INTERNATIONAL AUDIO LABORATORIES ERLANGEN

AUDIO LABS

Ringvorlesung WS 2021/22

Aktuelle Perspektiven der Digital Humanities

Neue Wege für die Musikforschung mittels Digitaler Signalverarbeitung (Teil I)

Meinard Müller, Christof Weiß

International Audio Laboratories Erlangen

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FAU Friedrich-Alexander Universität Erlangen-Nürnberg

Fraunhofer IIS

Meinard Müller

- Mathematics (Diplom/Master)
  Computer Science (PhD)
  Information Retrieval (Habilitation)
- Since 2012: Professor
  Semantic Audio Processing
- President of the International Society for Music Information Retrieval (MIR)
- IEEE Fellow for contributions to Music Signal Processing

universitätbonn

FAU Friedrich-Alexander Universität Erlangen-Nürnberg

ISMIR

IEEE

Christof Weiß

- Physics Diploma & Composition
- Ph. D. in Media Technology
- Postdoc in Music Processing & Composer
- 2018: KlarText Award for Science Communication
- 2021: Postdoc at Télécom ParisTech

Julius-Maximilians-Universität Würzburg

Hochschule für Musik Würzburg

Fraunhofer IDMT

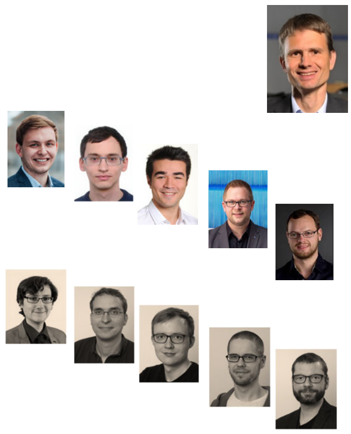
FAU Friedrich-Alexander Universität Erlangen-Nürnberg

TELECOM ParisTech

Group Members

- Sebastian Rosenzweig
- Michael Krause
- Yigitcan Özer
- Peter Meier (external)
- Christof Weiß (Paris)

- Frank Zalkow
- Christian Dittmar
- Stefan Balke
- Jonathan Driedger
- Thomas Prätzlich
- …

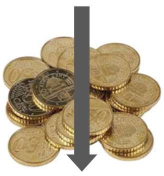


International Audio Laboratories Erlangen

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
- Large Technical Faculty

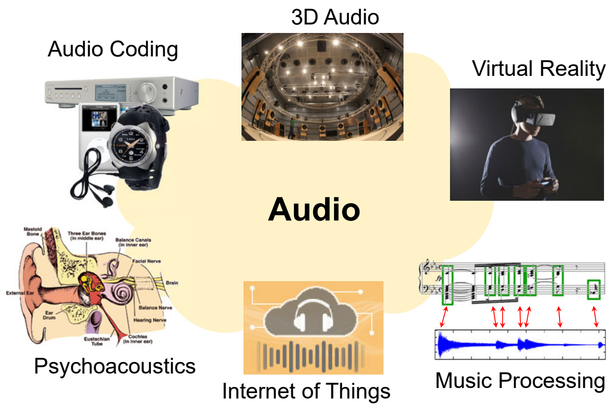
AudioLabs – FAU

- Prof. Dr. Jürgen Herre
  Audio Coding
- Prof. Dr. Bernd Edler
  Audio Signal Analysis
- Prof. Dr. Meinard Müller
  Semantic Audio Processing
- Prof. Dr. Emanuël Habets
  Spatial Audio Signal Processing
- Prof. Dr. Nils Peters
  Audio Signal Processing
- Dr. Stefan Turowski
  Coordinator AudioLabs-FAU

International Audio Laboratories Erlangen

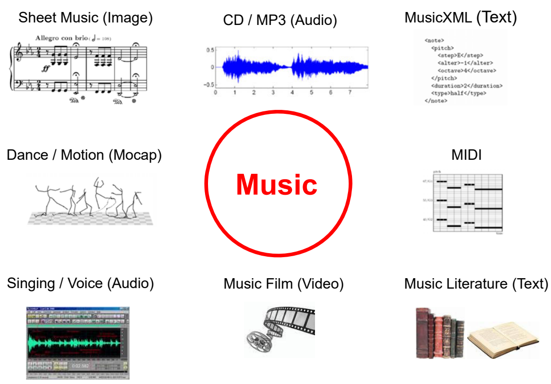
Audio

International Audio Laboratories Erlangen

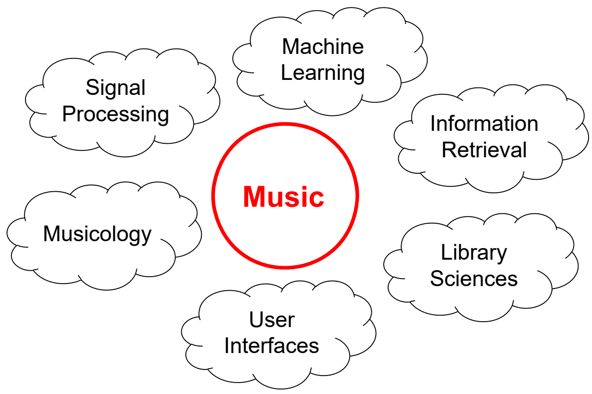


Music

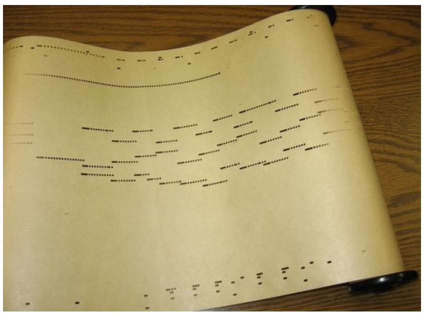
Music Information Retrieval (MIR)



Music Information Retrieval (MIR)

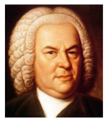


Piano Roll Representation



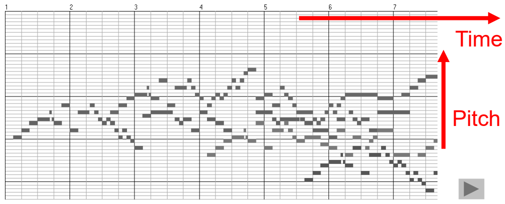
Player Piano (1900)

Piano Roll Representation (MIDI)

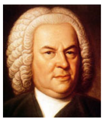


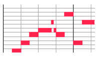
J.S. Bach, C-Major Fuge

(Well Tempered Piano, BWV 846)

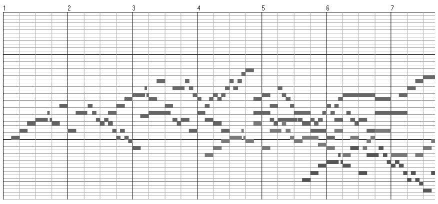


Piano Roll Representation (MIDI)



Query: 

Goal: Find all occurrences of the query



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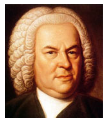
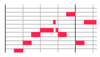
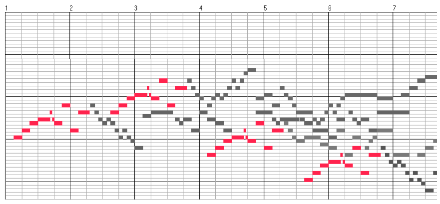


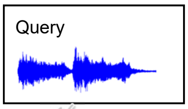
Query: 

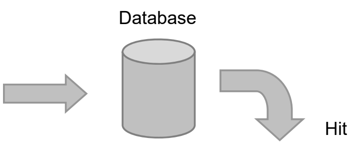
Goal: Find all occurrences of the query

Matches:



Music Retrieval





Audio-ID

Bernstein (1962)
Beethoven, Symphony No. 5

Version-ID

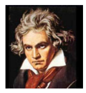
Beethoven, Symphony No. 5:
- Bernstein (1962)
- Karajan (1982)
- Gould (1992)

Category-ID

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

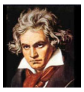
Music Synchronization: Audio-Audio

Beethoven's Fifth



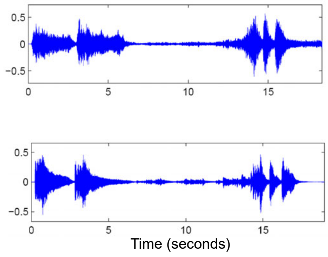
Music Synchronization: Audio-Audio

Beethoven's Fifth



Orchester
(Karajan)

Piano
(Scherbakov)



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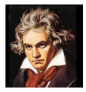
Beethoven's Fifth



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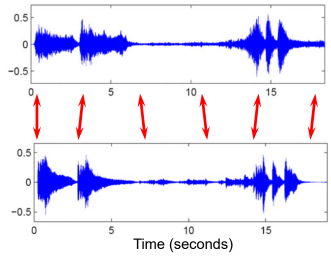
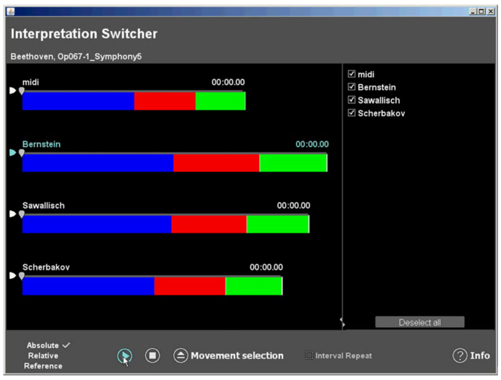


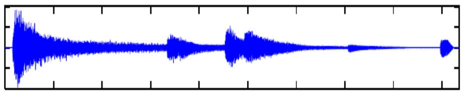
Application: Interpretation Switcher



Music Synchronization: Image-Audio

Image

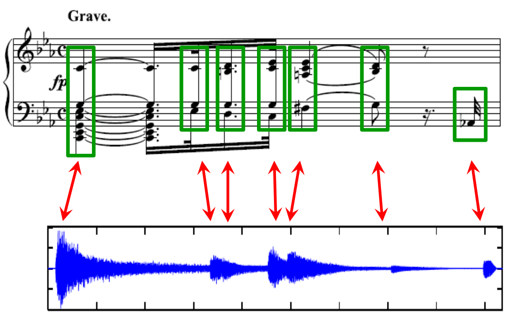
Audio



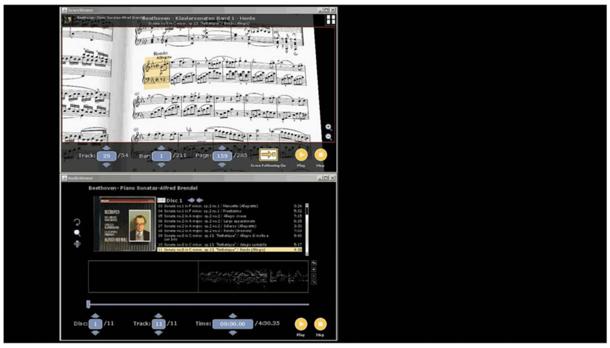
Music Synchronization: Image-Audio

Image

Audio



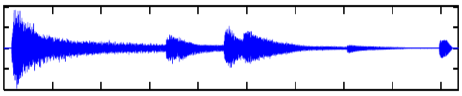
Application: Score Viewer



How to make the data comparable?

Image

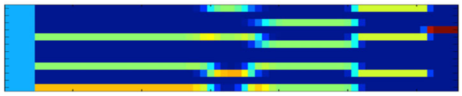
Audio



How to make the data comparable?

Image Processing: Optical Music Recognition

Image



Audio

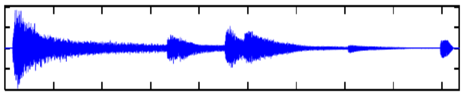


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Image Processing: Optical Music Recognition

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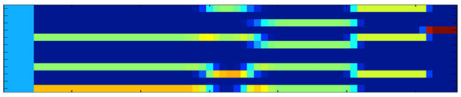
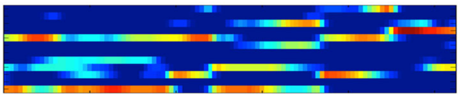


Audio

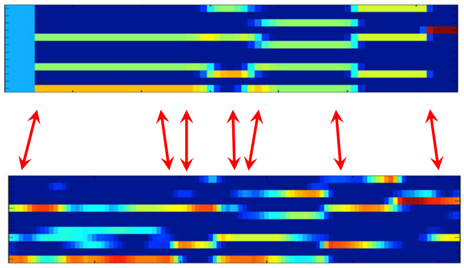


Audio Processing: Fourier Analysis

How to make the data comparable?

Image Processing: Optical Music Recognition

Image

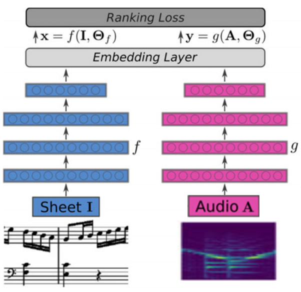


Audio

Audio Processing: Fourier Analysis

Music Synchronization: Image-Audio

Deep Learning Approach

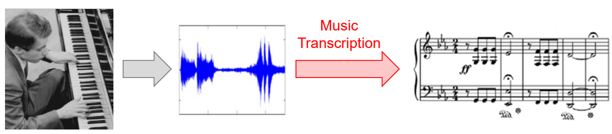


- Cross-modal embedding
- Requires corresponding snippets of audio and sheet music for training
- Triplet Loss function $\max(0, d(x^a, y^p) - d(x^a, y^n) + \alpha)$
- Problem very hard
  - Performance variations
  - Layout variations

Cross-Modal Retrieval
Dorfer et al.: End-to-End Cross-Modality Retrieval with CCA Projections and Pairwise Ranking Loss. International Journal of Multimedia Information Retrieval, 2018.

Automatic Music Transcription

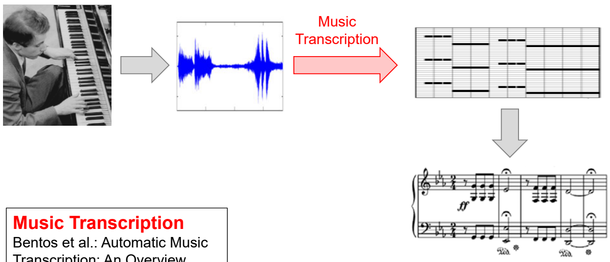
Task: Convert a music recording into sheet music



Music Transcription
Bentos et al.: Automatic Music Transcription: An Overview. IEEE Signal Processing Magazine 36(1), 2019.

Automatic Music Transcription

Task: Convert a music recording into sheet music
(or another symbolic music representation)



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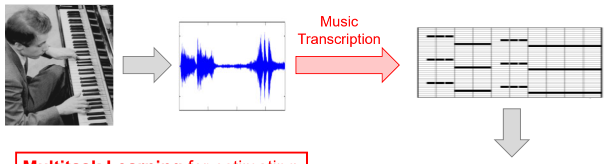


Multitask Learning for estimating
- pitches,
- note onsets & offsets,
- beat & measure positions,
- musical voices & instrumentation,
- pedalling, dynamics, …

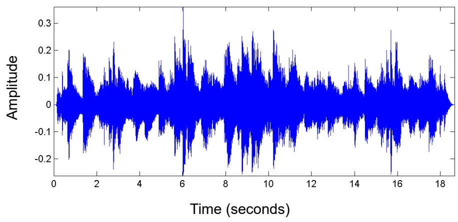
Why is Music Processing Challenging?

Example: Chopin, Mazurka Op. 63 No. 3

Why is Music Processing Challenging?

Example: Chopin, Mazurka Op. 63 No. 3

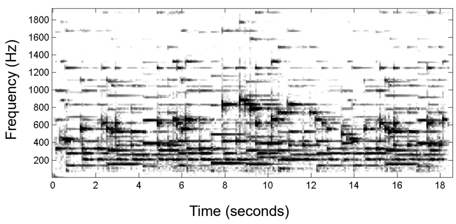
- Waveform



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

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

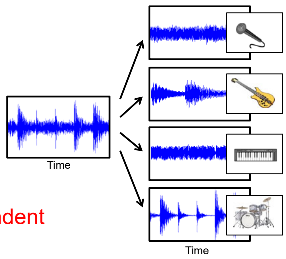
- Decomposition of audio stream into different sound sources
- Central task in digital signal processing
- "Cocktail party effect"

Source Separation

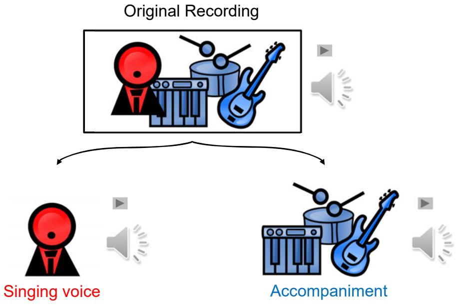
- Decomposition of audio stream into different sound sources
- Central task in digital signal processing
- "Cocktail party effect"
- Several input signals
- Sources are assumed to be statistically independent

Source Separation (Music)

- Main melody, accompaniment, drum track
- Instrumental voices
- Individual note events
- Only mono or stereo
- Sources are often highly dependent

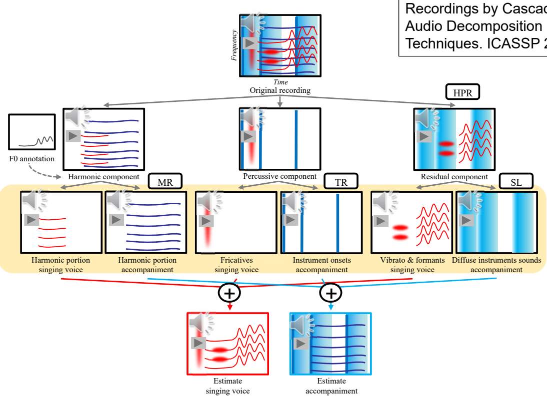


Singing Voice Extraction



Singing Voice Extraction

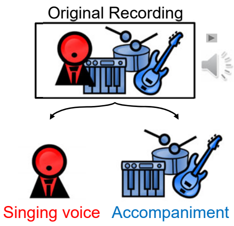
Traditional Approach
Driedger, Müller: Extracting Singing Voice from Music Recordings by Cascading Audio Decomposition Techniques. ICASSP 2015.



Singing Voice Extraction

DL-Based Approach
Stöter, Uhlich Luitkus, Mitsufuji: Open-Unmix – A Reference Implementation for Music Source Separation. JOSS 2019.

Deep learning has lead to breakthrough



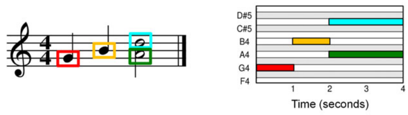
Reference voices:

Engineering approach:

Deep learning approach:

Score-Informed Audio Decomposition

Exploit musical score to support decomposition process

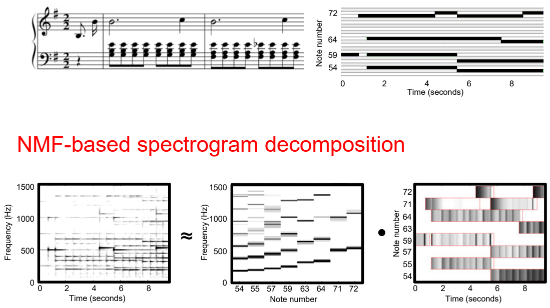


Prior Knowledge
Ewert, Pardo, Müller, Plumbley: Score-Informed Source Separation for Musical Audio Recordings. IEEE SPM, 2014.

Score-Informed Audio Decomposition

Exploit musical score to support decomposition process

NMF-based spectrogram decomposition



Score-Informed Audio Decomposition

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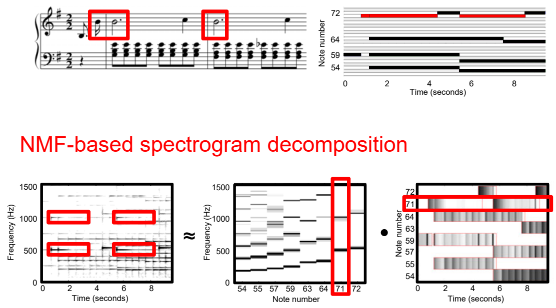
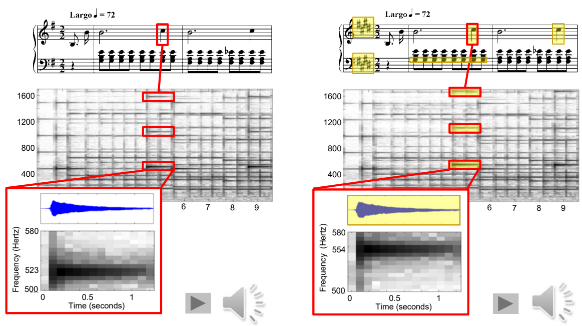
NMF-based spectrogram decomposition

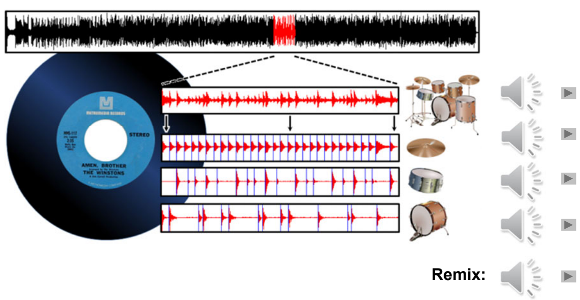


Score-Informed Audio Decomposition

Application: Audio editing



Informed Drum-Sound Decomposition



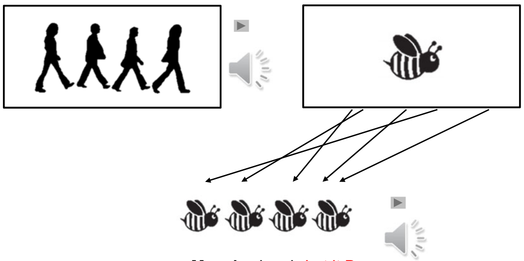
Remix:

Literature: [Dittmar/Müller, IEEE/ACM-TASLP 2016]
Demo: https://www.audiolabs-erlangen.de/resources/MIR/2016-IEEE-TASLP-DrumSeparation

Audio Mosaicing

Target signal: Beatles–Let it be

Source signal: Bees



Mosaic signal: Let it Bee

Literature: [Driedger/Müller, ISMIR 2015]
Demo: https://www.audiolabs-erlangen.de/resources/MIR/2015-ISMIR-LetItBee

Motivic Similarity

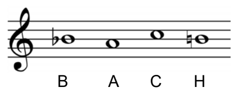
Beethoven's Fifth (1st Mov.)

Beethoven's Fifth (3rd Mov.)

Beethoven's Appassionata

Motivic Similarity

Motivic Similarity



Computational Analysis of Traditional Georgian Vocal Music

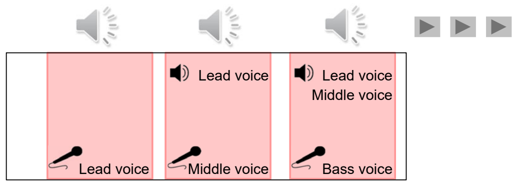
- Partner: Prof. Frank Scherbaum
  Potsdam University
- Duration: 2018 – 2022
- Objectives
  - Harmonic and melodic singing analysis
  - New sensors (larynx microphones)
  - Digital humanities

https://www.audiolabs-erlangen.de/resources/MIR/2017-GeorgianMusic-Erkomaishvili
https://www.audiolabs-erlangen.de/resources/MIR/2018-ISMIR-LBD-ThroatMics

Traditional Georgian Vocal Music

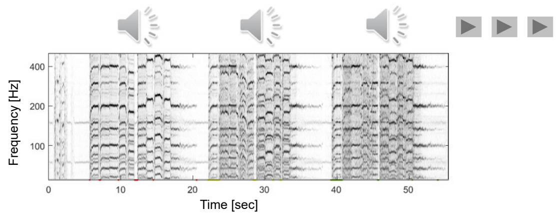
Which scale? Harmonic/melodic intervals? Singer interaction?

Traditional Georgian Vocal Music



- Master chanter: Artem Erkomaishvili
- Recordings of 100 songs (1966)
- Example song: Da sulisatsa (#87)

Traditional Georgian Vocal Music



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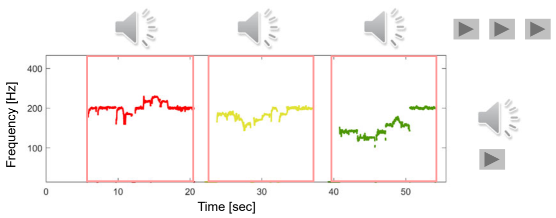
Traditional Georgian Vocal Music



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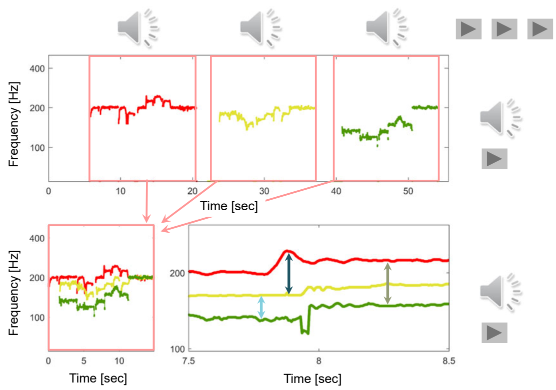
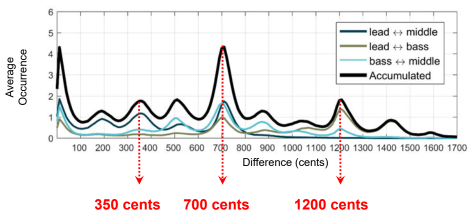
Traditional Georgian Vocal Music



Traditional Georgian Vocal Music



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

Automated Methods and Tools for Analyzing and Structuring Choral Music

DFG

- Partner: Carus-Verlag
- Duration: 2018 – 2021
- Objectives
  - Navigation, visualization, sonification of musical structures
  - Practicability & applications (music education, musicology)
  - Web-based prototypes for interactive interfaces

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

Carus

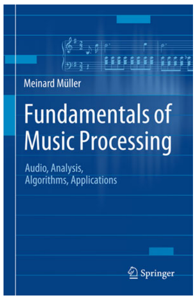
https://www.audiolabs-erlangen.de/resources/MIR/2018-ISMIR-LBD-Carus

Computer-Assisted Analysis of Harmonic Structures

- Partner: Prof. Rainer Kleinertz
  Saarland University
- Duration: 2014 – 2023
- Objectives
  - Computer-assisted harmonic structures
  - Beethoven's Piano Sonatas
  - Wagner's "Der Ring des Nibelungen"

Weiß, Kleinertz (Ringvorlesung, 10.01.2022):
Neue Wege für die Musikforschung mittels Digitaler Signalverarbeitung II

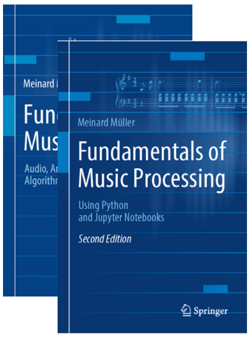
Fundamentals of Music Processing (FMP)



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

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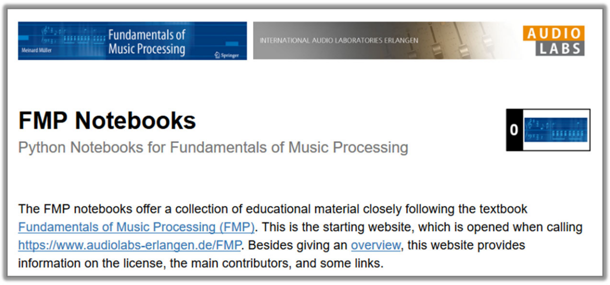
FMP Notebooks: Education & Research



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

FMP Notebooks

Part	Title	Notions, Techniques & Algorithms	HTML	IPYNB
B	Basics	Basic information on Python, Jupyter notebooks, Anaconda package management system, Python environments, visualizations, and other topics	[html]	[ipynb]
0	Overview	Overview of the notebooks (https://www.audiolabs-erlangen.de/FMP)	[html]	[ipynb]
1	Music Representations	Music notation, MIDI, audio signal, waveform, pitch, loudness, timbre	[html]	[ipynb]
2	Fourier Analysis of Signals	Discrete/analog signal, sinusoid, exponential, Fourier transform, Fourier representation, DFT, FFT, STFT	[html]	[ipynb]
3	Music Synchronization	Chroma feature, dynamic programming, dynamic time warping (DTW), alignment, user interface	[html]	[ipynb]
4	Music Structure Analysis	Similarity matrix, repetition, thumbnail, homogeneity, novelty, evaluation, precision, recall, F-measure, visualization, scape plot	[html]	[ipynb]
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- Part 1 to Part 8: Different music processing scenarios

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Structured in 10 parts

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  - Python programming
  - Other technical concepts underlying these notebooks
- Part 0: Starting notebook
- Part 1 to Part 8: Different music processing scenarios

Part 6: Tempo and Beat Tracking

Part	Title	Notions, Techniques & Algorithms	HTML	IPYNB
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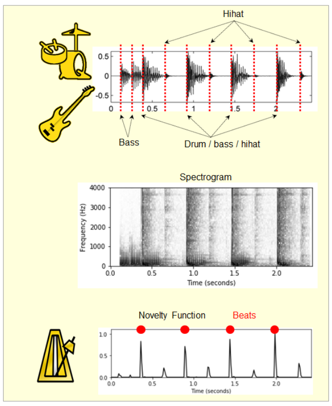
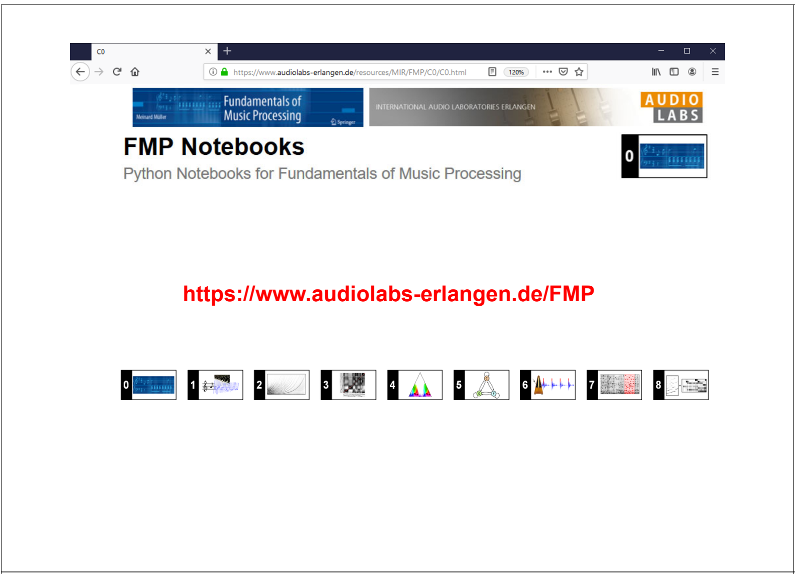
Part 6: Tempo and Beat Tracking

- When listening to a piece of music, we as humans are often able to tap along with the musical beat
- Automated beat tracking: Simulate this cognitive process by a computer




Fundamentals of Music Processing
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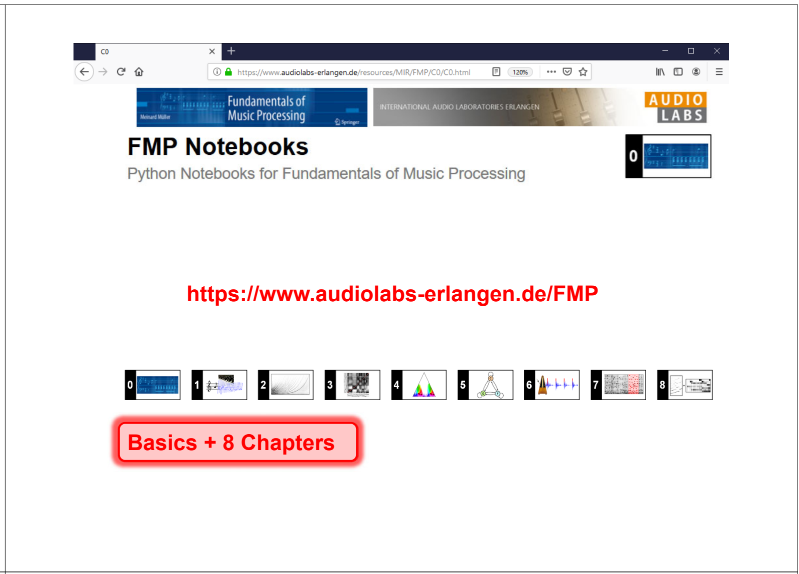
AUDIO LABS
FMP Notebooks
Python Notebooks for Fundamentals of Music Processing
https://www.audiolabs-erlangen.de/FMP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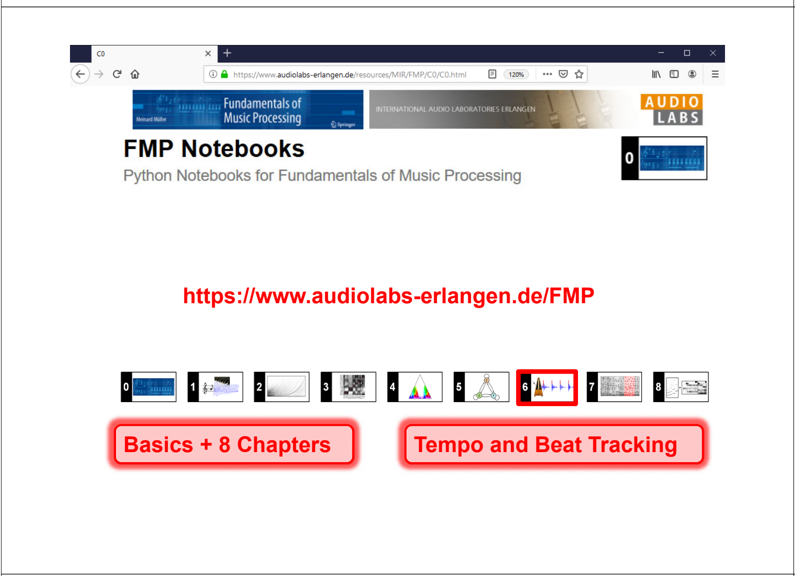
INTERNATIONAL AUDIO LABORATORIES ERLANGEN
AUDIO LABS
FMP Notebooks
Python Notebooks for Fundamentals of Music Processing
https://www.audiolabs-erlangen.de/FMP
Basics + 8 Chapters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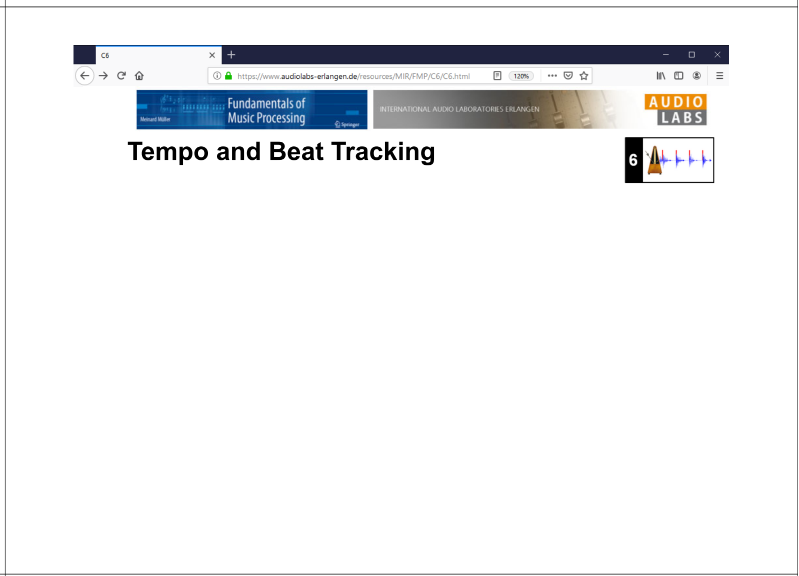
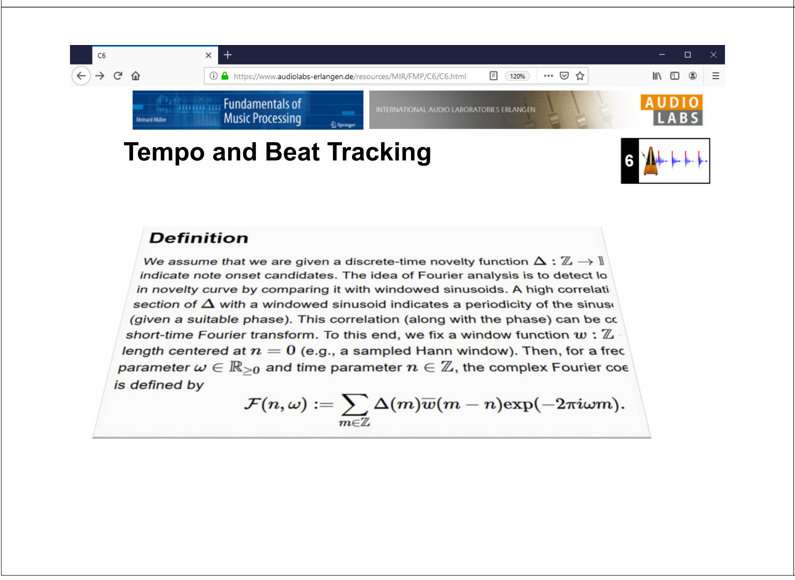
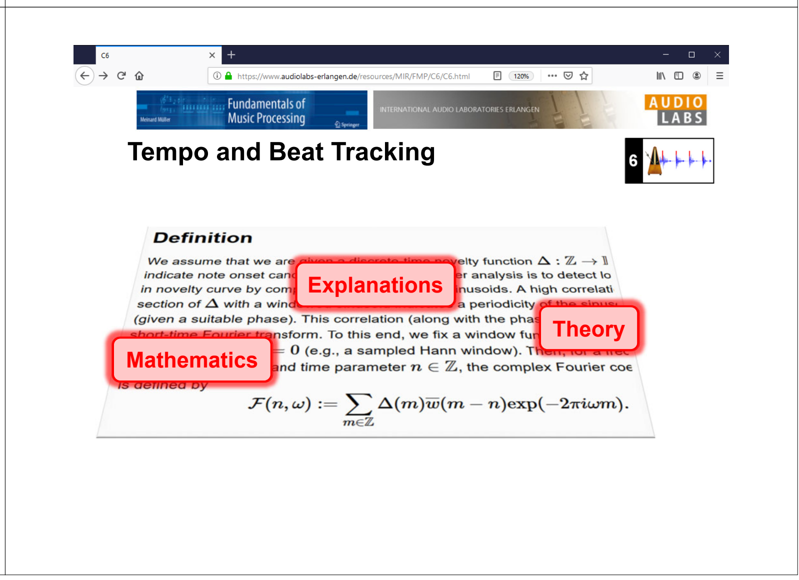
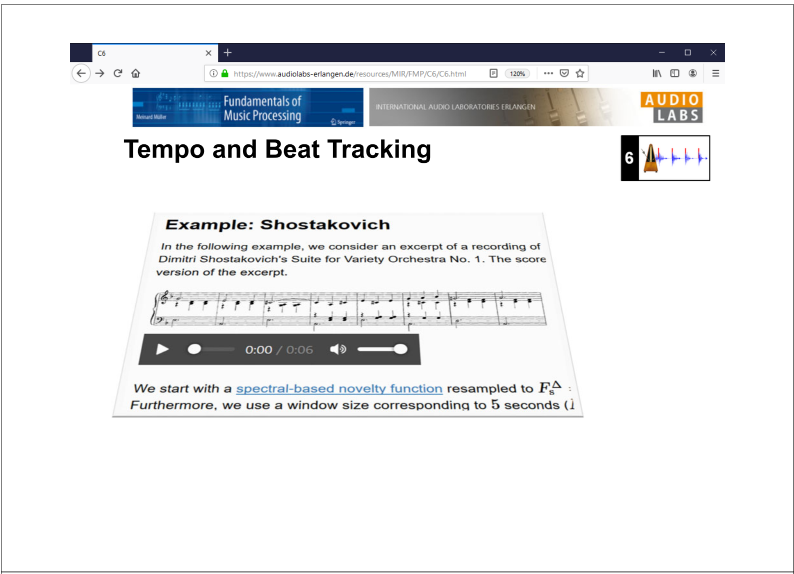
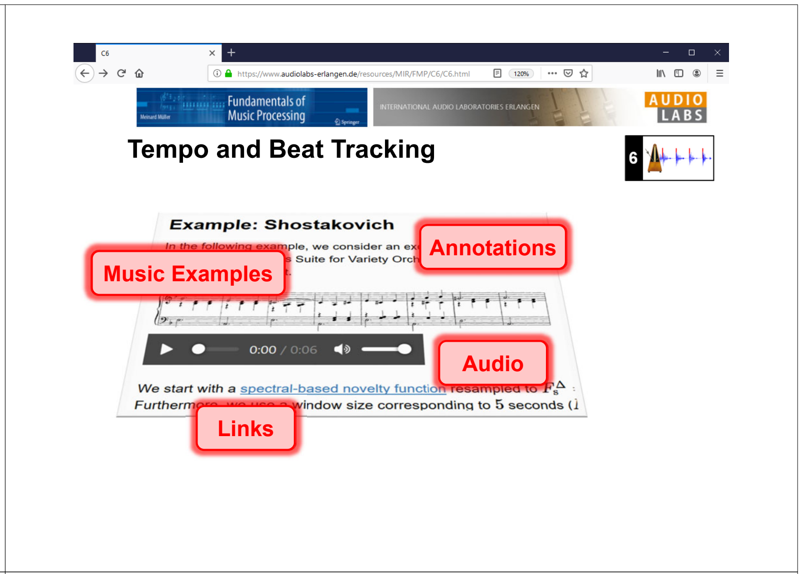
Tempo and Beat Tracking

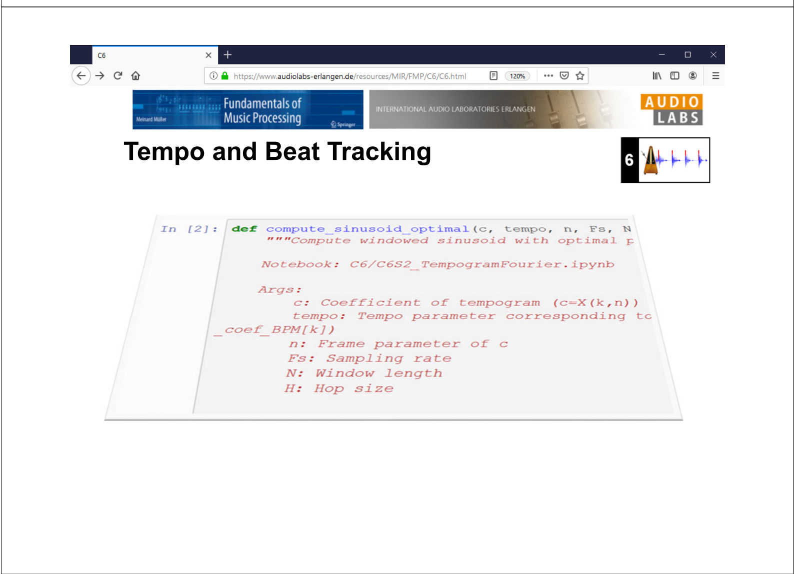

Fundamentals of Music Processing
INTERNATIONAL AUDIO LABORATORIES ERLANGEN
AUDIO LABS
Tempo and Beat Tracking

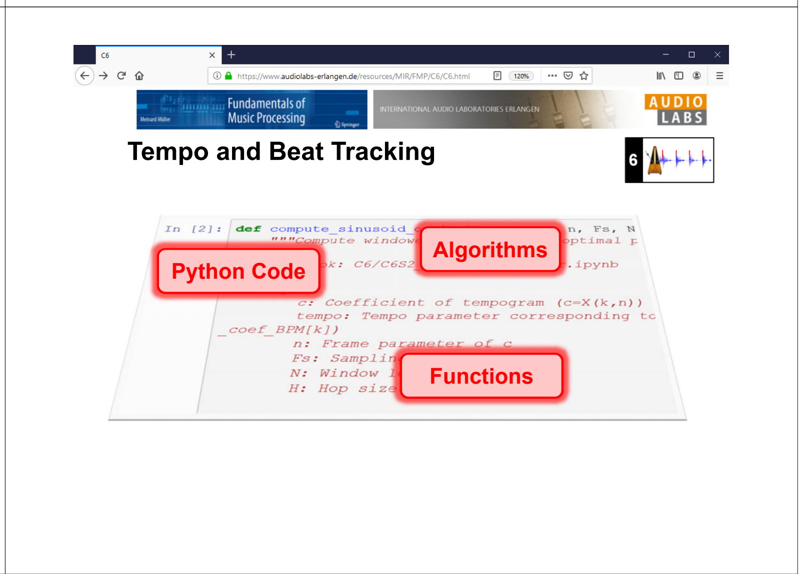

Fundamentals of Music Processing
INTERNATIONAL AUDIO LABORATORIES ERLANGEN
AUDIO LABS
Tempo and Beat Tracking
Definition
We assume that we are given a discrete-time novelty function $\Delta : \mathbb{Z} \to \mathbb{R}$
indicate note onset candidates. The idea of Fourier analysis is to detect lo
in novelty curve by comparing it with windowed sinusoids. A high correlati
section of Δ with a windowed sinusoid indicates a periodicity of the sinus
(given a suitable phase). This correlation (along with the phase) can be co
short-time Fourier transform. To this end, we fix a window function $w : \mathbb{Z}$
length centered at $n = 0$ (e.g., a sampled Hann window). Then, for a freq
parameter $\omega \in \mathbb{R}_{\geq 0}$ and time parameter $n \in \mathbb{Z}$, the complex Fourier coe
is defined by
$\mathcal{F}(n,\omega) := \sum_{m\in\mathbb{Z}} \Delta(m)\overline{w}(m-n)\exp(-2\pi i\omega m).$

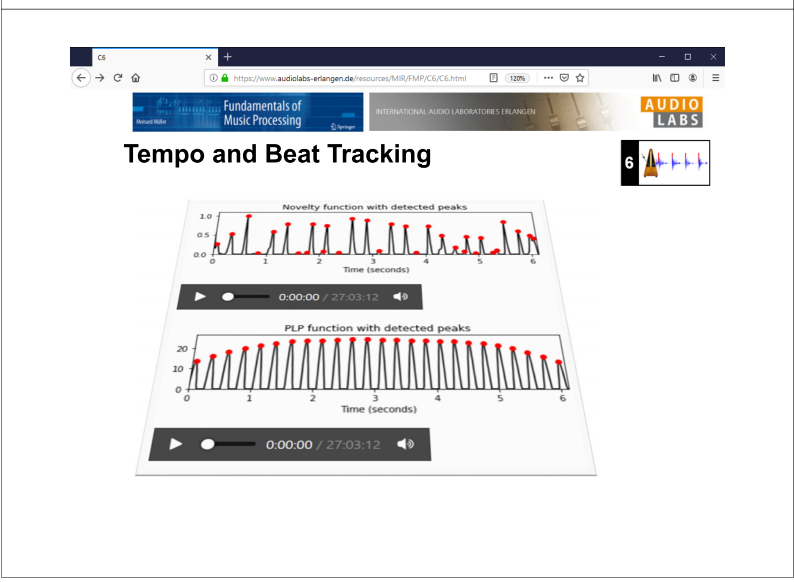

Fundamentals of Music Processing
INTERNATIONAL AUDIO LABORATORIES ERLANGEN
AUDIO LABS
Tempo and Beat Tracking
Definition
Explanations
Theory
Mathematics
$\mathcal{F}(n,\omega) := \sum_{m\in\mathbb{Z}} \Delta(m)\overline{w}(m-n)\exp(-2\pi i\omega m).$

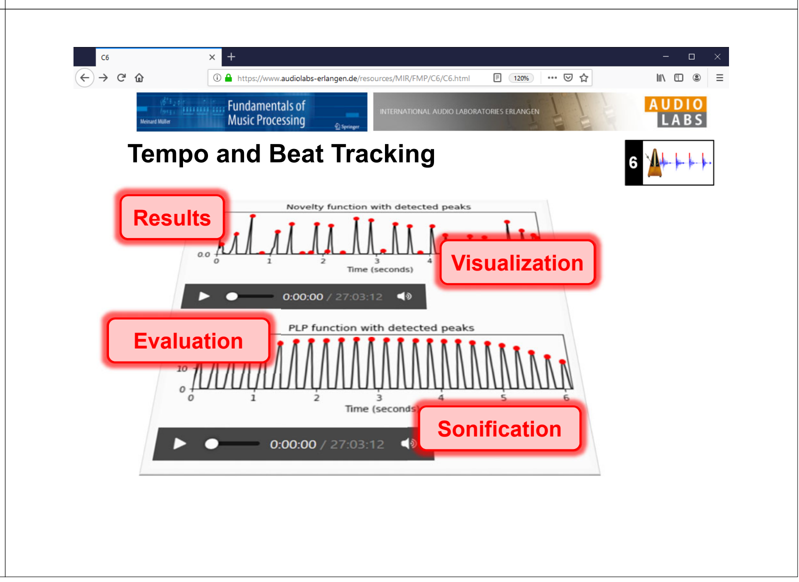

Fundamentals of Music Processing
AUDIO LABS
Tempo and Beat Tracking
Example: Shostakovich
In the following example, we consider an excerpt of a recording of Dimitri Shostakovich's Suite for Variety Orchestra No. 1. The score version of the excerpt.
0:00 / 0:06
We start with a spectral-based novelty function resampled to
Furthermore, we use a window size corresponding to 5 seconds


Tempo and Beat Tracking
Example: Shostakovich
Annotations
Music Examples
Audio
Links

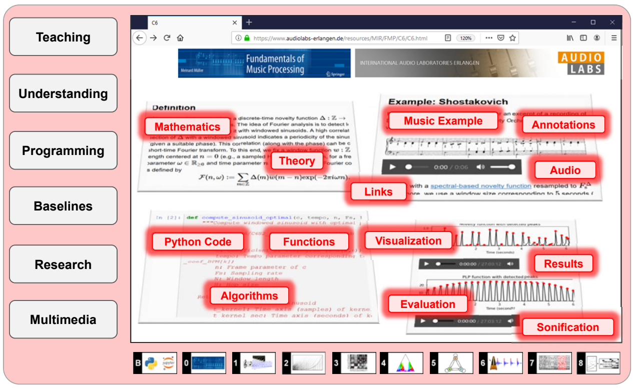

Tempo and Beat Tracking
In [2]: def compute_sinusoid_optimal(c, tempo, n, Fs, N
"""Compute windowed sinusoid with optimal p
Notebook: C6/C6S2_TempogramFourier.ipynb
Args:
c: Coefficient of tempogram (c=X(k,n))
tempo: Tempo parameter corresponding to
_coef_BPM[k])
n: Frame parameter of c
Fs: Sampling rate
N: Window length
H: Hop size


Tempo and Beat Tracking
Algorithms
Python Code
Functions


Tempo and Beat Tracking
Novelty function with detected peaks
Time (seconds)
0:00:00 / 27:03:12
PLP function with detected peaks
Time (seconds)
0:00:00 / 27:03:12


Tempo and Beat Tracking
Results
Visualization
Evaluation
Sonification

FMP Notebooks



References

- 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

Resources

- librosa:
  https://librosa.org/
- madmom:
  https://github.com/CPJKU/madmom
- Essentia Python tutorial:
  https://essentia.upf.edu/essentia_python_tutorial.html
- mirdata:
  https://github.com/mir-dataset-loaders/mirdata
- open-unmix:
  https://github.com/sigsep/open-unmix-pytorch
- Open Source Tools & Data for Music Source Separation:
  https://source-separation.github.io/tutorial/landing.html