

FMP Notebooks: Interaktives Lehren und Lernen der Digitalen Musikverarbeitung

Meinard Müller

International Audio Laboratories Erlangen
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Ringvorlesung Musikdatenanalyse

3. Februar 2023



Meinard Müller



- Mathematics (Diplom/Master)
Computer Science (PhD)
Information Retrieval (Habilitation)



- Since 2012: Professor
Semantic Audio Processing



- Former President of the International Society for
Music Information Retrieval (MIR)



- IEEE Fellow for contributions to
Music Signal Processing



Meinard Müller: Research Group Semantic Audio Processing

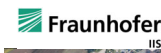
- Michael Krause
- Yigitcan Özer
- Simon Schwär
- Johannes Zeitler
- Peter Meier (external)



- Christof Weiß
- Sebastian Rosenzweig
- Frank Zalkow
- Christian Dittmar
- Stefan Balke
- Jonathan Driedger
- Thomas Prätzlich
- ...



International Audio Laboratories Erlangen



- Fraunhofer Institute for
Integrated Circuits IIS
- Largest Fraunhofer
institute with
≈ 1000 members
- Applied research for
sensor, audio, and
media technology



- Friedrich-Alexander
Universität Erlangen-
Nürnberg (FAU)
- One of Germany's
largest universities with
≈ 40,000 students
- Strong Technical
Faculty

International Audio Laboratories Erlangen

Audio

International Audio Laboratories Erlangen

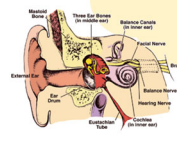
Audio Coding



3D Audio



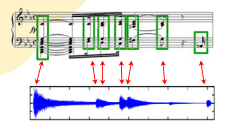
Audio



Psychoacoustics



Internet of Things



Music Processing

AudioLabs – FAU

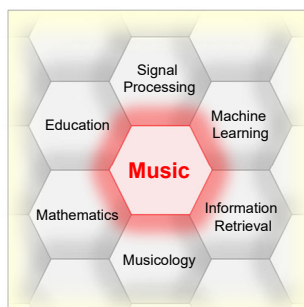
- Prof. Dr. Jürgen Herre
Audio Coding
- Prof. Dr. Bernd Edler
Audio Signal Analysis
- Prof. Dr. Meinard Müller
Semantic Audio Processing
- Prof. Dr. Emanuël Habets
Spatial Audio Signal Processing
- Prof. Dr. Nils Peters
Audio Signal Processing
- Dr. Stefan Turowski
Coordinator AudioLabs-FAU



Music Processing

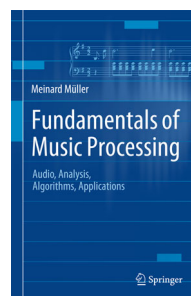


Music Processing: A Multifaceted Research Area



- Music is a ubiquitous and vital part of our lives
- Digital music services: Spotify, Pandora, iTunes, ...
- Music yields intuitive entry point to support and motivate education in technical disciplines
- Music bridges the gap between engineering, computer science, mathematics, and the humanities

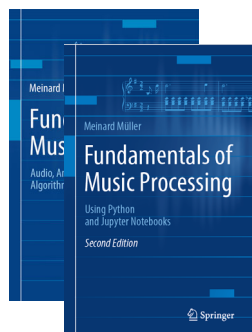
Fundamentals of Music Processing (FMP)



Meinard Müller
Fundamentals of Music Processing
Audio, Analysis, Algorithms, Applications
Springer, 2015

Accompanying website:
www.music-processing.de

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2nd edition
Meinard Müller
Fundamentals of Music Processing
Using Python and Jupyter Notebooks
Springer, 2021

Fundamentals of Music Processing (FMP)

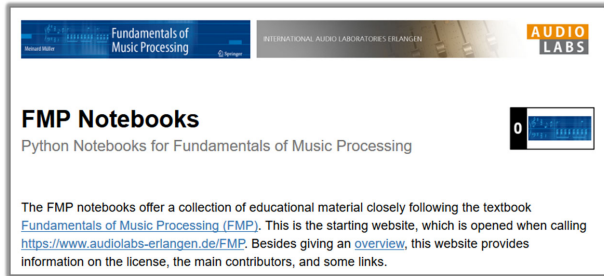
| Chapter | Music Processing Scenario |
|---------|--|
| 1 | Music Representations |
| 2 | Fourier Analysis of Signals |
| 3 | Music Synchronization |
| 4 | Music Structure Analysis |
| 5 | Chord Recognition |
| 6 | Tempo and Beat Tracking |
| 7 | Content-Based Audio Retrieval |
| 8 | Musically Informed Audio Decomposition |

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FMP Notebooks: Education & Research



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

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.

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

FMP Notebooks

| Part | Title | Notions, Techniques & Algorithms | HTML | IPYNB |
|------|--|--|----------------------|-----------------------|
| B | Basics | Basic information on Python, Jupyter notebooks, Anaconda package management system, Python environments, visualizations, and other topics | html | ipynb |
| 0 | Overview | Overview of the notebooks (https://www.audiolabs-erlangen.de/FMP) | html | ipynb |
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- Part 1 to Part 8: Different music processing scenarios

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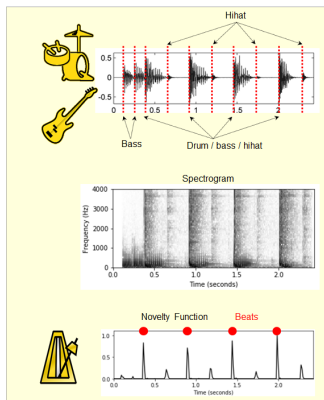
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Part 6: Tempo and Beat Tracking

Part 6: Tempo and Beat Tracking

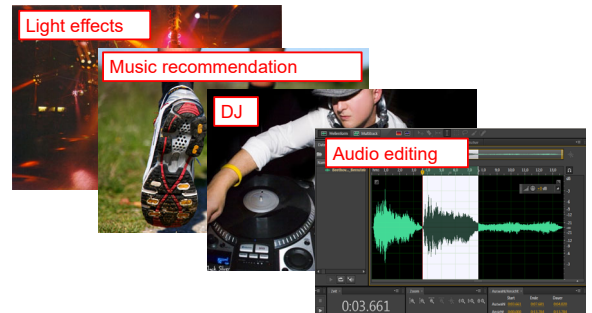


- When listening to a piece of music, we as humans are often able to tap along with the musical beat
- Automated beat tracking: Simulate this cognitive process by a computer



Tempo and Beat Tracking

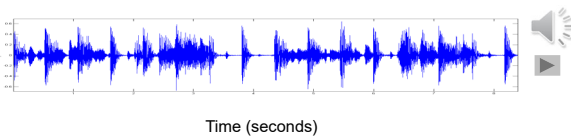
Basic task: "Tapping the foot when listening to music"



Tempo and Beat Tracking

Basic task: "Tapping the foot when listening to music"

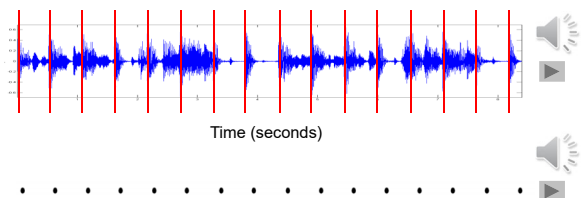
Example: Queen – Another One Bites The Dust



Tempo and Beat Tracking

Basic task: "Tapping the foot when listening to music"

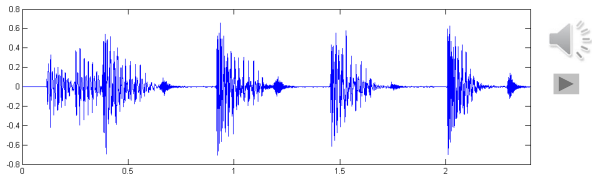
Example: Queen – Another One Bites The Dust



Tempo and Beat Tracking

Tasks

- Onset detection
- Beat tracking
- Tempo estimation



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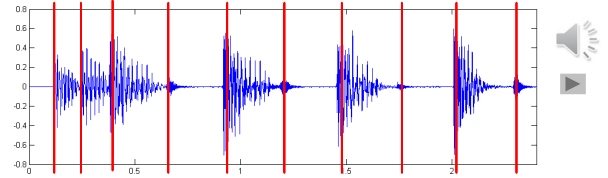
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Tempo and Beat Tracking

Tasks

- Onset detection
- Beat tracking
- Tempo estimation



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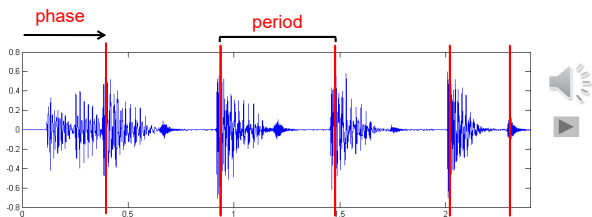
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Tempo and Beat Tracking

Tasks

- Onset detection
- Beat tracking
- Tempo estimation



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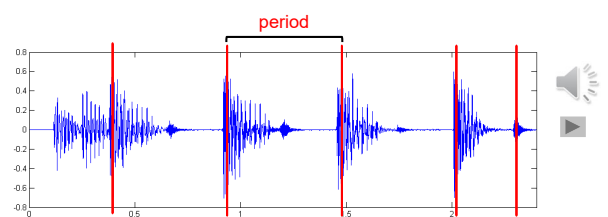
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Tempo and Beat Tracking

Tasks

- Onset detection
 - Beat tracking
 - Tempo estimation
- Tempo := 60 / period
Beats per minute (BPM)



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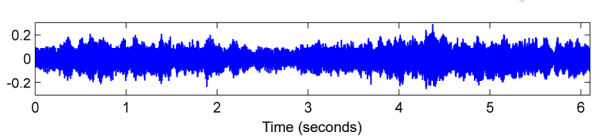
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Onset Detection (Spectral Flux)



Audio recording

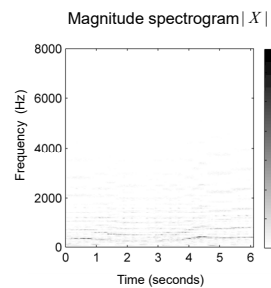


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Onset Detection (Spectral Flux)



Steps:

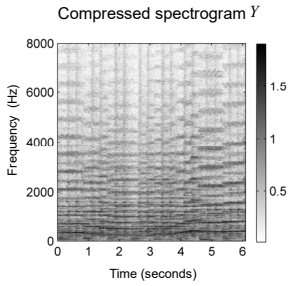
- Spectrogram

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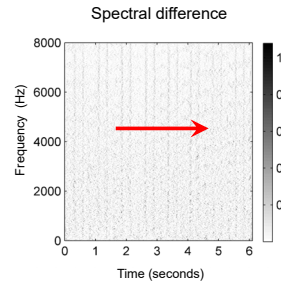


Onset Detection (Spectral Flux)



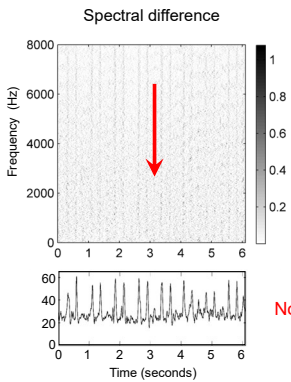
- Steps:**
1. Spectrogram
 2. Logarithmic compression

Onset Detection (Spectral Flux)



- Steps:**
1. Spectrogram
 2. Logarithmic compression
 3. Differentiation & half wave rectification

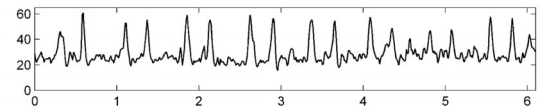
Onset Detection (Spectral Flux)



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

Onset Detection (Spectral Flux)

Novelty function

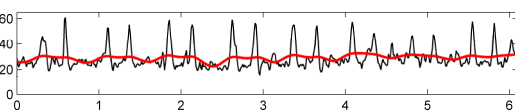


Onset Detection (Spectral Flux)

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

Novelty function

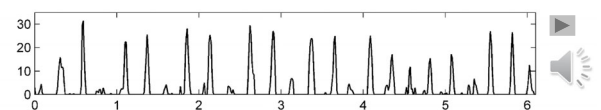
Substraction of local average



Onset Detection (Spectral Flux)

- Steps:**
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 5. Normalization

Normalized novelty function



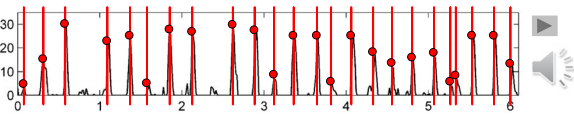
Onset Detection (Spectral Flux)

Steps:

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4. Accumulation
5. Normalization

Normalized novelty function

Peak positions indicate beat candidates



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Onset Detection (Spectral Flux)

Deep Learning

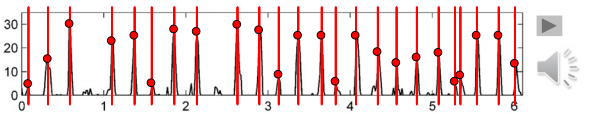
1. Input representation
2. Sigmoid activation
3. Convolution & rectified linear unit (ReLU)
4. Pooling
5. Convolution & ReLU

Steps:

1. Spectrogram
2. Logarithmic compression
3. Differentiation & half wave rectification
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5. Normalization

Normalized novelty function

Peak positions indicate beat candidates



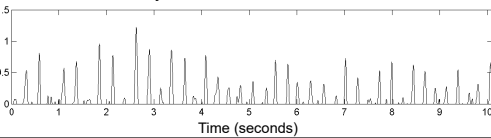
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Local Pulse and Tempo Tracking

Normalized novelty function



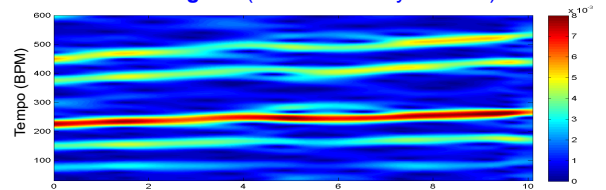
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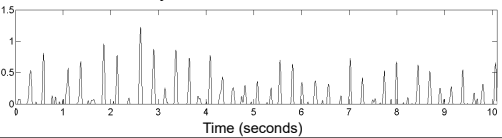
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Local Pulse and Tempo Tracking

Fourier temogram (STFT of novelty function)



Normalized novelty function



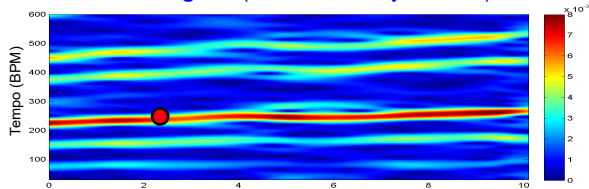
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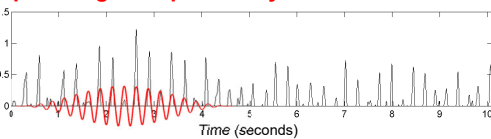
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Local Pulse and Tempo Tracking

Fourier temogram (STFT of novelty function)



Optimizing local periodicity kernel



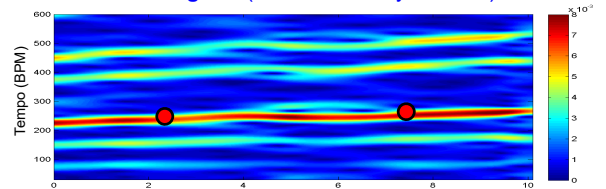
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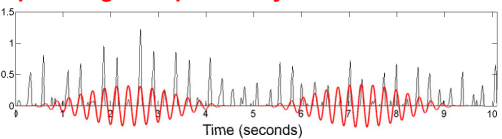
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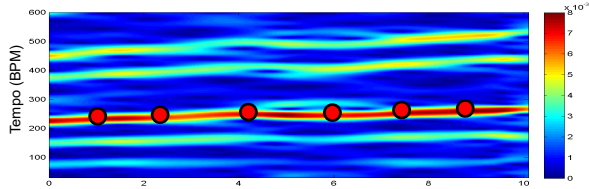
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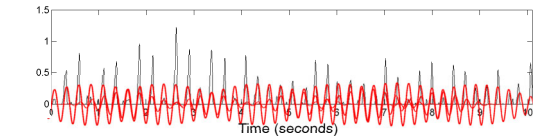
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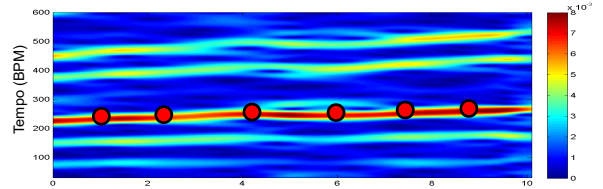
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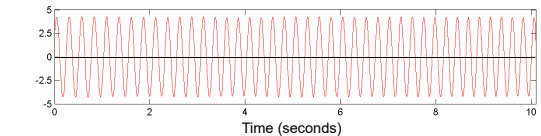


Local Pulse and Tempo Tracking

Fourier temogram (STFT of novelty function)



Accumulation of kernels



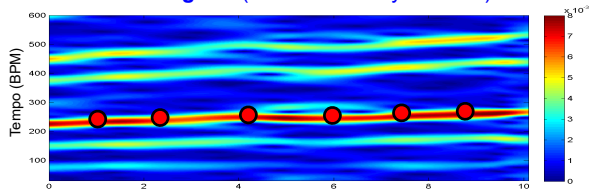
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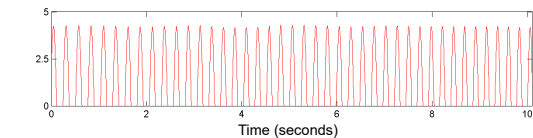


Local Pulse and Tempo Tracking

Fourier temogram (STFT of novelty function)



Halfwave rectification



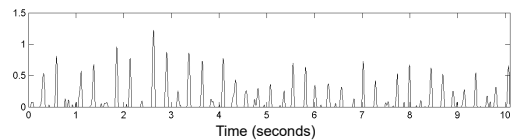
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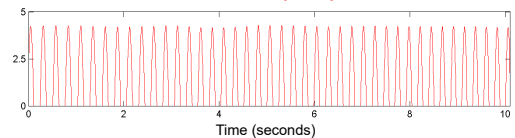


Local Pulse and Tempo Tracking

Novelty Curve



Predominant Local Pulse (PLP)



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FMP Notebooks

Structured in 10 parts

- Part B: Basic introductions to
 - Jupyter notebook framework
 - Python programming
 - Other technical concepts underlying these notebooks
- Part 0: Starting notebook
- Part 1 to Part 8: Different music processing scenarios

| Part | Title | Notions, Techniques & Algorithms | HTML | IPYNB |
|------|--|---|----------------------|-----------------------|
| B | Basics | Basic information on Python, Jupyter notebooks, Anaconda package management system, Python environments, visualizations, and other topics | html | ipynb |
| 0 | Overview | Overview of the notebooks (https://www.audiolabs-erlangen.de/FMP/) | html | ipynb |
| 1 | Music Representations | Music notation, MIDI, audio signal, waveform, pitch, loudness, timbre | html | ipynb |
| 2 | Fourier Analysis of Signals | Discrete-time signal, sinusoid, exponential, Fourier transforms, Fourier representation, DFT, FFT, STFT | html | ipynb |
| 3 | Music Synchronization | Chroma features, dynamic programming, dynamic time warping (DTW), alignment, user interface | html | ipynb |
| 4 | | Similarity matrix, repetition | html | ipynb |
| 5 | | | html | ipynb |
| 6 | Tempo and Beat Tracking | Onset, novelty, tempo, tempogram, beat, periodicity, Fourier analysis, autocorrelation | html | ipynb |
| 7 | Content-Based Audio Retrieval | Identification, fingerprint, indexing, inverted list, matching, version, cover song | html | ipynb |
| 8 | Musically Informed Audio Decomposition | Harmonic/percussive separation, signal reconstruction, instantaneous frequency, fundamental frequency (F0), trajectory, non-negative matrix factorization (NMF) | html | ipynb |

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Part B: Basics

| Topic | Description |
|--|---|
| Get Started | Explanation on how to install and use the FMP notebooks |
| Installation | Installation of Python using Conda |
| Jupyter Notebook | Usage of Jupyter notebook framework |
| Python Basics | Introduction of data types, control structures, and functions |
| Python Style Guide | Recommendations for programming style |
| Multimedia | Integration of multimedia objects into notebooks |
| Python Visualization | Generation of figures and images |
| Python Audio | Reading and writing audio files |
| Numba | Acceleration of Python functions via JIT compilation |
| Annotation Visualization | Visualization of annotations (single value, segments) |
| Sonification | Sonification methods (onsets, F0 trajectories, pitch, chroma) |
| libfmp | Library of FMP-specific Python functions |
| MIR Resources | Links to resources that are useful for MIR |

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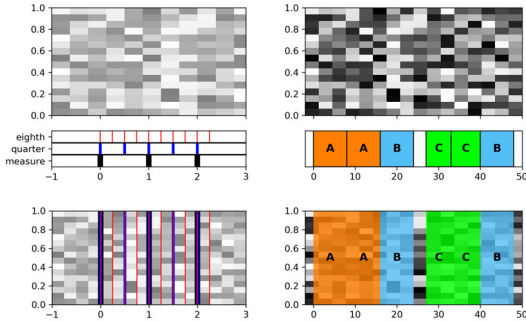
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Part B: Basics

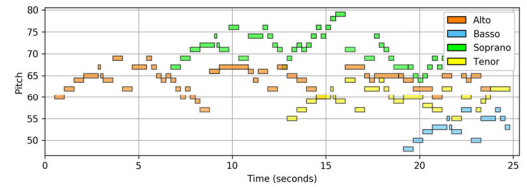
Annotation Visualization

Examples for visualizing annotations of time positions and segments.



Part 1: Music Representations

Symbolic Format: CSV

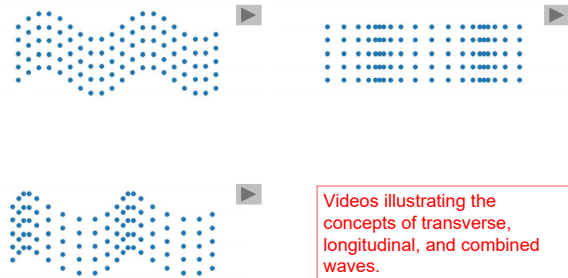


Visualization of a piano-roll representation (Fugue BWV 846 by Bach).



Part 1: Music Representations

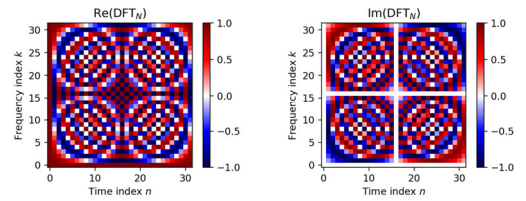
Waves and Waveforms



Videos illustrating the concepts of transverse, longitudinal, and combined waves.

Part 2: Fourier Analysis of Signals

Discrete Fourier Transform (DFT)

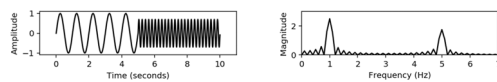


The matrix DFT_N and a visualization of its real and imaginary parts for the case $N = 32$

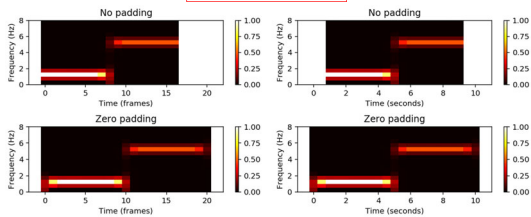
Part 2: Fourier Analysis of Signals

STFT: Padding

Time-domain signal and magnitude Fourier transform.



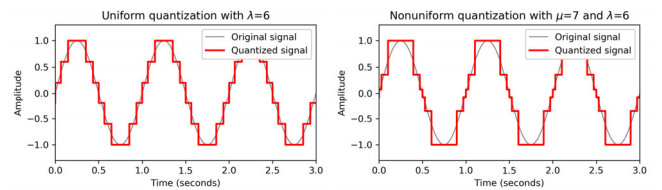
Magnitude STFT.



Part 2: Fourier Analysis of Signals

Digital Signals: Quantization

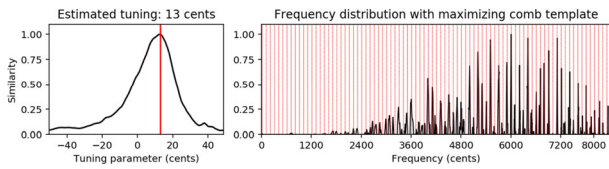
Uniform and nonuniform quantization (based on μ -law encoding) using $\lambda = 6$ quantization levels.



Part 3: Music Synchronization

Transposition and Tuning

Tuning procedure using a comb-filter approach.



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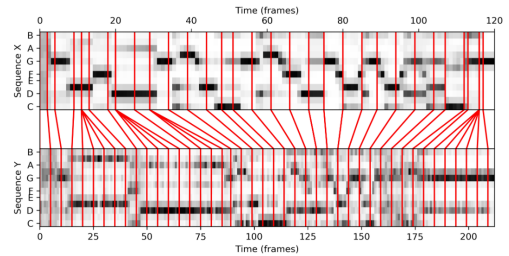
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Part 3: Music Synchronization

Music Synchronization

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



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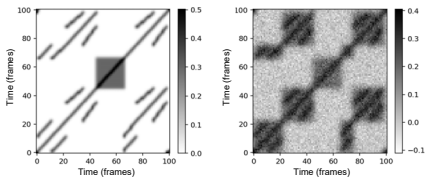
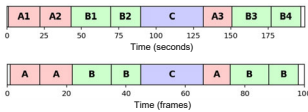


Part 4: Music Structure Analysis

SSM: Synthetic Generation

Structure annotation and different synthetically generated SSMs.

| | start | end | label |
|---|--------|--------|-------|
| 0 | 0.00 | 1.01 | |
| 1 | 1.01 | 22.11 | A1 |
| 2 | 22.11 | 43.06 | A2 |
| 3 | 43.06 | 69.42 | B1 |
| 4 | 69.42 | 89.57 | B2 |
| 5 | 89.57 | 131.64 | C |
| 6 | 131.64 | 150.84 | A3 |
| 7 | 150.84 | 176.96 | B3 |
| 8 | 176.96 | 196.90 | B4 |
| 9 | 196.90 | 199.64 | |



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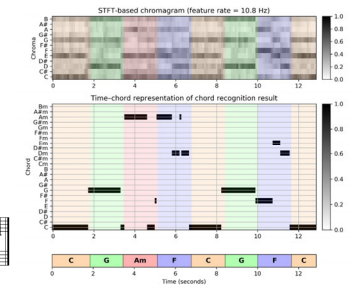
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Part 5: Chord Recognition

Template-Based Chord Recognition

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



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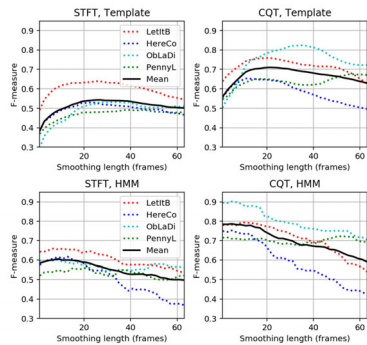


Part 5: Chord Recognition

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).



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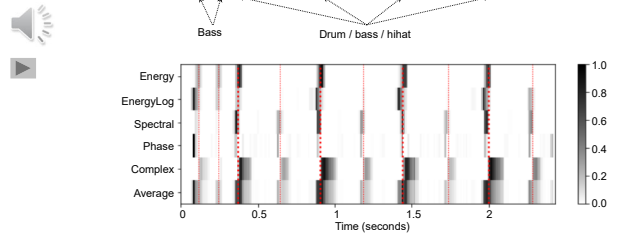
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Part 6: Tempo and Beat Tracking

Novelty: Comparison of Approaches

Comparison of novelty detectors using a matrix-based visualization.



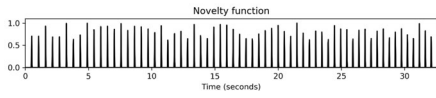
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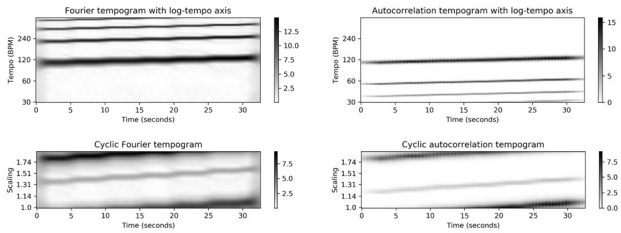


Part 6: Tempo and Beat Tracking

Cyclic Tempogram



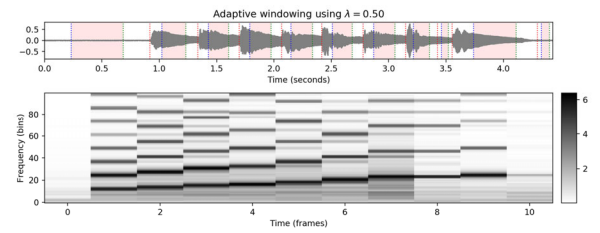
Different tempogram representations of a click track with increasing tempo.



Part 6: Tempo and Beat Tracking

Adaptive Windowing

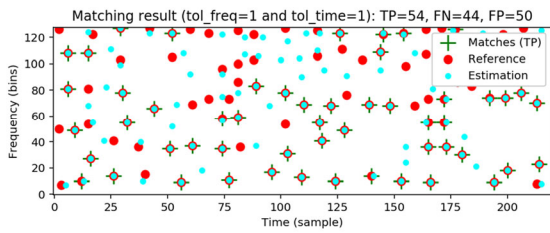
Example of adaptive windowing using a parameter λ to control the neighborhood's relative size to be excluded.



Part 7: Content-Based Audio Retrieval

Audio Identification

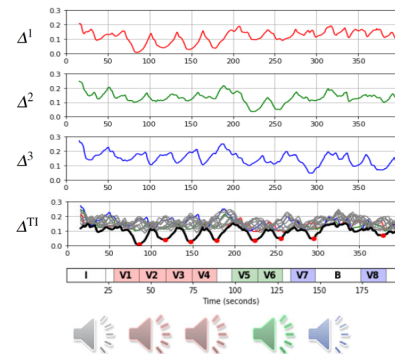
Evaluation measures that indicate the agreement between two constellation maps computed for an original version (Reference) and a noisy version (Estimation).



Part 7: Content-Based Audio Retrieval

Audio Matching

Transposition-invariant matching function illustrated by Zager and Evans' song "In the Year 2525."



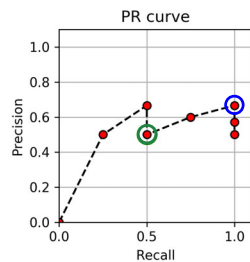
Part 7: Content-Based Audio Retrieval

Evaluation Measures

Various evaluation metrics applied to a toy example.

| Rank | ID | Score | χ_0 | P(r) | R(r) | F(r) |
|------|----|-------|----------|------|------|------|
| 1 | 6 | 3.70 | False | 0.00 | 0.00 | 0.00 |
| 2 | 3 | 3.60 | True | 0.50 | 0.25 | 0.33 |
| 3 | 4 | 3.50 | True | 0.67 | 0.50 | 0.57 |
| 4 | 5 | 3.20 | False | 0.50 | 0.50 | 0.50 |
| 5 | 8 | 3.10 | True | 0.60 | 0.75 | 0.67 |
| 6 | 2 | 2.60 | True | 0.67 | 1.00 | 0.80 |
| 7 | 7 | 1.50 | False | 0.57 | 1.00 | 0.73 |
| 8 | 1 | 0.70 | False | 0.50 | 1.00 | 0.67 |

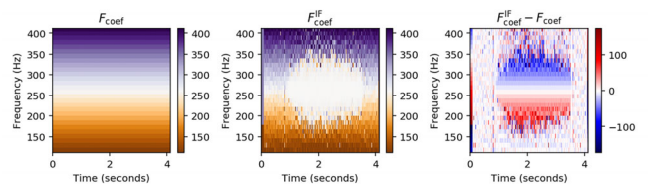
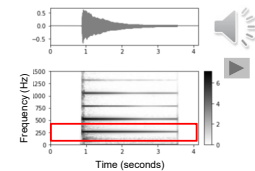
Break-even point = 0.50
 $F_{max} = 0.80$
 Average precision = 0.60833



Part 8: Audio Decomposition

Instantaneous Frequency Estimation

Interpretation of time-frequency bins of an STFT using (frame-dependent) instantaneous frequency values.



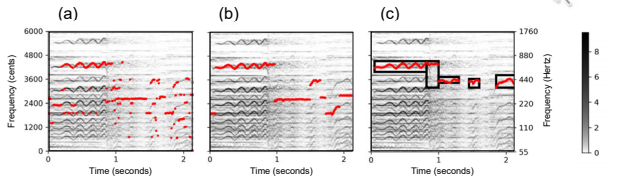
Part 8: Audio Decomposition

Fundamental Frequency Tracking

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



Figure 8.10a from [Müller, FMP, Springer 2015]



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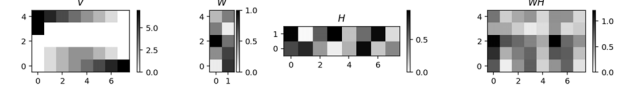


Part 8: Audio Decomposition

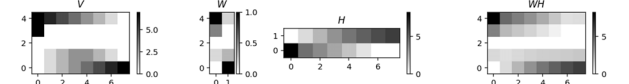
Nonnegative Matrix Factorization (NMF)

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.



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Basics + 8 Chapters

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Basics + 8 Chapters

Tempo and Beat Tracking

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Tempo and Beat Tracking

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Tempo and Beat Tracking

6

Definition

We assume that we are given a discrete-time novelty function $\Delta : \mathbb{Z} \rightarrow \mathbb{I}$ indicate note onset candidates. The idea of Fourier analysis is to detect lo in novelty curve by comparing it with windowed sinusoids. A high correlati section of Δ with a windowed sinusoid indicates a periodicity of the strou (given a suitable phase). This correlation (along with the phase) can be cc short-time Fourier transform. To this end, we fix a window function $w : \mathbb{Z}$ length centered at $n = 0$ (e.g., a sampled Hann window). Then, for a fre parameter $\omega \in \mathbb{R}_{\geq 0}$ and time parameter $n \in \mathbb{Z}$, the complex Fourier coe is defined by

$$\mathcal{F}(n, \omega) := \sum_{m \in \mathbb{Z}} \Delta(m) \bar{w}(m - n) \exp(-2\pi i \omega m).$$

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Tempo and Beat Tracking

6

Example: Shostakovich

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

We start with a [spectral-based novelty function](#) resampled to F_s^{Δ} . Furthermore, we use a window size corresponding to 5 seconds (1

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Tempo and Beat Tracking

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Tempo and Beat Tracking

6

```
In [2]: def compute_sinusoid_optimal(c, tempo, n, Fs, N
      """Compute windowed sinusoid with optimal p
      Notebook: C6/C6S2_TempogramFourier.ipynb

      Args:
      c: Coefficient of tempogram (c=X(k,n))
      tempo: Tempo parameter corresponding to
      _coef_BPM[k]
      n: Frame parameter of c
      Fs: Sampling rate
      N: Window length
      H: Hop size
```

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References

- Meinard Müller: Fundamentals of Music Processing – Using Python and Jupyter Notebooks. 2nd Edition, Springer, 2021. <https://www.springer.com/gp/book/9783030698072>
- Meinard Müller and Frank Zalkow: libfmp: A Python Package for Fundamentals of Music Processing. Journal of Open Source Software (JOSS), 6(63): 1–5, 2021. <https://joss.theoj.org/papers/10.21105/joss.03326>
- Meinard Müller: An Educational Guide Through the FMP Notebooks for Teaching and Learning Fundamentals of Music Processing. Proc. International Society for Music Information Retrieval Conference (ISMIR): 573–580, 2019. <https://www.mdpi.com/2624-6120/2/2/18>
- Meinard Müller and Frank Zalkow: FMP Notebooks: Educational Material for Teaching and Learning Fundamentals of Music Processing. Signals, 2(2): 245–285, 2021. <https://zenodo.org/record/3527872#.YQhEQOqzaUk>
- Meinard Müller, Brian McFee, and Katherine Kinnaird: Interactive Learning of Signal Processing Through Music: Making Fourier Analysis Concrete for Students. IEEE Signal Processing Magazine, 38(3): 73–84, 2021. <https://ieeexplore.ieee.org/document/9418542>

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Resources (Group Meinard Müller)

- FMP Notebooks: <https://www.audiolabs-erlangen.de/FMP>
- libfmp: <https://github.com/meinardmueller/libfmp>
- synctoolbox: <https://github.com/meinardmueller/synctoolbox>
- libtsm: <https://github.com/meinardmueller/libtsm>
- Preparation Course Python (PCP) Notebooks: <https://www.audiolabs-erlangen.de/resources/MIR/PCP/PCP.html>
<https://github.com/meinardmueller/PCP>

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Resources

- librosa: <https://librosa.org/>
- madmom: <https://github.com/CPJKU/madmom>
- Essentia Python tutorial: https://essentia.upf.edu/essentia_python_tutorial.html
- mirdata: <https://github.com/mir-dataset-loaders/mirdata>
- open-unmix: <https://github.com/sigsep/open-unmix-pytorch>
- Open Source Tools & Data for Music Source Separation: <https://source-separation.github.io/tutorial/landing.html>

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