INTERNATIONAL AUDIO LABORATORIES ERLANGEN
A joint institution of Fraunhofer IIS and Universität Erlangen-Nürnberg

AUDIO LABS

Digitale Musikverarbeitung: Vom Scheitern Lernen

Meinard Müller
International Audio Laboratories Erlangen
meinard.mueller@audiolabs-erlangen.de

Digitalität & Kulturelle Resilienz:
Afghanische Musik in der Diaspora

Nürnberg, 09. Januar 2025

FAU Friedrich-Alexander-Universität Erlangen-Nürnberg

Fraunhofer IIS

Meinard Müller

- Mathematics (Diplom/Master, 1997)
  Computer Science (PhD, 2001)
  Information Retrieval (Habilitation, 2007)
- Senior Researcher (2007-2012)
- Professor Semantic Audio Processing (since 2012)
- Former President of the International Society for Music Information Retrieval (MIR)
- IEEE Fellow for contributions to Music Signal Processing

universitätbonn

max planck institut informatik

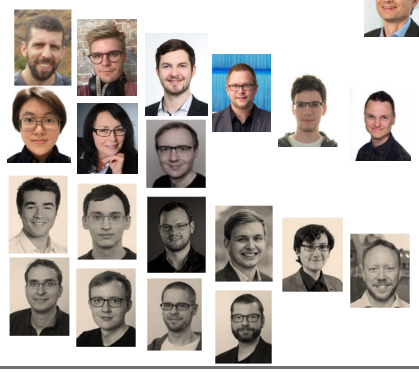
FAU

ISMIR

IEEE

Meinard Müller: Research Group

- Ben Maman
- Simon Schwär
- Johannes Zeitler
- Peter Meier
- Sebastian Strahl
- Uli Berendes
- Ching-Yu Chiu (Sunny)
- Vlora Arifi-Müller
- Stefan Balke
- Yigitcan Özer
- Michael Krause
- Christof Weiß
- Sebastian Rosenzweig
- Frank Zalkow
- Hendrik Schreiber
- Christian Dittmar
- Stefan Balke
- Jonathan Driedger
- Thomas Prätzlich
- …



International Audio Laboratories Erlangen

Fraunhofer IIS

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

mp3

AUDIO LABS

FAU Friedrich-Alexander-Universität Erlangen-Nürnberg

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

International Audio Laboratories Erlangen

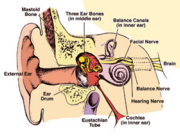
Audio

International Audio Laboratories Erlangen

Audio Coding

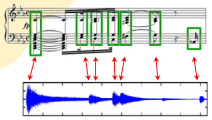
3D Audio

Audio



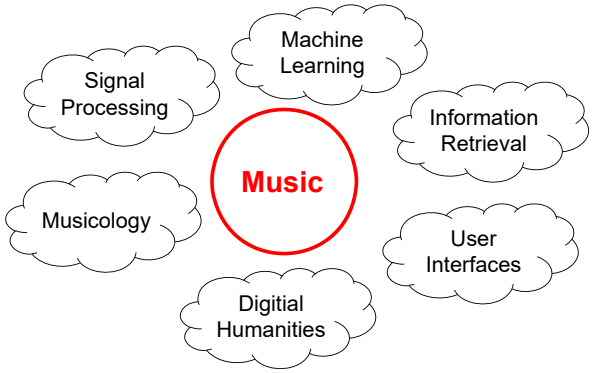
Psychoacoustics

Internet of Things



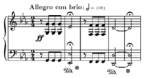
Music Processing

Music Information Retrieval (MIR)

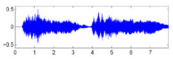


Music Information Retrieval (MIR)

Sheet Music (Image)



CD / MP3 (Audio)



MusicXML (Text)

Dance / Motion (Mocap)

Music

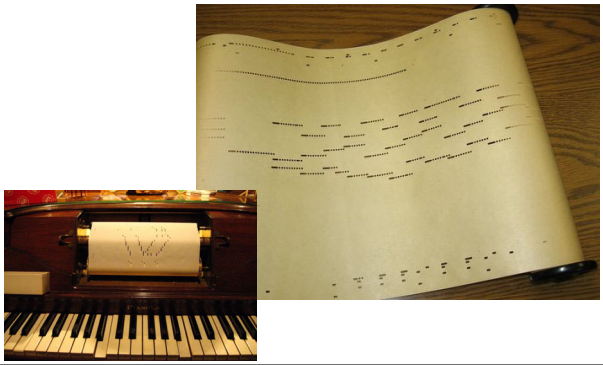
MIDI

Singing / Voice (Audio)

Music Film (Video)

Music Literature (Text)

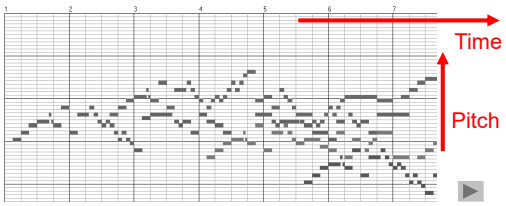
Piano Roll Representation (1900)



Piano Roll Representation

J.S. Bach, C-Major Fuge

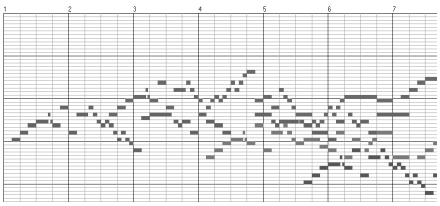
(Well Tempered Piano, BWV 846)



Piano Roll Representation

Query:

Goal: Find all occurrences of the query

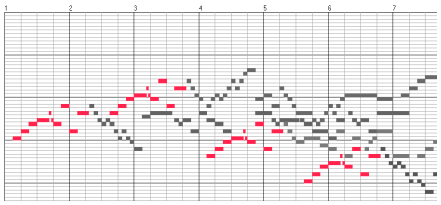


Piano Roll Representation

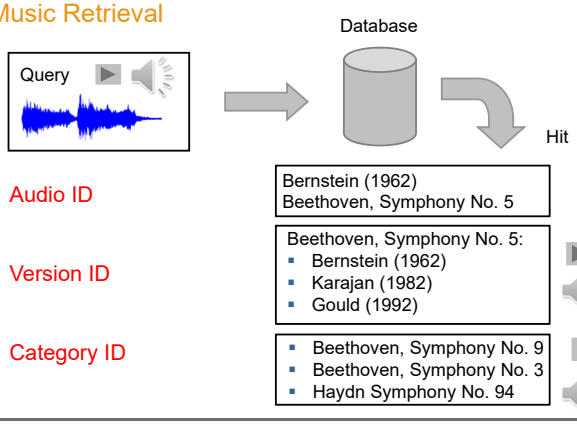
Query:

Goal: Find all occurrences of the query

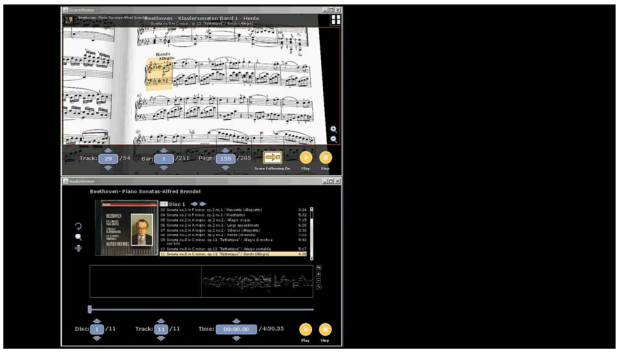
Matches:



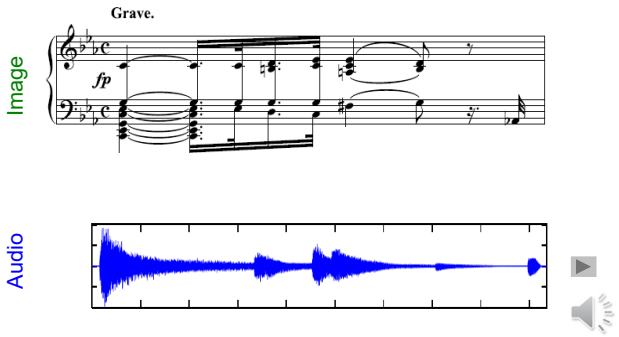
Music Retrieval



Music Synchronization

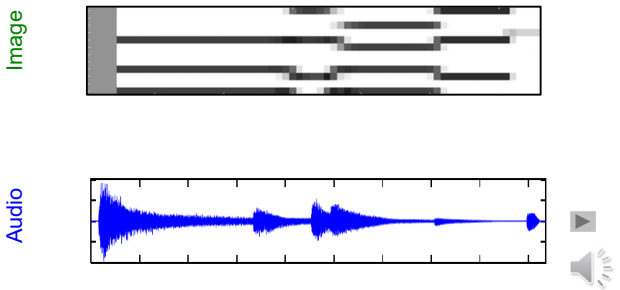


Music Synchronization: Image-Audio



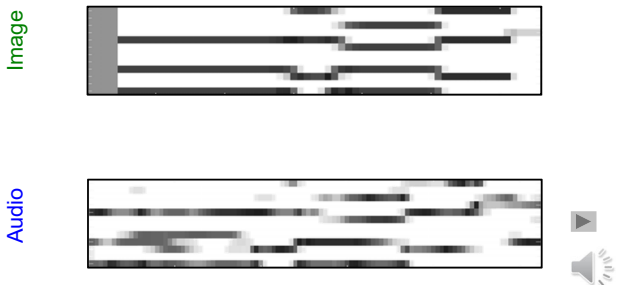
Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition



Music Synchronization: Image-Audio

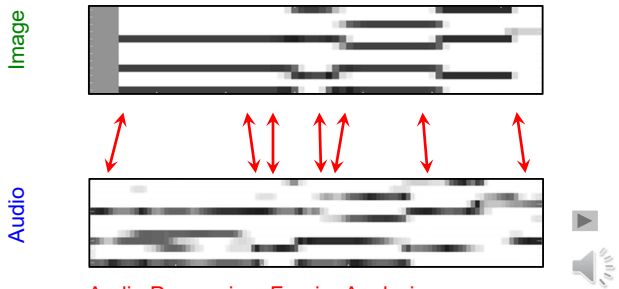
Image Processing: Optical Music Recognition



Audio Processing: Fourier Analysis

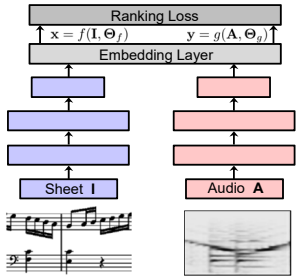
Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition



Audio Processing: Fourier Analysis

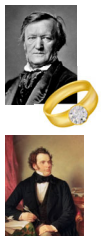
Music Synchronization: Image-Audio



- Deep learning
- Embedding techniques
- Weak annotations
- Loss functions
- …

Music Scenarios

- Freischütz Digital
- Wagner's Ring
- Georgian Music
- Schubert Winterreise
- Piano Concerto



Scenario: Freischütz Digital

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

Scenario: Freischütz Digital

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Scenario: Freischütz Digital

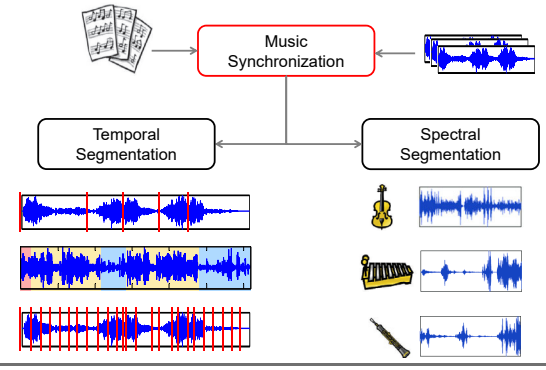
Recordings

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

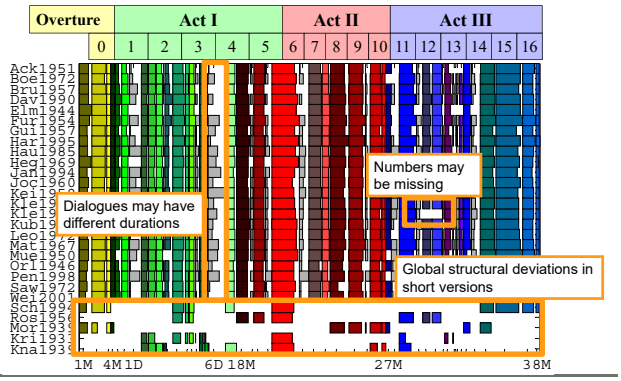
Example: Song (No. 4) from "Der Freischütz"

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



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 Röwenstrunk, 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.

Scenario: Wagner’s Ring

- DFG (2014 – 2024)
- 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

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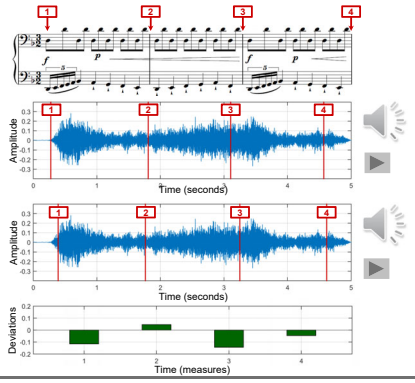
- Large-scale work
- Four operas
  - ca.15 hours
  - 21941 measures
- 16 performances
- Manual measure annotations

Scenario: Wagner's Ring



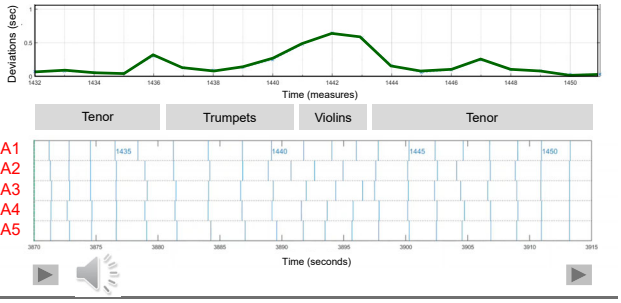
Annotator 1

Annotator 2

Deviations

Scenario: Wagner's Ring

Standard deviations among **annotators**



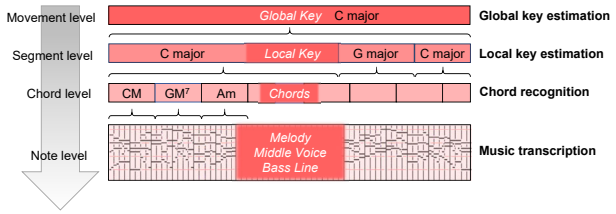
Scenario: Wagner's Ring

- 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, Vlora 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.

Computational Musicology: Harmony Analysis

- Different concepts
- Different temporal levels



Computational Musicology: Harmony Analysis

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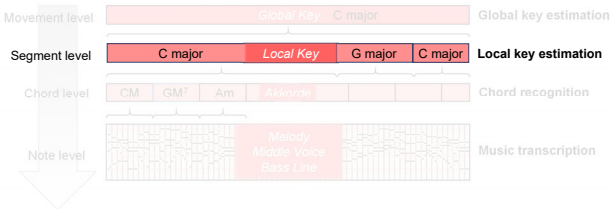
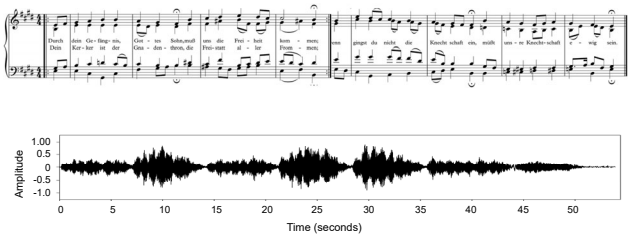
- Different temporal levels



Local Key Estimation

Example: J.S. Bach, Choral "Durch Dein Gefängnis" (*Johannespassion*)



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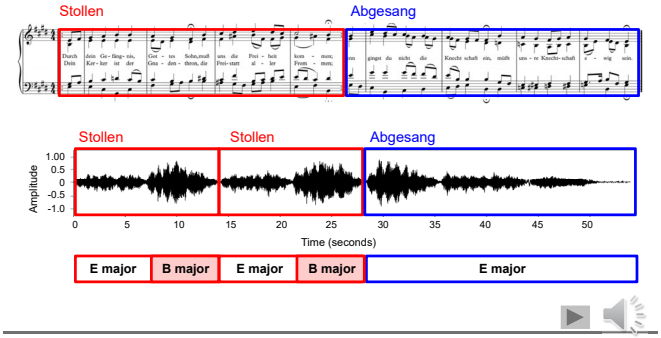
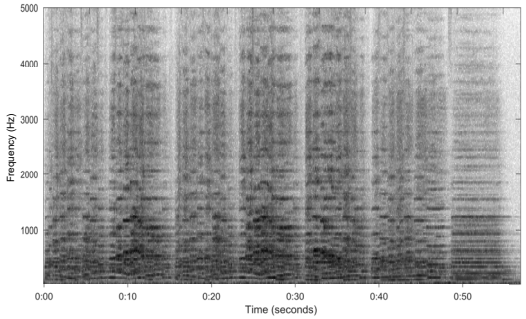


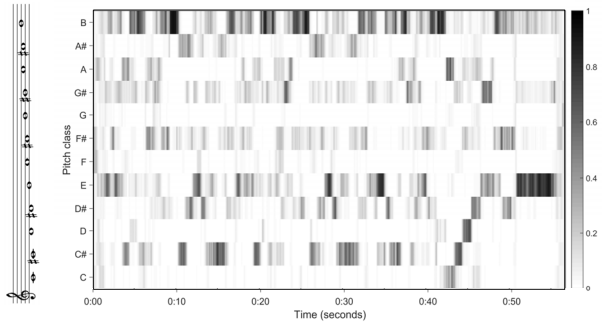
Local Key Estimation

Spectrogram



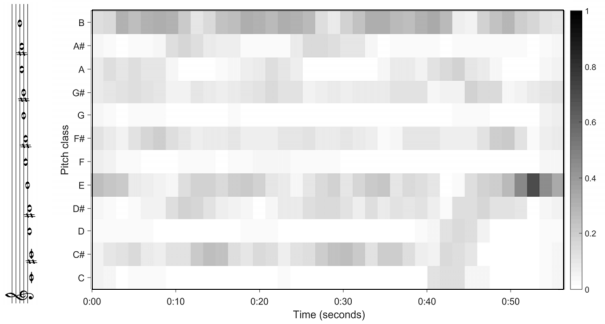
Local Key Estimation

Chromagram



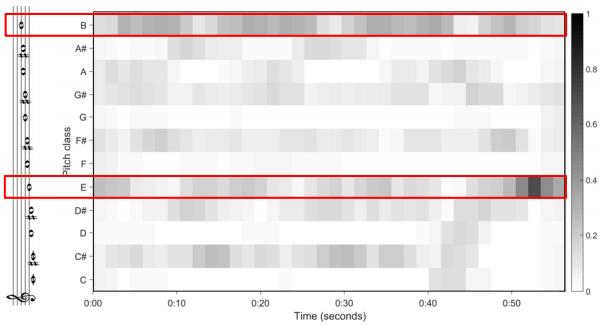
Local Key Estimation

Chromagram after smoothing



Local Key Estimation

Arrange pitch classes according to **perfect fifth** series



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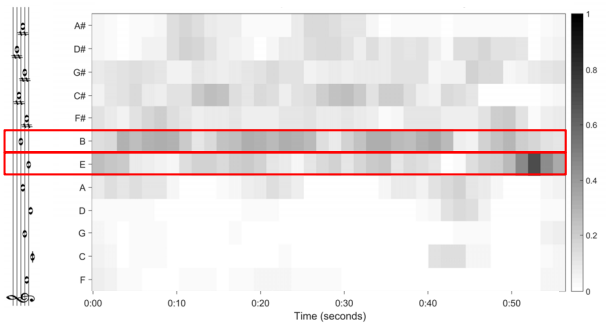
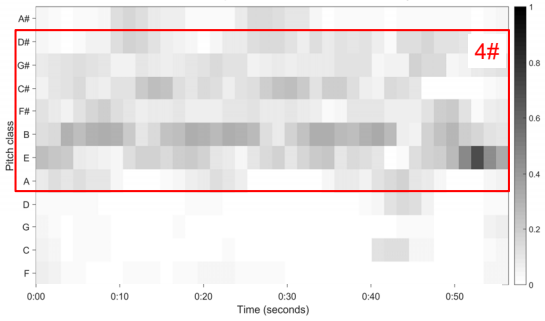


Local Key Estimation

Summarize pitch class content according to **diatonic scales**



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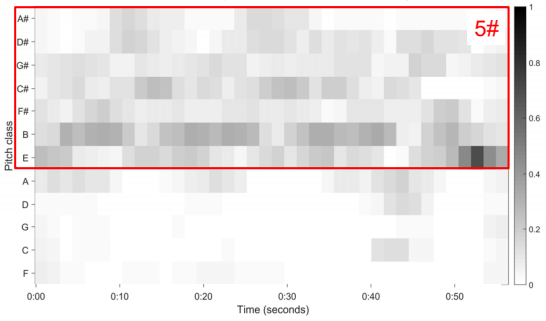
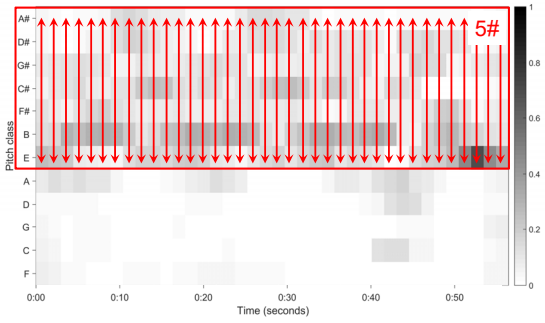


Local Key Estimation

Summarize pitch class content according to **diatonic scales**

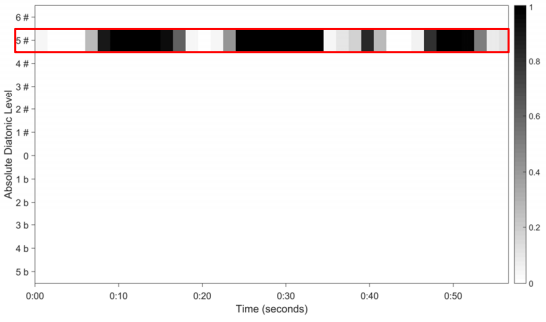
Multiply chroma values (in each column)



Local Key Estimation

Summarize pitch class content according to **diatonic scales**

Multiply chroma values



Local Key Estimation

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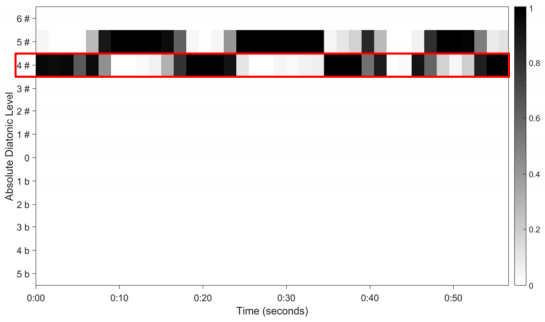

Local Key Estimation

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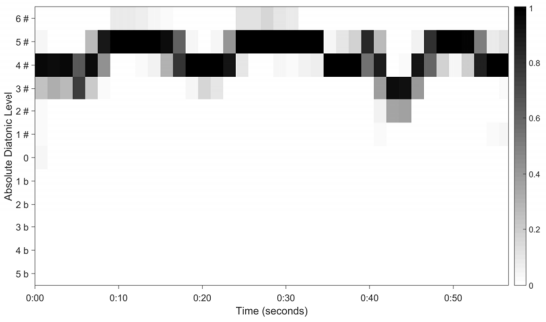
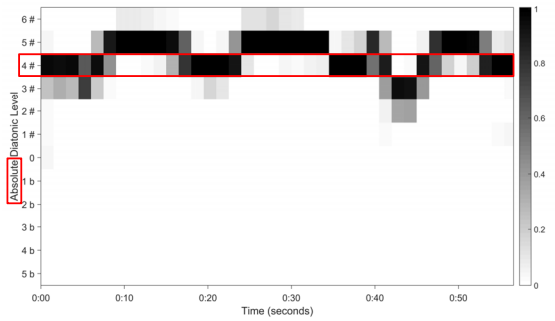


Local Key Estimation

Normalize representation relative to global key

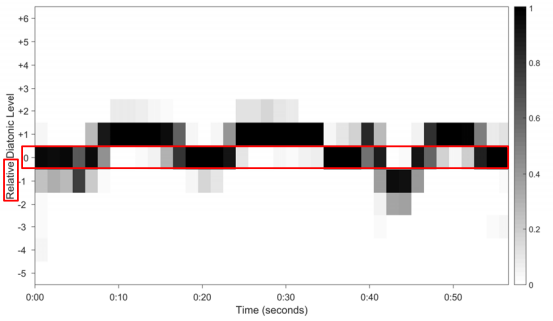
4 #
(E major)



Local Key Estimation

Normalize representation relative to global key

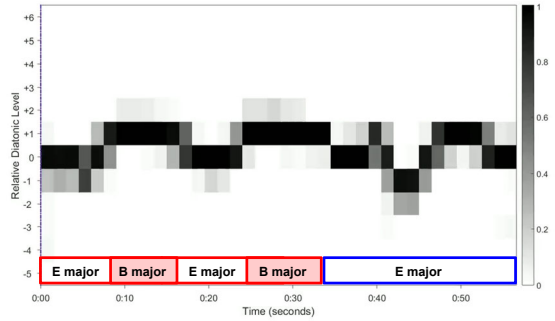
4 #
(E major)



Local Key Estimation

J.S. Bach: Choral "Durch Dein Gefängnis" (*Johannespassion*)
Recording: Scholars Baroque Ensemble, Naxos 1994

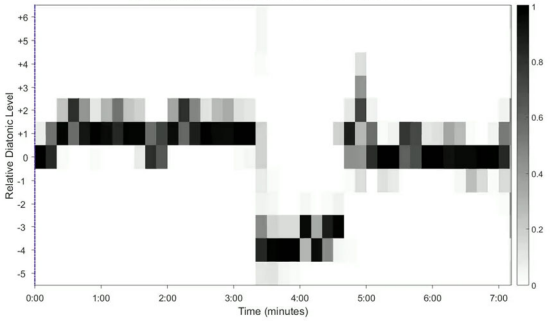
4 #
(E major)



Local Key Estimation

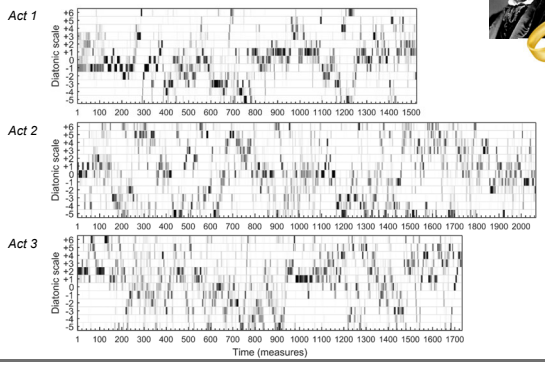
L. v. Beethoven: Piano Sonata No. 10 (Op. 14 Nr. 2), 1. Allegro
Recording: Barenboim, EMI 1998

1 #
(G major)



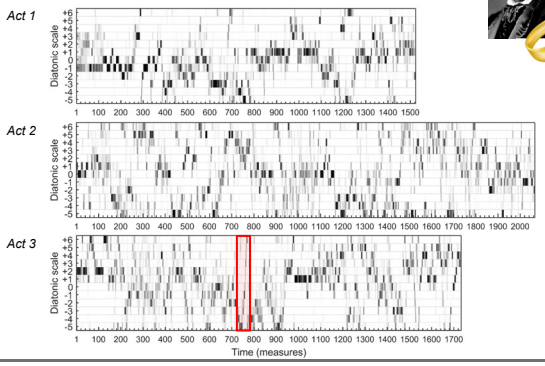
Local Key Estimation

R. Wagner: WWV 86 B (*Die Walküre*)



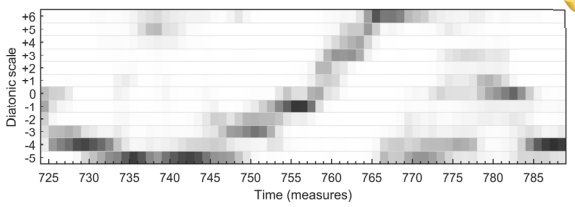
Local Key Estimation

R. Wagner: WWV 86 B (*Die Walküre*)



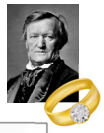
Local Key Estimation

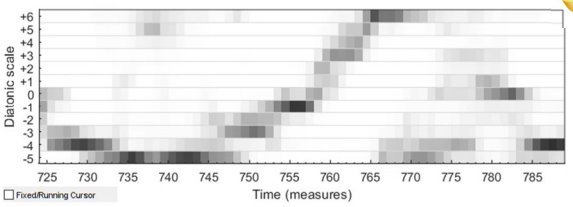
R. Wagner: WWV 86 B (*Die Walküre*)
Act 3, measure 724–789 (*Wotan's punishment*)



Local Key Estimation

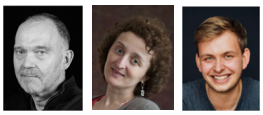
R. Wagner: WWV 86 B (*Die Walküre*)
Act 3, measure 724–789 (*Wotan's punishment*)





Scenario: Georgian Music

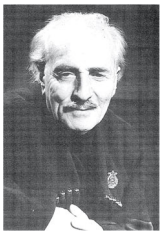
- DFG (2018 – 2022)
- Potsdam
  (Prof. Scherbaum, Ethnomusicology)
- Erlangen
  (Prof. Müller, Computer Science)
- Objectives
  - Harmonic and melodic singing analysis
  - New sensors (larynx microphones)
  - Digital humanities



Scenario: Georgian Music

Erkomaishvili Dataset

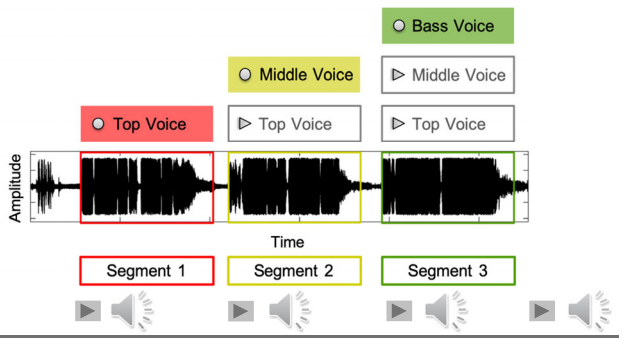
- Collection of traditional
  three-voice Georgian songs
- Performed by the former
  Georgian master chanter
  Artem Erkomaishvili (1887-1967)
- Recordings of 100 songs
  using tape recorders (1966)



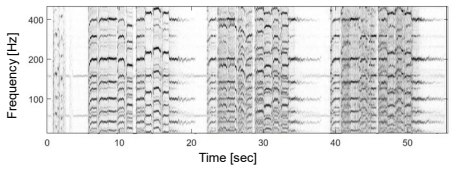
"Original masterpieces of Georgian musical thinking." (Shugliashvili, 2014)

Scenario: Georgian Music

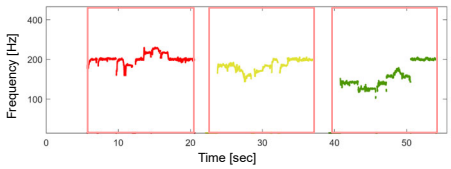
Erkomaishvili Dataset



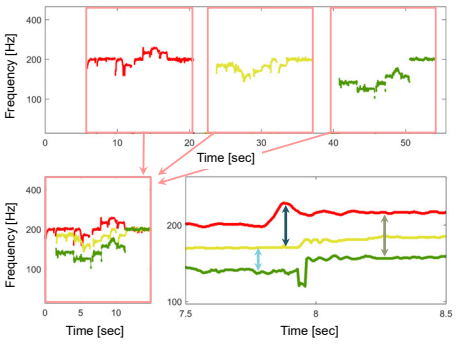
Traditional Georgian Vocal Music



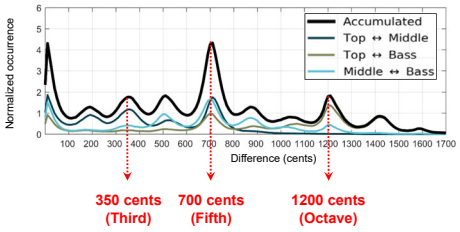
Traditional Georgian Vocal Music



Traditional Georgian Vocal Music



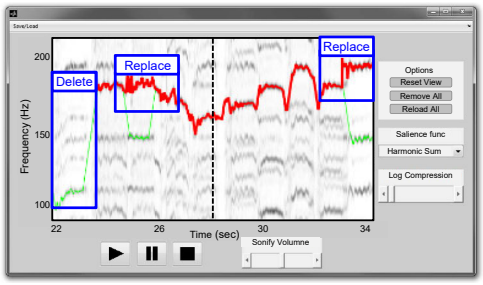
Traditional Georgian Vocal Music



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

Scenario: Georgian Music

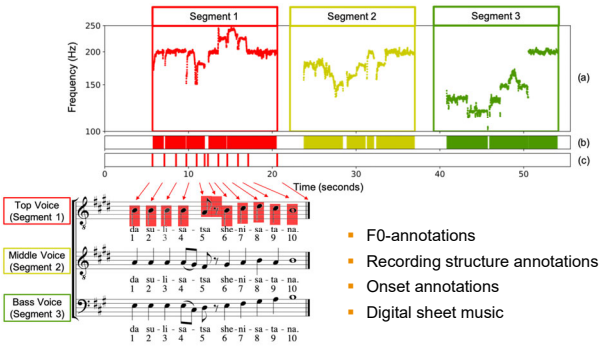
Interactive F0 Annotation Tool



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

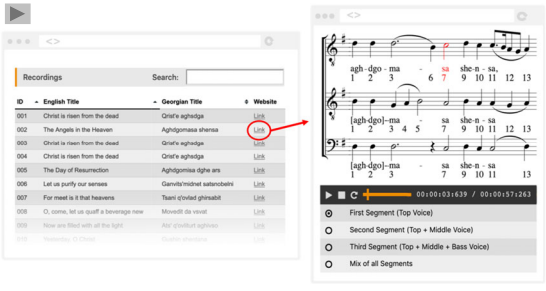
Notewise Annotations



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

Scenario: Georgian Music

Webbased Interfaces



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

Scenario: Georgian Music

Conclusions

- 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, Vlora 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: Georgian Music

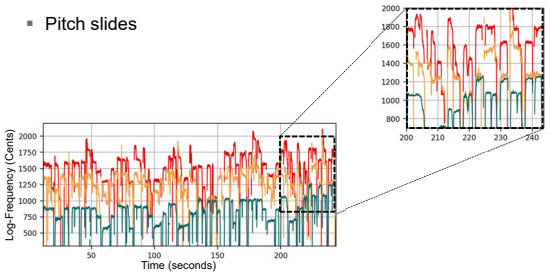
Field Recordings (GVM Collection)

- Recordings from field expedition in 2016
- 216 performances
- Multitrack audio + video
  - Room, HSM, LRX
- Total duration: 6 h

Room Microphone

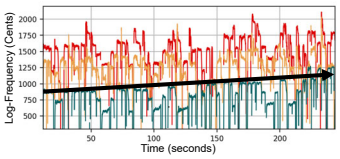
Zär Recordings: Melodic Analysis

- Subset of GVM: Funeral songs (Zär)
- Musical characteristics
  - Pitch slides



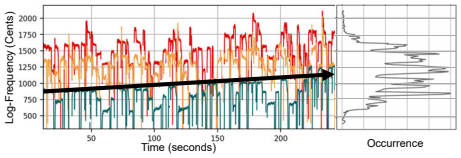
Zär Recordings: Melodic Analysis

- Subset of GVM: Funeral songs (Zär)
- Musical characteristics
  - Pitch slides
  - Pitch drift



Zär Recordings: Melodic Analysis

- Subset of GVM: Funeral songs (Zär)
- Musical characteristics
  - Pitch slides
  - Pitch drift

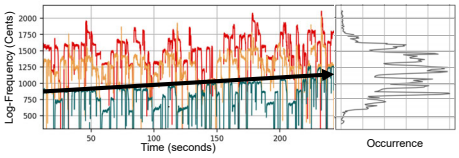


Pitch Inventory

Zär Recordings: Melodic Analysis

- Subset of GVM: Funeral songs (Zär)
- Musical characteristics
  - Pitch slides
  - Pitch drift

Noise & Blurring



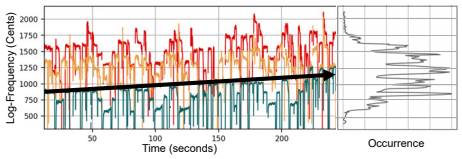
Pitch Inventory

Zär Recordings: Melodic Analysis

- Subset of GVM: Funeral songs (Zär)
- Musical characteristics
  - Pitch slides
  - Pitch drift

Noise & Blurring

- Task: Remove pitch slides & compensate for pitch drift

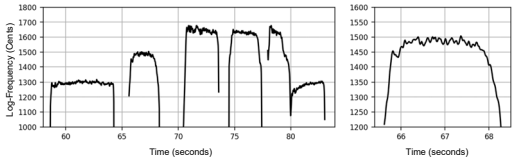


Pitch Inventory

Stable Region Detection

Morphological Approach

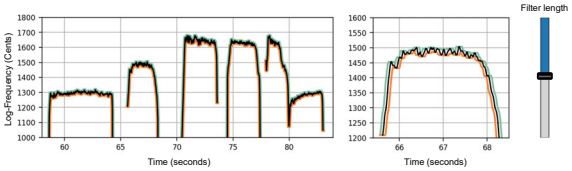
1. F0-Trajectory



Stable Region Detection

Morphological Approach

2. Min-/Max-filtering (erosion/dilation)



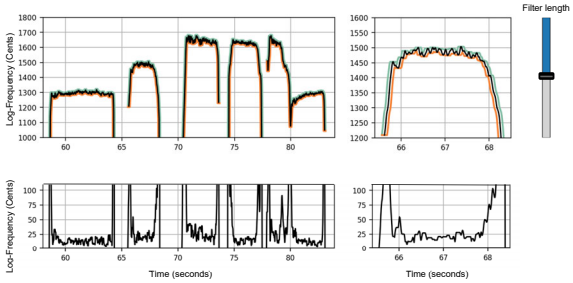
Min-filtered trajectory Max-filtered trajectory

Vávra, Nový, Mašková, Kotlíková, and Netrvalová: **Morphological filtration for time series**. APLIMAT, pp. 983–990, 2004.

Stable Region Detection

Morphological Approach

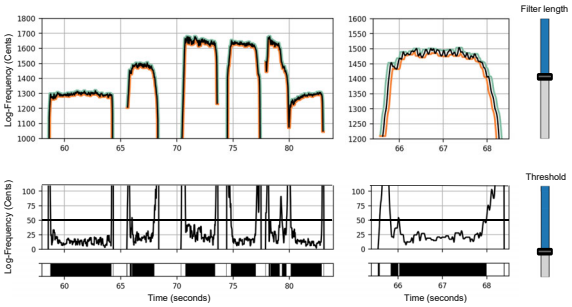
3. Morphological gradient



Stable Region Detection

Morphological Approach

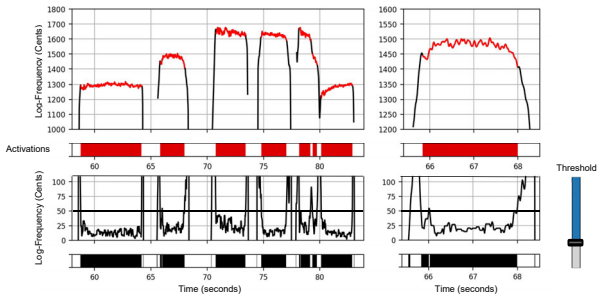
4. Thresholding



Stable Region Detection

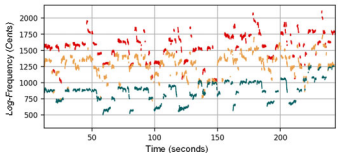
Morphological Approach

5. Stable regions



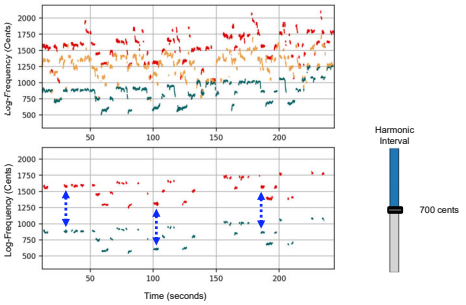
Pitch Drift Estimation

1. Stable regions



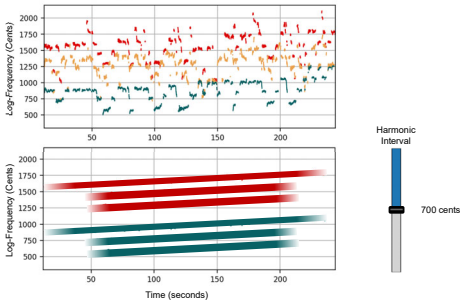
Pitch Drift Estimation

2. Harmonic interval filtering



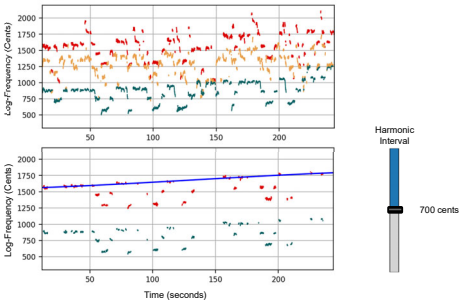
Pitch Drift Estimation

3. Scale degree clustering



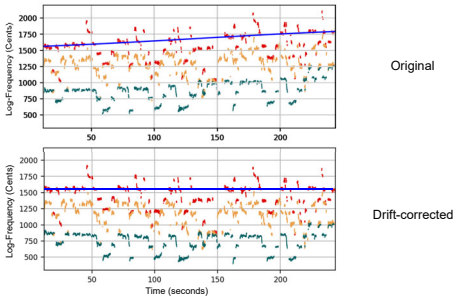
Pitch Drift Estimation

4. Polynomial fitting

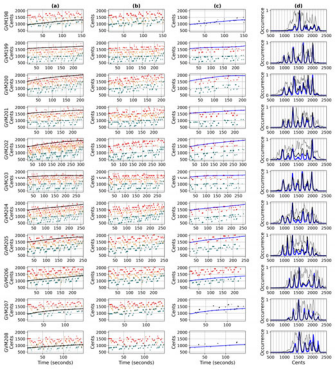


Pitch Drift Estimation

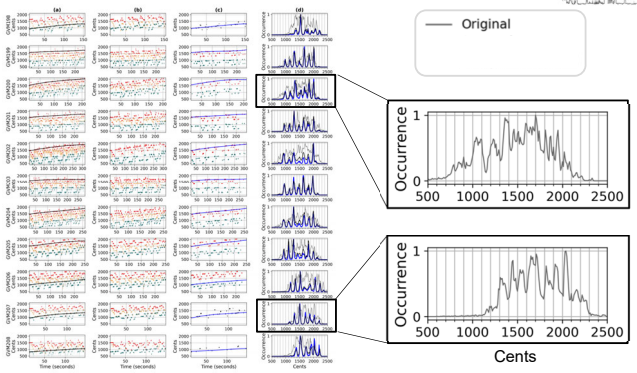
5. Drift correction



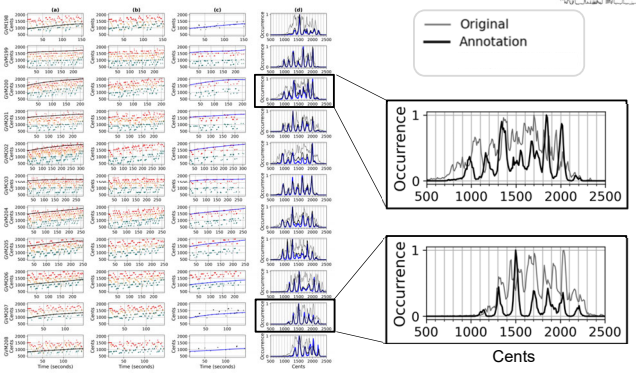
Pitch Inventories of Zär Performances



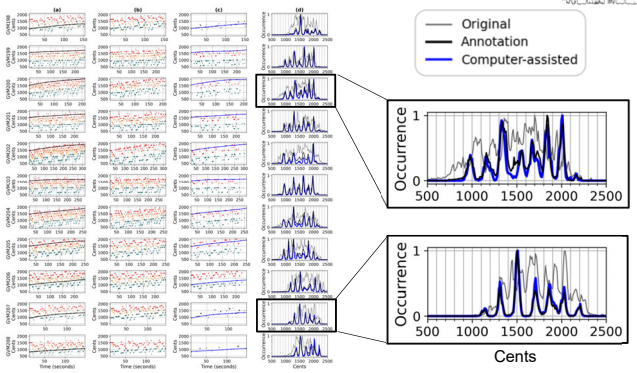
Pitch Inventories of Zär Performances



Pitch Inventories of Zär Performances



Pitch Inventories of Zär Performances



Scenario: Georgian Music

Publications

Computational Tools and Datasets

- Rosenzweig/Scherbaum/Müller. Interactive Tools. **ACM-JOCCH 2022**
- Rosenzweig/Scherbaum/Müller. F0-Reliability. **ICASSP 2021**
- Rosenzweig/Scherbaum/Müller. Stable Regions. **ISMIR 2019**
- Rosenzweig/Scherbaum/Shugliashvili/Arifi-Müller/Müller. Erkomaishvili Dataset. **TISMIR 2020**

Musicological Studies:

- Scherbaum/Mzhavanadze/Arom/Rosenzweig/Müller. Erkomaishvili. **Univ.-Verlag Potsdam 2020**
- Scherbaum/Mzhavanadze/Rosenzweig/Müller. GVM Collection. **FMA 2019**
- Scherbaum/Müller/Rosenzweig. Erkomaishvili. **FMA 2017**
- Scherbaum/Müller/Rosenzweig. Erkomaishvili. **GI 2017**

https://www.audiolabs-erlangen.de/resources/MIR/2022-GeorgianMusic-Zaer

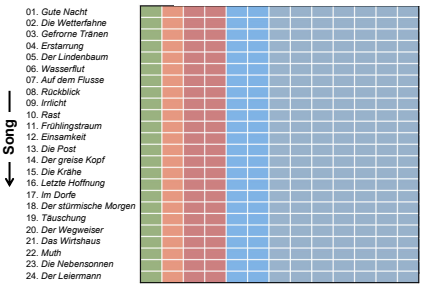
Sebastian Rosenzweig:
PhD in Engineering

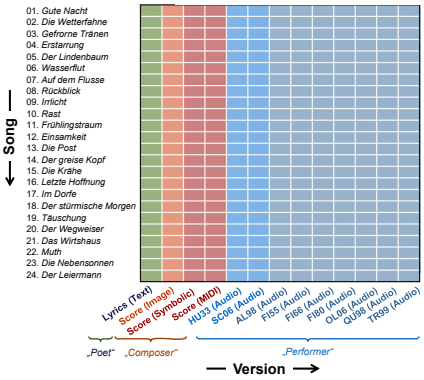
Frank Scherbaum:
Honorary Doctorate in Musicology

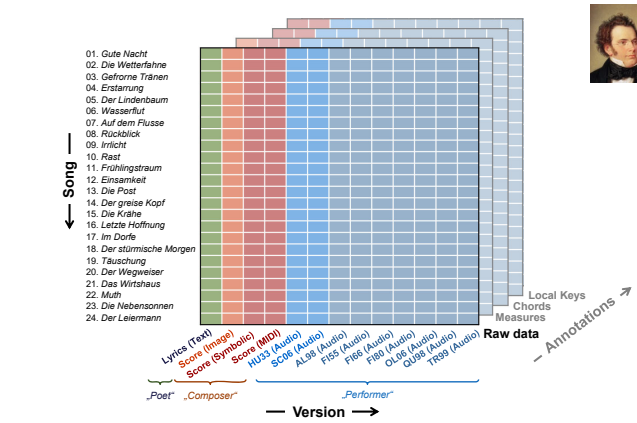
Scenario: Schubert Winterreise

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

Scenario: Schubert Winterreise

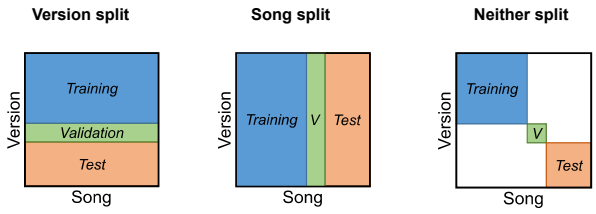






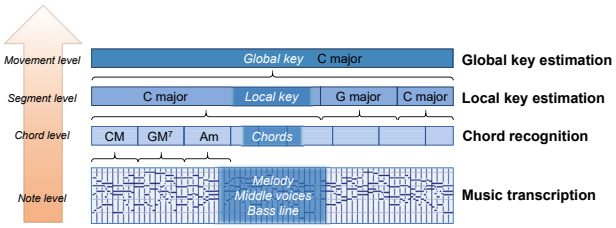
Scenario: Schubert Winterreise

Cross-Version Evaluation



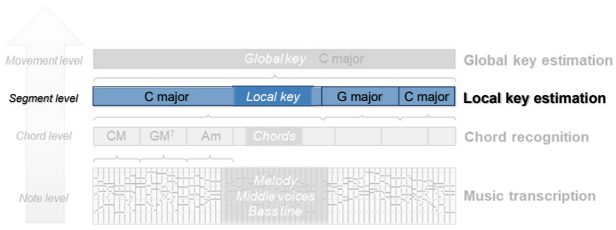
Scenario: Schubert Winterreise

Harmony Analysis



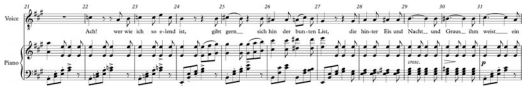
Scenario: Schubert Winterreise

Harmony Analysis

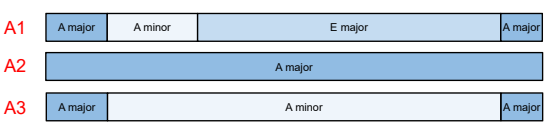


Scenario: Schubert Winterreise

Harmony Analysis



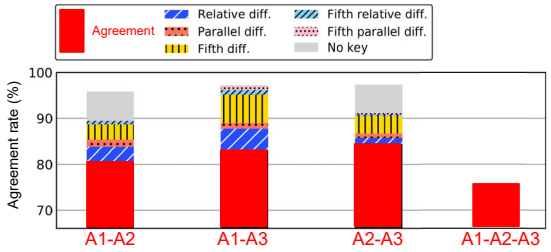
Annotations



Scenario: Schubert Winterreise

Harmony Analysis

Annotator agreements and differences



Scenario: Schubert Winterreise

Harmony Analysis

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

Christof Weiß, Frank Zalkow, Vlora 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.

Scenario: Piano Concerto

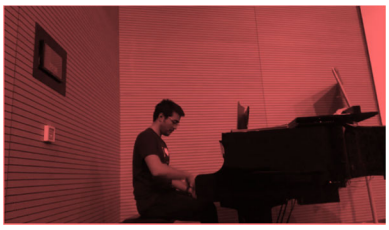
- Piano concerto recordings
  - Western Classical Music
  - Solo piano accompanied by orchestra
- MIR objectives
  - Automated accompaniment
  - Score following
  - Source separation
  - …

Scenario: Piano Concerto

- Yigitcan Özer
- PhD student in engineering
- Pianist

Scenario: Piano Concerto

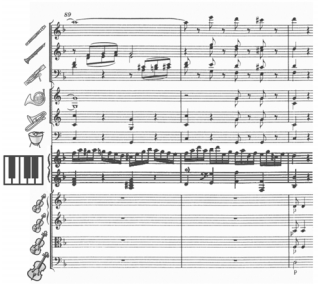
- Yigitcan Özer
- PhD student in engineering
- Pianist

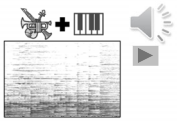


Only Piano!

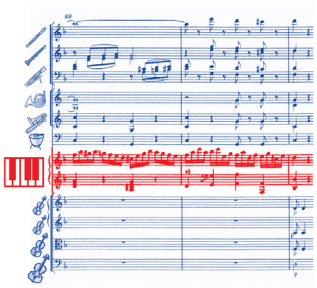
Where is the orchestra?

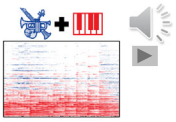
Scenario: Piano Concerto



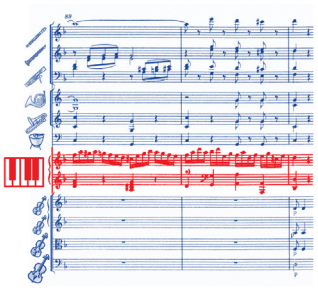


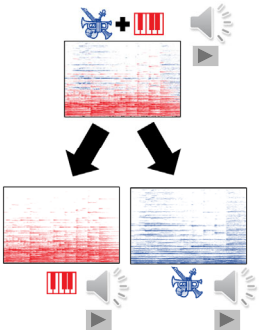
Scenario: Piano Concerto



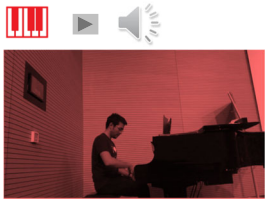


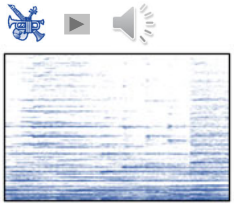
Scenario: Piano Concerto





Scenario: Piano Concerto

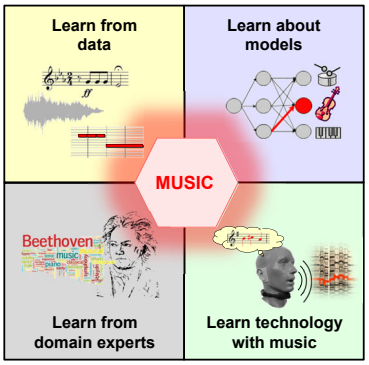




Conclusions

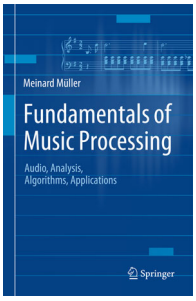
- Computational music research
  1. Research question
  2. Data preparation
  3. Actual research
- Challenges
  - Formalization of research question hard → requires simplification
  - Underlying model assumptions often violated
  - Data digitization & annotation → availability, inconsistency, subjectivity
- Analyses, data curation & tool development cannot be separated
  - Needs to be an interactive and iterative process
  - Requires a continuous dialogue between domain experts and computer scientists
  - Requires a mutual understanding and common language

Learning with Music Signals: Technology Meets Education



- Machine learning for music signal processing
- Interpretable models and knowledge integration
- Music understanding and applications
- Interactive learning in engineering through music

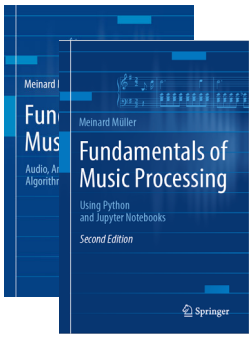
Fundamentals of Music Processing (FMP)



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

Accompanying website:
www.music-processing.de

Fundamentals of Music Processing (FMP)



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Fundamentals of Music Processing
Using Python and Jupyter Notebooks
Springer, 2021

Fundamentals of Music Processing (FMP)

Chapter		Music Processing Scenario
1		Music Represenations
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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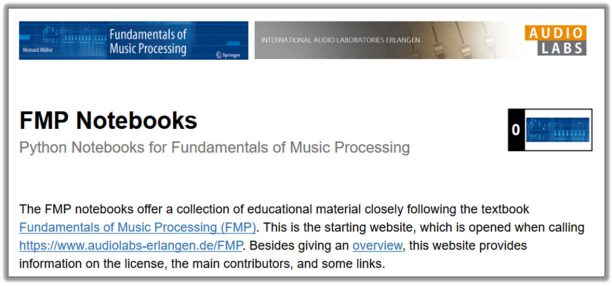
FMP Notebooks: Education & Research



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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

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