Lecture

Music Processing

Beethoven, Bach, and Billions of Bytes

New Alliances between Music and Computer Science

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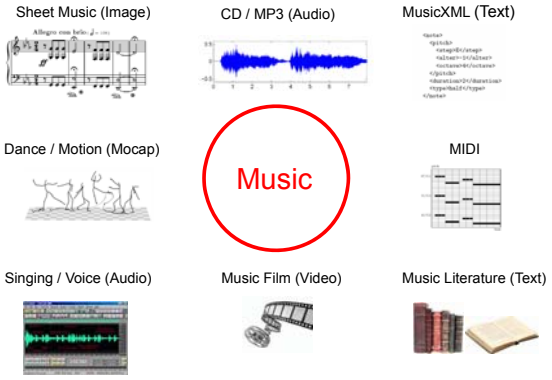
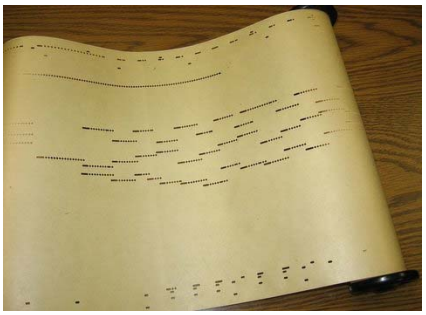
Music Representations



Research Goals

- Music Information Retrieval (MIR) → ISMIR
- Analysis of music signals
  (harmonic, melodic, rhythmic, motivic aspects)
- Design of musically relevant audio features
- Tools for multimodal search and interaction

Piano Roll Representation

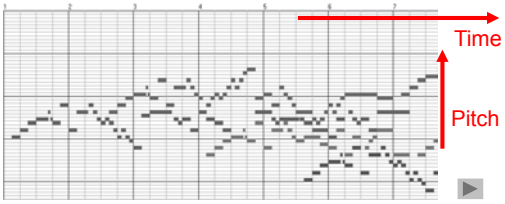


Player Piano (1900)

Piano Roll Representation (MIDI)

J.S. Bach, C-Major Fuge

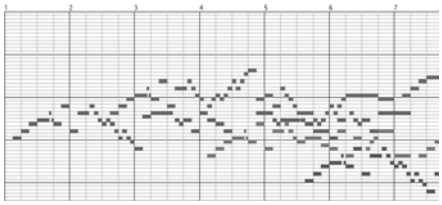
(Well Tempered Piano, BWV 846)



Piano Roll Representation (MIDI)

Query: 

Goal: Find all occurrences of the query

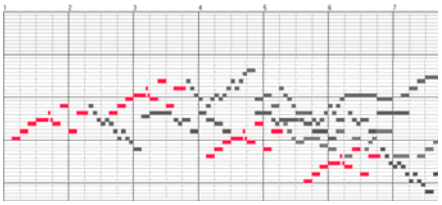


Piano Roll Representation (MIDI)

Query: 

Goal: Find all occurrences of the query

Matches:



Audio Data

Various interpretations – Beethoven's Fifth

Bernstein
Karajan
Scherbakov (piano)
MIDI (piano)

Memory Requirements

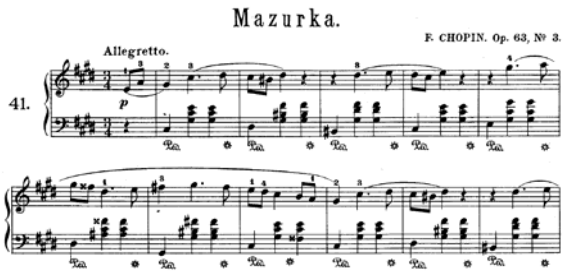
1 Bit	=	1: on 0: off
1 Byte	=	8 Bits
1 Kilobyte (KB)	=	1 Thousand Bytes
1 Megabyte (MB)	=	1 Million Bytes
1 Gigabyte (GB)	=	1 **Billion Bytes**
1 Terabyte (TB)	=	1000 Billion Bytes

Memory Requirements

12.000 MIDI files	<	350 MB
One audio CD	≈	650 MB
Two audio CDs	>	1 **Billion Bytes**
1000 audio CDs	≈	**Billions of Bytes**

Why is Music Processing Challenging?

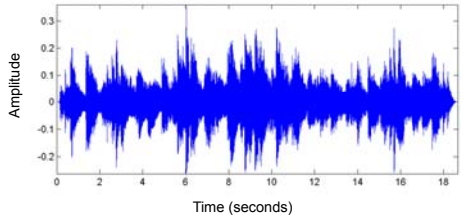
Example: Chopin, Mazurka Op. 63 No. 3



Why is Music Processing Challenging?

Example: Chopin, Mazurka Op. 63 No. 3

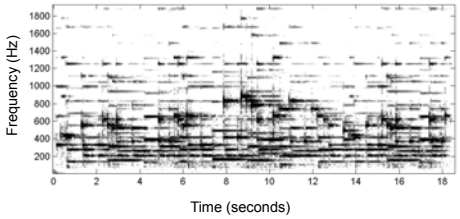
- Waveform



Why is Music Processing Challenging?

Example: Chopin, Mazurka Op. 63 No. 3

- Waveform / Spectrogram



Why is Music Processing Challenging?

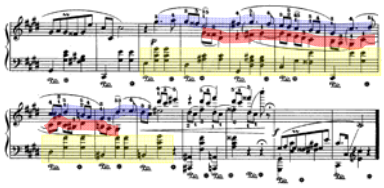
Example: Chopin, Mazurka Op. 63 No. 3

- Waveform / Spectrogram
- Performance
  - Tempo
  - Dynamics
  - Note deviations
  - Sustain pedal

Why is Music Processing Challenging?

Example: Chopin, Mazurka Op. 63 No. 3

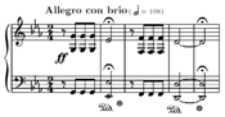
- Waveform / Spectrogram
- Performance
  - Tempo
  - Dynamics
  - Note deviations
  - Sustain pedal
- Polyphony



Main Melody
Additional melody line
Accompaniment

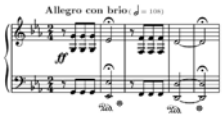
Music Synchronization: Audio-Audio

Beethoven's Fifth

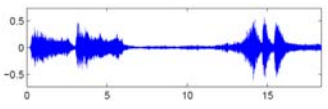


Music Synchronization: Audio-Audio

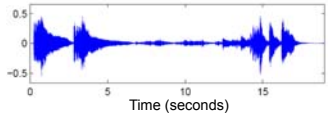
Beethoven's Fifth



Orchester (Karajan)



Piano (Scherbakov)



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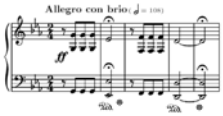

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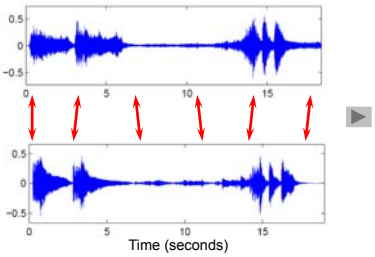


Application: Interpretation Switcher

Music Synchronization: Audio-Audio

Two main steps:

1.) Audio features

- Robust but discriminative
- Chroma features
- Robust to variations in instrumentation, timbre, dynamics
- Correlate to harmonic progression

2.) Alignment procedure

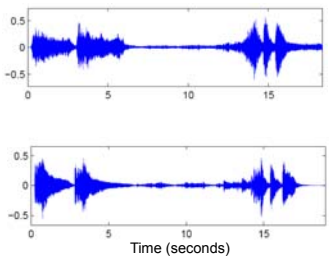
- Deals with local and global tempo variations
- Needs to be efficient

Music Synchronization: Audio-Audio

Beethoven's Fifth

Orchester (Karajan)

Piano (Scherbakov)



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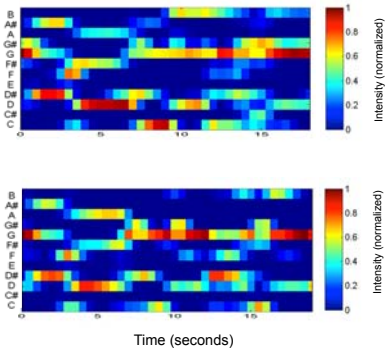

Music Synchronization: Audio-Audio

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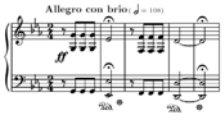
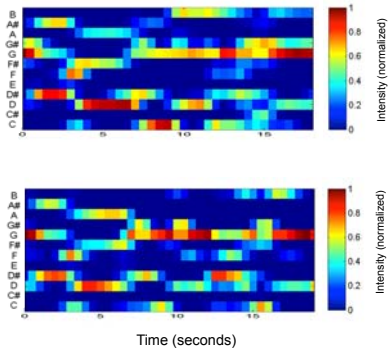


Piano (Scherbakov)



Music Synchronization: Audio-Audio

Beethoven's Fifth

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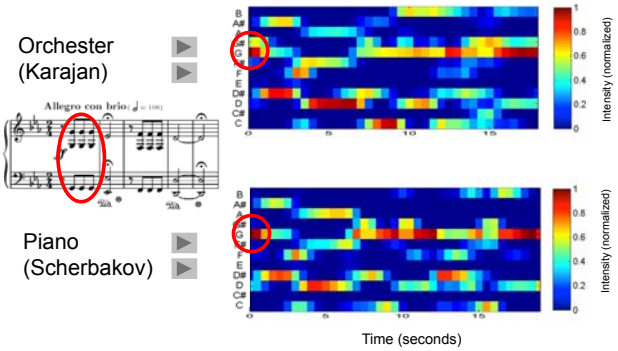

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Music Synchronization: Audio-Audio

Beethoven's Fifth

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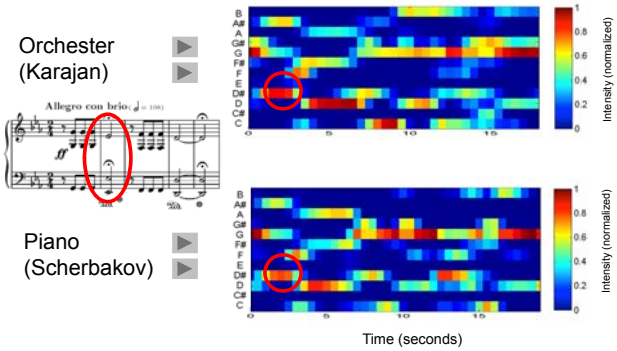

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Music Synchronization: Audio-Audio

Beethoven's Fifth

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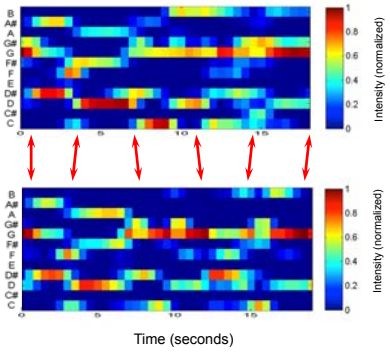
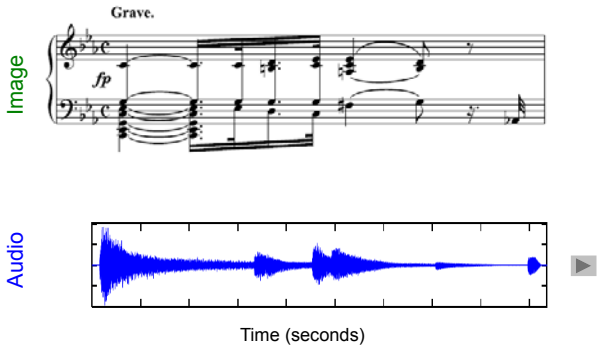
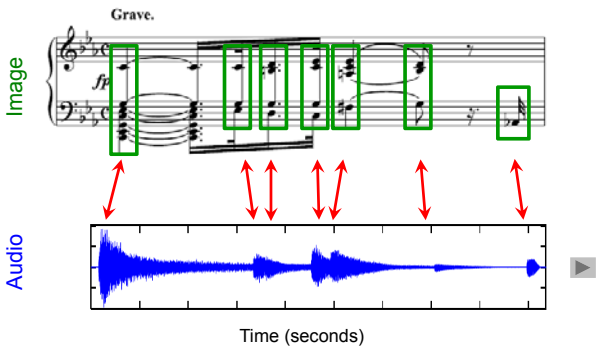


Piano (Scherbakov)

Music Synchronization: Image-Audio



Music Synchronization: Image-Audio



Music Synchronization: Image-Audio

Convert into common mid-level feature representation

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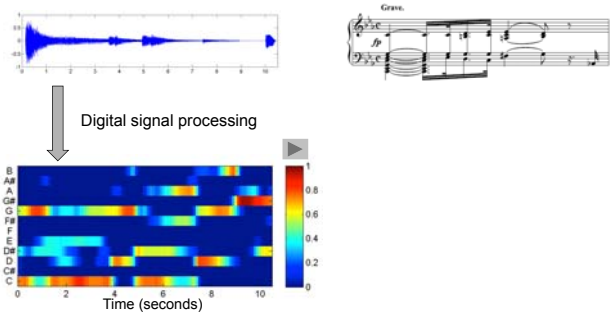
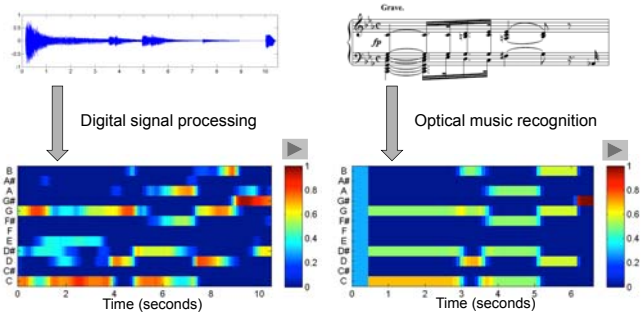


Audio chroma representation

Music Synchronization: Image-Audio

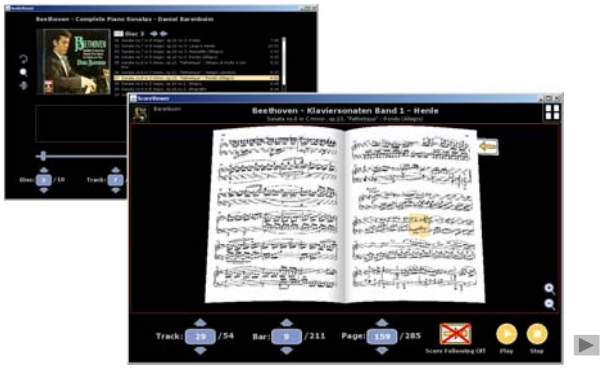
Convert into common mid-level feature representation



Audio chroma representation

Image chroma representation

Application: Score Viewer

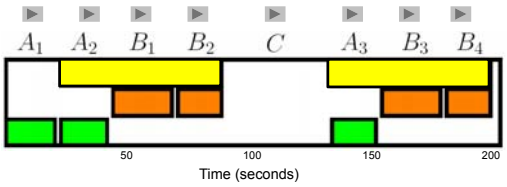


Audio Structure Analysis

Given: CD recording

Goal: Automatic extraction of the repetitive structure
(or of the musical form)

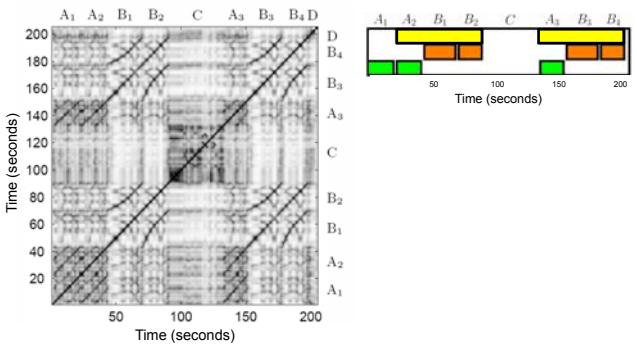
Example: Brahms Hungarian Dance No. 5 (Ormandy)



Basic Procedure

Self-similarity matrix

Similarity structure



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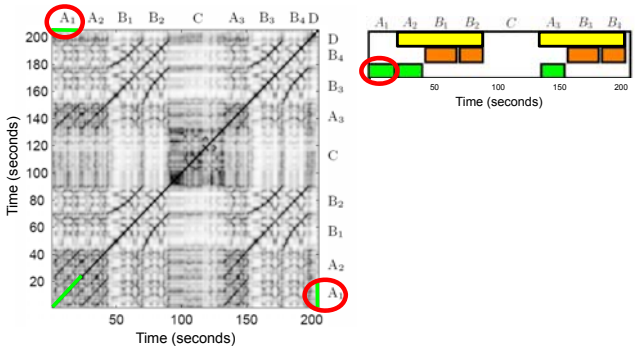

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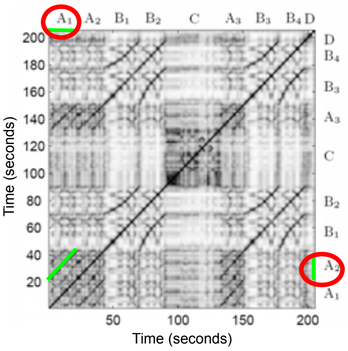
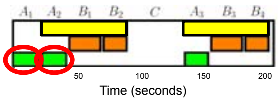


Similarity structure



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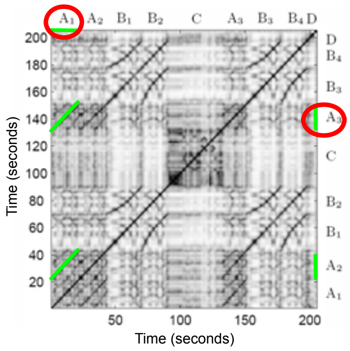
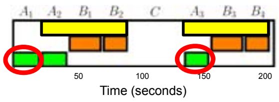


Similarity structure



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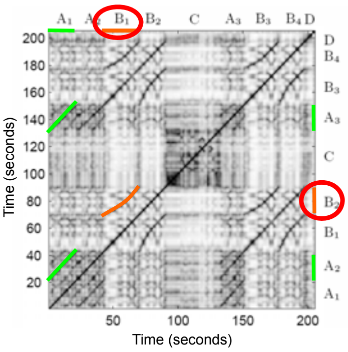

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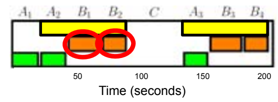

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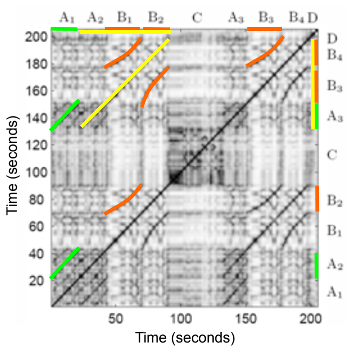

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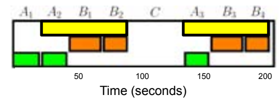

Music Processing

Coarse Level	**Fine Level**
What do different versions have in common?	What are the characteristics of a specific version?

Music Processing

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What do different versions have in common?	What are the characteristics of a specific version?
What makes up a piece of music?	What makes music come alive?

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What do different versions have in common?	What are the characteristics of a specific version?
What makes up a piece of music?	What makes music come alive?
Identify despite of differences	Identify the differences

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Coarse Level	Fine Level
What do different versions have in common?	What are the characteristics of a specific version?
What makes up a piece of music?	What makes music come alive?
Identify despite of differences	Identify the differences
Example tasks: **Audio Matching** **Cover Song Identification**	Example tasks: **Tempo Estimation** **Performance Analysis**

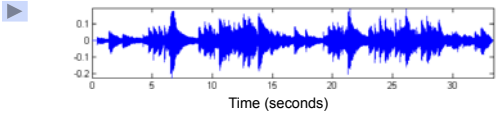
Performance Analysis

1. Capture nuances regarding tempo, dynamics, articulation, timbre, …
2. Discover commonalities between different performances and derive general performance rules
3. Characterize the style of a specific musician (``Horowitz Factor´´)

Performance Analysis: Tempo Curves

Schumann: Träumerei

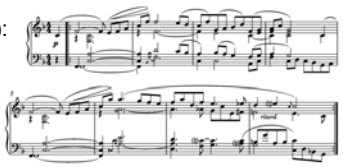
Performance:



Performance Analysis: Tempo Curves

Schumann: Träumerei

Score (reference):



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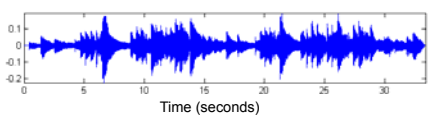

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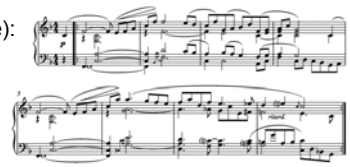
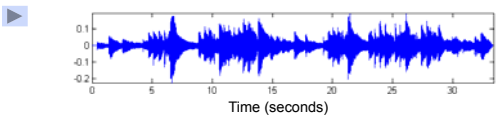


Strategy: Compute score-audio synchronization and derive tempo curve

Performance:



Performance Analysis: Tempo Curves

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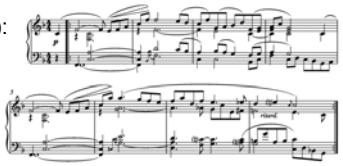
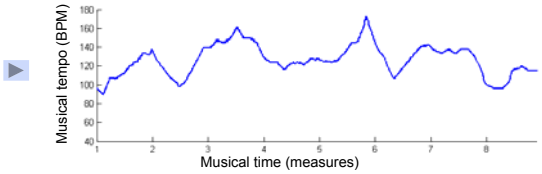


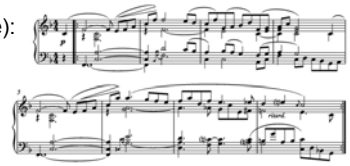
Tempo Curve:



Performance Analysis: Tempo Curves

Schumann: Träumerei

Score (reference):



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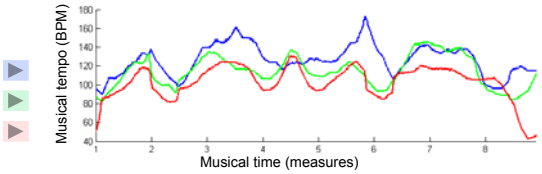

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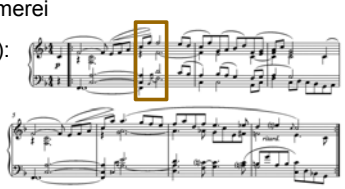

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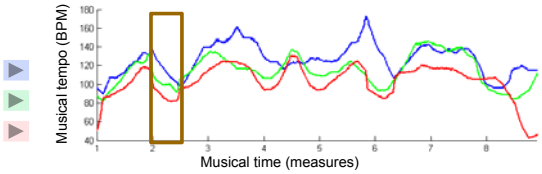
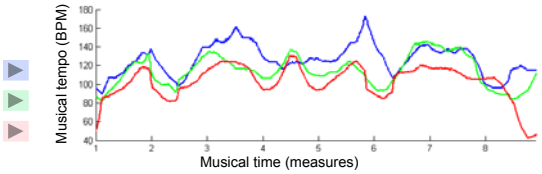


Performance Analysis

Schumann: Träumerei

What can be done if no reference is available?

Tempo Curves:



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Relative	**Absolute**
Given: Several versions	Given: One version

Music Processing

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Given: Several versions	Given: One version
Comparison of extracted parameters	Direct interpretation of extracted parameters

Music Processing

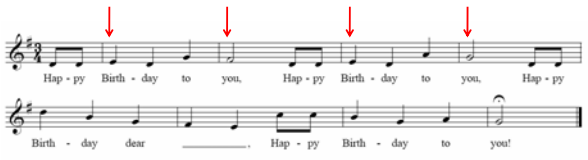
Relative	Absolute
Given: Several versions	Given: One version
Comparison of extracted parameters	Direct interpretation of extracted parameters
Extraction errors have often no consequence on final result	Extraction errors immediately become evident

Music Processing

Relative	Absolute
Given: Several versions	Given: One version
Comparison of extracted parameters	Direct interpretation of extracted parameters
Extraction errors have often no consequence on final result	Extraction errors immediately become evident
Example tasks: **Music Synchronization** **Genre Classification**	Example tasks: **Music Transcription** **Tempo Estimation**

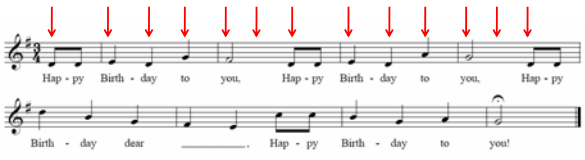
Tempo Estimation

Measure



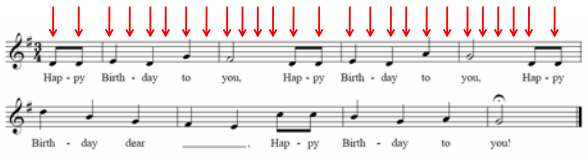
Tempo Estimation

Tactus (beat)



Tempo Estimation

Tatum (temporal atom)



Tempo Estimation and Beat Tracking

Example: Chopin – Mazurka Op. 68-3

Pulse level: Quarter note

Tempo: ???

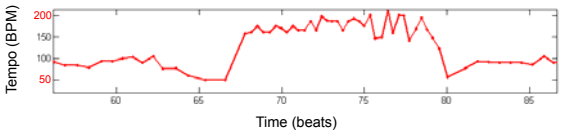
Tempo Estimation and Beat Tracking

Example: Chopin – Mazurka Op. 68-3

Pulse level: Quarter note

Tempo: 50-200 BPM

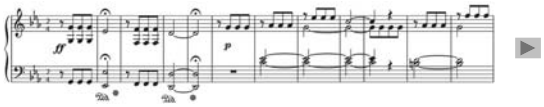
Tempo curve



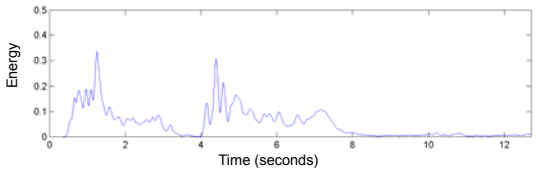
Tempo Estimation

- Which temporal level?
- Local tempo deviations
- Sparse information
  (e.g., only note onsets available)
- Vague information
  (e.g., extracted note onsets corrupt)

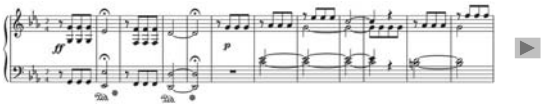
Tempo Estimation



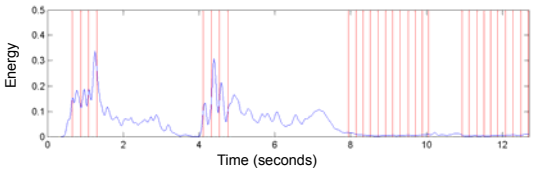
Local Energy Curve:



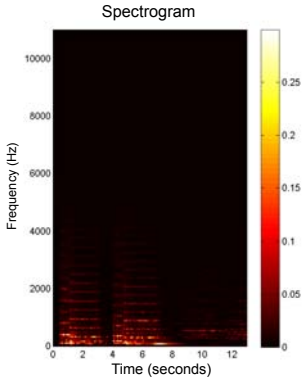
Tempo Estimation



Local Energy Curve: Note Onset Positions



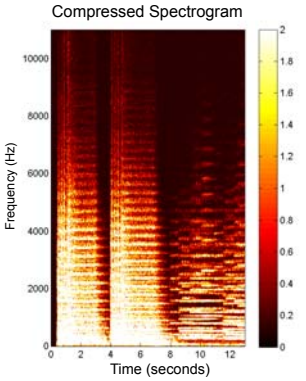
Tempo Estimation



Steps:

1. Spectrogram

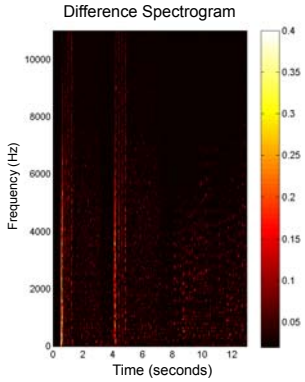
Tempo Estimation



Steps:

1. Spectrogram
2. Log Compression

Tempo Estimation



Steps:

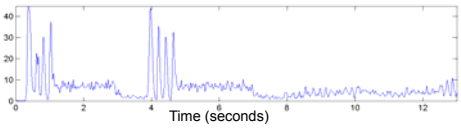
1. Spectrogram
2. Log Compression
3. Differentiation

Tempo Estimation

Steps:

1. Spectrogram
2. Log Compression
3. Differentiation
4. Accumulation

Novelty Curve

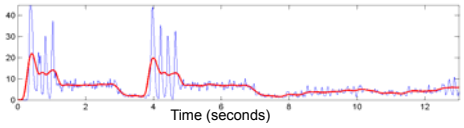


Tempo Estimation

Steps:

1. Spectrogram
2. Log Compression
3. Differentiation
4. Accumulation

Novelty Curve
Local Average

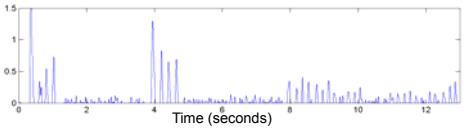


Tempo Estimation

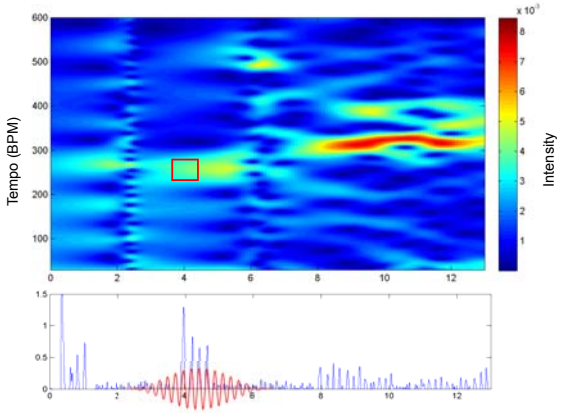
Steps:

1. Spectrogram
2. Log Compression
3. Differentiation
4. Accumulation
5. Normalization

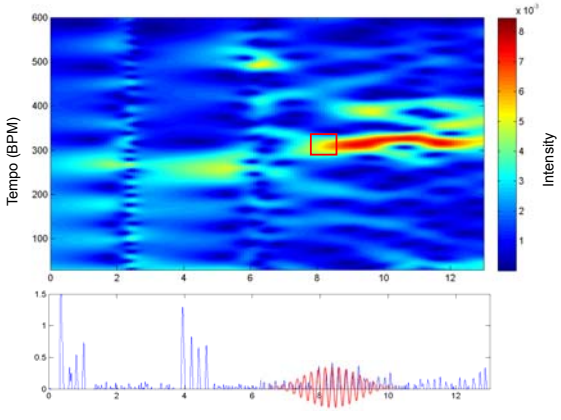
Novelty Curve



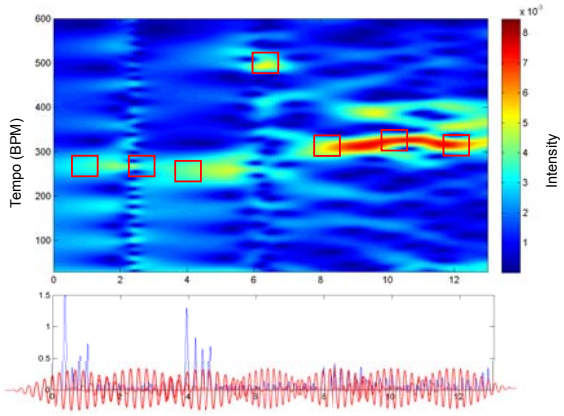
Tempo Estimation



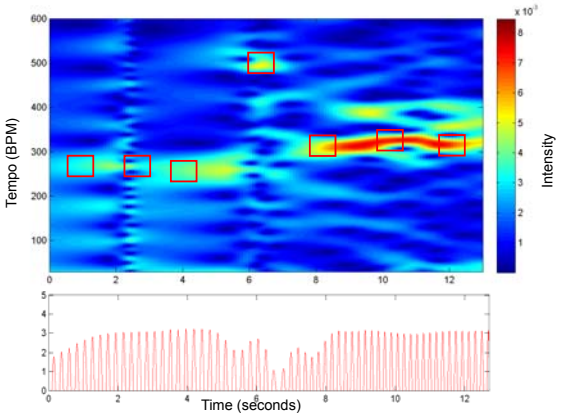
Tempo Estimation



Tempo Estimation

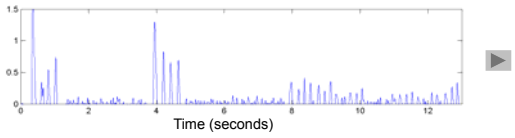


Tempo Estimation

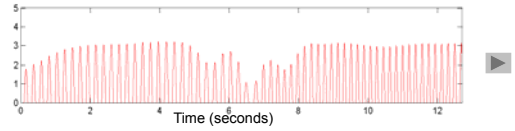


Tempo Estimation

Novelty Curve

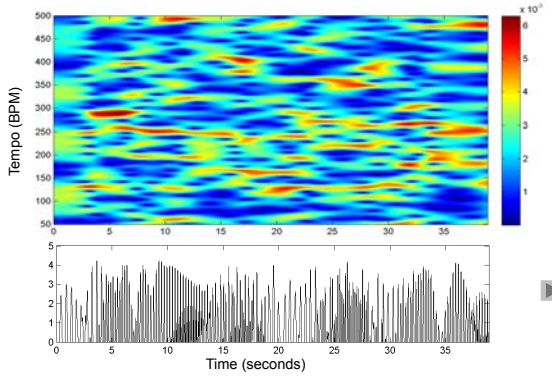


Predominant Local Pulse (PLP)



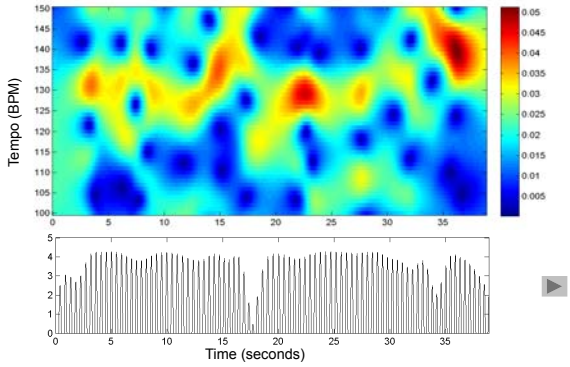
Tempo Estimation

Borodin – String Quartet No. 2

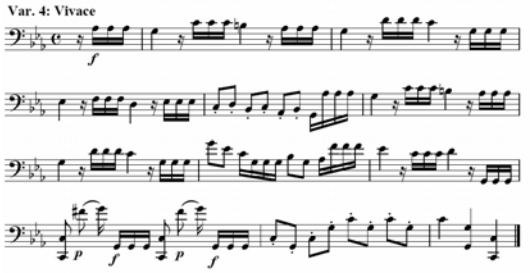


Tempo Estimation

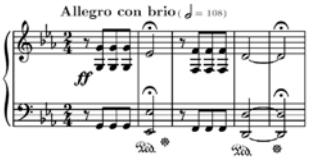
Borodin – String Quartet No. 2



Motivic Similarity

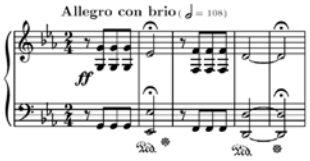


Motivic Similarity



Beethoven's Fifth (1st Mov.)

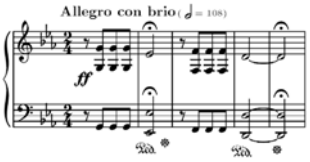
Motivic Similarity



Beethoven's Fifth (1st Mov.)

Beethoven's Fifth (3rd Mov.)

Motivic Similarity

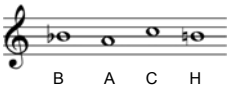


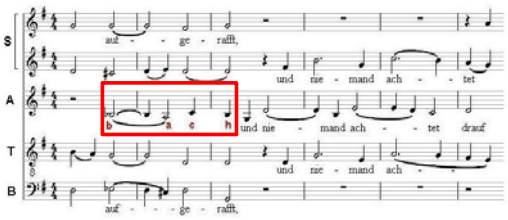
Beethoven's Fifth (1st Mov.)

Beethoven's Fifth (3rd Mov.)

Beethoven's Appassionata

Motivic Similarity





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- Verena Thomas (Bonn University)

Selected Publications (Music Processing)

- M. Müller, P.W. Ellis, A. Klapuri, G. Richard (2011):
  Signal Processing for Music Analysis.
  IEEE Journal of Selected Topics in Signal Processing, Vol. 5, No. 6, pp. 1088-1110.
- P. Grosche and M. Müller (2011):
  Extracting Predominant Local Pulse Information from Music Recordings.
  IEEE Trans. on Audio, Speech & Language Processing, Vol. 19, No. 6, pp. 1688-1701.
- M. Müller, M. Clausen, V. Konz, S. Ewert, C. Fremerey (2010):
  A Multimodal Way of Experiencing and Exploring Music.
  Interdisciplinary Science Reviews (ISR), Vol. 35, No. 2.
- M. Müller and S. Ewert (2010):
  Towards Timbre-Invariant Audio Features for Harmony-Based Music.
  IEEE Trans. on Audio, Speech & Language Processing, Vol. 18, No. 3, pp. 649-662.
- F. Kurth, M. Müller (2008):
  Efficient Index-Based Audio Matching.
  IEEE Trans. Audio, Speech & Language Processing, Vol. 16, No. 2, 382-395.
- M. Müller (2007):
  Information Retrieval for Music and Motion.
  Monograph, Springer, 318 pages