Slide 1

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

AUDIO LABS

Learning with Music Signals: Technology Meets Education

Meinard Müller

International Audio Laboratories Erlangen

meinard.mueller@audiolabs-erlangen.de

Visualisierungskolloquium

Stuttgart, 24. Januar 2025

FAU Friedrich-Alexander-Universität Erlangen-Nürnberg

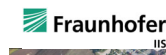Fraunhofer IIS

Slide 2

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

universität bonn
mpii max planck institut informatik
FAU
ISMIR
IEEE

Slide 3

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
- …

Slide 4

International Audio Laboratories Erlangen

Fraunhofer IIS

mp3

AUDIO LABS

FAU Friedrich-Alexander-Universität Erlangen-Nürnberg

- 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

Slide 5

International Audio Laboratories Erlangen

Audio

Slide 6

International Audio Laboratories Erlangen

Audio Coding

3D Audio

Audio
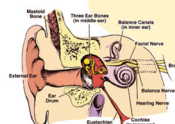
Psychoacoustics

Internet of Things

Music Processing
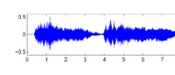
Slide 7:

Music

Slide 8:
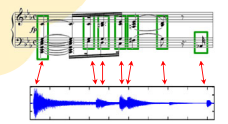
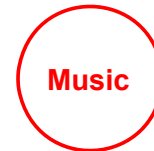# Music Information Retrieval (MIR)

Sheet Music (Image)   CD / MP3 (Audio)   MusicXML (Text)

Dance / Motion (Mocap)   Music   MIDI

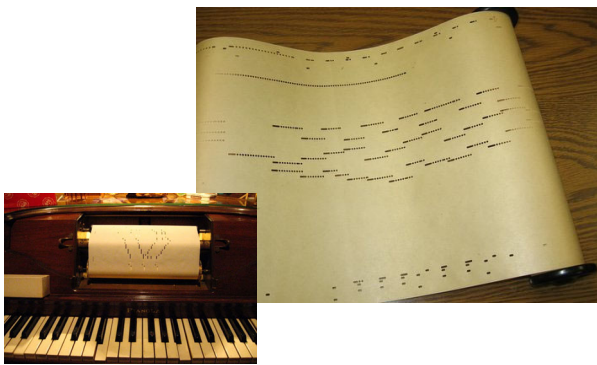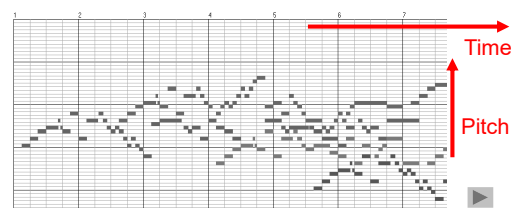Singing / Voice (Audio)   Music Film (Video)   Music Literature (Text)

Slide 9:

Piano Roll Representation (1900)

Slide 10:

Piano Roll Representation

J.S. Bach, C-Major Fuge

(Well Tempered Piano, BWV 846)

Time

Pitch

Slide 11:

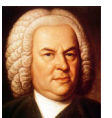# Piano Roll Representation

Query:

Goal: Find all occurrences of the query
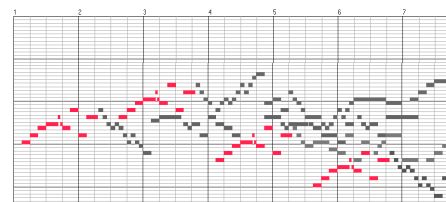

Slide 12:
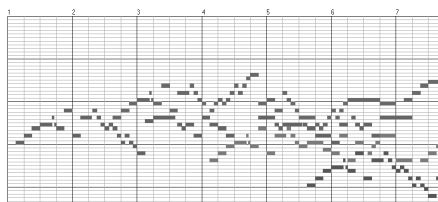
Piano Roll Representation

Query:

Goal: Find all occurrences of the query

Matches:

Music Retrieval

Query → Database → Hit

Audio ID
Bernstein (1962)
Beethoven, Symphony No. 5

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

Category ID
- Beethoven, Symphony No. 9
- Beethoven, Symphony No. 3
- Haydn Symphony No. 94
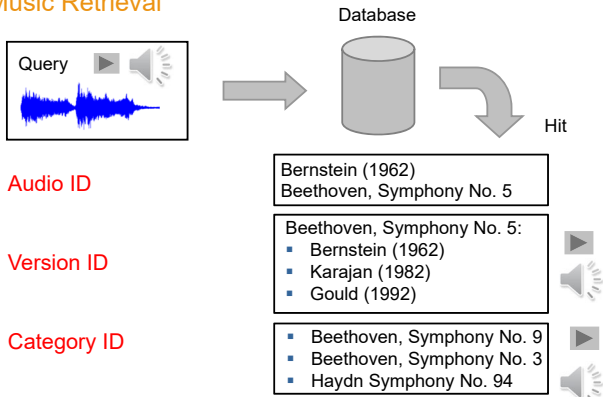
Music Synchronization

Music Synchronization: Image-Audio
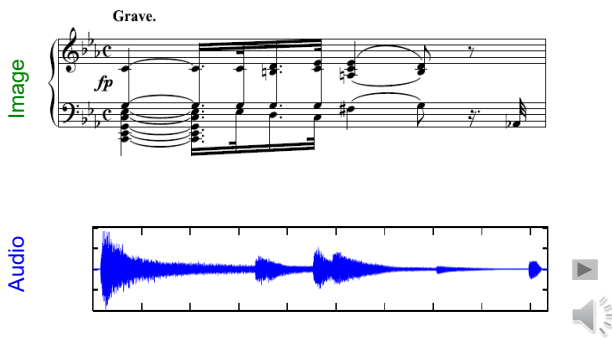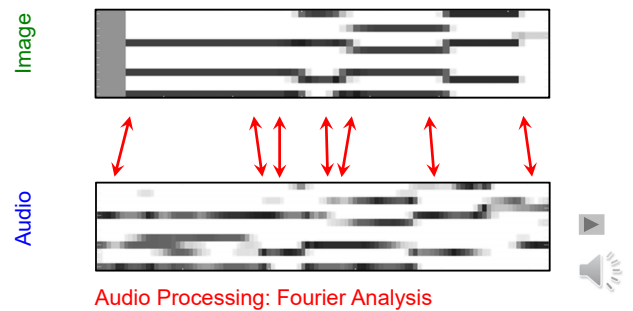
Image

Audio

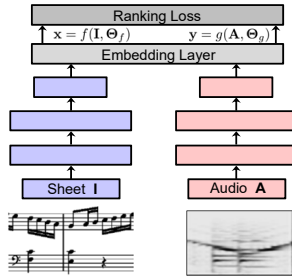## Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition

Image

Audio

Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition

Image

Audio

Audio Processing: Fourier Analysis

Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition
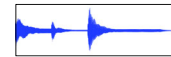
Image

Audio

Audio Processing: Fourier Analysis
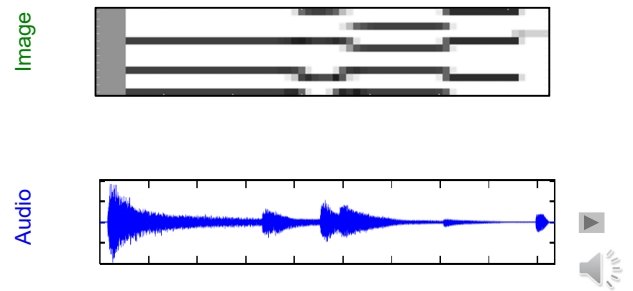
Music Synchronization: Image-Audio

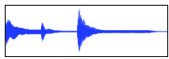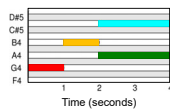

- Deep learning
- Embedding techniques
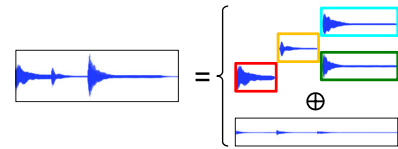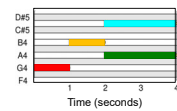- Weak annotations
- Loss functions
- …

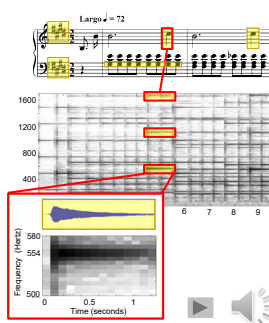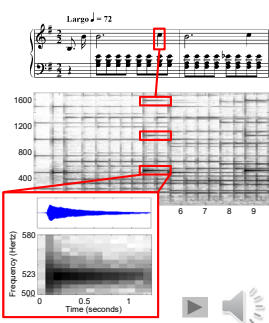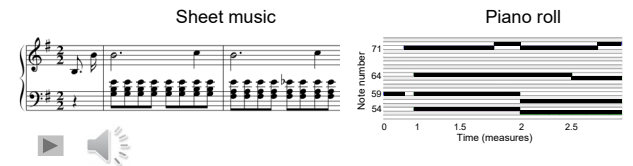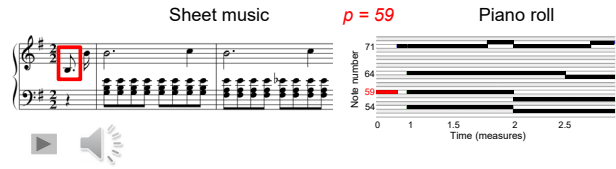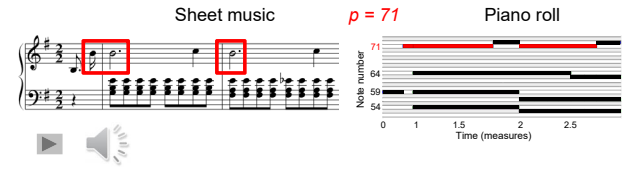## Score-Informed Audio Decomposition

Score-Informed Audio Decomposition

Score-Informed Audio Decomposition

Score-Informed Audio Decomposition

Score-Informed Audio Decomposition

Sheet music

Piano roll

Score-Informed Audio Decomposition

Sheet music   *p = 59*   Piano roll

Score-Informed Audio Decomposition

Sheet music   *p = 71*   Piano roll

Score-Informed Audio Decomposition

Sheet music   *p = 71*   Piano roll

Spectrogram

Score-Informed Audio Decomposition

Sheet music   *p = 71*   Piano roll

Spectrogram   Spectral patterns   Activity patterns

Score-Informed Audio Decomposition

Sheet music   *p = 71*   Piano roll
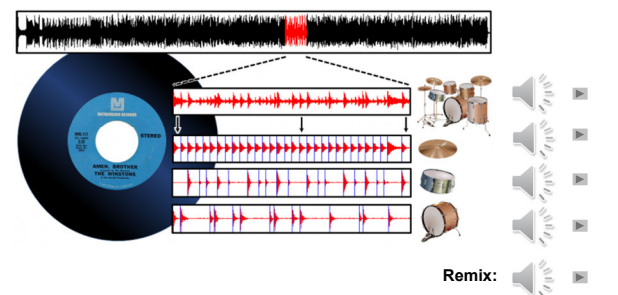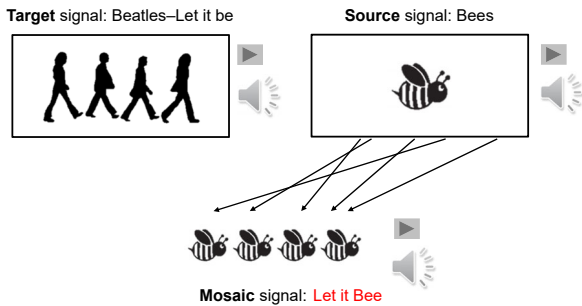
Spectrogram   Spectral patterns   Activity patterns
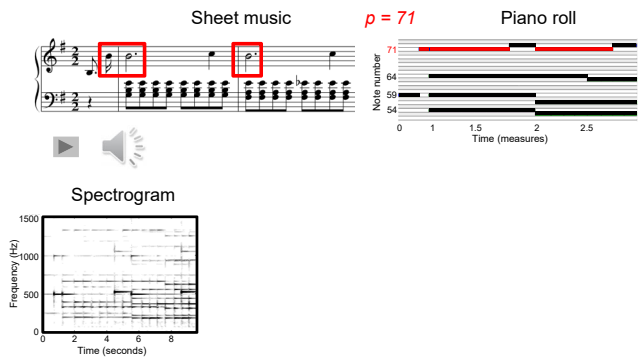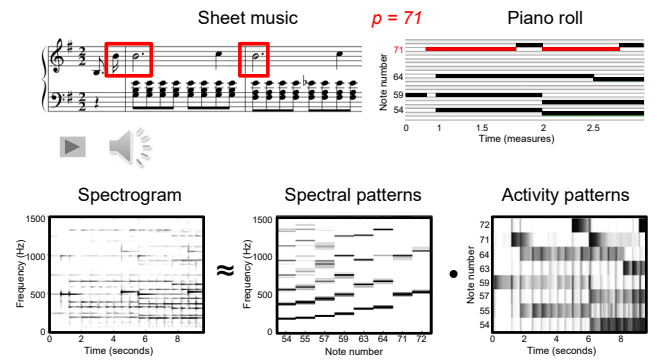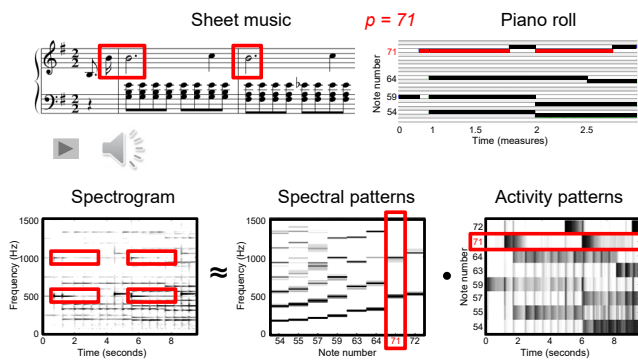
Score-Informed Audio Decomposition

Informed Drum-Sound Decomposition

Remix:

Score-Informed Audio Decomposition

Audio mosaicing (style transfer)

Target signal: Beatles–Let it be   **Source** signal: Bees

Mosaic signal: Let it Bee

Why is Music Processing Challenging?
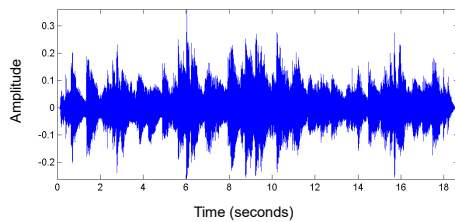
Example: Chopin, Mazurka Op. 63 No. 3

Why is Music Processing Challenging?

Example: Chopin, Mazurka Op. 63 No. 3

- Waveform

Why is Music Processing Challenging?

Example: Chopin, Mazurka Op. 63 No. 3

- Waveform / Spectrogram
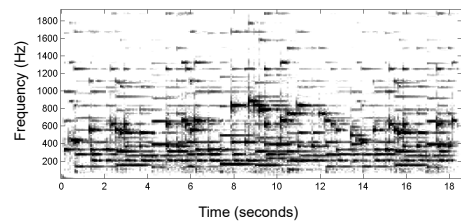
Why is Music Processing Challenging?

Example: Chopin, Mazurka Op. 63 No. 3

- Waveform / Spectrogram

- Performance
  - Tempo
  - Dynamics
  - Note deviations
  - Sustain pedal

- Polyphony

Main Melody
Additional melody line
Accompaniment

Source Separation

- Decomposition of audio stream into different sound sources

- Central task in digital signal processing

- "Cocktail party effect"

Source Separation

- Decomposition of audio stream into different sound sources

- Central task in digital signal processing

- "Cocktail party effect"

- Several input signals

- Sources are assumed to be statistically independent

Source Separation (Music)

- Main melody, accompaniment, drum track

- Instrumental voices

- Individual note events

- Only mono or stereo

- Sources are often highly dependent
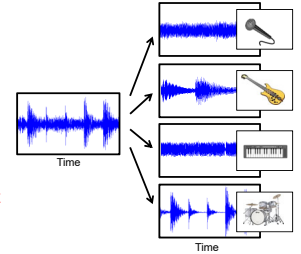
AI-Based Source Separation
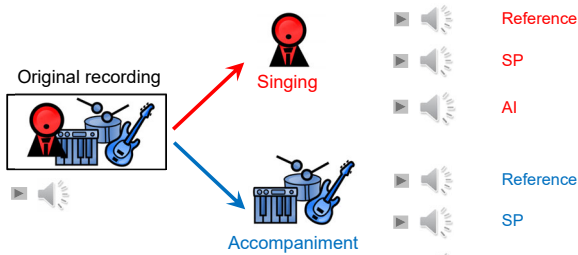
- Reference: Best possible result
- SP: Using traditional signal processing
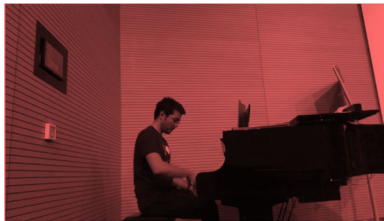- AI: Using data-driven approach

AI-Based Source Separation

- Yigitcan Özer
- PhD student in engineering
- Pianist

AI-Based Source Separation

- Yigitcan Özer
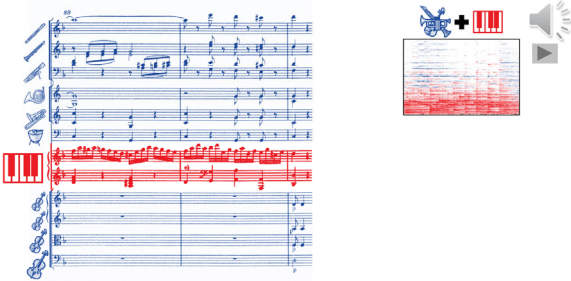- PhD student in engineering
- Pianist

Only Piano!

Where is the orchestra?

AI-Based Source Separation

Yigitcan Özer, Meinard Müller: **Source Separation of Piano Concertos Using Musically Motivated Augmentation Techniques.** IEEE/ACM Trans. ASLP, 32: 1214–1225, 2024.

AI-Based Source Separation

Yigitcan Özer, Meinard Müller: **Source Separation of Piano Concertos Using Musically Motivated Augmentation Techniques.** IEEE/ACM Trans. ASLP, 32: 1214–1225, 2024.

AI-Based Source Separation

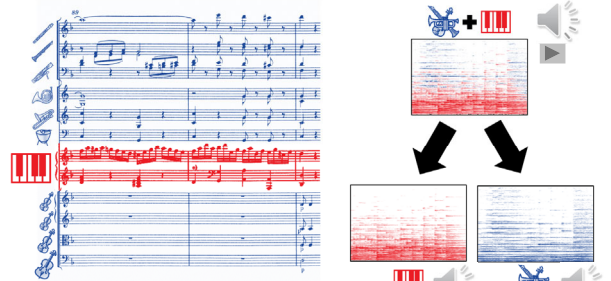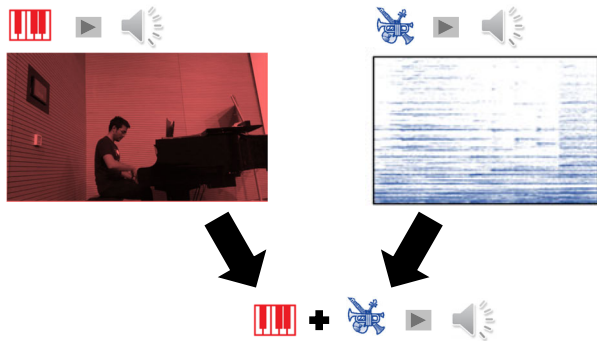

Yigitcan Özer, Meinard Müller: **Source Separation of Piano Concertos Using Musically Motivated Augmentation Techniques.** IEEE/ACM Trans. ASLP, 32: 1214–1225, 2024.

AI-Based Source Separation
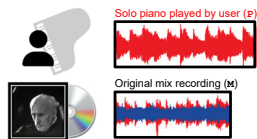
Accompaniment Creation

Our Vision

- Lonely pianist plays solo piano part
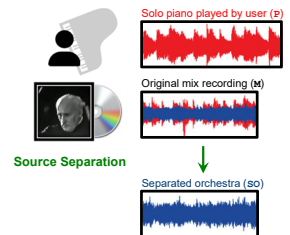
Accompaniment Creation

Our Vision

- Lonely pianist plays solo piano part
- Select full mix recording of concerto
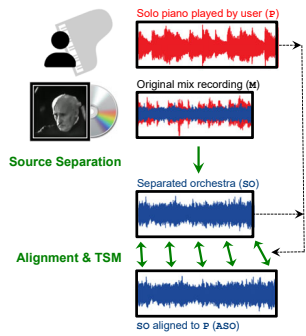
Accompaniment Creation

Our Vision

- Lonely pianist plays solo piano part
- Select full mix recording of concerto
- Isolate orchestra track
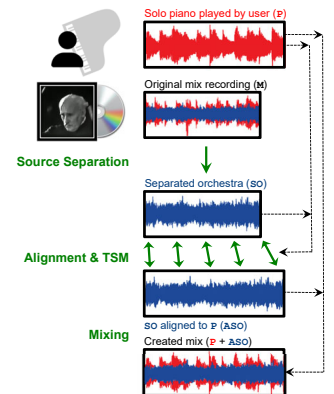
Accompaniment Creation

Our Vision

- Lonely pianist plays solo piano part
- Select full mix recording of concerto
- Isolate orchestra track
- Align to the solo performance

Solo piano played by user (P)

Original mix recording (M)

Source Separation

Separated orchestra (SO)

Alignment & TSM

SO aligned to P (ASO)

Accompaniment Creation

Our Vision

- Lonely pianist plays solo piano part
- Select full mix recording of concerto
- Isolate orchestra track
- Align to the solo performance
- Create own coherent mix

Solo piano played by user (P)

Original mix recording (M)

Source Separation

Separated orchestra (SO)

Alignment & TSM

SO aligned to P (ASO)

Mixing

Created mix (P + ASO)

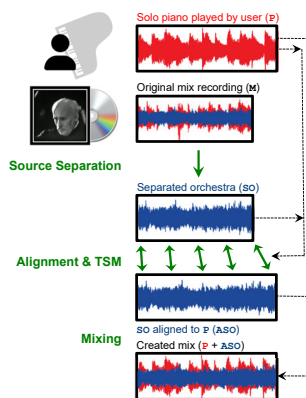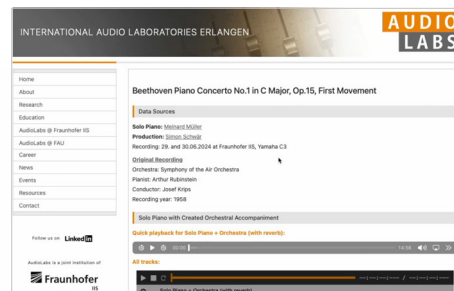## Accompaniment Creation

Our Vision

- Lonely pianist plays solo piano part
- Select full mix recording of concerto
- Isolate orchestra track
- Align to the solo performance
- Create own coherent mix

**Make lonely pianist happy with "Berliner Philharmoniker"**

Solo piano played by user (P)

Original mix recording (M)

Source Separation

Separated orchestra (SO)

Alignment & TSM

SO aligned to P (ASO)

Mixing

Created mix (P + ASO)

Accompaniment Creation

INTERNATIONAL AUDIO LABORATORIES ERLANGEN

Beethoven Piano Concerto No.1 in C Major, Op.15, First Movement

Beethoven: Piano Concerto No. 1

Lonely pianist: Meinard Müller

Recording (1958): Symphony of the Air Orchestra

Yiğitcan Özer, Simon Schwär, Meinard Müller: **Piano Concerto Accompaniment Creation.** In Late-Breaking Demos of the International Society for Music Information Retrieval Conference (ISMIR), 2024.

Accompaniment Creation

INTERNATIONAL AUDIO LABORATORIES ERLANGEN

Mozart Piano Concerto No.20 in D Minor, KV 466, First Movement
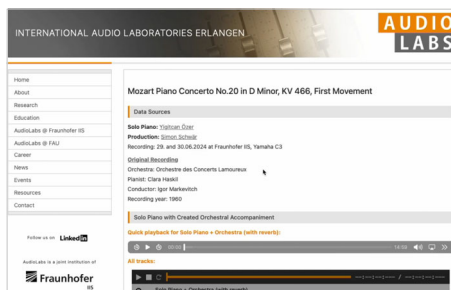
Mozart: Piano Concerto No. 20

Lonely pianist: Yiğitcan Özer

Recording (1960): Orchestre des Concerts Lamoureux

Yiğitcan Özer, Simon Schwär, Meinard Müller: **Piano Concerto Accompaniment Creation.** In Late-Breaking Demos of the International Society for Music Information Retrieval Conference (ISMIR), 2024.

AI-Based Source Separation

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

Learning with Music Signals: Technology Meets Education
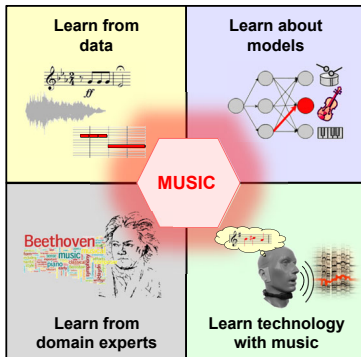
- Machine learning for music signal processing

- Interpretable models and knowledge integration

- Music understanding and applications

- Interactive learning in engineering through music

Computational Musicology

- Cooperation:
  - Rainer Kleinertz (Saarbrücken)
  - Stephanie Klauk (Saarbrücken)
  - Christof Weiß (Würzburg)

- Objectives
  - Harmony-based structural analysis
  - Beethoven Sonatas & Wagner's Ring
  - Interdisciplinary dialogue
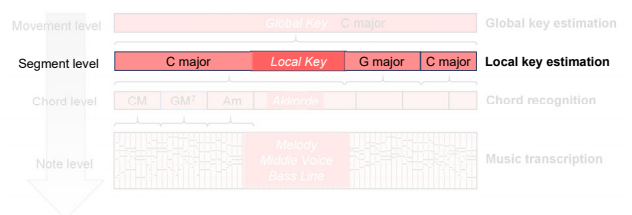
- Since 2014: DFG-funded project
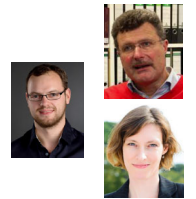
Computational Musicology: Harmony Analysis

- Different concepts
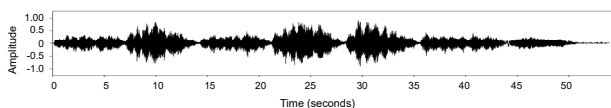- Different temporal levels
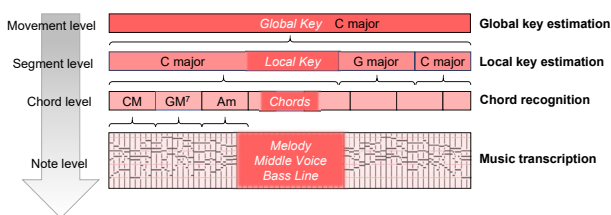
Computational Musicology: Harmony Analysis

- Different concepts
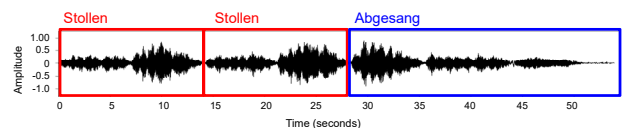- Different temporal levels

Local Key Estimation

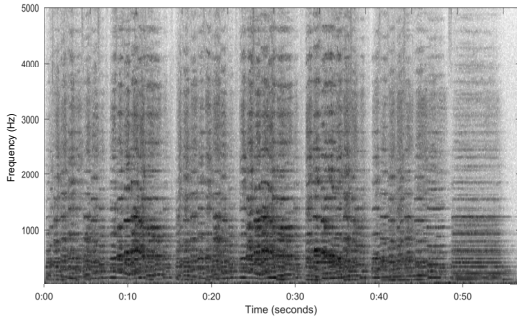Example: J.S. Bach, Choral "Durch Dein Gefängnis" (*Johannespassion*)

Local Key Estimation

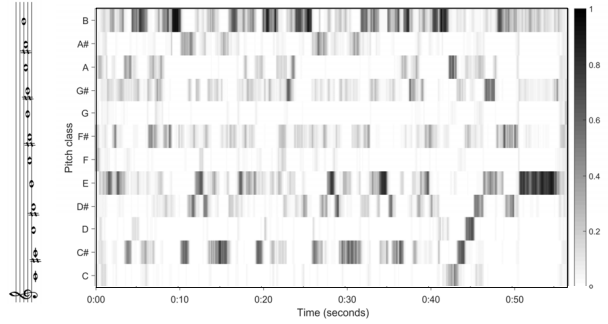Example: J.S. Bach, Choral "Durch Dein Gefängnis" (*Johannespassion*)
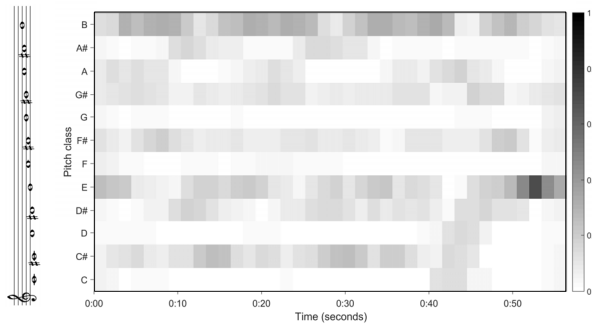
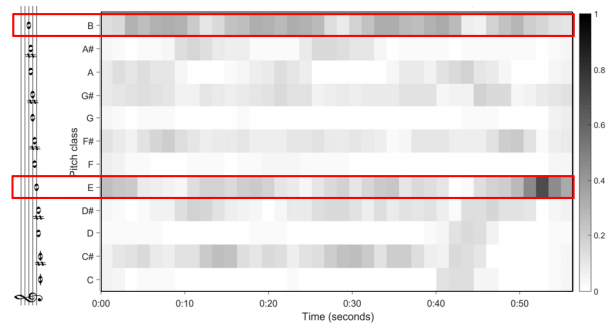# Local Key Estimation
Spectrogram

Local Key Estimation
Chromagram

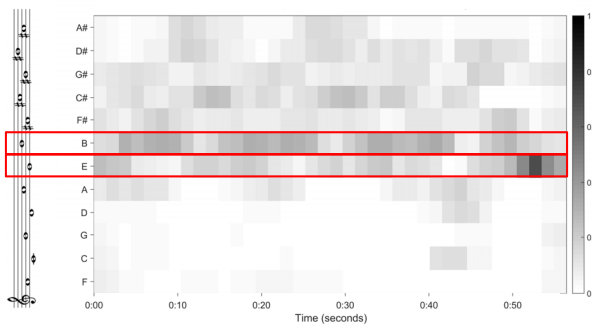# Local Key Estimation
Chromagram after smoothing

Local Key Estimation
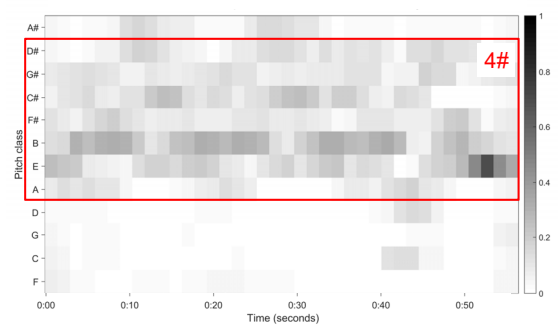## Arrange pitch classes according to **perfect fifth** series

Local Key Estimation
Arrange pitch classes according to **perfect fifth** series

Local Key Estimation
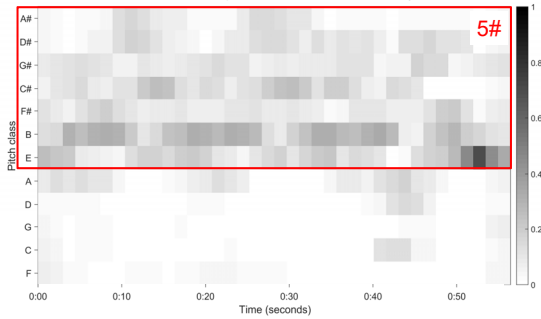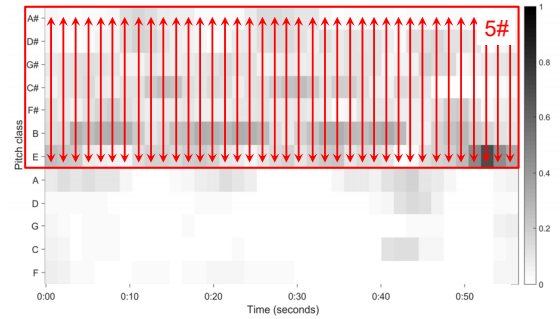## Summarize pitch class content according to **diatonic scales**

Local Key Estimation

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

Local Key Estimation

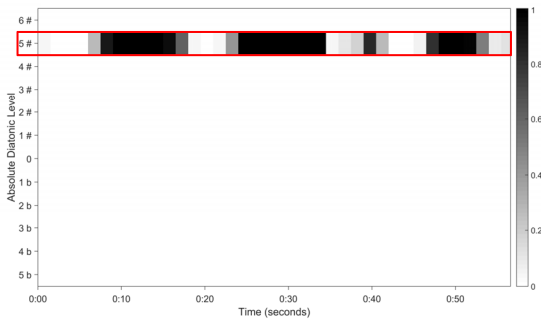Summarize pitch class content according to **diatonic scales**
Multiply chroma values (in each column)

Local Key Estimation

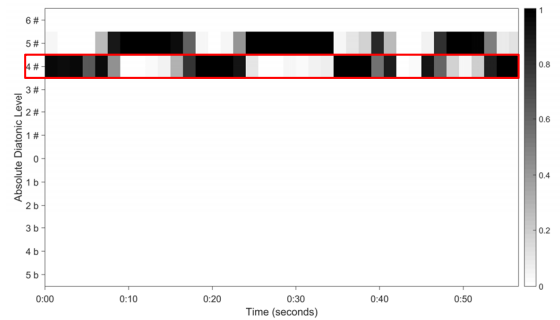Summarize pitch class content according to **diatonic scales**
Multiply chroma values

Local Key Estimation

Summarize pitch class content according to **diatonic scales**
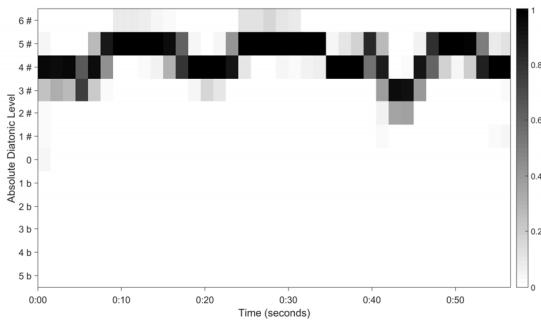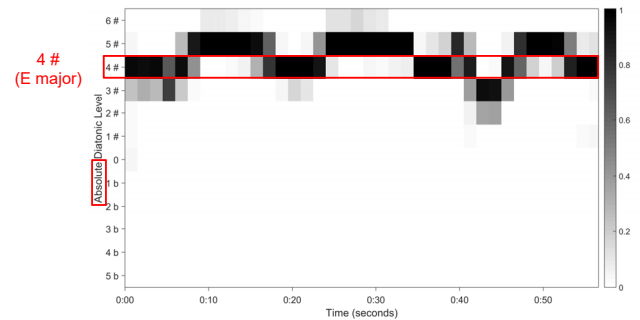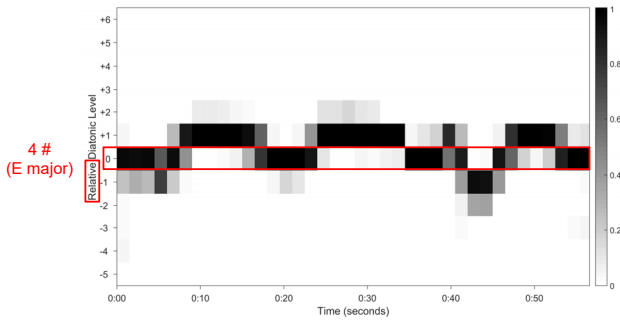Multiply chroma values

Local Key Estimation

Summarize pitch class content according to **diatonic scales**
Multiply chroma values

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)

E major | B major | E major | B major | E major
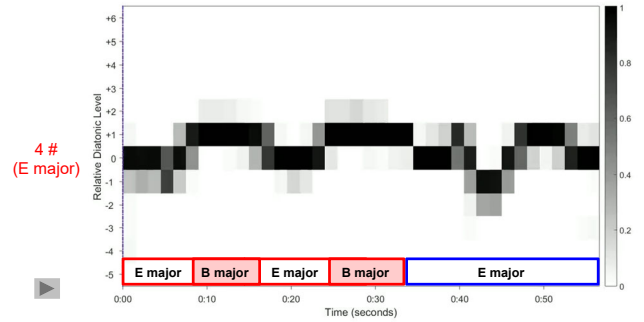
Local Key Estimation

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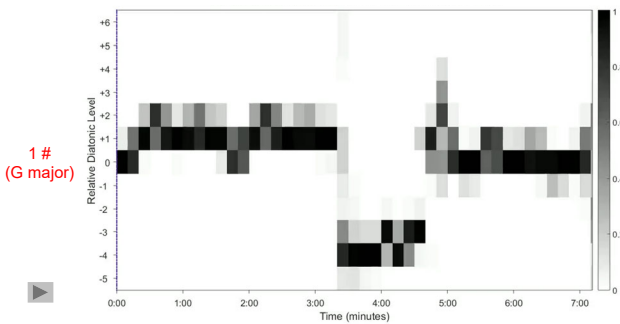
1 #
(G major)

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*)

Computational Ethnomusicology: Traditional Georgian Vocal Music
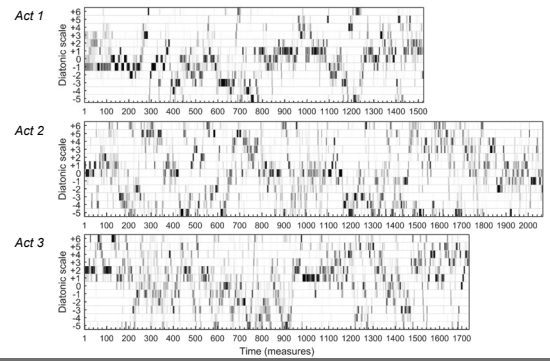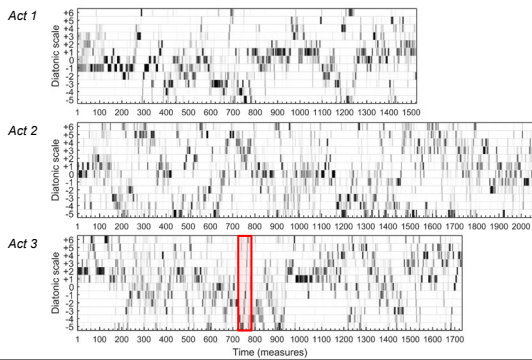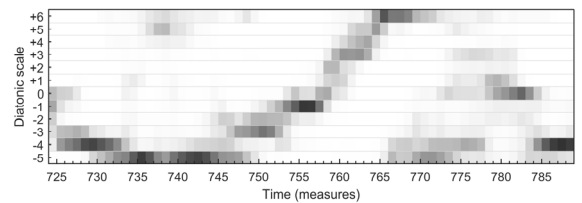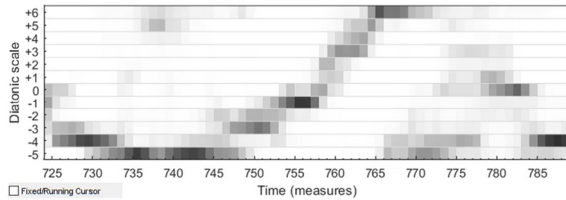
- Interdisciplinary research project
  - Prof. Dr. Frank Scherbaum (Potsdam)
  - Dr. Nana Mzhavanadze (Tbilisi)
  - Sebastian Rosenzweig (FAU)

- Objective: Tonal analysis

- 2018 – 2022: DFG-funded project

Traditional Georgian Vocal 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)
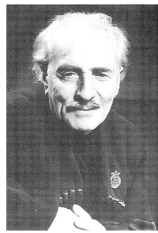
"O*riginal masterpieces of Georgian musical thinking.*" (Shugliashvili, 2014)

Traditional Georgian Vocal Music

Example: Erkomaishvili corpus

Traditional Georgian Vocal Music

Traditional Georgian Vocal Music

Traditional Georgian Vocal Music

Traditional Georgian Vocal Music

350 cents (Third)   **700 cents (Fifth)**   **1200 cents (Octave)**
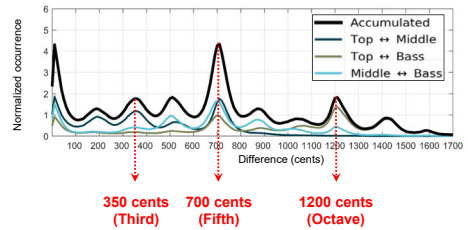
- Peak at 350 cents (between minor and major third)
- **Non-western temperament**

Traditional Georgian Vocal Music

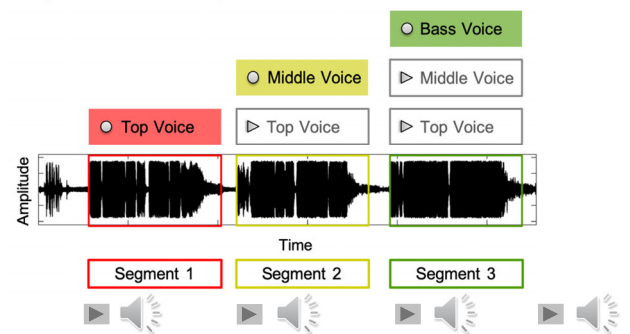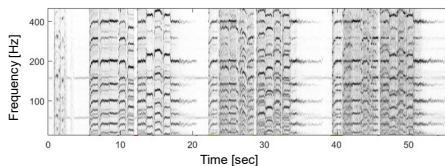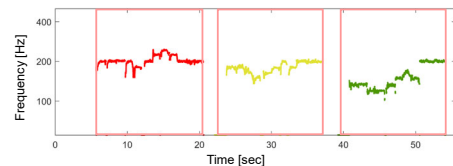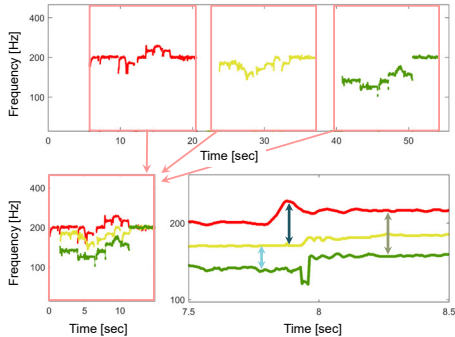- Recordings from field expedition in 2016
- 216 performances
- Multitrack audio + video
    - Room, HSM, LRX
- Total duration: 6 h

Room
Microphone

Music Information Retrieval (MIR)
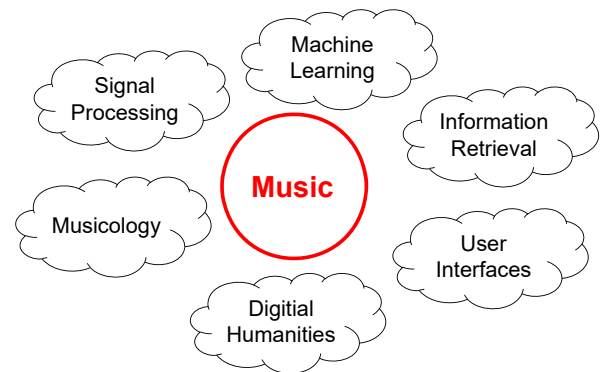
Fundamentals of Music Processing (FMP)
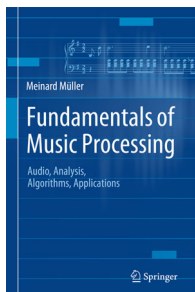
Meinard Müller
Fundamentals of Music Processing
Audio, Analysis, Algorithms, Applications
Springer, 2015

Accompanying website:
www.music-processing.de

Fundamentals of Music Processing (FMP)

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

Accompanying website:
www.music-processing.de

2nd edition
Meinard Müller
Fundamentals of Music Processing
Using Python and Jupyter Notebooks
Springer, 2021

Fundamentals of Music Processing (FMP)

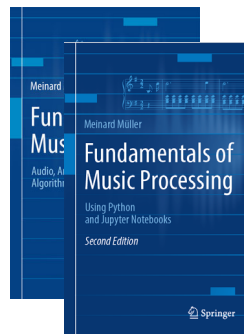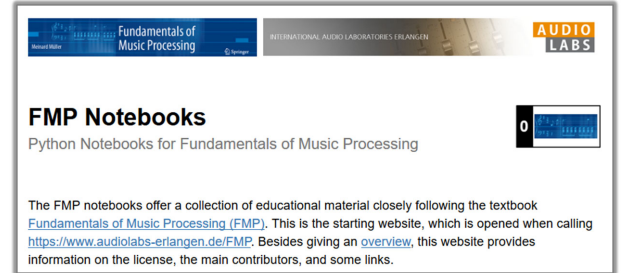| Chapter	Music Processing Scenario	
1		Music Represenations
2		Fourier Analysis of Signals
3		Music Synchronization
4		Music Structure Analysis
5		Chord Recognition
6		Tempo and Beat Tracking
7		Content-Based Audio Retrieval
8		Musically Informed Audio Decomposition

Meinard Müller
Fundamentals of Music Processing
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2nd edition
Meinard Müller
Fundamentals of Music Processing
Using Python and Jupyter Notebooks
Springer, 2021

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). 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

References (FMP Notebooks)

- Meinard Müller: Fundamentals of Music Processing – Using Python and Jupyter Notebooks. 2nd Edition, Springer, 2021.
https://www.springer.com/gp/book/9783030698072

- Meinard Müller and Frank Zalkow: libfmp: A Python Package for Fundamentals of Music Processing. Journal of Open Source Software (JOSS), 6(63): 1–5, 2021.
https://joss.theoj.org/papers/10.21105/joss.03326

- Meinard Müller: An Educational Guide Through the FMP Notebooks for Teaching and Learning Fundamentals of Music Processing. Signals, 2(2): 245–285, 2021.
https://www.mdpi.com/2624-6120/2/2/18

- Meinard Müller and Frank Zalkow: FMP Notebooks: Educational Material for Teaching and Learning Fundamentals of Music Processing. Proc. International Society for Music Information Retrieval Conference (ISMIR): 573–580, 2019.
https://zenodo.org/record/3527872#.YOhEQOgzaUk

- Meinard Müller, Brian McFee, and Katherine Kinnaird: Interactive Learning of Signal Processing Through Music: Making Fourier Analysis Concrete for Students. IEEE Signal Processing Magazine, 38(3): 73–84, 2021.
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