

Lecture

Music Processing

Beethoven, Bach, and Billions of Bytes

New Alliances between Music and Computer Science

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Music

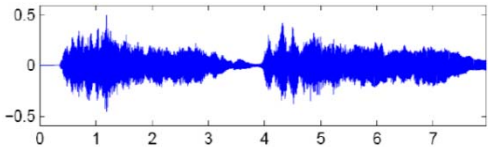


Music Processing

Sheet Music (Image)



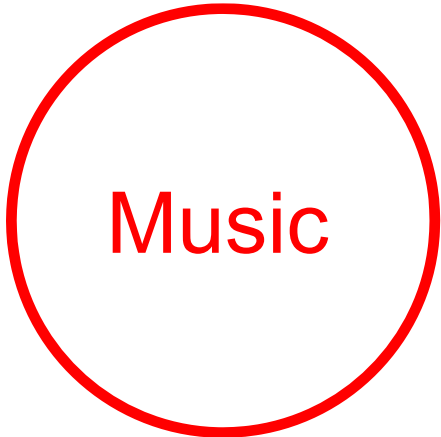
CD / MP3 (Audio)



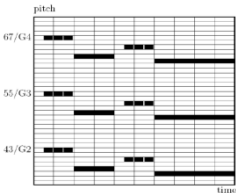
MusicXML (Text)

```
<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)



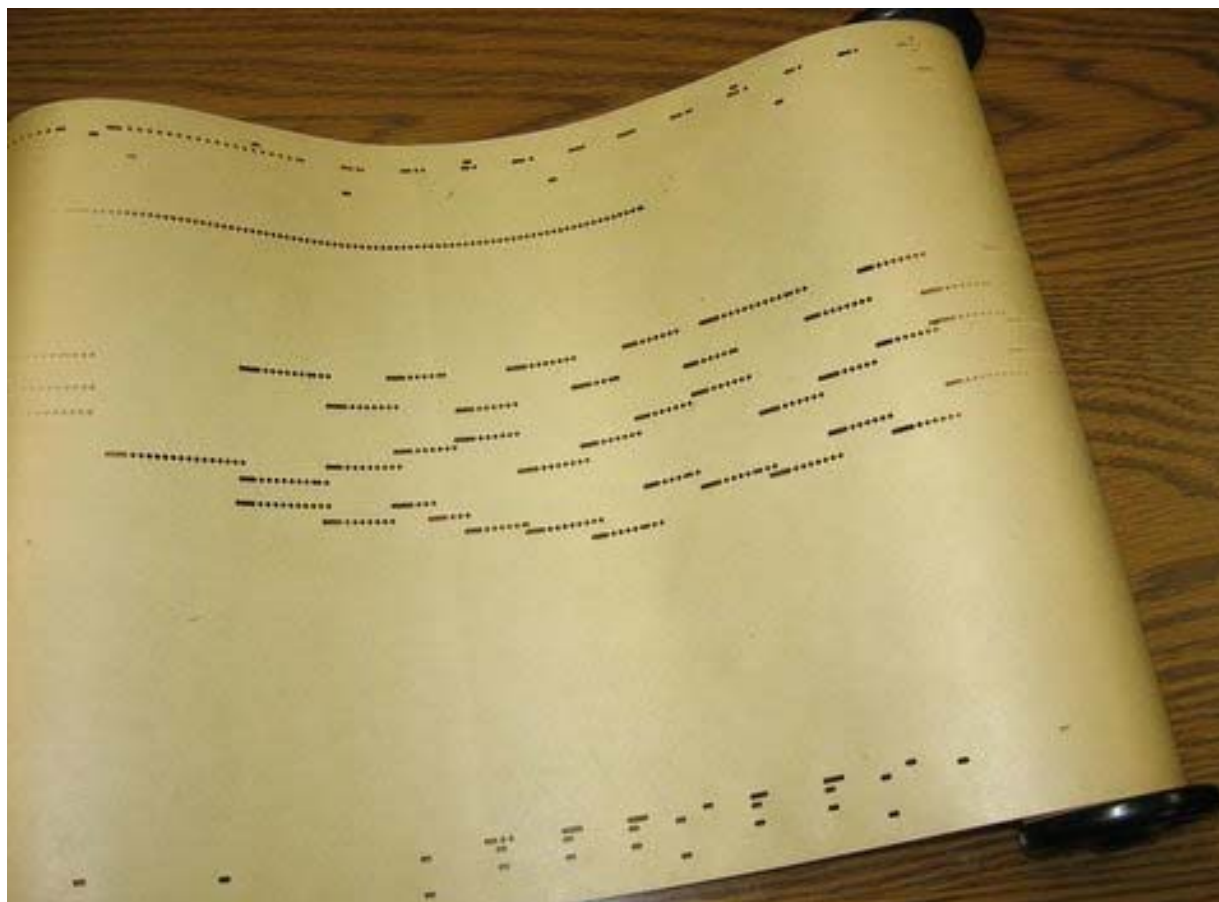
Music Literature (Text)



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



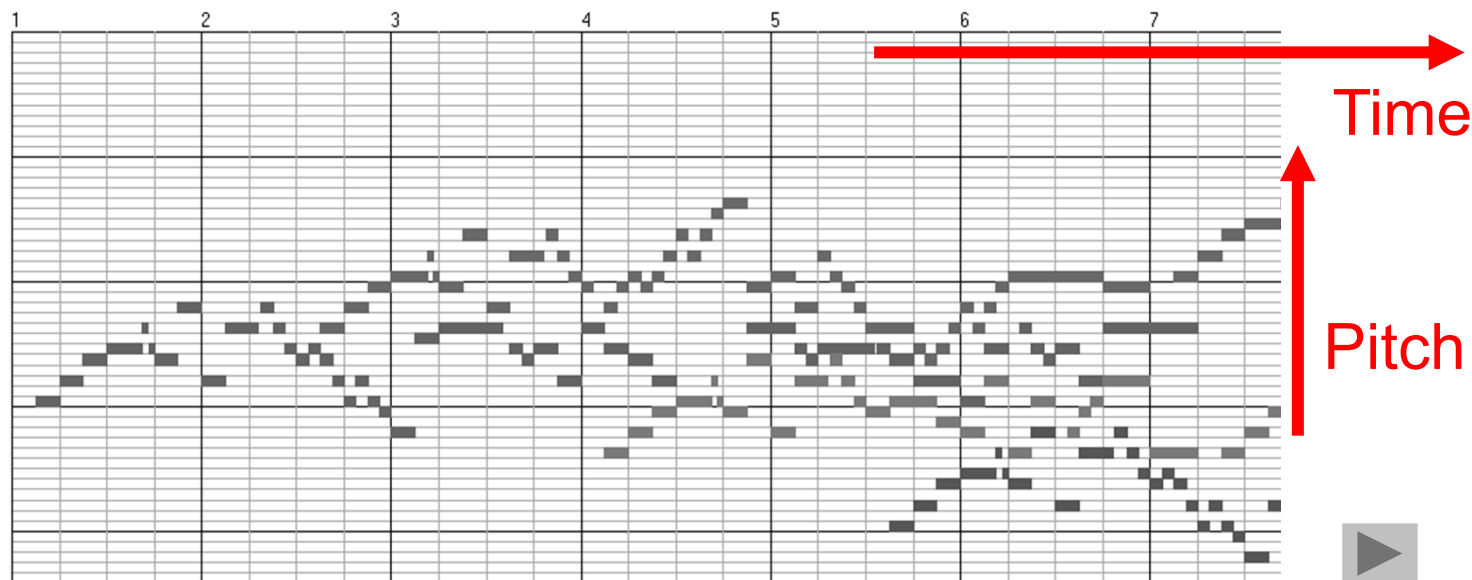
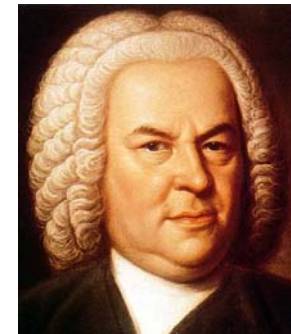
Player Piano (1900)



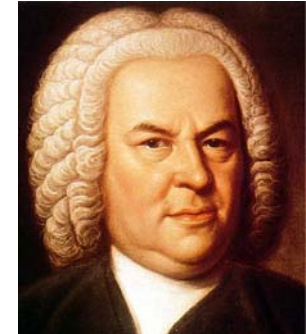
Piano Roll Representation (MIDI)

J.S. Bach, C-Major Fuge

(Well Tempered Piano, BWV 846)



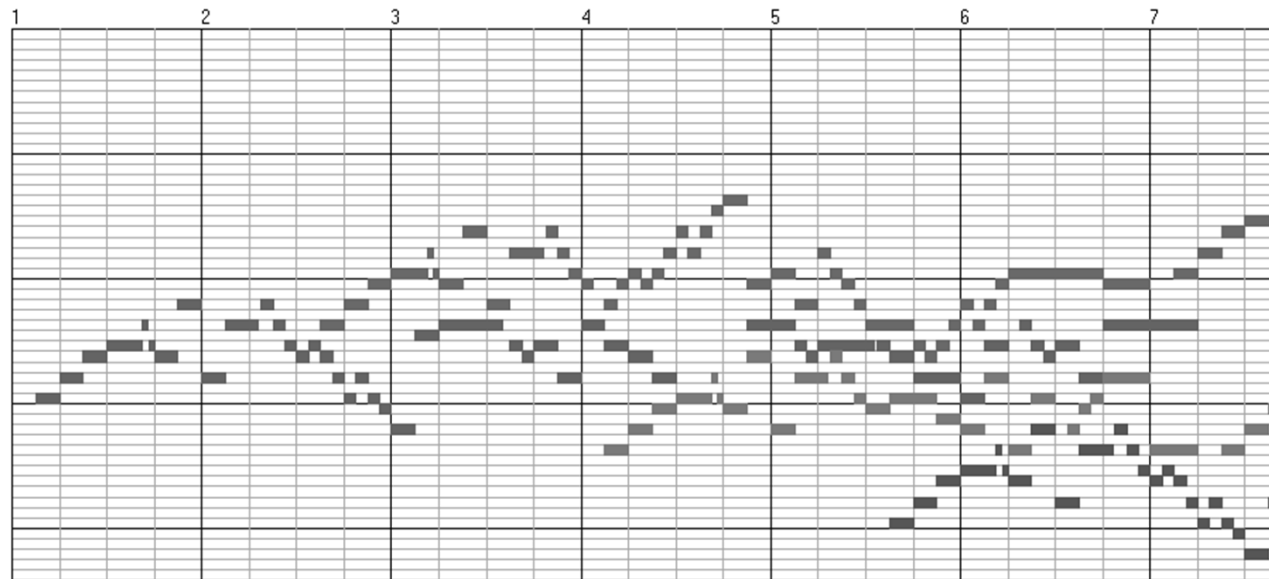
Piano Roll Representation (MIDI)



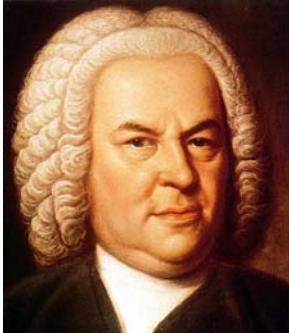
Query:



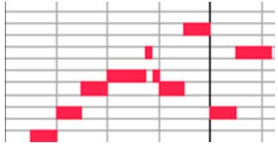
Goal: Find all occurrences of the query



Piano Roll Representation (MIDI)

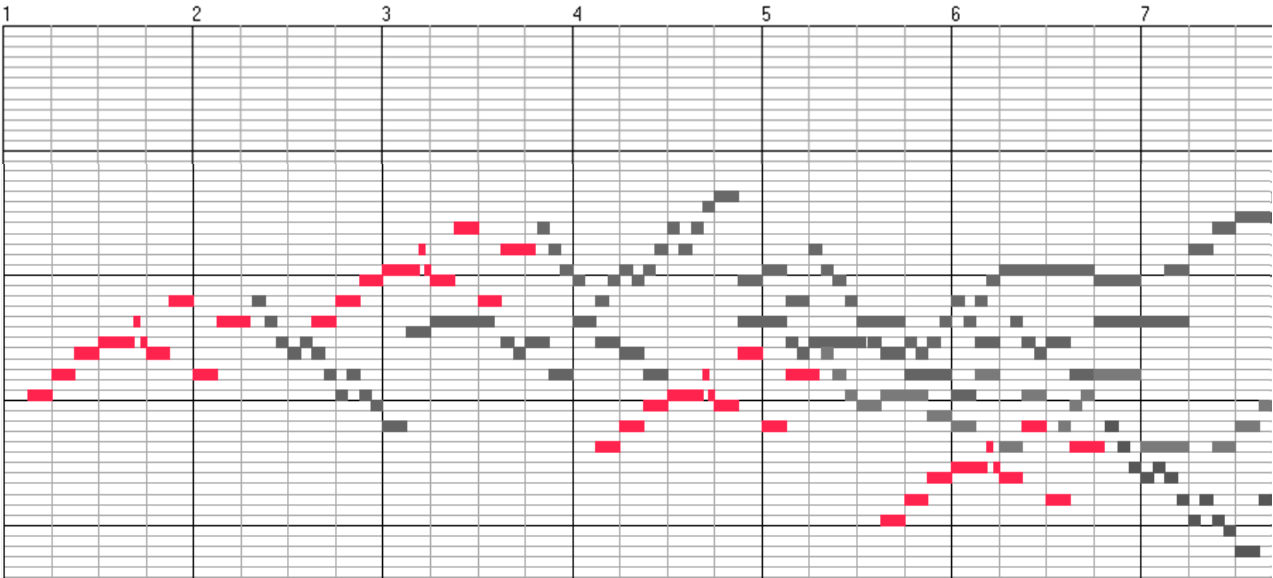


Query:

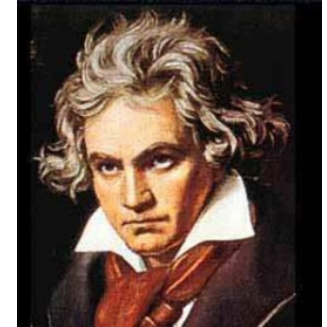


Goal: Find all occurrences of the query

Matches:



Audio Data



Various interpretations – Beethoven's Fifth

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 Billion Bytes
1 Terabyte (TB)	=	1000 Billion Bytes

Audio Data (Memory Requirements)

12.000 MIDI files < 350 MB

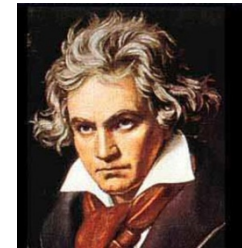
One audio CD \approx 650 MB

Two audio CDs > **1 Billion Bytes**

1000 audio CDs \approx **Billions of Bytes**

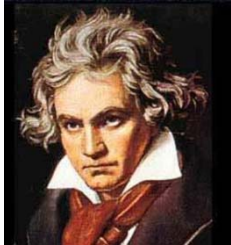
Music Synchronization: Audio-Audio

Beethoven's Fifth

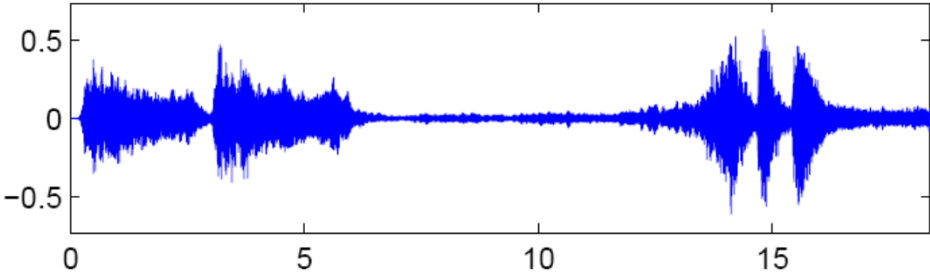


Music Synchronization: Audio-Audio

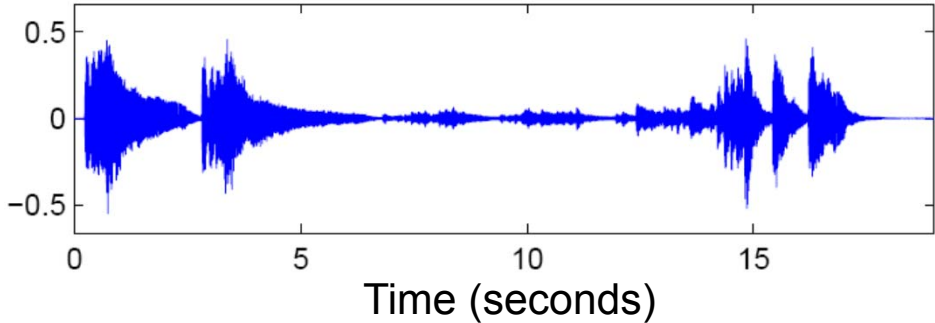
Beethoven's Fifth



Orchester
(Karajan)

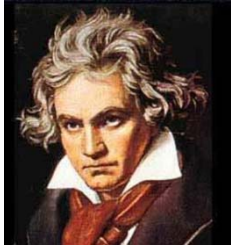


Piano
(Scherbakov)

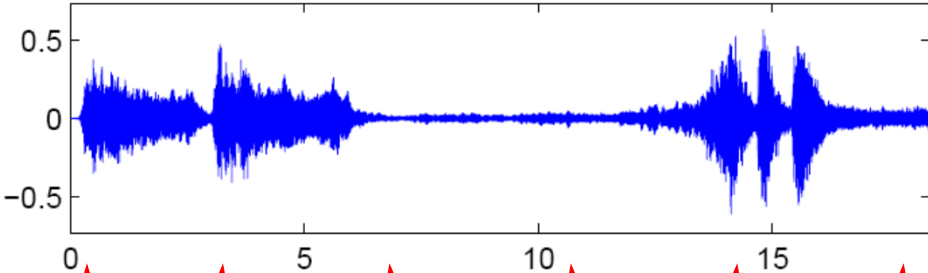


Music Synchronization: Audio-Audio

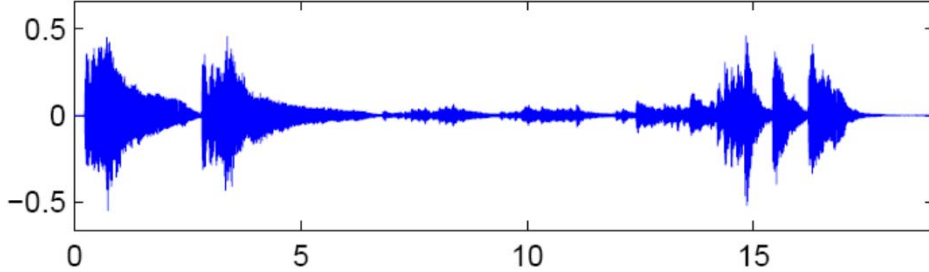
Beethoven's Fifth



Orchester
(Karajan)



Piano
(Scherbakov)



Time (seconds)

Application: Interpretation Switcher

Interpretation Switcher
Beethoven, Op067-1_Symphony5

Interpretation Progress Bars:

- midi**: 00:44.18
- Bernstein**: 01:00.64
- Sawallisch**: 00:58.35
- Scherbakov**: 00:52.45

Selected Interpretations:

- midi
- Bernstein
- Sawallisch
- Scherbakov

Playback Controls:

- Absolute ✓
- Relative
- Reference
- Pause (||)
- Stop (■)
- Up Arrow (↑)
- Movement selection
- Interval Repeat (☐)
- Info (?)

Buttons: Deselect all



Music Synchronization: Image-Audio

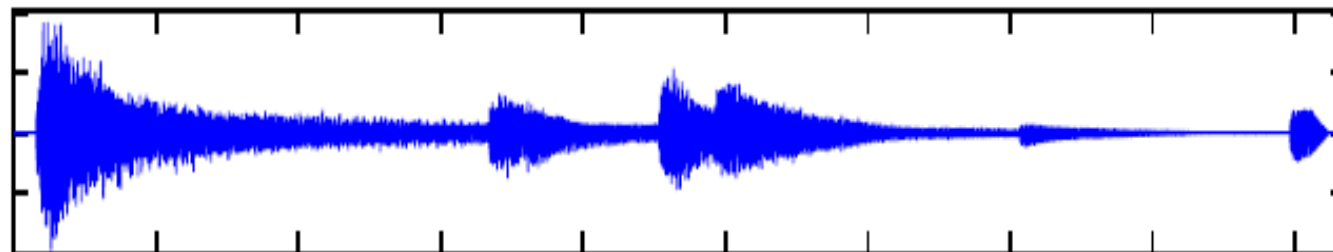
Image

Grave.

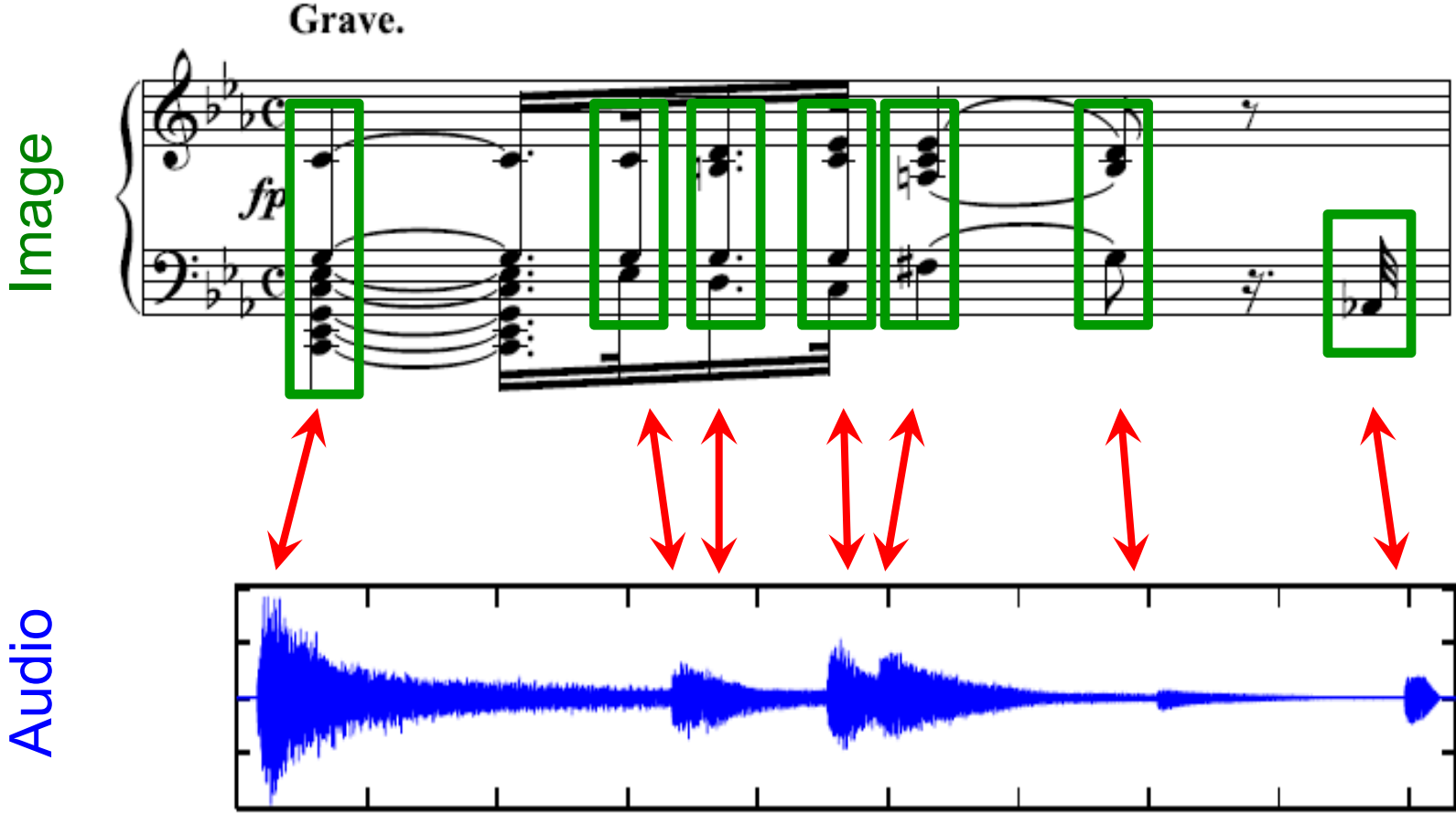


The image shows a musical score for piano, marked "Grave." and "fp". The score is written in G major (one sharp) and common time (C). It consists of two staves: a treble clef staff and a bass clef staff. The music features a slow, somber tempo with a focus on sustained chords and melodic lines. The treble staff begins with a half note chord (G4, B4, D5) followed by a series of chords and a final half note chord. The bass staff begins with a half note chord (G2, B2, D3) followed by a series of chords and a final half note chord. The overall mood is solemn and reflective.

Audio



Music Synchronization: Image-Audio

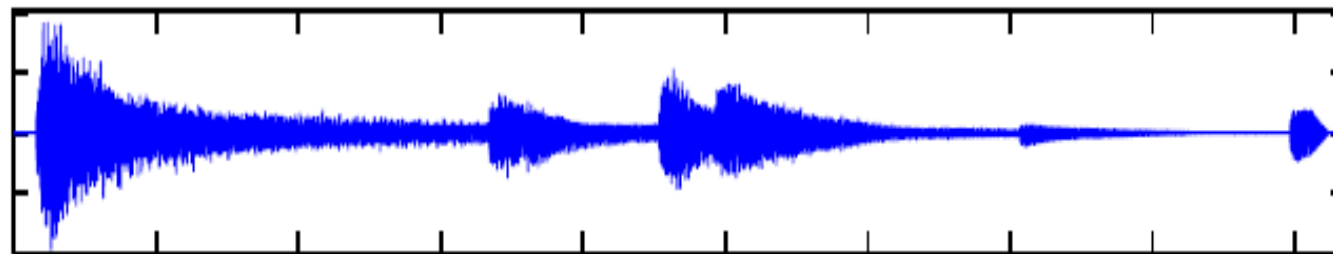


How to make the data comparable?

Image



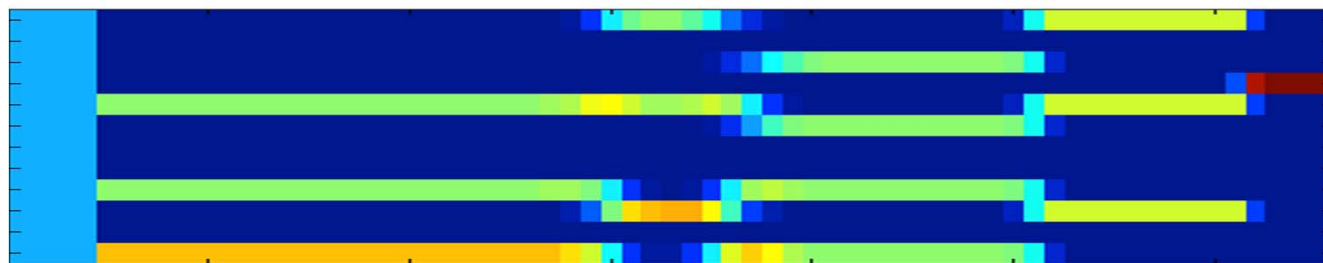
Audio



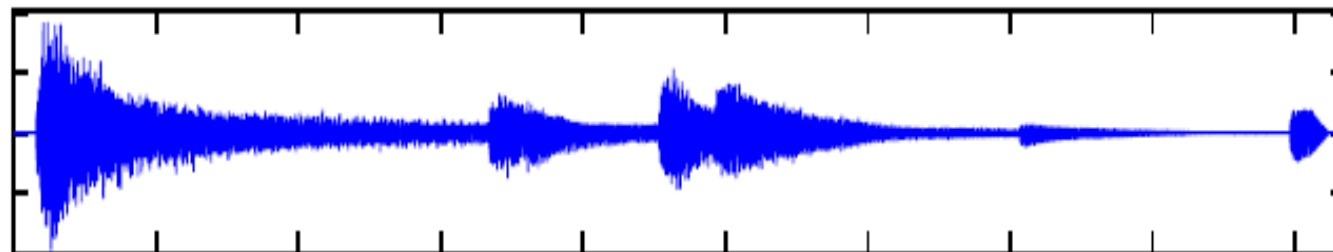
How to make the data comparable?

Image Processing: Optical Music Recognition

Image



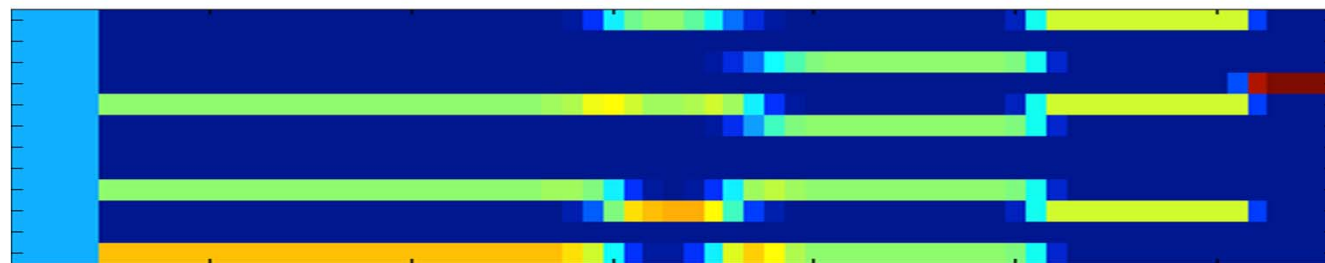
Audio



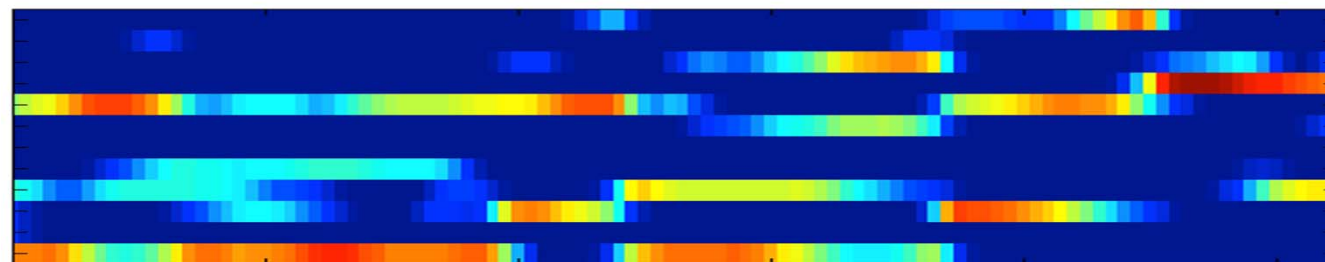
How to make the data comparable?

Image Processing: Optical Music Recognition

Image



Audio

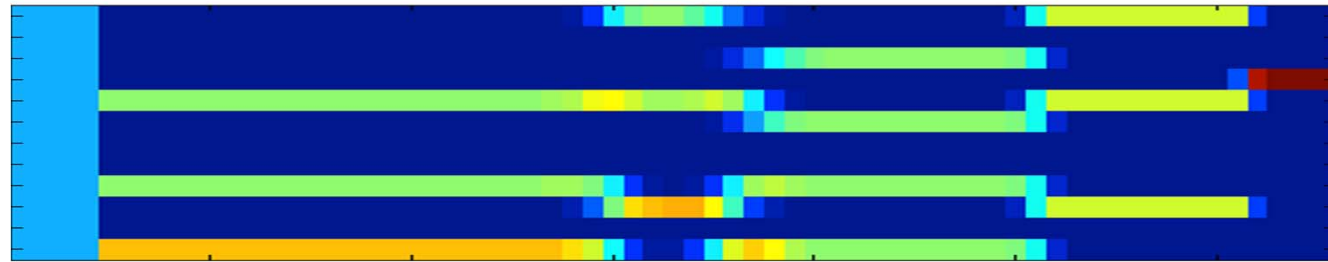


Audio Processing: Fourier Analyse

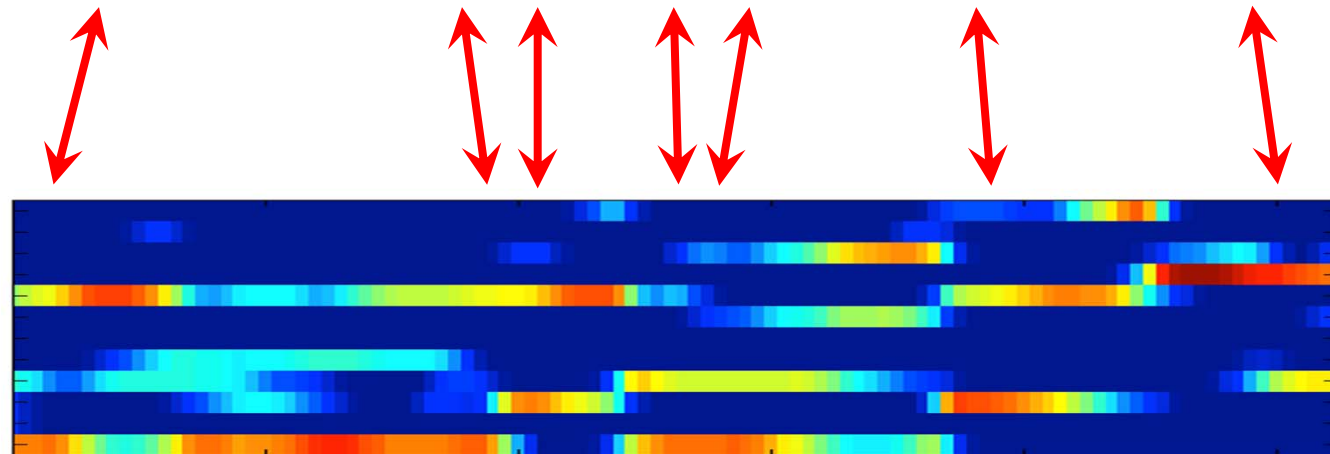
How to make the data comparable?

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

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
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

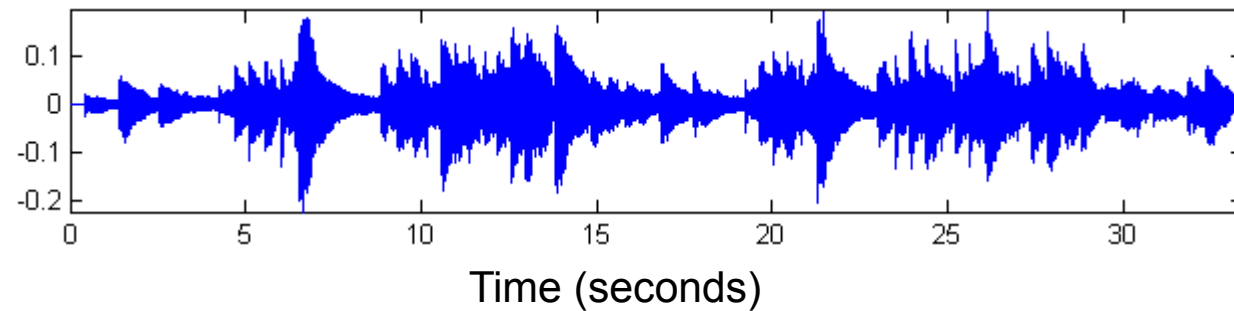
Music Processing

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: Audio Matching Cover Song Identification	Example tasks: Tempo Estimation Performance Analysis

Performance Analysis

Schumann: Träumerei

Performance:



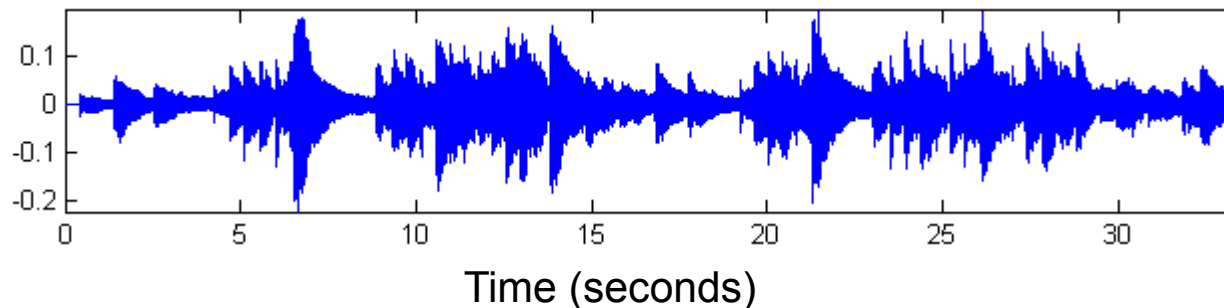
Performance Analysis

Schumann: Träumerei

Score (reference):



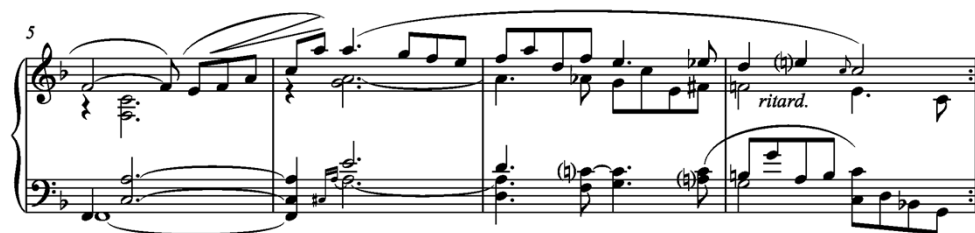
Performance:



Performance Analysis

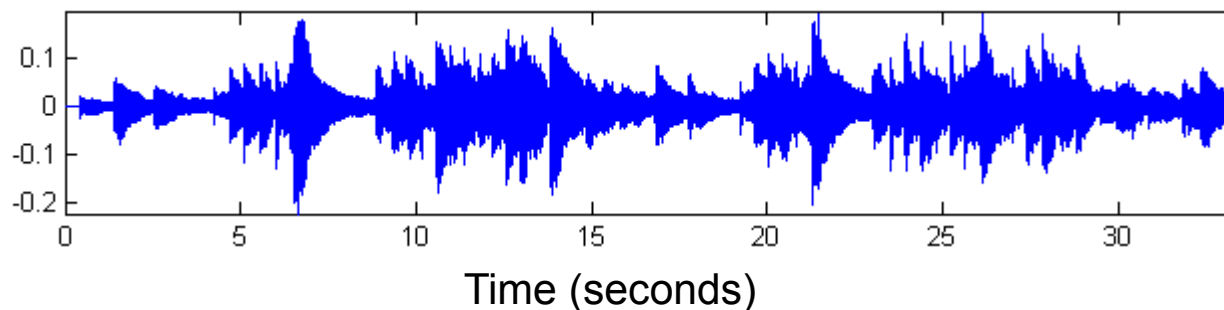
Schumann: Träumerei

Score (reference):



Strategy: Compute score-audio synchronization and derive tempo curve

Performance:



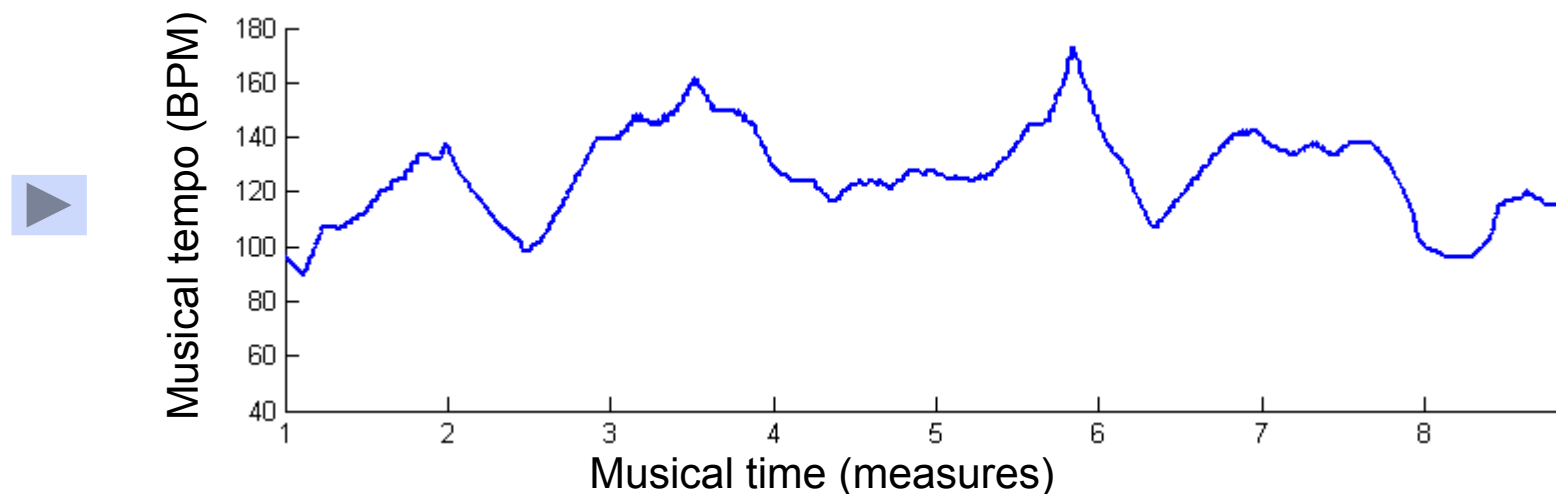
Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curve:



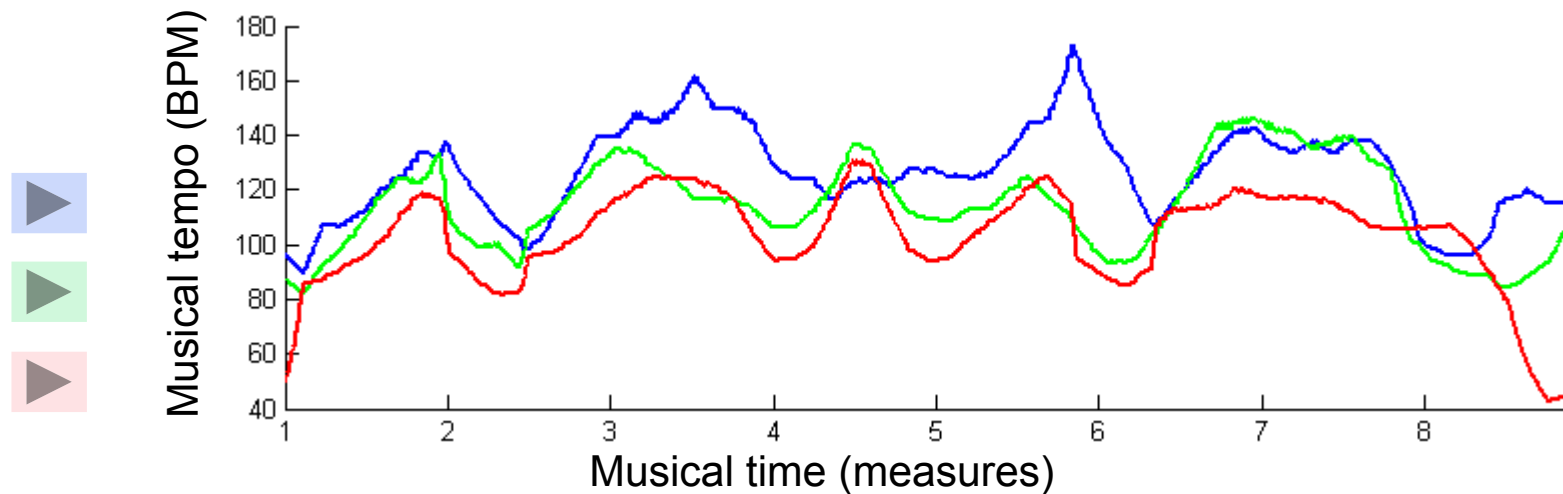
Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curves:



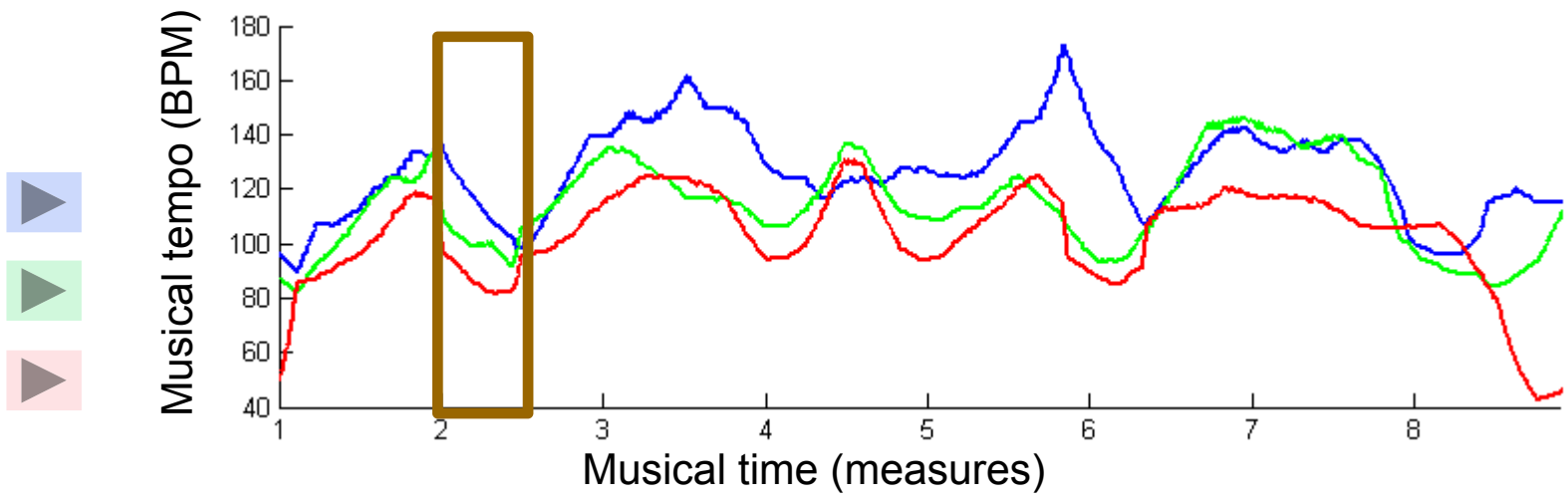
Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curves:



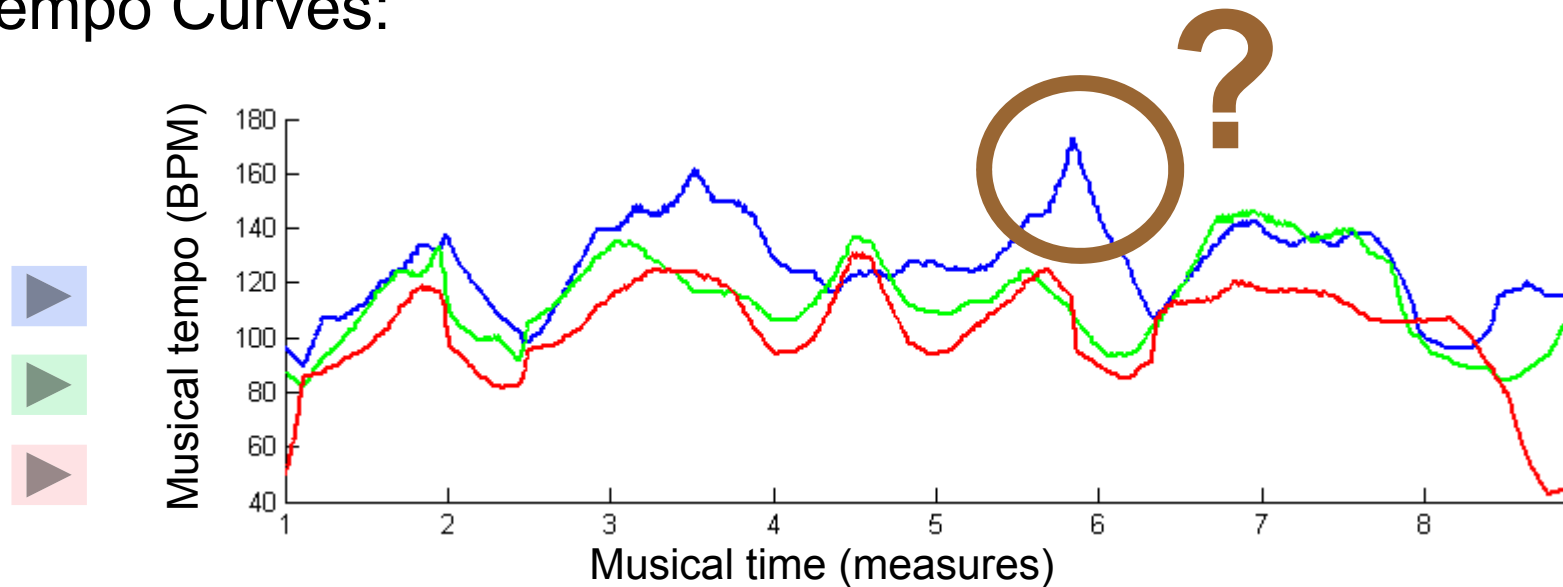
Performance Analysis

Schumann: Träumerei

Score (reference):



Tempo Curves:

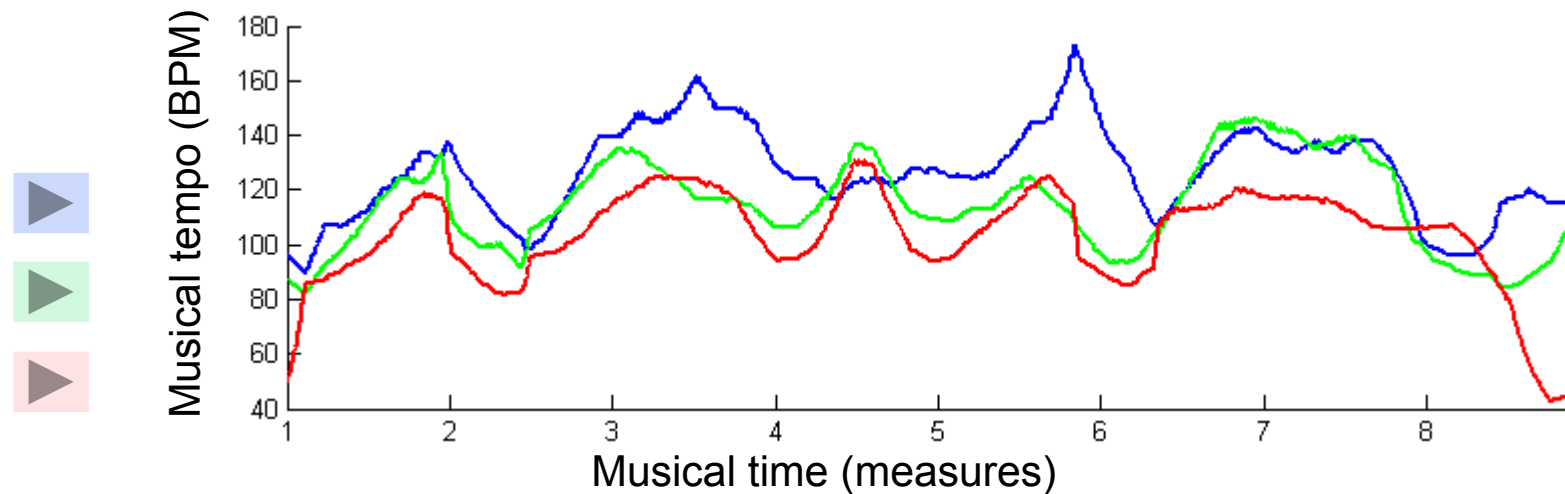


Performance Analysis

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
Given: Several versions	Given: One version
Comparison of extracted parameters	Direct interpretation of extracted parameters

Music Processing

Relative	Absolute
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

Relative	Absolute
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: Music Synchronization Genre Classification	Example tasks: Music Transcription Tempo Estimation

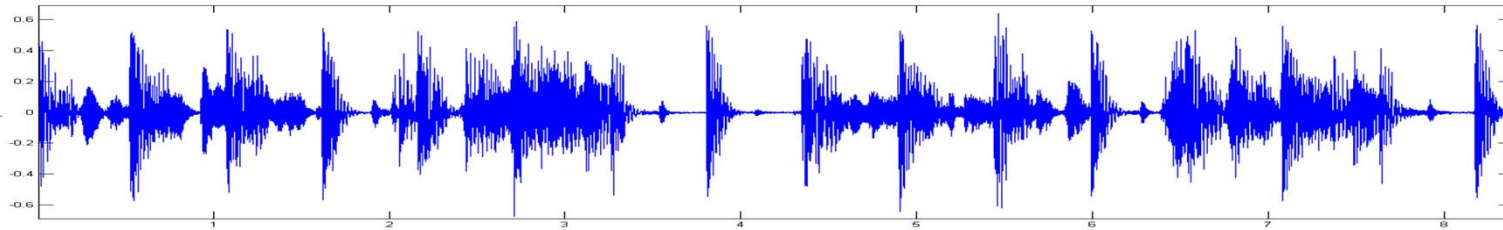
Tempo Estimation and Beat Tracking

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

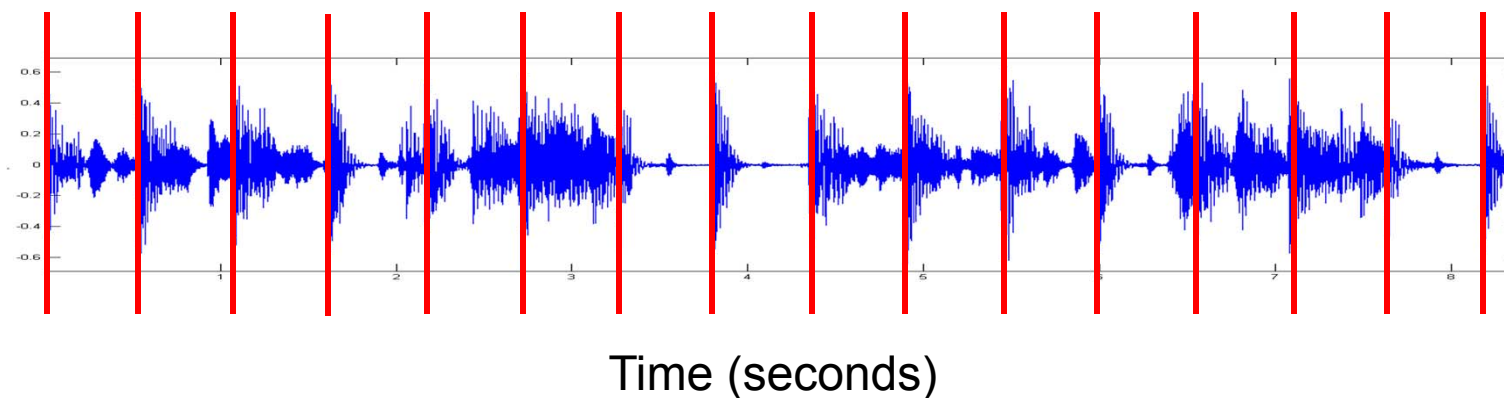


Time (seconds)

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 "Hap - py". The second staff contains the continuation: "Birth - day dear _____," and "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.

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: 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 final 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 on the first staff, with the first arrow above the first note of the first phrase, and subsequent arrows above each note in the sequence.

Tempo Estimation and Beat Tracking

Example: Chopin – Mazurka Op. 68-3

Pulse level: Quarter note

Tempo: ???



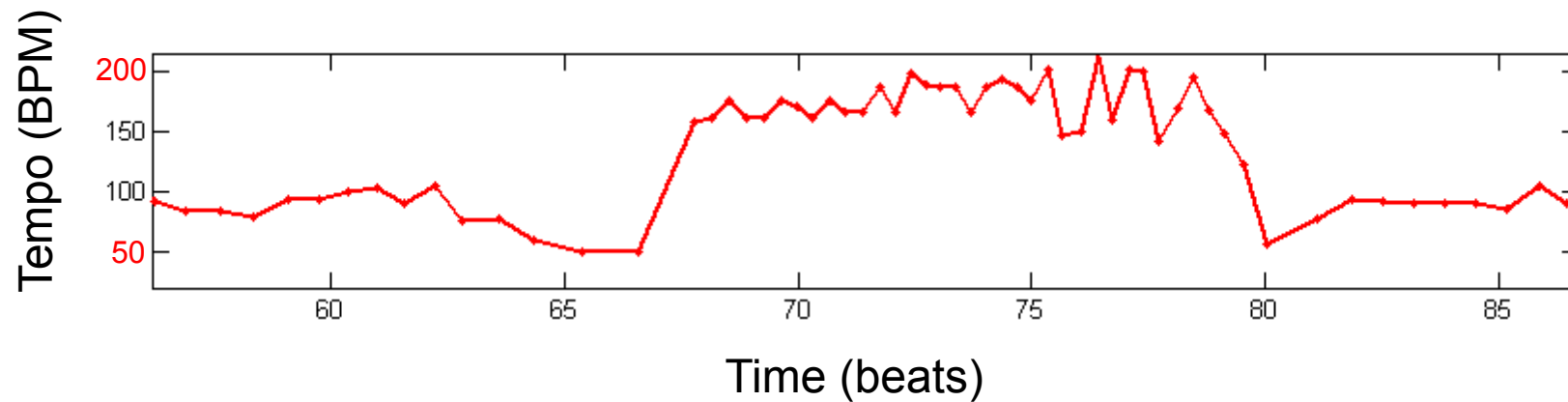
Tempo Estimation and Beat Tracking

Example: Chopin – Mazurka Op. 68-3

Pulse level: Quarter note

Tempo: **50-200 BPM** 

Tempo curve

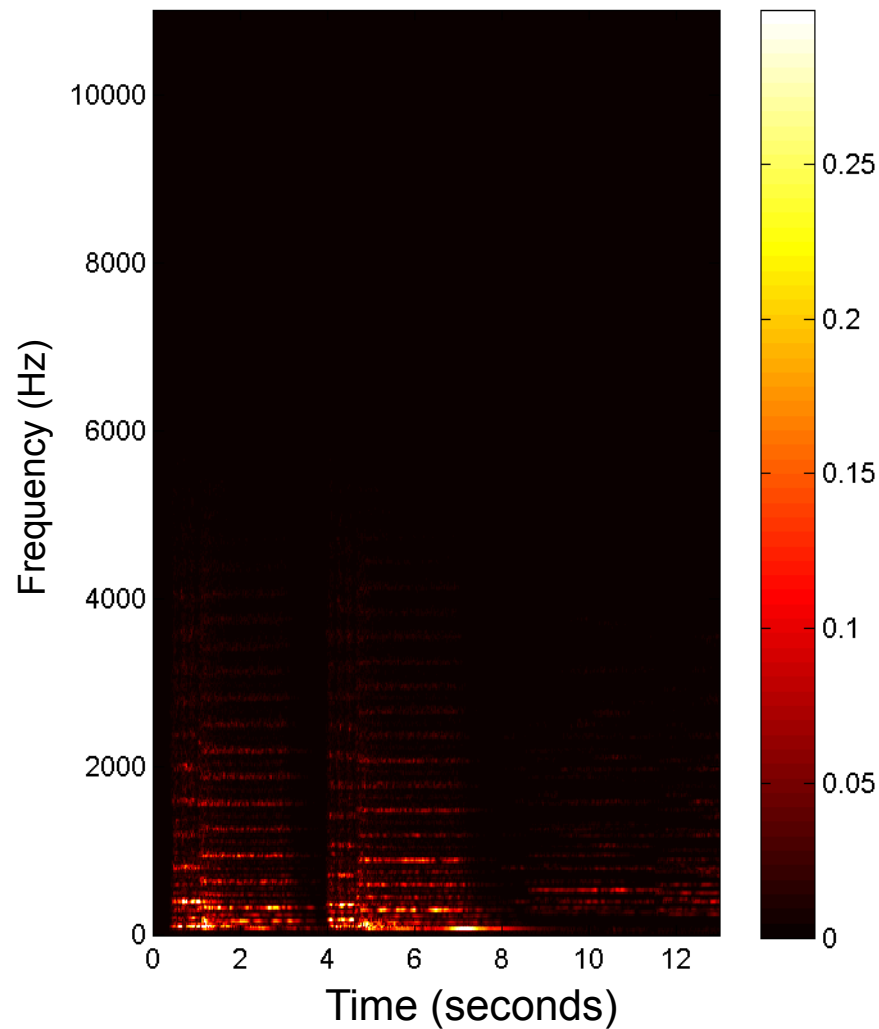


Tempo Estimation and Beat Tracking

- 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

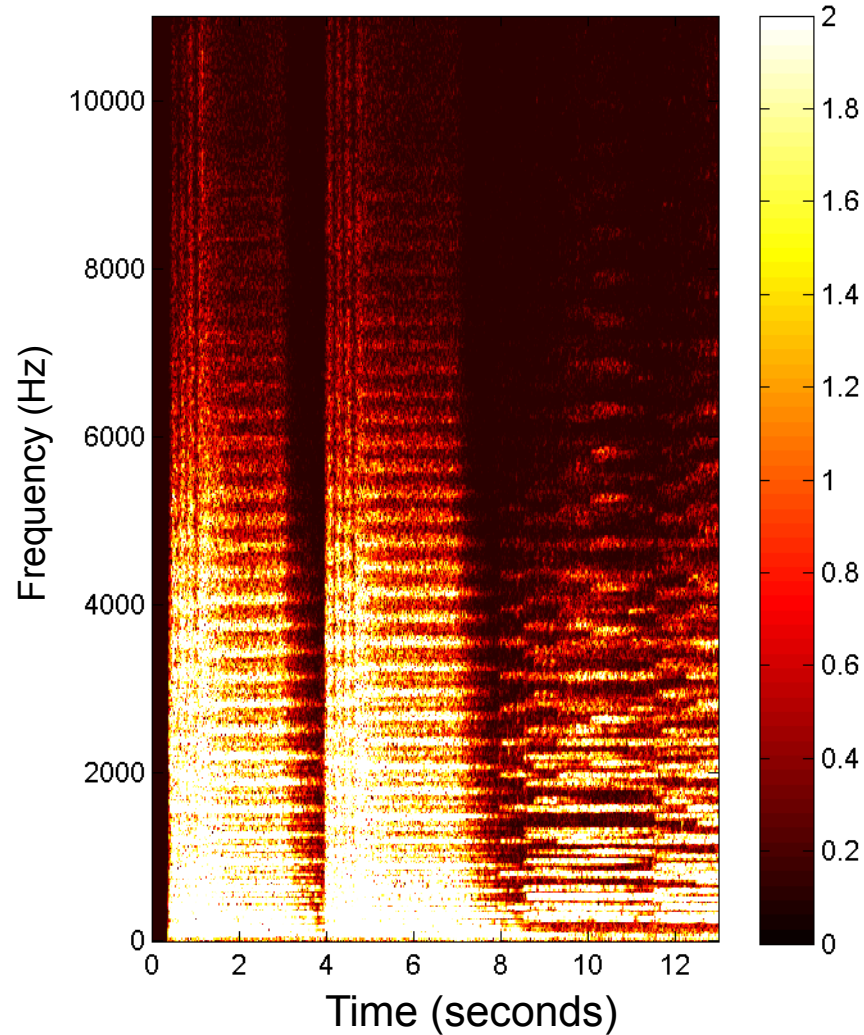


Steps:

1. Spectrogram

Tempo Estimation and Beat Tracking

Compressed Spectrogram

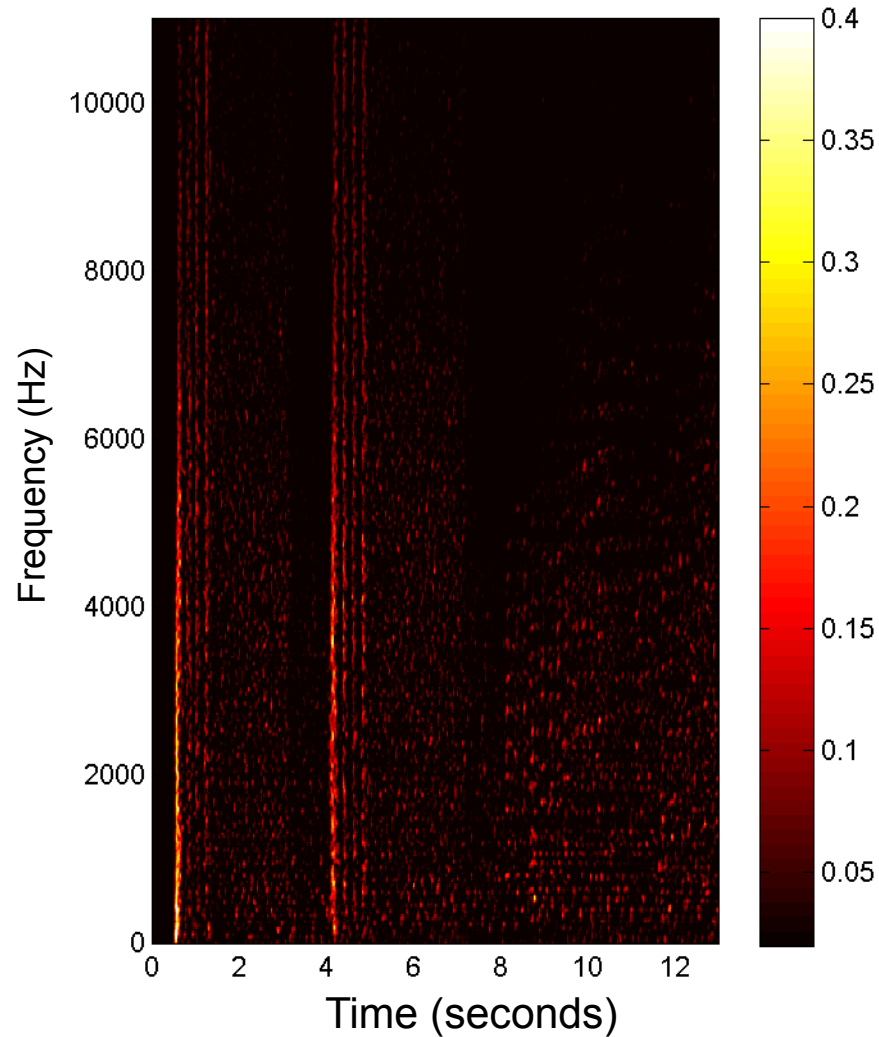


Steps:

1. Spectrogram
2. Log Compression

Tempo Estimation and Beat Tracking

Difference Spectrogram



Steps:

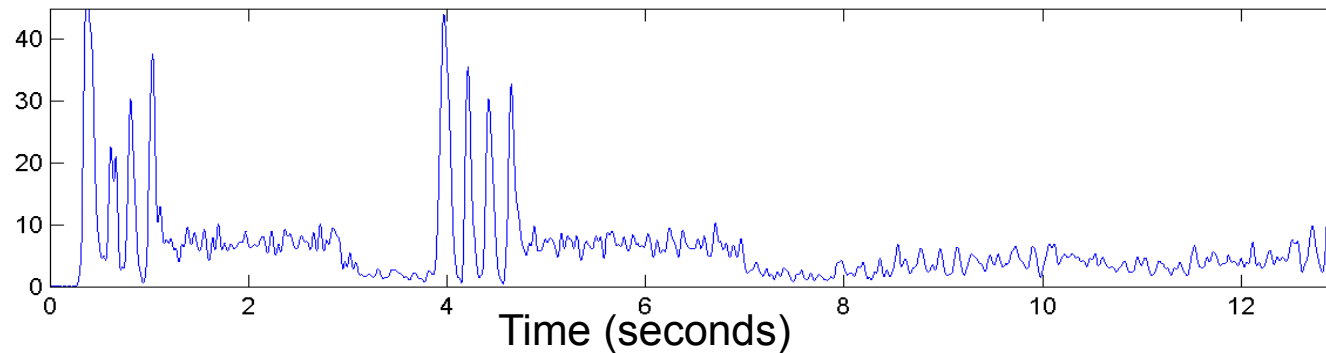
1. Spectrogram
2. Log Compression
3. Differentiation

Tempo Estimation and Beat Tracking

Steps:

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

Novelty Curve

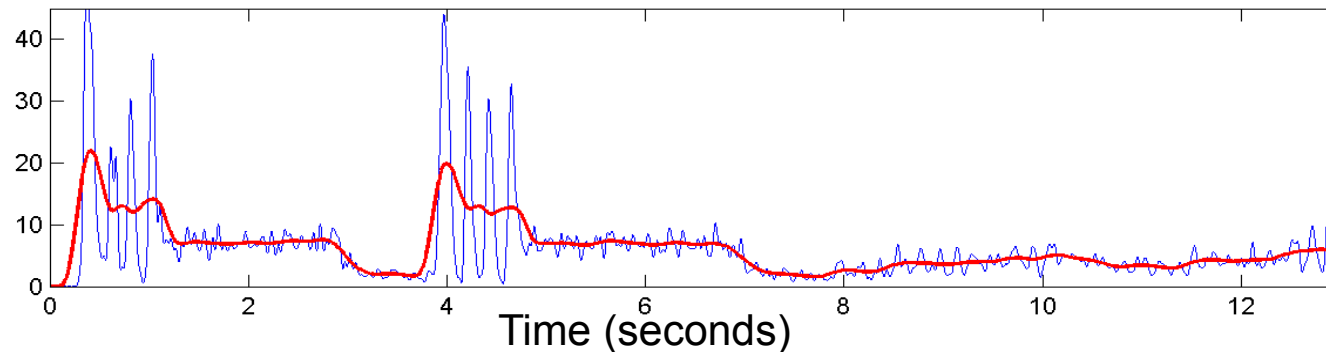


Tempo Estimation and Beat Tracking

Steps:

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

Novelty Curve Local Average

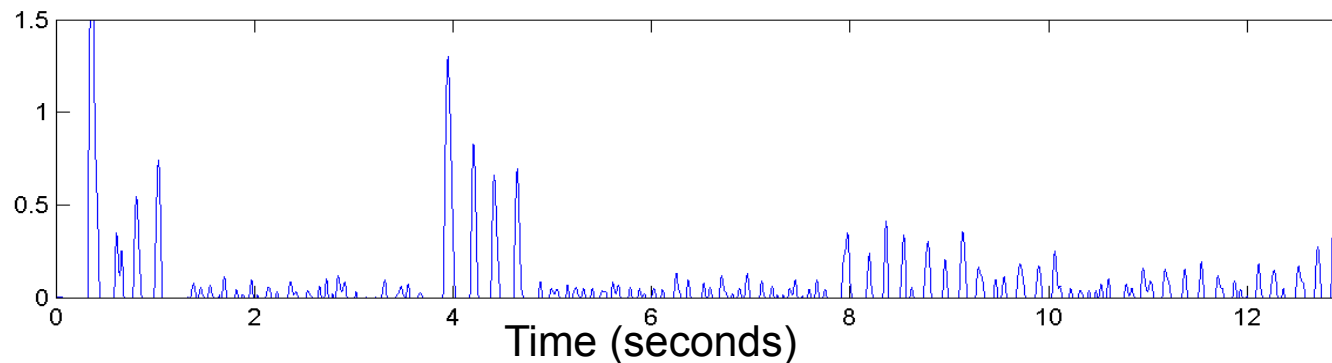


Tempo Estimation and Beat Tracking

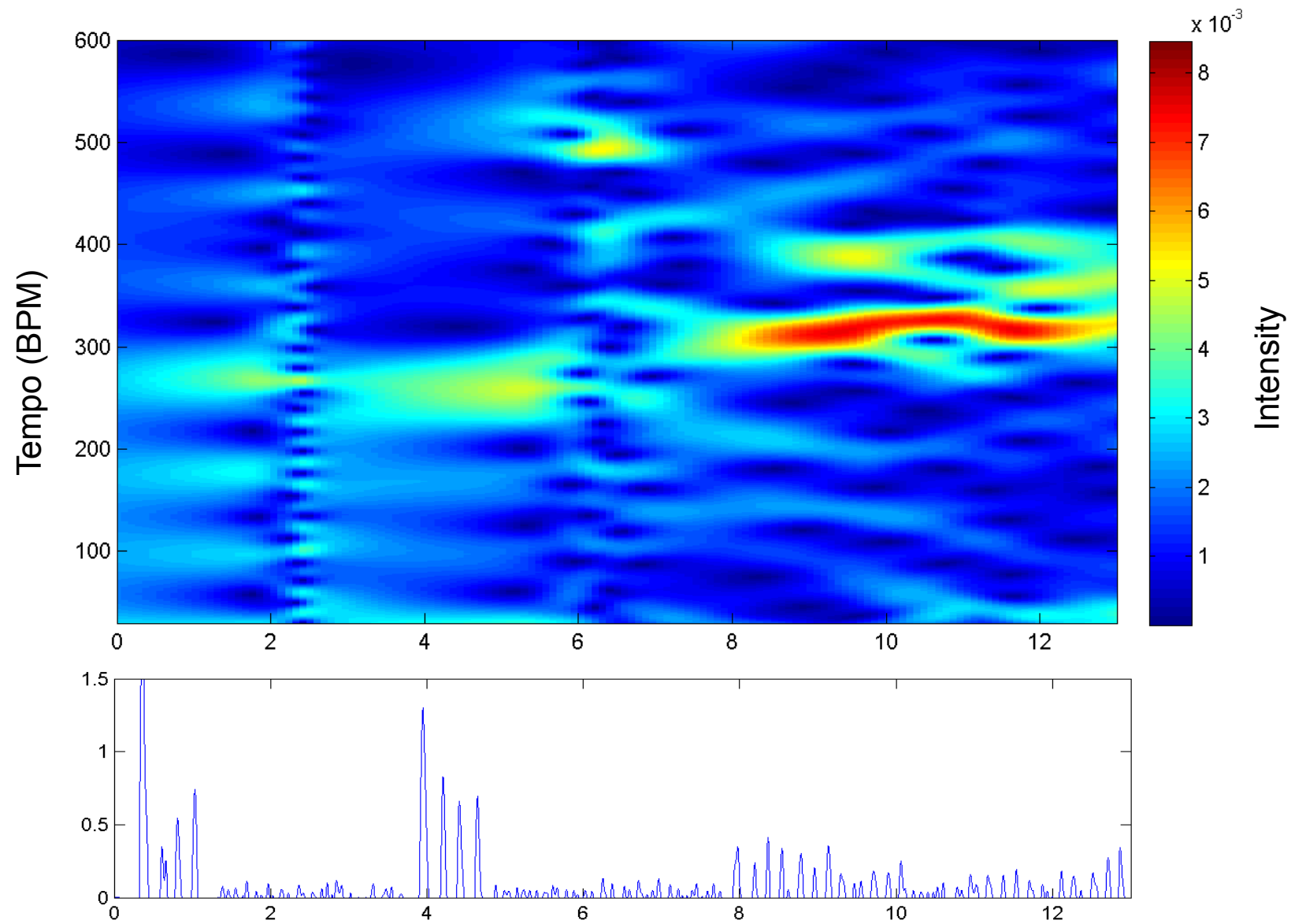
Steps:

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

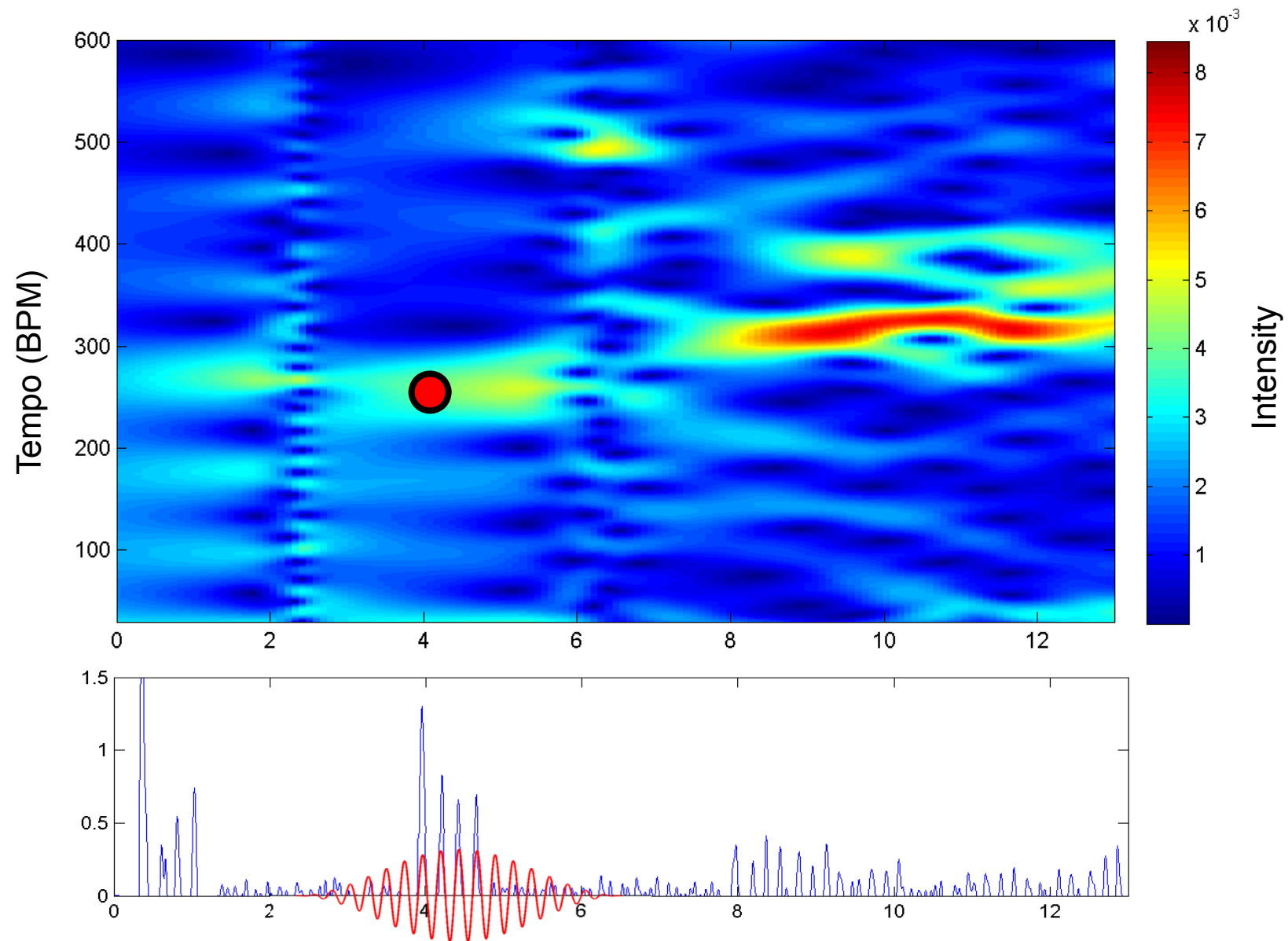
Novelty Curve



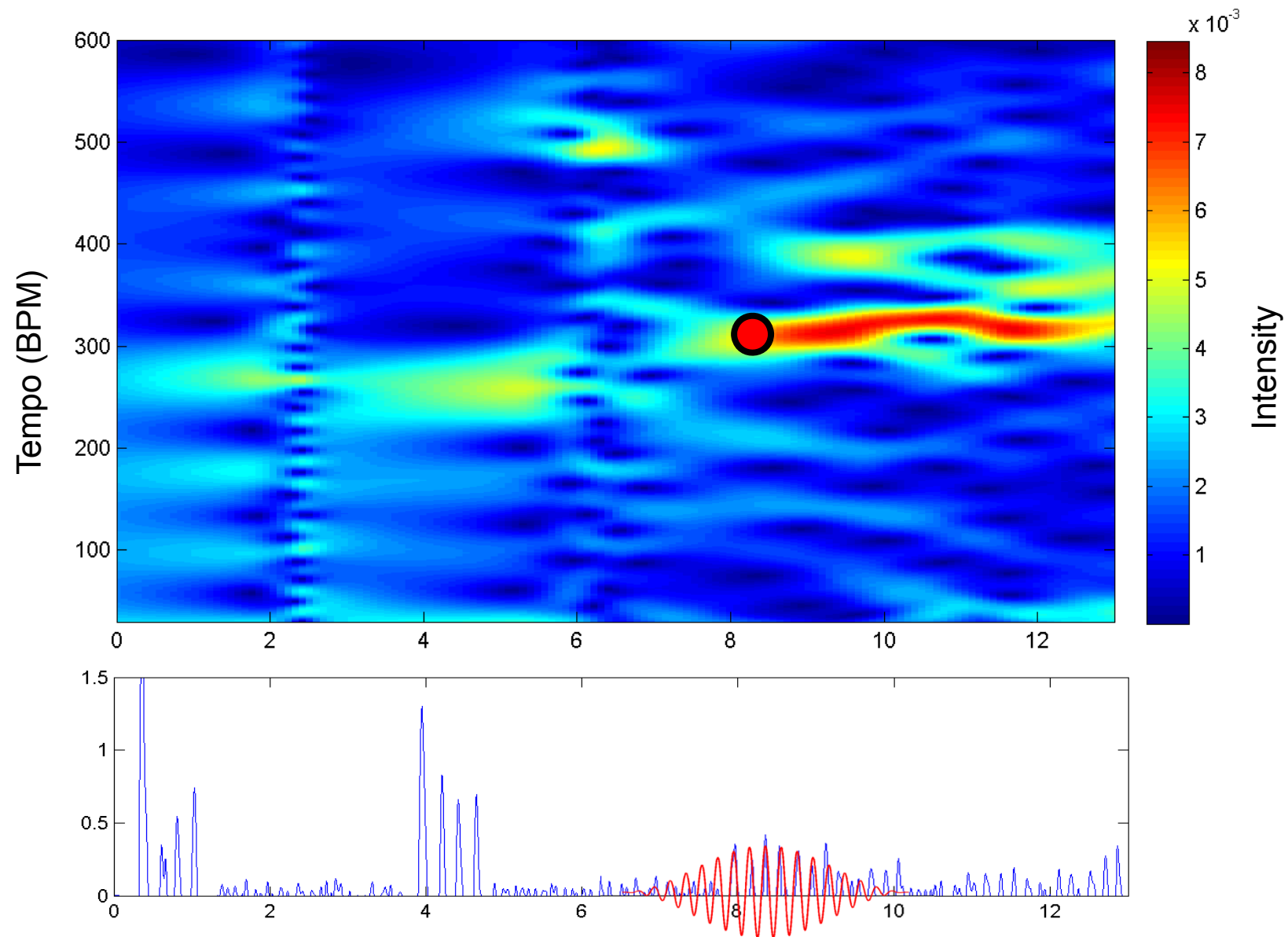
Tempo Estimation and Beat Tracking



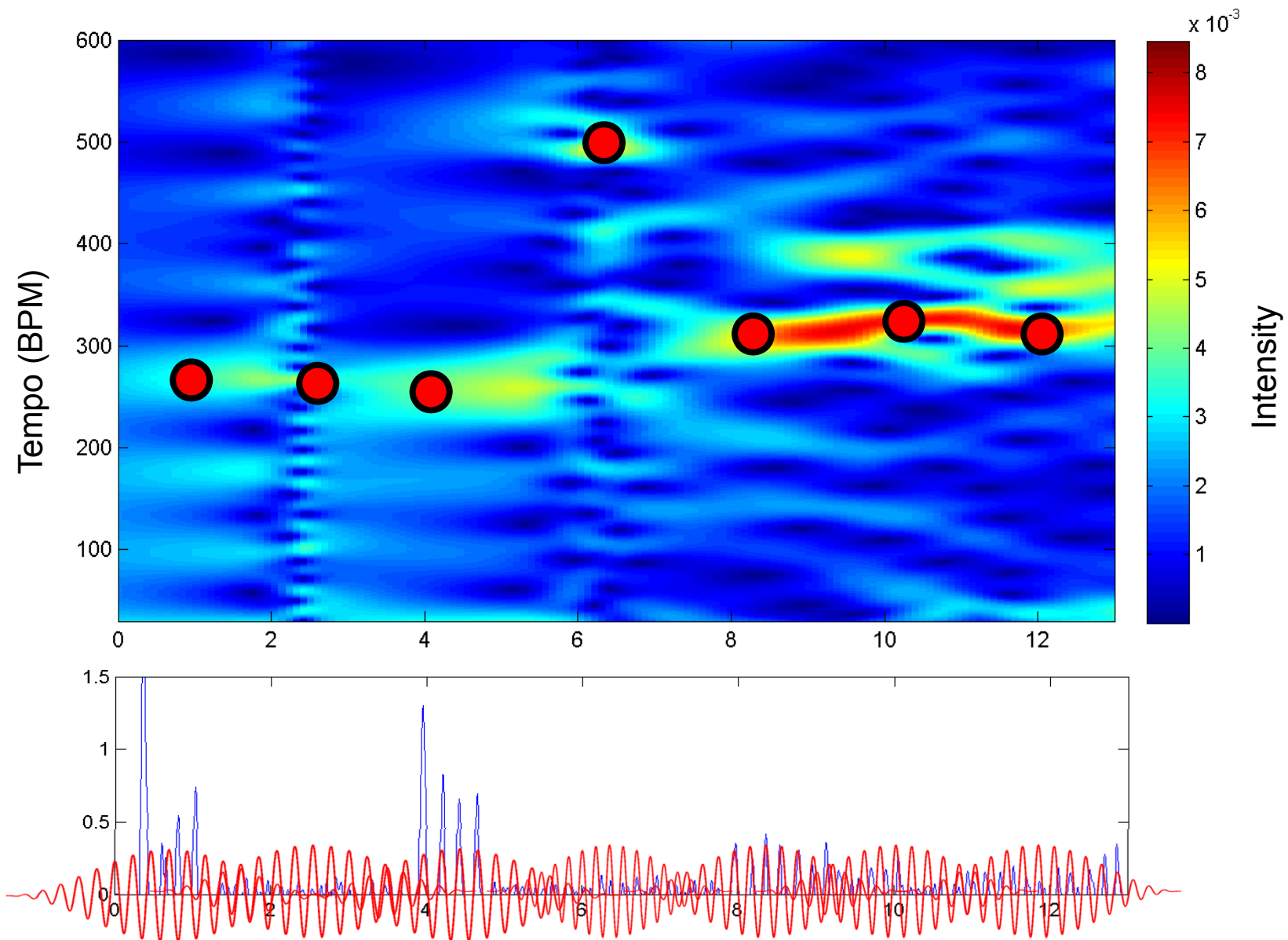
Tempo Estimation and Beat Tracking



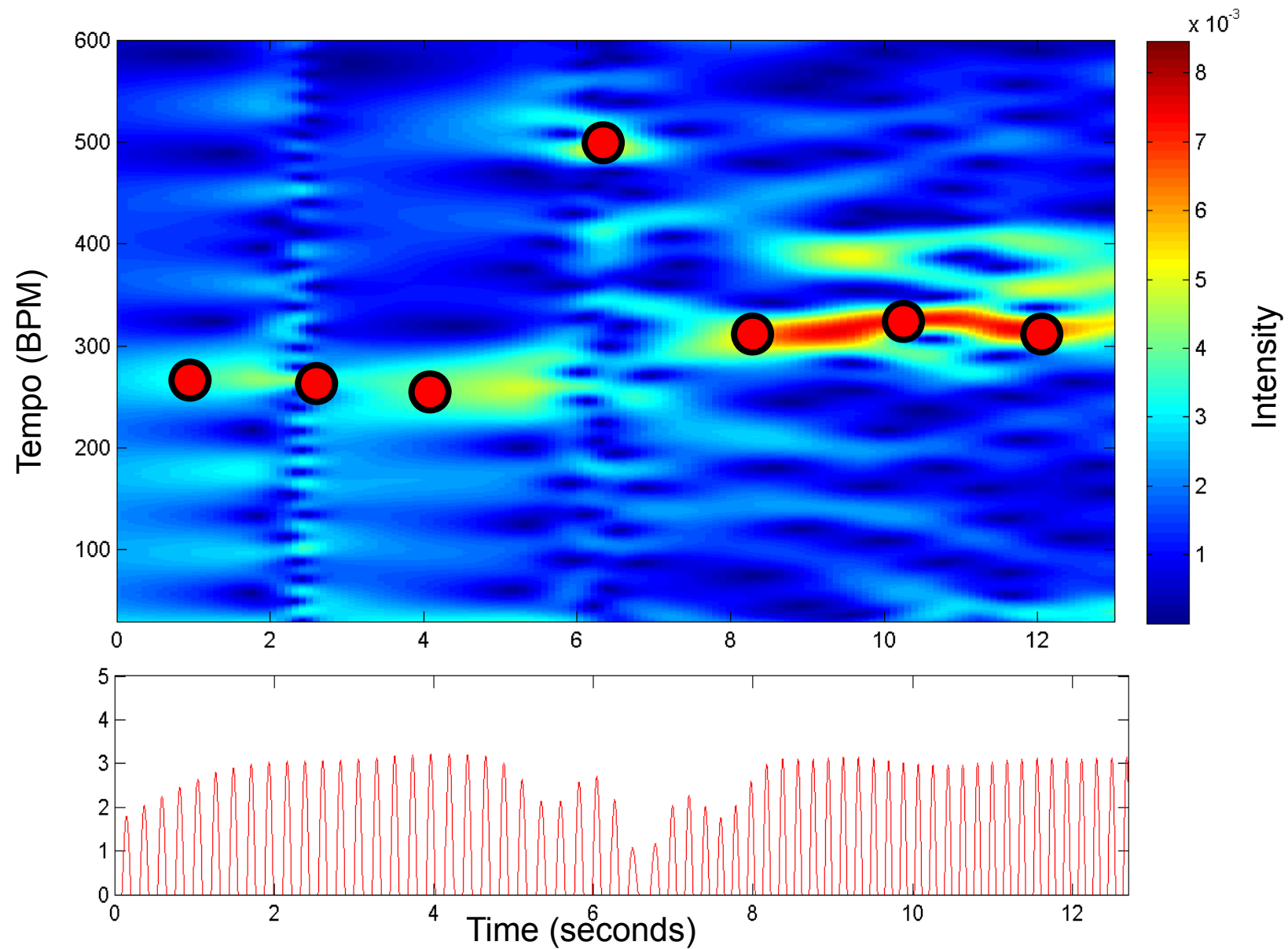
Tempo Estimation and Beat Tracking



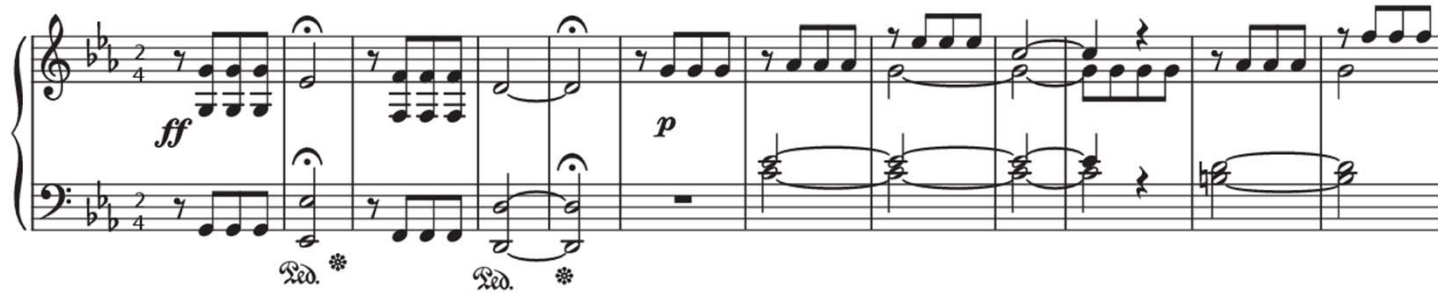
Tempo Estimation and Beat Tracking



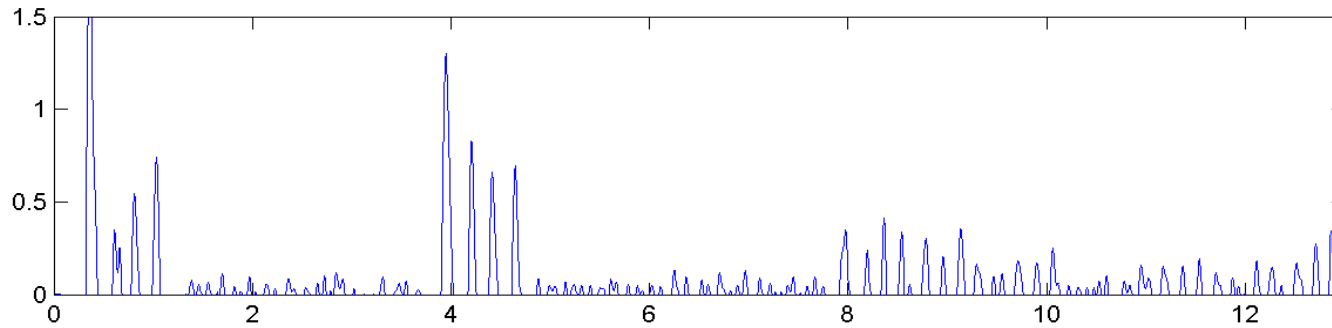
Tempo Estimation and Beat Tracking



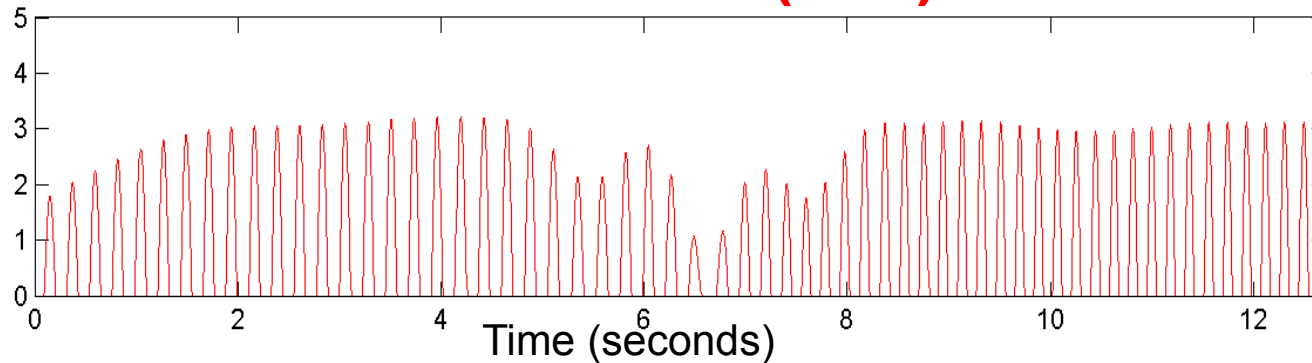
Tempo Estimation and Beat Tracking



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 piano introduction. The dynamic is marked 'ff' (fortissimo). The score includes a 'Ped.' (pedal) marking with an asterisk, indicating a sustained pedal point. The notation is in G major and consists of two staves: a treble clef staff and a bass clef staff. The treble staff begins with a series of chords, while the bass staff begins with a series of eighth notes. The 'Ped.' marking is placed below the bass staff, indicating a sustained pedal point.

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



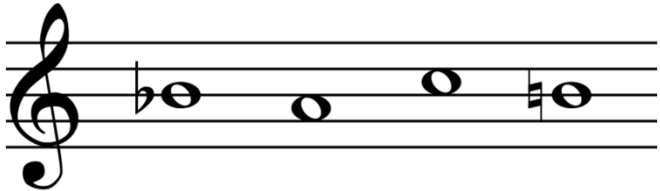
Motivic Similarity

Var. 4: Vivace

The musical score consists of four staves of music in bass clef, 2/4 time, with a key signature of two flats (B-flat and E-flat). The first staff begins with a forte (*f*) dynamic marking. The second and third staves continue the melodic and rhythmic patterns. The fourth staff features alternating piano (*p*) and forte (*f*) dynamics, with a final double bar line. The notation includes various rhythmic values such as eighth and sixteenth notes, as well as rests and slurs.



Motivic Similarity



A musical staff in treble clef showing a four-note motif: B (B-flat), A, C, and H (B-natural). The notes are spaced across the staff: B is on the second line, A is on the first space, C is on the second space, and H is on the second line.

B A C H



A musical score for Soprano (S), Alto (A), Tenor (T), and Bass (B) in 4/4 time. 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-flat, A, C, and B-natural.

S auf - - ge - rafft, und nie - mand ach - - tet

A **b a c h** und nie - mand ach - - tet drauf

T und nie - mand ach - - tet

B auf - - - ge - rafft,



Book Project

A First Course on Music Processing

Textbook (approx. 500 pages)

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. Music Transcription



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