

Lecture

## Music Processing

# Beethoven, Bach, and Billions of Bytes

**New Alliances between Music and Computer Science**

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Music

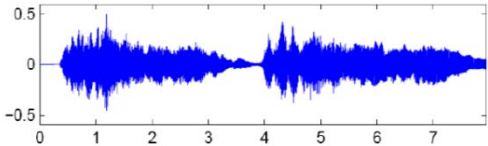


# Music Processing

Sheet Music (Image)



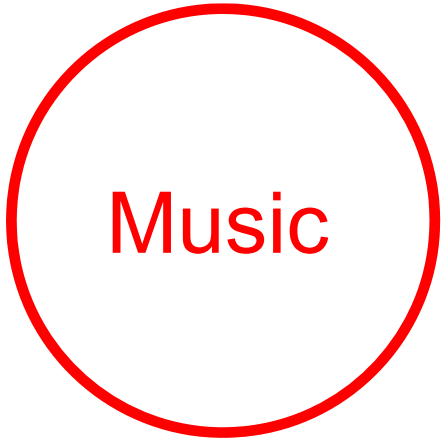
CD / MP3 (Audio)



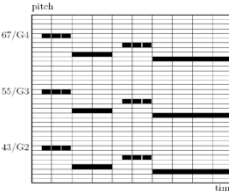
MusicXML (Text)

```
<note>  
  <pitch>  
    <step>E</step>  
    <alter>-1</alter>  
    <octave>4</octave>  
  </pitch>  
  <duration>2</duration>  
  <type>half</type>  
</note>
```

Dance / Motion (Mocap)



MIDI



Singing / Voice (Audio)



Music Film (Video)



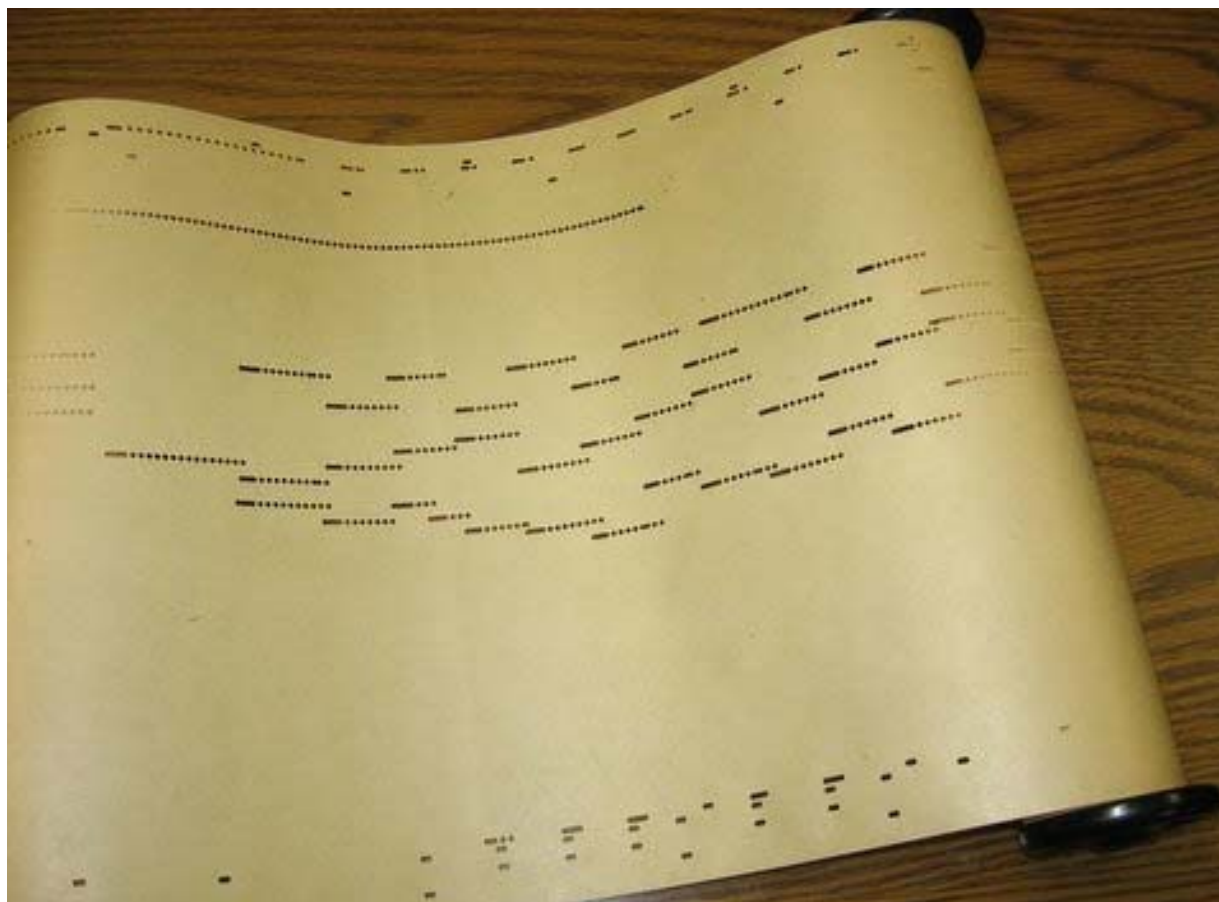
Music Literature (Text)



# 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



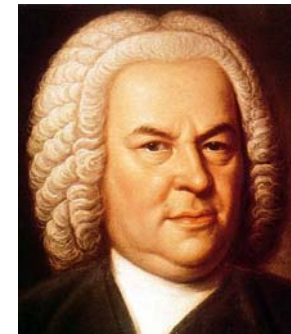
# Player Piano (1900)



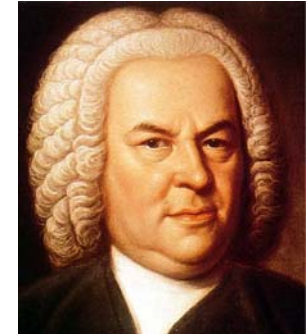
# Piano Roll Representation (MIDI)

J.S. Bach, C-Major Fuge

(Well Tempered Piano, BWV 846)



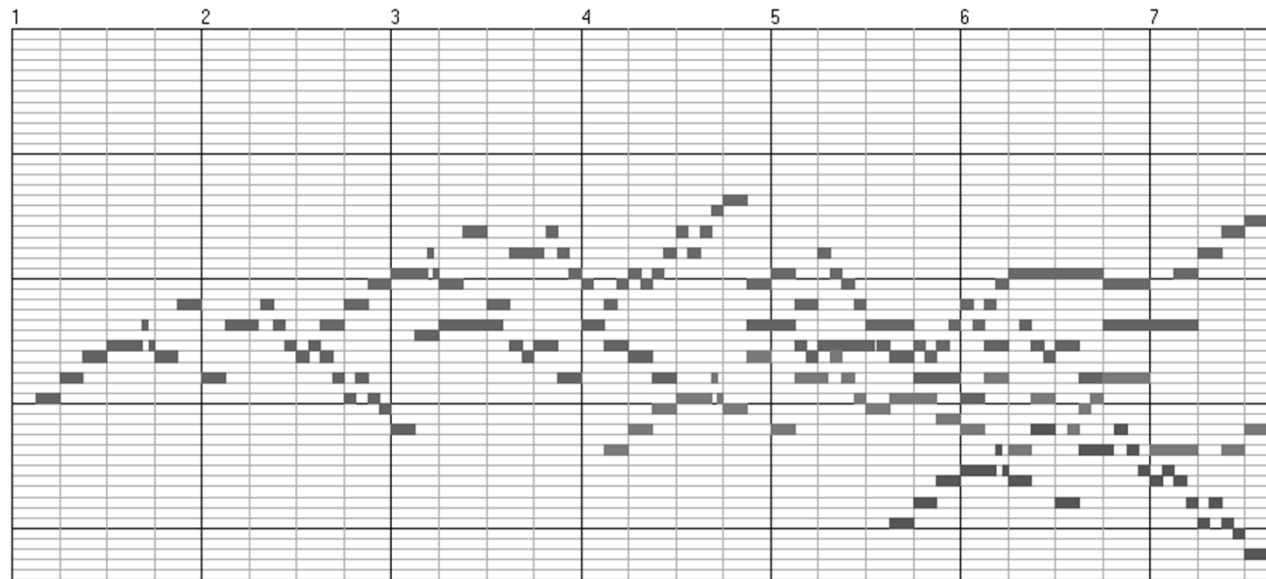
# Piano Roll Representation (MIDI)



Query:

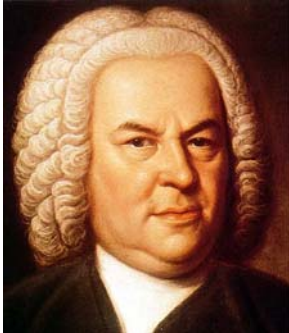


Goal: Find all occurrences of the query





# Piano Roll Representation (MIDI)

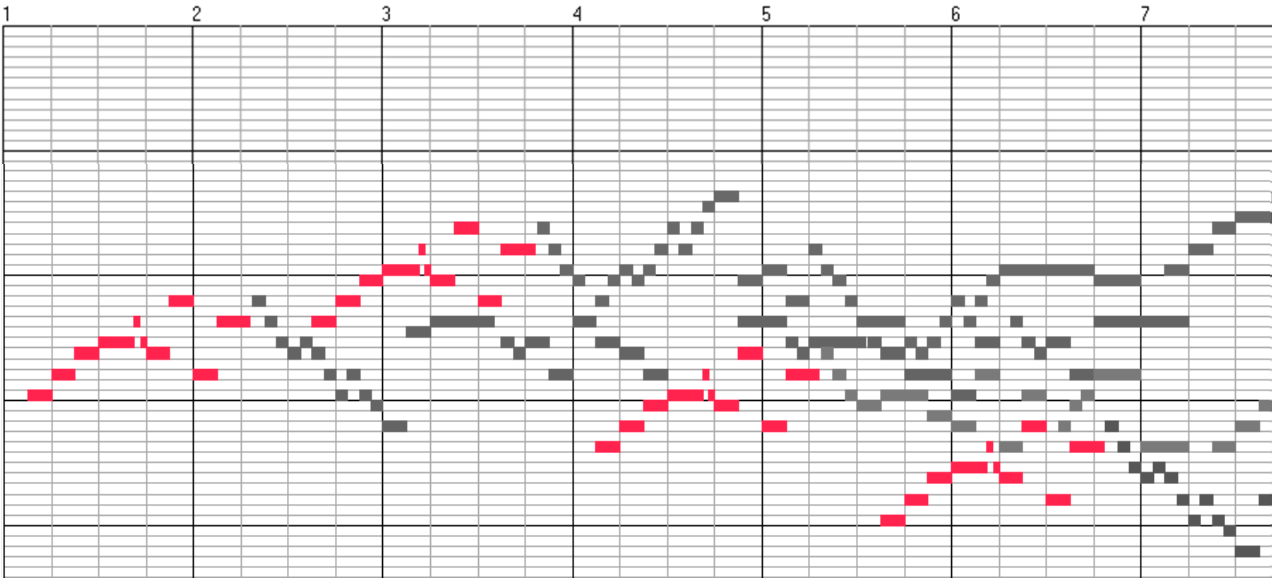


Query:

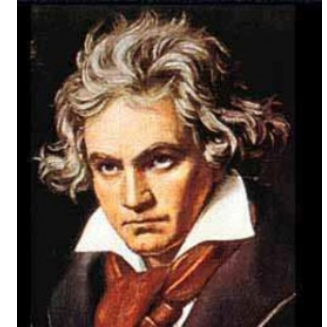


Goal: Find all occurrences of the query

Matches:



# Audio Data



Various interpretations – Beethoven's Fifth

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Bernstein



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Karajan



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Scherbakov (piano)



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MIDI (piano)

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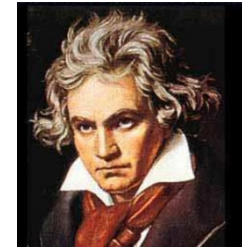


# Audio Data (Memory Requirements)

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

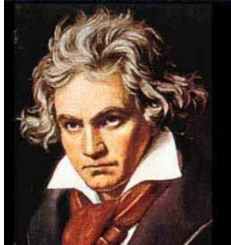
# Music Synchronization: Audio-Audio

Beethoven's Fifth

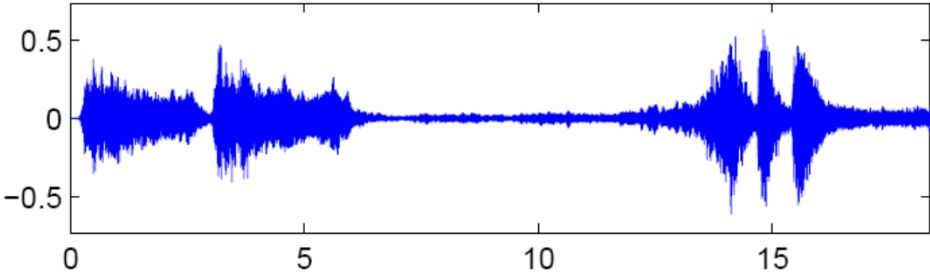


# Music Synchronization: Audio-Audio

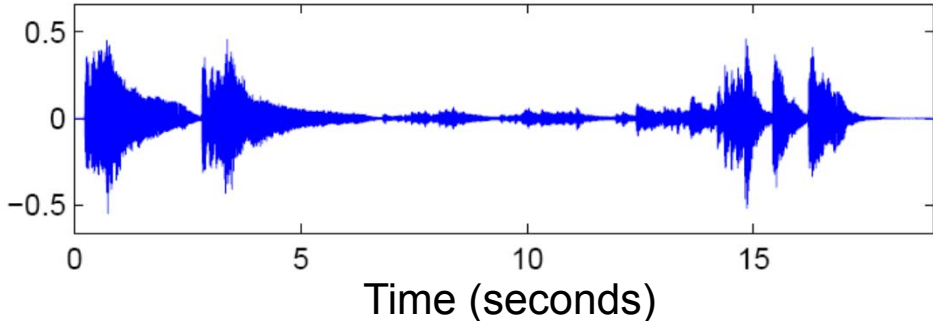
Beethoven's Fifth



Orchester  
(Karajan)

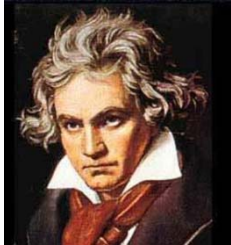


Piano  
(Scherbakov)

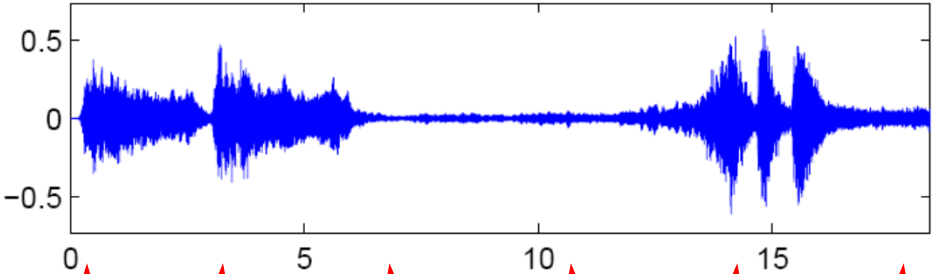


# Music Synchronization: Audio-Audio

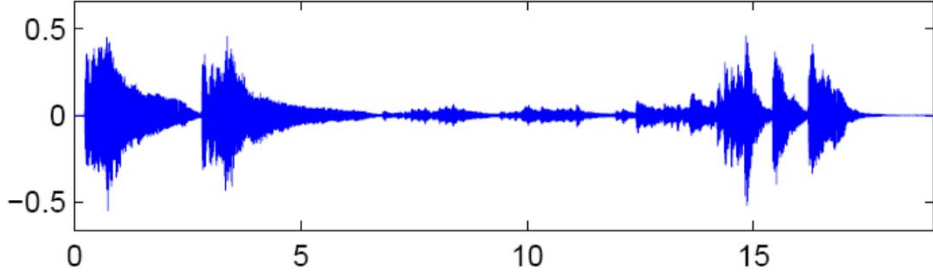
Beethoven's Fifth



Orchester  
(Karajan)



Piano  
(Scherbakov)



Time (seconds)



# Application: Interpretation Switcher

**Interpretation Switcher**  
Beethoven, Op067-1\_Symphony5

Interpretation	Duration
midi	00:44.18
Bernstein	01:00.64
Sawallisch	00:58.35
Scherbakov	00:52.45

midi  
 Bernstein  
 Sawallisch  
 Scherbakov

Deselect all

Absolute ✓  
Relative  
Reference

⏸ ⏹ ⏮ **Movement selection**  Interval Repeat **Info**



# Music Synchronization: Image-Audio

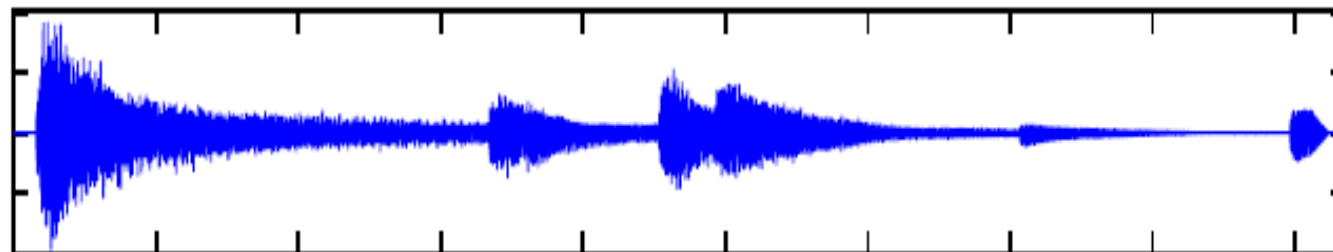
Image

Grave.



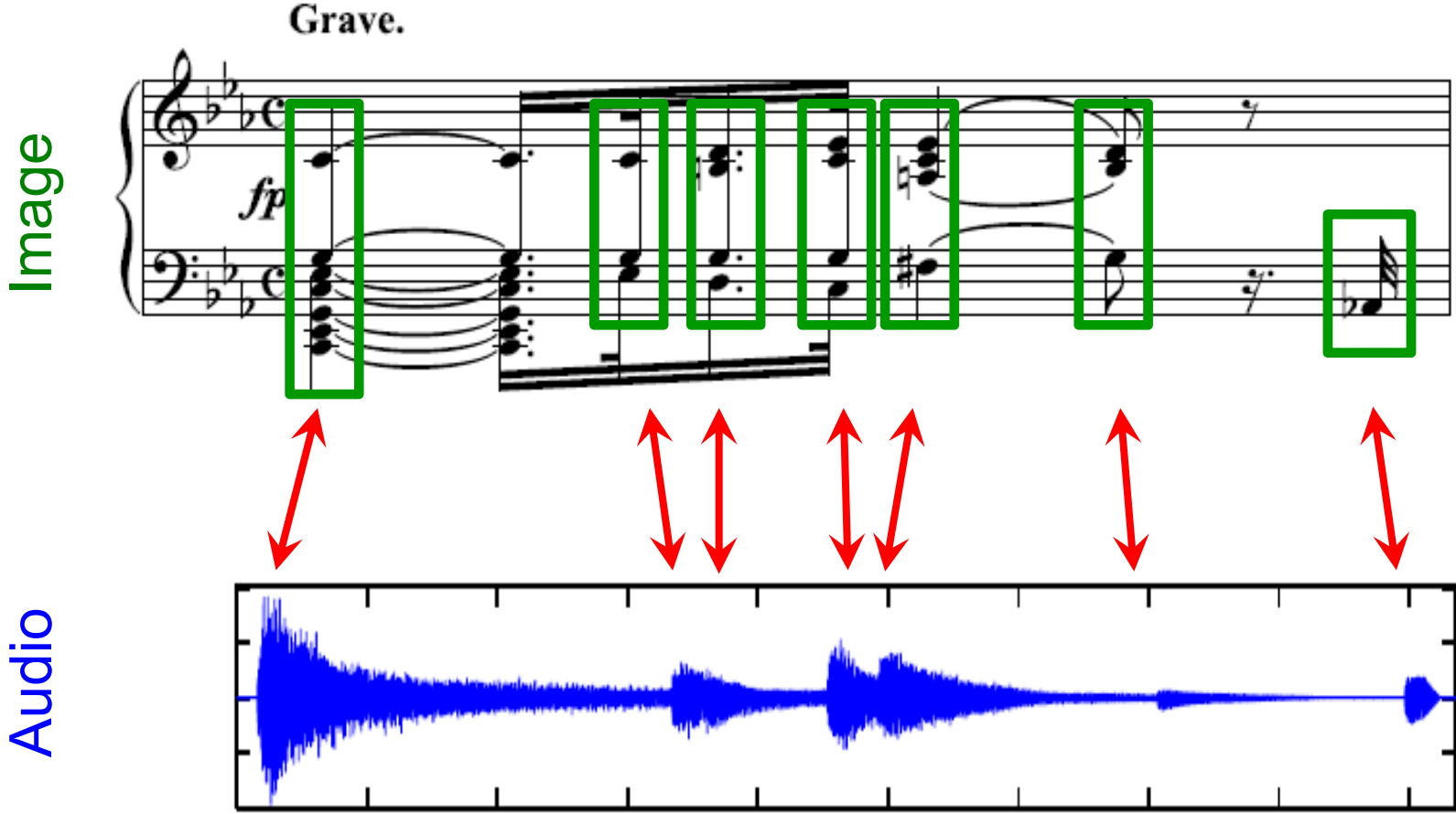
The image shows a musical score for piano, marked "Grave." and "fp". The score is written in G major (one sharp) and common time (C). It consists of two staves: a treble clef staff and a bass clef staff. The music is characterized by a slow tempo and a somber mood. The treble staff begins with a half note G4, followed by a half note A4, and then a half note B4. The bass staff begins with a half note G2, followed by a half note F2, and then a half note E2. The music continues with various chords and melodic lines, including a prominent bass line with a half note G2, a half note F2, and a half note E2. The score ends with a final chord in the treble staff.

Audio





# Music Synchronization: Image-Audio

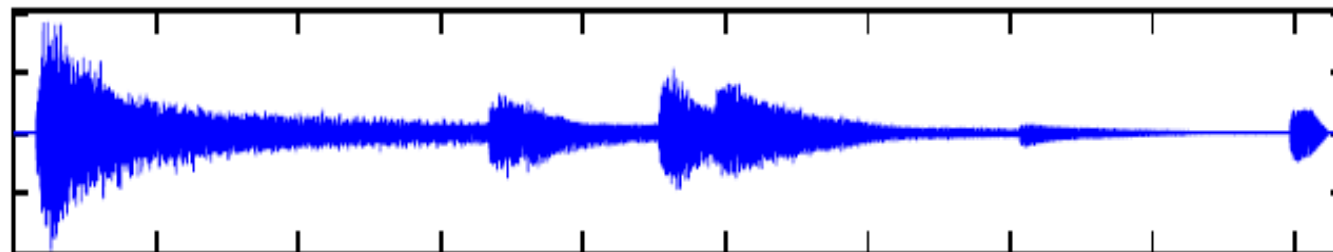


# How to make the data comparable?

Image



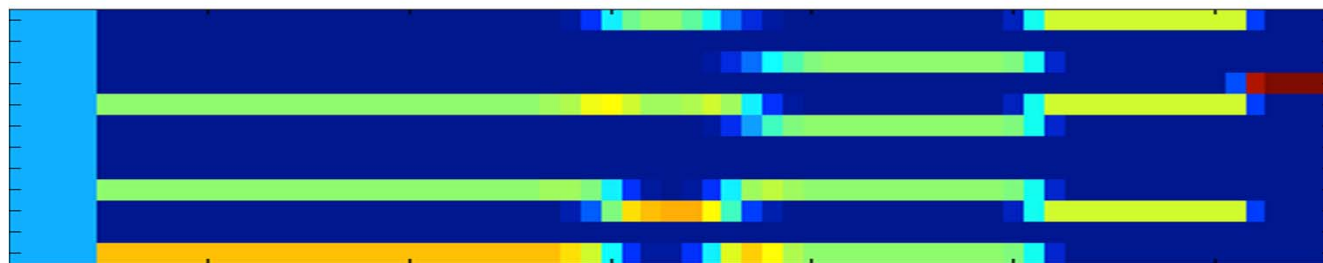
Audio



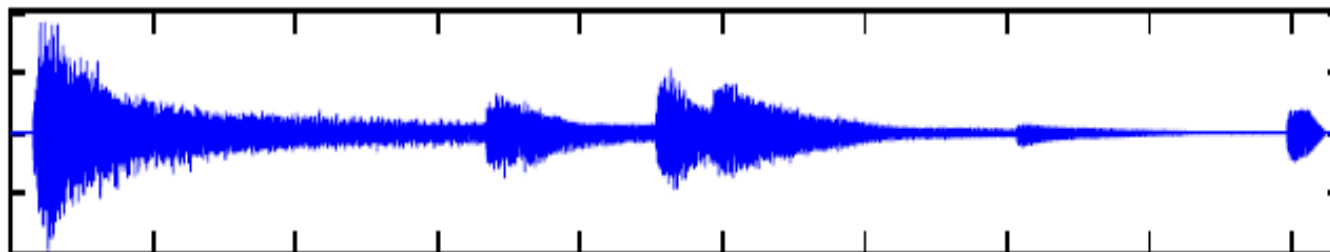
# How to make the data comparable?

## Image Processing: Optical Music Recognition

Image



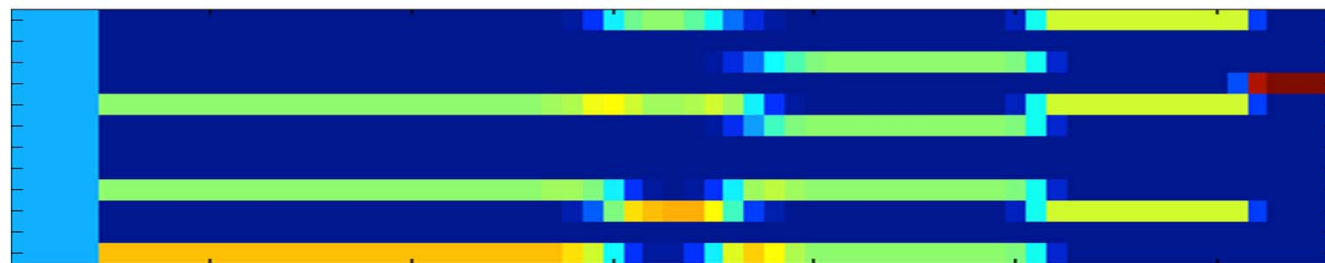
Audio



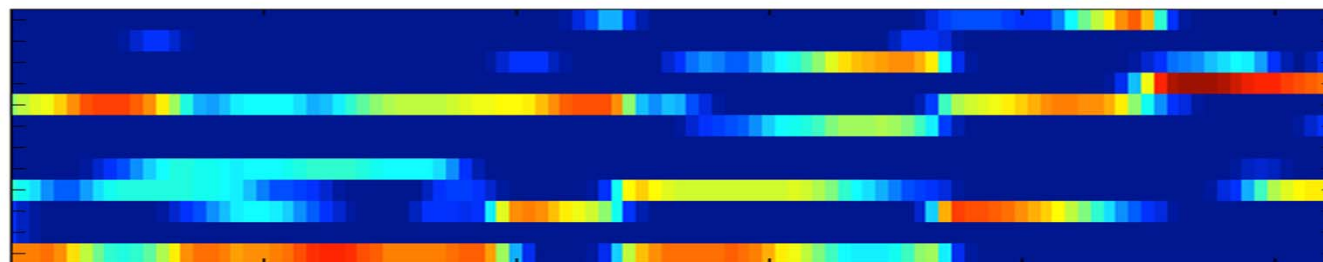
# How to make the data comparable?

## Image Processing: Optical Music Recognition

Image



Audio

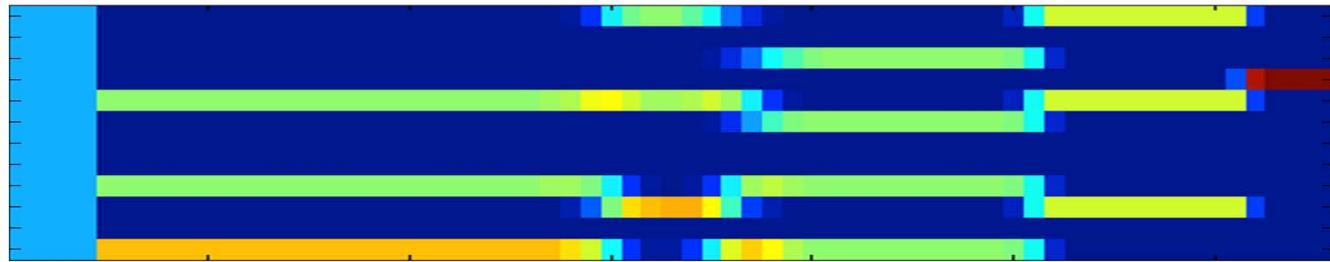


## Audio Processing: Fourier Analyse

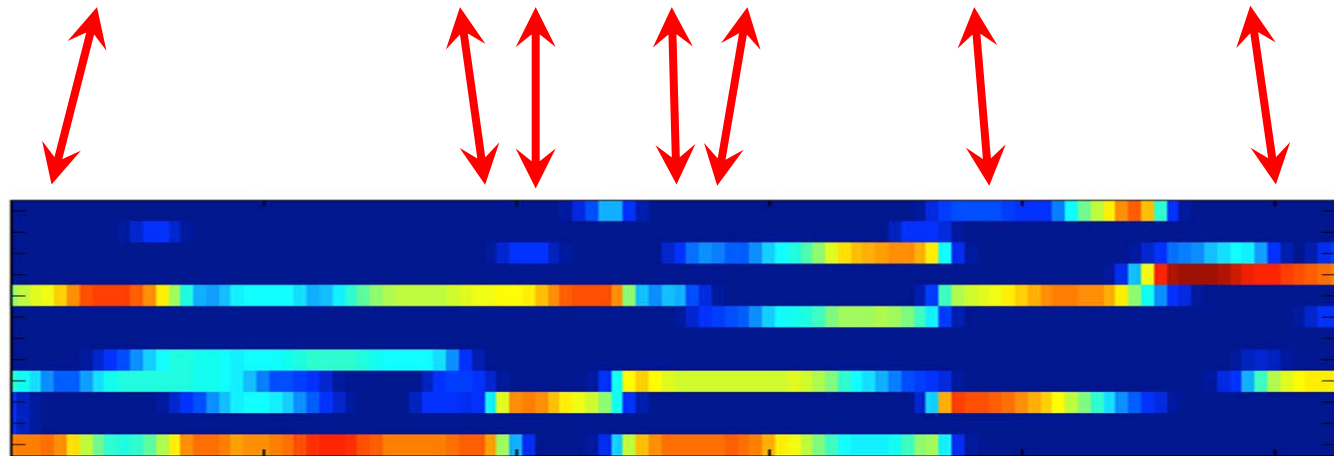
# How to make the data comparable?

## Image Processing: Optical Music Recognition

Image



Audio




## Audio Processing: Fourier Analyse



# Application: Score Viewer

AudioViewer

Beethoven - Complete Piano Sonatas - Daniel Barenboim



Disc 3

01 Sonata no.7 in D major, op.10 no.3: Presto	7:08
02 Sonata no.7 in D major, op.10 no.3: Largo e mesto	10:02
03 Sonata no.7 in D major, op.10 no.3: Menuetto (Allegro)	2:53
04 Sonata no.7 in D major, op.10 no.3: Rondo (Allegro)	4:05
05 Sonata no.8 in C minor, op.13, "Pathetique" / Allegro di molto e con brio	9:32
06 Sonata no.8 in C minor, op.13, "Pathetique" / Adagio cantabile	5:19
07 Sonata no.8 in C minor, op.13, "Pathetique" / Rondo (Allegro)	4:53
08 Sonata no.9 in E major, op.14 no.1: Allegro	6:48
09 Sonata no.9 in E major, op.14 no.1: Allegretto	4:16
10 Sonata no.9 in E major, op.14 no.1: Adagio	


Disc: 3 / 10    Track: 7

ScoreViewer

Barenboim

Beethoven - Klaviersonaten Band 1 - Henle

Sonata no.8 in C minor, op.13, "Pathetique" / Rondo (Allegro)



Track: 29 / 54    Bar: 9 / 211    Page: 159 / 285

Score Following Off    Play    Stop



# Music Processing

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

# Music Processing

<b>Coarse Level</b>	<b>Fine Level</b>
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

<b>Coarse Level</b>	<b>Fine Level</b>
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

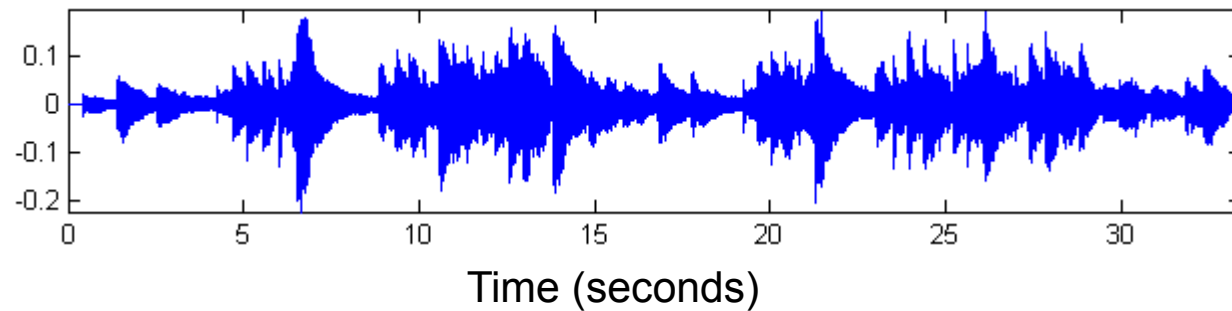
# Music Processing

<b>Coarse Level</b>	<b>Fine Level</b>
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:



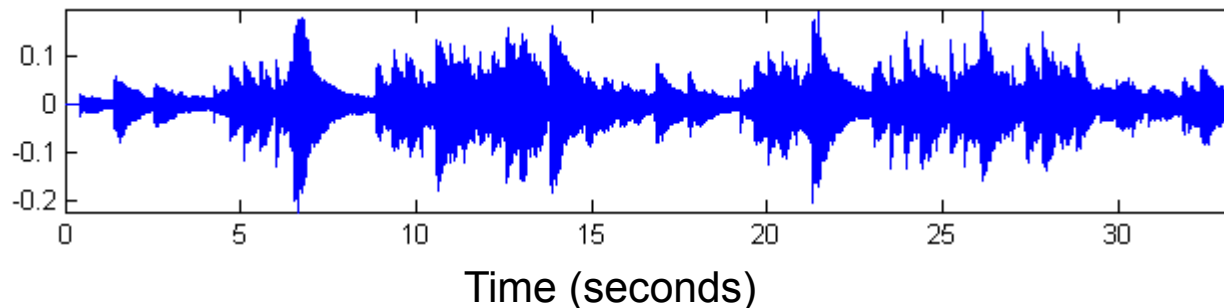
# Performance Analysis

Schumann: Träumerei

Score (reference):



Performance:



# Performance Analysis

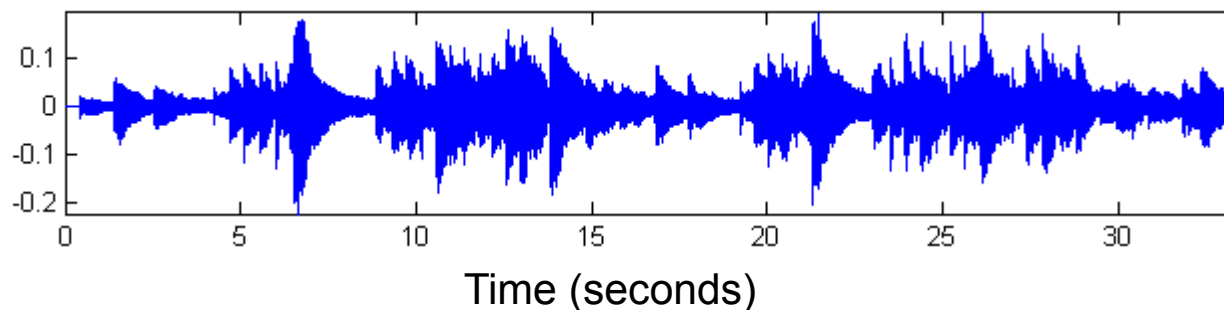
Schumann: Träumerei

Score (reference):



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

Performance:



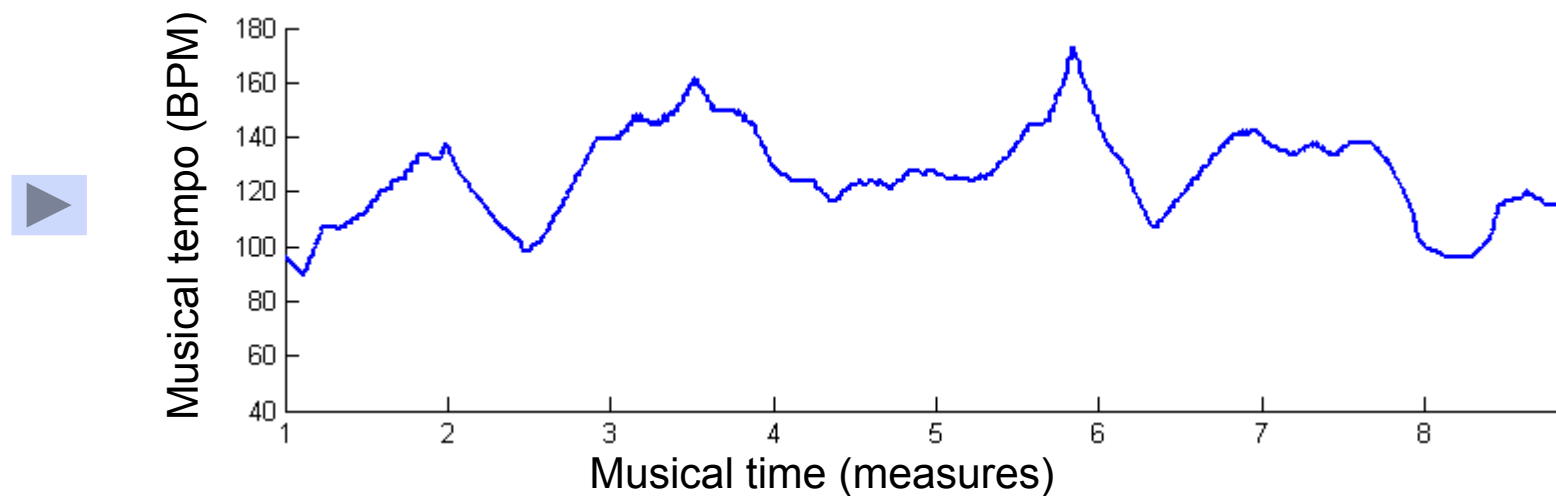
# Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curve:



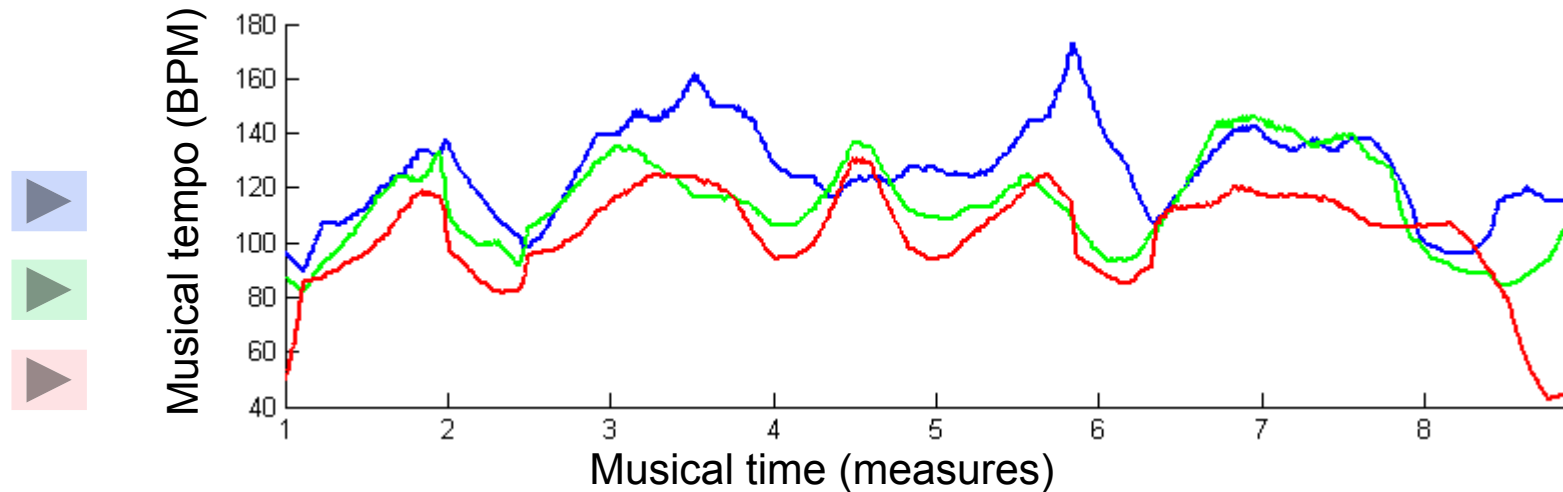
# Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curves:



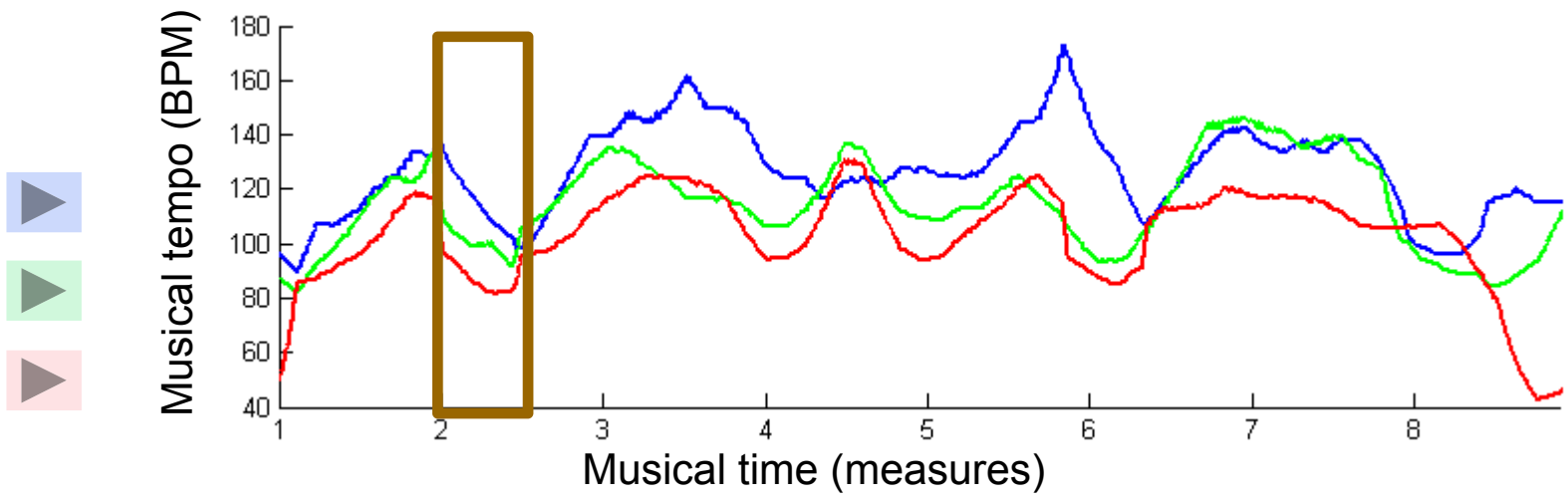
# Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curves:





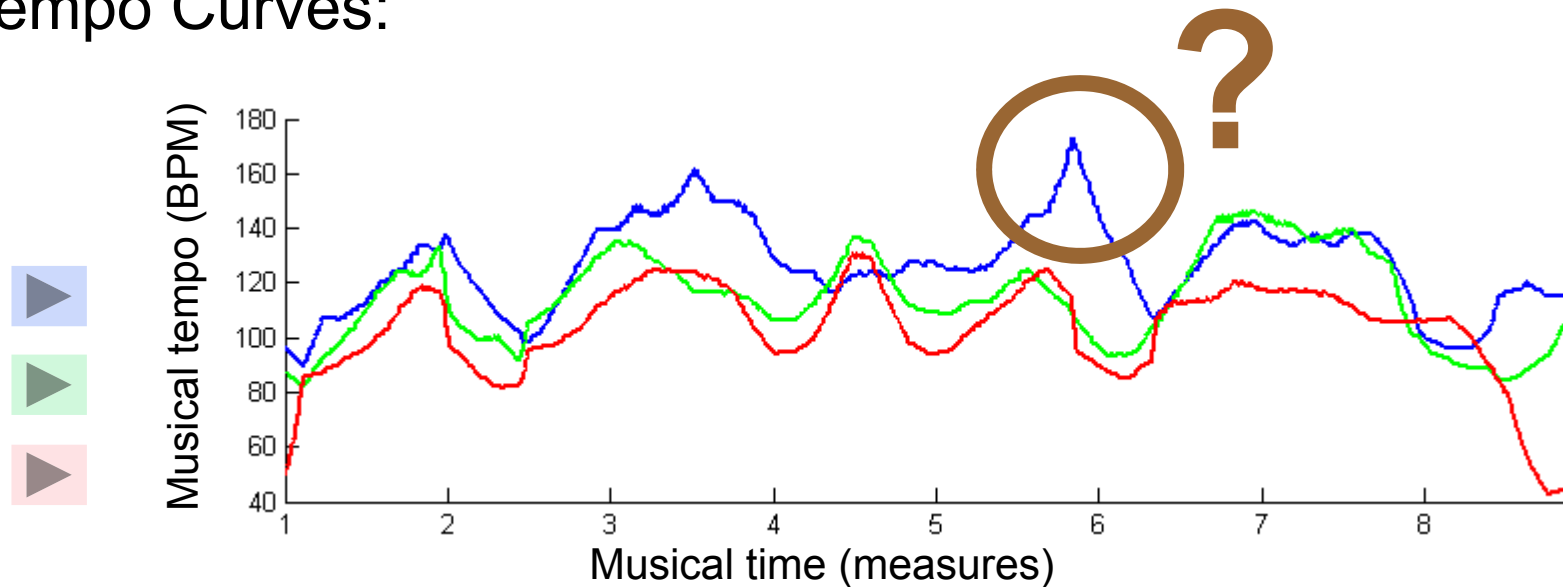
# Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curves:

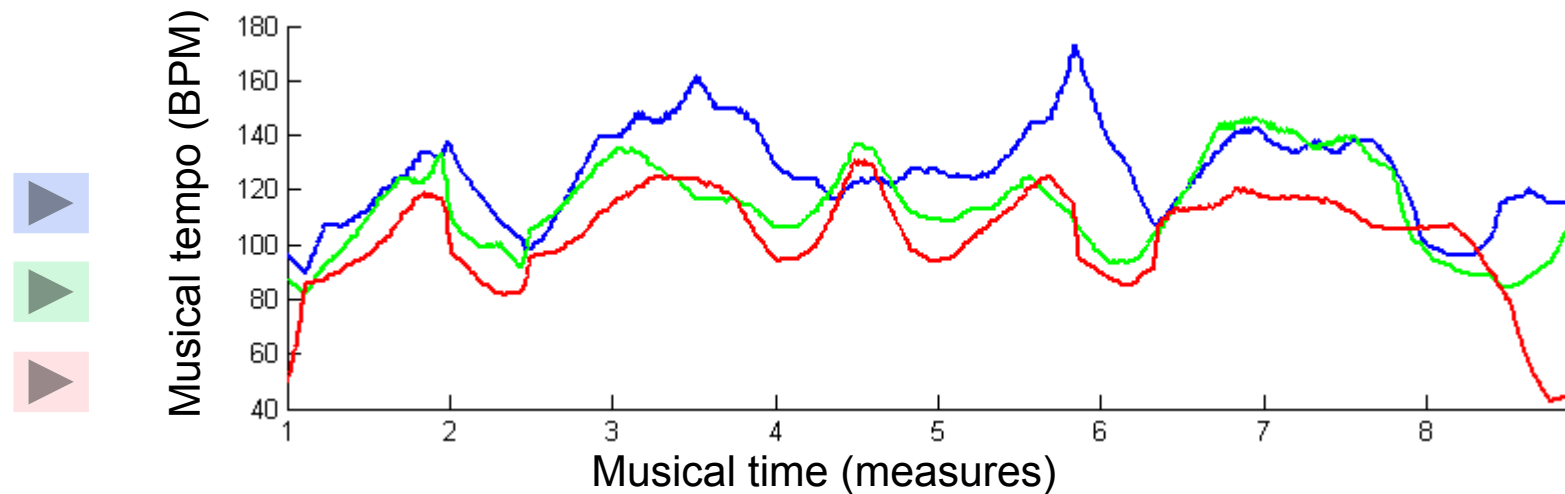


# Performance Analysis

Schumann: Träumerei

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

Tempo Curves:



# Music Processing

<b>Relative</b>	<b>Absolute</b>
Given: Several versions	Given: One version

# Music Processing

<b>Relative</b>	<b>Absolute</b>
Given: Several versions	Given: One version
Comparison of extracted parameters	Direct interpretation of extracted parameters

# Music Processing

<b>Relative</b>	<b>Absolute</b>
Given: Several versions	Given: One version
Comparison of extracted parameters	Direct interpretation of extracted parameters
Extraction errors have often no consequence on final result	Extraction errors immediately become evident

# Music Processing

<b>Relative</b>	<b>Absolute</b>
Given: Several versions	Given: One version
Comparison of extracted parameters	Direct interpretation of extracted parameters
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>

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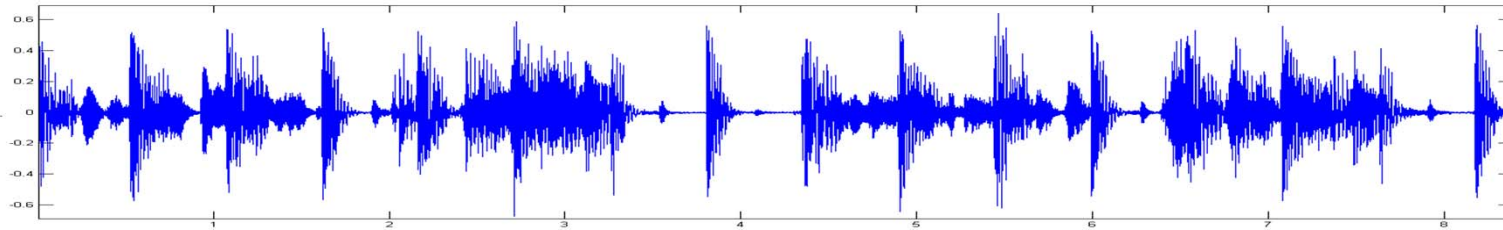
# Tempo Estimation and Beat Tracking

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

# Tempo Estimation and Beat Tracking

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

Example: Queen – Another One Bites The Dust



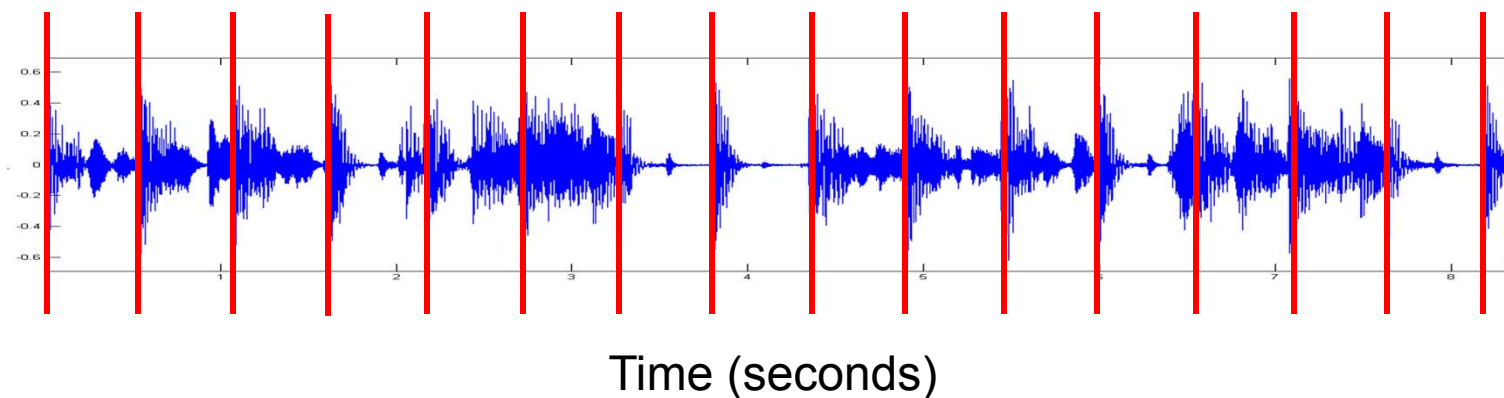
Time (seconds)



# Tempo Estimation and Beat Tracking

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**

The image shows a musical score for the song "Happy Birthday to you" in 3/4 time. The score is written on two staves. The first staff contains the first two phrases of the song: "Hap - py Birth - day to you," and "Hap - py Birth - day to you," followed by the start of a third phrase "Hap - py". The second staff contains the continuation: "Birth - day dear \_\_\_\_\_," followed by "Hap - py Birth - day to you!". Four red arrows point downwards to the first note of each of the four measures in the first staff, indicating the pulse level at the measure level.

# Tempo Estimation and Beat Tracking

Example: Happy Birthday to you

Pulse level: **Tactus (beat)**

The image shows a musical score for the song "Happy Birthday to you" in 3/4 time. The score is written on two staves. The first staff contains the first two phrases of the song: "Hap - py Birth - day to you, Hap - py Birth - day to you, Hap - py". The second staff contains the third phrase: "Birth - day dear \_\_\_\_\_, Hap - py Birth - day to you!". Red arrows point down to the first note of each measure in the first staff, indicating the pulse level (Tactus) at the start of each measure. The lyrics are written below the notes.

# Tempo Estimation and Beat Tracking

Example: Happy Birthday to you

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

The image shows a musical score for the song "Happy Birthday to you" in 3/4 time. The score is written on two staves. The first staff contains the melody for the first two phrases: "Hap - py Birth - day to you, Hap - py Birth - day to you, Hap - py". The second staff contains the melody for the final phrase: "Birth - day dear \_\_\_\_\_, Hap - py Birth - day to you!". Above the first staff, there are 24 red arrows pointing downwards, indicating the pulse level (Tatum) for each note. The arrows are placed above the notes, showing a regular interval between them, which corresponds to the tempo of the music.

# Tempo Estimation and Beat Tracking

Example: Chopin – Mazurka Op. 68-3

Pulse level: Quarter note

Tempo: ???



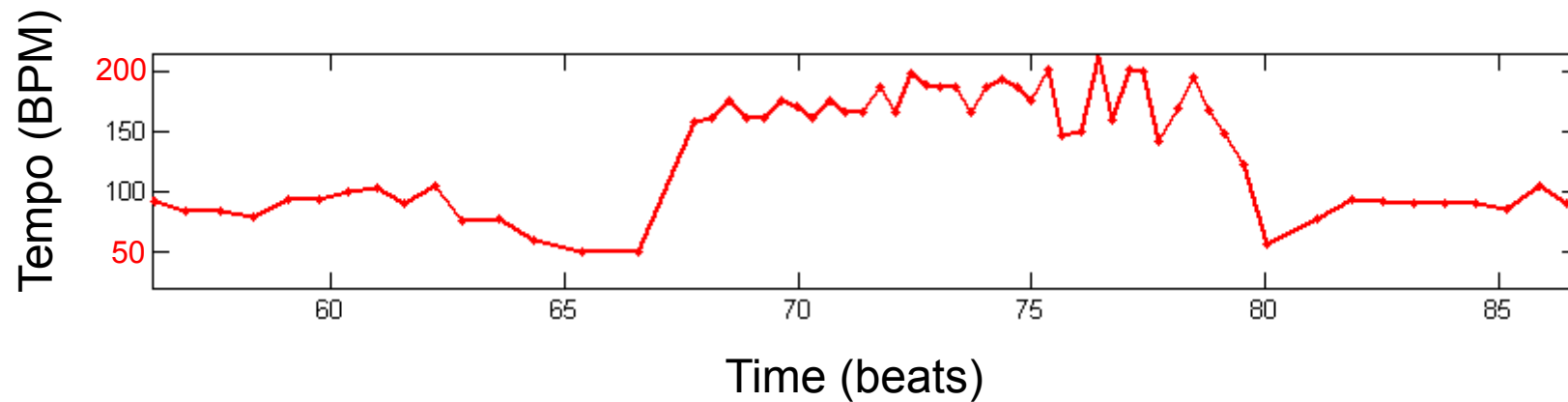
# Tempo Estimation and Beat Tracking

Example: Chopin – Mazurka Op. 68-3

Pulse level: Quarter note

Tempo: **50-200 BPM** 

Tempo curve

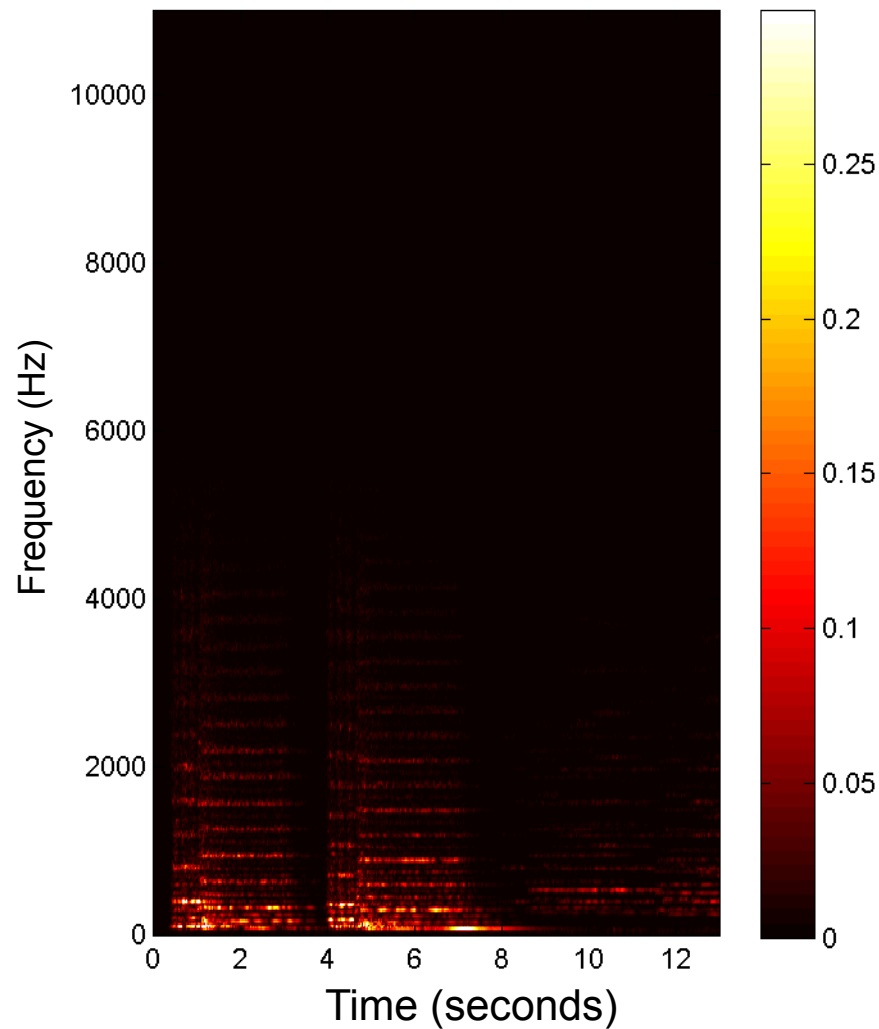


# Tempo Estimation and Beat Tracking

- 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

Spectrogram



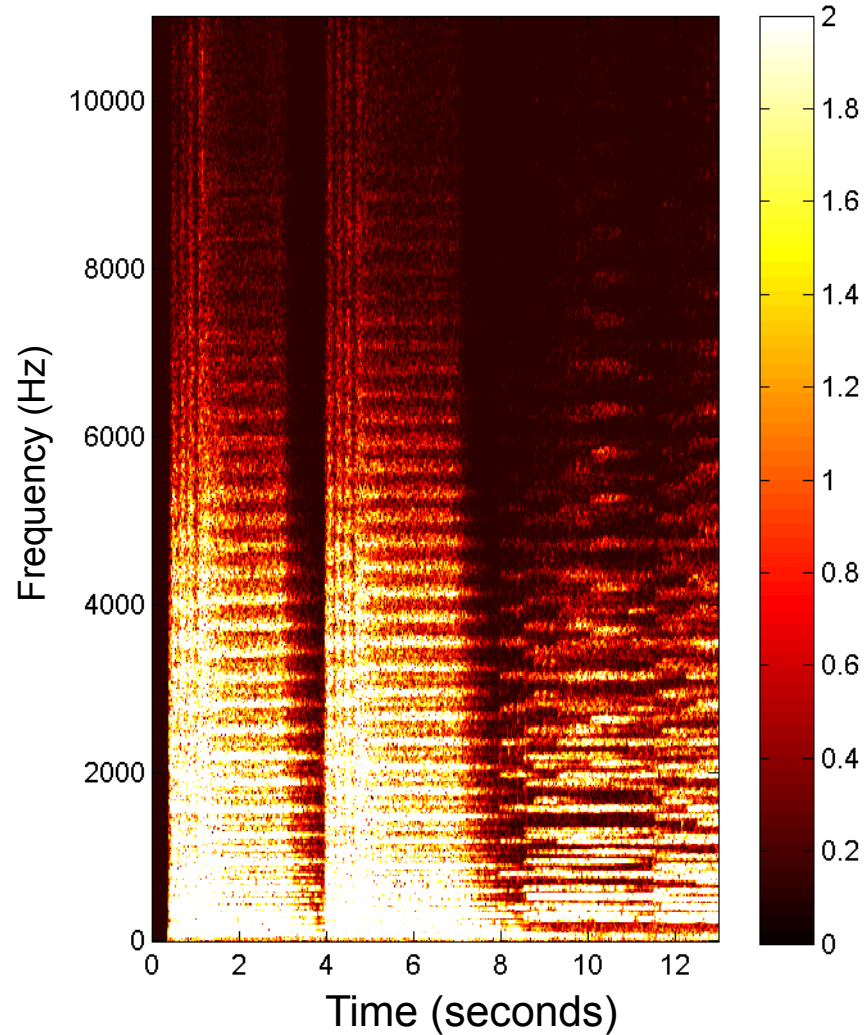
## Steps:

1. Spectrogram



# Tempo Estimation and Beat Tracking

Compressed Spectrogram

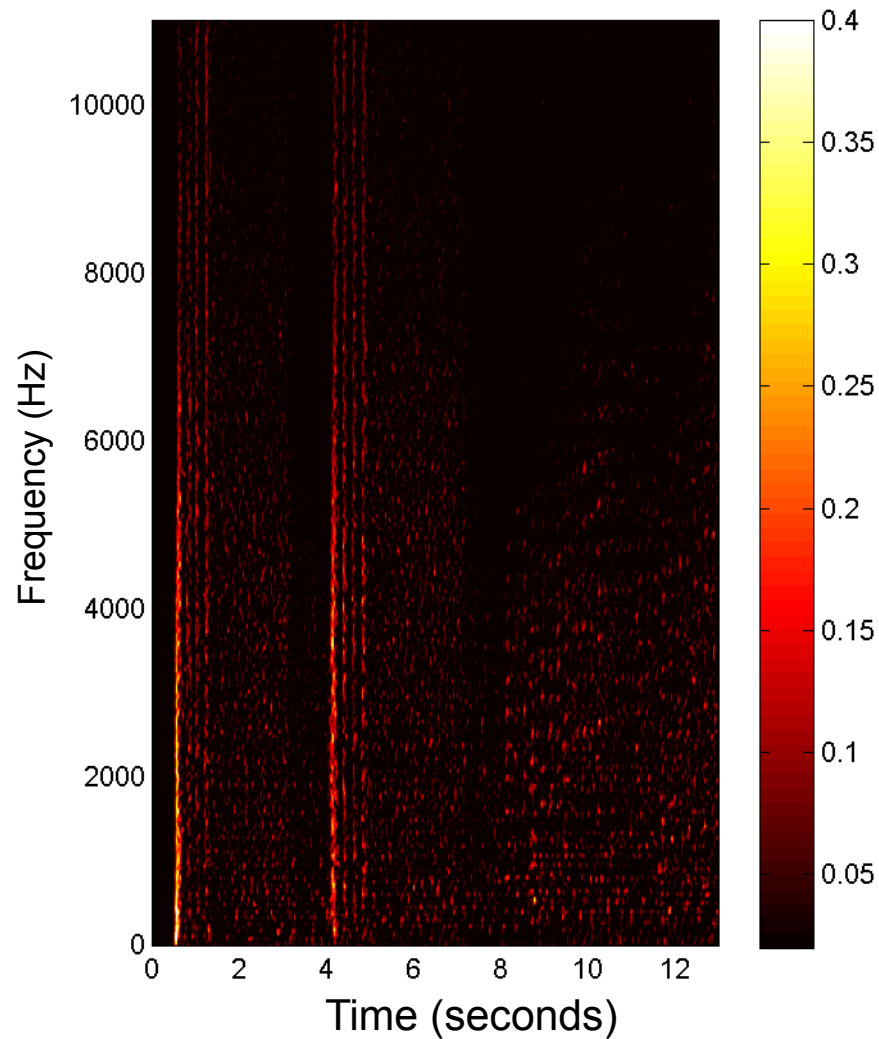


## Steps:

1. Spectrogram
2. Log Compression

# Tempo Estimation and Beat Tracking

Difference Spectrogram



## Steps:

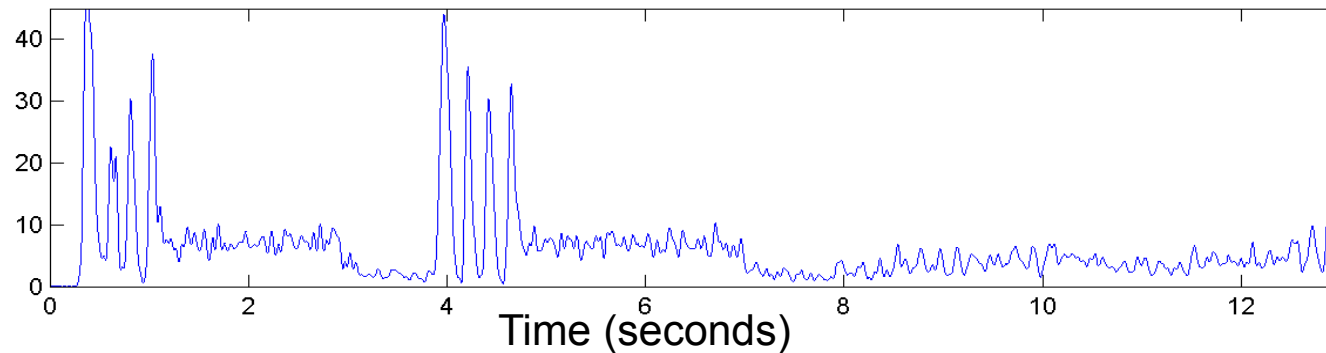
1. Spectrogram
2. Log Compression
3. Differentiation

# Tempo Estimation and Beat Tracking

## Steps:

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

## Novelty Curve

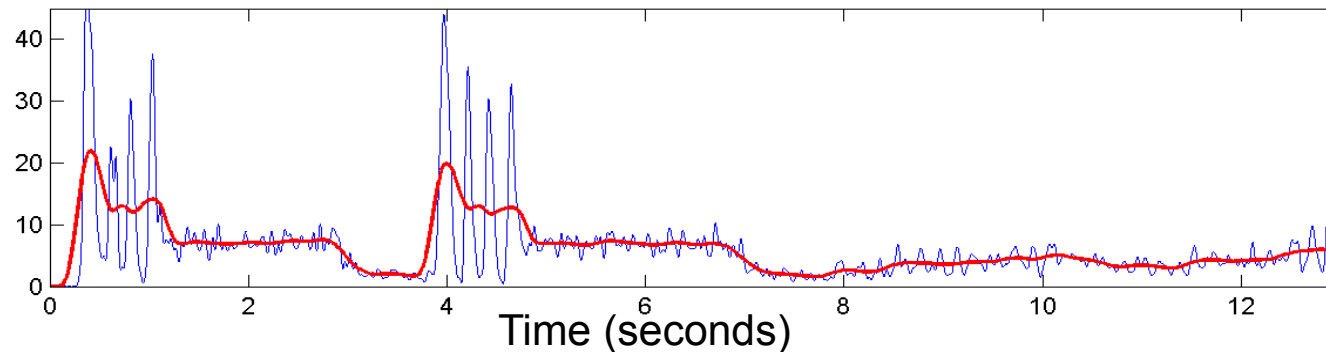


# Tempo Estimation and Beat Tracking

## Steps:

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

## Novelty Curve Local Average

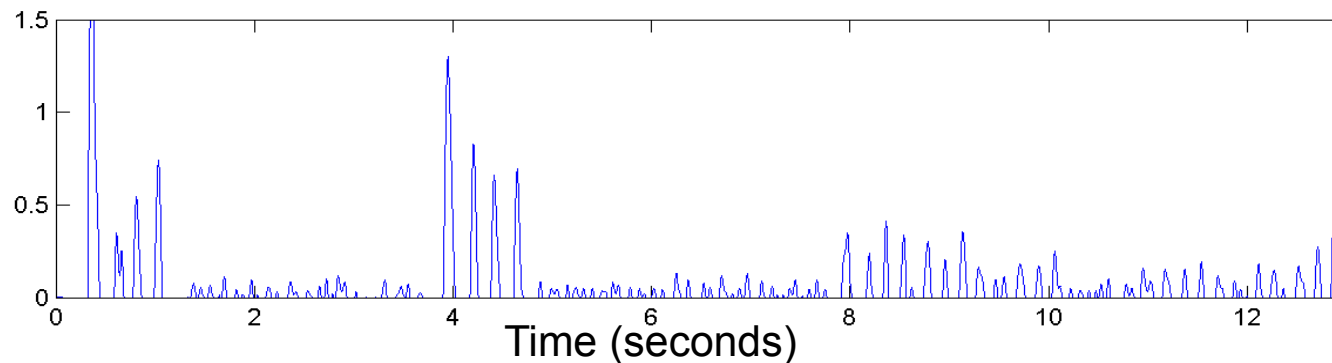


# Tempo Estimation and Beat Tracking

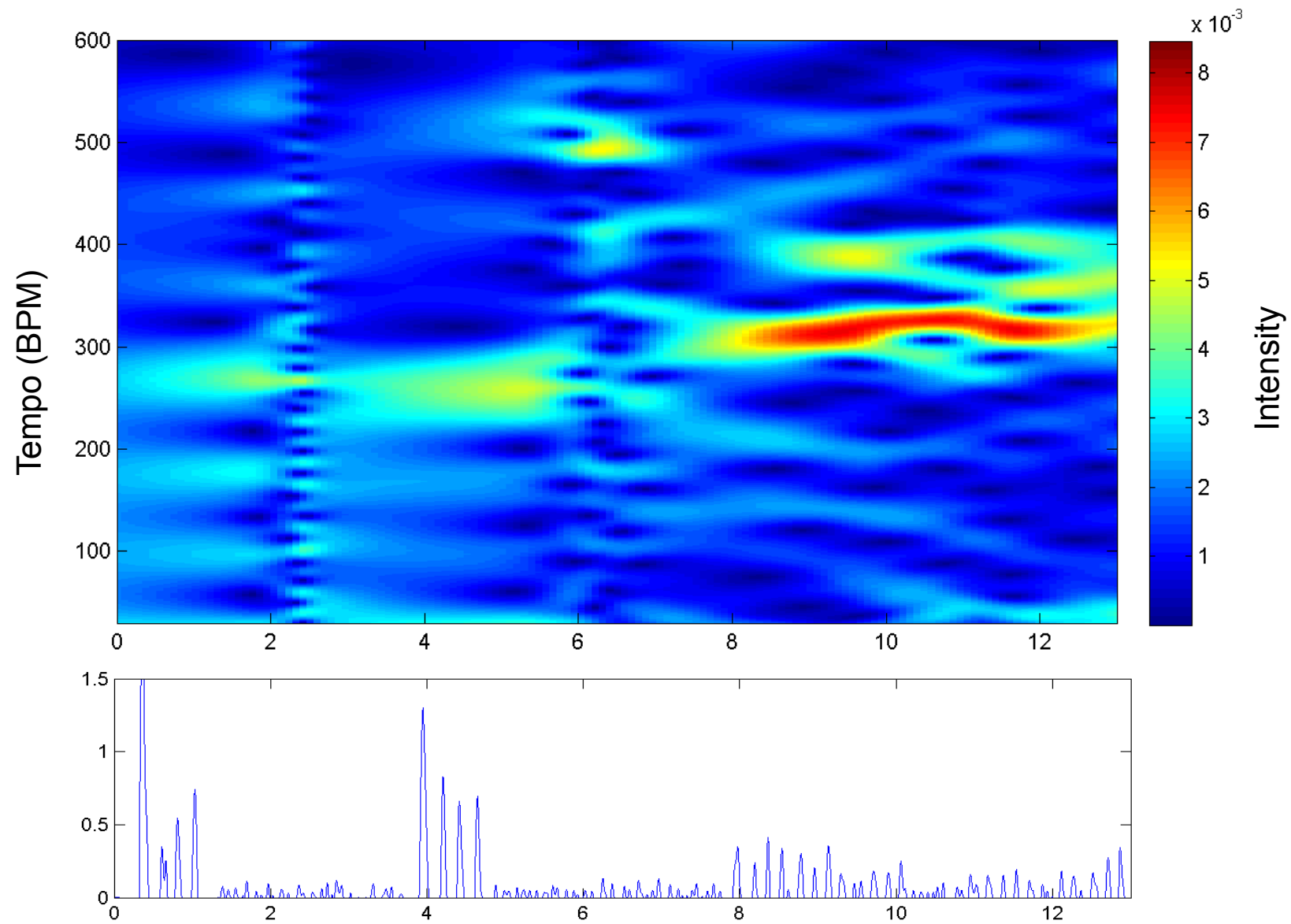
## Steps:

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

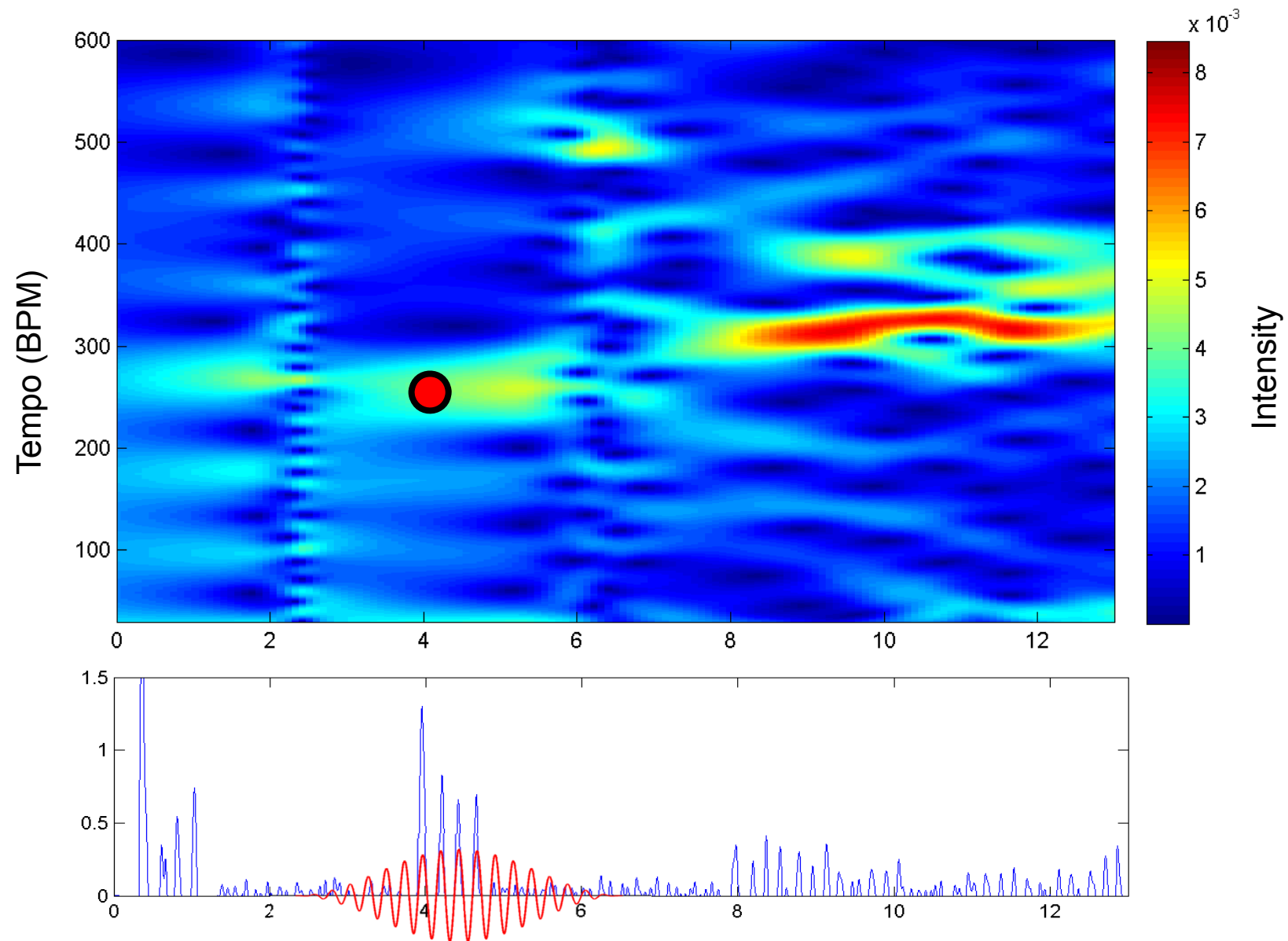
## Novelty Curve



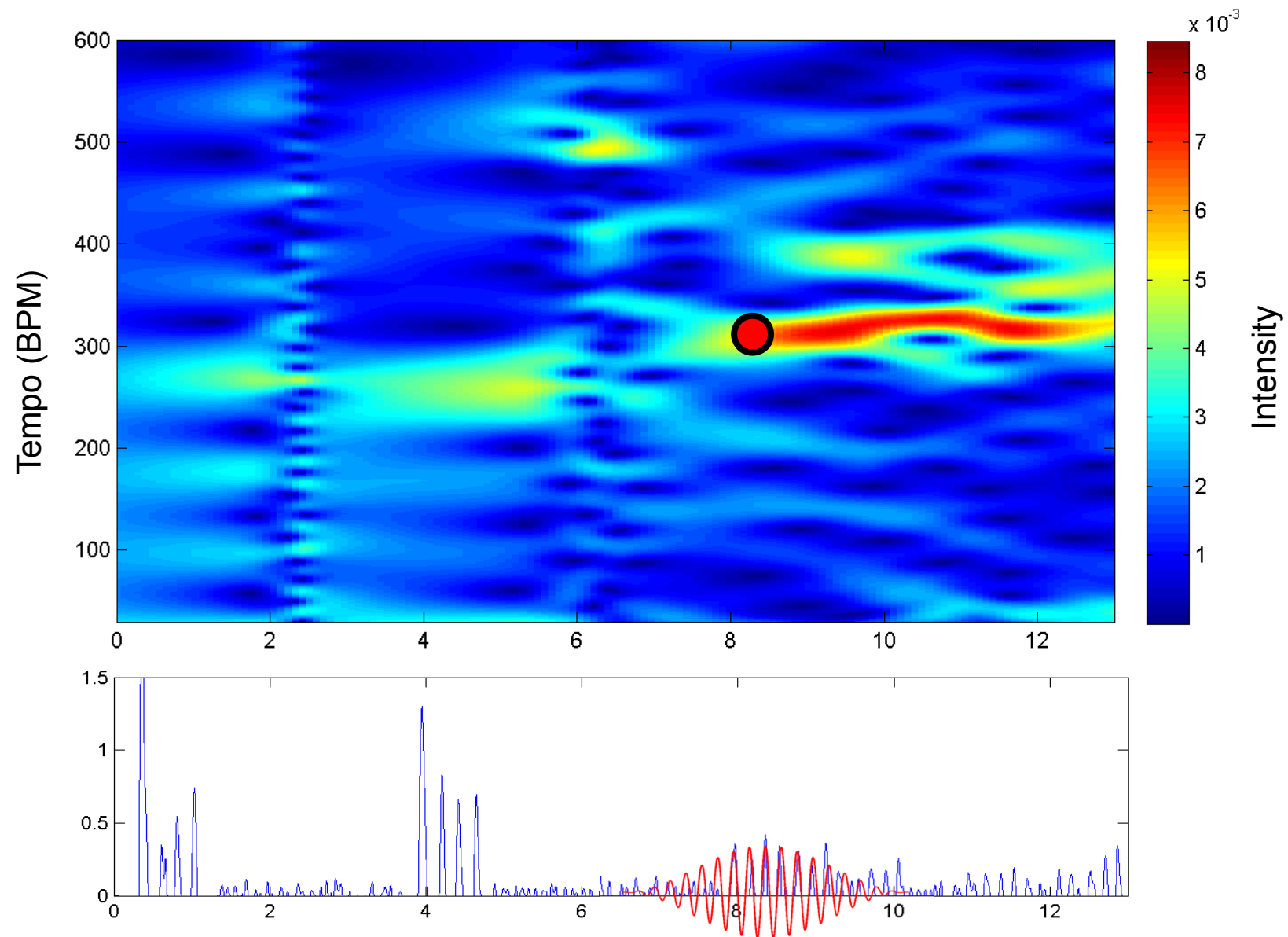
# Tempo Estimation and Beat Tracking



# Tempo Estimation and Beat Tracking

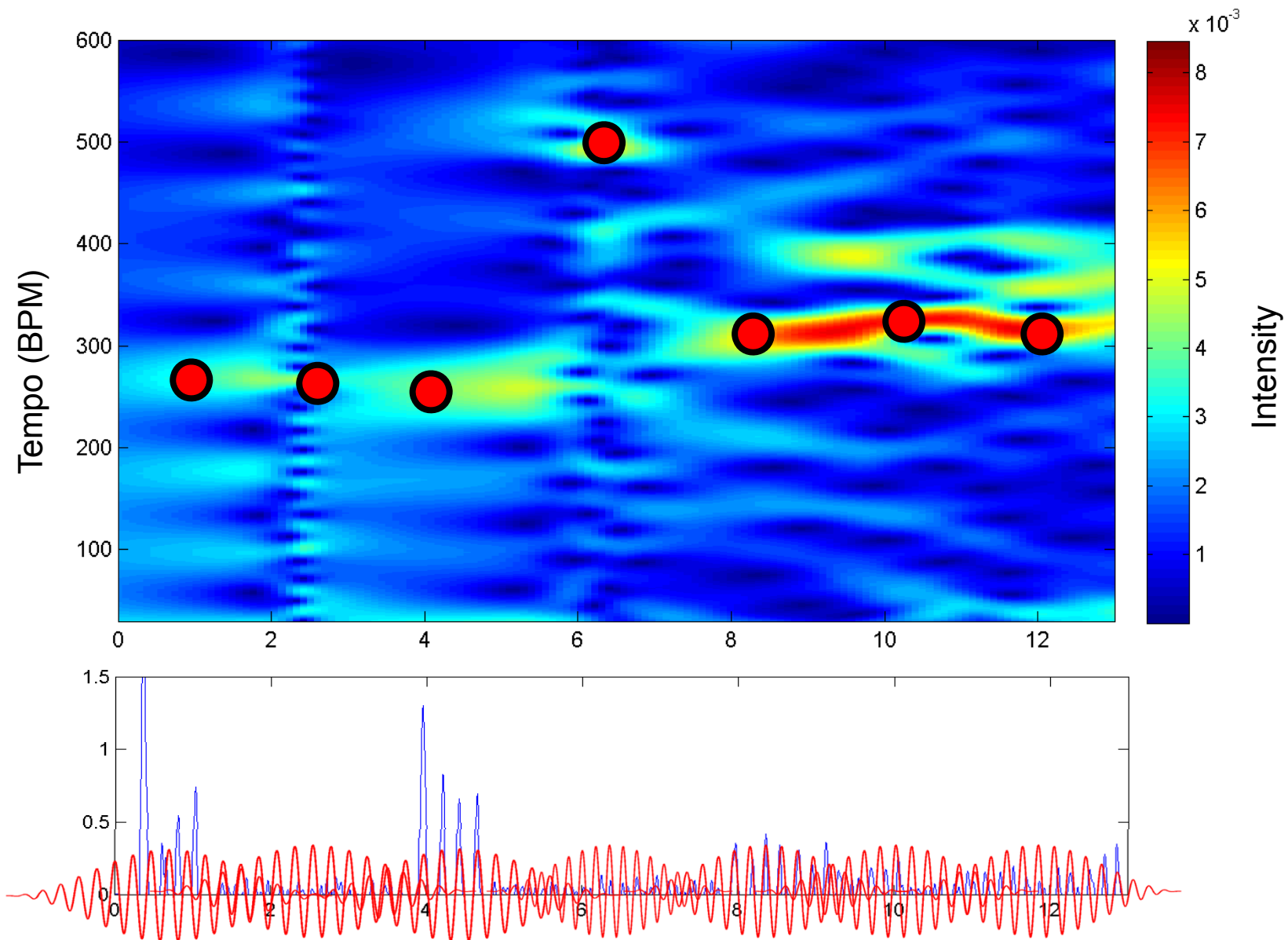


# Tempo Estimation and Beat Tracking

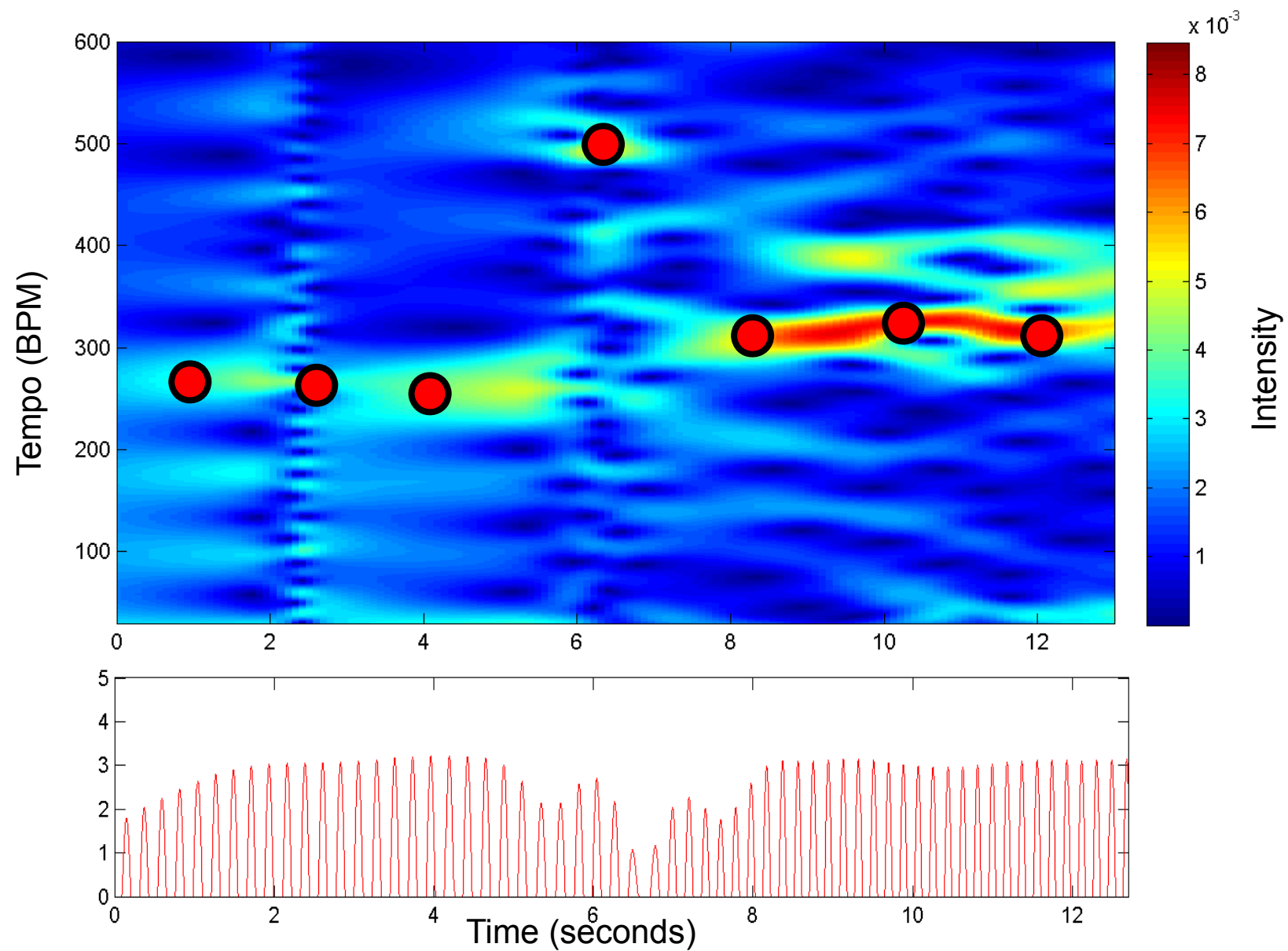




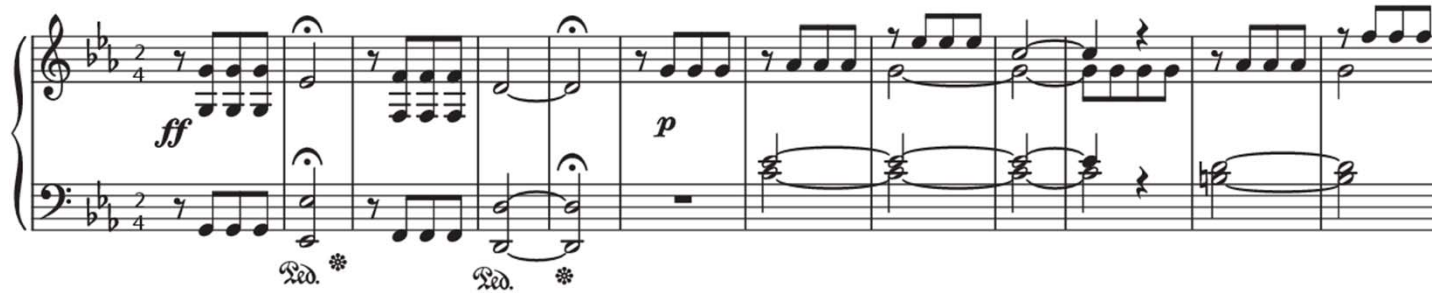
# Tempo Estimation and Beat Tracking



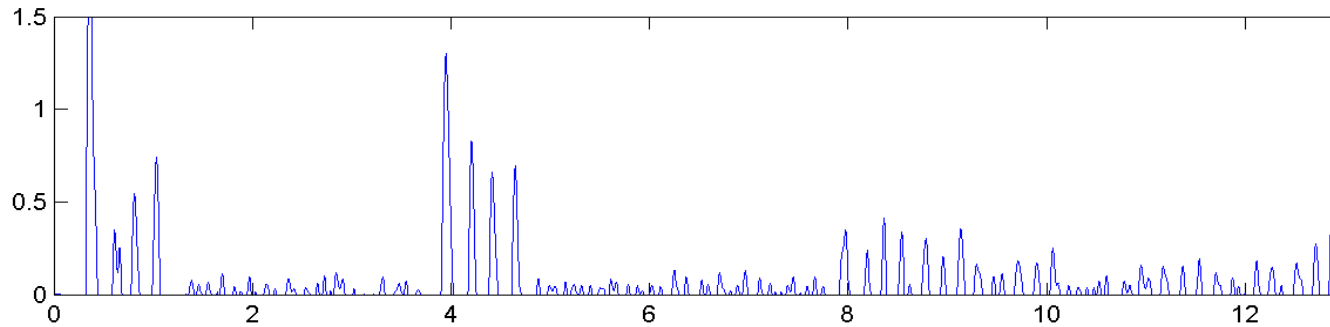
# Tempo Estimation and Beat Tracking



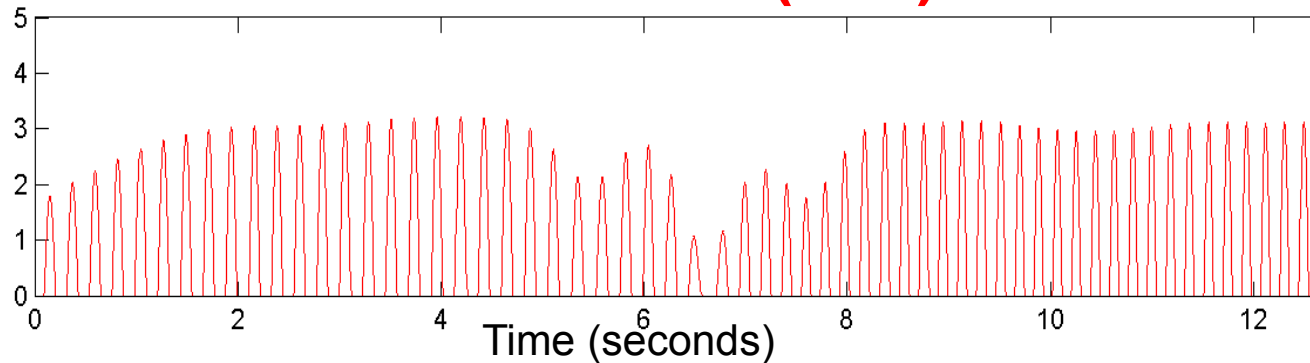
# Tempo Estimation and Beat Tracking



## Novelty Curve



## Predominant Local Pulse (PLP)



# Tempo Estimation and Beat Tracking

Light effects

Music recommendation

DJ

Audio editing



# Motivic Similarity

Allegro con brio (♩ = 108)

The image shows a musical score for the first movement of Beethoven's Fifth Symphony, marked 'Allegro con brio' with a tempo of 108 quarter notes per minute. The score is in 2/4 time and features a key signature of two flats (B-flat and E-flat). The first staff (treble clef) begins with a fortissimo (ff) dynamic and contains a series of chords and a melodic line. The second staff (bass clef) contains a similar rhythmic and melodic pattern. Two asterisks (\*) are placed below the second staff, with the word 'Red.' written above them, indicating a redaction or a specific annotation related to the motivic similarity being discussed.

Beethoven's Fifth (1st Mov.)



# Motivic Similarity

Allegro con brio (♩ = 108)

*ff*

Ped. \*      Ped. \*

Beethoven's Fifth (1st Mov.)



Beethoven's Fifth (3rd Mov.)



# Motivic Similarity

Allegro con brio (♩ = 108)

The image shows a musical score for the first movement of Beethoven's Fifth Symphony. It is in 2/4 time and marked 'Allegro con brio' with a tempo of 108 quarter notes per minute. The score is written for piano and features a prominent motif in the bass line, marked with 'Ped.' and an asterisk. The dynamic is marked 'ff' (fortissimo). The score is in the key of D minor.

Beethoven's Fifth (1st Mov.)



Beethoven's Fifth (3rd Mov.)



Beethoven's Appassionata



# Motivic Similarity

Var. 4: Vivace

The musical score consists of four staves of bass clef notation in 3/4 time. The first staff begins with a forte (*f*) dynamic and features a series of eighth-note patterns. The second staff continues with similar eighth-note motifs, including a triplet. The third staff shows more complex rhythmic patterns with sixteenth notes and slurs. The fourth staff concludes with a sequence of notes marked with piano (*p*) and forte (*f*) dynamics, ending with a double bar line.





# Motivic Similarity

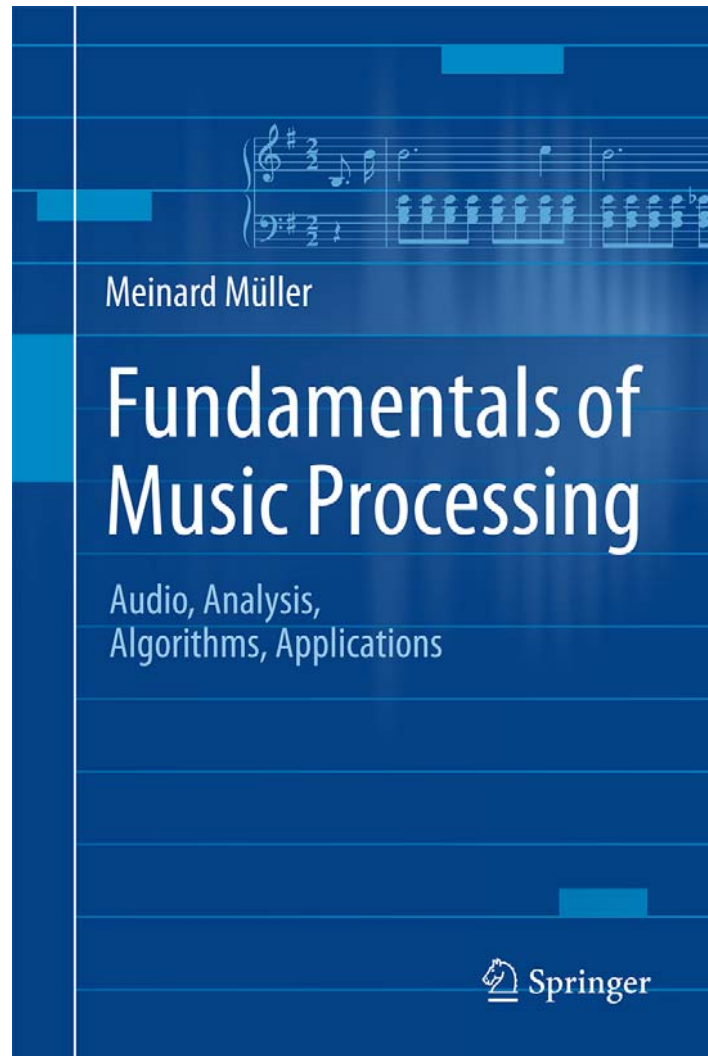
A musical staff in treble clef showing a four-note motif: B (half note), A (quarter note), C (quarter note), and H (half note). The notes are written on a five-line staff with a key signature of one sharp (F#).



A musical score for four voices: Soprano (S), Alto (A), Tenor (T), and Bass (B). The score is in 4/4 time with a key signature of one sharp (F#). The lyrics are: "auf - - ge - rafft, und nie - mand ach - - tet und nie - mand ach - - tet drauf". A red box highlights a four-note motif in the Alto part, with the notes labeled 'b', 'a', 'c', and 'h' in red. The notes are: B (half note), A (quarter note), C (quarter note), and H (half note). The notes are written on a five-line staff with a key signature of one sharp (F#).



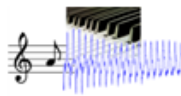

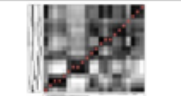


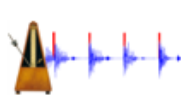
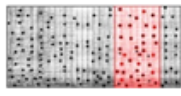
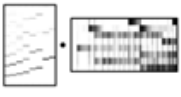
# Book: Fundamentals of Music Processing



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

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