

## Beethoven, Bach, and Billions of Bytes

When Music meets Computer Science

**Meinard Müller**

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School of Mathematics  
University of Edinburgh  
24.11.2017



## Meinard Müller



- Mathematics (Diplom/Master)  
Computer Science (PhD)  
Information Retrieval (Habilitation)  
**Bonn University**
- Combinatorics (Postdoc)  
**Keio University, Japan**
- Senior Researcher  
**Max-Planck Institute, Saarland**
- Professor: Semantic Audio Processing  
**Erlangen-Nürnberg University**

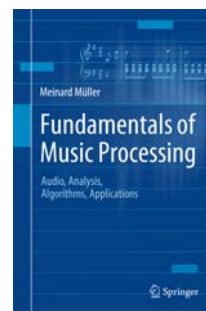


## Group Members

- Stefan Balke
- Christian Dittmar
- Patricio López-Serrano
- Christof Weiß
- Frank Zalkow
- Sebastian Rosenzweig



## Book: Fundamentals of Music Processing



Meinard Müller  
Fundamentals of Music Processing  
Audio, Analysis, Algorithms, Applications  
483 p., 249 illus., 30 illus. in color, hardcover  
ISBN: 978-3-319-21944-8  
Springer, 2015

Accompanying website:  
[www.music-processing.de](http://www.music-processing.de)

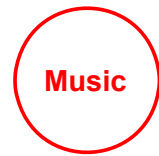
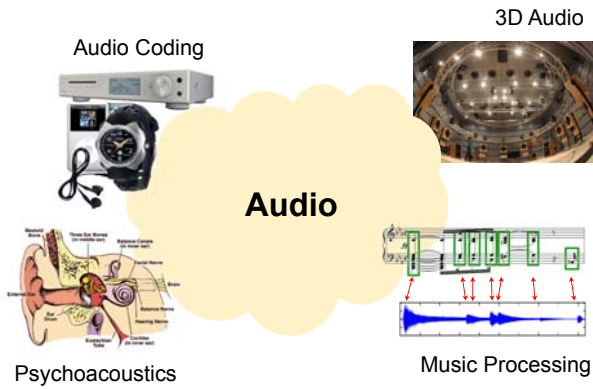
## International Audio Laboratories Erlangen



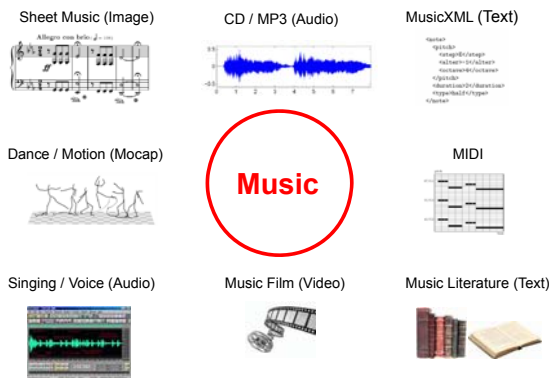
## International Audio Laboratories Erlangen



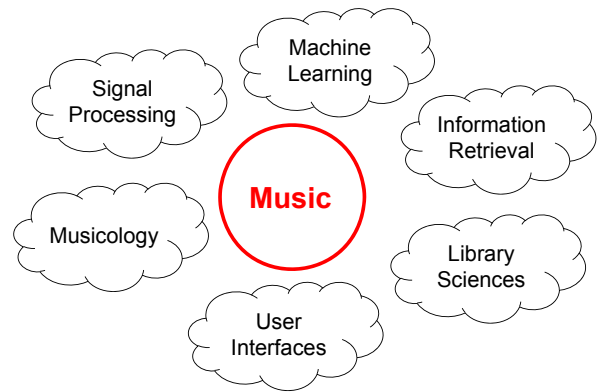
## International Audio Laboratories Erlangen



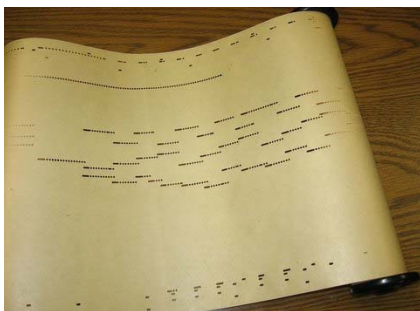
## Music Information Retrieval (MIR)



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## Piano Roll Representation

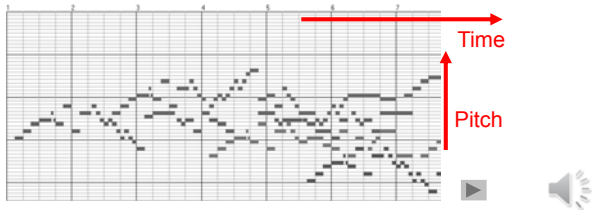


## Player Piano (1900)



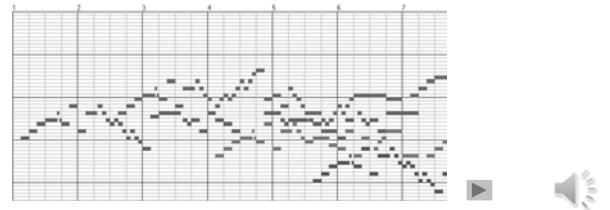
## Piano Roll Representation (MIDI)

J.S. Bach, C-Major Fuge  
(Well Tempered Piano, BWV 846)



## Piano Roll Representation (MIDI)

Query:   
Goal: Find all occurrences of the query

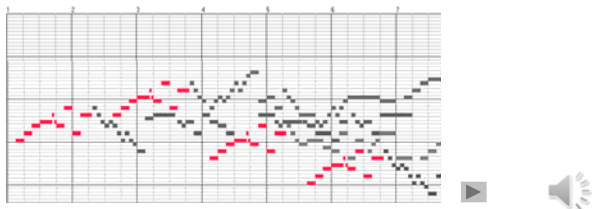


## Piano Roll Representation (MIDI)

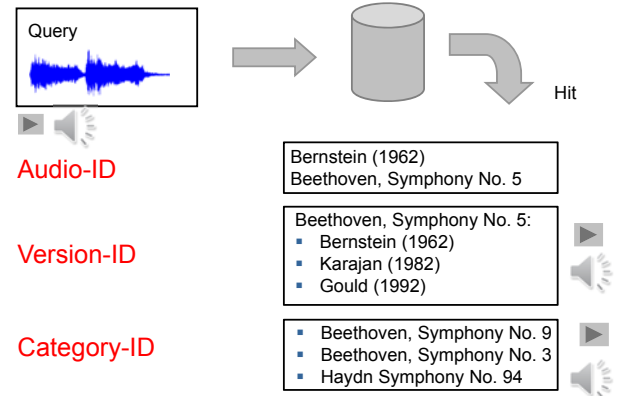
Query:   
Goal: Find all occurrences of the query



Matches:



## Music Retrieval



## Music Synchronization: Audio-Audio

Beethoven's Fifth

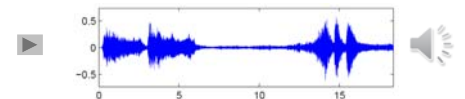


## Music Synchronization: Audio-Audio

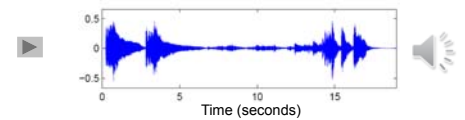
Beethoven's Fifth



Orchester  
(Karajan)



Piano  
(Scherbakov)

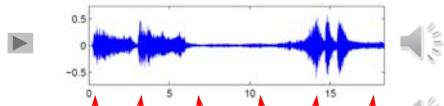


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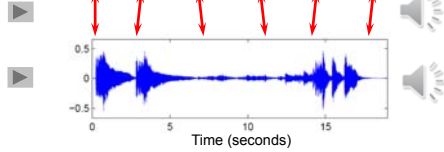
Beethoven's Fifth



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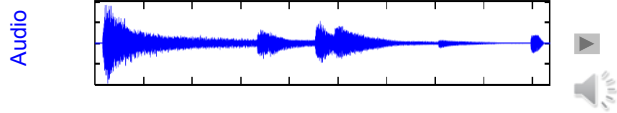
Piano  
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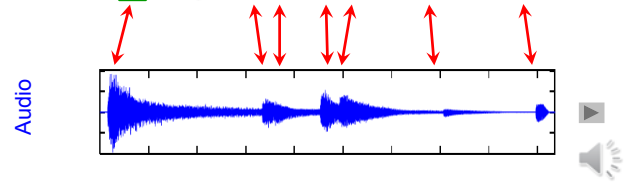
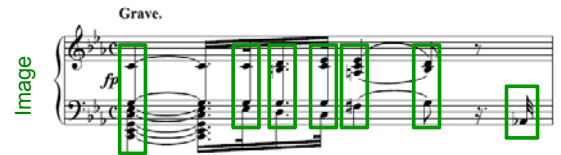
## Application: Interpretation Switcher



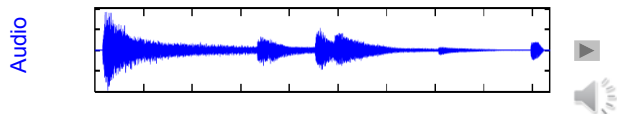
## Music Synchronization: Image-Audio



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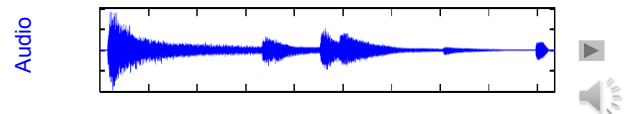
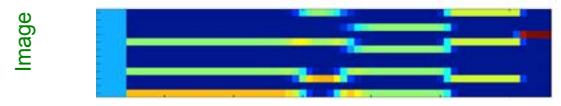


## How to make the data comparable?



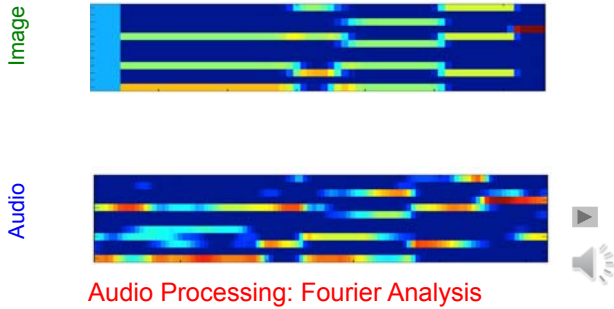
## How to make the data comparable?

### Image Processing: Optical Music Recognition



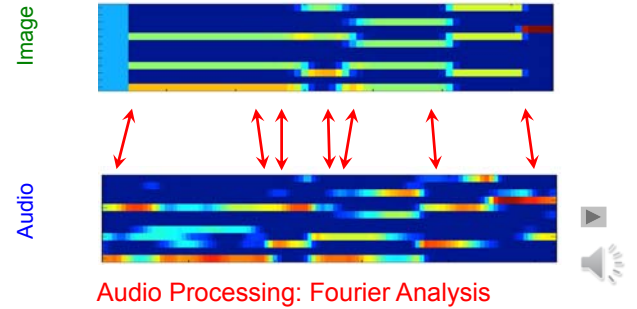
## How to make the data comparable?

### Image Processing: Optical Music Recognition



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### Image Processing: Optical Music Recognition



## Application: Score Viewer



## Music Processing

Coarse Level	Fine Level
What do different versions have in common?	What are the characteristics of a specific version?

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What makes up a piece of music?	What makes music come alive?

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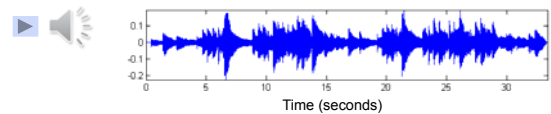
## Music Processing

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Identify despite of differences	Identify the differences
Example tasks: <b>Audio Matching</b> <b>Cover Song Identification</b>	Example tasks: <b>Tempo Estimation</b> <b>Performance Analysis</b>

## Performance Analysis

Schumann: Träumerei

Performance:



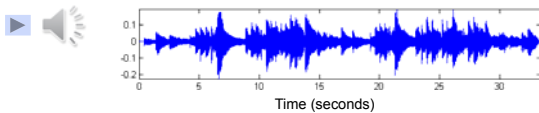
## Performance Analysis

Schumann: Träumerei

Score (reference):



Performance:



## Performance Analysis

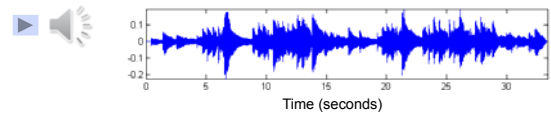
Schumann: Träumerei

Score (reference):



**Strategy: Compute score-audio synchronization and derive tempo curve**

Performance:



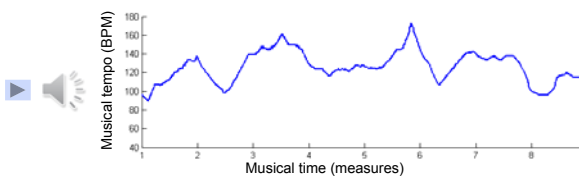
## Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curve:



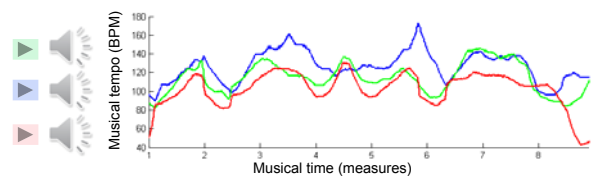
## Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curves:



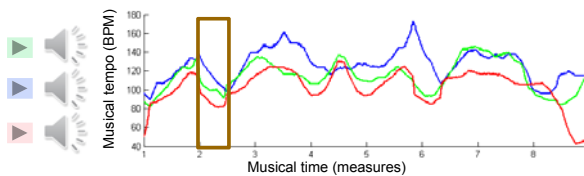
## Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curves:



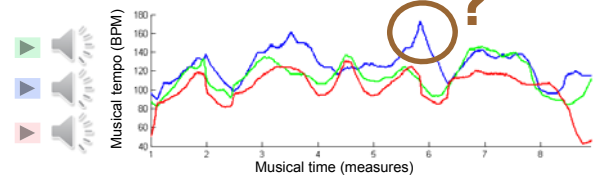
## Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curves:

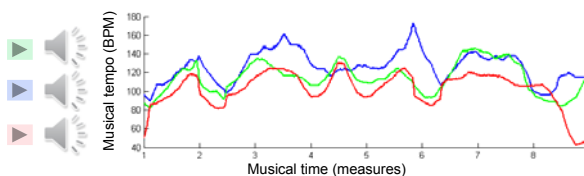


## Performance Analysis

Schumann: Träumerei

**What can be done if no reference is available?**

Tempo Curves:



## Music Processing

Relative	Absolute
Given: Several versions	Given: One version

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Comparison of extracted parameters	Direct interpretation of extracted parameters

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Extraction errors have often no consequence on final result	Extraction errors immediately become evident
Example tasks: <b>Music Synchronization</b> <b>Genre Classification</b>	Example tasks: <b>Music Transcription</b> <b>Tempo Estimation</b>

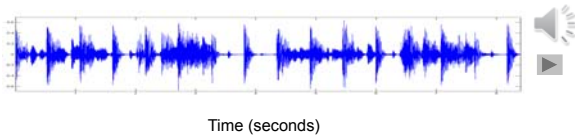
## Tempo Estimation and Beat Tracking

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

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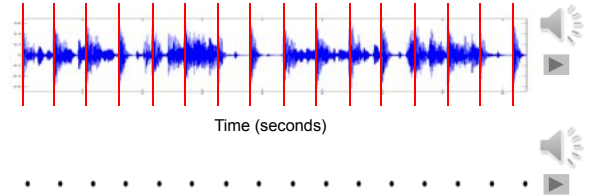
Example: Queen – Another One Bites The Dust



## Tempo Estimation and Beat Tracking

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

Example: Queen – Another One Bites The Dust



## Tempo Estimation and Beat Tracking

Example: Happy Birthday to you

Pulse level: **Measure**

## Tempo Estimation and Beat Tracking

Example: Happy Birthday to you

Pulse level: **Tactus (beat)**



## Tempo Estimation and Beat Tracking

Example: Happy Birthday to you

Pulse level: **Tatum (temporal atom)**



Hap - py Birth - day to you, Hap - py Birth - day to you, Hap - py  
Birth - day dear \_\_\_\_\_, Hap - py Birth - day to you!

## Tempo Estimation and Beat Tracking

Example: Chopin – Mazurka Op. 68-3

Pulse level: Quarter note

Tempo: ???



## Tempo Estimation and Beat Tracking

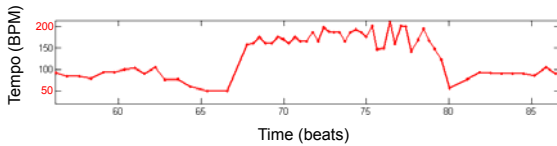
Example: Chopin – Mazurka Op. 68-3

Pulse level: Quarter note

Tempo: **50-200 BPM**



Tempo curve



## Tempo Estimation and Beat Tracking

- Which temporal level?
- Local tempo deviations
- Sparse information (e.g., only note onsets available)
- Vague information (e.g., extracted note onsets corrupt)

## Why is Music Processing Challenging?

Example: Chopin, Mazurka Op. 63 No. 3



Mazurka.

Allegretto.

F. CHOPIN, Op. 63, No. 3.

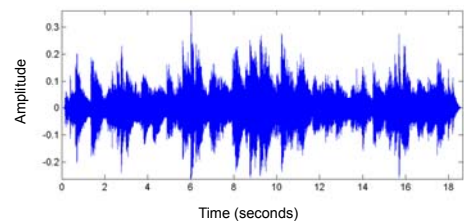


41.

## Why is Music Processing Challenging?

Example: Chopin, Mazurka Op. 63 No. 3

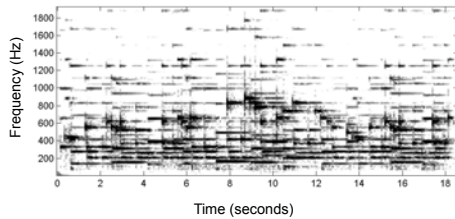
- Waveform



## 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

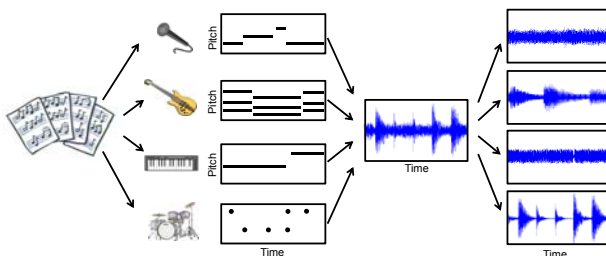
## Source Separation

- Decomposition of audio stream into different sound sources
- Central task in digital signal processing
- “Cocktail party effect”
- Sources are often assumed to be statistically independent
- This is often not the case in music



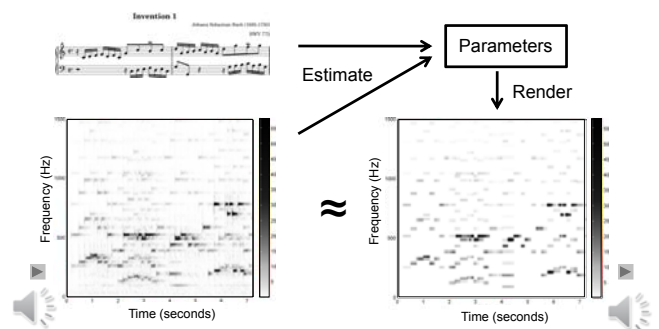
**Strategy:** Exploit additional information (e.g. musical score) to support the separation process

## Score-Informed Source Separation

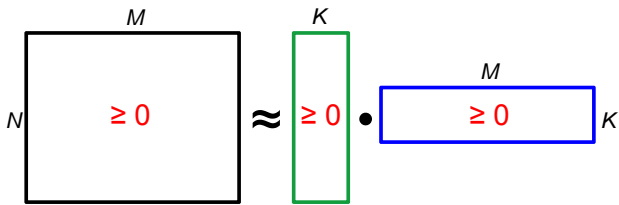


## Parametric Model Approach

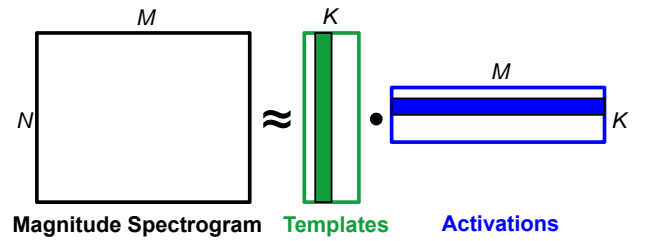
Rebuild spectrogram information



## NMF (Nonnegative Matrix Factorization)



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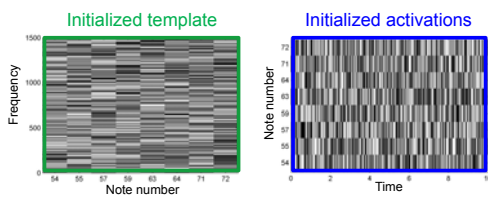
Templates: Pitch + Timbre

"How does it sound"

Activations: Onset time + Duration

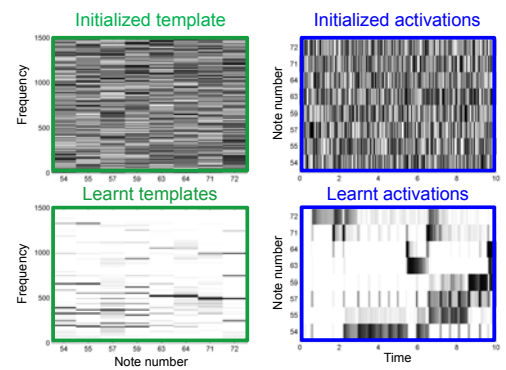
"When does it sound"

## NMF-Decomposition



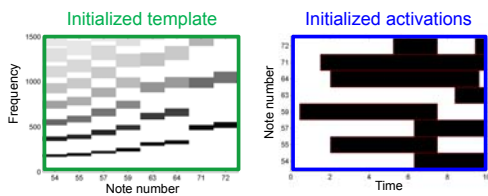
Random initialization

## NMF-Decomposition



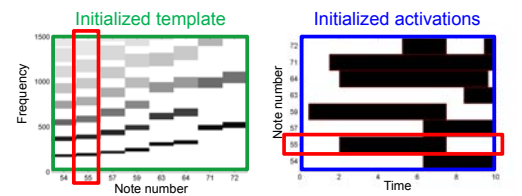
Random initialization  $\rightarrow$  No semantic meaning

## NMF-Decomposition



Constrained initialization

## NMF-Decomposition

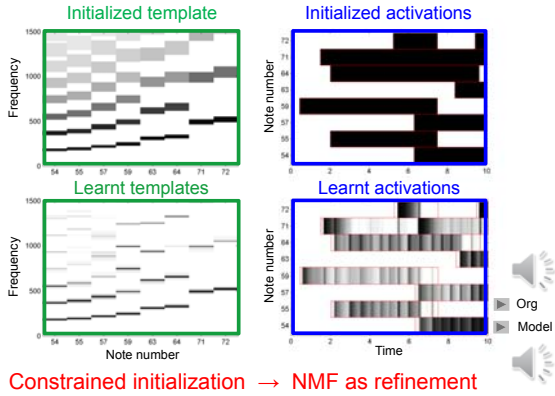


Template constraint for  $p=55$

Activation constraints for  $p=55$

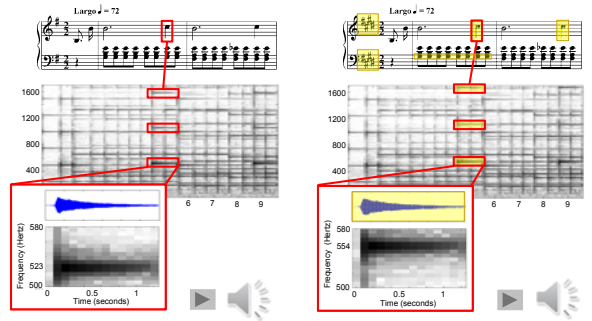
Constrained initialization

## NMF-Decomposition

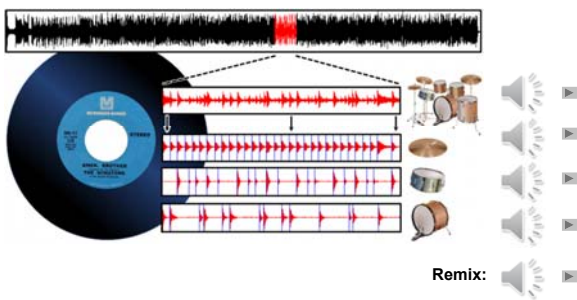


## Score-Informed Audio Decomposition

Application: Audio editing

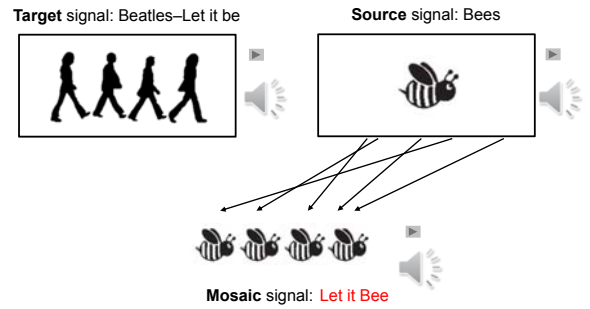


## Informed Drum-Sound Decomposition



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

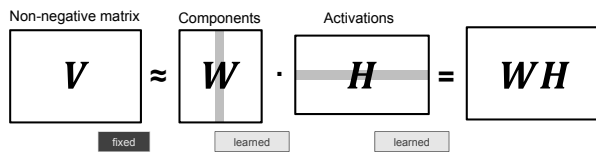
## Audio Mosaicing



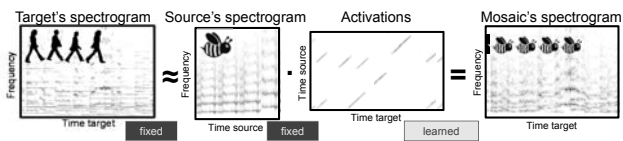
Literature: [Driedger/Müller, ISMIR 2015]  
 Demo: <https://www.audiolabs-erlangen.de/resources/MIR/2015-ISMIR-LettBee>

## NMF-Inspired Audio Mosaicing

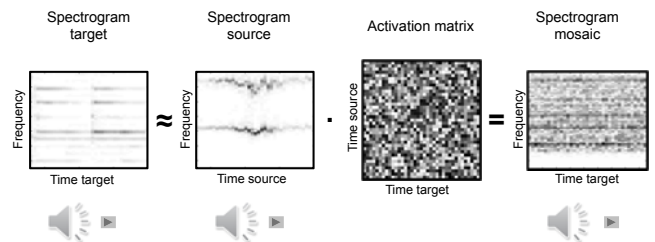
Non-negative matrix factorization (NMF)



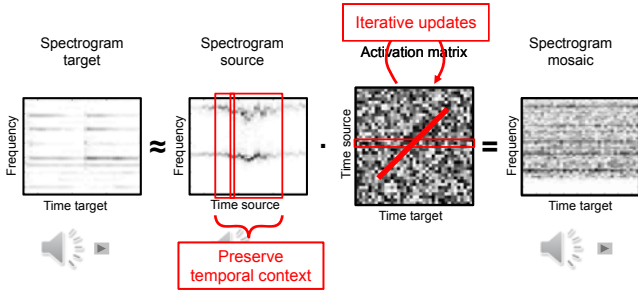
Proposed audio mosaicing approach



## NMF-Inspired Audio Mosaicing

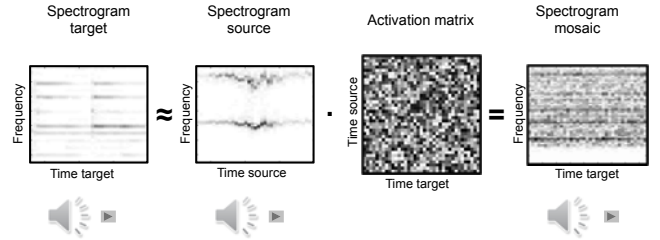


## NMF-Inspired Audio Mosaicing

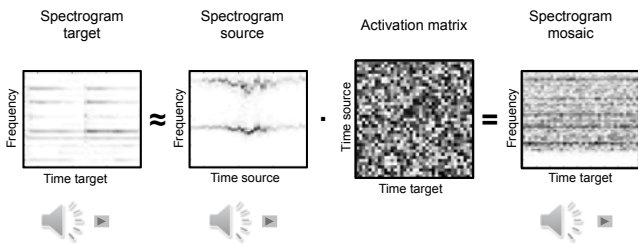


Core idea: support the development of sparse diagonal activation structures

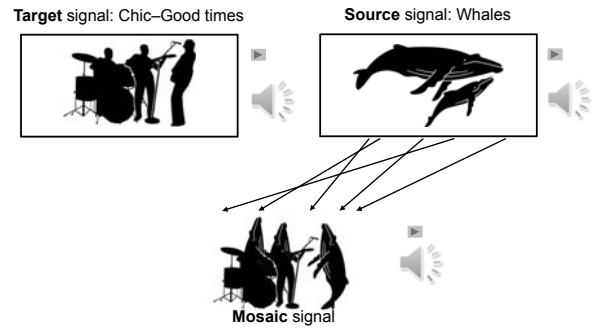
## NMF-Inspired Audio Mosaicing



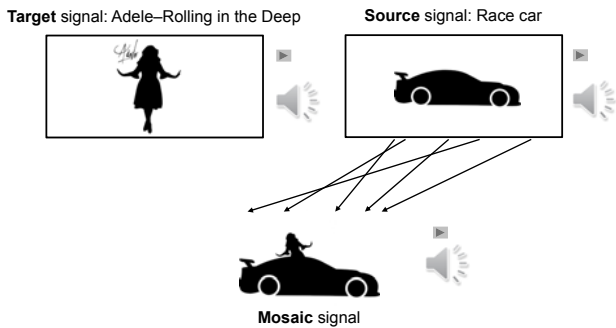
## NMF-Inspired Audio Mosaicing



## Audio Mosaicing



## Audio Mosaicing



## Motivic Similarity



- Beethoven's Fifth (1st Mov.)
- Beethoven's Fifth (3rd Mov.)
- Beethoven's Appassionata

## Motivic Similarity

Var. 4: Vivace

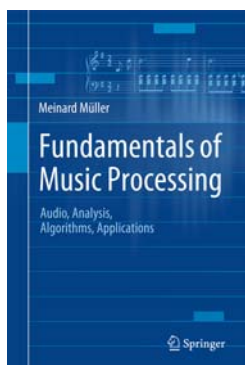
▶ 🔊

## Motivic Similarity

▶ 🔊

▶ 🔊

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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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