

Annotations and Analyses in Computational Musicology: Separate it or not?

Meinard Müller, Viora Arifi-Müller, Christof Weiß

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Possibilities and Limitations of Digital Annotation Tools for Audio-Visual Material with a focus on Sound and Music
Mainz, May 2–4, 2022



Meinard Müller



- Mathematics (Diplom/Master)
Computer Science (PhD)
Information Retrieval (Habilitation)



- Since 2012: Professor
Semantic Audio Processing



- Former President of the International Society for Music Information Retrieval (MIR)



- IEEE Fellow for contributions to Music Signal Processing

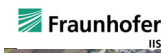


Meinard Müller: Research Group Semantic Audio Processing

- Christof Weiß
- Viora 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

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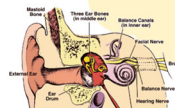
Audio Coding



3D Audio



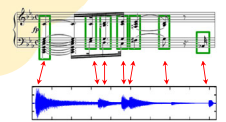
Audio



Psychoacoustics



Internet of Things



Music Processing

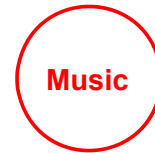
AudioLabs – FAU

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- Prof. Dr. Meinard Müller
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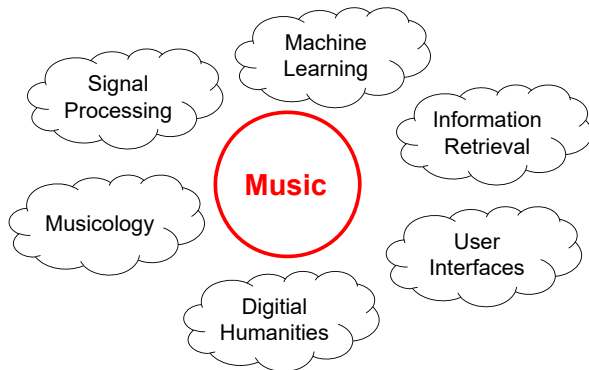


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Music Information Retrieval (MIR)



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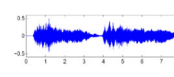


Music Information Retrieval (MIR)

Sheet Music (Image)



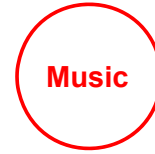
CD / MP3 (Audio)



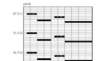
MusicXML (Text)

```
<?xml version="1.0" encoding="UTF-8" >
<musicxml>
<score>
<staff>
<note>
</note>
</staff>
</score>
</musicxml>
```

Dance / Motion (Mocap)



MIDI



Singing / Voice (Audio)



Music Film (Video)



Music Literature (Text)



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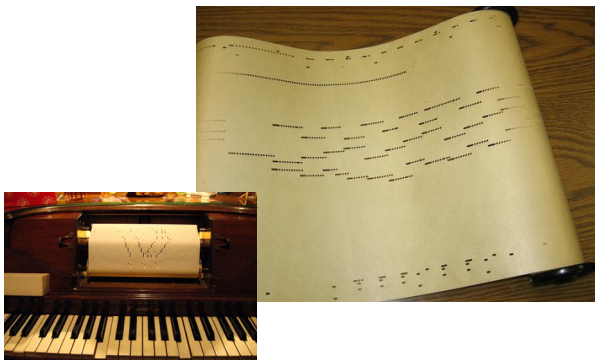


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Piano Roll Representation (1900)



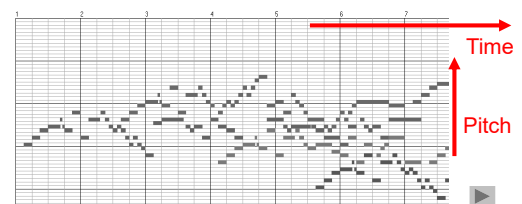
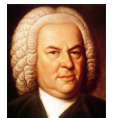
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Piano Roll Representation

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



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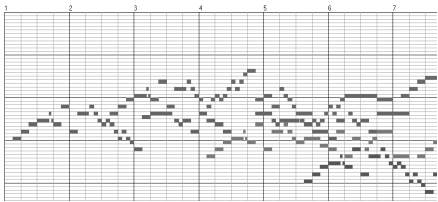
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Piano Roll Representation

Query: 

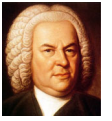
Goal: Find all occurrences of the query



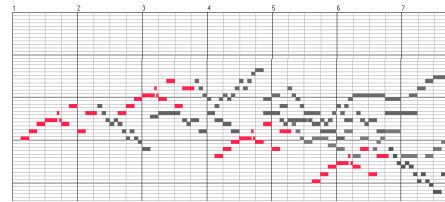
Piano Roll Representation

Query: 

Goal: Find all occurrences of the query



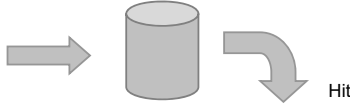
Matches:



Music Retrieval



Database



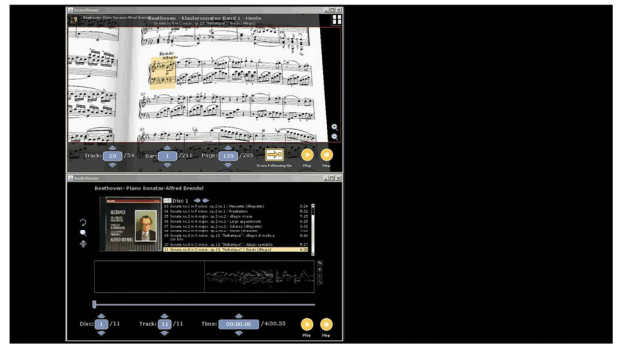
Audio ID

Version ID

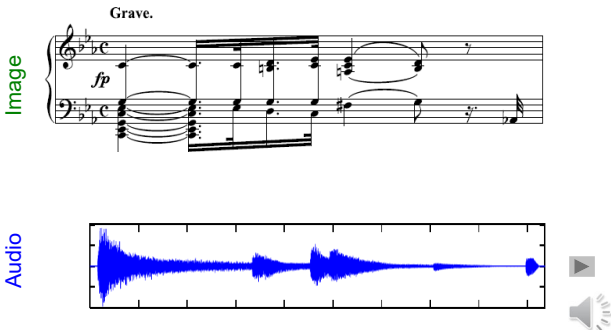
Category ID

- Hit
- 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

Score Following

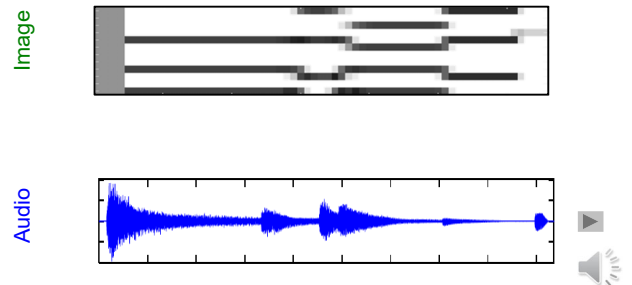


Music Synchronization: Image-Audio



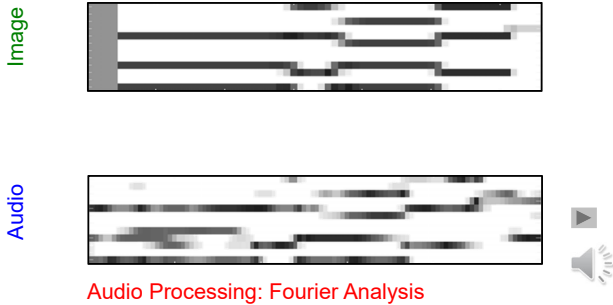
Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition



Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition



Audio Processing: Fourier Analysis

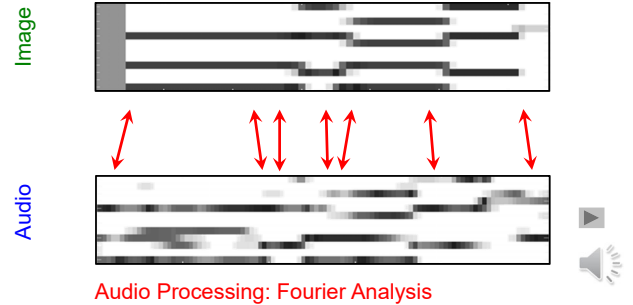
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Annotations and Analyses in
Computational Musicology



Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition



Audio Processing: Fourier Analysis

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Annotations and Analyses in
Computational Musicology



Music Scenarios

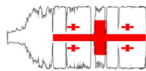
- Freischütz Digital



- Wagner's Ring



- Georgian Music



- Schubert Winterreise



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Annotations and Analyses in
Computational Musicology



Scenario: Freischütz Digital



- BMBF (2012 – 2016)

- Detmold/Paderborn
(Prof. Veit, Digital Editions)

- Frankfurt
(Prof. Betzwieser, Musicology)

- Erlangen
(Prof. Müller, Computer Science)



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(Prof. Müller, Computer Science)



Audio

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Annotations and Analyses in
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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"

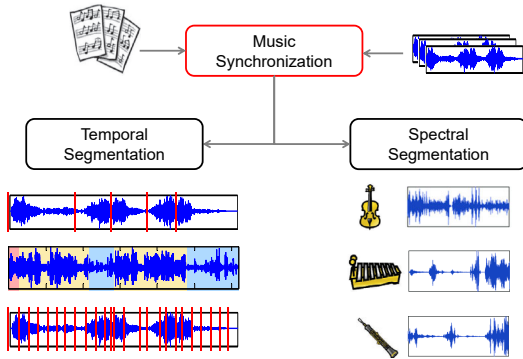
Variations	Performance
	Kleiber C. , 1973
Tempo	Elmendorff, 1944
Language	Penin (fr.), 1998
Key	Orlov (russ.), 1946
Sound quality	Gui (it.), 1957

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Computational Musicology



Scenario: Freischütz Digital

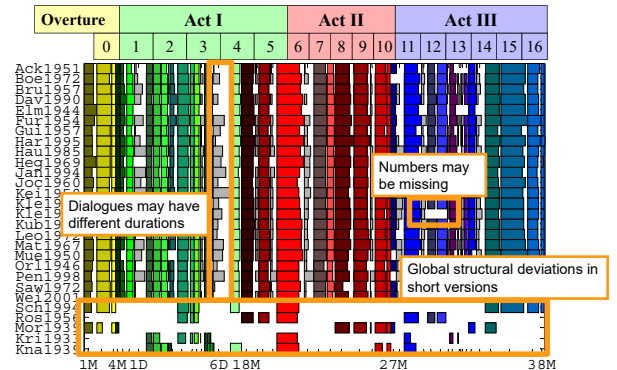


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Scenario: Freischütz Digital



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Annotations and Analyses in
Computational Musicology



Scenario: Freischütz Digital



- Global inconsistencies and deviations
- Annotation process raises research questions
 - Structure analysis
 - Partial alignment
 - Language detection
 - Key detection
 - ...
- Annotation process becomes the subject of research

Daniel Rösenstrunk, Thomas Prätzlich, Thomas Betzwieser, Meinard Müller, Gerdt Szwillus, Joachim Veit:
Das Gesamtkunstwerk Oper aus Datensicht — Aspekte des Umgangs mit einer heterogenen Datenlage im
BMBF-Projekt Freischütz Digital¹, Datenbank-Spektrum, 15(1): 65–72, 2015.

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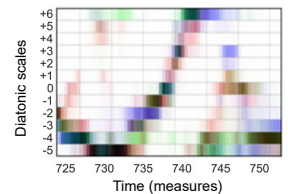
Annotations and Analyses in
Computational Musicology



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



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Annotations and Analyses in
Computational Musicology



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

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Annotations and Analyses in
Computational Musicology



Scenario: Wagner's Ring



No.	Conductor	Recording	hh:mm:ss
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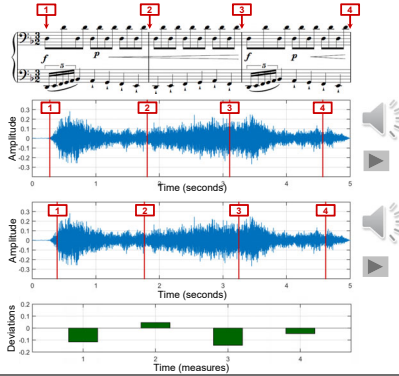
- Large-scale work
- Four operas
 - ca. 15 hours
 - 21941 measures
- 16 performances
- Manual measure annotations

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Annotations and Analyses in
Computational Musicology



Scenario: Wagner's Ring



Annotator 1

Annotator 2

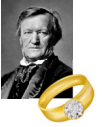
Deviations

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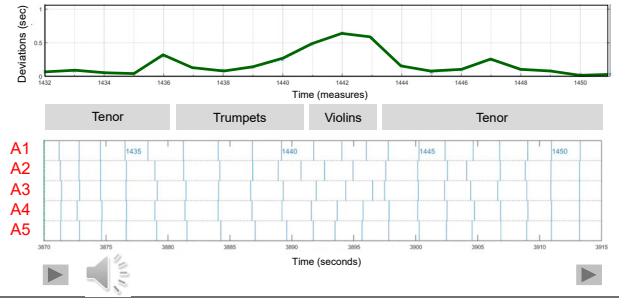
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Scenario: Wagner's Ring



Standard deviations among annotators



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Annotations and Analyses in
Computational Musicology



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 Arifi-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.

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Annotations and Analyses in
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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



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Annotations and Analyses in
Computational Musicology

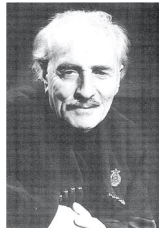


Scenario: Georgian Music

Erkomaishvili Dataset



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



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

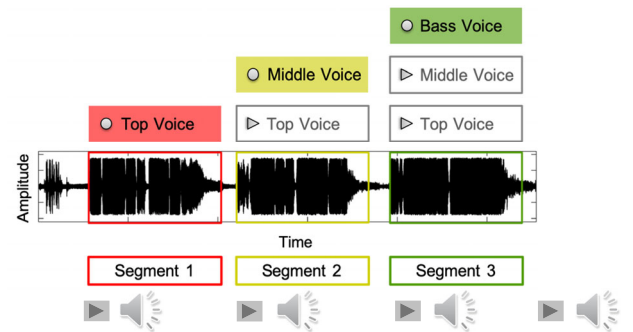
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Annotations and Analyses in
Computational Musicology



Scenario: Georgian Music

Erkomaishvili Dataset

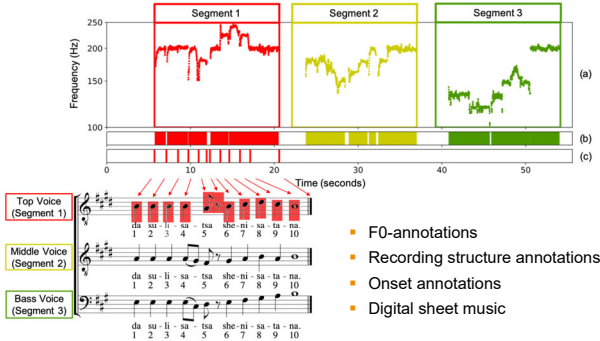
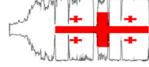


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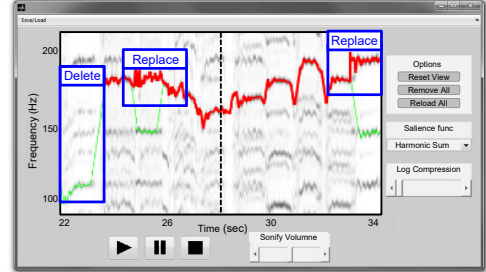
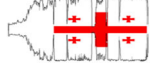
Scenario: Georgian Music Erkomaishvili Dataset



- F0-annotations
- Recording structure annotations
- Onset annotations
- Digital sheet music



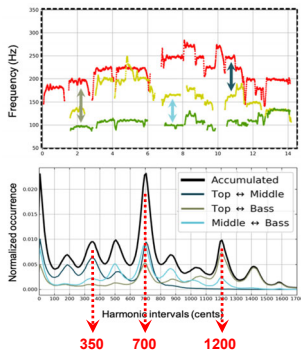
Scenario: Georgian Music Interactive F0 Annotation Tool



Meinard Müller, Sebastian Rosenzweig, Jonathan Driedger, and Frank Scherbaum:
Interactive Fundamental Frequency Estimation with Applications to Ethnomusicological Research.
 In Proceedings of the AES Conference on Semantic Audio, 2017.



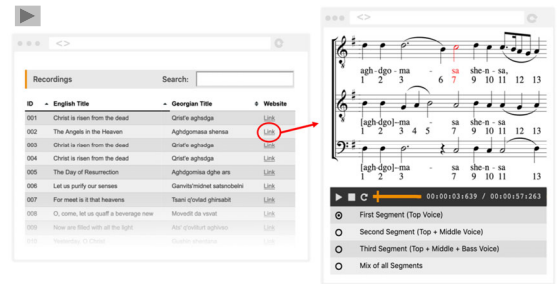
Scenario: Georgian Music Erkomaishvili Dataset



- Superimposed F0-trajectories
- Measuring harmonic intervals
- Peak at 350 cents (between minor and major third)
- Non-western temperament



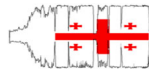
Scenario: Georgian Music Erkomaishvili Dataset



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



Scenario: Georgian Music Erkomaishvili Dataset



- 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 (TISMIR), 3(1): 31–41, 2020.



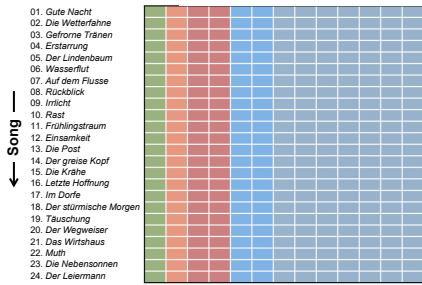
Scenario: Schubert Winterreise



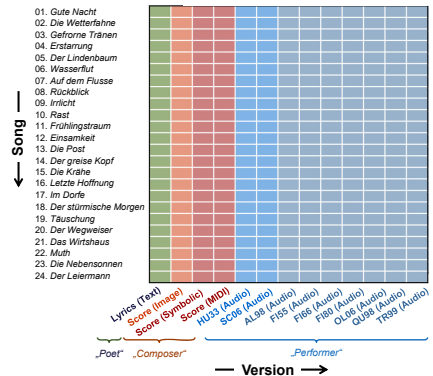
- Winterreise
 - Song cycle for voice and piano
 - Music: Franz Schubert (1828)
 - Poems: Wilhelm Müller
- MIR Objectives
 - Music synchronization
 - Structure analysis
 - Harmonic analysis
 - Activity detection (singing, lyrics, ...)
 - ...



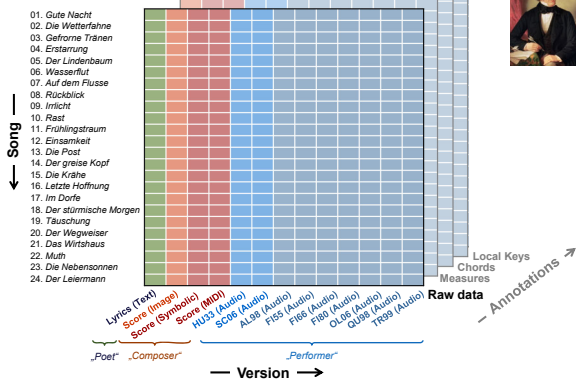
Scenario: Schubert Winterreise



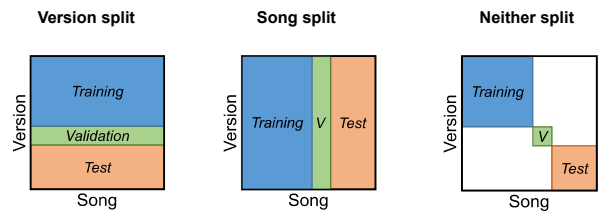
Scenario: Schubert Winterreise



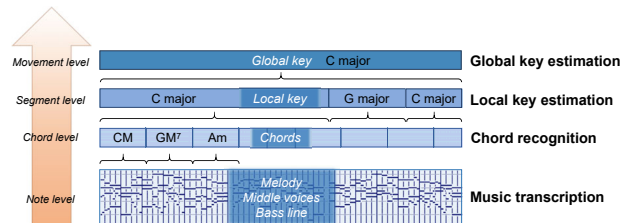
Scenario: Schubert Winterreise



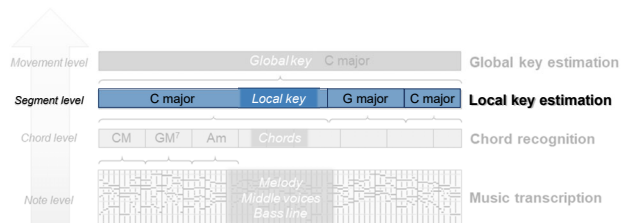
Scenario: Schubert Winterreise Cross-Version Evaluation



Scenario: Schubert Winterreise Harmony Analysis



Scenario: Schubert Winterreise Harmony Analysis



Scenario: Schubert Winterreise Harmony Analysis



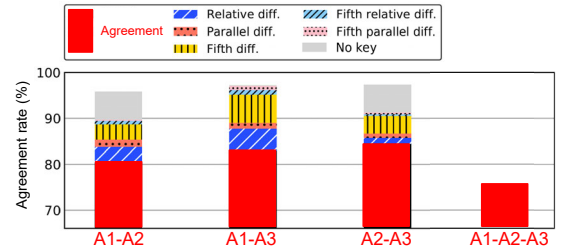
Annotations

A1	A major	A minor	E major	A major
A2	A major			
A3	A major	A minor	A major	

Scenario: Schubert Winterreise Harmony Analysis



Annotator agreements and differences



Scenario: Schubert Winterreise Harmony Analysis

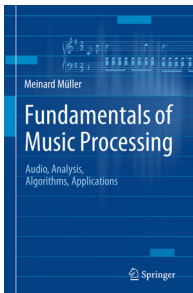
- Harmony-related annotations
 - Hierarchical nature of musical structures
 - High degree of subjectivity
 - Dependence on user needs and applications
- ...

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 (JOCCH), 15(2): 1–18, 2021.

Conclusions

- 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

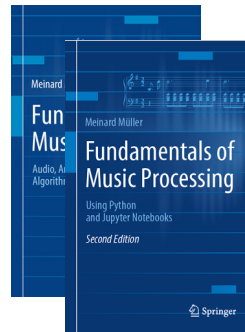
Fundamentals of Music Processing (FMP)



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

Accompanying website:
www.music-processing.de

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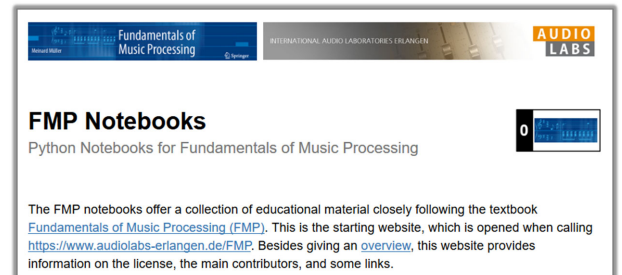
Chapter	Music Processing Scenario
1	Music Representations
2	Fourier Analysis of Signals
3	Music Synchronization
4	Music Structure Analysis
5	Chord Recognition
6	Tempo and Beat Tracking
7	Content-Based Audio Retrieval
8	Musically Informed Audio Decomposition

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FMP Notebooks: Education & Research



FMP Notebooks
Python Notebooks for Fundamentals of Music Processing

The FMP notebooks offer a collection of educational material closely following the textbook [Fundamentals of Music Processing \(FMP\)](https://www.audiolabs-erlangen.de/FMP). This is the starting website, which is opened when calling <https://www.audiolabs-erlangen.de/FMP>. Besides giving an [overview](#), this website provides information on the license, the main contributors, and some links.

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

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>

References

- Meinard Müller: **Fundamentals of Music Processing – Using Python and Jupyter Notebooks**. 2nd Edition, Springer, 2021.
- Daniel Rösenstrunk, Thomas Prätzlich, Thomas Betzwieser, Meinard Müller, Gerd Szwillus, Joachim Veit: **Das Gesamtkunstwerk Oper aus Datensicht — Aspekte des Umgangs mit einer heterogenen Datenlage im BMBF-Projekt Freischütz Digital**. Datenbank-Spektrum, 15(1): 65–72, 2015.
- Christof Weiß, Viora Arifi-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.
- 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 (TISMIR), 3(1): 31–41, 2020.
- Meinard Müller, Sebastian Rosenzweig, Jonathan Driedger, and Frank Scherbaum: **Interactive Fundamental Frequency Estimation with Applications to Ethnomusicological Research**. In Proceedings of the AES Conference on Semantic Audio, 2017.
- Christof Weiß, Frank Zalkow, Viora Arifi-Müller, Meinard Müller, Hendrik Vincent Koops, Anja Volk, Harald Grohgan: **Schubert Winterreise Dataset: A Multimodal Scenario for Music Analysis**. ACM Journal on Computing and Cultural Heritage (JOCCH), 15(2): 1–18, 2021.
- Christof Weiß, Hendrik Schreiber, Meinard Müller: **Local Key Estimation in Music Recordings: A Case Study Across Songs, Versions, and Annotators**. IEEE/ACM Transactions on Audio, Speech, and Language Processing, 28: 2919–2932, 2020.