INTERNATIONAL AUDIO LABORATORIES ERLANGEN

AUDIO LABS

Tutorial
Automatisierte Methoden der Musikverarbeitung
47. Jahrestagung der Gesellschaft für Informatik

Tempo and Beat Tracking

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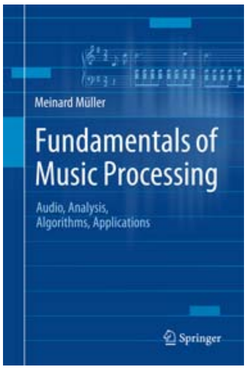
FAU Friedrich-Alexander Universität Erlangen-Nürnberg

Fraunhofer IIS

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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Chapter 6: Tempo and Beat Tracking

Tempo and beat are further fundamental properties of music. In Chapter 6, we introduce the basic ideas on how to extract tempo-related information from audio recordings. In this scenario, a first challenge is to locate note onset information—a task that requires methods for detecting changes in energy and spectral content. To derive tempo and beat information, note onset candidates are then analyzed with regard to quasiperiodic patterns. This leads us to the study of general methods for local periodicity analysis of time series.

Introduction

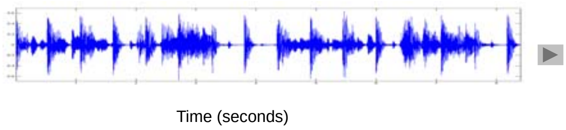
Basic beat tracking task:

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

“Tapping the foot when listening to music”

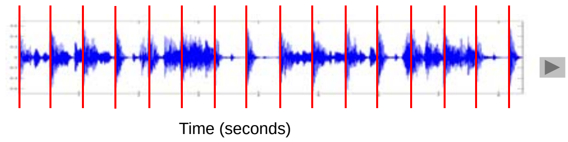
Introduction

Example: Queen – Another One Bites The Dust



Introduction

Example: Queen – Another One Bites The Dust



Introduction

Example: Happy Birthday to you

Pulse level: **Measure**

Introduction

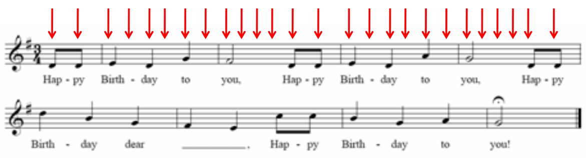
Example: Happy Birthday to you

Pulse level: **Tactus (beat)**

Introduction

Example: Happy Birthday to you

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



Introduction

Example: Chopin – Mazurka Op. 68-3

Pulse level: Quarter note

Tempo: ???

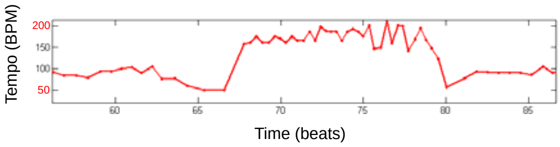
Introduction

Example: Chopin – Mazurka Op. 68-3

Pulse level: Quarter note

Tempo: 50-200 BPM

Tempo curve



Introduction

Example: Borodin – String Quartet No. 2

Pulse level: Quarter note

Tempo: 120-140 BPM (roughly)

Beat tracker without any prior knowledge

Beat tracker with prior knowledge on rough tempo range

Introduction

Challenges in beat tracking

- Pulse level often unclear
- Local/sudden tempo changes (e.g. rubato)
- Vague information

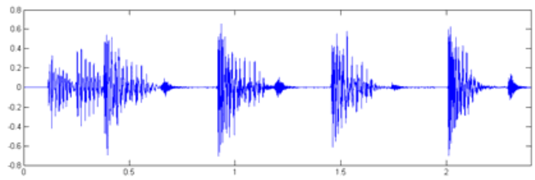
  (e.g., soft onsets, extracted onsets corrupt)
- Sparse information

  (often only note onsets are used)

Introduction

Tasks

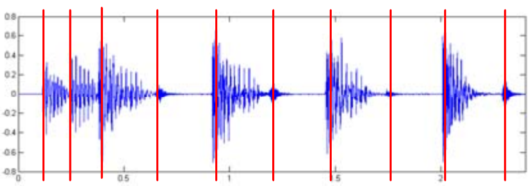
- Onset detection
- Beat tracking
- Tempo estimation



Introduction

Tasks

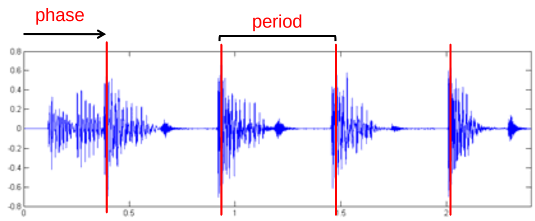
- Onset detection
- Beat tracking
- Tempo estimation



Introduction

Tasks

- Onset detection
- Beat tracking
- Tempo estimation



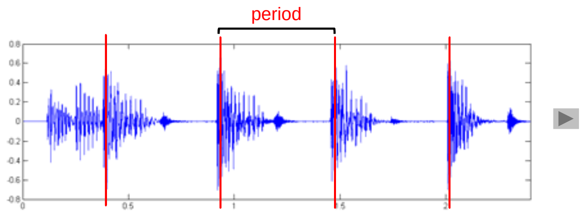
Introduction

Tasks

- Onset detection
- Beat tracking
- Tempo estimation

Tempo := 60 / period

Beats per minute (BPM)



Onset Detection

- Finding start times of perceptually relevant acoustic events in music signal
- Onset is the time position where a note is played
- Onset typically goes along with a change of the signal's properties:
  - energy or loudness
  - pitch or harmony
  - timbre

Onset Detection

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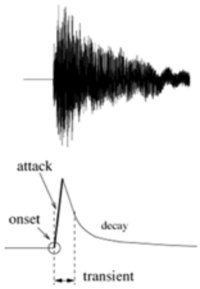
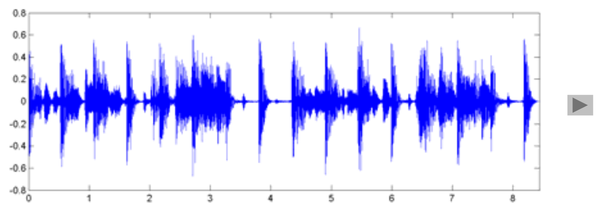


[Bello et al., IEEE-TASLP 2005]

Onset Detection (Energy-Based)

Steps

Waveform



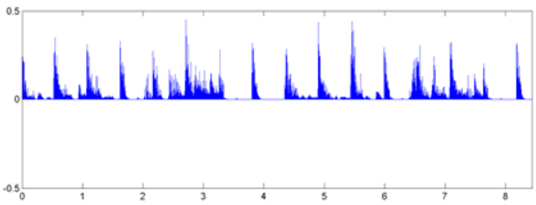
Time (seconds)

Onset Detection (Energy-Based)

Steps

1. Amplitude squaring

Squared waveform



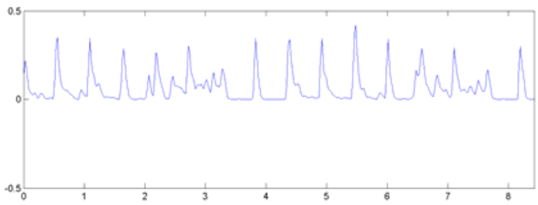
Time (seconds)

Onset Detection (Energy-Based)

Steps

1. Amplitude squaring
2. Windowing

Energy envelope



Time (seconds)

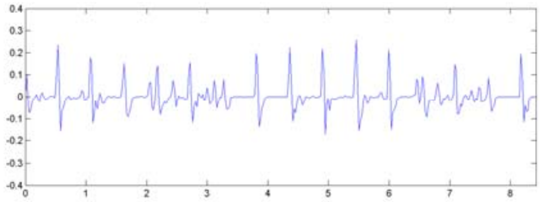
Onset Detection (Energy-Based)

Steps

1. Amplitude squaring
2. Windowing
3. Differentiation

Capturing energy changes

Differentiated energy envelope



Time (seconds)

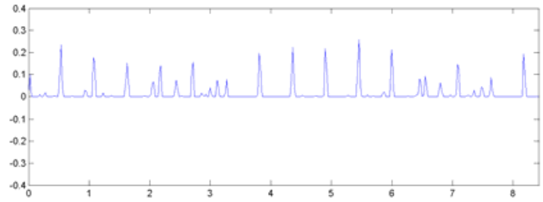
Onset Detection (Energy-Based)

Steps

1. Amplitude squaring
2. Windowing
3. Differentiation
4. Half wave rectification

Only energy increases are relevant for note onsets

Novelty curve



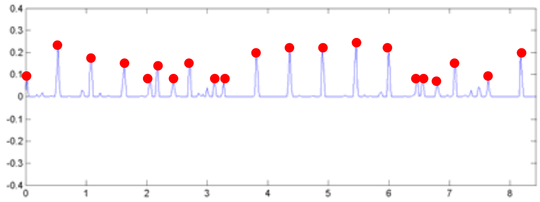
Time (seconds)

Onset Detection (Energy-Based)

Steps

1. Amplitude squaring
2. Windowing
3. Differentiation
4. Half wave rectification
5. Peak picking

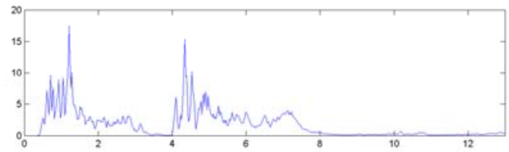
Peak positions indicate note onset candidates



Time (seconds)

Onset Detection (Energy-Based)

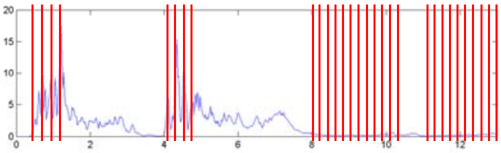
Energy envelope



Time (seconds)

Onset Detection (Energy-Based)

Energy envelope / note onsets positions

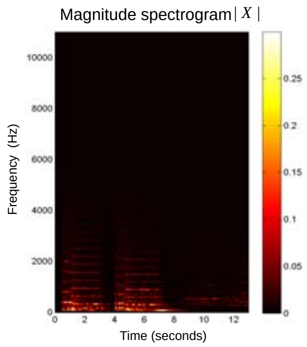


Time (seconds)

Onset Detection

- Energy curves often only work for percussive music
- Many instruments such as strings have weak note onsets
- No energy increase may be observable in complex sound mixtures
- More refined methods needed that capture
  - changes of spectral content
  - changes of pitch
  - changes of harmony

Onset Detection (Spectral-Based)

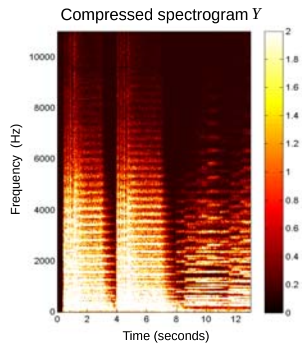


Steps:

1. Spectrogram

- *Aspects concerning pitch, harmony, or timbre are captured by spectrogram*
- *Allows for detecting local energy changes in certain frequency ranges*

Onset Detection (Spectral-Based)



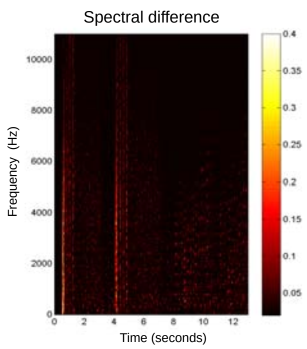
Steps:

1. Spectrogram
2. Logarithmic compression

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

- *Accounts for the logarithmic sensation of sound intensity*
- *Dynamic range compression*
- *Enhancement of low-intensity values*
- *Often leading to enhancement of high-frequency spectrum*

Onset Detection (Spectral-Based)

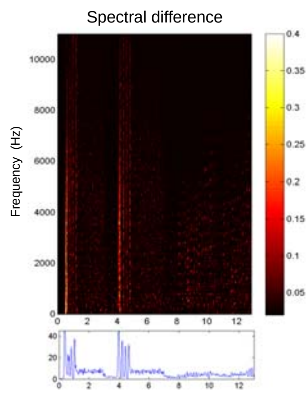


Steps:

1. Spectrogram
2. Logarithmic compression
3. Differentiation

- *First-order temporal difference*
- *Captures changes of the spectral content*
- *Only positive intensity changes considered*

Onset Detection (Spectral-Based)



Steps:

1. Spectrogram
2. Logarithmic compression
3. Differentiation
4. Accumulation

- *Frame-wise accumulation of all positive intensity changes*
- *Encodes changes of the spectral content*

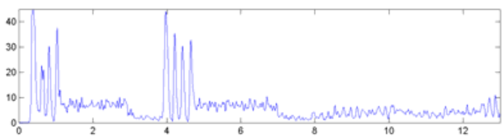
Novelty curve

Onset Detection (Spectral-Based)

Steps:

1. Spectrogram
2. Logarithmic compression
3. Differentiation
4. Accumulation

Novelty curve



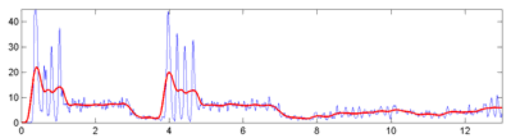
Onset Detection (Spectral-Based)

Steps:

1. Spectrogram
2. Logarithmic compression
3. Differentiation
4. Accumulation
5. Normalization

Novelty curve

Substraction of local average

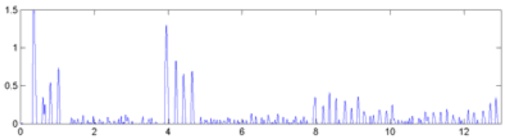


Onset Detection (Spectral-Based)

Steps:

1. Spectrogram
2. Logarithmic compression
3. Differentiation
4. Accumulation
5. Normalization

Normalized novelty curve

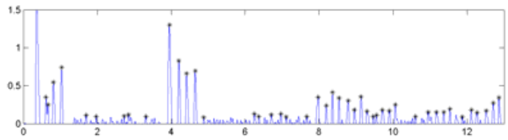


Onset Detection (Spectral-Based)

Steps:

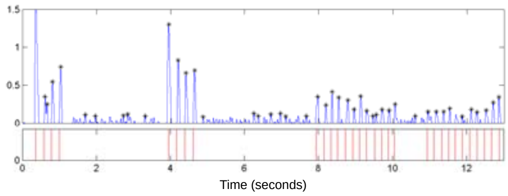
1. Spectrogram
2. Logarithmic compression
3. Differentiation
4. Accumulation
5. Normalization
6. Peak picking

Normalized novelty curve



Onset Detection

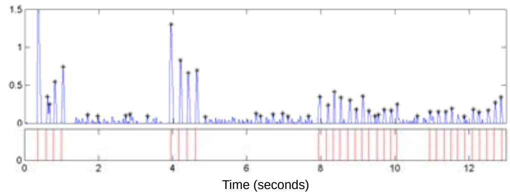
Peak picking



- Peaks of the novelty curve indicate note onset candidates

Onset Detection

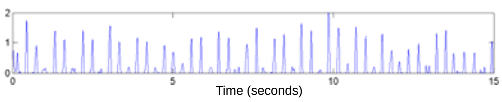
Peak picking



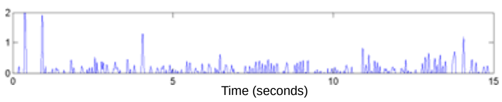
- Peaks of the novelty curve indicate note onset candidates
- In general many spurious peaks
- Usage of local thresholding techniques
- Peak-picking very fragile step in particular for soft onsets

Onset Detection

Shostakovich – 2nd Waltz



Borodin – String Quartet No. 2



Onset Detection

Drumbeat

Going Home

Lyphard melodie

Por una cabeza

Donau

Tempo Estimation and Beat Tracking

What is a beat?

- Steady pulse that drives music forward and provides the temporal framework of a piece of music
- Sequence of perceived pulses that are equally spaced in time
- The pulse a human taps along when listening to the music

[Parncutt 1994]
[Sethares 2007]
[Large/Palmer 2002]
[Lerdahl/ Jackendoff 1983]
[Fitch/ Rosenfeld 2007]

The term tempo then refers to the speed of the pulse.

Tempo Estimation and Beat Tracking

Strategy

- Analyze the novelty curve with respect to reoccurring or quasi-periodic patterns
- Avoid the explicit determination of note onsets (no peak picking)

Tempo Estimation and Beat Tracking

Strategy

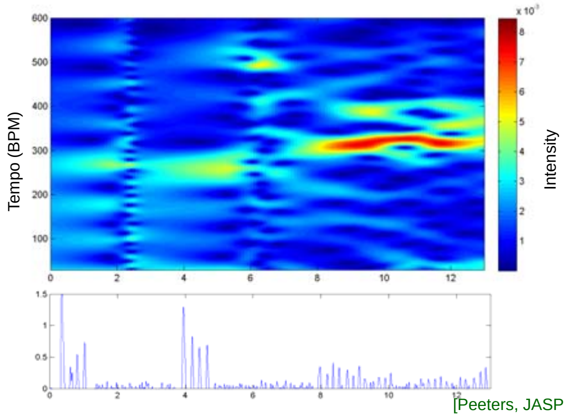
- Analyze the novelty curve with respect to reoccurring or quasi-periodic patterns
- Avoid the explicit determination of note onsets (no peak picking)

Methods

- Comb-filter methods
- Autocorrelation
- Fourier transfrom

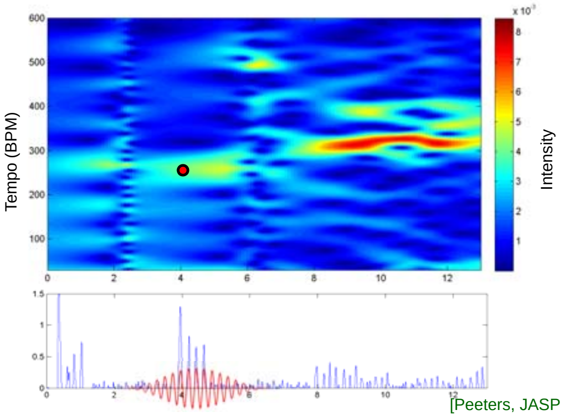
[Scheirer, JASA 1998]
[Ellis, JNMR 2007]
[Davies/Plumbley, IEEE-TASLP 2007]
[Peeters, JASP 2007]
[Grosche/Müller, ISMIR 2009]
[Grosche/Müller, IEEE-TASLP 2011]

Tempo Estimation and Beat Tracking



[Peeters, JASP 2007]

Tempo Estimation and Beat Tracking



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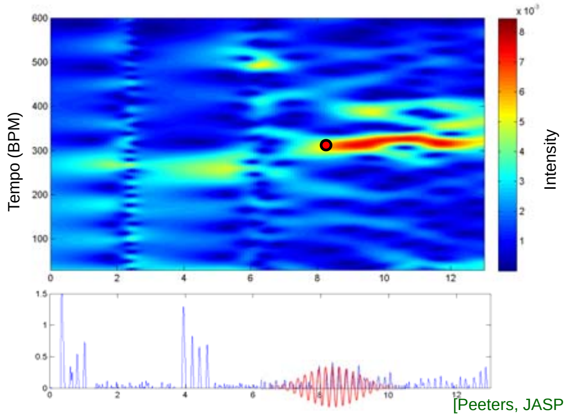
Tempo Estimation and Beat Tracking



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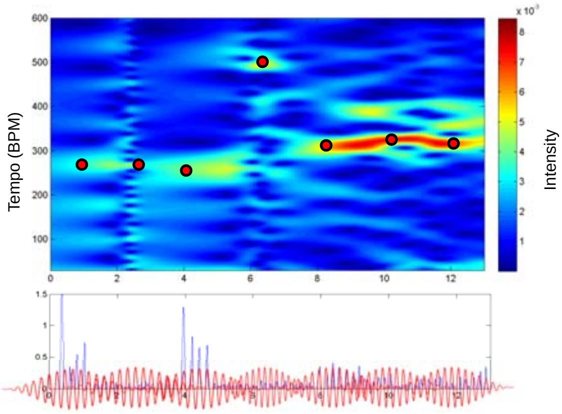
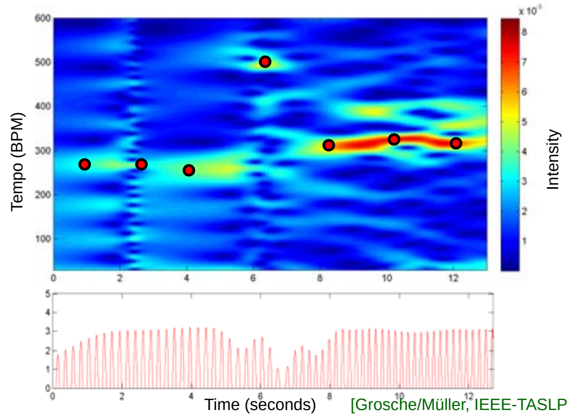
Tempo Estimation and Beat Tracking



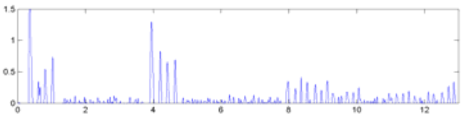
Tempo Estimation and Beat Tracking



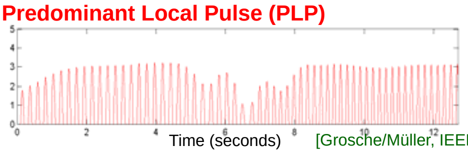
[Grosche/Müller, IEEE-TASLP 2011]

Tempo Estimation and Beat Tracking

Novelty Curve



Predominant Local Pulse (PLP)



[Grosche/Müller, IEEE-TASLP 2011]

Tempo Estimation and Beat 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

[Grosche/Müller, IEEE-TASLP 2011]

Tempo Estimation and Beat Tracking

- Local tempo at time t : $\tau_t \in \Theta$ $\quad \Theta = $ [60:240] BPM
- Phase $\varphi_t := \frac{1}{2\pi} \arccos\left(\frac{\mathrm{Re}(\mathcal{T}(t,\tau_t))}{|\mathcal{T}(t,\tau_t)|}\right)$
- Sinusoidal kernel $\kappa_t : \mathbb{Z} \to \mathbb{R}$

$$\kappa_t(n) := W(n-t)\cos(2\pi(\tau_t/60 \cdot n - \varphi_t)) \qquad n \in \mathbb{Z}$$

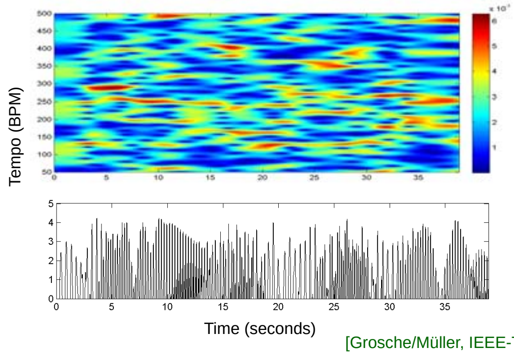
- Periodicity curve $\Gamma : [1:T] \to \mathbb{R}_{\geq 0}$

$$\Gamma(n) = \left| \sum_{t \in [1:T]} \kappa_t(n) \right|_{\geq 0} \qquad n \in [1:T]$$

[Grosche/Müller, IEEE-TASLP 2011]

Tempo Estimation and Beat Tracking

Borodin – String Quartet No. 2

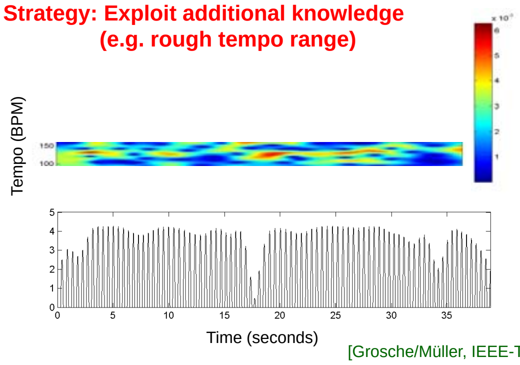


[Grosche/Müller, IEEE-TASLP 2011]

Tempo Estimation and Beat Tracking

Borodin – String Quartet No. 2

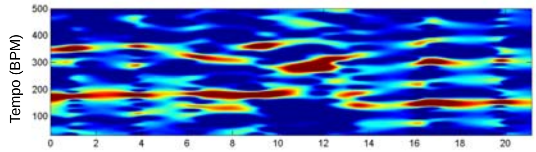
Strategy: Exploit additional knowledge (e.g. rough tempo range)



[Grosche/Müller, IEEE-TASLP 2011]

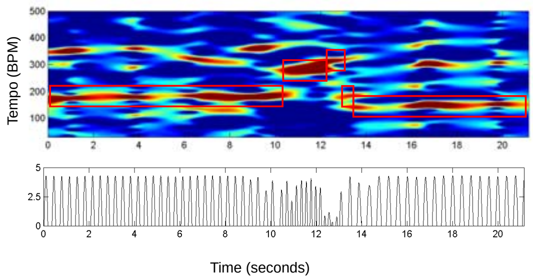
Tempo Estimation and Beat Tracking

Brahms Hungarian Dance No. 5



Tempo Estimation and Beat Tracking

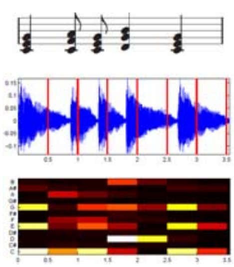
Brahms Hungarian Dance No. 5



Applications

- Feature design
  (beat-synchronous features, adaptive windowing)
- Digital DJ / audio editing
  (mixing and blending of audio material)
- Music classification
- Music recommendation
- Performance analysis
  (extraction of tempo curves)

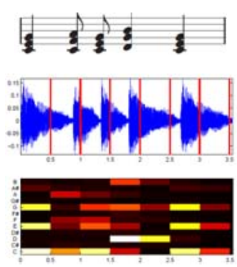
Application: Feature Design



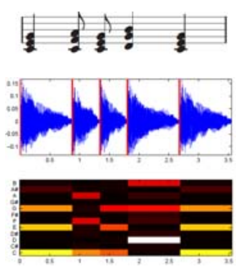
Fixed window size

[Ellis et al., ICASSP 2008] [Bello/Pickens, ISMIR 2005]

Application: Feature Design



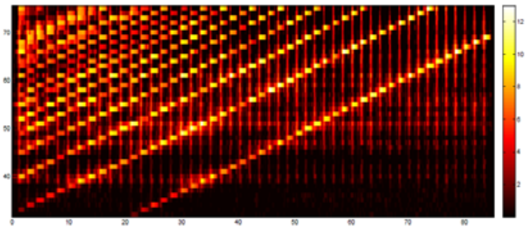
Fixed window size



Adaptive window size

[Ellis et al., ICASSP 2008] [Bello/Pickens, ISMIR 2005]

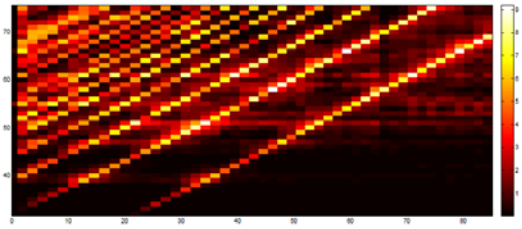
Application: Feature Design



Time
(seconds)

Fixed window size (100 ms)

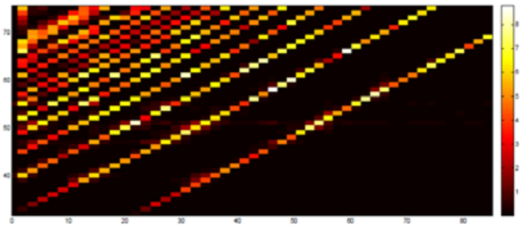
Application: Feature Design



Time
(seconds)

Adative window size (roughly 1200 ms)
Note onset positions define boundaries

Application: Feature Design



Time
(seconds)

Adative window size (roughly 1200 ms)
Note onset positions define boundaries

Denoising by excluding boundary neighborhoods

Application: Audio Editing (Digital DJ)

http://www.mixxx.org/

Application: Beat-Synchronous Light Effects