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

FMP Notebooks

Teaching and Learning Fundamentals of Music Processing

Meinard Müller

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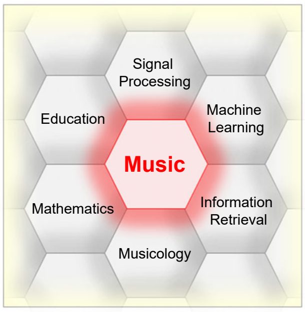
FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

Fraunhofer IIS

Music Processing

Music Processing: A Multifaceted Research Area



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

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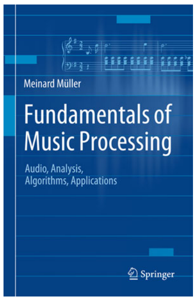
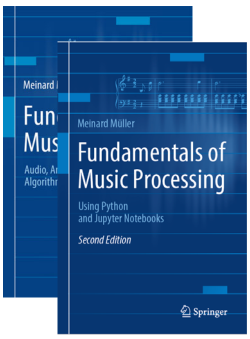
Fundamentals of Music Processing (FMP)



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 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

Fundamentals of Music Processing — INTERNATIONAL AUDIO LABORATORIES ERLANGEN — AUDIO LABS

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

FMP Notebooks: Education & Research

- … provide educational material for teaching and learning fundamentals of music processing.
- … combine textbook-like explanations, technical concepts, mathematical details, Python code examples, illustrations, and sound examples.
- … bridge the gap between theory and practice being based on interactive Jupyter notebook framework.
- … are freely accessible under a Creative Commons license.

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]
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8	Musically Informed Audio Decomposition	Harmonic/percussive separation, signal reconstruction, instantaneous frequency, fundamental frequency (F0), trajectory, nonnegative matrix factorization (NMF)	[html]	[ipynb]

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- Part 0: Starting notebook

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- Part 1 to Part 8: Different music processing scenarios

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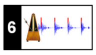
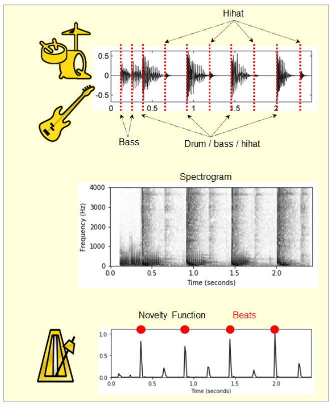
Part 6: Tempo and Beat Tracking

Part 6: Tempo and Beat Tracking

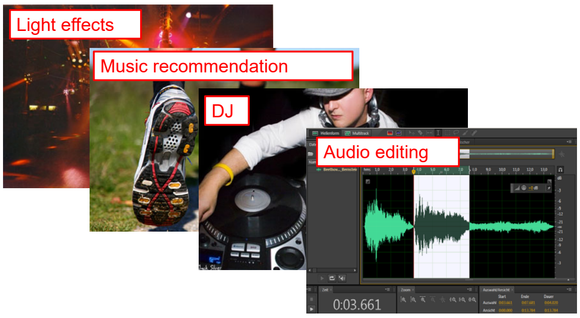


- When listening to a piece of music, we as humans are often able to tap along with the musical beat
- Automated beat tracking: Simulate this cognitive process by a computer



Tempo and Beat Tracking

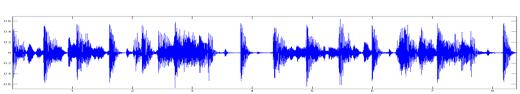
Basic task: “Tapping the foot when listening to music”



Tempo and Beat Tracking

Basic task: “Tapping the foot when listening to music”

Example: Queen – Another One Bites The Dust

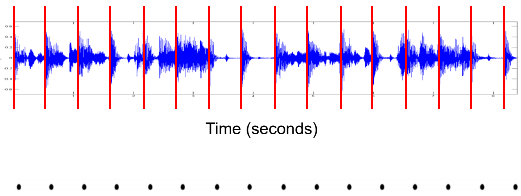


Time (seconds)

Tempo and Beat Tracking

Basic task: “Tapping the foot when listening to music”

Example: Queen – Another One Bites The Dust

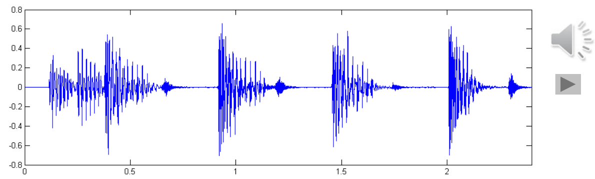


Time (seconds)

Tempo and Beat Tracking

Tasks

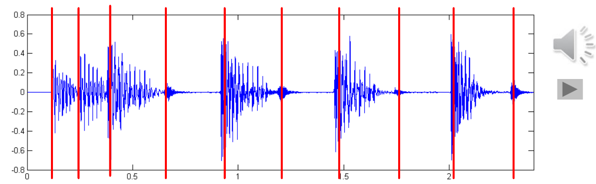
- Onset detection
- Beat tracking
- Tempo estimation



Tempo and Beat Tracking

Tasks

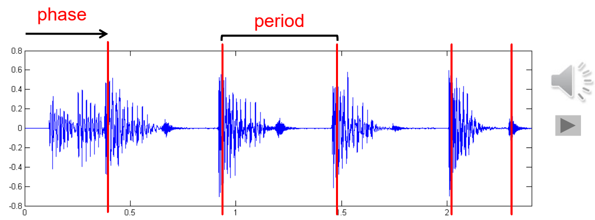
- Onset detection
- Beat tracking
- Tempo estimation



Tempo and Beat Tracking

Tasks

- Onset detection
- Beat tracking
- Tempo estimation



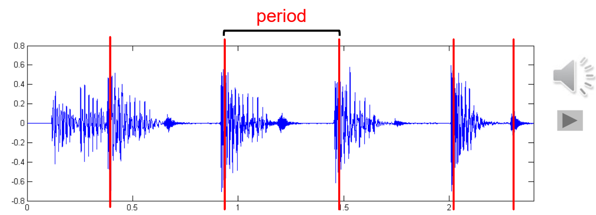
Tempo and Beat Tracking

Tasks

- Onset detection
- Beat tracking
- Tempo estimation

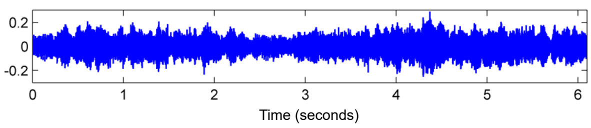
Tempo := 60 / period

Beats per minute (BPM)

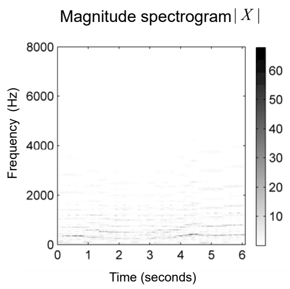


Onset Detection (Spectral Flux)

Audio recording



Onset Detection (Spectral Flux)

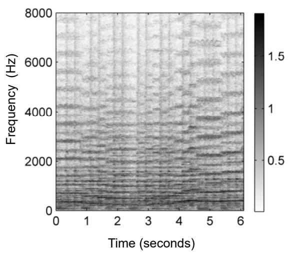


Steps:

1. Spectrogram

Onset Detection (Spectral Flux)

Compressed spectrogram Y



Steps:

1. Spectrogram
2. Logarithmic compression

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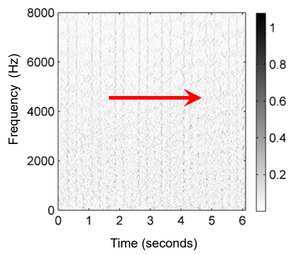
Onset Detection (Spectral Flux)

Spectral difference



Steps:

1. Spectrogram
2. Logarithmic compression
3. Differentiation &
   half wave rectification

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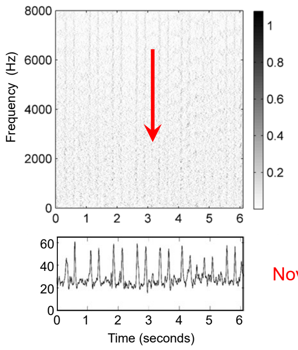
Onset Detection (Spectral Flux)

Spectral difference



Novelty curve

Steps:

1. Spectrogram
2. Logarithmic compression
3. Differentiation &
   half wave rectification
4. Accumulation

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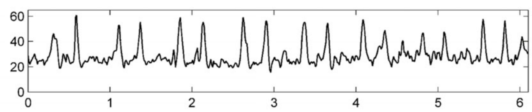
Onset Detection (Spectral Flux)

Steps:

1. Spectrogram
2. Logarithmic compression
3. Differentiation &
   half wave rectification
4. Accumulation

Novelty function



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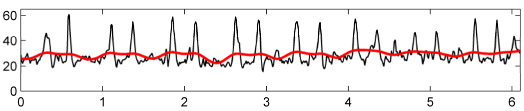
Onset Detection (Spectral Flux)

Steps:

1. Spectrogram
2. Logarithmic compression
3. Differentiation &
   half wave rectification
4. Accumulation
5. Normalization

Novelty function

Substraction of local average



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Onset Detection (Spectral Flux)

Steps:

1. Spectrogram
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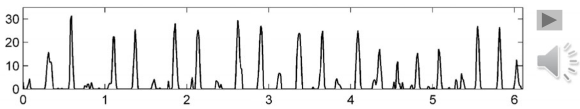
4. Accumulation
5. Normalization

Normalized novelty function



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Onset Detection (Spectral Flux)

Steps:

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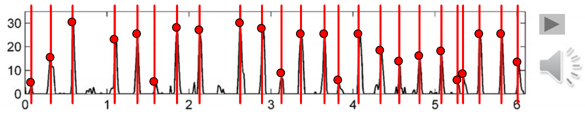
5. Normalization

Normalized novelty function

Peak positions indicate beat candidates



Onset Detection (Spectral Flux)

Deep Learning

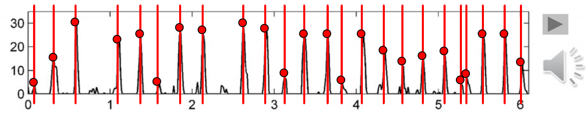
1. Input representation
2. Sigmoid activation
3. Convolution & rectified linear unit (ReLU)
4. Pooling
5. Convolution & ReLU

Steps:

1. Spectrogram
2. Logarithmic compression
3. Differentiation & half wave rectification
4. Accumulation
5. Normalization

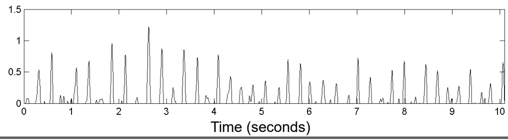
Normalized novelty function

Peak positions indicate beat candidates



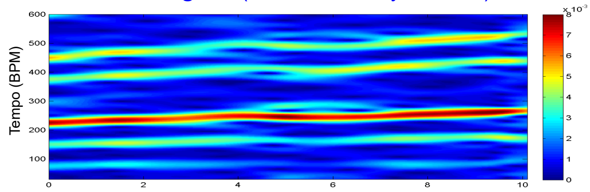
Local Pulse and Tempo Tracking

Normalized novelty function

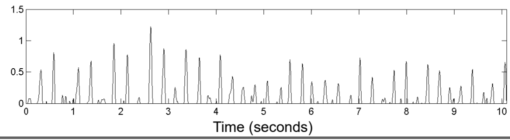


Local Pulse and Tempo Tracking

Fourier temogram (STFT of novelty function)



Normalized novelty function



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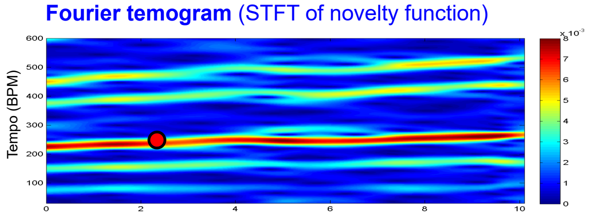
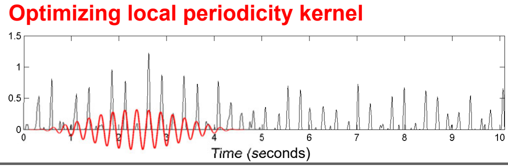


Optimizing local periodicity kernel



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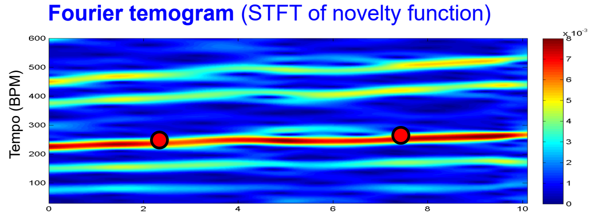

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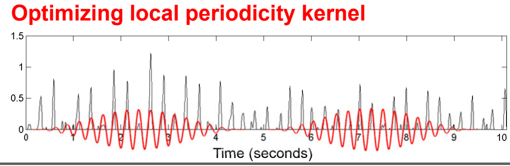

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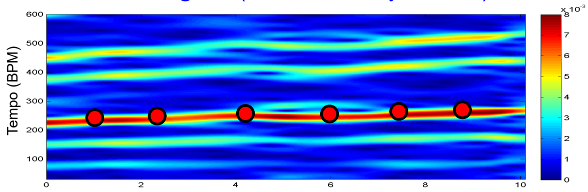

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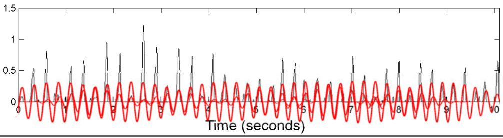

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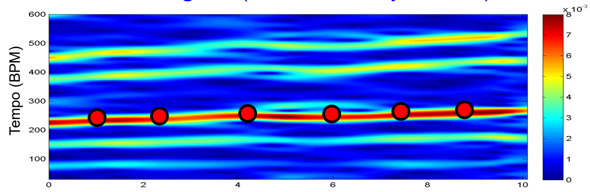
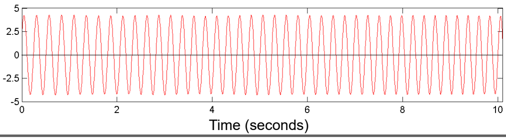
Local Pulse and Tempo Tracking

Fourier temogram (STFT of novelty function)



Accumulation of kernels



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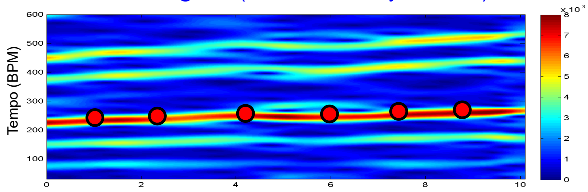
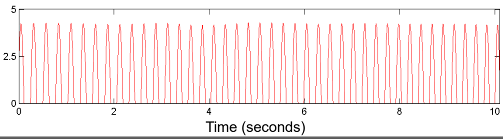


Halfwave rectification



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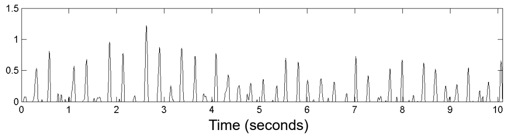
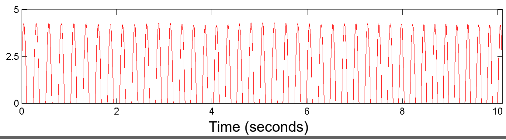
Local Pulse and Tempo Tracking

Novelty Curve



Predominant Local Pulse (PLP)



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FMP Notebooks

Structured in 10 parts

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

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		Similarity matrix, repetition,	[html]	[ipynb]
5				[ipynb]
6	Tempo and Beat Tracking	Onset, novelty, tempo, tempogram, beat, periodicity, Fourier analysis, autocorrelation	[html]	[ipynb]
7	Content-Based Audio Retrieval	Identification, fingerprint, indexing, inverted list, matching, version, cover song	[html]	[ipynb]
8	Musically Informed Audio Decomposition	Harmonic/percussive separation, signal reconstruction, instantaneous frequency, fundamental frequency (F0), trajectory, nonnegative matrix factorization (NMF)	[html]	[ipynb]

Part 6: Tempo and Beat Tracking

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Part B: Basics

Topic	Description
Get Started	Explanation on how to install and use the FMP notebooks
Installation	Installation of Python using Conda
Jupyter Notebook	Usage of Jupyter notebook framework
Python Basics	Introduction of data types, control structures, and functions
Python Style Guide	Recommendations for programming style
Multimedia	Integration of multimedia objects into notebooks
Python Visualization	Generation of figures and images
Python Audio	Reading and writing audio files
Numba	Acceleration of Python functions via JIT compilation
Annotation Visualization	Visualization of annotations (single value, segments)
Sonification	Sonification methods (onsets, F0 trajectories, pitch, chroma)
libfmp	Library of FMP-specific Python functions
MIR Resources	Links to resources that are useful for MIR

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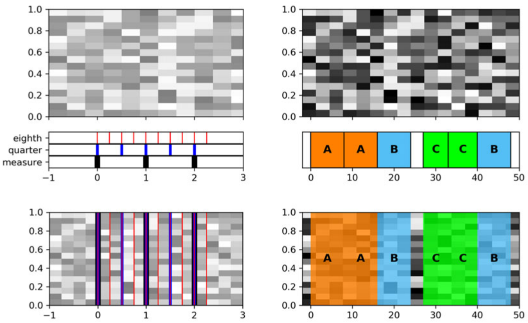
Part B: Basics
Annotation Visualization

Examples for visualizing annotations of time positions and segments.



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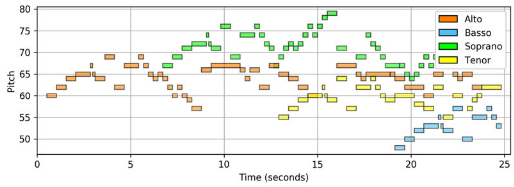
AUDIO LABS

Part 1: Music Representations
Symbolic Format: CSV



Visualization of a piano-roll representation (Fugue BWV 846 by Bach).

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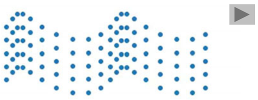
Part 1: Music Representations
Waves and Waveforms



Videos illustrating the concepts of transverse, longitudinal, and combined waves.

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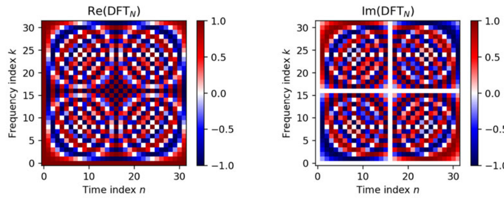
AUDIO LABS

Part 2: Fourier Analysis of Signals
Discrete Fourier Transform (DFT)



The matrix DFT_N and a visualization of its real and imaginary parts for the case $N = 32$

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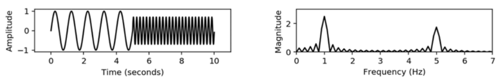
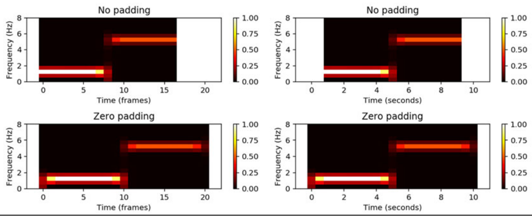
AUDIO LABS

Part 2: Fourier Analysis of Signals
STFT: Padding

Time-domain signal and magnitude Fourier transform.



Magnitude STFT.



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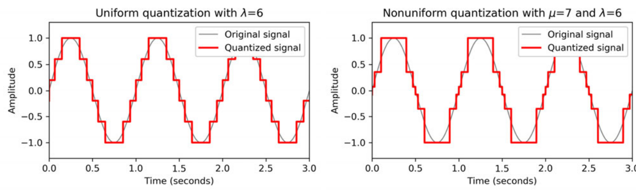
Part 2: Fourier Analysis of Signals
Digital Signals: Quantization

Uniform and nonuniform quantization (based on μ-law encoding) using $\lambda = 6$ quantization levels.



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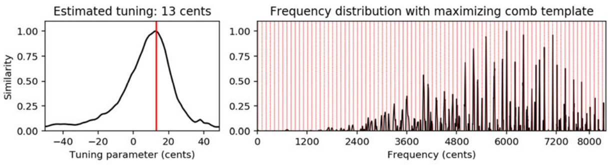
AUDIO LABS

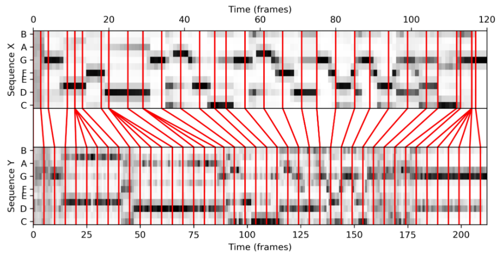
Part 3: Music Synchronization
Transposition and Tuning

Tuning procedure using a comb-filter approach.



Part 3: Music Synchronization
Music Synchronization

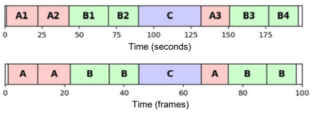
Music synchronization result obtained for two input chromagrams (obtained from two recordings of the beginning of Beethoven's Fifth Symphony).

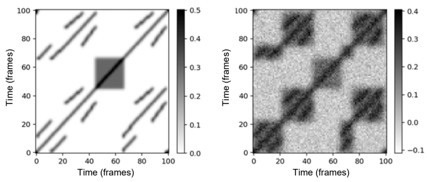


Part 4: Music Structure Analysis
SSM: Synthetic Generation

Structure annotation and different synthetically generated SSMs.

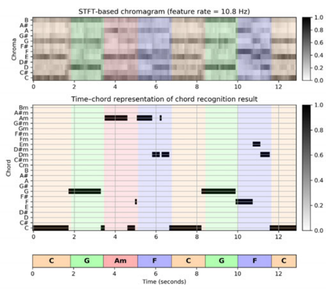
	start	end	label
0	0.00	1.01	
1	1.01	22.11	A1
2	22.11	43.06	A2
3	43.06	69.42	B1
4	69.42	89.57	B2
5	89.57	131.64	C
6	131.64	150.84	A3
7	150.84	176.96	B3
8	176.96	196.90	B4
9	196.90	199.64	





Part 5: Chord Recognition
Template-Based Chord Recognition

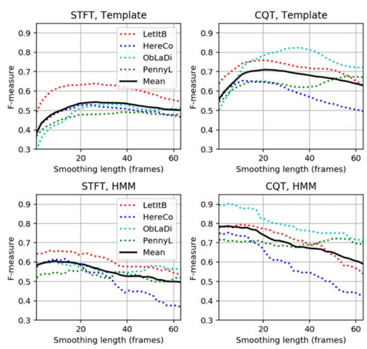
Chord recognition task illustrated by the first measures of the Beatles song "Let It Be."



Part 5: Chord Recognition
Experiments: Beatles Collection

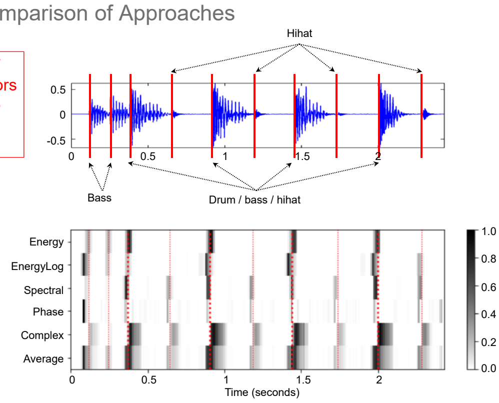
Prefiltering experiments for a template-based and an HMM-based chord recognizer applied to two different input chroma representations (STFT, CQT).

The evaluation is performed on the basis of four Beatles songs (LetItB, HereCo, ObLaDi, PennyL).



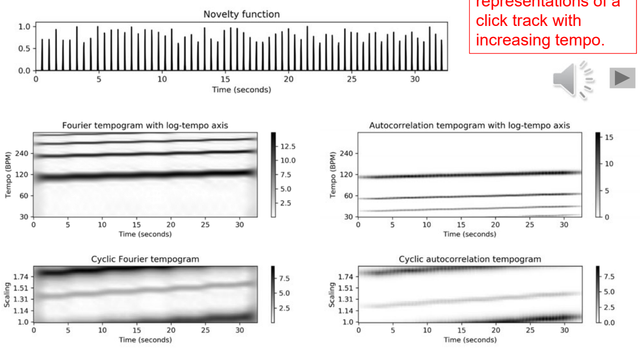
Part 6: Tempo and Beat Tracking
Novelty: Comparison of Approaches

Comparison of novelty detectors using a matrix-based visualization.



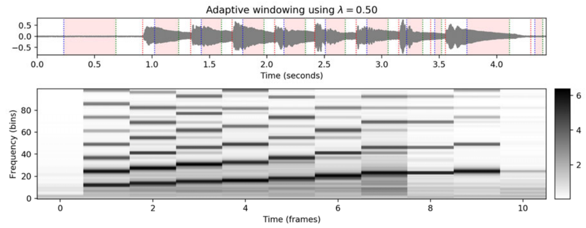
Part 6: Tempo and Beat Tracking
Cyclic Tempogram

Different tempogram representations of a click track with increasing tempo.



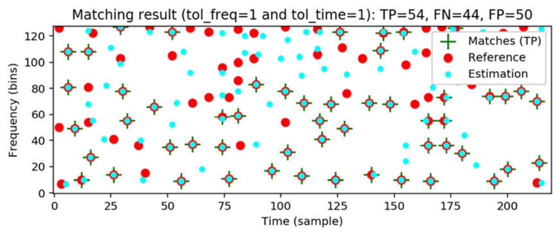
Part 6: Tempo and Beat Tracking
Adaptive Windowing

Example of adaptive windowing using a parameter λ to control the neighborhood's relative size to be excluded.



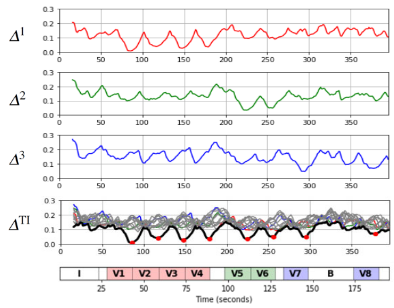
Part 7: Content-Based Audio Retrieval
Audio Identification

Evaluation measures that indicate the agreement between two constellation maps computed for an original version (Reference) and a noisy version (Estimation).



Part 7: Content-Based Audio Retrieval
Audio Matching

Transposition-invariant matching function illustrated by Zager and Evans' song "In the Year 2525."



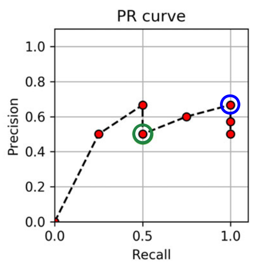
I V1 V2 V5 V6

Part 7: Content-Based Audio Retrieval
Evaluation Measures

Various evaluation metrics applied to a toy example.

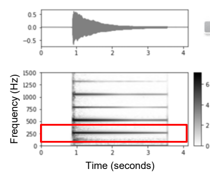
Rank	ID	Score	χ_Q	P(r)	R(r)	F(r)
1	6	3.70	False	0.00	0.00	0.00
2	3	3.60	True	0.50	0.25	0.33
3	4	3.50	True	0.67	0.50	0.57
4	5	3.20	False	0.50	0.50	0.50
5	8	3.10	True	0.60	0.75	0.67
6	2	2.60	True	0.67	1.00	0.80
7	7	1.50	False	0.57	1.00	0.73
8	1	0.70	False	0.50	1.00	0.67

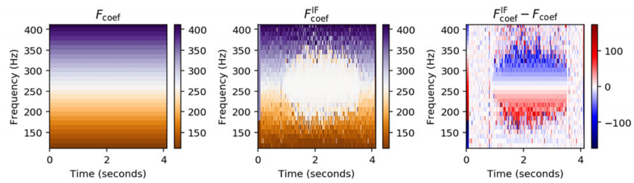
Break-even point = 0.50
F_max = 0.80
Average precision = 0.60833



Part 8: Audio Decomposition
Instantaneous Frequency Estimation

Interpretation of time–frequency bins of an STFT using (frame-dependent) instantaneous frequency values.



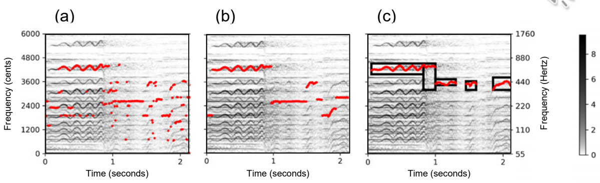


Part 8: Audio Decomposition

Fundamental Frequency Tracking

Salience representation with trajectories computed by
(a) a frame-wise approach,
(b) an approach using continuity constraints, and
(c) a score-informed approach.

Figure 8.10a from [Müller, FMP, Springer 2015]



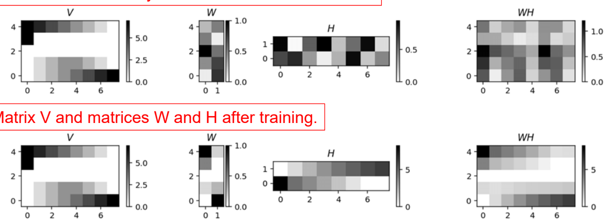
Part 8: Audio Decomposition

Nonnegative Matrix Factorization (NMF)

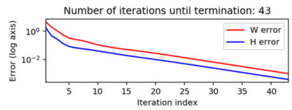
NMF procedure applied to a toy example.

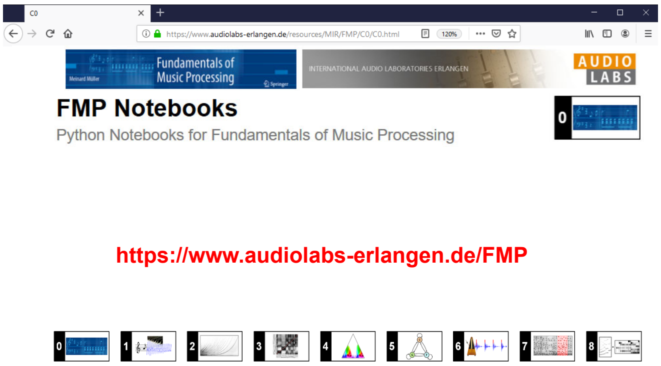
Matrix *V* and randomly initialized matrices *W* and *H*.

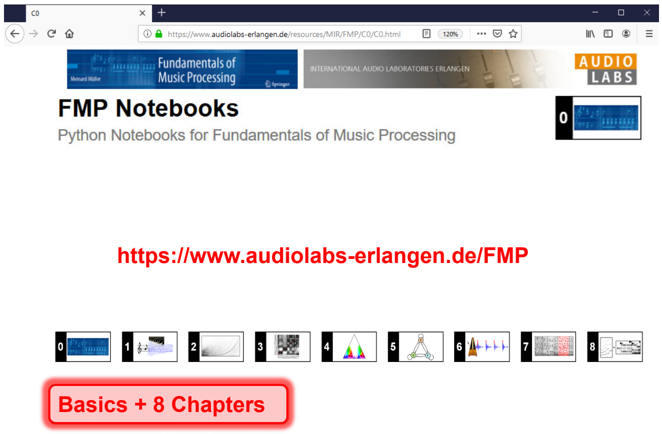
Matrix V and matrices W and H after training.

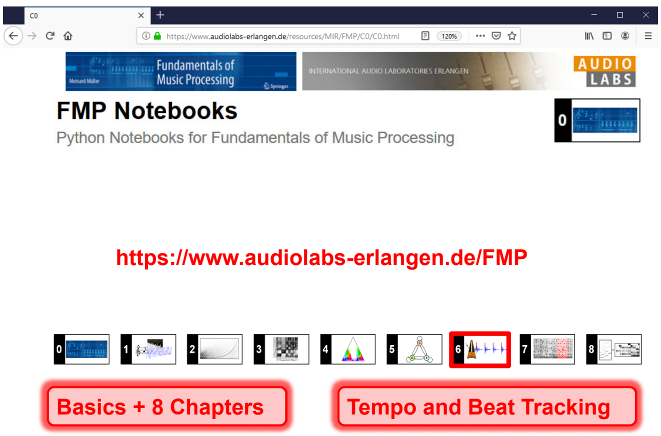


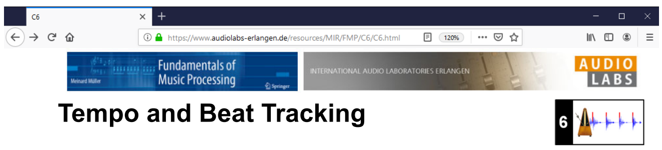
Error terms over iteration.

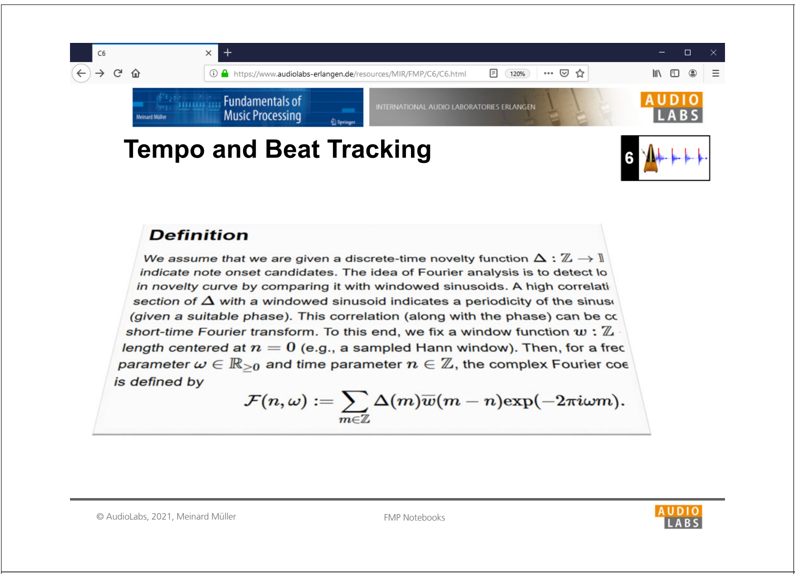











Fundamentals of Music Processing
INTERNATIONAL AUDIO LABORATORIES ERLANGEN
AUDIO LABS
Tempo and Beat Tracking
6
Definition
We assume that we are given a discrete-time novelty function Δ : ℤ → ℝ
indicate note onset candidates. The idea of Fourier analysis is to detect lo
in novelty curve by comparing 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 : ℤ
length centered at n = 0 (e.g., a sampled Hann window). Then, for a freq
parameter ω ∈ ℝ≥0 and time parameter n ∈ ℤ, the complex Fourier coe
is defined by
F(n, ω) := Σ_{m∈ℤ} Δ(m) w̄(m − n) exp(−2πiωm).
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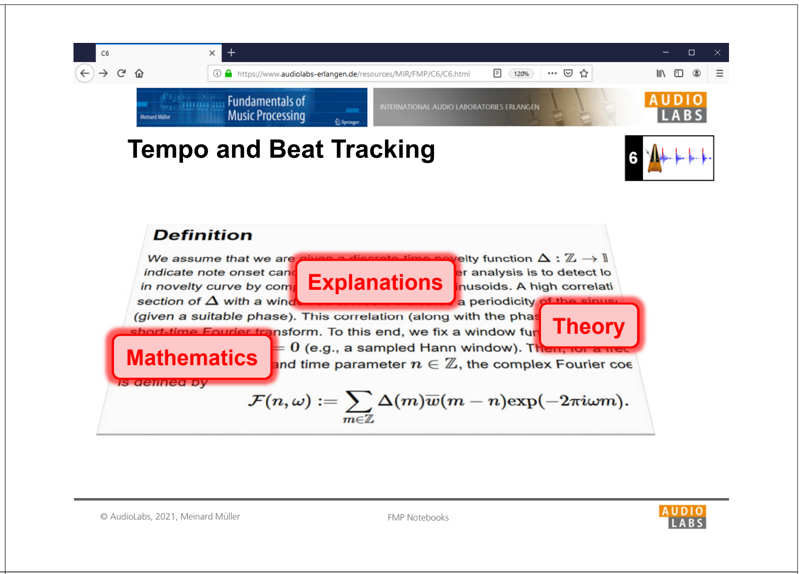
Fundamentals of Music Processing
AUDIO LABS
Tempo and Beat Tracking
6
Definition
Explanations
Theory
Mathematics
F(n, ω) := Σ_{m∈ℤ} Δ(m) w̄(m − n) exp(−2πiωm).
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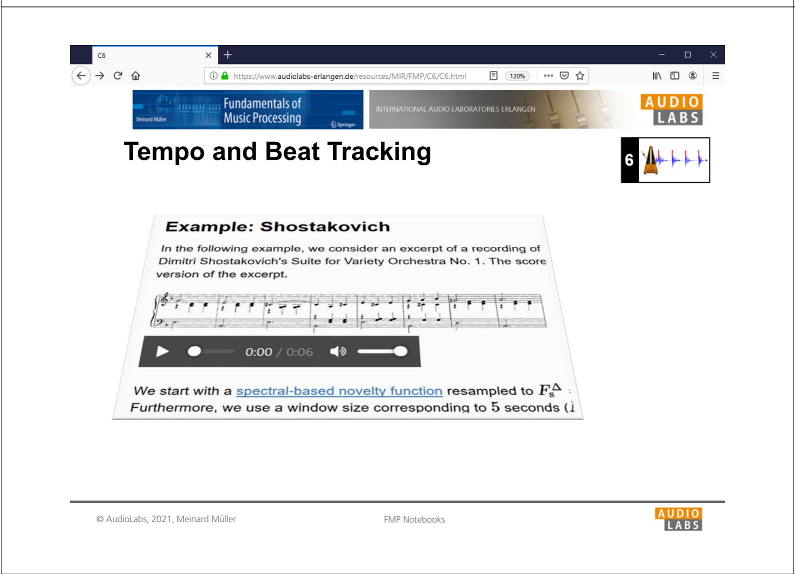
Fundamentals of Music Processing
AUDIO LABS
Tempo and Beat Tracking
6
Example: Shostakovich
In the following example, we consider an excerpt of a recording of
Dimitri Shostakovich's Suite for Variety Orchestra No. 1. The score
version of the excerpt.
0:00 / 0:06
We start with a spectral-based novelty function resampled to F_s^Δ
Furthermore, we use a window size corresponding to 5 seconds
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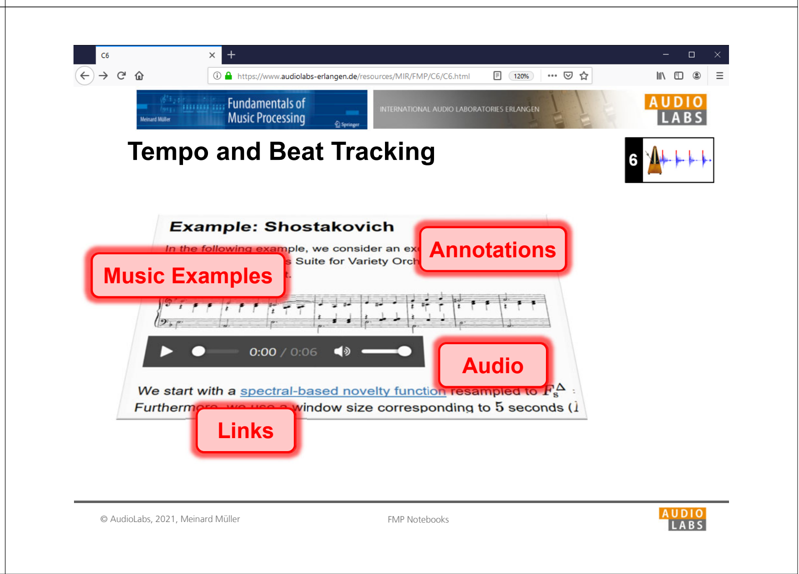
AUDIO LABS


Fundamentals of Music Processing
AUDIO LABS
Tempo and Beat Tracking
6
Example: Shostakovich
Annotations
Music Examples
Audio
Links
0:00 / 0:06
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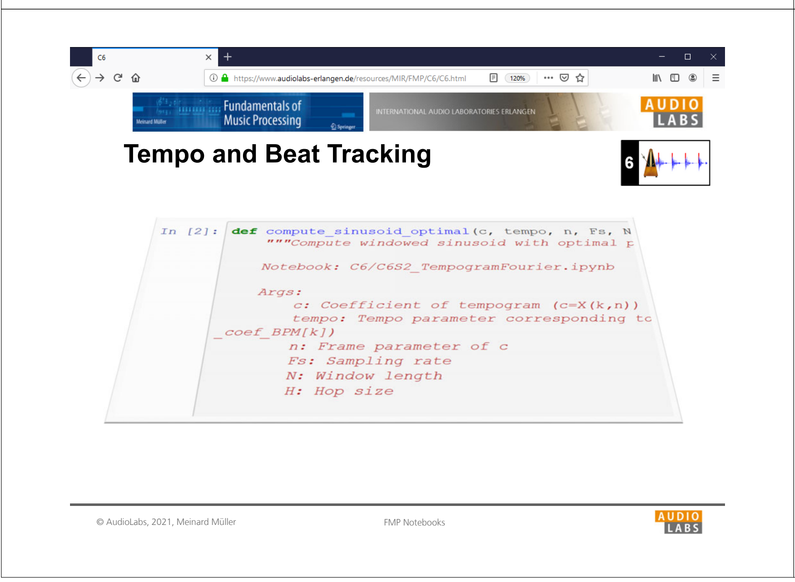
Fundamentals of Music Processing
AUDIO LABS
Tempo and Beat Tracking
6
In [2]: def compute_sinusoid_optimal(c, tempo, n, Fs, N
"""Compute windowed sinusoid with optimal p
Notebook: C6/C6S2_TempogramFourier.ipynb
Args:
c: Coefficient of tempogram (c=X(k,n))
tempo: Tempo parameter corresponding to
_coef_BPM[k])
n: Frame parameter of c
Fs: Sampling rate
N: Window length
H: Hop size
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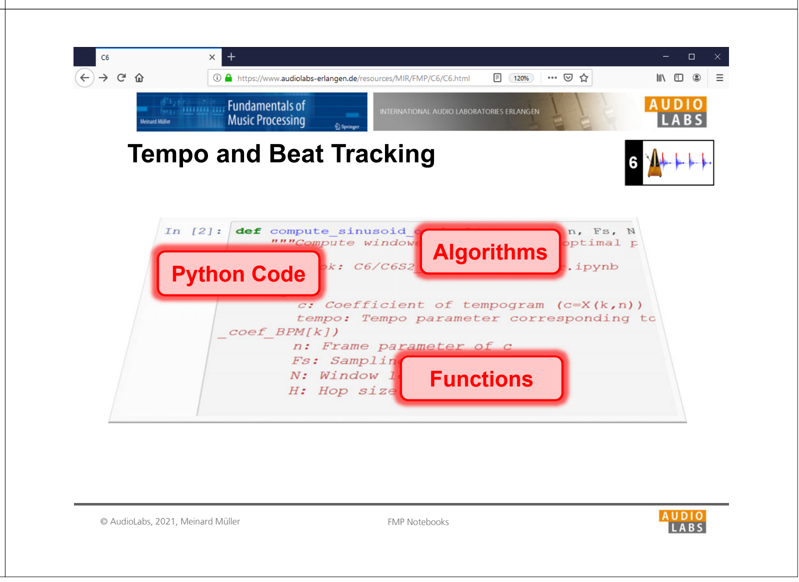
Fundamentals of Music Processing
AUDIO LABS
Tempo and Beat Tracking
6
Algorithms
Python Code
Functions
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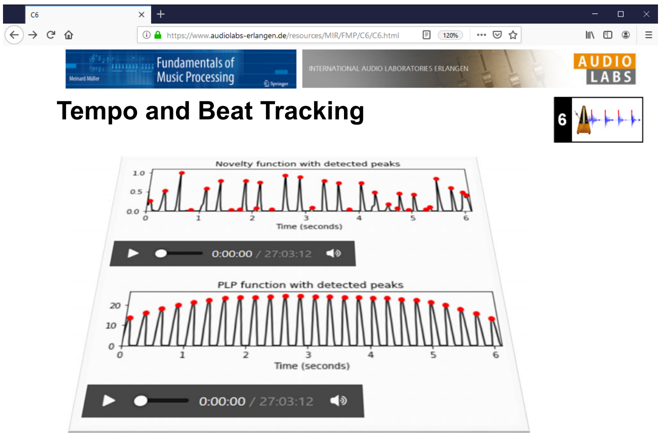
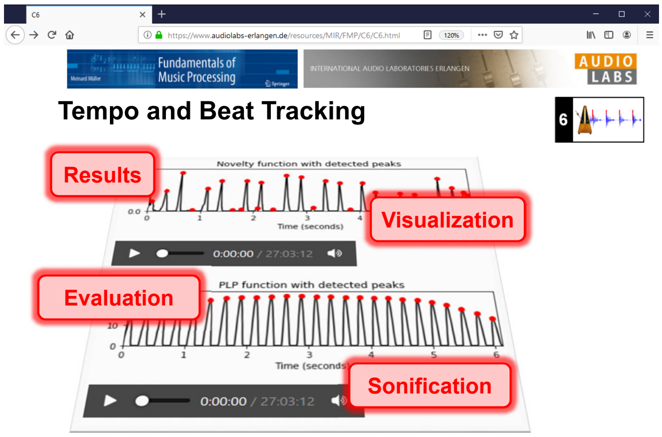
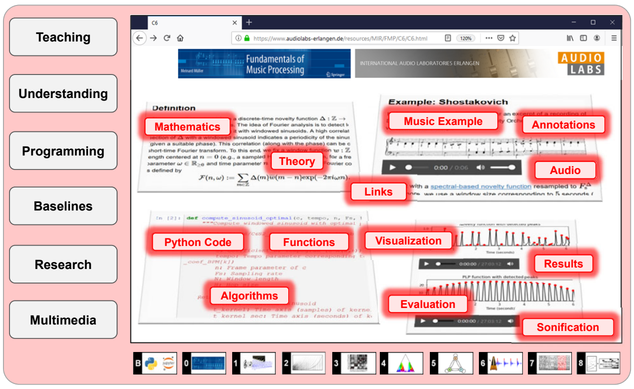




FMP Notebooks



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