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

AUDIO LABS

# Learning-By-Doing: Using the FMP Python Notebooks for Audio and Music Processing

**Meinard Müller**

International Audio Laboratories Erlangen
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**Deep Learning Indaba𝕏**

Nigeria, 24 Sep – 25 Sep 2021

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)
- Member of the Senior Editorial Board of the IEEE Signal Processing Magazine
- IEEE Fellow for contributions to Music Signal Processing

universitätbonn — FAU — ISMIR — IEEE



## Meinard Müller: Research Group

Semantic Audio Processing

- 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
- Strong Technical Faculty



## International Audio Laboratories Erlangen

**Audio**

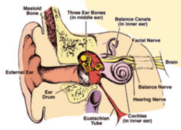


## International Audio Laboratories Erlangen

**Audio**

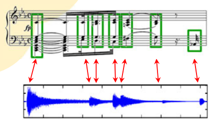
Audio Coding

3D Audio



Psychoacoustics

Internet of Things



Music Processing

## AudioLabs – FAU

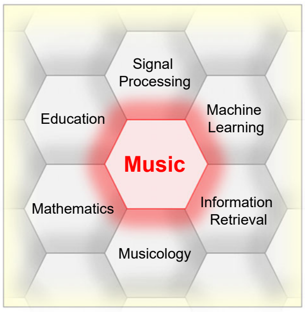
- Prof. Dr. Jürgen Herre
  Audio Coding
- Prof. Dr. Bernd Edler
  Audio Signal Analysis
- Prof. Dr. Meinard Müller
  Semantic Audio Processing
- Prof. Dr. Emanuël Habets
  Spatial Audio Signal Processing
- Prof. Dr. Nils Peters
  Audio Signal Processing
- Dr. Stefan Turowski
  Coordinator AudioLabs-FAU



## Music Processing



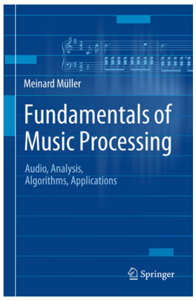

## Music Processing: A Multifaceted Research Area




- 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



## Fundamentals of Music Processing (FMP)




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

Accompanying website:
www.music-processing.de



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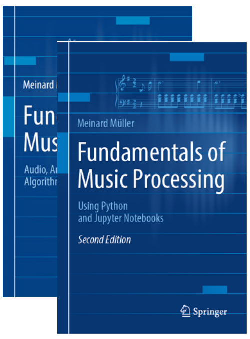


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2nd edition
Meinard Müller
Fundamentals of Music Processing
Using Python and Jupyter Notebooks
Springer, 2021



## Fundamentals of Music Processing (FMP)

| Chapter | | Music Processing Scenario |
|---|---|---|
| 1 | | Music Represenations |
| 2 | | Fourier Analysis of Signals |
| 3 | | Music Synchronization |
| 4 | | Music Structure Analysis |
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## FMP Notebooks: Education & Research


**FMP Notebooks**

Python Notebooks for Fundamentals of Music Processing

The FMP notebooks offer a collection of educational material closely following the textbook Fundamentals of Music Processing (FMP). 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] |
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**Part 6: Tempo and Beat Tracking**

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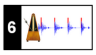
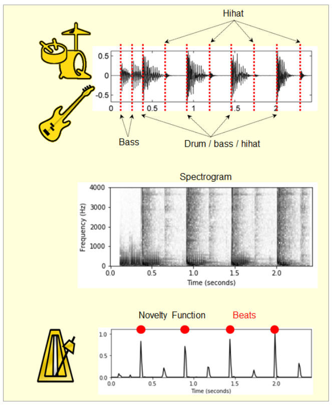
## Part 6: Tempo and Beat Tracking



- 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

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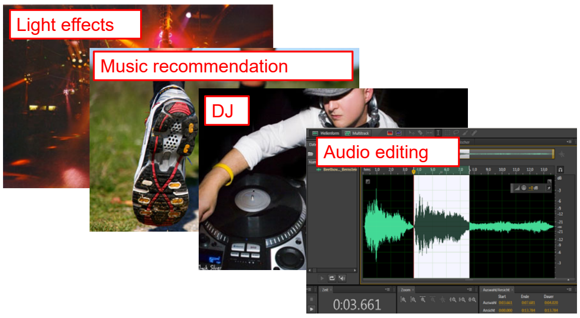
## Tempo and Beat Tracking

Basic task: "Tapping the foot when listening to music"

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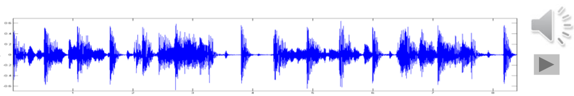
## Tempo and Beat Tracking

Basic task: "Tapping the foot when listening to music"

Example: Queen – Another One Bites The Dust



Time (seconds)

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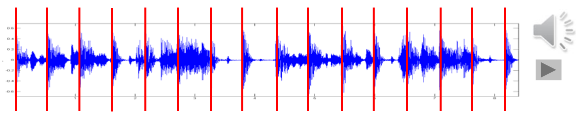
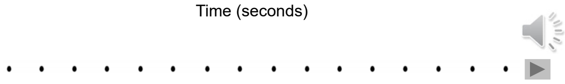
## Tempo and Beat Tracking

Basic task: "Tapping the foot when listening to music"

Example: Queen – Another One Bites The Dust



Time (seconds)



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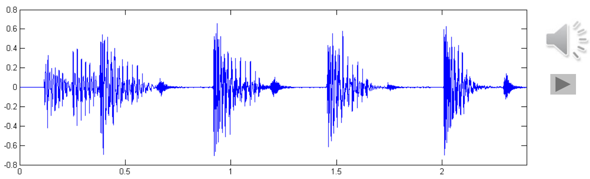
## Tempo and Beat Tracking

Tasks

- Onset detection
- Beat tracking
- Tempo estimation

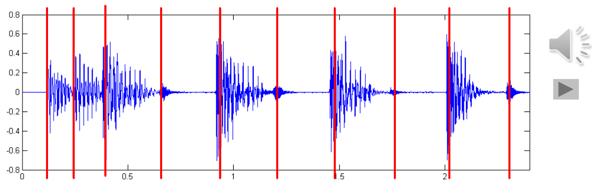




## Tempo and Beat Tracking

Tasks

- Onset detection
- Beat tracking
- Tempo estimation

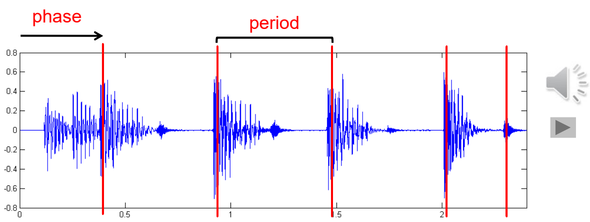




## Tempo and Beat Tracking

Tasks

- Onset detection
- Beat tracking
- Tempo estimation





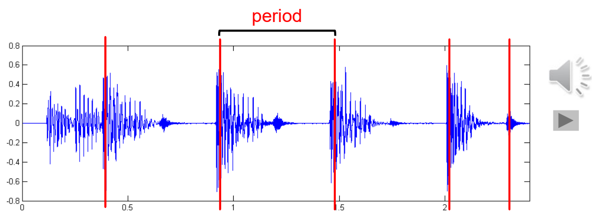

## Tempo and Beat Tracking

Tasks

- Onset detection
- Beat tracking
- Tempo estimation

Tempo := 60 / period

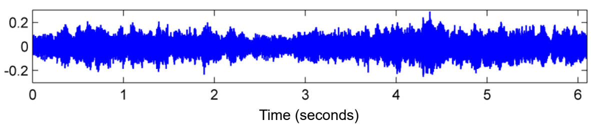
Beats per minute (BPM)





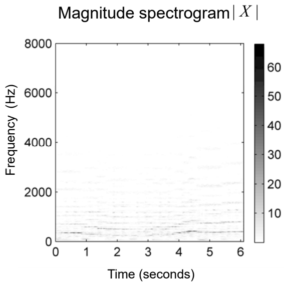

## Onset Detection (Spectral Flux)

Audio recording






## Onset Detection (Spectral Flux)

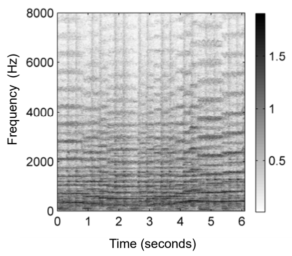



**Steps:**

1. Spectrogram

## Onset Detection (Spectral Flux)

Compressed spectrogram $Y$



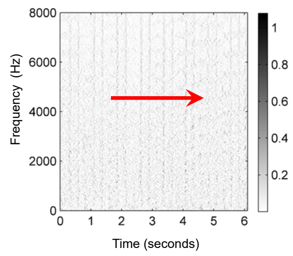

**Steps:**

1. Spectrogram
2. Logarithmic compression



## Onset Detection (Spectral Flux)

Spectral difference



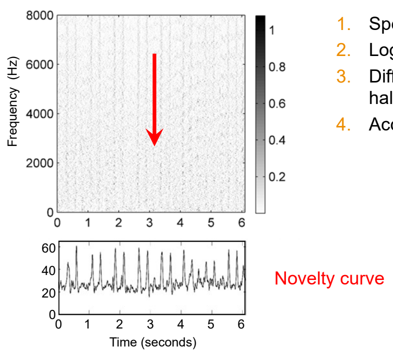

**Steps:**

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



## Onset Detection (Spectral Flux)

Spectral difference




**Steps:**

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

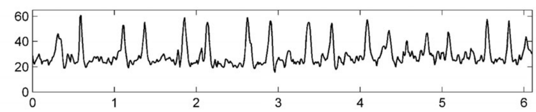


## Onset Detection (Spectral Flux)

**Steps:**

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

Novelty function





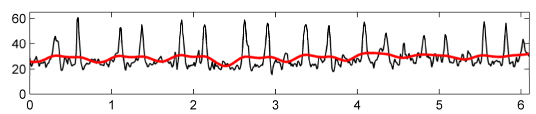
## Onset Detection (Spectral Flux)

**Steps:**

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

Novelty function

Substraction of local average



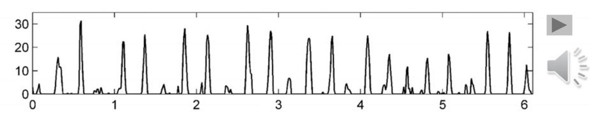


## Onset Detection (Spectral Flux)

**Steps:**

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

Normalized novelty function



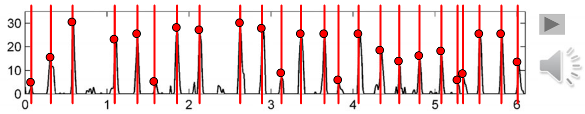
## Onset Detection (Spectral Flux)

**Steps:**

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

Normalized novelty function

Peak positions indicate beat candidates






## Onset Detection (Spectral Flux)

**Deep Learning**

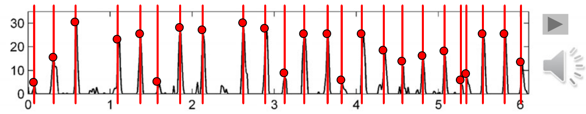
1. Input representation
2. Sigmoid activation
3. Convolution & rectified linear unit (ReLU)
4. Pooling
5. Convolution & ReLU

**Steps:**

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

Normalized novelty function

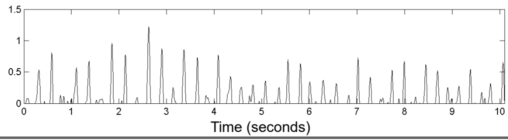
Peak positions indicate beat candidates






## Local Pulse and Tempo Tracking

Normalized novelty function

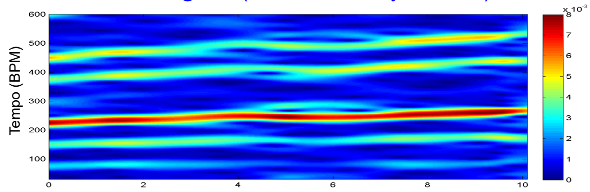




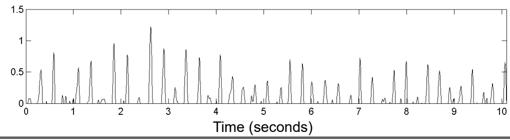


## Local Pulse and Tempo Tracking

**Fourier temogram** (STFT of novelty function)




Normalized novelty function

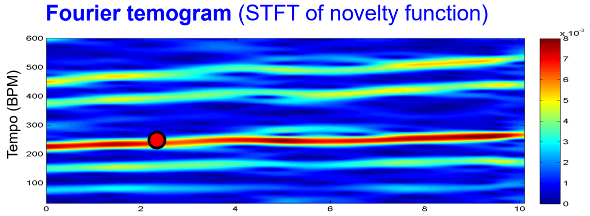




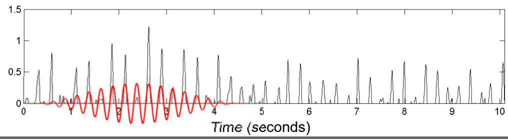


## Local Pulse and Tempo Tracking

**Fourier temogram** (STFT of novelty function)




**Optimizing local periodicity kernel**

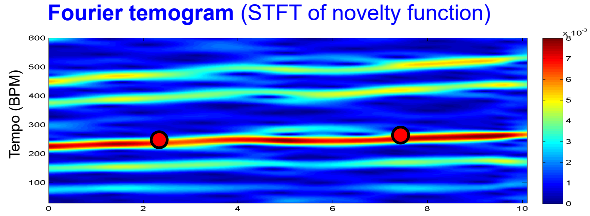




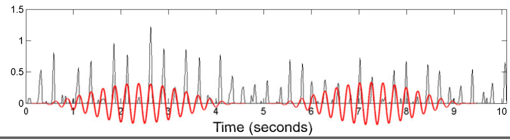


## Local Pulse and Tempo Tracking

**Fourier temogram** (STFT of novelty function)

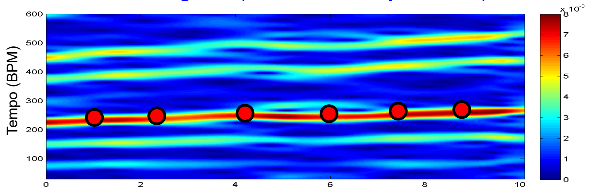



**Optimizing local periodicity kernel**

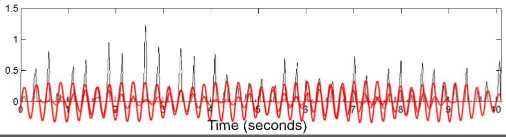


## Local Pulse and Tempo Tracking

**Fourier temogram** (STFT of novelty function)




**Optimizing local periodicity kernel**

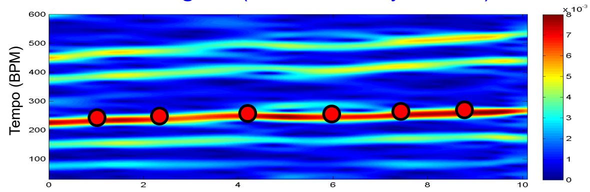




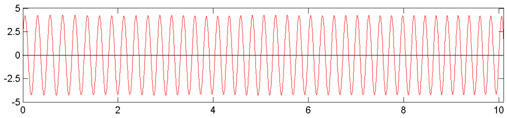


## Local Pulse and Tempo Tracking

**Fourier temogram** (STFT of novelty function)




**Accumulation of kernels**

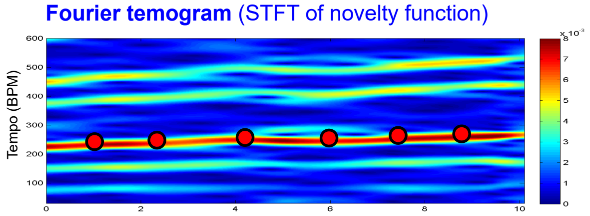




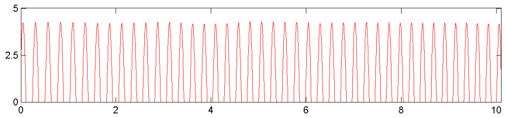


## Local Pulse and Tempo Tracking

**Fourier temogram** (STFT of novelty function)




**Halfwave rectification**

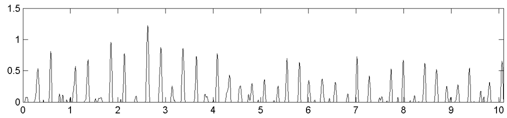




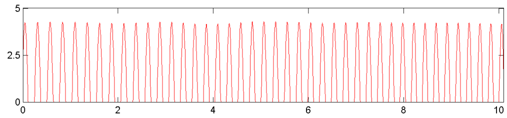


## Local Pulse and Tempo Tracking

**Novelty Curve**




**Predominant Local Pulse (PLP)**







## 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



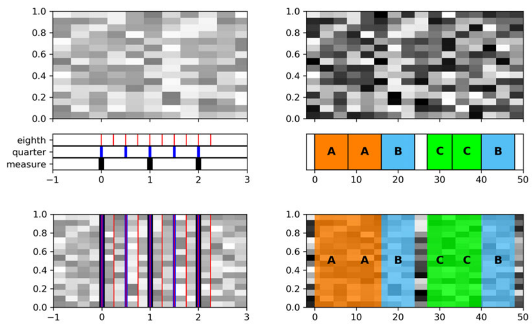


## Part B: Basics

| 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 |

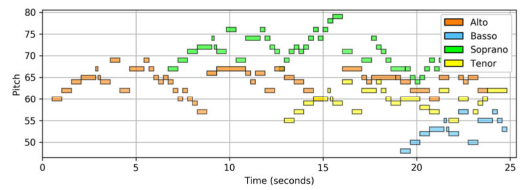
## Part B: Basics
Annotation Visualization

Examples for visualizing annotations of time positions and segments.






## Part 1: Music Representations
Symbolic Format: CSV




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

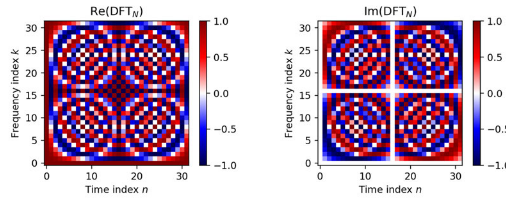


## Part 1: Music Representations
Waves and Waveforms

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



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

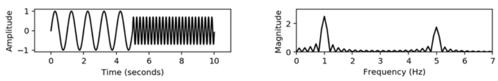



The matrix $\mathrm{DFT}_N$ and a visualization of its real and imaginary parts for the case $N = 32$

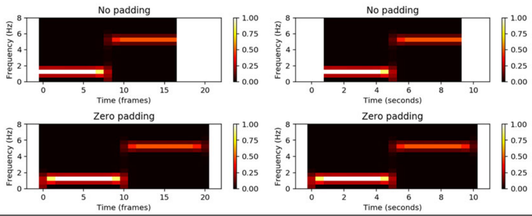


## Part 2: Fourier Analysis of Signals
STFT: Padding

Time-domain signal and magnitude Fourier transform.



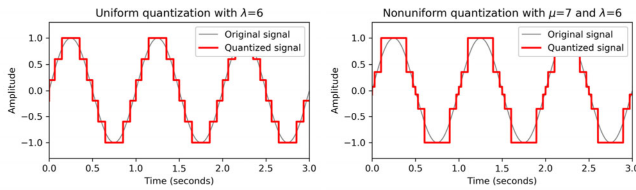

Magnitude STFT.





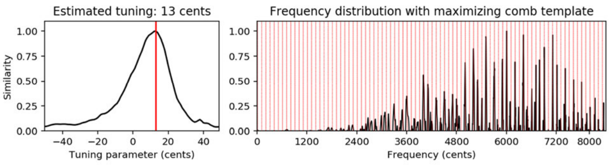

## Part 2: Fourier Analysis of Signals
Digital Signals: Quantization

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



## Part 3: Music Synchronization
### Transposition and Tuning

Tuning procedure using a comb-filter approach.

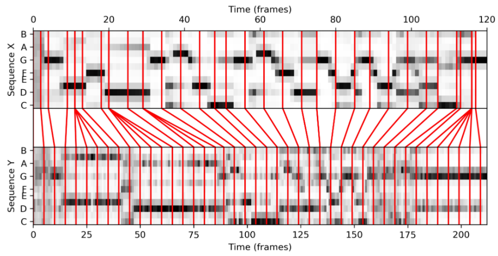






## Part 3: Music Synchronization
### Music Synchronization

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



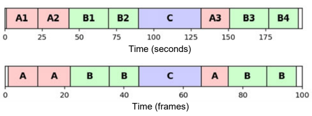


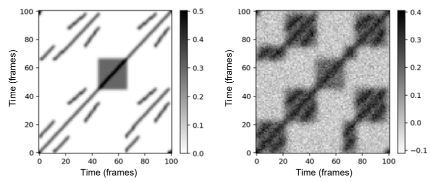


## Part 4: Music Structure Analysis
### SSM: Synthetic Generation

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 | |



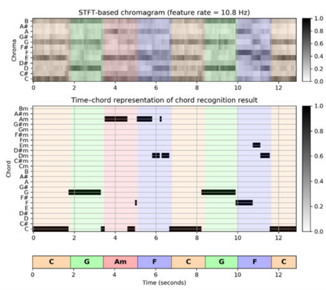







## Part 5: Chord Recognition
### Template-Based Chord Recognition

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

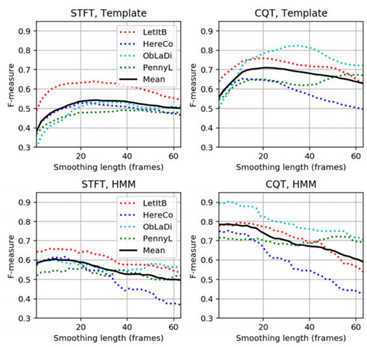




## Part 5: Chord Recognition
### Experiments: Beatles Collection

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).

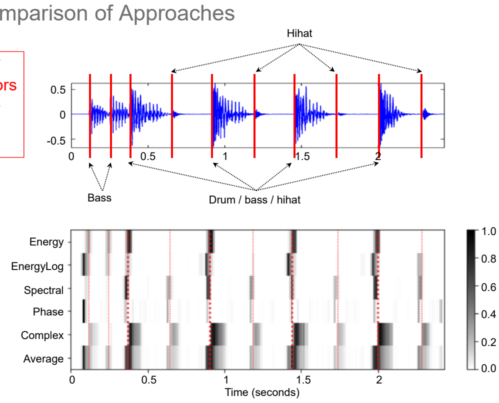






## Part 6: Tempo and Beat Tracking
### Novelty: Comparison of Approaches

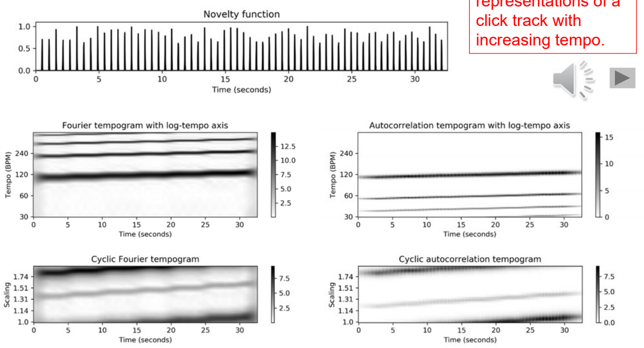
Comparison of novelty detectors using a matrix-based visualization.



## Part 6: Tempo and Beat Tracking

### Cyclic Tempogram

Different tempogram representations of a click track with increasing tempo.

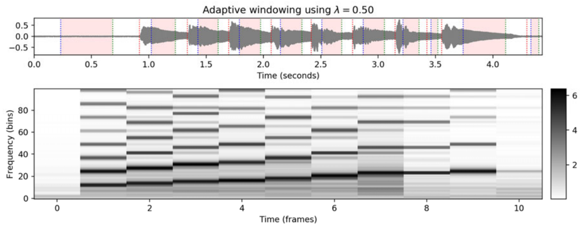


## Part 6: Tempo and Beat Tracking

### Adaptive Windowing

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

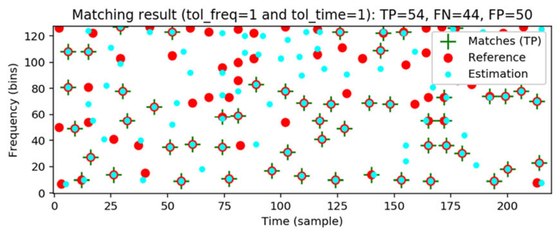



## Part 7: Content-Based Audio Retrieval

### Audio Identification

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

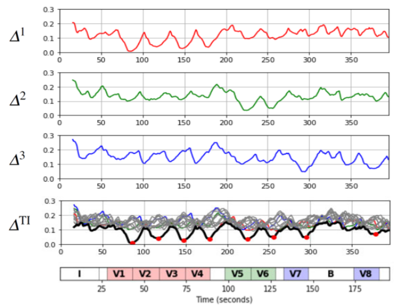


## Part 7: Content-Based Audio Retrieval

### Audio Matching

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




I V1 V2 V5 V6

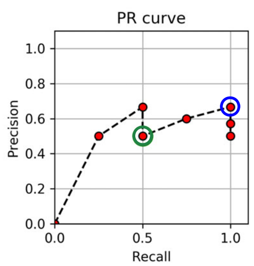
## Part 7: Content-Based Audio Retrieval

### Evaluation Measures

Various evaluation metrics applied to a toy example.

| Rank | ID | Score | $\chi_Q$ | 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

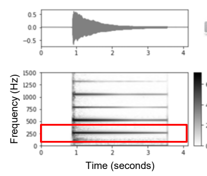


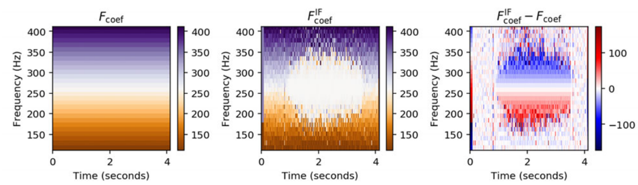

 

## Part 8: Audio Decomposition

### Instantaneous Frequency Estimation

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



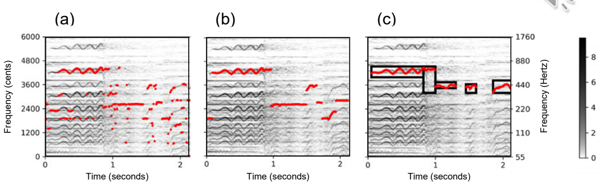



## Part 8: Audio Decomposition
Fundamental Frequency Tracking

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]





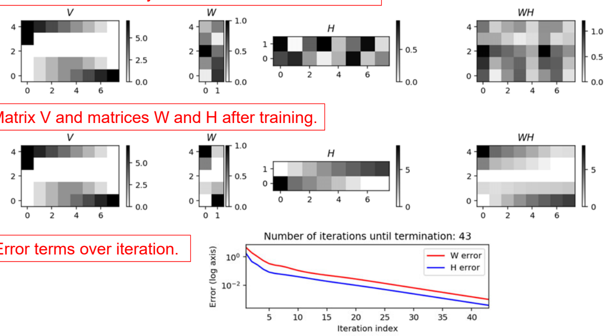

## Part 8: Audio Decomposition
Nonnegative Matrix Factorization (NMF)

NMF procedure applied to a toy example.

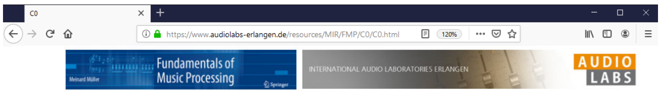
Matrix *V* and randomly initialized matrices *W* and *H*.

Matrix V and matrices W and H after training.

Error terms over iteration.

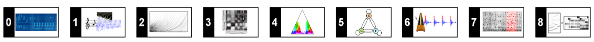




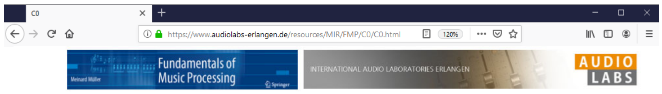




## FMP Notebooks
Python Notebooks for Fundamentals of Music Processing

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





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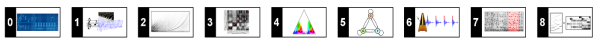
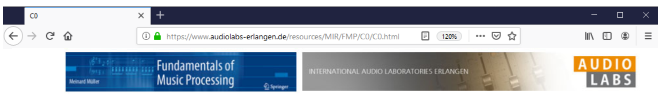


**Basics + 8 Chapters**



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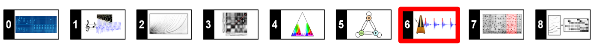
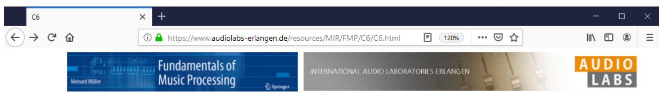
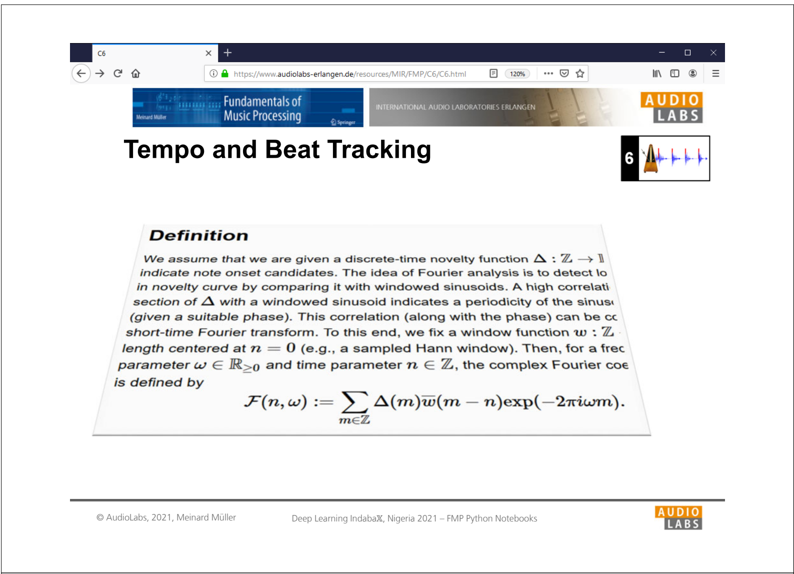


**Basics + 8 Chapters** **Tempo and Beat Tracking**






## Tempo and Beat Tracking


Fundamentals of Music Processing
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
$\mathcal{F}(n,\omega) := \sum_{m\in\mathbb{Z}} \Delta(m)\overline{w}(m-n)\exp(-2\pi i\omega m).$
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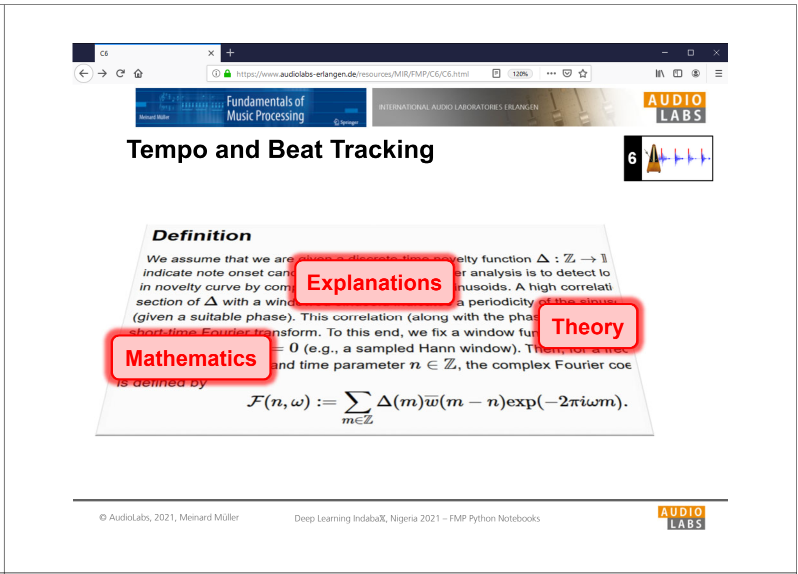
Fundamentals of Music Processing
AUDIO LABS
Tempo and Beat Tracking
6
Definition
Explanations
Theory
Mathematics
$\mathcal{F}(n,\omega) := \sum_{m\in\mathbb{Z}} \Delta(m)\overline{w}(m-n)\exp(-2\pi i\omega m).$
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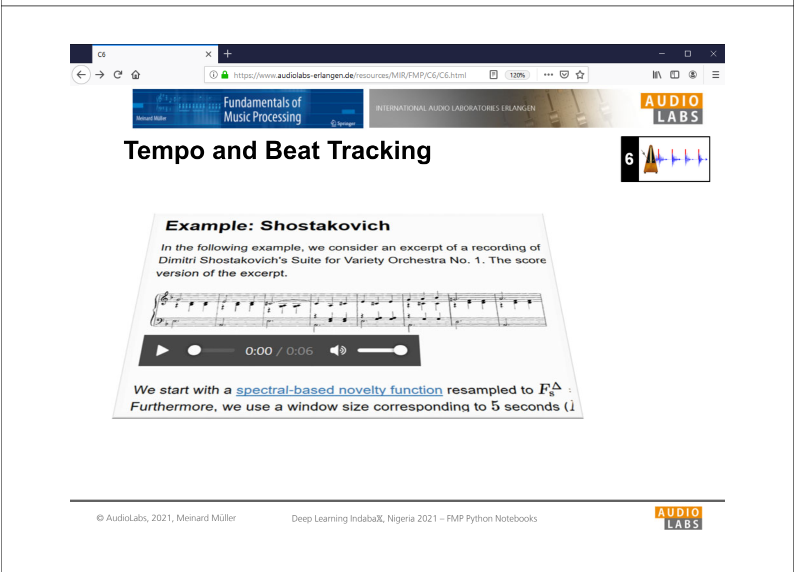
Fundamentals of Music Processing
AUDIO LABS
Tempo and Beat Tracking
6
Example: Shostakovich
In the following example, we consider an excerpt of a recording of
Dimitri Shostakovich's Suite for Variety Orchestra No. 1. The score
version of the excerpt.
0:00 / 0:06
We start with a spectral-based novelty function resampled to $F_s^\Delta$
Furthermore, we use a window size corresponding to 5 seconds (
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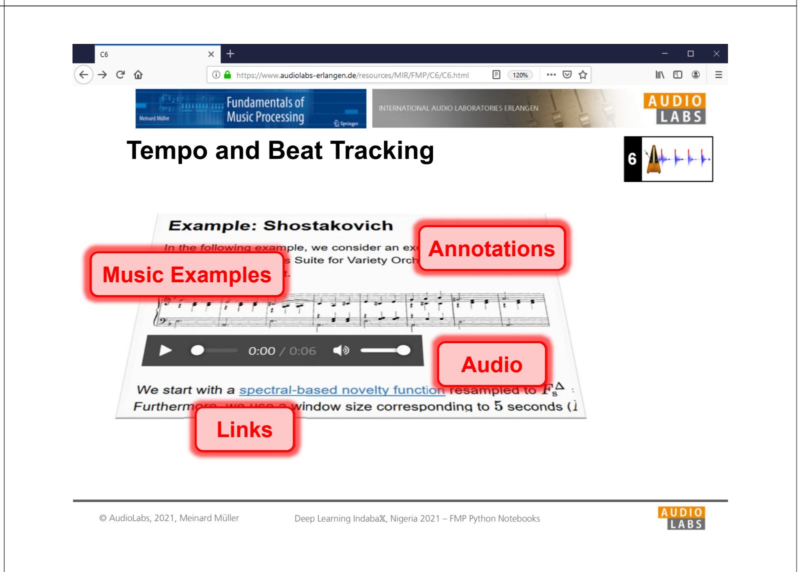
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6
Example: Shostakovich
Annotations
Music Examples
Audio
Links
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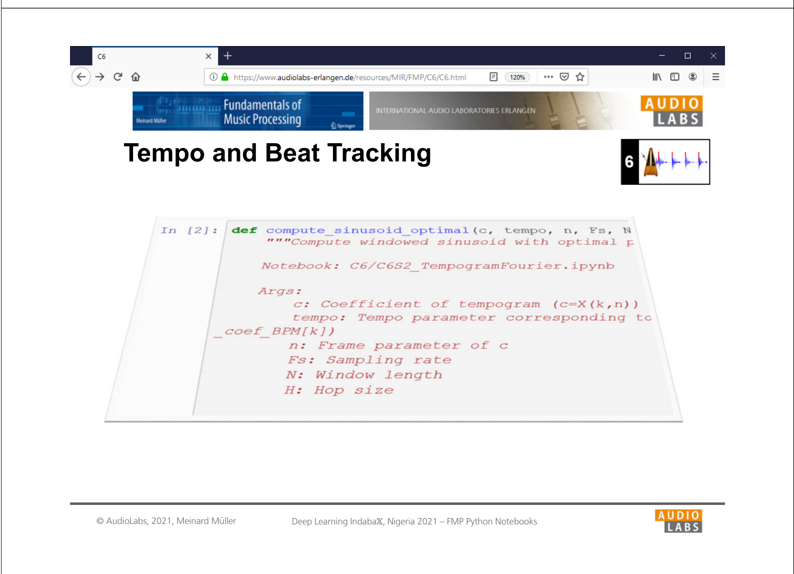
Fundamentals of Music Processing
AUDIO LABS
Tempo and Beat Tracking
6
In [2]: def compute_sinusoid_optimal(c, tempo, n, Fs, N
"""Compute windowed sinusoid with optimal p
Notebook: C6/C6S2_TempogramFourier.ipynb
Args:
c: Coefficient of tempogram (c=X(k,n))
tempo: Tempo parameter corresponding to
_coef_BPM[k])
n: Frame parameter of c
Fs: Sampling rate
N: Window length
H: Hop size
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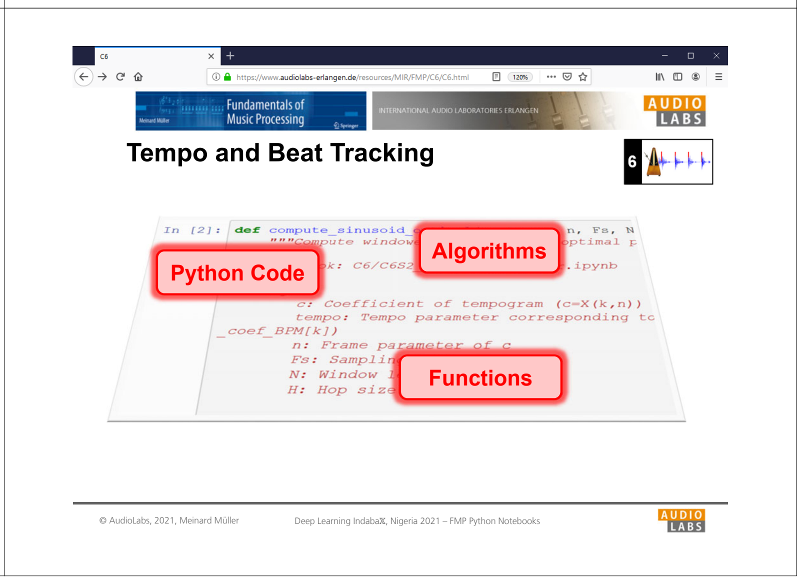
Fundamentals of Music Processing
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6
Algorithms
Python Code
Functions
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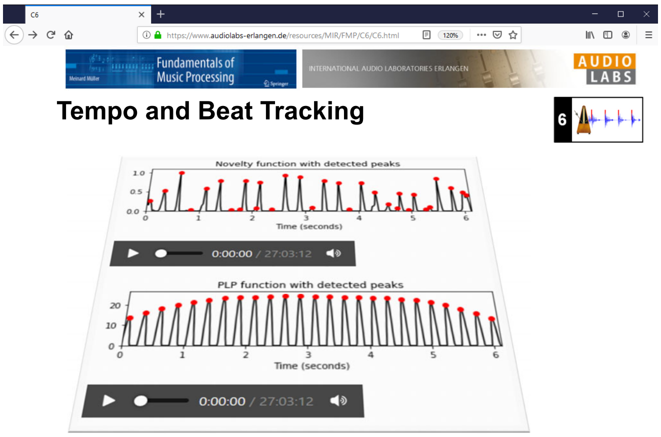
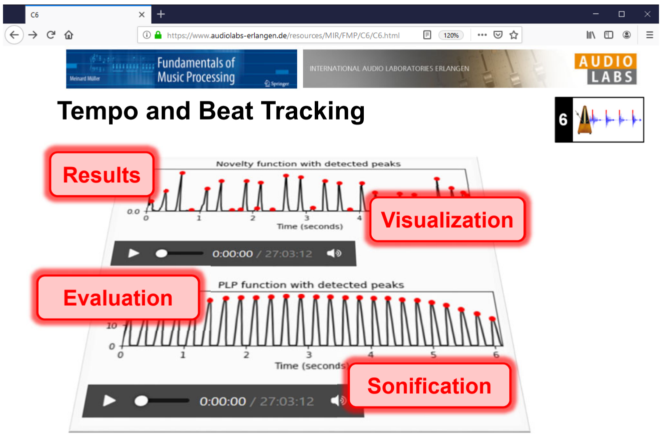
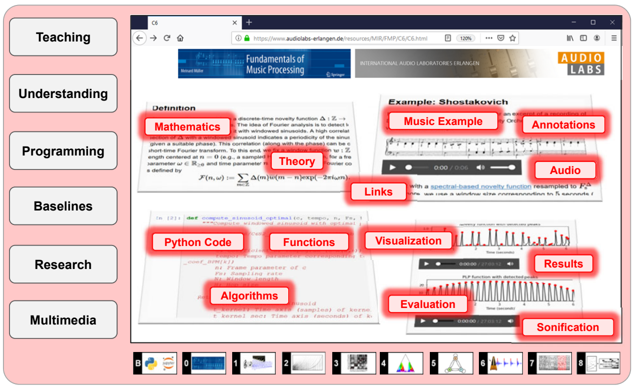







## FMP Notebooks






## References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  https://joss.theoj.org/papers/10.21105/joss.03326
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  https://www.mdpi.com/2624-6120/2/2/18
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  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