

New Avenues for Music Research Using Digital Signal Processing

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Workshop

Understanding Beethoven – Musicology and Computer Science in Dialogue
14. – 16. Juli 2022



Meinard Müller



- Mathematics (Diplom/Master, 1997)
Computer Science (PhD, 2001)
Information Retrieval (Habilitation, 2007)
Bonn University



- Senior Researcher (2007-2012)
Max-Planck Institute, Saarland



- Professor Semantic Audio Processing (since 2012)
Erlangen-Nürnberg University



Meinard Müller: Research Group

- Christof Weiß
- Vlora Arifi-Müller
- Sebastian Rosenzweig
- Michael Krause
- Yigitcan Özer
- Simon Schwär
- Peter Meier (external)



International Audio Laboratories Erlangen



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

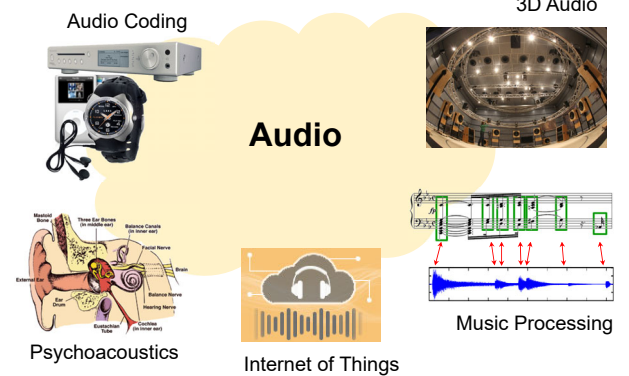


- Friedrich-Alexander Universität Erlangen-Nürnberg (FAU)
- One of Germany's largest universities with ≈ 40,000 students
- Strong Technical Faculty

International Audio Laboratories Erlangen

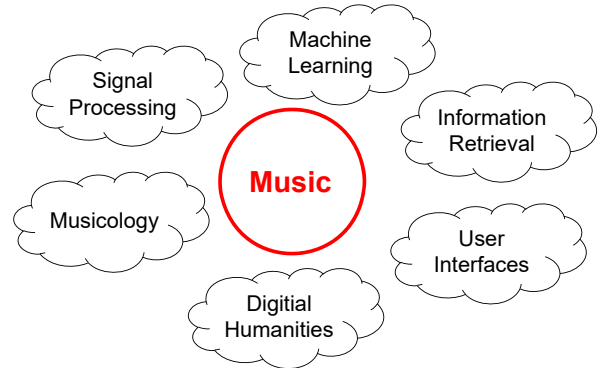
Audio

International Audio Laboratories Erlangen





Music Information Retrieval (MIR)

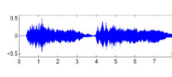


Music Information Retrieval (MIR)

Sheet Music (Image)



CD / MP3 (Audio)



MusicXML (Text)

```
<?xml version="1.0" encoding="UTF-8" standalone="no" >
<musicxml>
<score>
<part name="V1" id="P1">
<measure number="1">
<note>
<pitch name="C4" />
<rest />
</measure>
</part>
</score>
</musicxml>
```

Dance / Motion (Mocap)



MIDI



Singing / Voice (Audio)



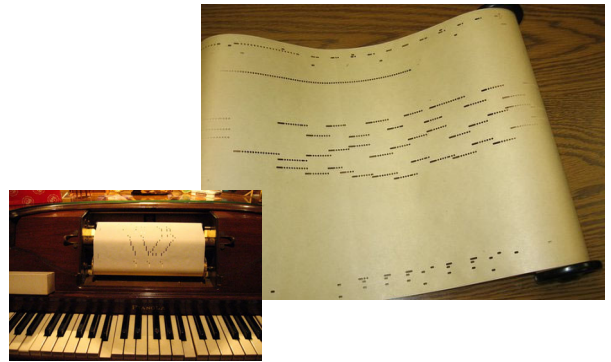
Music Film (Video)



Music Literature (Text)

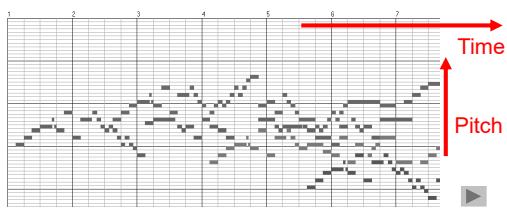


Piano Roll Representation (1900)



Piano Roll Representation

J.S. Bach, C-Major Fuge
(Well Tempered Piano, BWV 846)

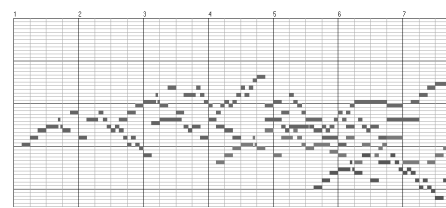


Piano Roll Representation

Query:



Goal: Find all occurrences of the query

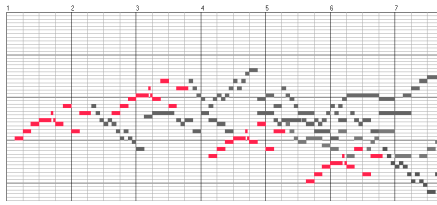


Piano Roll Representation

Query: 

Goal: Find all occurrences of the query

Matches:



Music Retrieval



Audio ID

Version ID

Category ID

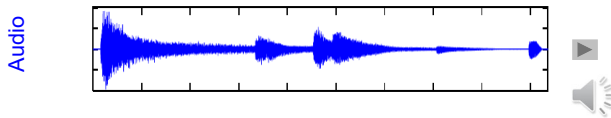


Bernstein (1962)
Beethoven, Symphony No. 5

- Beethoven, Symphony No. 5:
 - Bernstein (1962)
 - Karajan (1982)
 - Gould (1992)

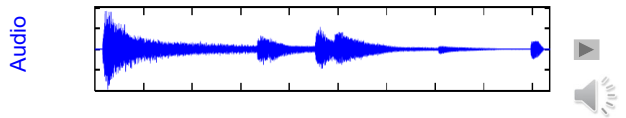
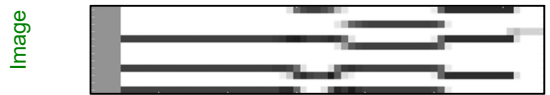
- Beethoven, Symphony No. 9
- Beethoven, Symphony No. 3
- Haydn Symphony No. 94

Music Synchronization: Image-Audio



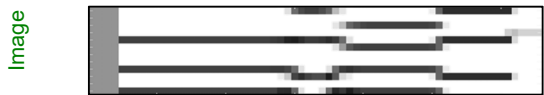
Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition



Music Synchronization: Image-Audio

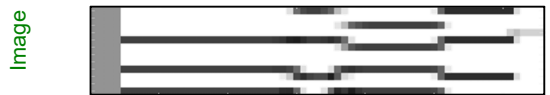
Image Processing: Optical Music Recognition



Audio Processing: Fourier Analysis

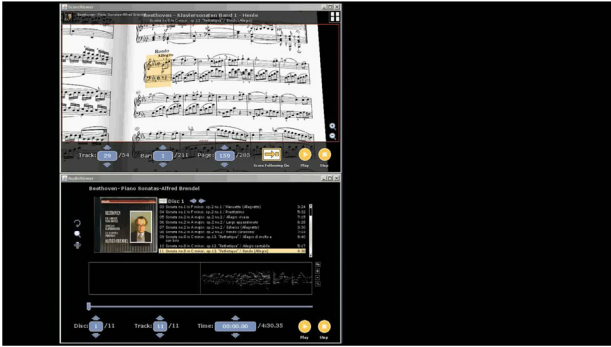
Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition



Audio Processing: Fourier Analysis

Music Synchronization



Music Scenarios

- Freischütz Digital



- Wagner's Ring



- Georgian Music



- Schubert Winterreise



Scenario: Freischütz Digital



- BMBF (2012 – 2016)
- Detmold/Paderborn (Prof. Veit, Digital Editions)
- Frankfurt (Prof. Betzwieser, Musicology)
- Erlangen (Prof. Müller, Computer Science)



Scenario: Freischütz Digital



Audio

- BMBF (2012 – 2016)
- Detmold/Paderborn (Prof. Veit, Digital Editions)
- Frankfurt (Prof. Betzwieser, Musicology)
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Scenario: Freischütz Digital



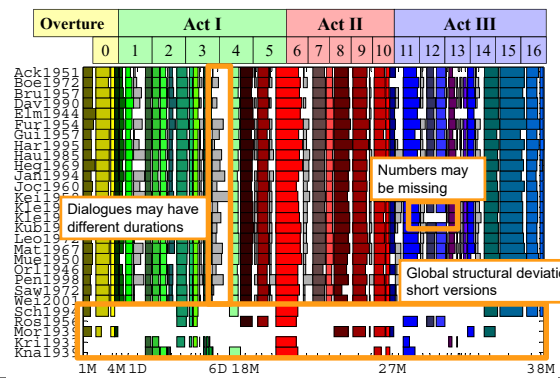
Recordings

- 23 mostly complete recordings
- 10 abridged/short versions
- Recorded between 1933 and 2001

Example: Song (No. 4) from "Der Freischütz"

Variations	Performance
	Kleiber C. , 1973
Tempo	Elmendorff, 1944
Language	Penin (fr.), 1998
Key	Orlov (russ.), 1946
Sound quality	Gui (it.), 1957

Scenario: Freischütz Digital



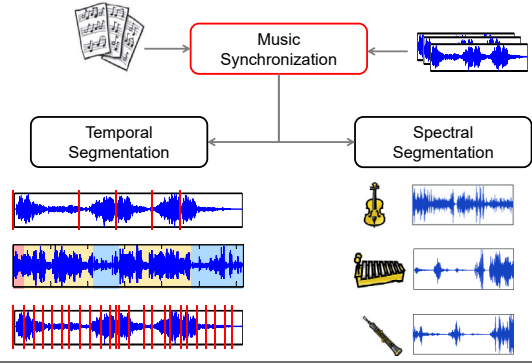
Scenario: Freischütz Digital

Example: Carl Maria von Weber: "Der Freischütz" (No. 4)



Introduction Stanzas Dialogues

Scenario: Freischütz Digital



Scenario: Freischütz Digital

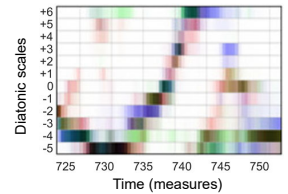


- Extraction of musical form
- Finding (nearly) repeating patterns
- Instrument detection and classification
- Language detection
- Detection of musical keys, chords, ...
- Detection of time signature, tempo, measures, beats, ...
- ...

Scenario: Wagner's Ring



- DFG (2014 – 2023)
- Saarbrücken (Prof. Kleinertz, Musicology)
- Erlangen (Prof. Müller, Computer Science)
- Objectives
 - Harmony-based structural analysis
 - Visualization techniques
 - Exploration of interdisciplinary research



Scenario: Wagner's Ring



No.	Conductor	Recording	hh:mm:ss
1	Barenboim	1991–92	14:54:55
2	Boulez	1980–81	13:44:38
3	Böhm	1967–71	13:39:28
4	Furtwängler	1953	15:04:22
5	Haitink	1988–91	14:27:10
6	Janowski	1980–83	14:08:34
7	Karajan	1967–70	14:58:08
8	Keilberth/Furtwängler	1952–54	14:19:56
9	Krauss	1953	14:12:27
10	Levine	1987–89	15:21:52
11	Neuhold	1993–95	14:04:35
12	Sawallisch	1989	14:06:50
13	Solti	1958–65	14:36:58
14	Swarowsky	1968	14:56:34
15	Thielemann	2011	14:31:13
16	Weigle	2010–12	14:48:46

- Large-scale work
- Four operas
 - ca. 15 hours
 - 21941 measures
- 16 performances

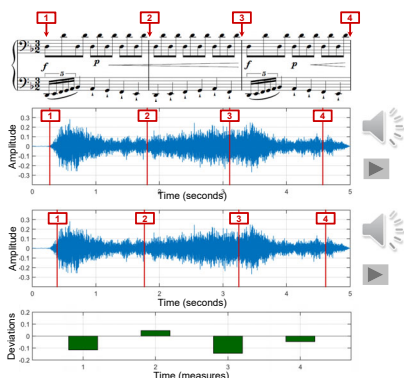
Scenario: Wagner's Ring



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- Large-scale work
- Four operas
 - ca. 15 hours
 - 21941 measures
- 16 performances
- Manual measure annotations

Scenario: Wagner's Ring



Annotator 1

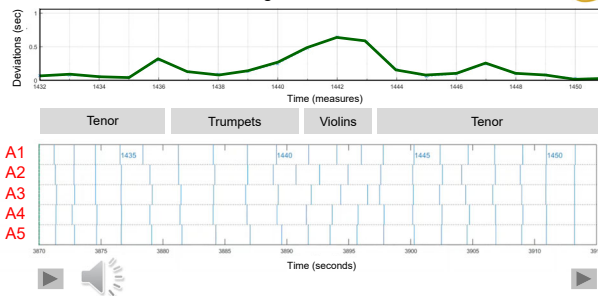
Annotator 2

Deviations

Scenario: Wagner's Ring



Standard deviations among annotators



Scenario: Wagner's Ring



- Measure position ambiguities
 - Rhythm or beat unclear
 - Vague note onset positions
 - Non-synchronous parts (e.g., singers and orchestra)
 - ...
- Introduce confidence measures
 - Cross-annotator agreement
 - Cost function based on novelty and homogeneity
 - ...

Christof Weiß, Viora Anfi-Müller, Thomas Prätzlich, Rainer Kleinertz, Meinard Müller:
Analyzing Measure Annotations for Western Classical Music Recordings.
In Proceedings of the International Society for Music Information Retrieval Conference (ISMIR): 517–523, 2016.

Scenario: Georgian Music



- DFG (2018 – 2022)
- Potsdam (Prof. Scherbaum, Ethnomusicology)
- Erlangen (Prof. Müller, Computer Science)
- Objectives
 - Harmonic and melodic singing analysis
 - New sensors (larynx microphones)
 - Digital humanities



Scenario: Georgian Music

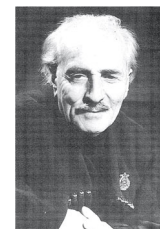


Scenario: Georgian Music

Example: Erkomaishvili corpus



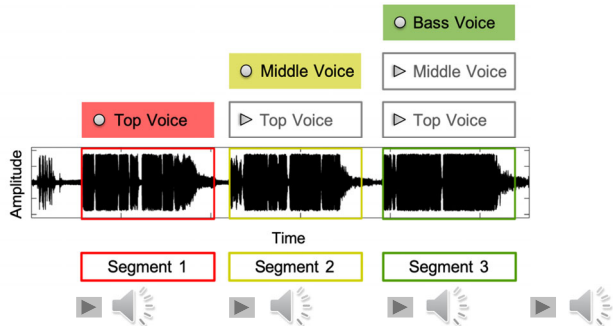
- Collection of traditional three-voice Georgian songs
- Performed by the former Georgian master chanter Artem Erkomaishvili (1887-1967)
- Recordings of 100 songs using tape recorders (1966)



“Original masterpieces of Georgian musical thinking.” (Shugliashvili, 2014)

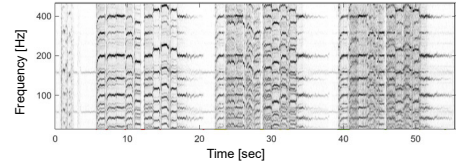
Scenario: Georgian Music

Example: Erkomaishvili corpus



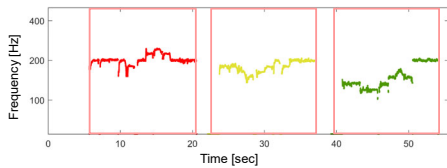
Scenario: Georgian Music

Example: Erkomaishvili corpus



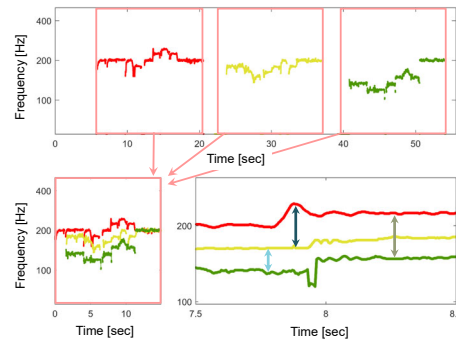
Scenario: Georgian Music

Example: Erkomaishvili corpus



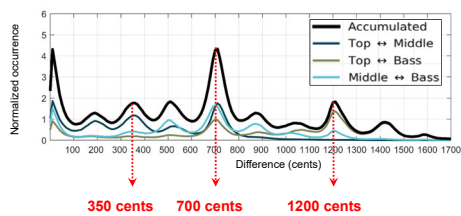
Scenario: Georgian Music

Example: Erkomaishvili corpus



Scenario: Georgian Music

Example: Erkomaishvili corpus



- Peak at 350 cents (between minor and major third)
- Non-western temperament

Scenario: Georgian Music

Example: Erkomaishvili corpus



<https://www.audiolabs-erlangen.de/resources/MIR/2019-GeorgianMusic-Erkomaishvili>

Scenario: Georgian Music

Example: Erkomaishvili corpus



- Temporal organization
 - No notion of meter
 - Continuous note transitions (glissando)
 - Voices not synchronous
- Tonal organization
 - Non-western temperament
 - Harmonic vs. melodic intonation
 - Transcription problematic
- Poor recording conditions

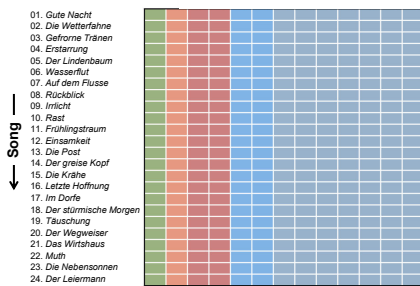
Sebastian Rosenzweig, Frank Scherbaum, David Shugliashvili, Viora Arifi-Müller, and Meinard Müller:
Erkomaishvili Dataset: A Curated Corpus of Traditional Georgian Vocal Music for Computational Musicology.
 Transactions of the International Society for Music Information Retrieval (TSMIR), 3(1): 31–41, 2020.

Scenario: Schubert Winterreise

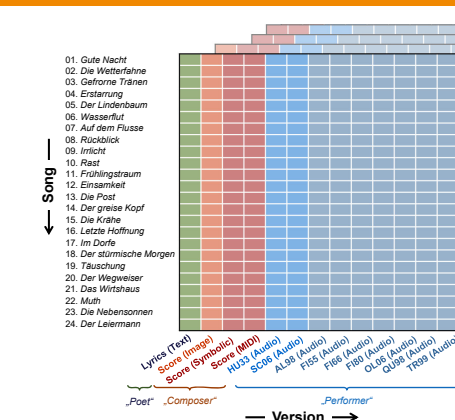
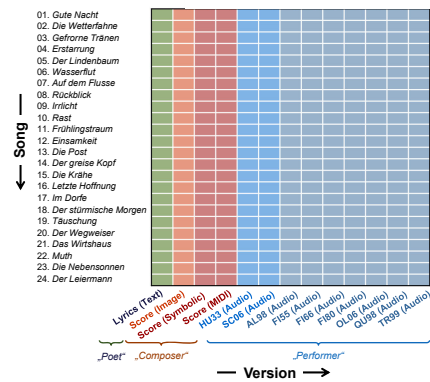


- Winterreise
 - Song cycle for voice and piano
 - Music: Franz Schubert (1828)
 - Poems: Wilhelm Müller
- MIR Objectives
 - Music synchronization
 - Structure analysis
 - Harmonic analysis
 - Activity detection (singing, lyrics, ...)
 - ...

Scenario: Schubert Winterreise

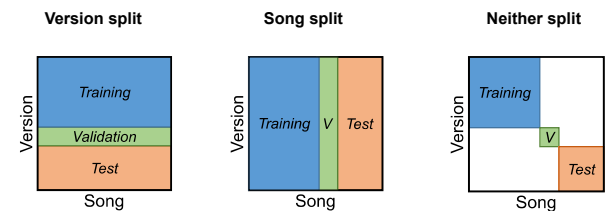


Scenario: Schubert Winterreise



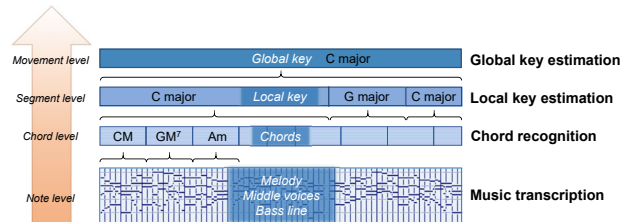
Scenario: Schubert Winterreise

Cross-Version Evaluation



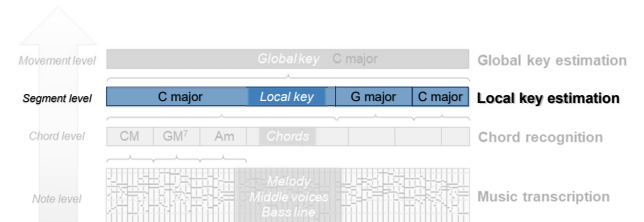
Scenario: Schubert Winterreise

Harmony Analysis



Scenario: Schubert Winterreise

Harmony Analysis

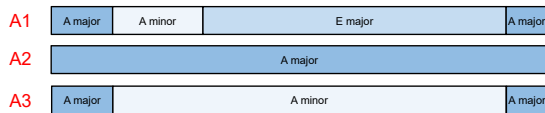


Scenario: Schubert Winterreise

Harmony Analysis



Annotations

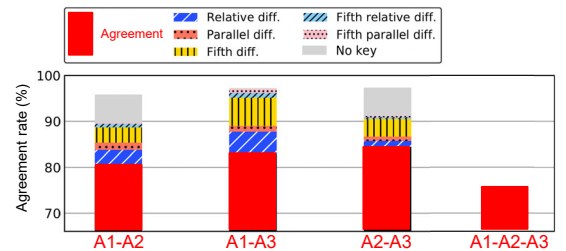


Scenario: Schubert Winterreise

Harmony Analysis



Annotator agreements and differences



Scenario: Schubert Winterreise



- Harmony-related annotations
 - Hierarchical nature of musical structures
 - High degree of subjectivity
 - Dependence on user needs and applications
- ...

Christof Weiß, Frank Zalkow, Viora Arifi-Müller, Meinard Müller, Hendrik Vincent Koops, Anja Volk, Harald Grohganz:
Schubert Winterreise Dataset: A Multimodal Scenario for Music Analysis.
ACM Journal on Computing and Cultural Heritage (JOCHC), 15(2): 1–18, 2021.

Conclusions (Annotations)

- Annotating music data is a challenge
 - Data inconsistencies
 - Underlying model assumptions often violated
 - High degree of subjectivity
 - Dependency on user needs and applications
 - Never trust your annotations!
- Annotations and analyses cannot be separated
 - Needs to be an interactive process
 - Requires a dialogue between domain experts and computer scientists
 - Requires an understanding and adaption of tools
- Opportunities
 - Annotation process becomes subject of research
 - Increasing appreciation of datasets
 - Great potential for interdisciplinary research

Why is Music Processing Challenging?

Example: Chopin, Mazurka Op. 63 No. 3  

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

Allegretto.

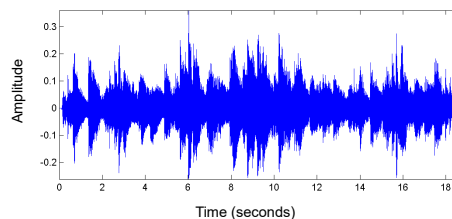
41. *p*



Why is Music Processing Challenging?

Example: Chopin, Mazurka Op. 63 No. 3

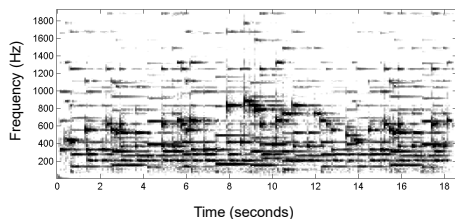
- Waveform





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



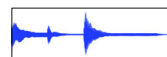
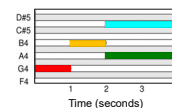
- Polyphony

- █ Main Melody
- █ Additional melody line
- █ Accompaniment

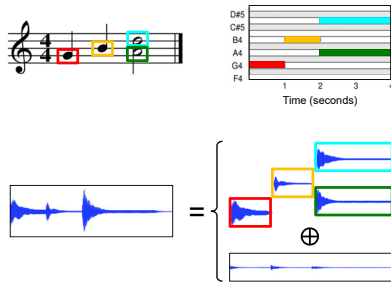
Score-Informed Audio Decomposition



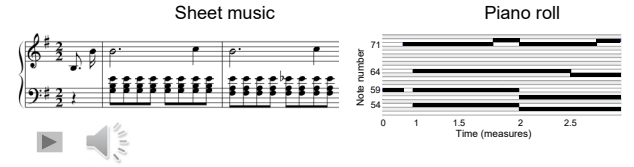

Score-Informed Audio Decomposition

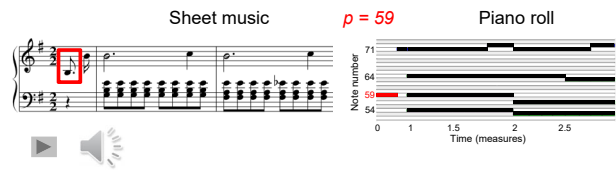
Score-Informed Audio Decomposition



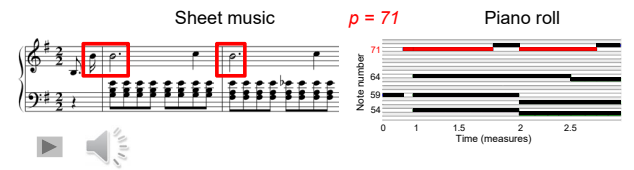
Score-Informed Audio Decomposition



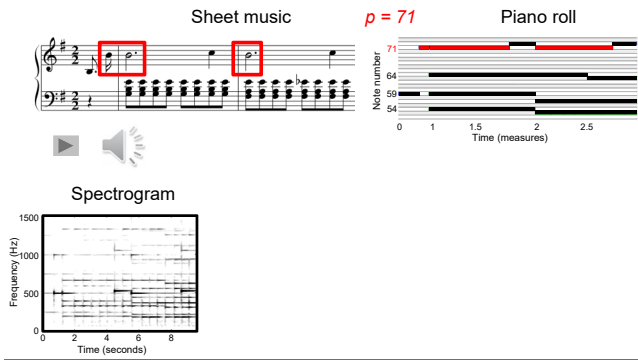
Score-Informed Audio Decomposition



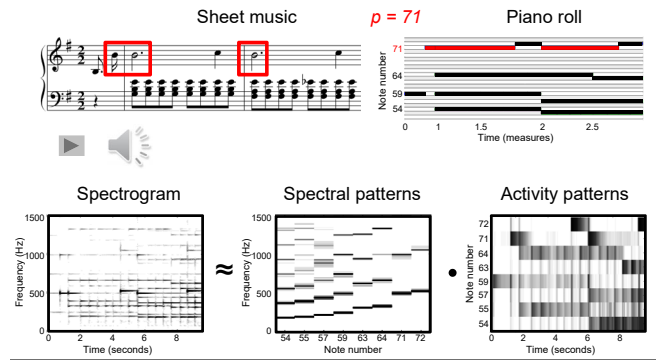
Score-Informed Audio Decomposition



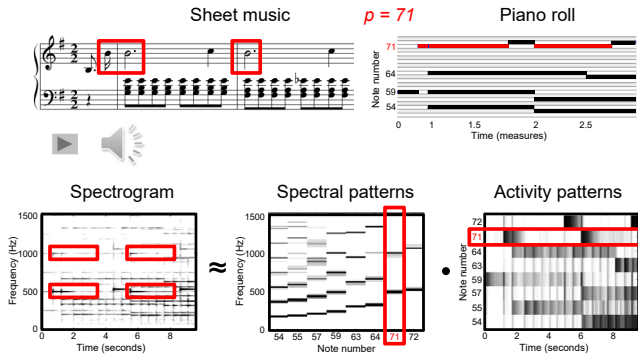
Score-Informed Audio Decomposition



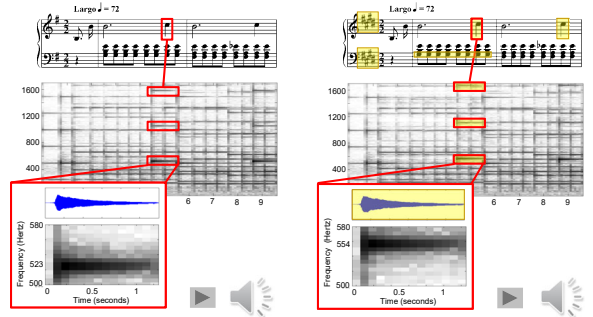
Score-Informed Audio Decomposition



Score-Informed Audio Decomposition

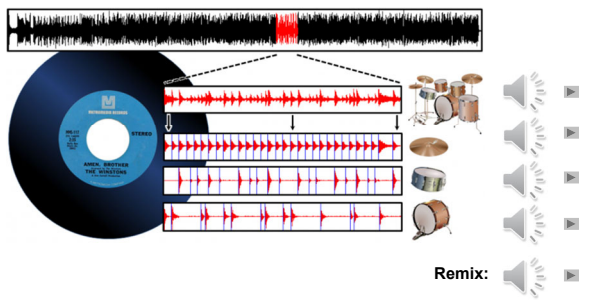


Score-Informed Audio Decomposition



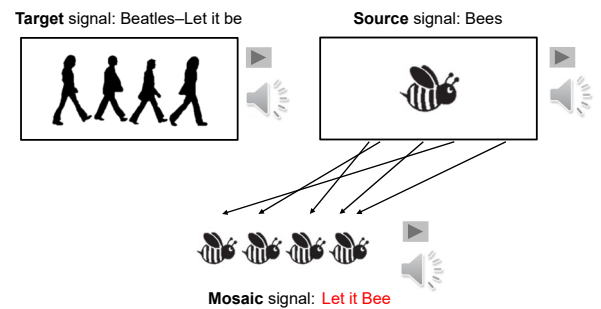
Score-Informed Audio Decomposition

Informed Drum-Sound Decomposition



Score-Informed Audio Decomposition

Audio mosaicing (style transfer)



Singing Voice Processing



Singing Voice Processing



Room
Microphone



AI-Based Source Separation



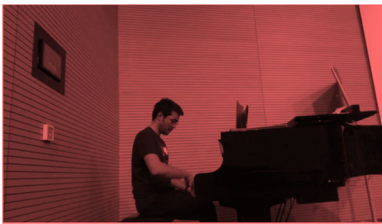
AI-Based Source Separation

- Yigitcan Özer
- PhD student in engineering
- Pianist



AI-Based Source Separation

- Yigitcan Özer
- PhD student in engineering
- Pianist



Only Piano!



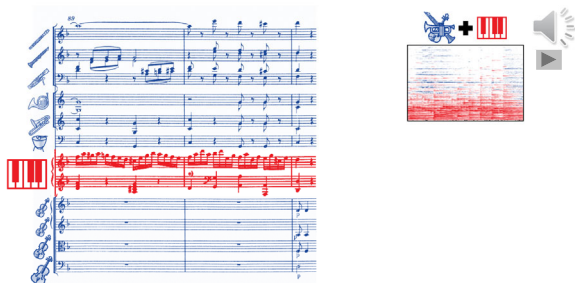
Where is the orchestra?



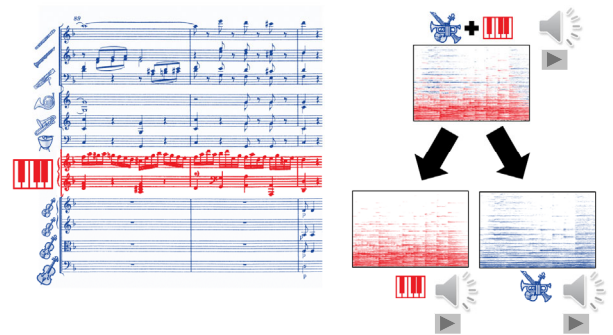
AI-Based Source Separation



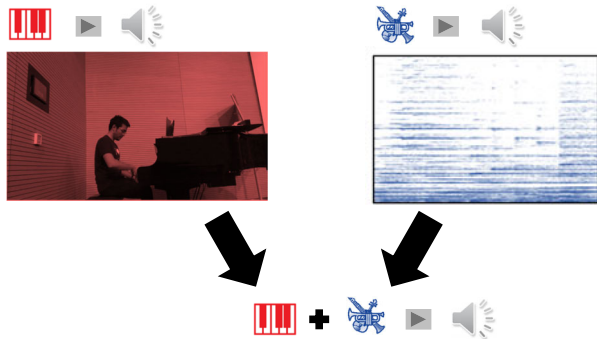
AI-Based Source Separation



AI-Based Source Separation



AI-Based Source Separation

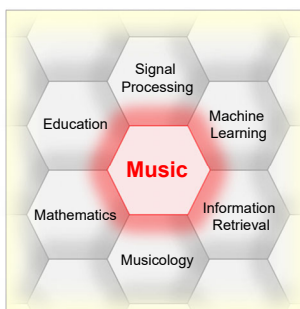


AI-Based Source Separation

Conclusions

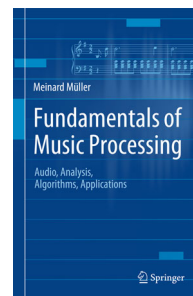
- Understanding modern machine learning techniques
- Critical questioning of artificial intelligence (AI) concepts
- Developing explainable AI models
- Educating next generation of scientists
- ...

Computational Music Research



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

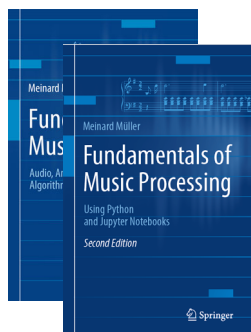
Fundamentals of Music Processing (FMP)



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

Accompanying website:
www.music-processing.de

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2nd edition
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Fundamentals of Music Processing (FMP)

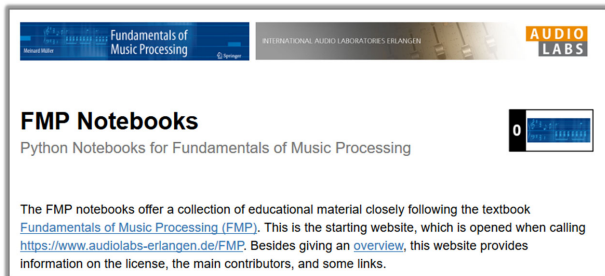
Chapter	Music Processing Scenario
1	Music Representations
2	Fourier Analysis of Signals
3	Music Synchronization
4	Music Structure Analysis
5	Chord Recognition
6	Tempo and Beat Tracking
7	Content-Based Audio Retrieval
8	Musically Informed Audio Decomposition

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FMP Notebooks: Education & Research



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

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<https://joss.theoj.org/papers/10.21105/joss.03326>
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<https://ieeexplore.ieee.org/document/9418542>

Resources (Group Meinard Müller)

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