



Tutorial T1
Fundamentals of Music Processing:
An Introduction using Python and Jupyter Notebooks

Tempo and Beat Tracking

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Introduction

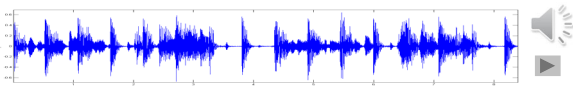
Basic beat tracking task:

Given an audio recording of a piece of music,
determine the periodic sequence of beat positions.

“Tapping the foot when listening to music”

Introduction

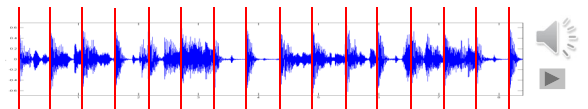
Example: Queen – Another One Bites The Dust



Time (seconds)

Introduction

Example: Queen – Another One Bites The Dust



Time (seconds)



Introduction

Example: Happy Birthday to you

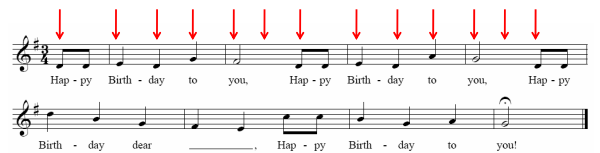
Pulse level: **Measure**



Introduction

Example: Happy Birthday to you

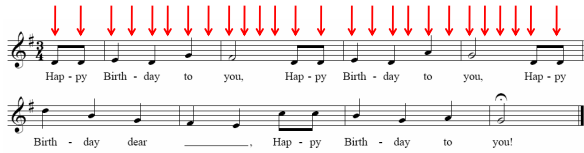
Pulse level: **Tactus (beat)**



Introduction

Example: Happy Birthday to you

Pulse level: **Tatum (temporal atom)**



Birth - day dear _____, Hap - py Birth - day to you!

Introduction

Example: Chopin – Mazurka Op. 68-3

Pulse level: Quarter note

Tempo: ???



Introduction

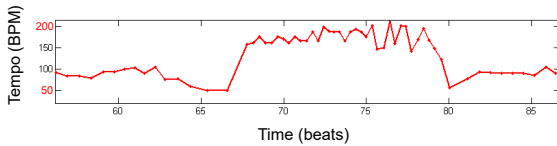
Example: Chopin – Mazurka Op. 68-3

Pulse level: Quarter note

Tempo: **50-200 BPM**



Tempo curve



Introduction

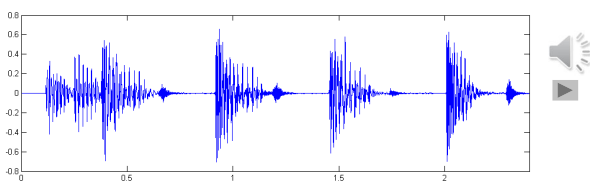
Challenges in beat tracking

- Pulse level often unclear
- Local/sudden tempo changes (e.g. rubato)
- Vague information (e.g., soft onsets, extracted onsets corrupt)
- Sparse information (often only note onsets are used)

Introduction

Tasks

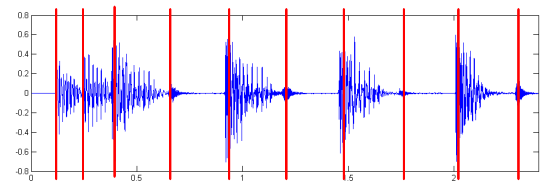
- Onset detection
- Beat tracking
- Tempo estimation



Introduction

Tasks

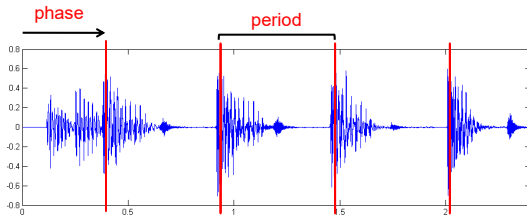
- **Onset detection**
- Beat tracking
- Tempo estimation



Introduction

Tasks

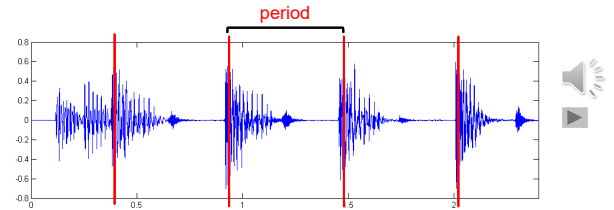
- Onset detection
- **Beat tracking**
- Tempo estimation



Introduction

Tasks

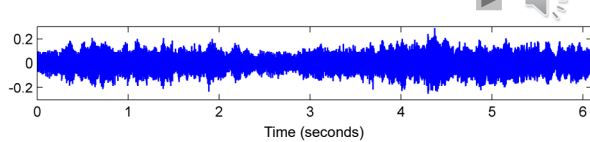
- Onset detection
 - Beat tracking
 - **Tempo estimation**
- Tempo := 60 / period
Beats per minute (BPM)



Onset Detection (Spectral-Based)

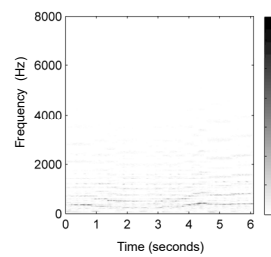


Audio recording



Onset Detection (Spectral-Based)

Magnitude spectrum $|X|$

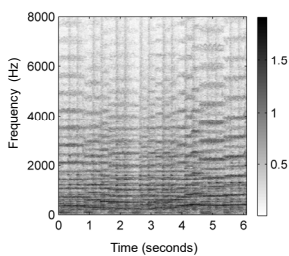


Steps:

1. Spectrogram

Onset Detection (Spectral-Based)

Compressed spectrogram Y



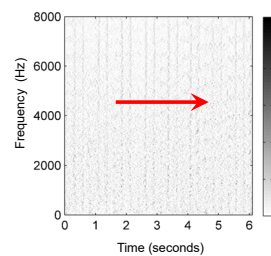
Steps:

1. Spectrogram
2. Logarithmic compression

$$Y = \log(1 + C \cdot |X|)$$

Onset Detection (Spectral-Based)

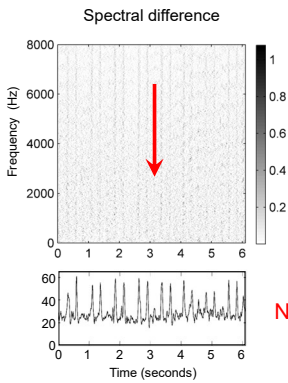
Spectral difference



Steps:

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

Onset Detection (Spectral-Based)



Steps:

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

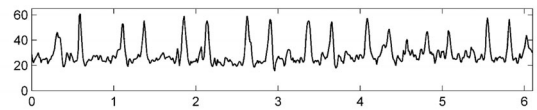
Novelty curve

Onset Detection (Spectral-Based)

Steps:

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

Novelty curve



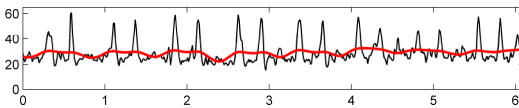
Onset Detection (Spectral-Based)

Steps:

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

Novelty curve

Subtraction of local average

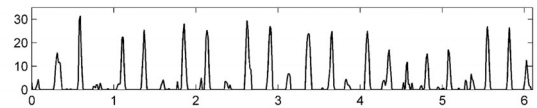


Onset Detection (Spectral-Based)

Steps:

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

Normalized novelty curve



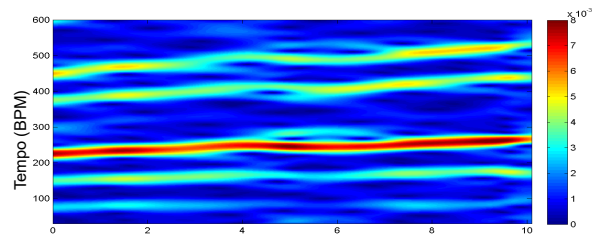
Tempogram (Fourier)

Definition: A **tempogram** is a time-tempo representation that encodes the local tempo of a music signal over time.

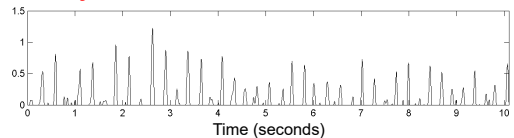
Fourier-based method

- Compute a spectrogram (STFT) of the novelty curve
- Convert frequency axis (given in Hertz) into tempo axis (given in BPM)
- Magnitude spectrogram indicates local tempo

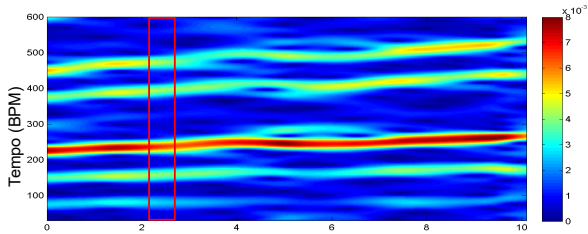
Tempogram (Fourier)



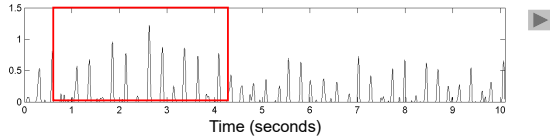
Novelty curve



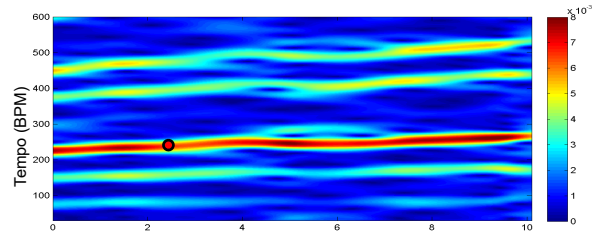
Tempogram (Fourier)



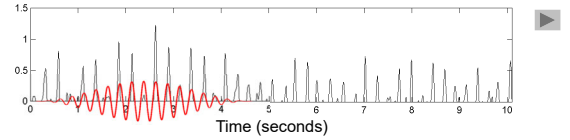
Novelty curve (local section)



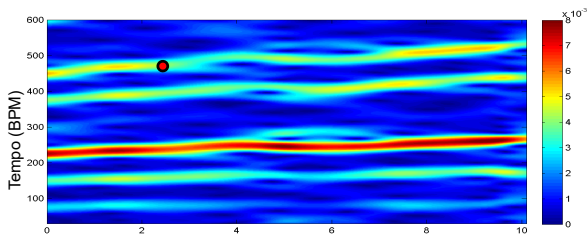
Tempogram (Fourier)



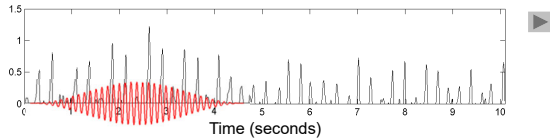
Windowed sinusoidal



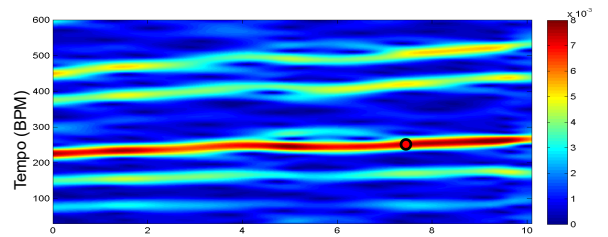
Tempogram (Fourier)



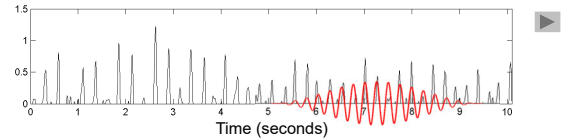
Windowed sinusoidal



Tempogram (Fourier)



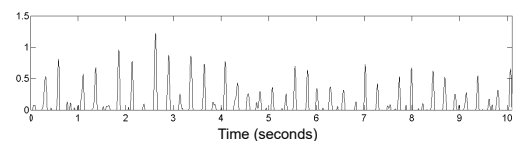
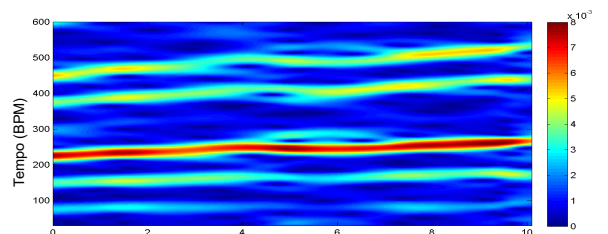
Windowed sinusoidal



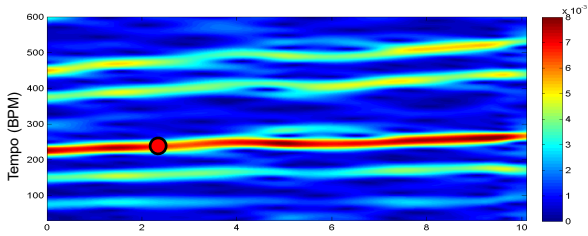
Beat Tracking

- Given the tempo, find the best sequence of beats
- Complex Fourier tempogram contains **magnitude** and **phase** information
- The **magnitude** encodes how well the novelty curve resonates with a sinusoidal kernel of a specific tempo
- The **phase** optimally aligns the sinusoidal kernel with the peaks of the novelty curve

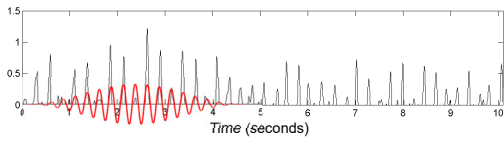
Local Pulse Tracking



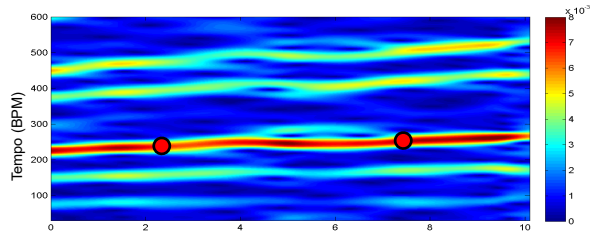
Local Pulse Tracking



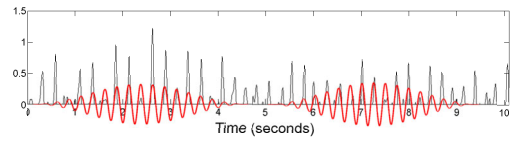
Optimizing local periodicity kernel



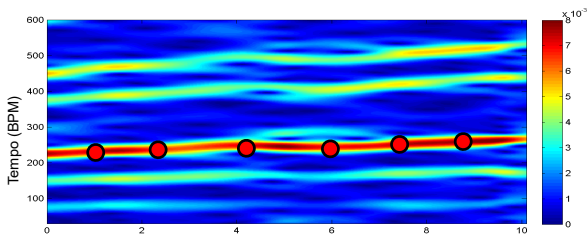
Local Pulse Tracking



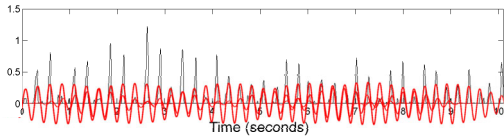
Optimizing local periodicity kernel



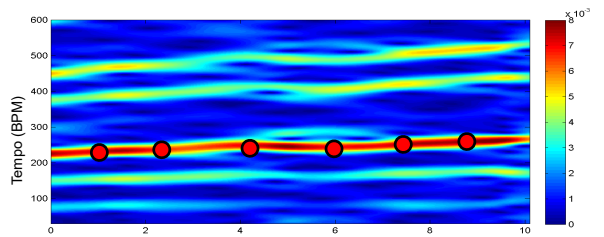
Local Pulse Tracking



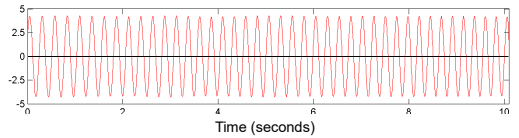
Optimizing local periodicity kernel



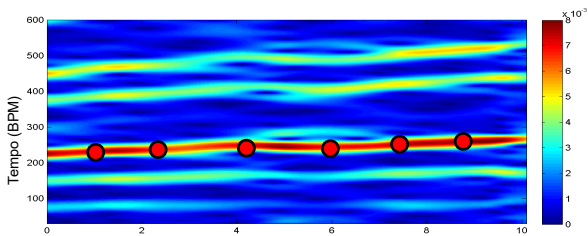
Local Pulse Tracking



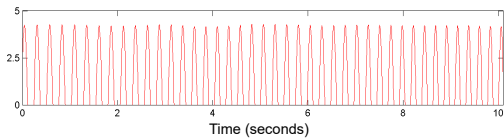
Accumulation of kernels



Local Pulse Tracking

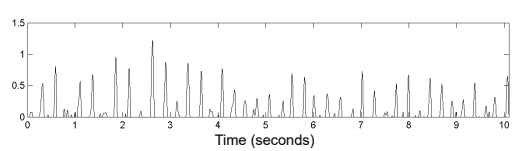


Halfwave rectification

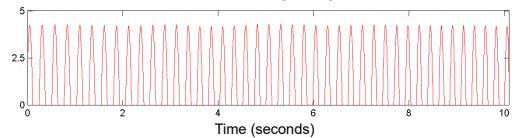


Local Pulse Tracking

Novelty Curve



Predominant Local Pulse (PLP)



Local Pulse Tracking

Novelty Curve

- Indicates note onset candidates
- Extraction errors in particular for soft onsets
- Simple peak-picking problematic



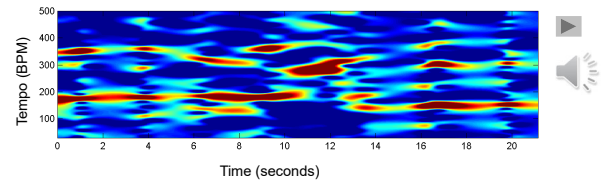
Predominant Local Pulse (PLP)

- Periodicity enhancement of novelty curve
- Accumulation introduces error robustness
- Locality of kernels handles tempo variations



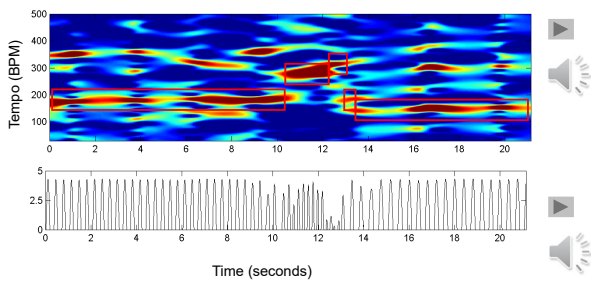
Local Pulse Tracking

Brahms Hungarian Dance No. 5



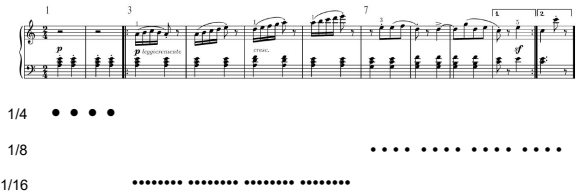
Local Pulse Tracking

Brahms Hungarian Dance No. 5



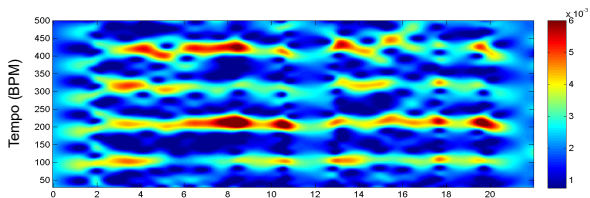
Pulse Levels

Piano Etude Op. 100 No. 2 by Burgmüller

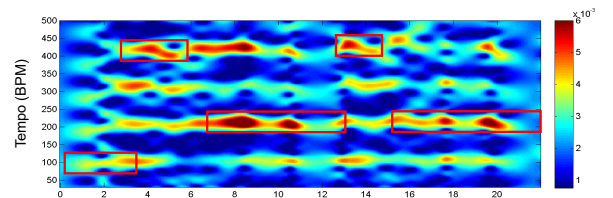


What is the pulse level: Measure – Tactus – Tatum?

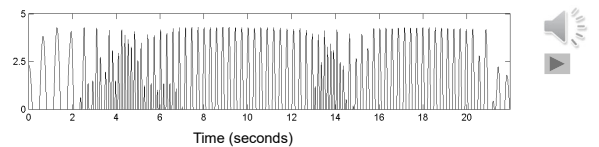
Pulse Levels



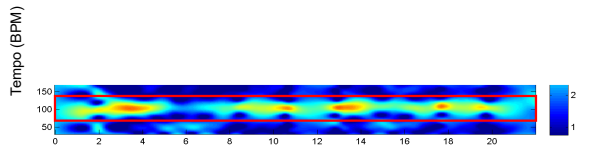
Pulse Levels



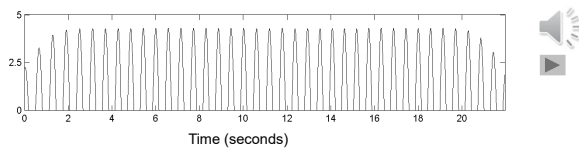
Switching of predominant pulse level



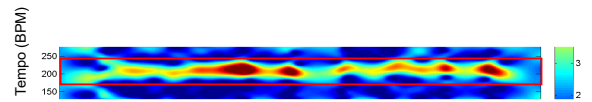
Pulse Levels



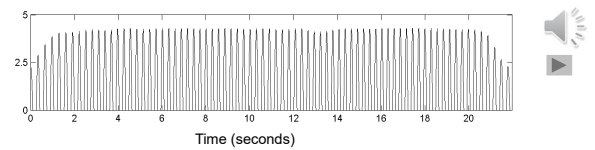
1/4 note pulse level



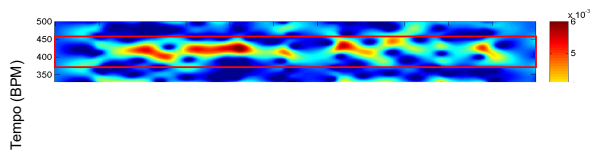
Pulse Levels



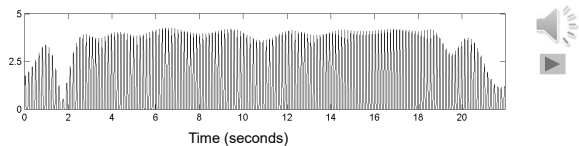
1/8 note pulse level



Pulse Levels



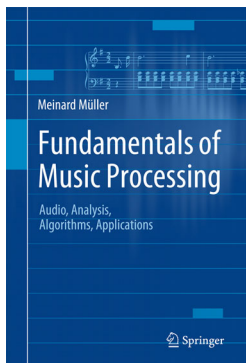
1/16 note pulse level



Summary

1. Onset Detection
 - Novelty curve (*something is changing*)
 - Indicates note onset candidates
 - Hard task for non-percussive instruments (strings)
2. Tempo Estimation
 - Fourier tempogram
 - Musical knowledge (tempo range, continuity)
3. Beat tracking
 - Find most likely beat positions
 - Exploiting phase information from Fourier tempogram

Book: Fundamentals of Music Processing



Meinard Müller
 Fundamentals of Music Processing
 Audio, Analysis, Algorithms, Applications
 483 p., 249 illus., hardcover
 ISBN: 978-3-319-21944-8
 Springer, 2015

Accompanying website:
www.music-processing.de

Book: Fundamentals of Music Processing

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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