

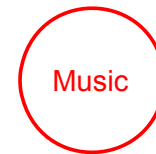
Lecture  
Music Processing

# Beethoven, Bach, and Billions of Bytes

New Alliances between Music and Computer Science

Meinard Müller

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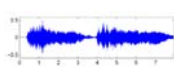


## Music Processing

Sheet Music (Image)



CD / MP3 (Audio)



MusicXML (Text)



Dance / Motion (Mocap)



MIDI



Singing / Voice (Audio)



Music Film (Video)



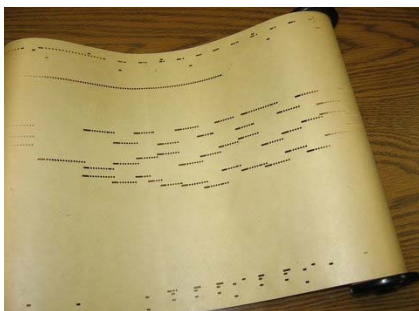
Music Literature (Text)



## Research Goals

- Music Information Retrieval (MIR) → ISMIR
- Analysis of music signals (harmonic, melodic, rhythmic, motivic aspects)
- Design of musically relevant audio features
- Tools for multimodal search and interaction

## Piano Roll Representation

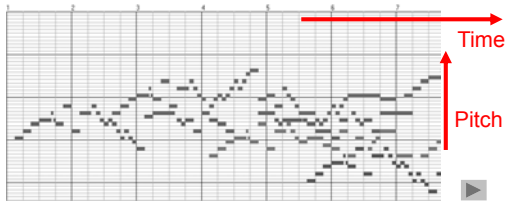


## Player Piano (1900)



## Piano Roll Representation (MIDI)

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

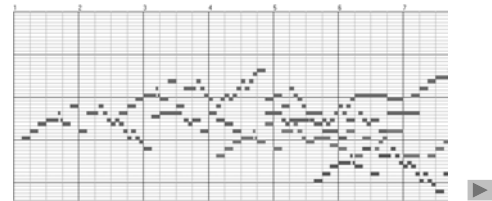


## Piano Roll Representation (MIDI)

Query:

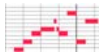


Goal: Find all occurrences of the query



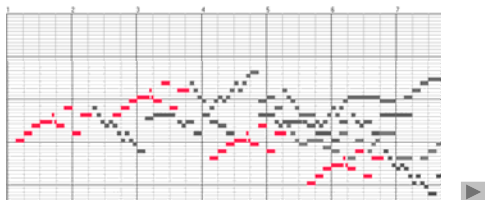
## Piano Roll Representation (MIDI)

Query:



Goal: Find all occurrences of the query

Matches:



## Audio Data

Various interpretations – Beethoven's Fifth



Bernstein



Karajan



Scherbakov (piano)



MIDI (piano)



## Audio Data (Memory Requirements)

1 Bit	=	1: on, 0: off
1 Byte	=	8 Bits
1 Kilobyte (KB)	=	1 Thousand Bytes
1 Megabyte (MB)	=	1 Million Bytes
1 Gigabyte (GB)	=	1 <b>Billion Bytes</b>
1 Terabyte (TB)	=	1000 Billion Bytes

Two audio CDs	>	1 <b>Billion Bytes</b>
1000 audio CDs	=	<b>Billions of Bytes</b>
12.000 MIDI files	<	350 MB

## Music Synchronization: Audio-Audio

Beethoven's Fifth

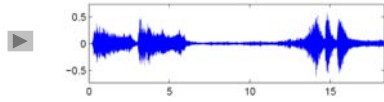


## Music Synchronization: Audio-Audio

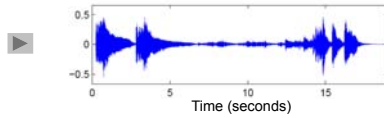
Beethoven's Fifth



Orchester (Karajan)



Piano (Scherbakov)



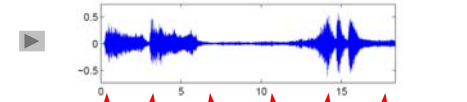
Time (seconds)

## Music Synchronization: Audio-Audio

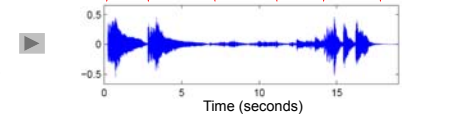
Beethoven's Fifth



Orchester (Karajan)



Piano (Scherbakov)

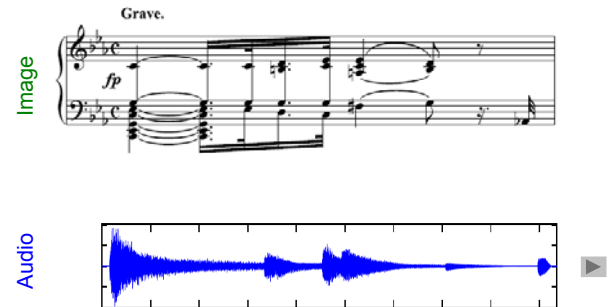


Time (seconds)

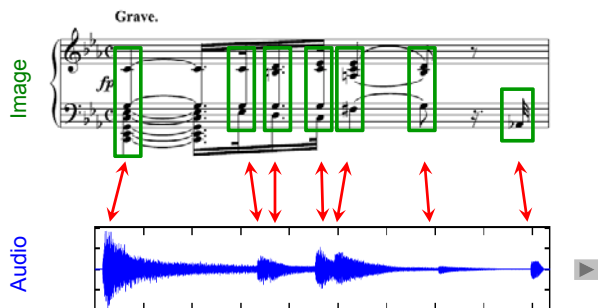
## Application: Interpretation Switcher



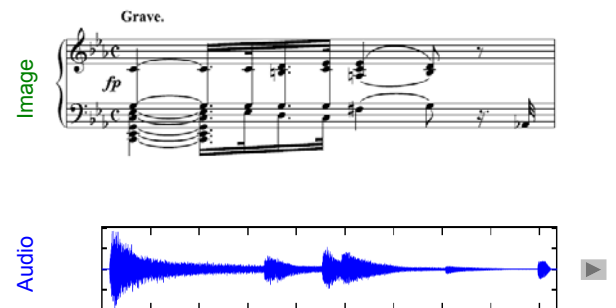
## Music Synchronization: Image-Audio



## Music Synchronization: Image-Audio

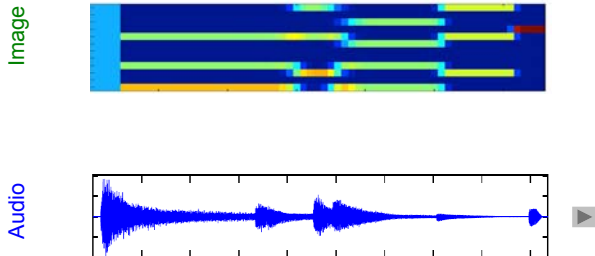


## How to make the data comparable?



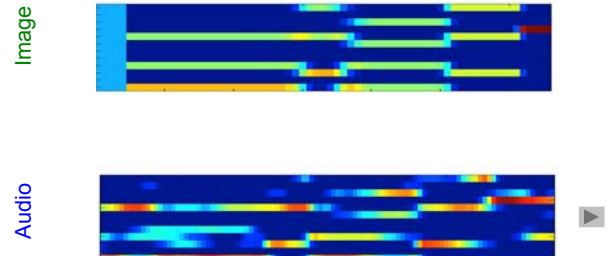
How to make the data comparable?

Image Processing: Optical Music Recognition



How to make the data comparable?

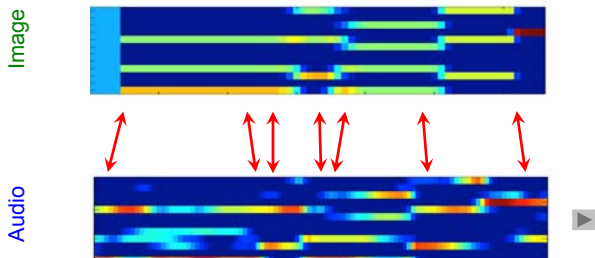
Image Processing: Optical Music Recognition



Audio Processing: Fourier Analyse

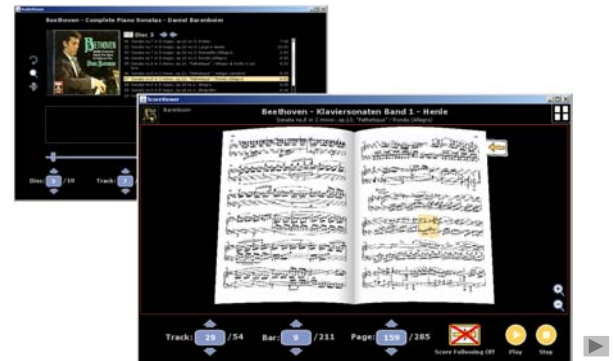
How to make the data comparable?

Image Processing: Optical Music Recognition



Audio Processing: Fourier Analyse

Application: Score Viewer



Music Processing

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

Music Processing

Coarse Level	Fine Level
What do different versions have in common?	What are the characteristics of a specific version?
What makes up a piece of music?	What makes music come alive?

## Music Processing

Coarse Level	Fine Level
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Identify despite of differences	Identify the differences

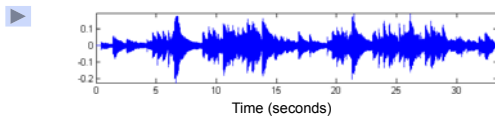
## Music Processing

Coarse Level	Fine Level
What do different versions have in common?	What are the characteristics of a specific version?
What makes up a piece of music?	What makes music come alive?
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:



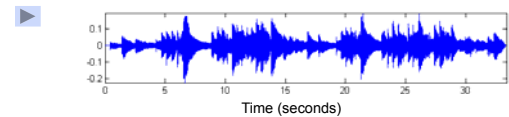
## Performance Analysis

Schumann: Träumerei

Score (reference):



Performance:



## Performance Analysis

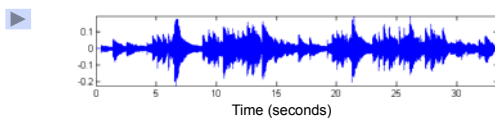
Schumann: Träumerei

Score (reference):



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

Performance:



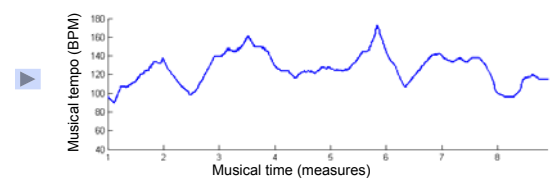
## Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curve:



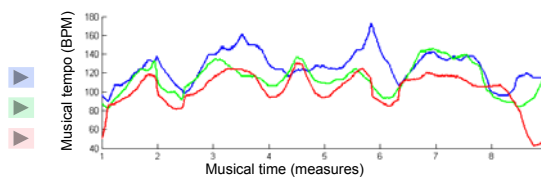
## Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curves:



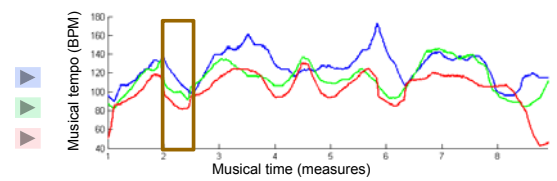
## Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curves:



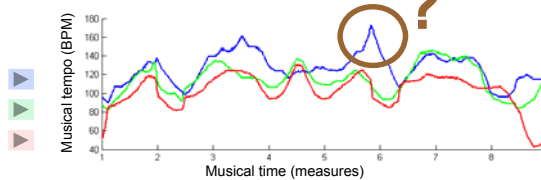
## Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curves:

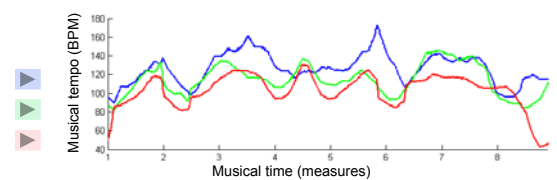


## Performance Analysis

Schumann: Träumerei

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

Tempo Curves:



## Music Processing

Relative	Absolute
Given: Several versions	Given: One version

## Music Processing

Relative	Absolute
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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

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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>

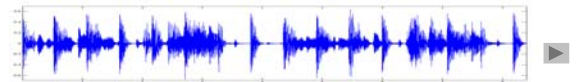
## Tempo Estimation and Beat Tracking

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

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Example: Queen – Another One Bites The Dust

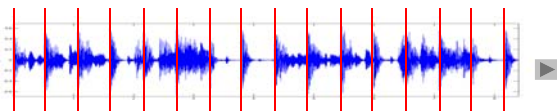


Time (seconds)

## Tempo Estimation and Beat Tracking

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

Example: Queen – Another One Bites The Dust



Time (seconds)



## 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)**



## Tempo Estimation and Beat Tracking

Example: Chopin – Mazurka Op. 68-3

Pulse level: Quarter note

Tempo: ???

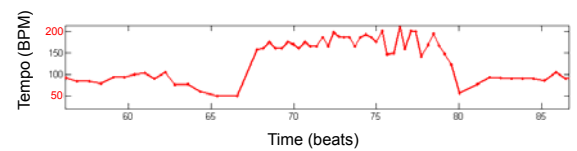
## Tempo Estimation and Beat Tracking

Example: Chopin – Mazurka Op. 68-3

Pulse level: Quarter note

Tempo: **50-200 BPM**

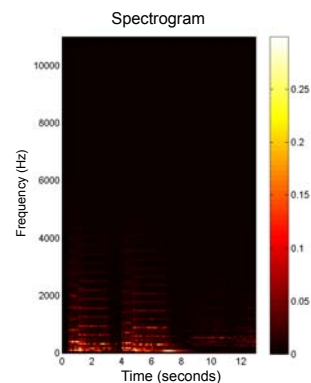
Tempo curve



## 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)

## Tempo Estimation and Beat Tracking

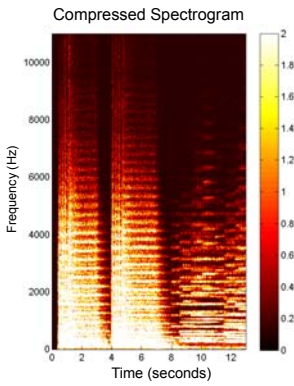


Steps:

1. Spectrogram



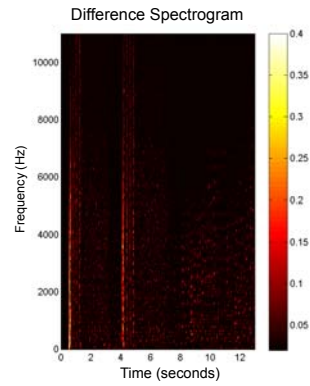
## Tempo Estimation and Beat Tracking



**Steps:**

1. Spectrogram
2. Log Compression

## Tempo Estimation and Beat Tracking



**Steps:**

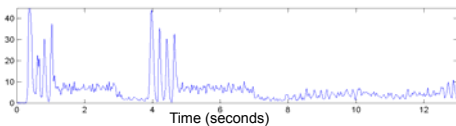
1. Spectrogram
2. Log Compression
3. Differentiation

## Tempo Estimation and Beat Tracking

**Steps:**

1. Spectrogram
2. Log Compression
3. Differentiation
4. Accumulation

**Novelty Curve**

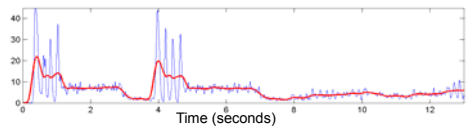


## Tempo Estimation and Beat Tracking

**Steps:**

1. Spectrogram
2. Log Compression
3. Differentiation
4. Accumulation

**Novelty Curve  
Local Average**

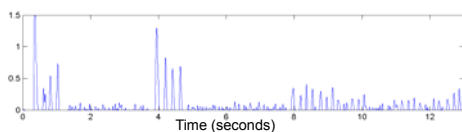


## Tempo Estimation and Beat Tracking

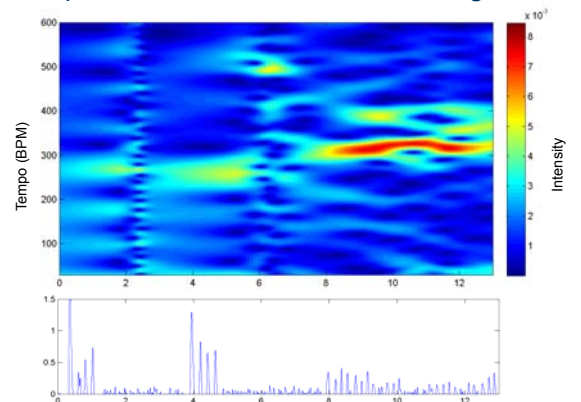
**Steps:**

1. Spectrogram
2. Log Compression
3. Differentiation
4. Accumulation
5. Normalization

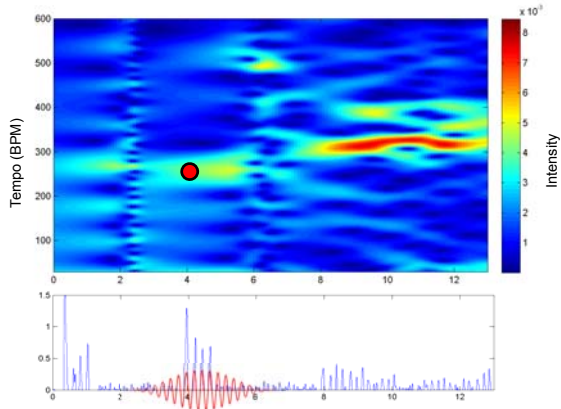
**Novelty Curve**



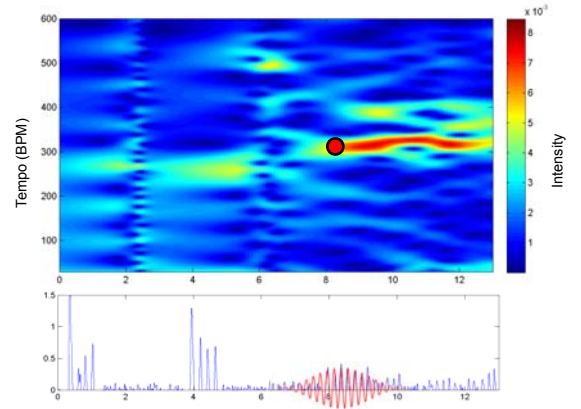
## Tempo Estimation and Beat Tracking



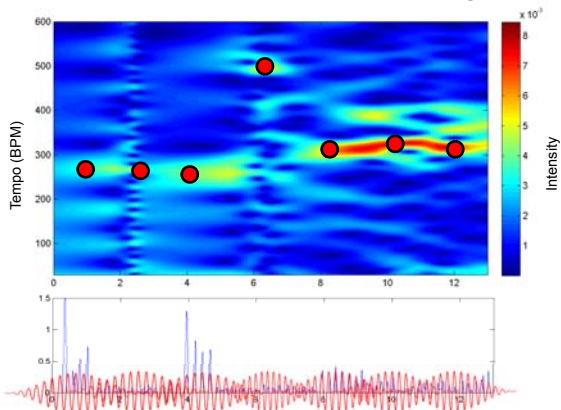
### Tempo Estimation and Beat Tracking



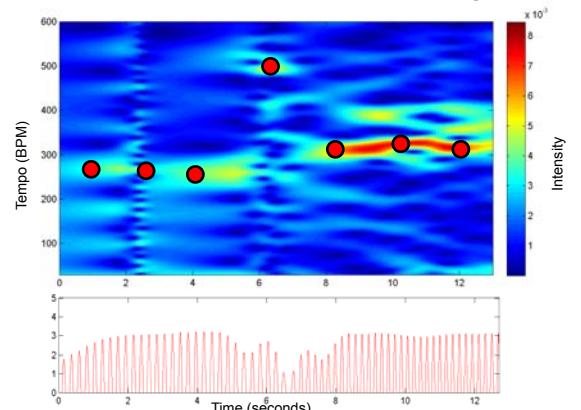
### Tempo Estimation and Beat Tracking



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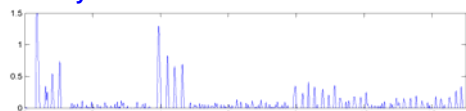
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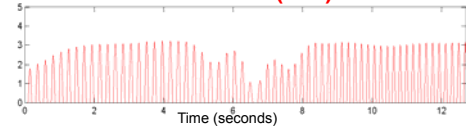
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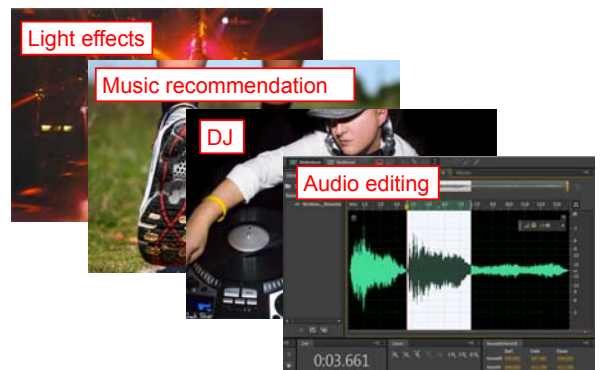
#### Novelty Curve



#### Predominant Local Pulse (PLP)



### Tempo Estimation and Beat Tracking



## Motivic Similarity



Beethoven's Fifth (1st Mov.) ▶

## Motivic Similarity



Beethoven's Fifth (1st Mov.) ▶

Beethoven's Fifth (3rd Mov.) ▶

## Motivic Similarity



Beethoven's Fifth (1st Mov.) ▶

Beethoven's Fifth (3rd Mov.) ▶

Beethoven's Appassionata ▶

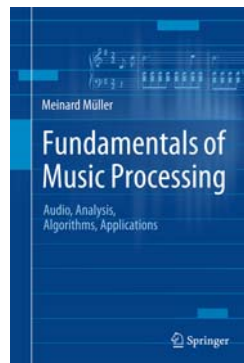
## Motivic Similarity



## Motivic Similarity



## Book: Fundamentals of Music Processing











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

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

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## Book: Fundamentals of Music Processing

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

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