

Beethoven, Bach, and Billions of Bytes

Music meets Computer Science

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IDEA Lecture, Max-Planck-Institut für empirische Ästhetik
17.02.2016



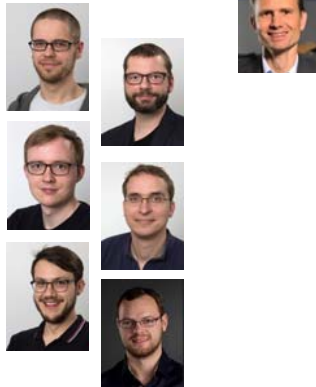
Meinard Müller



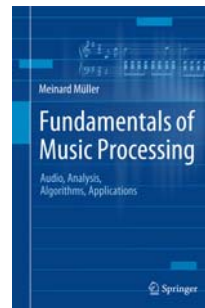
- 2001 PhD, Bonn University
- 2002/2003 Postdoc, Keio University, Japan
- 2007 Habilitation, Bonn University
"Information Retrieval for Music and Motion"
- 2007-2012 Senior Researcher
Max-Planck Institut für Informatik, Saarland
- 2012: Professor
Semantic Audio Processing
Universität Erlangen-Nürnberg

Group Members

- Jonathan Driedger
- Thomas Prätzlich
- Stefan Balke
- Christian Dittmar
- Patricio López-Serrano
- Christof Weiß



Book: Fundamentals of Music Processing



Meinard Müller
Fundamentals of Music Processing
Audio, Analysis, Algorithms, Applications
483 p., 249 illus., 30 illus. in color, hardcover
ISBN: 978-3-319-21944-8
Springer, 2015

Accompanying website:
www.music-processing.de

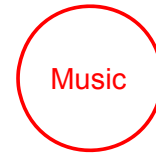
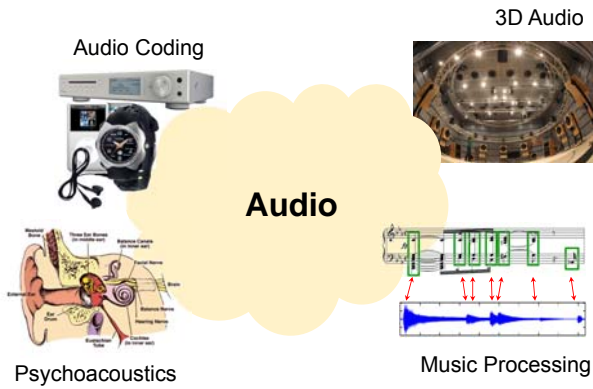
International Audio Laboratories Erlangen



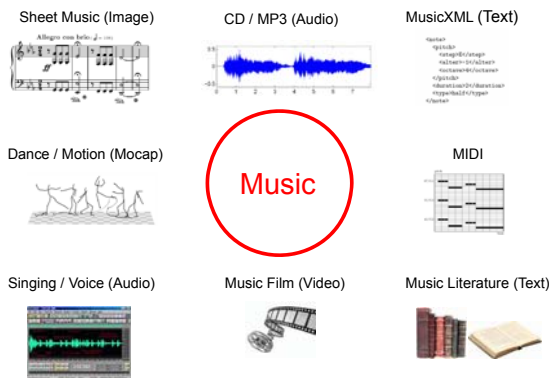
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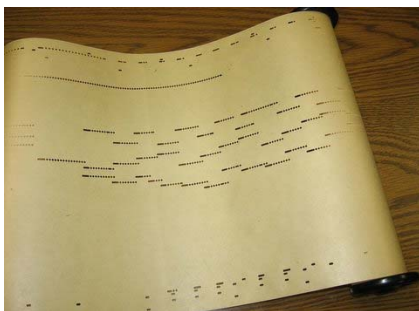
Music Processing



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)

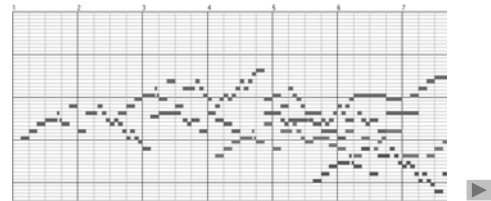


Piano Roll Representation (MIDI)

Query:

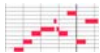


Goal: Find all occurrences of the query



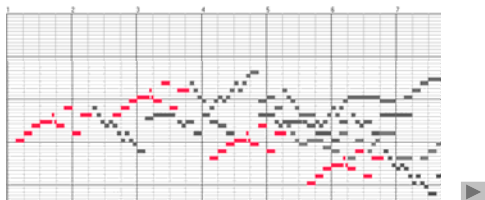
Piano Roll Representation (MIDI)

Query:



Goal: Find all occurrences of the query

Matches:



Audio Data

Various interpretations – Beethoven's Fifth



Bernstein



Karajan



Scherbakov (piano)



MIDI (piano)



Audio Data (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

Two audio CDs	>	1 Billion Bytes
1000 audio CDs	=	Billions of Bytes
12.000 MIDI files	<	350 MB

Music Synchronization: Audio-Audio

Beethoven's Fifth

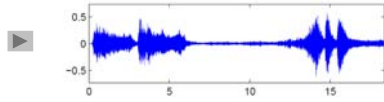


Music Synchronization: Audio-Audio

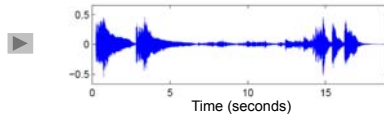
Beethoven's Fifth



Orchester (Karajan)



Piano (Scherbakov)



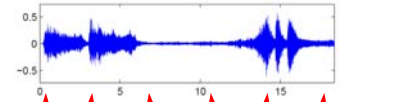
Time (seconds)

Music Synchronization: Audio-Audio

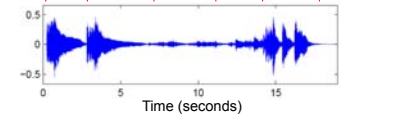
Beethoven's Fifth



Orchester (Karajan)



Piano (Scherbakov)

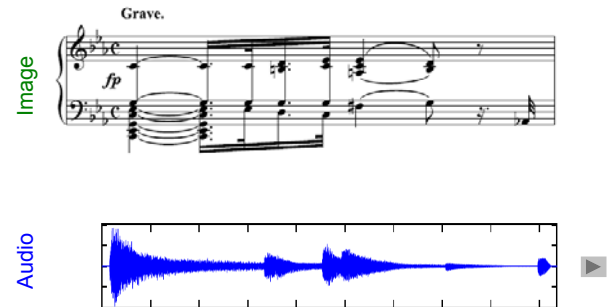


Time (seconds)

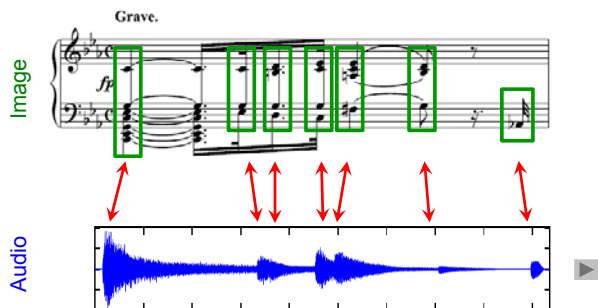
Application: Interpretation Switcher



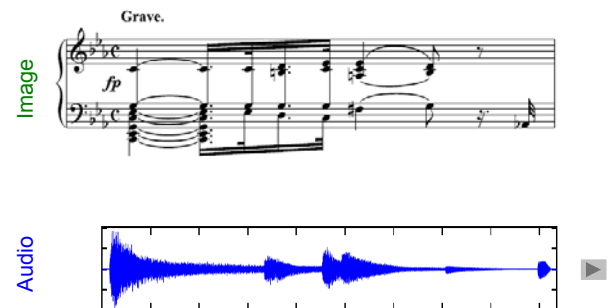
Music Synchronization: Image-Audio



Music Synchronization: Image-Audio

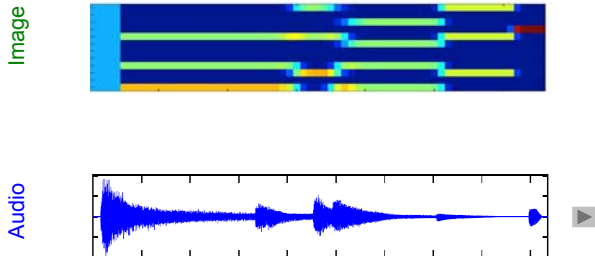


How to make the data comparable?



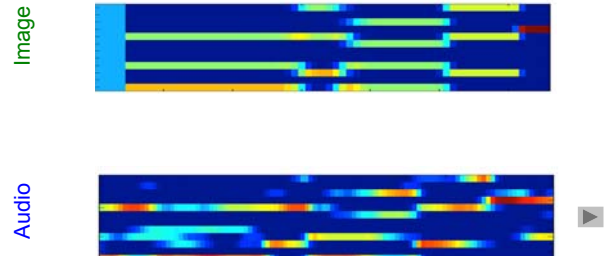
How to make the data comparable?

Image Processing: Optical Music Recognition



How to make the data comparable?

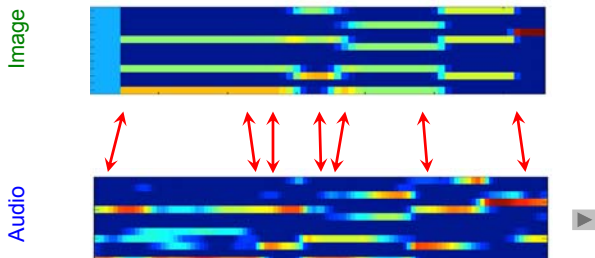
Image Processing: Optical Music Recognition



Audio Processing: Fourier Analyse

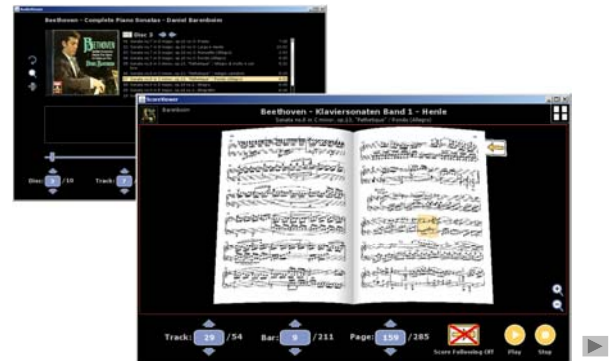
How to make the data comparable?

Image Processing: Optical Music Recognition



Audio Processing: Fourier Analyse

Application: Score Viewer



Music Processing

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

Music Processing

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?

Music Processing

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

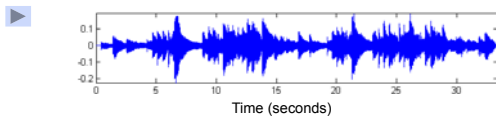
Music Processing

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

Schumann: Träumerei

Performance:



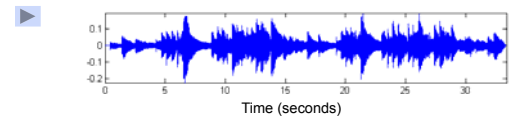
Performance Analysis

Schumann: Träumerei

Score (reference):



Performance:



Performance Analysis

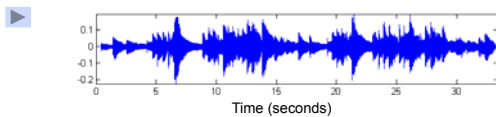
Schumann: Träumerei

Score (reference):



Strategy: Compute score-audio synchronization and derive tempo curve

Performance:



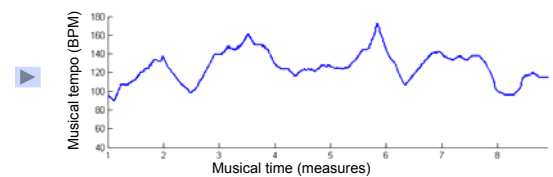
Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curve:



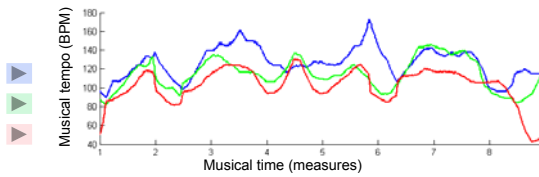
Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curves:



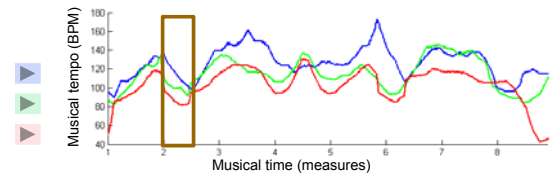
Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curves:



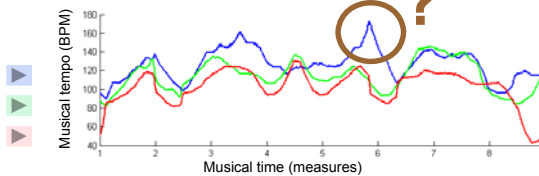
Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curves:

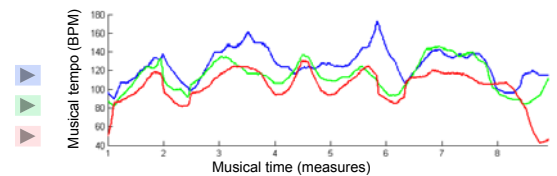


Performance Analysis

Schumann: Träumerei

What can be done if no reference is available?

Tempo Curves:



Music Processing

Relative	Absolute
Given: Several versions	Given: One version

Music Processing

Relative	Absolute
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

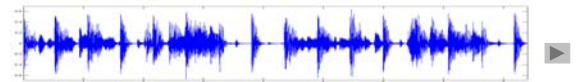
Tempo Estimation and Beat Tracking

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

Tempo Estimation and Beat Tracking

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

Example: Queen – Another One Bites The Dust

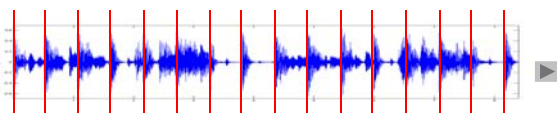


Time (seconds)

Tempo Estimation and Beat Tracking

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

Example: Queen – Another One Bites The Dust



Time (seconds)



Tempo Estimation and Beat Tracking

Example: Happy Birthday to you

Pulse level: **Measure**

Tempo Estimation and Beat Tracking

Example: Happy Birthday to you

Pulse level: **Tactus (beat)**

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

Tempo Estimation and Beat Tracking

Example: Happy Birthday to you

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

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

Tempo Estimation and Beat Tracking

Example: Chopin – Mazurka Op. 68-3

Pulse level: Quarter note

Tempo: ??? ▶

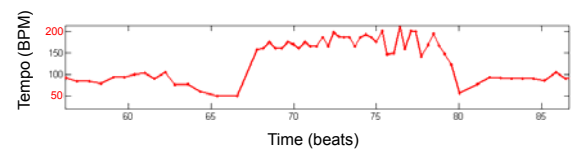
Tempo Estimation and Beat Tracking

Example: Chopin – Mazurka Op. 68-3

Pulse level: Quarter note

Tempo: **50-200 BPM** ▶

Tempo curve



Tempo Estimation and Beat Tracking

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

Why Is Music Processing Challenging?

Example: Chopin, Mazurka Op. 63 No. 3 ▶

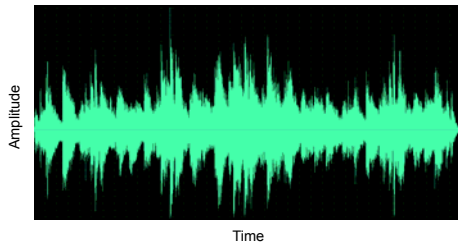
Mazurka.

Allegretto. F. CHOPIN, Op. 63, No. 3.

Why Is Music Processing Challenging?

Example: Chopin, Mazurka Op. 63 No. 3 ▶

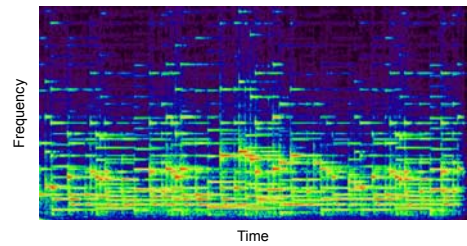
- Waveform



Why Is Music Processing Challenging?

Example: Chopin, Mazurka Op. 63 No. 3 ▶

- Waveform / Spectrogram



Why Is Music Processing Challenging?

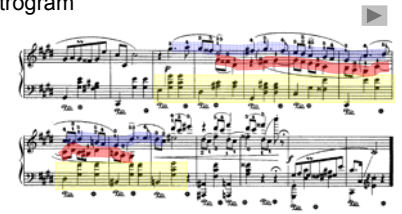
Example: Chopin, Mazurka Op. 63 No. 3 ▶

- 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



Legend for Polyphony:
— Main Melody (Blue)
— Additional melody line (Red)
— Accompaniment (Yellow)

Source Separation

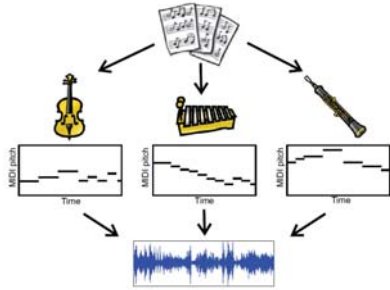
- Decomposition of audio stream into different sound sources
- Central task in digital signal processing
- “Cocktail party effect”
- Sources are often assumed to be statistically independent
- This is often not the case in music

Strategy: Exploit additional information (e.g. musical score) to support the separation process

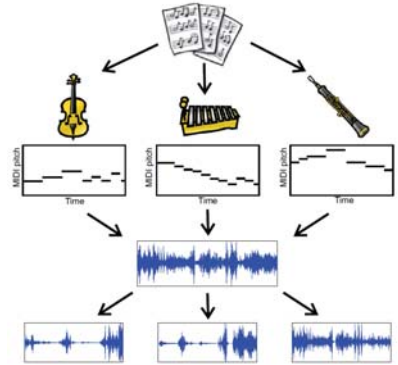
Score-Informed Source Separation



Score-Informed Source Separation

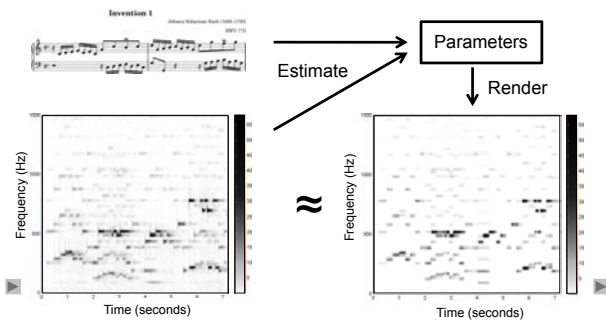


Score-Informed Source Separation

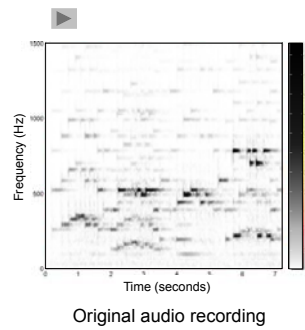


Score-Informed Source Separation

Goal: Approximate spectrogram using a parametric model exploiting availability of score information

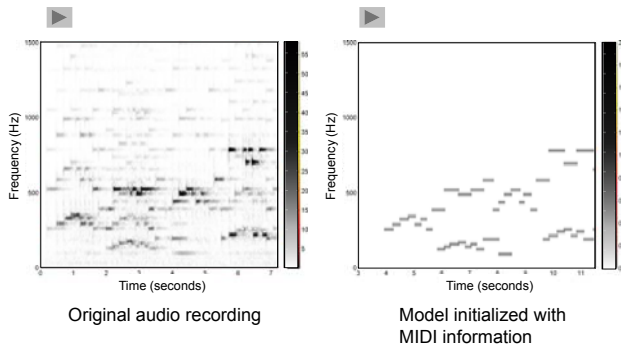


Score-Informed Source Separation



Original audio recording

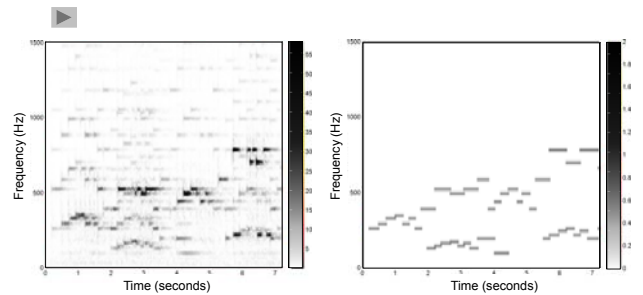
Score-Informed Source Separation



Original audio recording

Model initialized with MIDI information

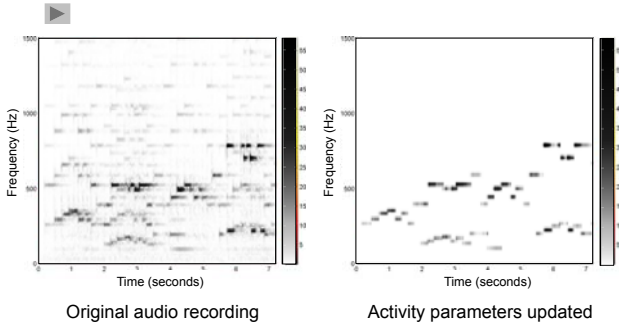
Score-Informed Source Separation



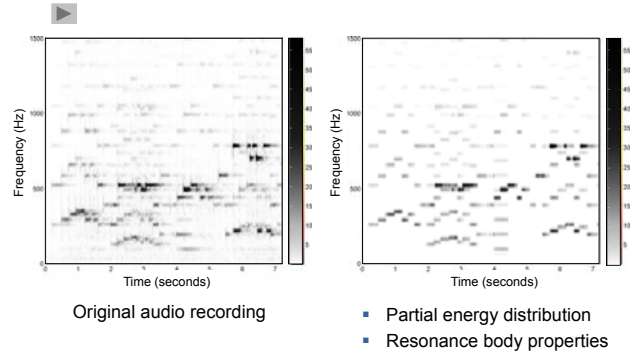
Original audio recording

- Temporal synchronization
- Tuning estimation

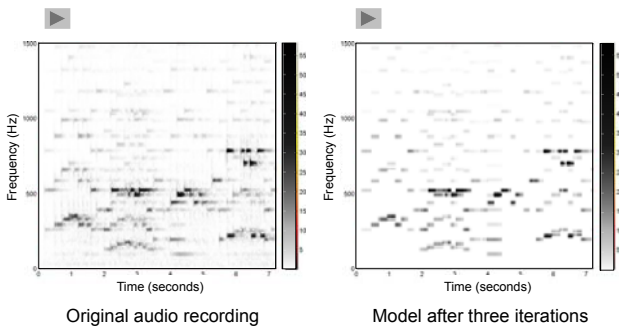
Score-Informed Source Separation



Score-Informed Source Separation



Score-Informed Source Separation



Note: Each note specified by the score parameterizes a portion of the spectrogram

Score-Informed Source Separation

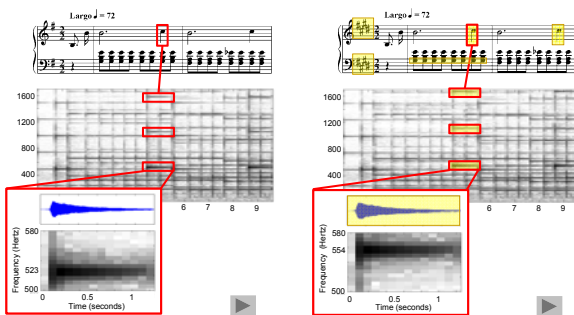
Experimental results for separating left and right hands for piano recordings:



Composer	Piece	Database	Results			
			L	R	Eq	Org
Bach	BWV 875, Prelude	SMD	▶▶▶▶	▶▶▶▶	▶▶▶▶	▶▶▶▶
Chopin	Op. 28, No. 15	SMD	▶▶▶▶	▶▶▶▶	▶▶▶▶	▶▶▶▶
Chopin	Op. 64, No. 1	European Archive	▶▶▶▶	▶▶▶▶	▶▶▶▶	▶▶▶▶

Score-Informed Source Separation

Audio editing



Harmonic Analysis

Signal

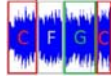


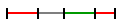
Harmonic Analysis

Signal



Result



Segmentation 
Chord label assignment C F G C

Harmonic Analysis

Signal



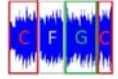
Feature Extraction




Classification



Result



Segmentation 
Chord label assignment C F G C

Cross-Version Analysis

General Procedure

- Conduct **analysis** for **multiple versions** of the **same object**
 - Harmonic analysis**
 - Different music recordings**
 - Same piece of music**
- Relate** the versions (using a **reference**)
 - Music synchronization**
 - Musical score**
- Compare analysis results across different versions
- Look for consistencies and inconsistencies

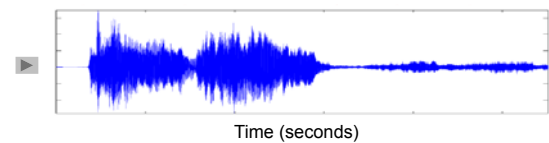
Barwise Synchronization



Barwise Synchronization

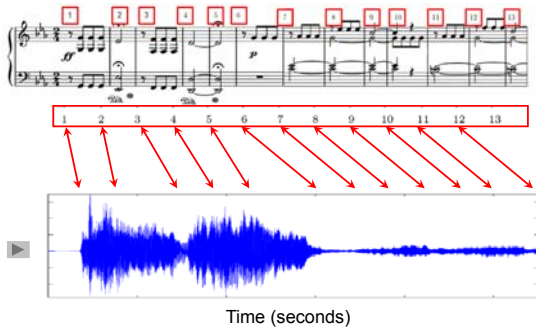


Barwise Synchronization



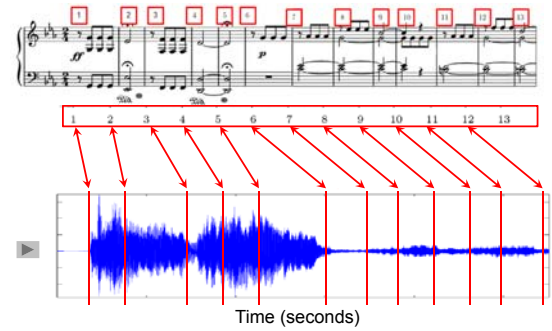
Barwise Synchronization

Music synchronization



Barwise Synchronization

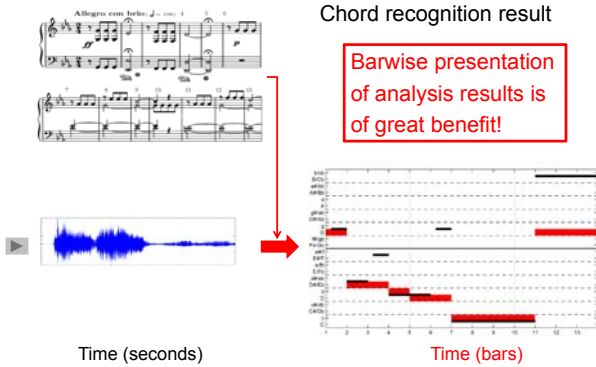
Transfer bar information to audio domain



Cross-Version Harmonic Analysis

Chord recognition result

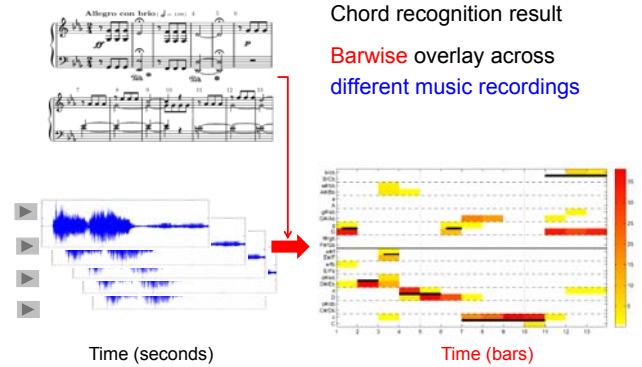
Barwise presentation of analysis results is of great benefit!



Cross-Version Harmonic Analysis

Chord recognition result

Barwise overlay across different music recordings

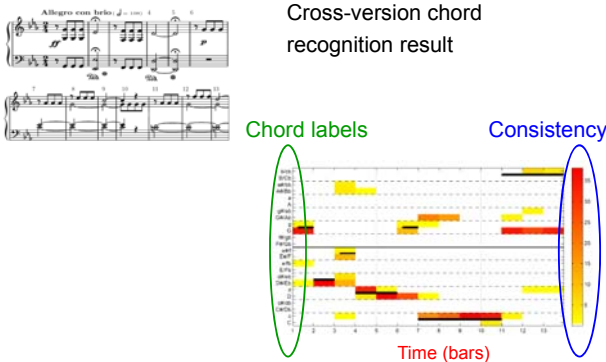


Cross-Version Harmonic Analysis

Cross-version chord recognition result

Chord labels

Consistency

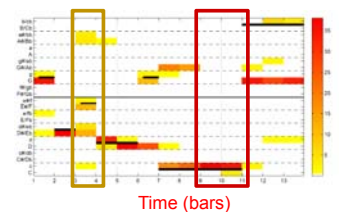


Cross-Version Harmonic Analysis

Cross-version chord recognition result

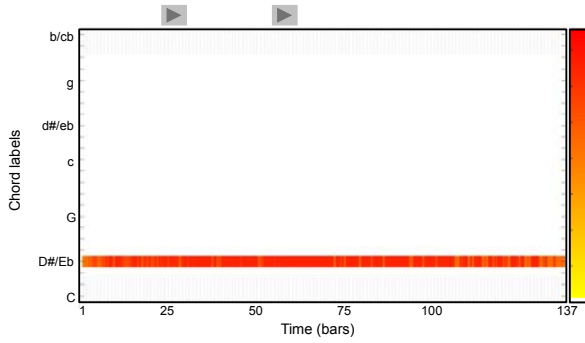
Highly consistent:
C-minor

Inconsistent:
F-minor, F-major,
B^b-major ... ???



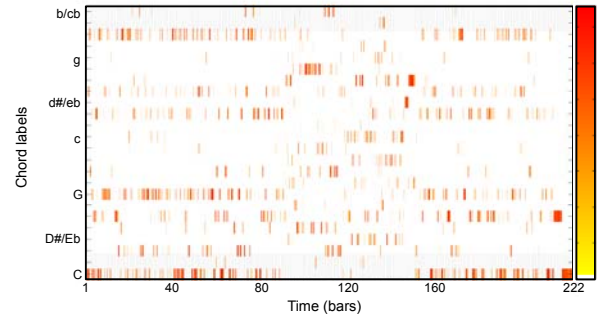
Examples

Wagner: Rheingold (Vorspiel)



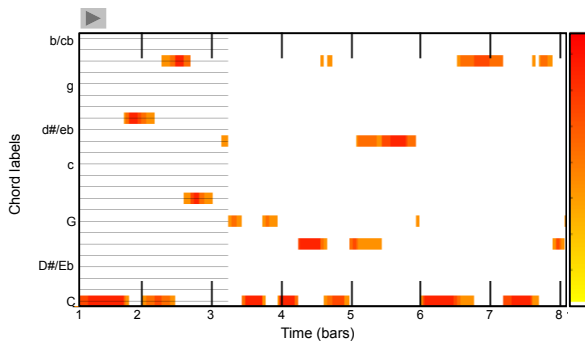
Examples

Wagner: Meistersinger (Vorspiel)



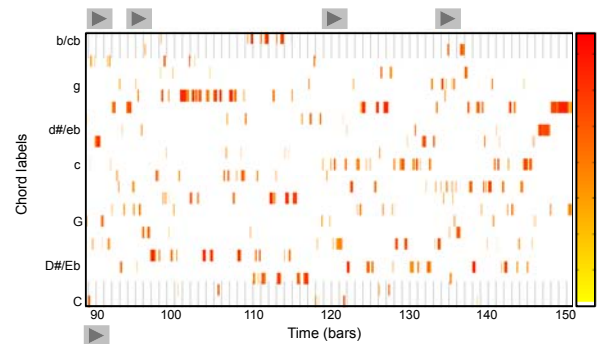
Examples

Wagner: Meistersinger (Vorspiel)



Examples

Wagner: Meistersinger (Vorspiel)



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



Motivic Similarity



Towards Interdisciplinary Research ...

- Music as challenging multimedia scenario
 - Different representations (audio, sheet music, video, ...)
 - Many musical aspects (harmony, rhythm, melody, timbre, ...)
 - Human involvement, emotions, ...
- Computer-based tools that assist musicologists
 - User interfaces
 - Visualizations
 - Large-scale analysis of music corpora
- Digital (computational) humanities

Interdisciplinary Projects

DFG-Project: **Harmonic Analysis Wagner**
2015-2018
Cooperation: Rainer Kleinertz



Christof Weiß



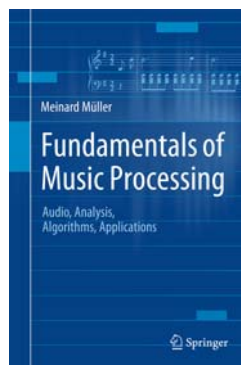
BMBF-Project: **Freischütz Digital**
2012-2015
Cooperation: Joachim Veit



Thomas Prätzlich











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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