Learning with Music Signals: Technology Meets Education

FMP Notebooks

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Saarbrücken, May 8, 2023
Tutorial T3, EUROGRAPHICS

Music Processing: A Multifaceted Research Area

- important part of our lives …
- … Spotify, Pandora, iTunes, …
- interdisciplinary research
- intuitive entry point to education

Fundamentals of Music Processing (FMP)

Meinard Müller
Fundamentals of Music Processing
Audio, Analysis, Algorithms, Applications
Springer, 2015
Accompanying website:
www.music-processing.de

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Fundamentals of Music Processing
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2nd edition
Meinard Müller
Fundamentals of Music Processing
Using Python and Jupyter Notebooks
Springer, 2021
FMP Notebooks: Education & Research

... provide educational material for teaching and learning fundamentals of music processing.

... combine textbook-like explanations, technical concepts, mathematical details, Python code examples, illustrations, and sound examples.

... bridge the gap between theory and practice being based on interactive Jupyter notebook framework.

... are freely accessible under a Creative Commons license.

Structured in 10 parts

- Part B: Basic introductions to
  - Jupyter notebook framework
  - Python programming
  - Other technical concepts underlying these notebooks

Structured in 10 parts

- Part 0: Starting notebook
### FMP Notebooks

Structured in 10 parts

1. **Part B: Basic introductions to**
   - Jupyter notebook framework
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2. **Part 0: Starting notebook**

3. **Part 1 to Part 8: Different music processing scenarios**

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### Tempo and Beat Tracking

**Basic task: “Tapping the foot when listening to music”**

**Example:**  Queen – Another One Bites The Dust

![Waveform](image)

*Time (seconds)*

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**Part 6: Tempo and Beat Tracking**

When listening to a piece of music, we as humans are often able to tap along with the musical beat.

Automated beat tracking: Simulate this cognitive process by a computer.

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**Light effects**

**Music recommendation**

**DJ**

**Audio editing**

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**Example:**  Queen – Another One Bites The Dust

![Waveform](image)

*Time (seconds)*
 Tempo and Beat Tracking

Tasks
- Onset detection
- Beat tracking
- Tempo estimation

Onset Detection (Spectral Flux)

Audio recording

Magnitude spectrogram $|X|$
Onset Detection (Spectral Flux)

Compressed spectrogram

Steps:
1. Spectrogram
2. Logarithmic compression

Onset Detection (Spectral Flux)

Spectral difference

Steps:
1. Spectrogram
2. Logarithmic compression
3. Differentiation & half wave rectification
4. Accumulation

Novelty curve

Onset Detection (Spectral Flux)

Steps:
1. Spectrogram
2. Logarithmic compression
3. Differentiation & half wave rectification
4. Accumulation
5. Normalization

Normalized novelty function
Onset Detection (Spectral Flux)

Steps:
1. Spectrogram
2. Logarithmic compression
3. Differentiation & half wave rectification
4. Accumulation
5. Normalization

Normalized novelty function
Peak positions indicate beat candidates

Deep Learning

Steps:
1. Spectrogram
2. Logarithmic compression
3. Differentiation & half wave rectification
4. Accumulation
5. Normalization

Normalized novelty function
Peak positions indicate beat candidates

Local Pulse and Tempo Tracking

Fourier temogram (STFT of novelty function)

Optimizing local periodicity kernel

Fourier temogram (STFT of novelty function)
Local Pulse and Tempo Tracking

Fourier temogram (STFT of novelty function)

Optimizing local periodicity kernel

Accumulation of kernels

Halfwave rectification

Novelty Curve

Predominant Local Pulse (PLP)

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Part B: Basics

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Part 6: Tempo and Beat Tracking

FMP Notebooks
Part B: Basics
Annotation Visualization
Examples for visualizing annotations of time positions and segments.

Part 1: Music Representations
Symbolic Format: CSV
Visualization of a piano-roll representation (Fugue BWV 846 by Bach).

Part 1: Music Representations
Waves and Waveforms
 Videos illustrating the concepts of transverse, longitudinal, and combined waves.

Part 2: Fourier Analysis of Signals
Discrete Fourier Transform (DFT)
The matrix $DFT_N$ and a visualization of its real and imaginary parts for the case $N = 32$

Part 2: Fourier Analysis of Signals
STFT: Padding
Time-domain signal and magnitude Fourier transform.
Magnitude STFT.

Part 2: Fourier Analysis of Signals
Digital Signals: Quantization
Uniform and nonuniform quantization (based on $\mu$-law encoding) using $\lambda = 6$ quantization levels.
Part 3: Music Synchronization
Transposition and Tuning

Tuning procedure using a comb-filter approach.

Music synchronization result obtained for two input chromagrams (obtained from two recordings of the beginning of Beethoven’s Fifth Symphony).

Part 4: Music Structure Analysis
SSM: Synthetic Generation

Structure annotation and different synthetically generated SSMs.

Part 5: Chord Recognition
Template-Based Chord Recognition

Chord recognition task illustrated by the first measures of the Beatles song “Let It Be.”

Part 5: Chord Recognition
Experiments: Beatles Collection

Prefiltering experiments for a template-based and an HMM-based chord recognizer applied to two different input chroma representations (STFT, CQT).

The evaluation is performed on the basis of four Beatles songs (LetItB, HereCo, ObLaDi, PennyL).

Part 6: Tempo and Beat Tracking
Novelty: Comparison of Approaches

Comparison of novelty detectors using a matrix-based visualization.
Part 8: Audio Decomposition

Fundamental Frequency Tracking

Salience representation with trajectories computed by
(a) a frame-wise approach,
(b) an approach using continuity constraints, and
(c) a score-informed approach.

Nonnegative Matrix Factorization (NMF)

NMF procedure applied to a toy example.

Matrix V and randomly initialized matrices W and H.

Matrix V and matrices W and H after training.

Error terms over iteration.

Talk Outline

https://www.audiolabs-erlangen.de/FMP

Basics + 8 Chapters
Definition

We assume that we are given a discrete-time novelty function \( \Delta : \mathbb{Z} \rightarrow \mathbb{R} \). The idea of Fourier analysis is to detect notes by comparing it with windows of white noise. A high correlation between \( \Delta \) and a window \( w \) indicates note onset candidates. This correlation can be computed using the short-time Fourier transform. In this end, we use a window function \( w_t \) that is time-centered at \( t = 0 \) (e.g., a sampled Hann window). Then, for a fixed parameter \( w \in \mathbb{R}^N \) and time parameter \( n \in \mathbb{Z} \), the complex Fourier transform is defined by

\[
\hat{\Delta}(n, \omega) = \sum_{m=-\infty}^{\infty} \Delta(m) \exp(-2\pi i m \omega).
\]

Explanations

Mathematics

Theory

Example: Shostakovich

In the following example, we consider an excerpt of a recording of Shostakovich's Suite for Variety Orchestra No. 1. The excerpt version of the excerpt.

We start with a spectral-based novelty function resampled to \( \mathbb{R} \). Furthermore, we use a window size corresponding to 5 seconds (\( N = 5 \)).

Music Examples

Annotations

Links

Audio

Python Code

Algorithms

Functions
Talk Outline

- Tempo and Beat Tracking
- Visualization
- Results
- Evaluation
- Sonification

FMP Notebooks

- Understanding
- Programming
- Baselines
- Research
- Multimedia

Resources (Group Meinard Müller)

- FMP Notebooks: 
  [https://www.audiolabs-erlangen.de/FMP](https://www.audiolabs-erlangen.de/FMP)
- libfmp: 
  [https://github.com/meinardmueller/libfmp](https://github.com/meinardmueller/libfmp)
- synctoolbox: 
  [https://github.com/meinardmueller/synctoolbox](https://github.com/meinardmueller/synctoolbox)
- librosa: 
  [https://librosa.org](https://librosa.org)
- madmom: 
  [https://github.com/CPJKU/madmom](https://github.com/CPJKU/madmom)
- Essentials Python tutorial: 
  [https://essentia.upf.edu/essentia_python_tutorial.html](https://essentia.upf.edu/essentia_python_tutorial.html)
- mirdata: 
  [https://github.com/MIR-dataset-loaders/mirdata](https://github.com/MIR-dataset-loaders/mirdata)
- open-unmix: 
  [https://github.com/sigsep/open-unmix-pytorch](https://github.com/sigsep/open-unmix-pytorch)
- Open Source Tools & Data for Music Source Separation: 

Resources

  [https://www.mdpi.com/2624-6120/2/2/18](https://www.mdpi.com/2624-6120/2/2/18)
  [https://zenodo.org/record/3527872#.YOhEQOgzaUk](https://zenodo.org/record/3527872#.YOhEQOgzaUk)