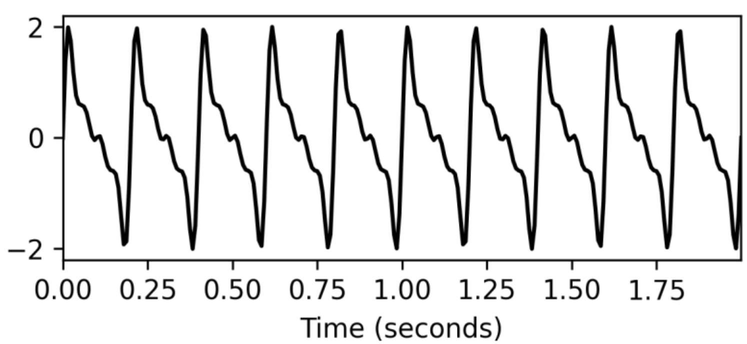


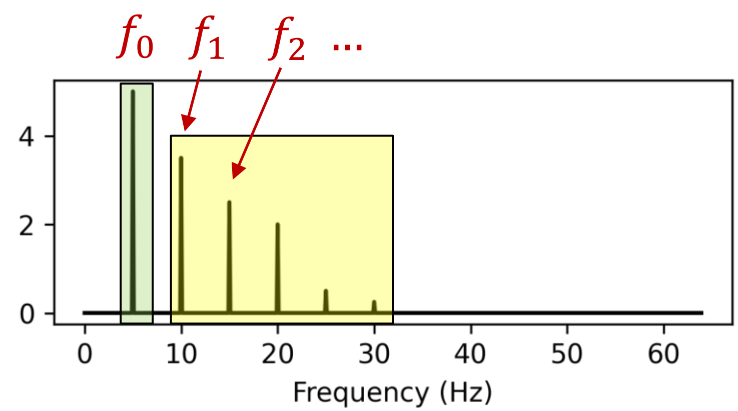

# Audio Processing
## Pitch

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

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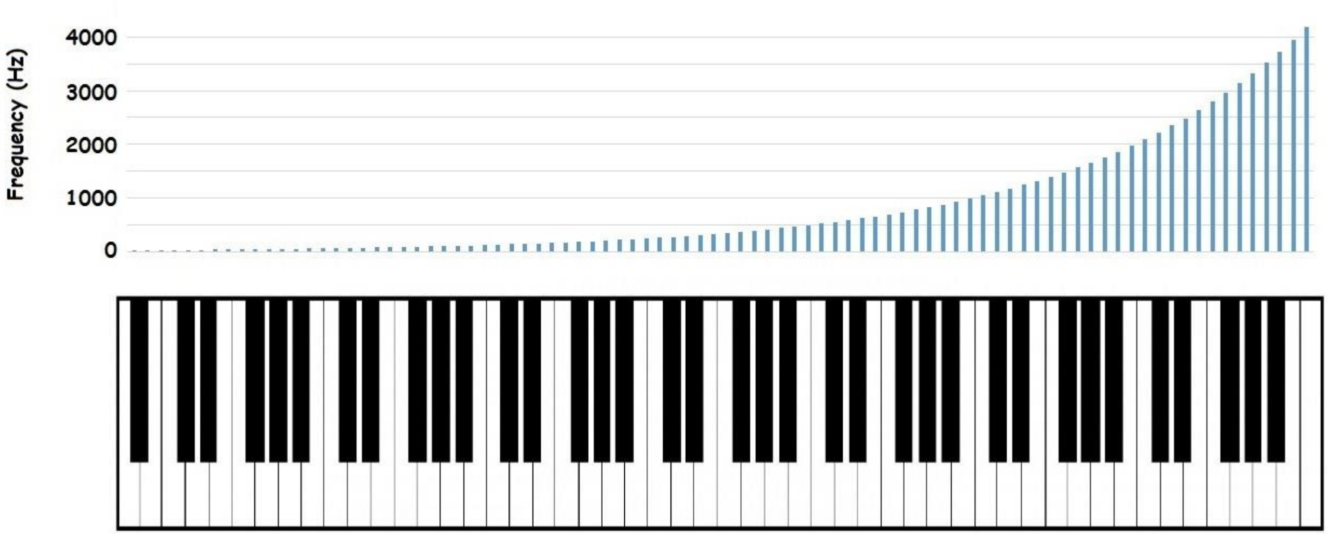



Fig. 2.5

# 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 |

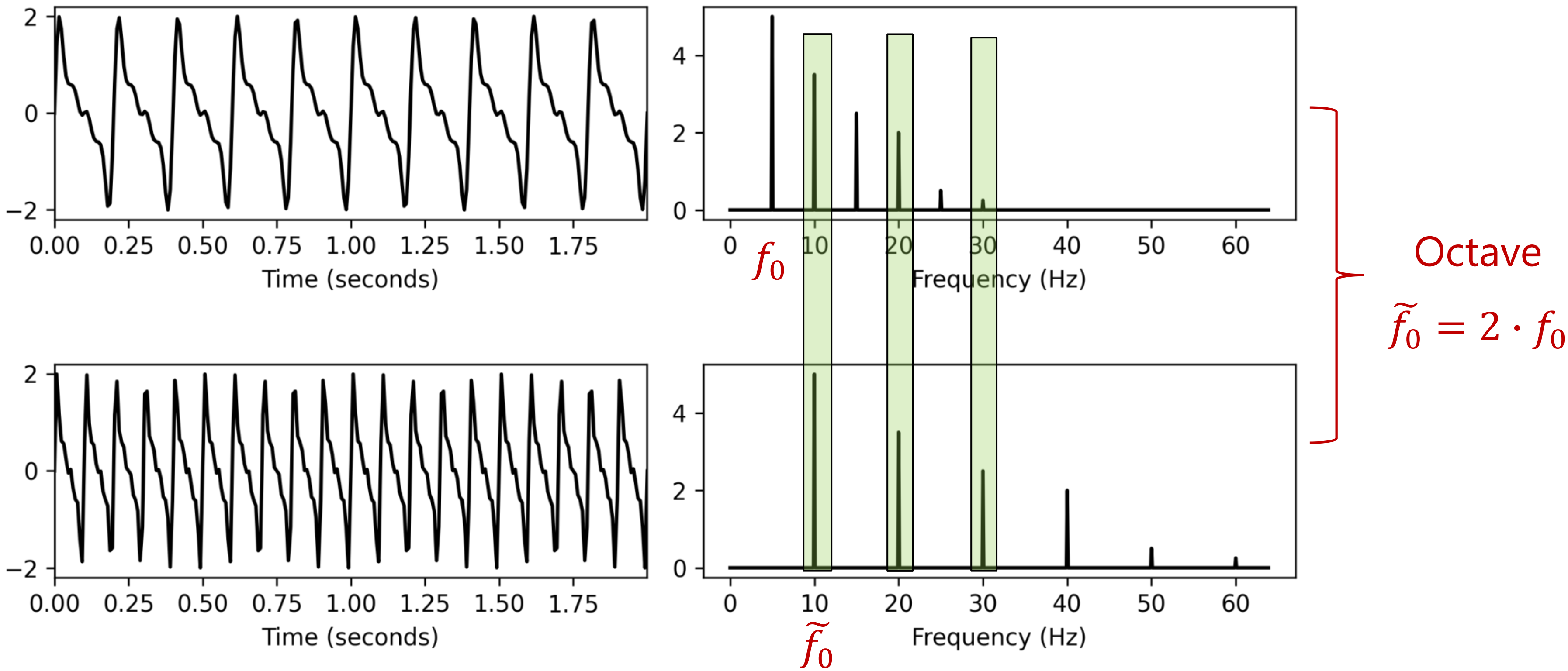
Octave intervals

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

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

# 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

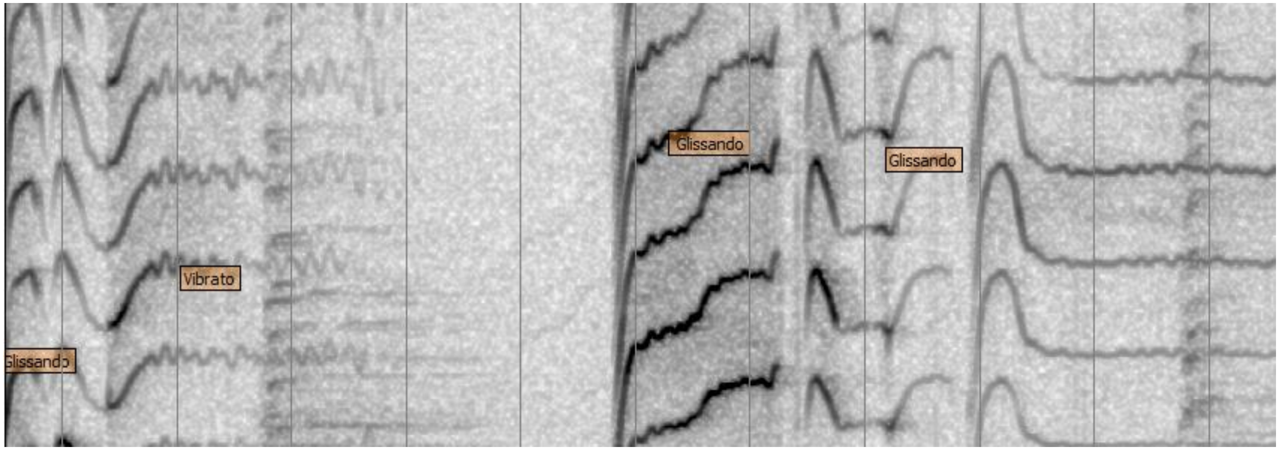
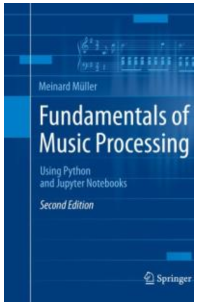



Fig. 2.6

Spectrogram example (frequency x time)

# Audio Processing
## Frequency Modulation

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




FMP Notebooks

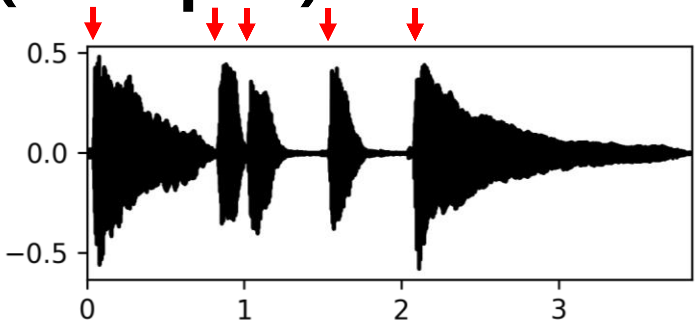
# Audio Processing
## Transients

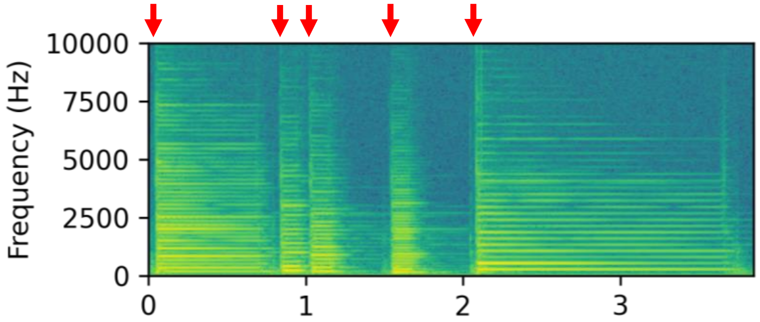
- Sound characteristics
    - High amplitude
    - Short duration
    - Wide-band signal
        - Energy distributed over large frequency range (not just a few frequencies)

# Audio Processing
## Transients (Examples)

- String instruments

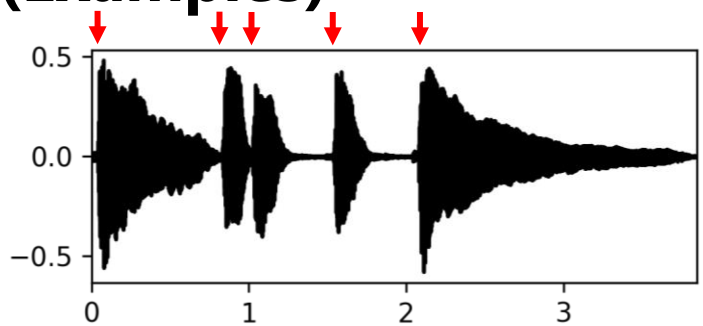
  Audio 1

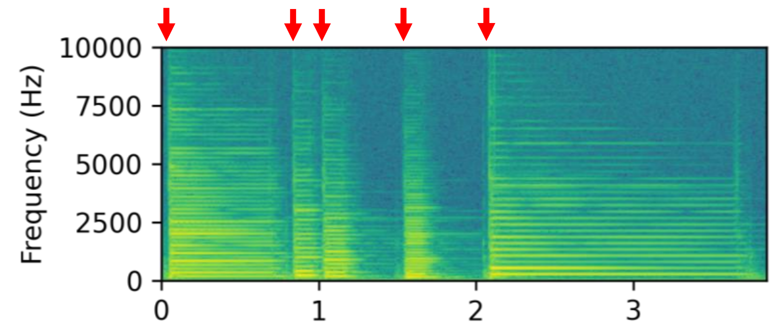


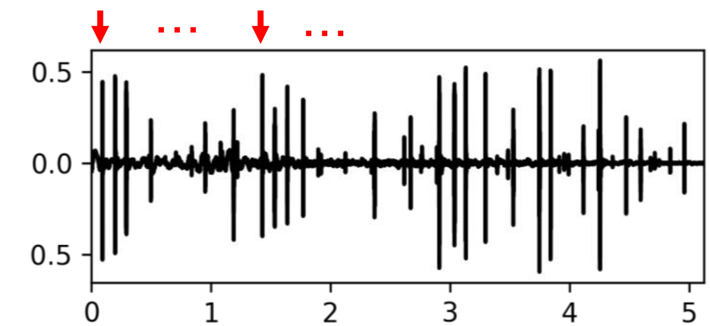
# Audio Processing
## Transients (Examples)

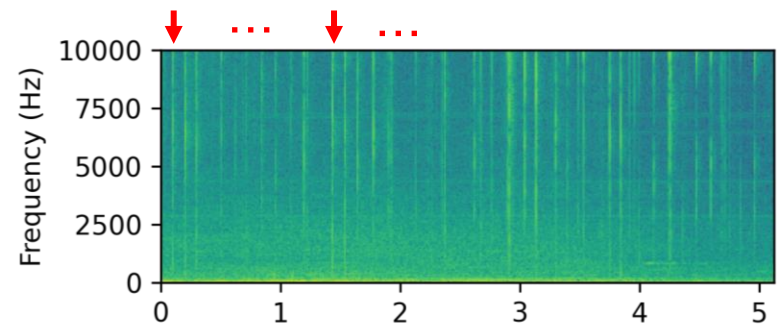
- String instruments
  Audio 1




- Bat vocalizations
  Audio 2



# Audio Processing

## Transients (Examples)

- String instruments

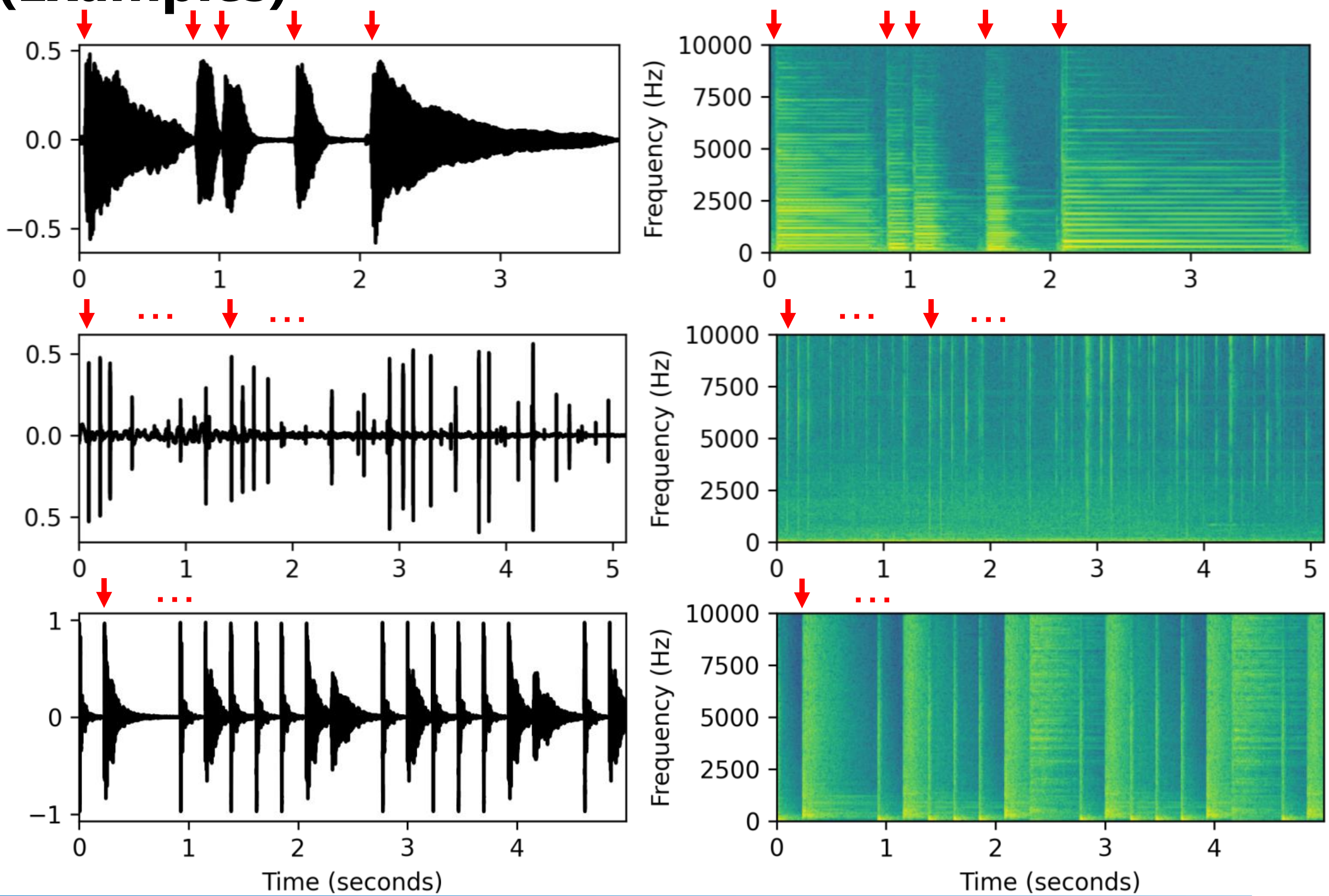
  Audio 1

- Bat vocalizations

  Audio 2

- Drum instruments

  Audio 3

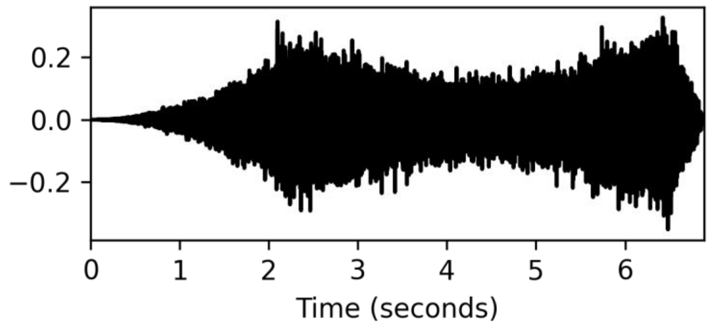


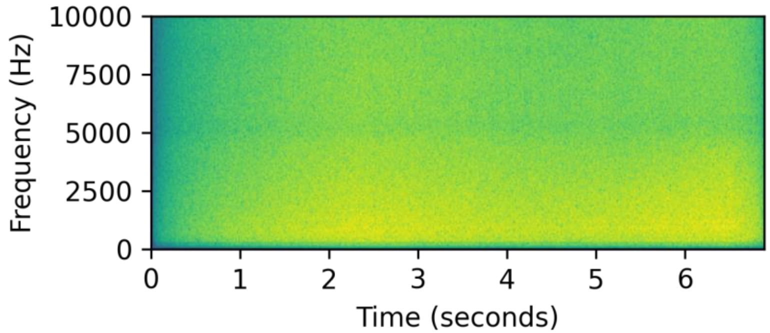
# Audio Processing
## Noise

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

# Audio Processing
## Noise

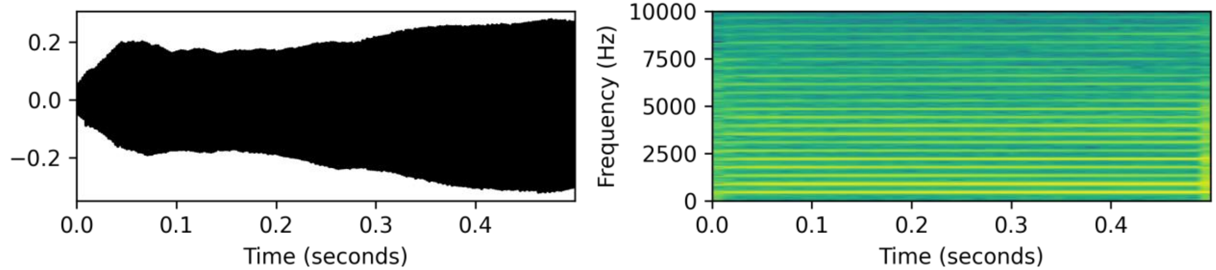
- Sound characteristics
  - Non-periodic, texture-like
  - Random fluctuations of air pressure
- Examples
  - Consonants (speech)
  - Wind (random aerodynamic turbulences)
  - Waves (ocean) Audio 4



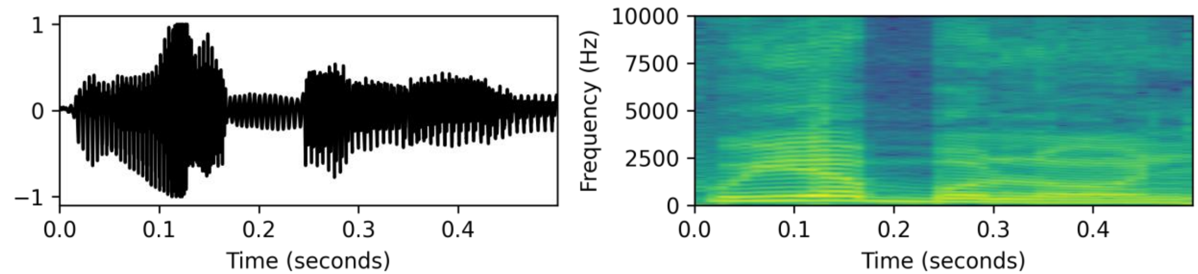



# Audio Processing
## Real-life Sound Examples

- Examples:
  - Music (violin)

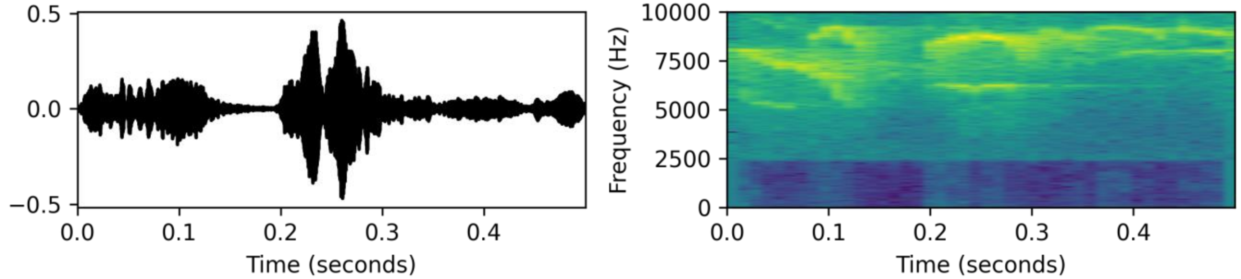



  - Male Speech

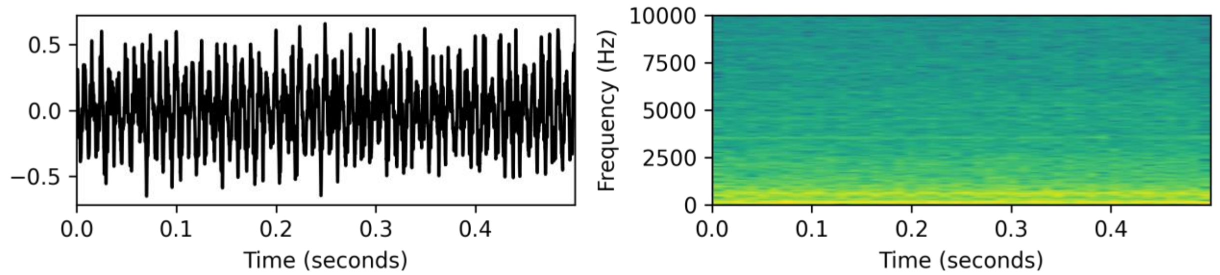


# Audio Processing
## Real-life Sound Examples

- Examples:
  - Bird singing




  - Running machine



# Audio Processing
## Temporal Envelope

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

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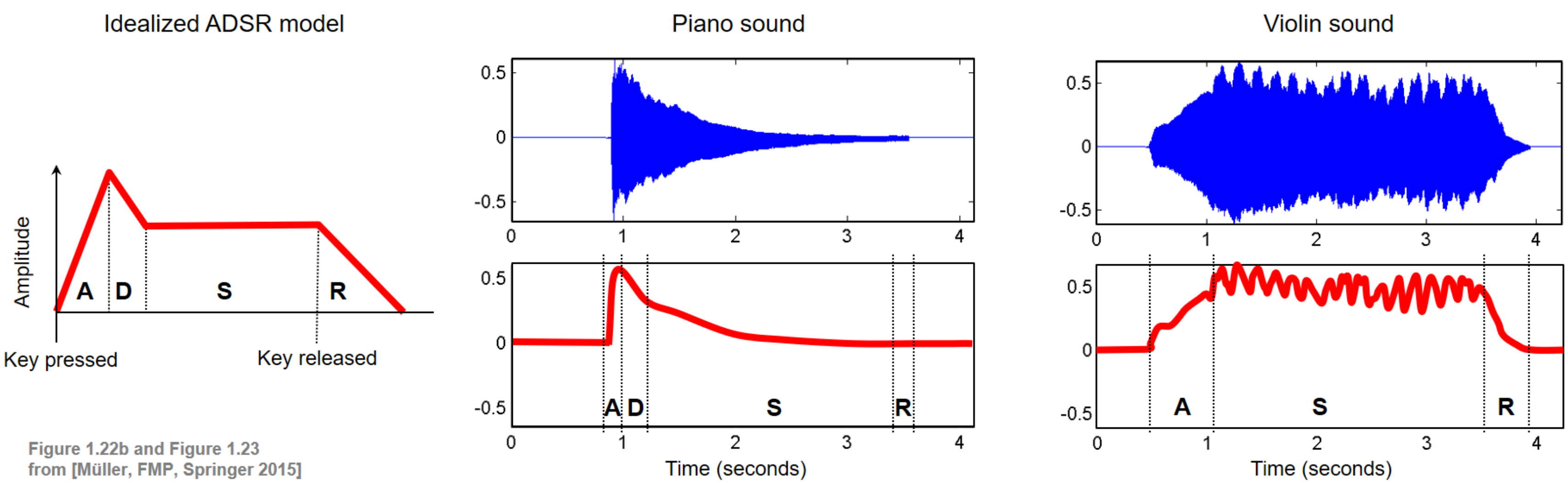
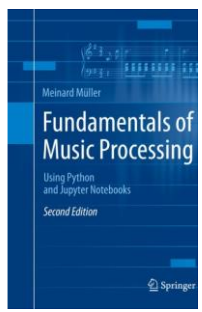



Fig. 2.7

# 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

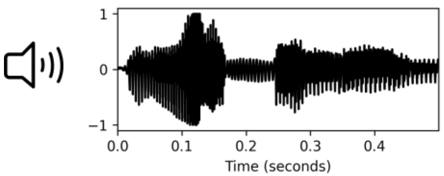
**(Subjective) perceptual attributes** ⟺ Correlations? ⟺ **(Objective) sound characteristics**

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

# Audio Processing
## Mel-Frequency Cepstral Coefficients (MFCC)

- Compact representation of spectral envelope

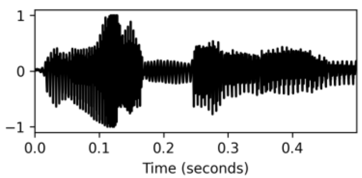
*Audio signal*

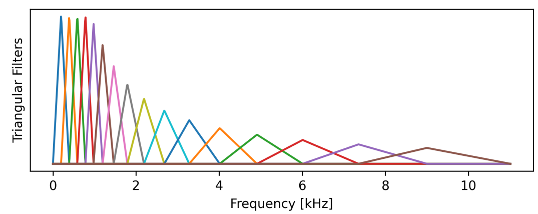


# Audio Processing
## Mel-Frequency Cepstral Coefficients (MFCC)

- Compact representation of spectral envelope

*Audio signal* → STFT → Mel Filterbank

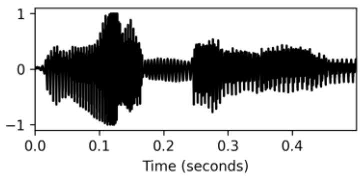


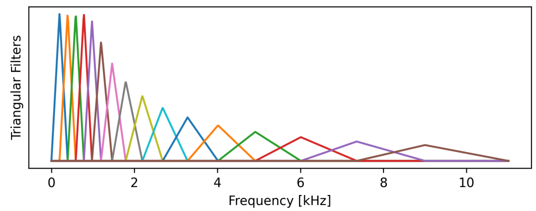



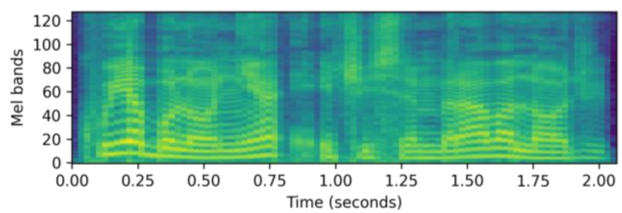
# Audio Processing
## Mel-Frequency Cepstral Coefficients (MFCC)

- Compact representation of spectral envelope

*Audio signal* → STFT → Mel Filterbank → Log-Magnitude



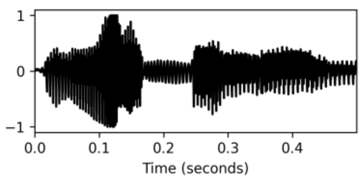



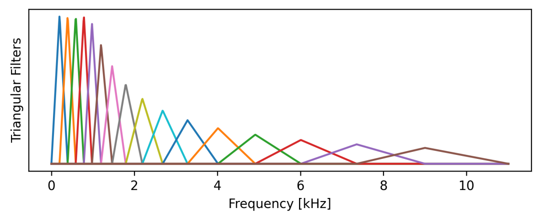



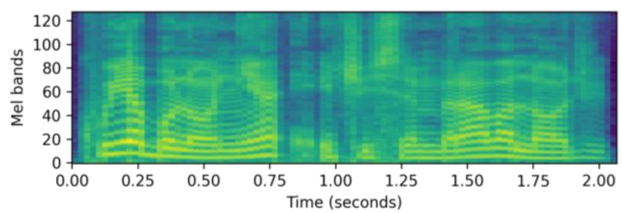
# Audio Processing
## Mel-Frequency Cepstral Coefficients (MFCC)

- Compact representation of spectral envelope

*Audio signal* → STFT



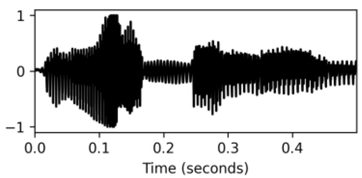




STFT → Mel Filterbank → Log-Magnitude → Discrete Cosine Transform (DCT)

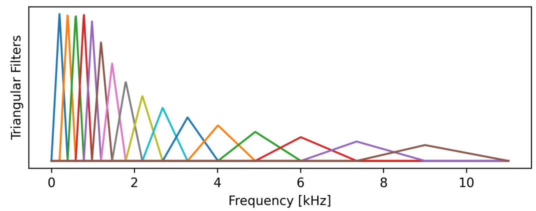
# Audio Processing
## Mel-Frequency Cepstral Coefficients (MFCC)

- Compact representation of spectral envelope

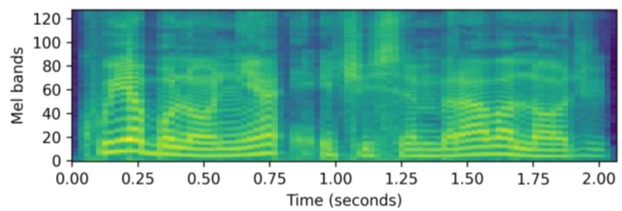
*Audio signal* → STFT




STFT → Mel Filterbank

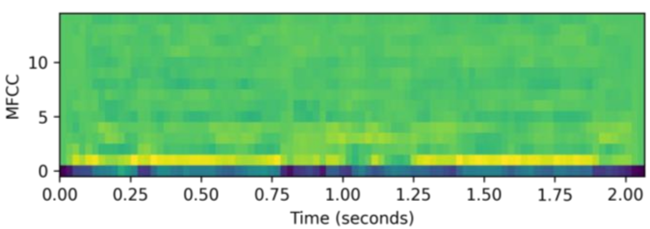



Mel Filterbank → Log-Magnitude




Log-Magnitude → Discrete Cosine Transform (DCT)

Discrete Cosine Transform (DCT) → *MFCC*



# 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

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## Constant-Q Transform

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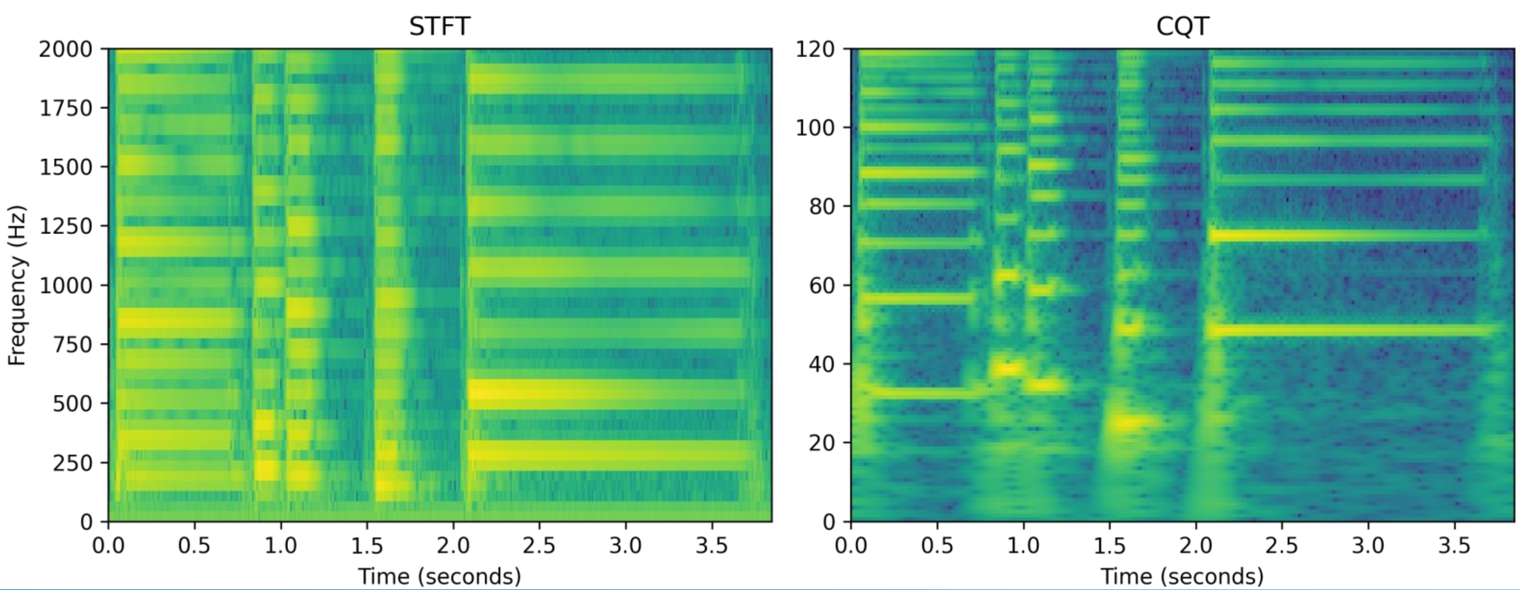
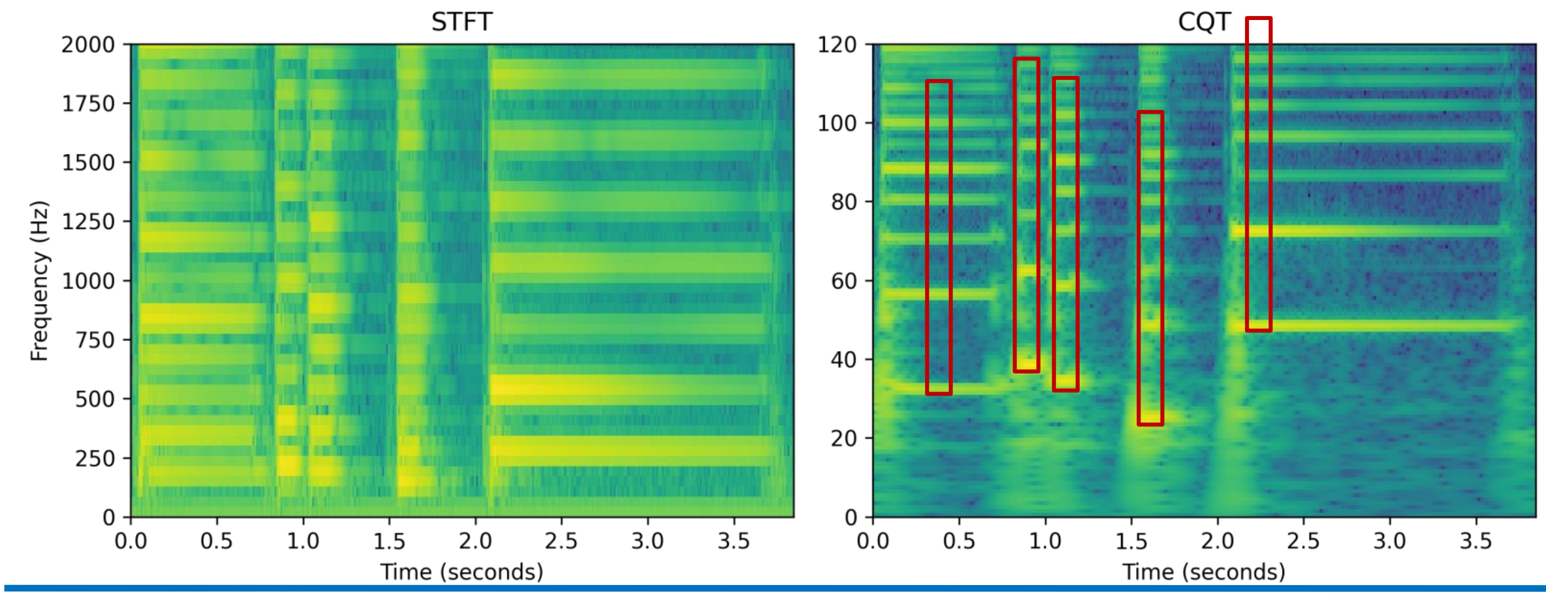



Audio 1

# 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]

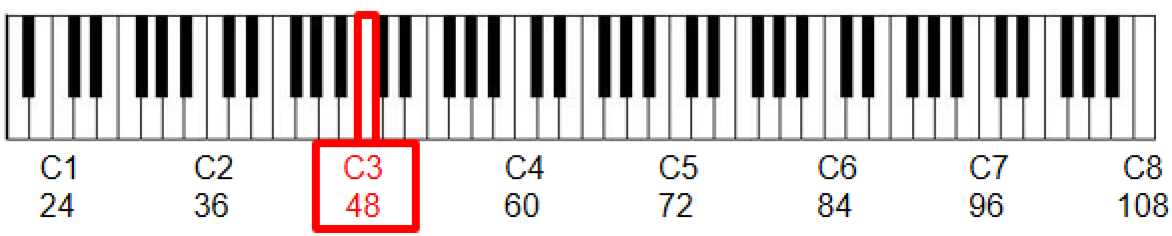
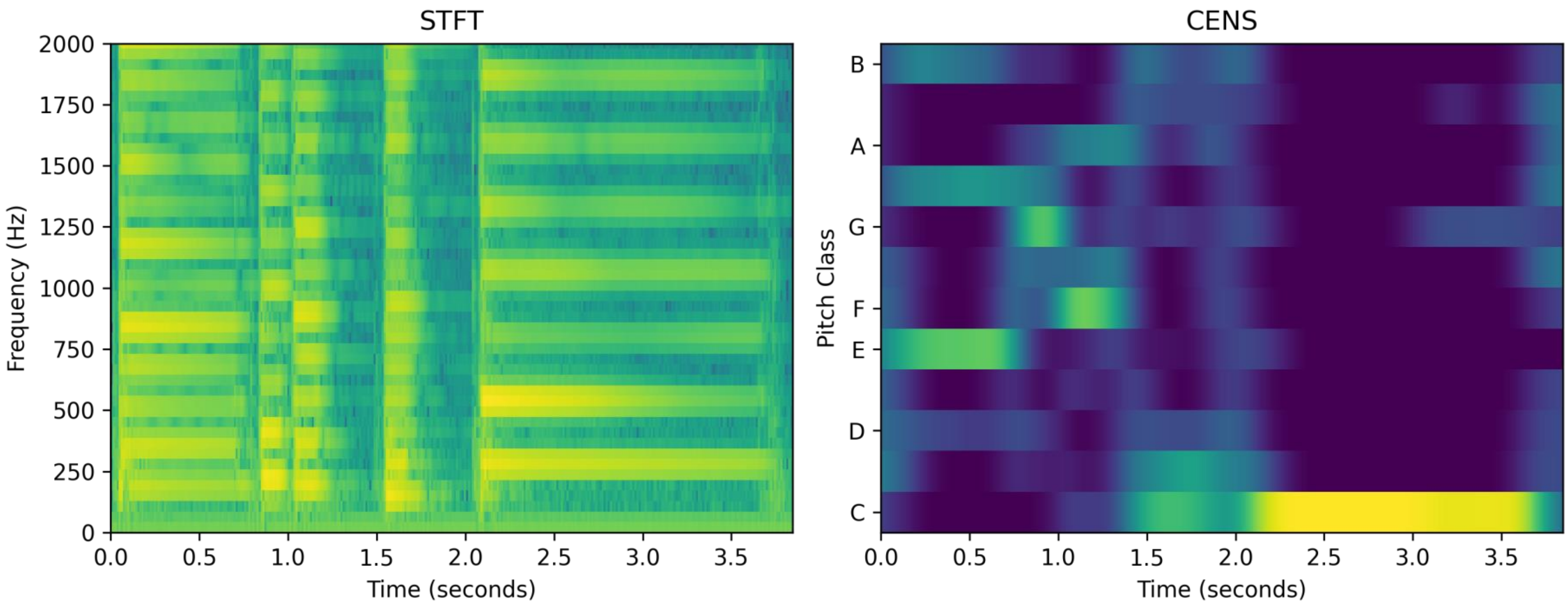



Fig. 2.8

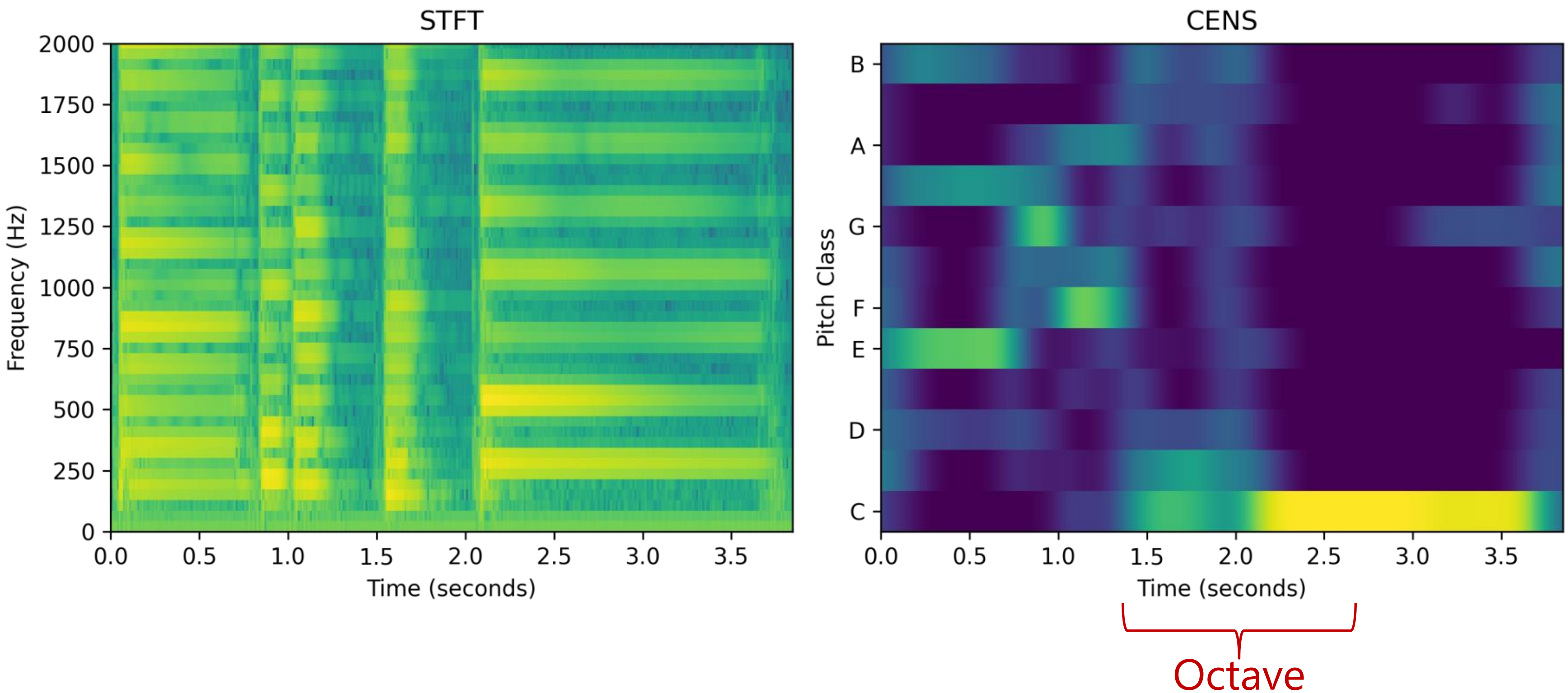
# Audio Processing
## Chroma Features

- Example Audio 1



# Audio Processing
## Chroma Features

- Example Audio 1



# Audio Processing

## Programming Session #2

Fig. 2.1

# AI-based Audio Analysis of Music and Soundscapes

## Audio Processing

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Fraunhofer IDMT

jakob.abesser@idmt.fraunhofer.de

# Images

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

Fig. 1.1: M. Müller (2015): Fundamentals of Music Processing (FMP), Springer, 2015, Tab. 1.1

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: M. Müller (2015): Fundamentals of Music Processing (FMP), Springer, 2015, Fig. 1.22b & Fig. 1.23

Fig. 2.8: M. Müller (2015): Fundamentals of Music Processing (FMP), Springer, 2015, Fig. 3.3a

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

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

# 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)