Lecture

Music Processing

Music Structure Analysis

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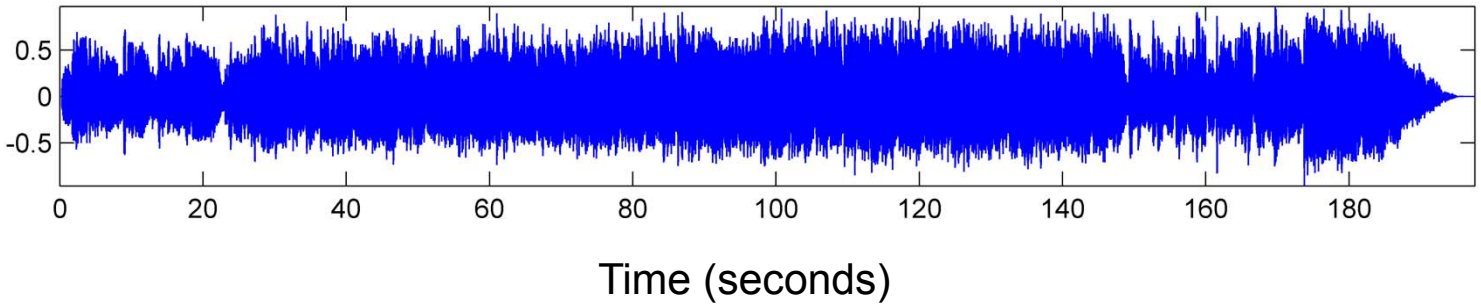
Fraunhofer IIS

Music Structure Analysis

Example: Zager & Evans “In The Year 2525”



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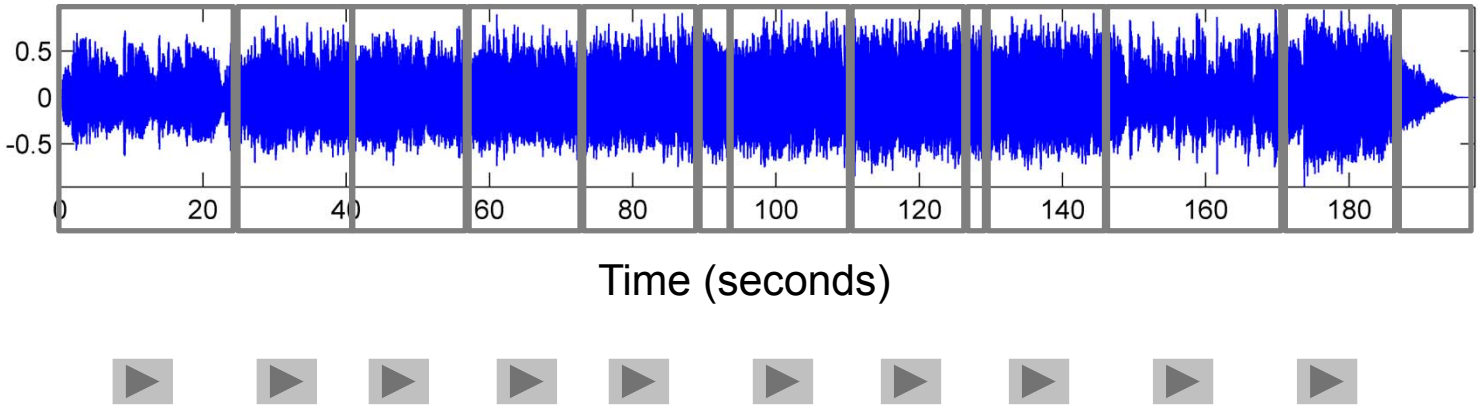

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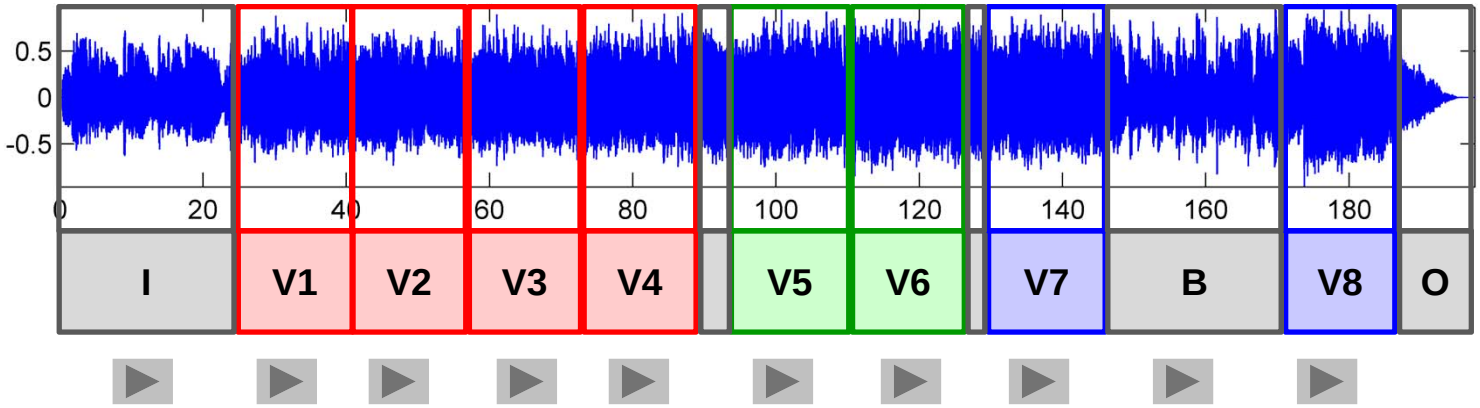
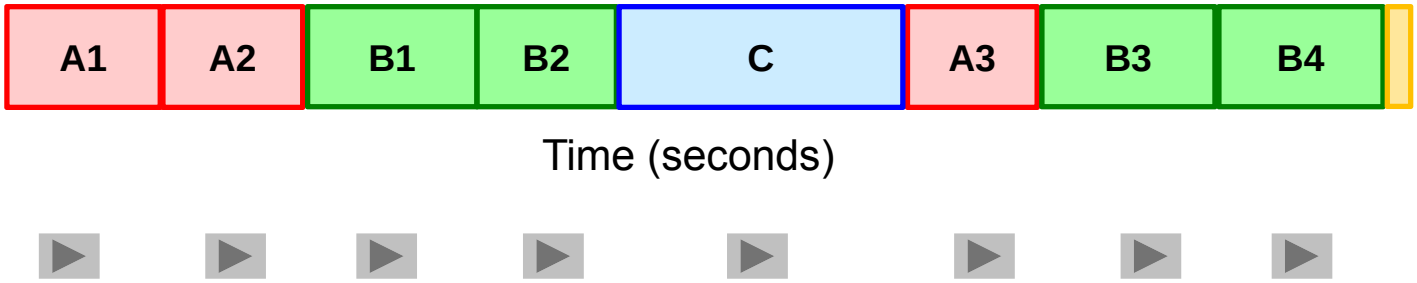


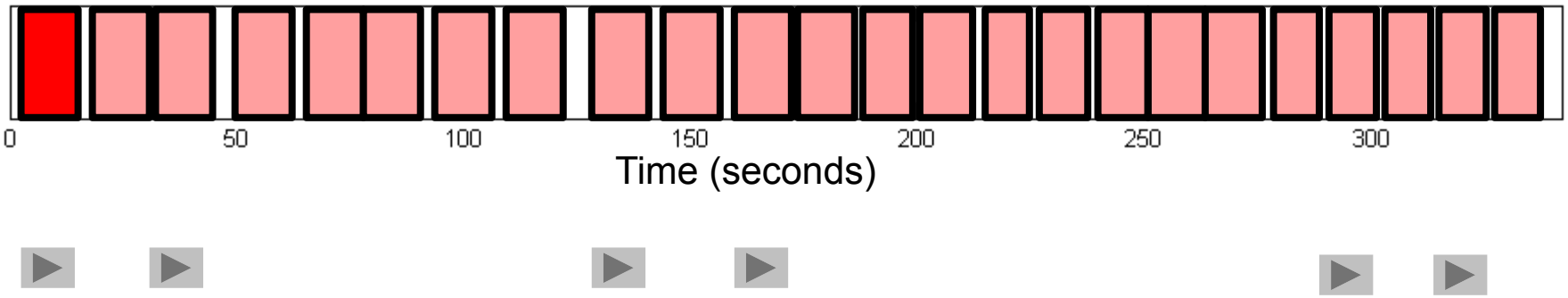
Music Structure Analysis

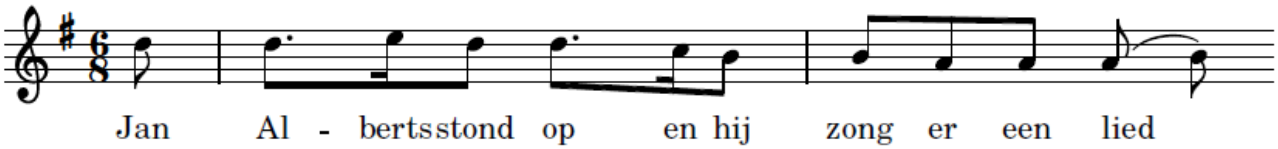
Example: Brahms Hungarian Dance No. 5 (Ormandy)



Music Structure Analysis

Example: Folk Song Field Recording
(Nederlandse Liederenbank)

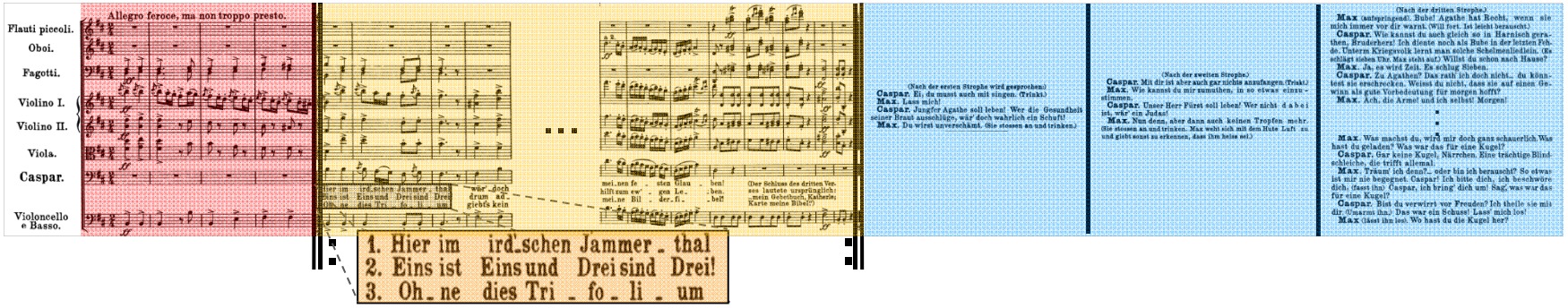




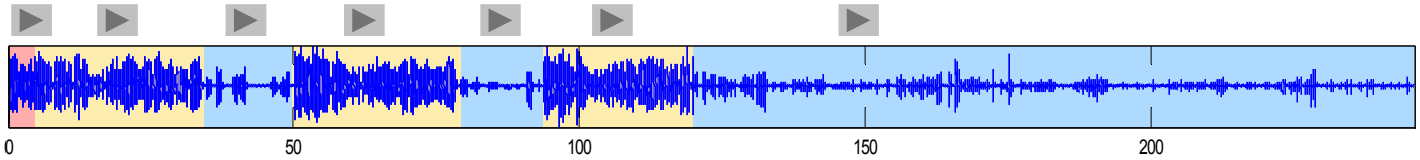
Music Structure Analysis

Example: Weber, Song (No. 4) from “Der Freischütz”

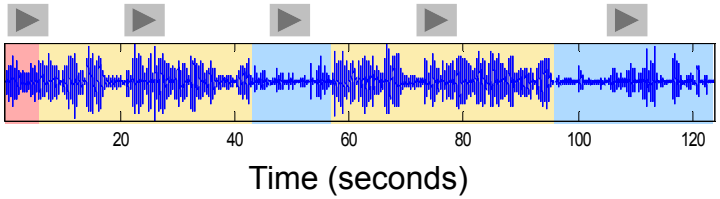
Introduction Stanzas Dialogues



Kleiber



Ackermann



Music Structure Analysis

General goal: Divide an audio recording into temporal segments corresponding to musical parts and group these segments into musically meaningful categories.

Examples:

- Stanzas of a folk song
- Intro, verse, chorus, bridge, outro sections of a pop song
- Exposition, development, recapitulation, coda of a sonata
- Musical form ABACADA … of a rondo

Music Structure Analysis

General goal: Divide an audio recording into temporal segments corresponding to musical parts and group these segments into musically meaningful categories.

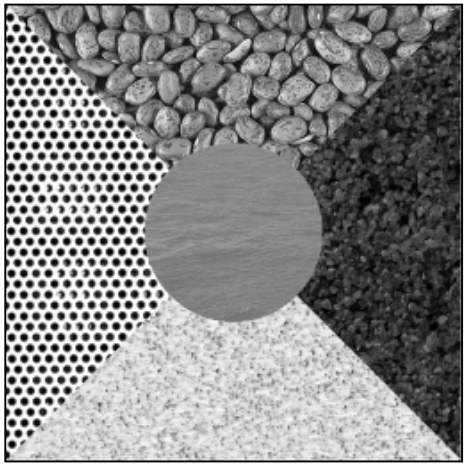
Challenge: There are many different principles for creating relationships that form the basis for the musical structure.

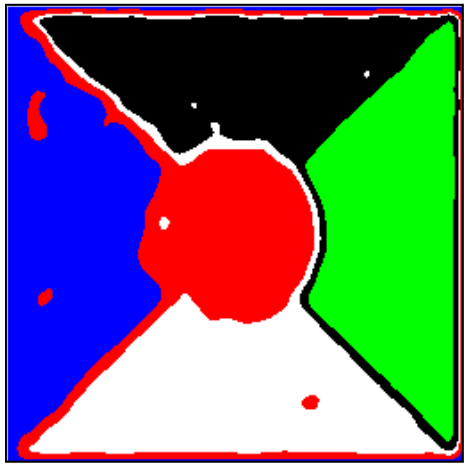
- Homogeneity: Consistency in tempo, instrumentation, key, …
- Novelty: Sudden changes, surprising elements …
- Repetition: Repeating themes, motives, rhythmic patterns,…

Music Structure Analysis

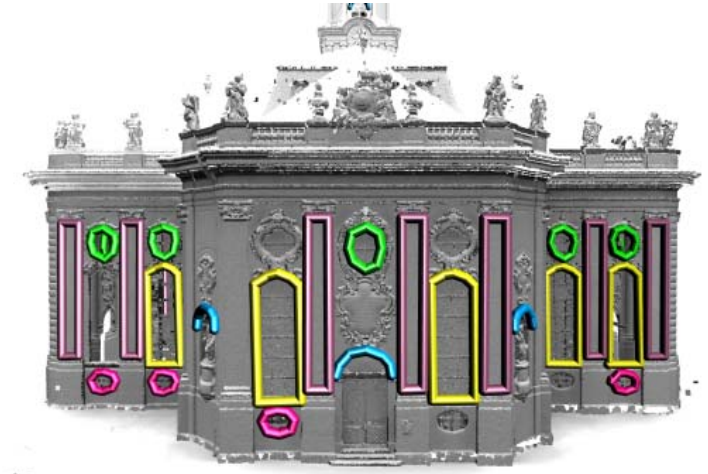
Novelty

Homogeneity





Repetition



Overview

- Introduction
- Feature Representations
- Self-Similarity Matrices
- Audio Thumbnailing
- Novelty-based Segmentation
- Converting Path to Block Structures

Thanks:

- Clausen, Ewert, Kurth, Grohganz, …
- Dannenberg, Goto
- Grosche, Jiang
- Paulus, Klapuri
- Peeters, Kaiser, …
- Serra, Gómez, …
- Smith, Fujinaga, …
- Wiering, …
- Wand, Sunkel, Jansen
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Feature Representation

General goal: Convert an audio recording into a mid-level representation that captures certain musical properties while supressing other properties.

- Timbre / Instrumentation
- Tempo / Rhythm
- Pitch / Harmony

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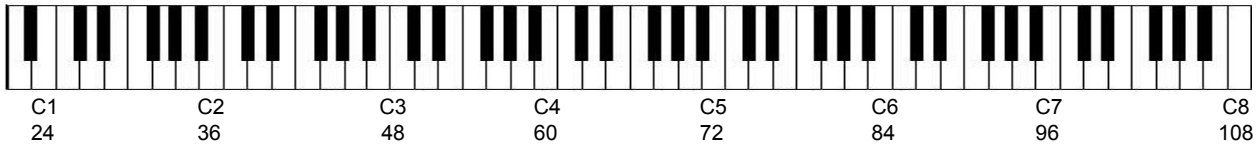
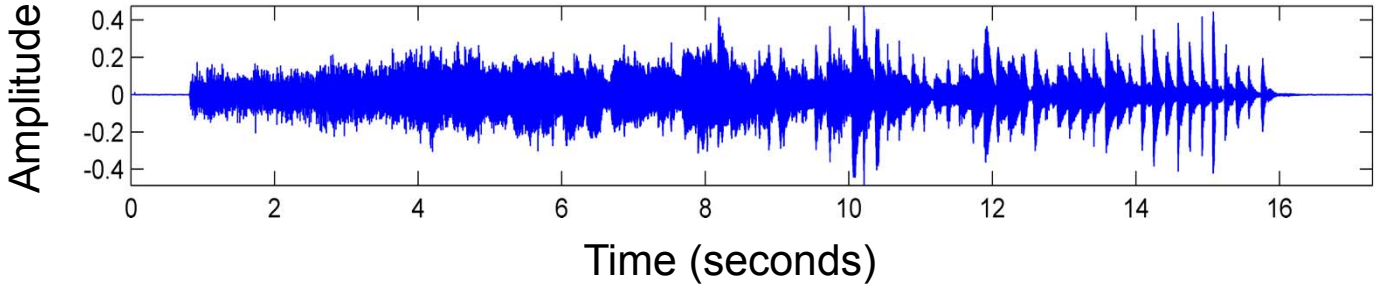
Feature Representation

Example: Chromatic scale



Waveform



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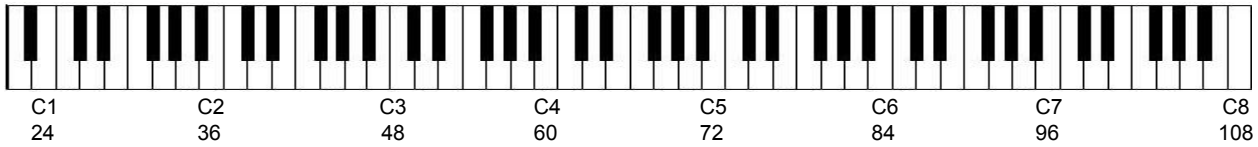
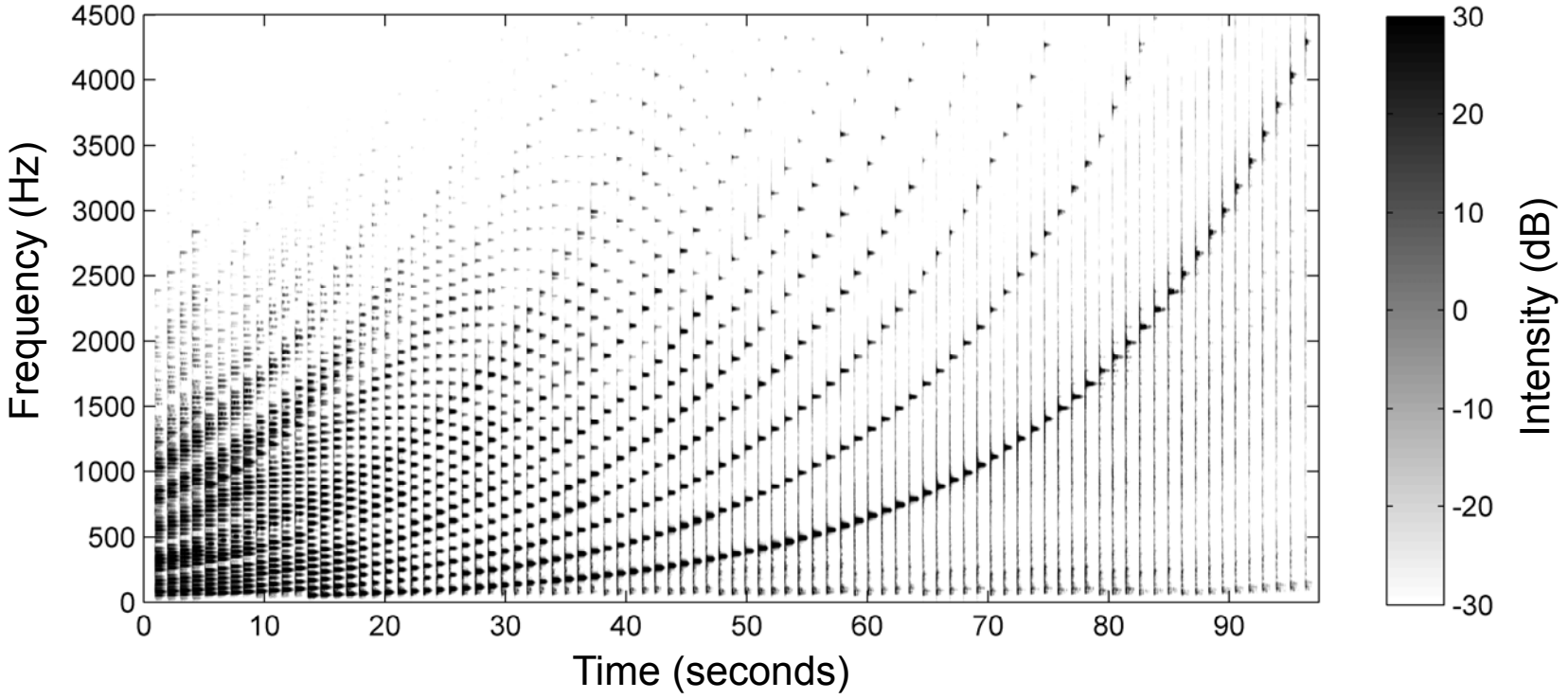


Spectrogram



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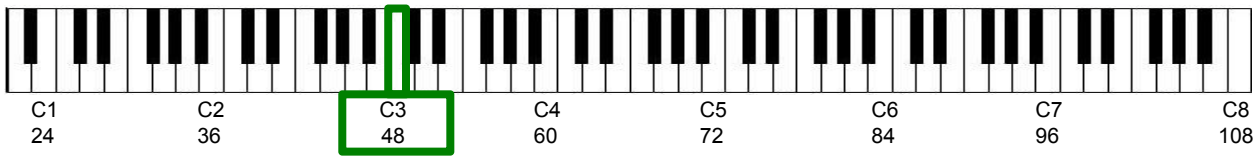

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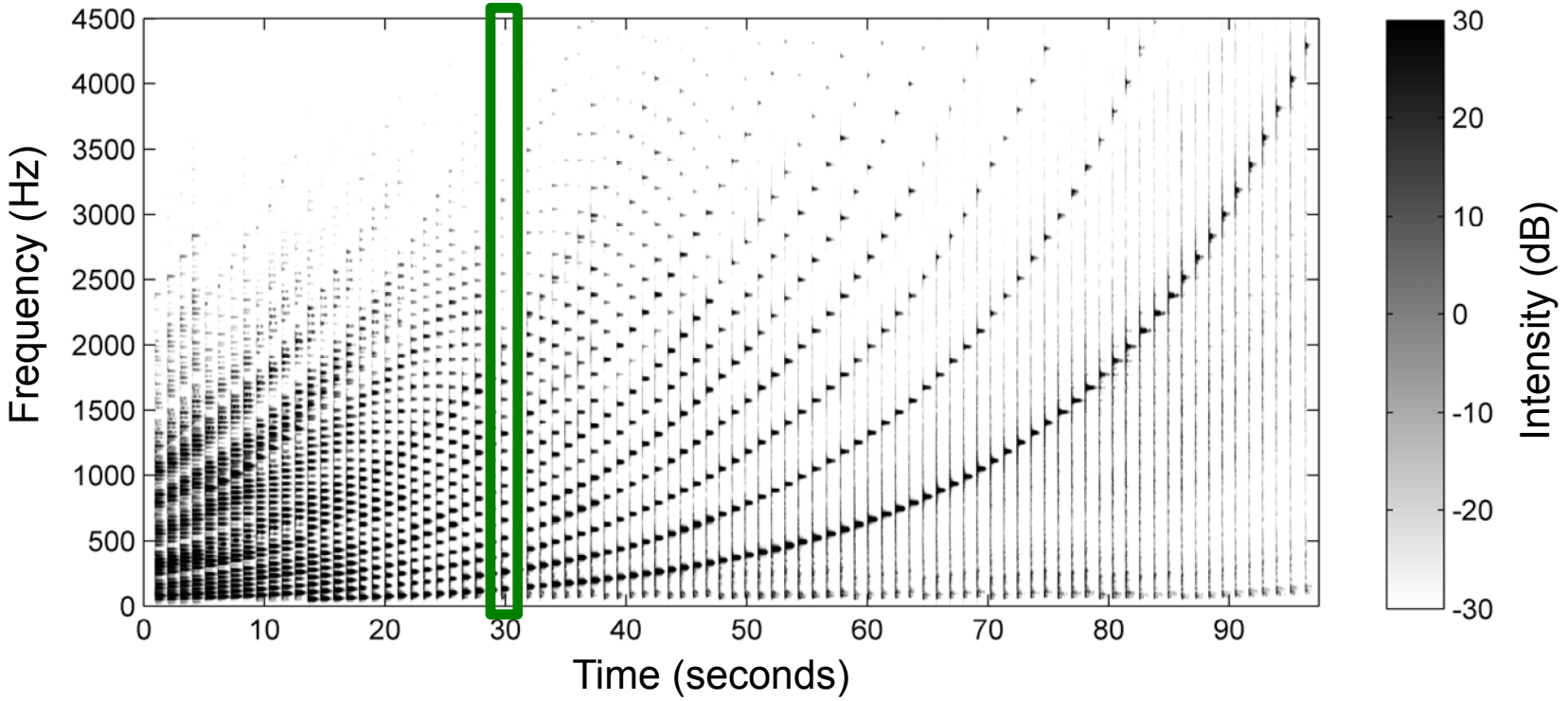

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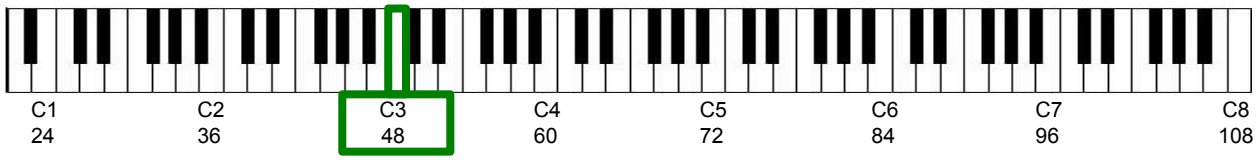

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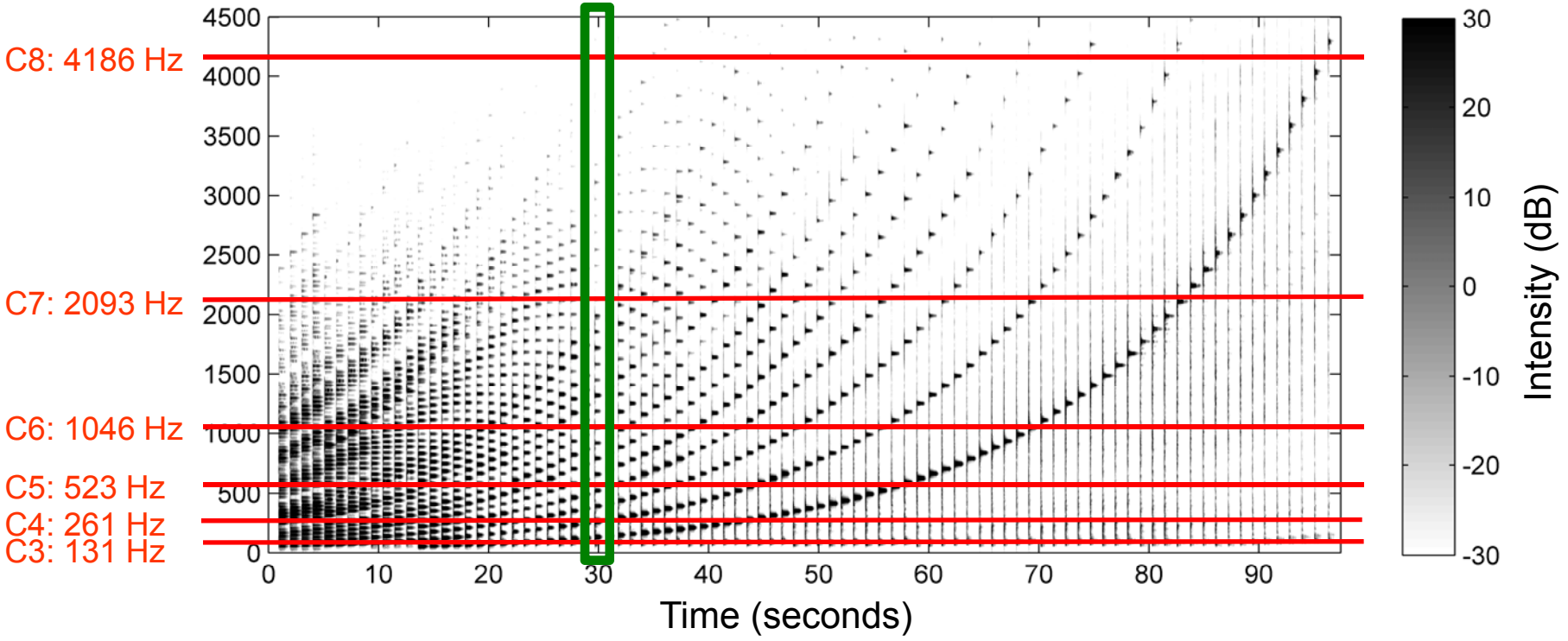

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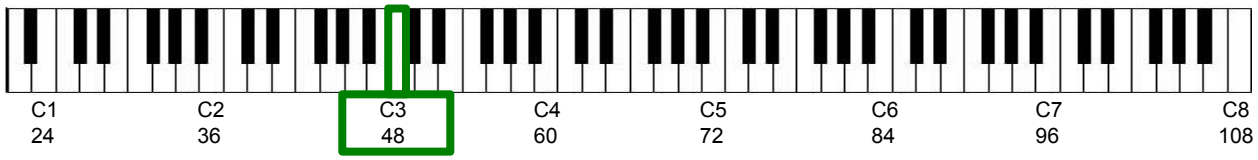
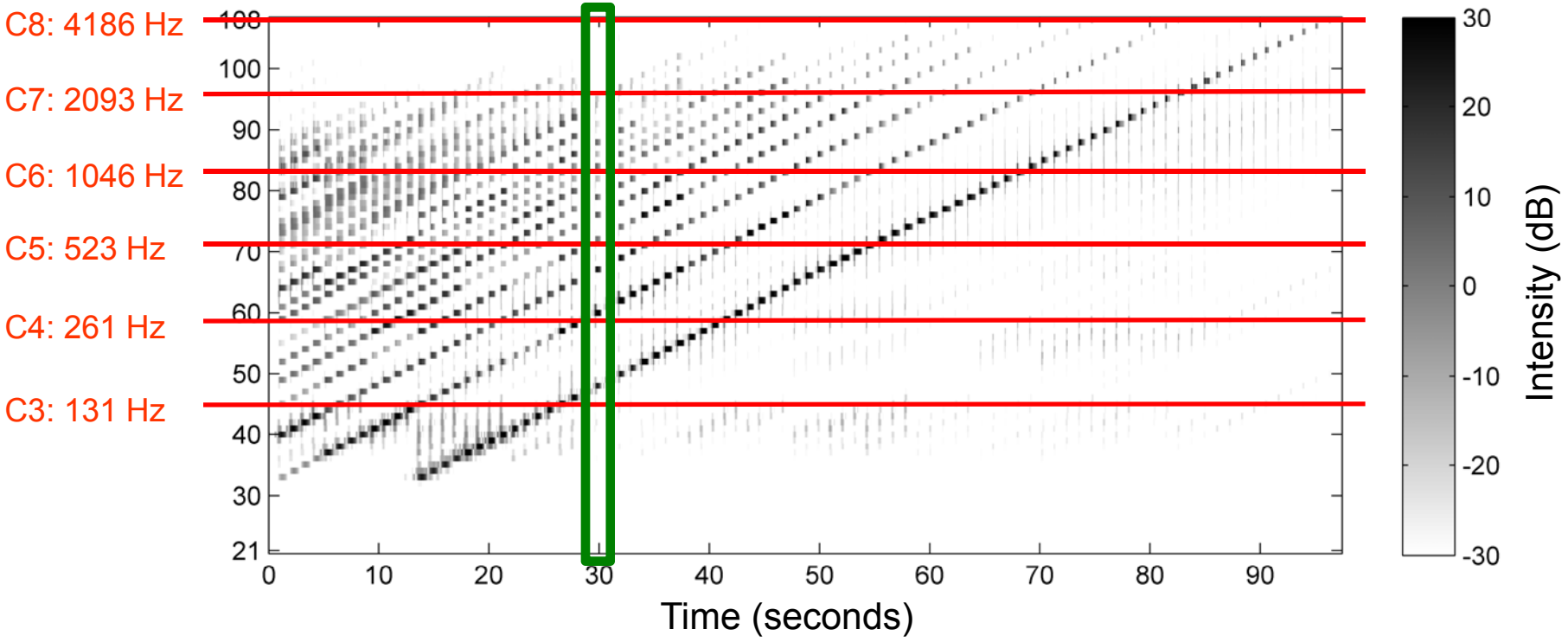


Log-frequency spectrogram



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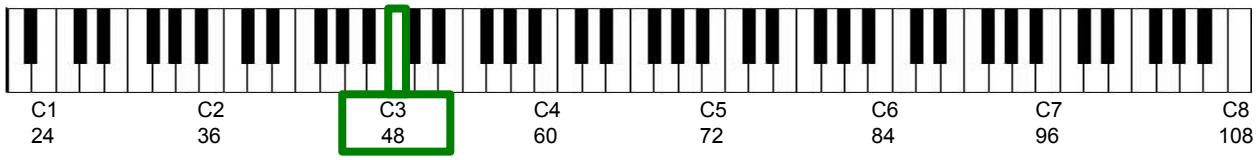

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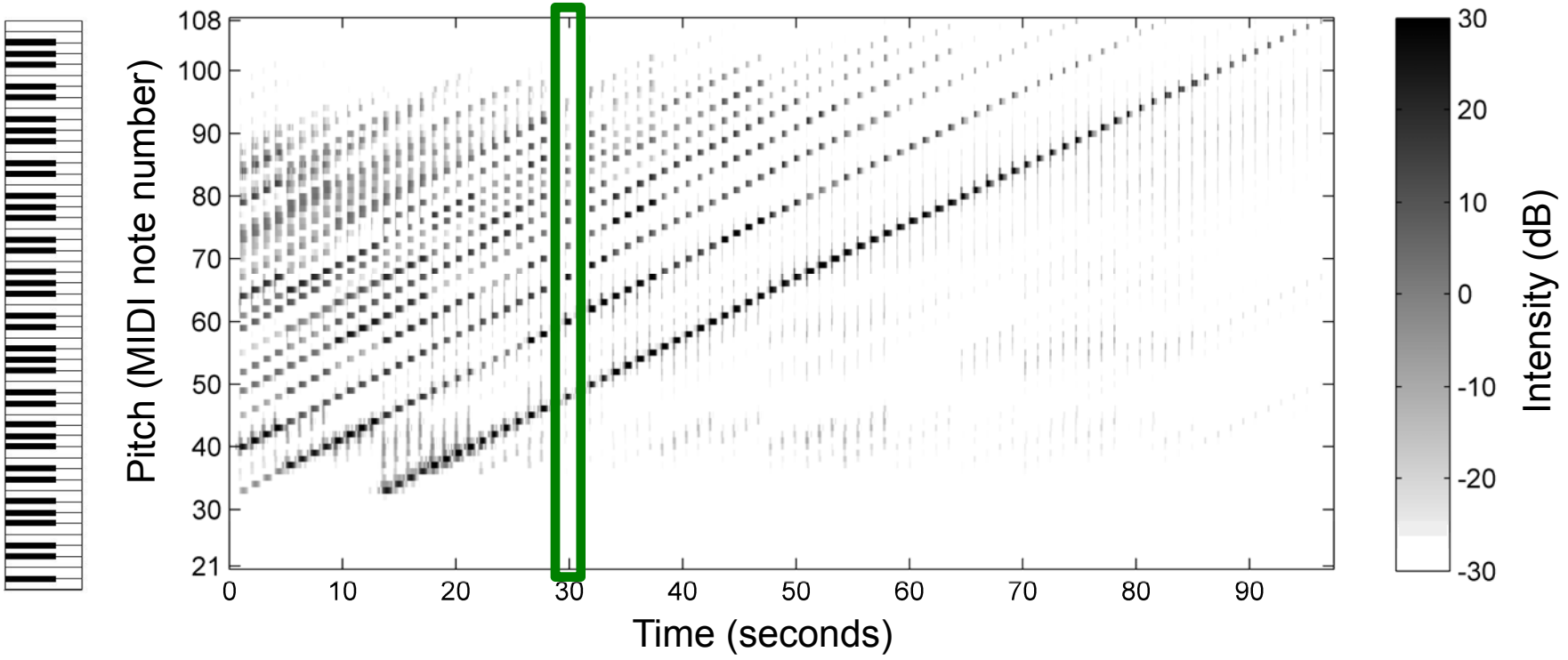

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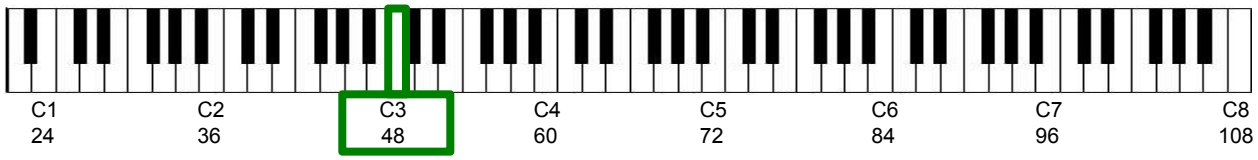

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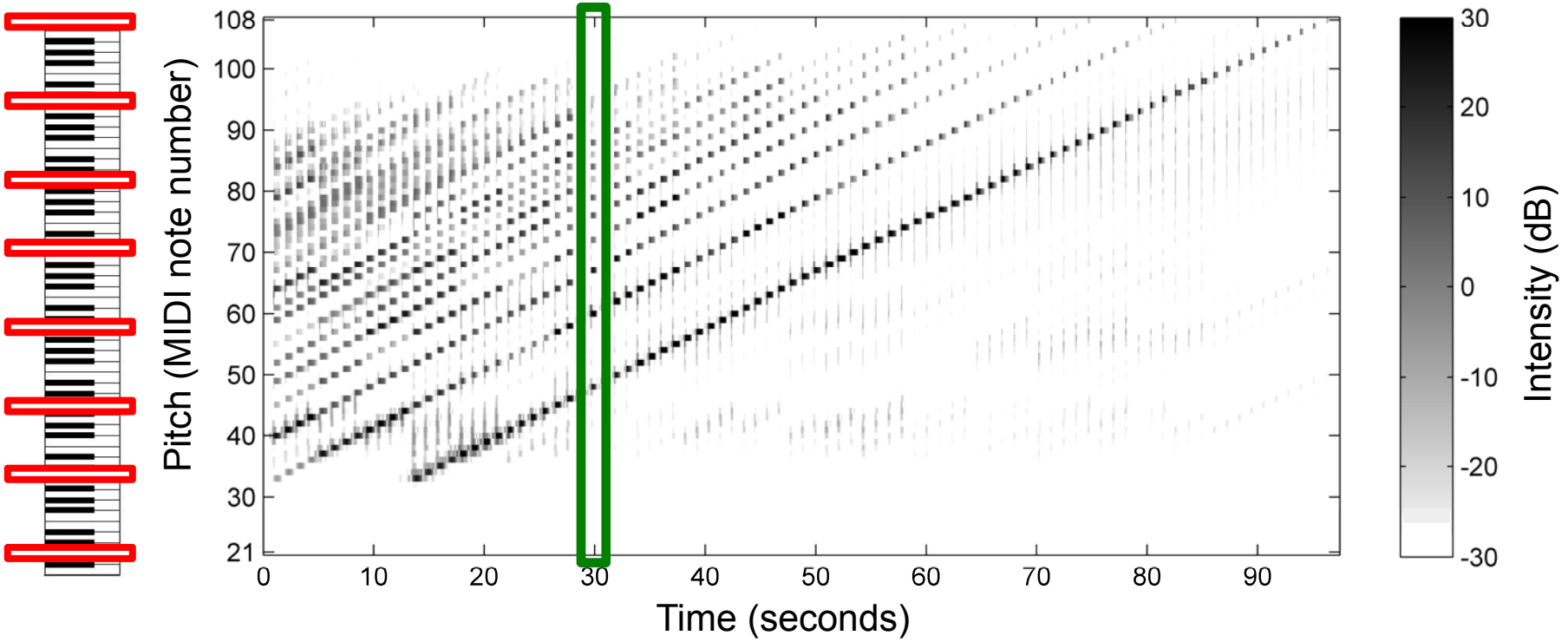
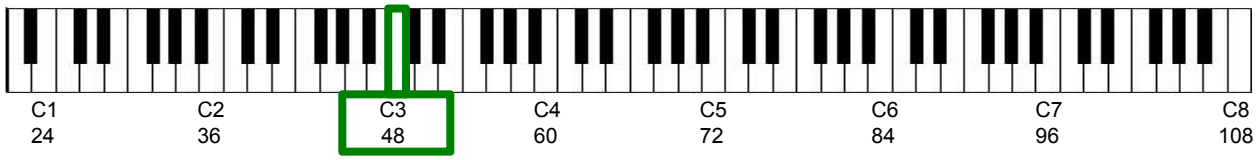


Chroma C

Feature Representation

Example: Chromatic scale



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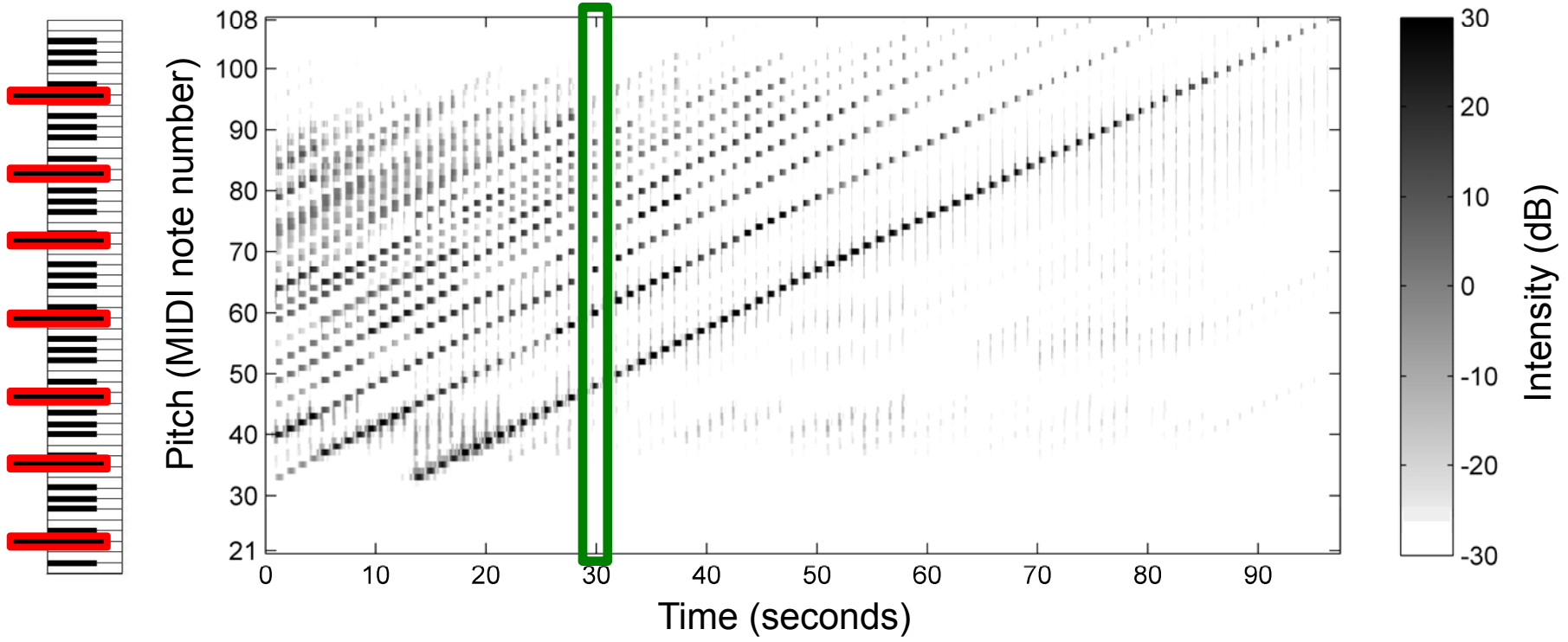

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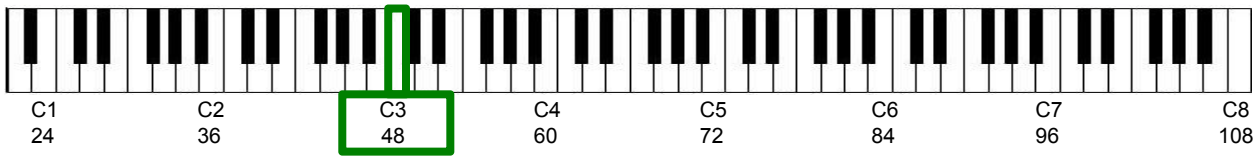
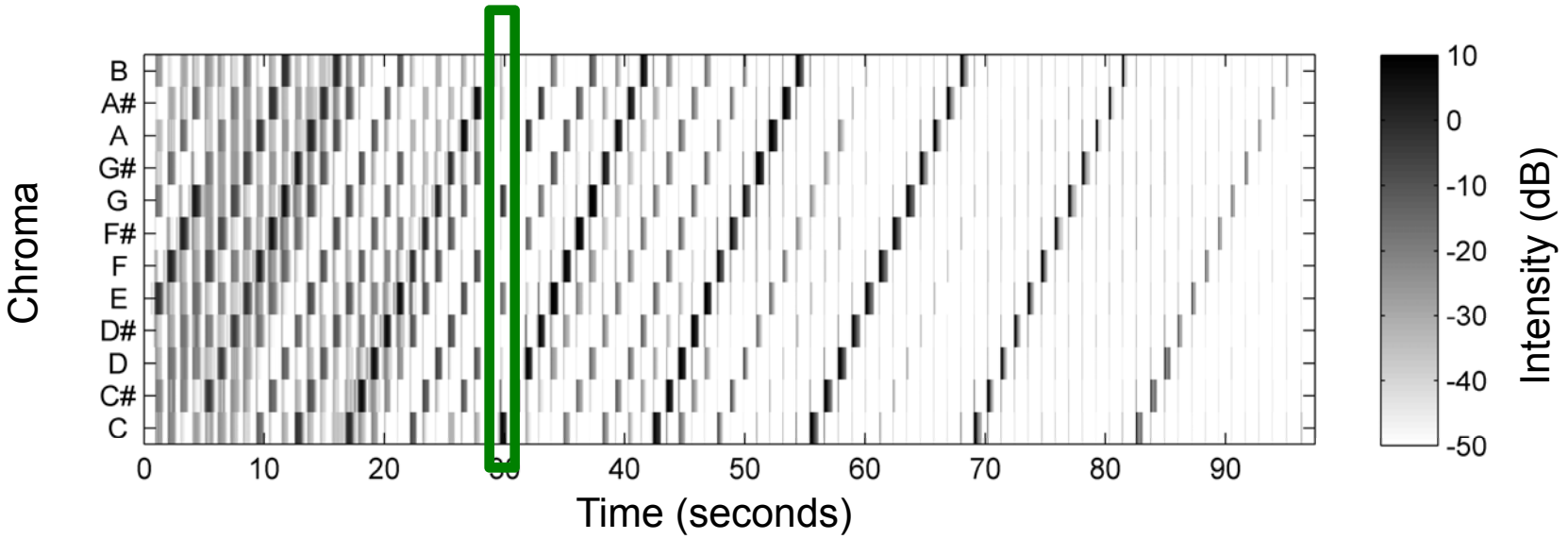


Chroma representation



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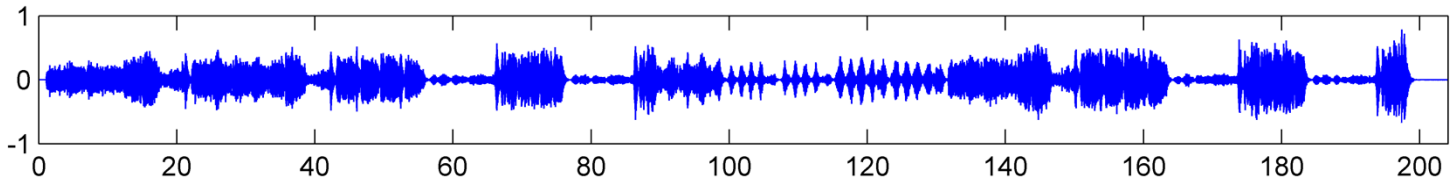

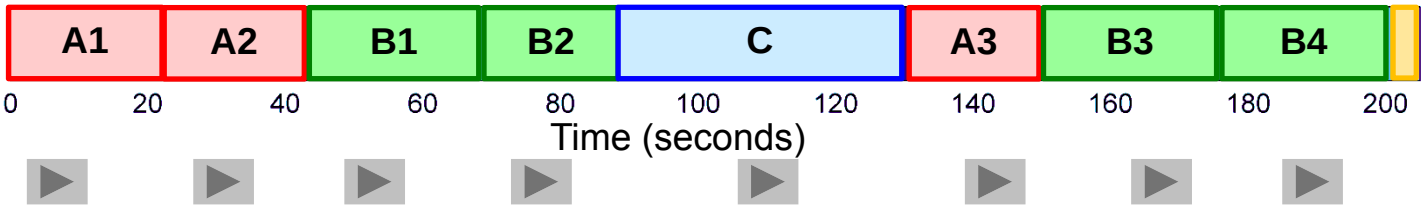

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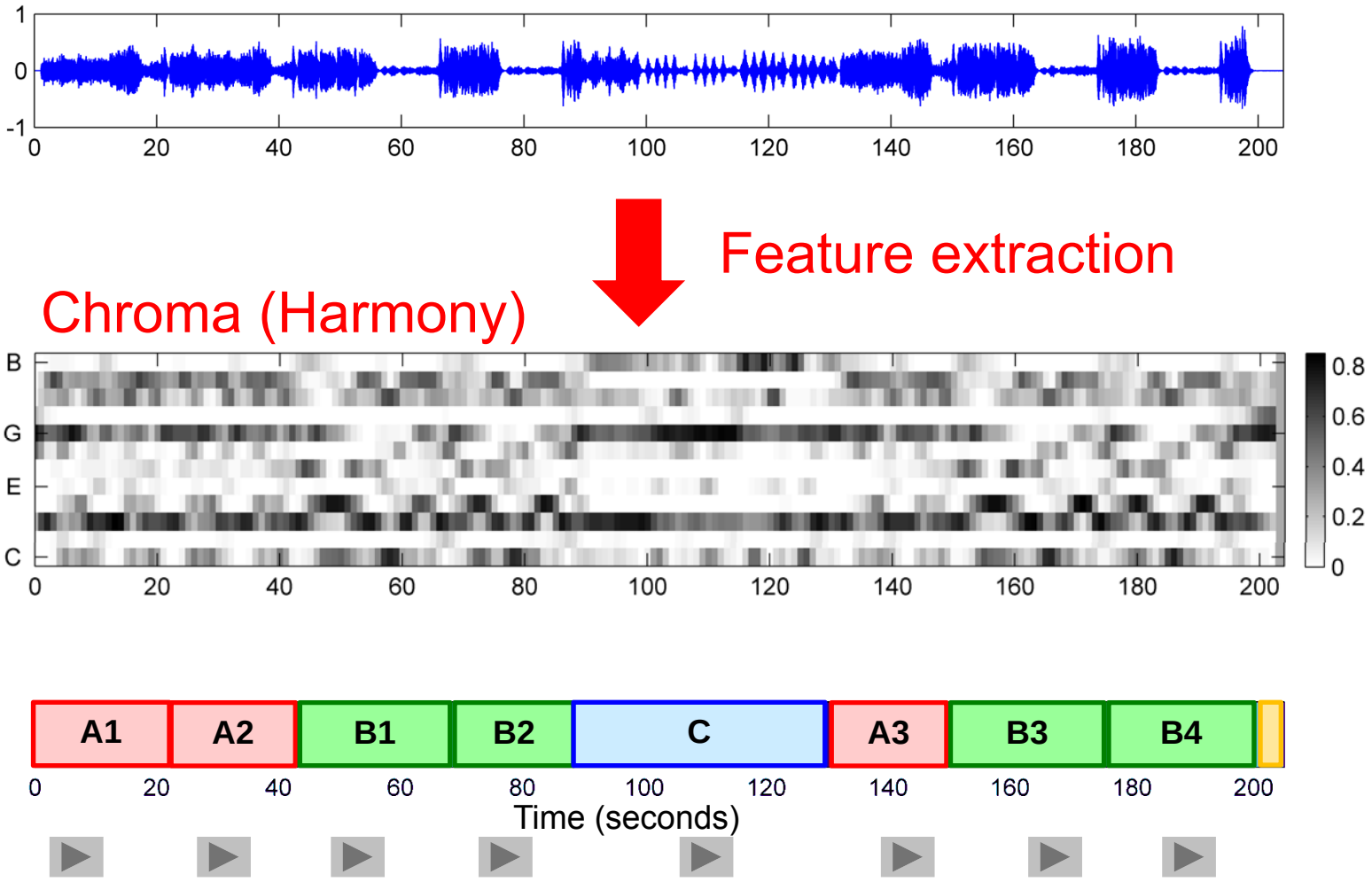

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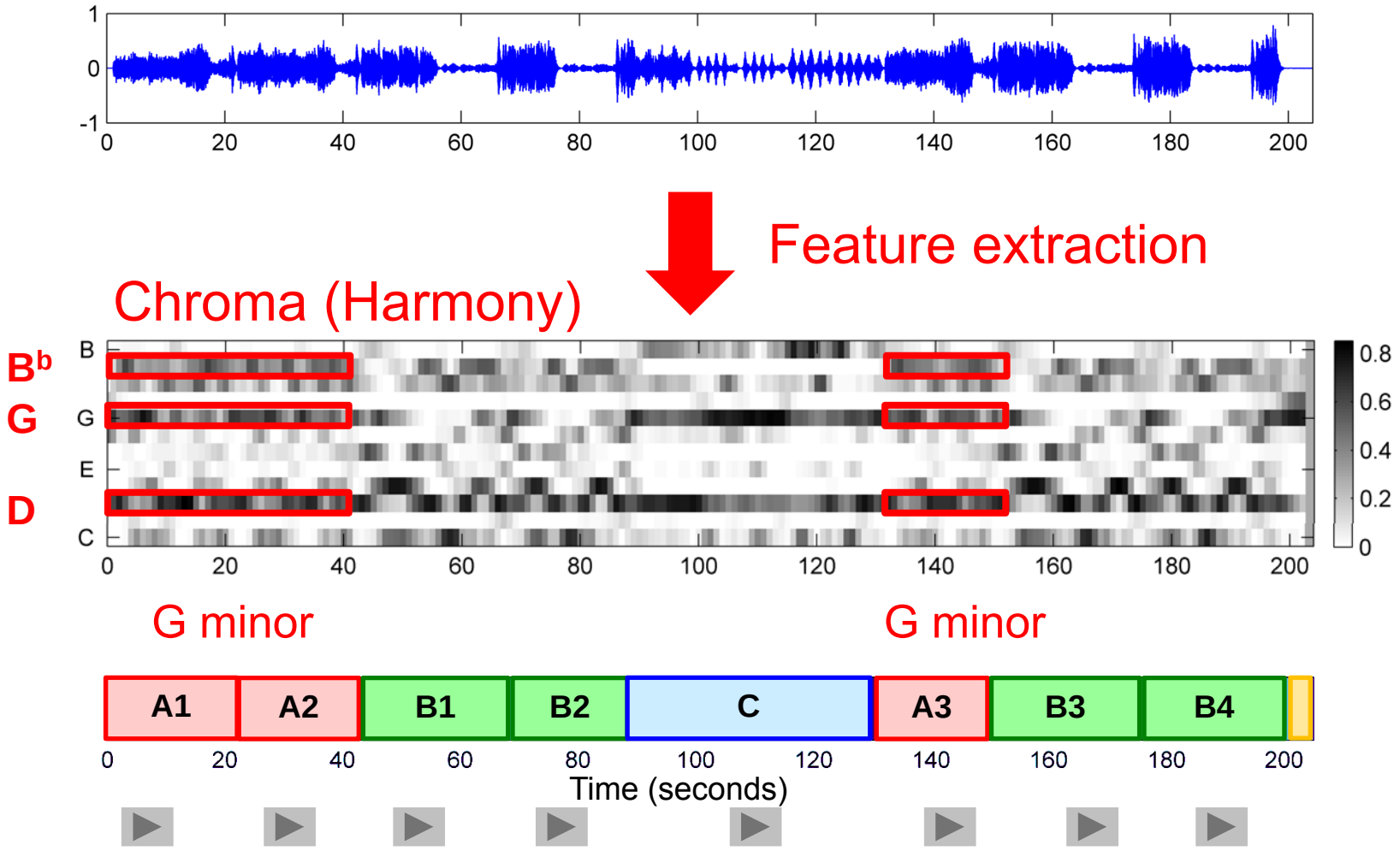

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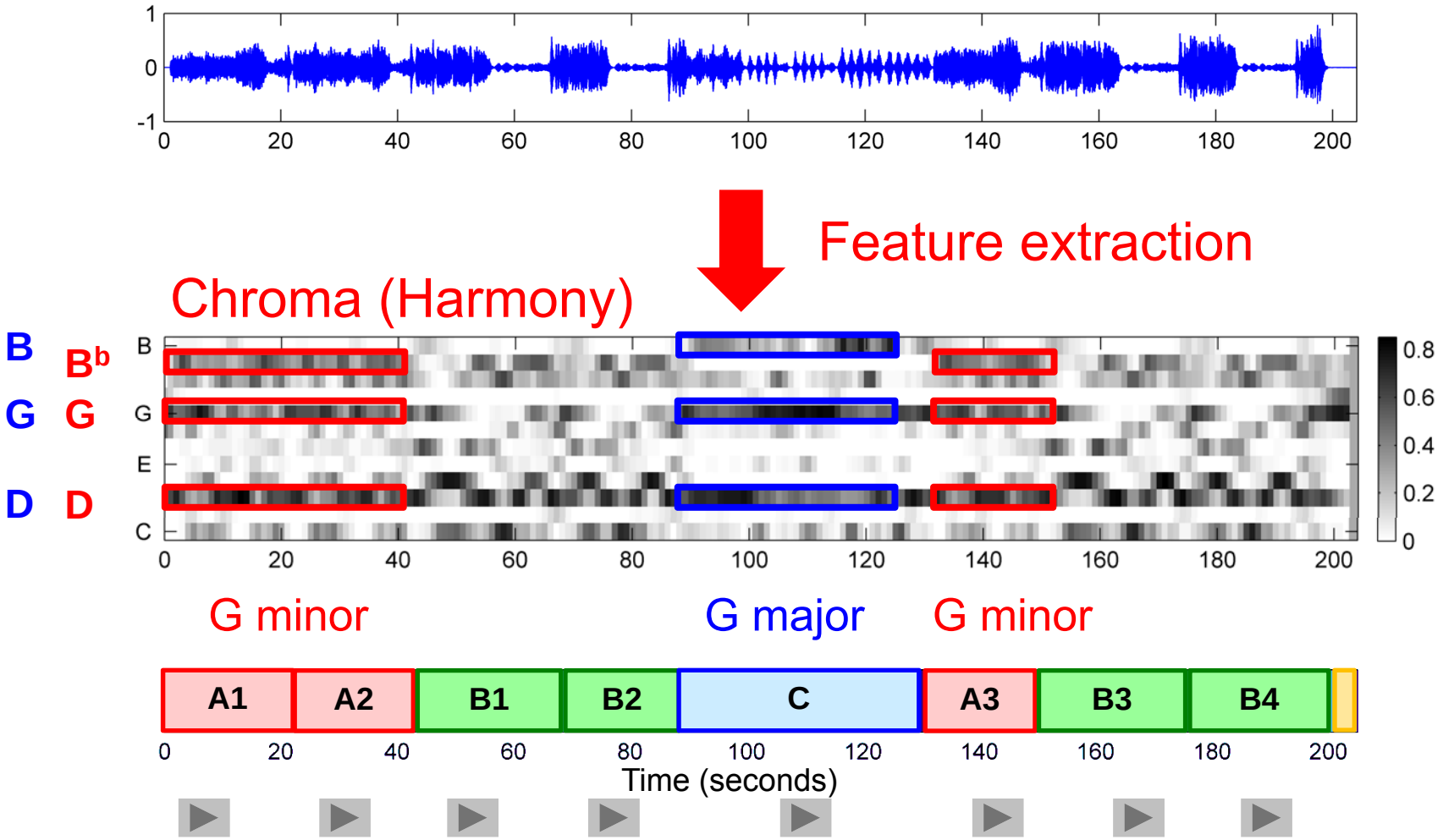

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Self-Similarity Matrix (SSM)

General idea: Compare each element of the feature sequence with each other element of the feature sequence based on a suitable similarity measure.

→ Quadratic self-similarity matrix

Self-Similarity Matrix (SSM)

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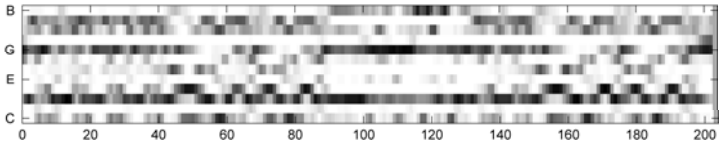

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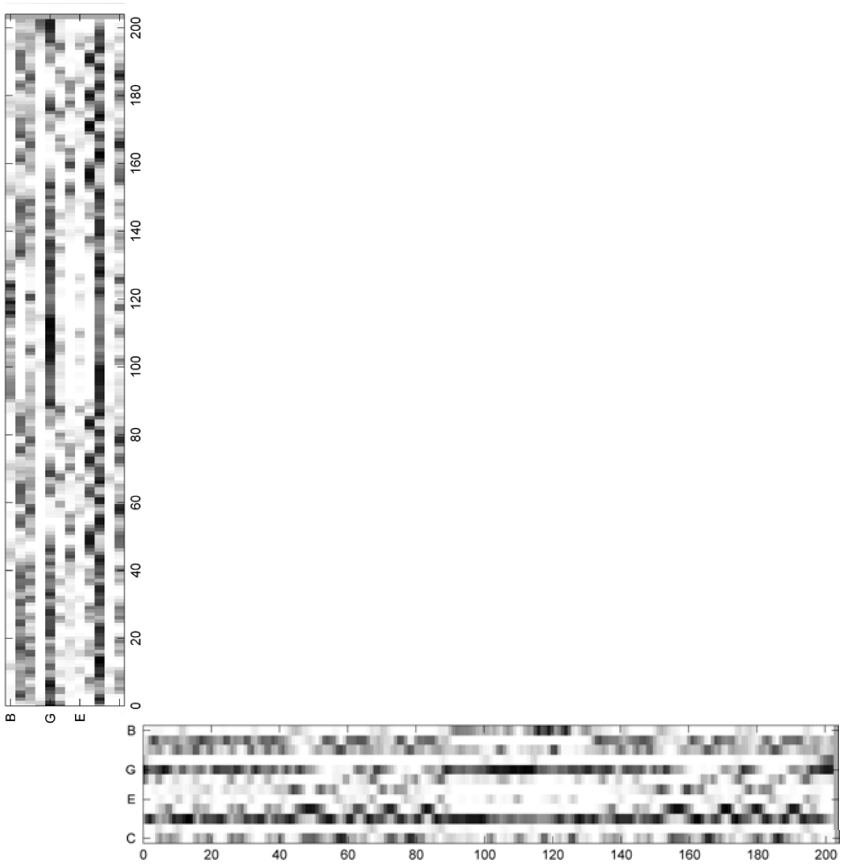

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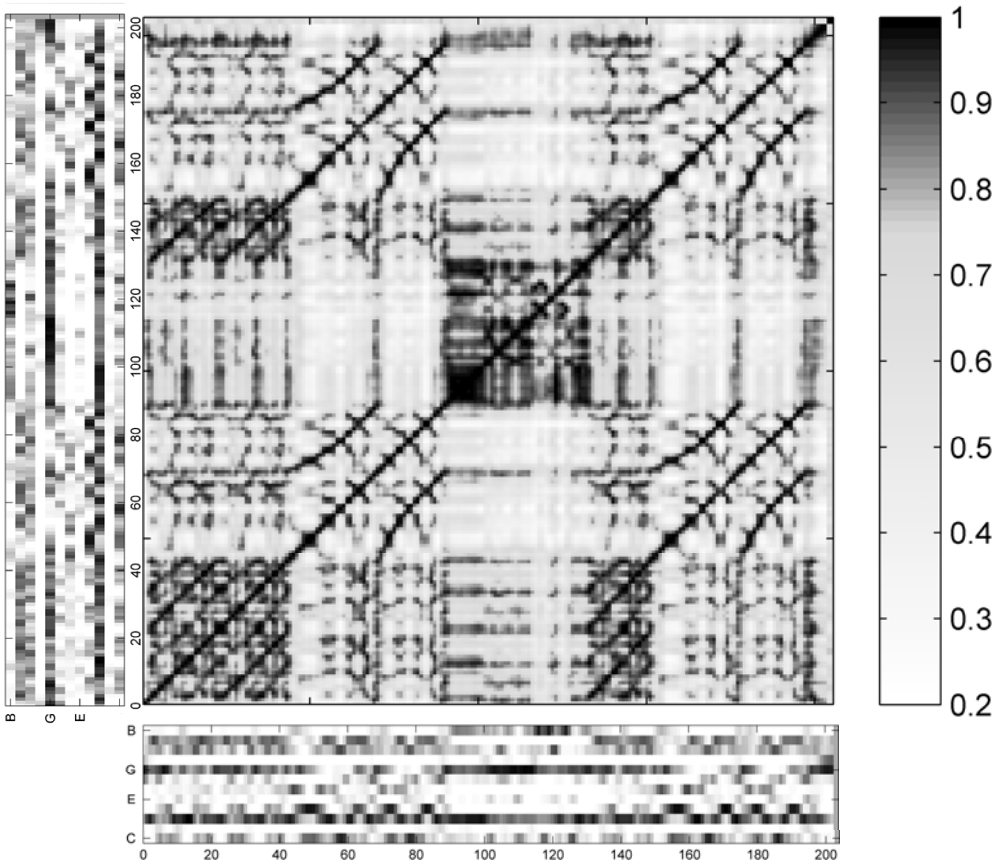

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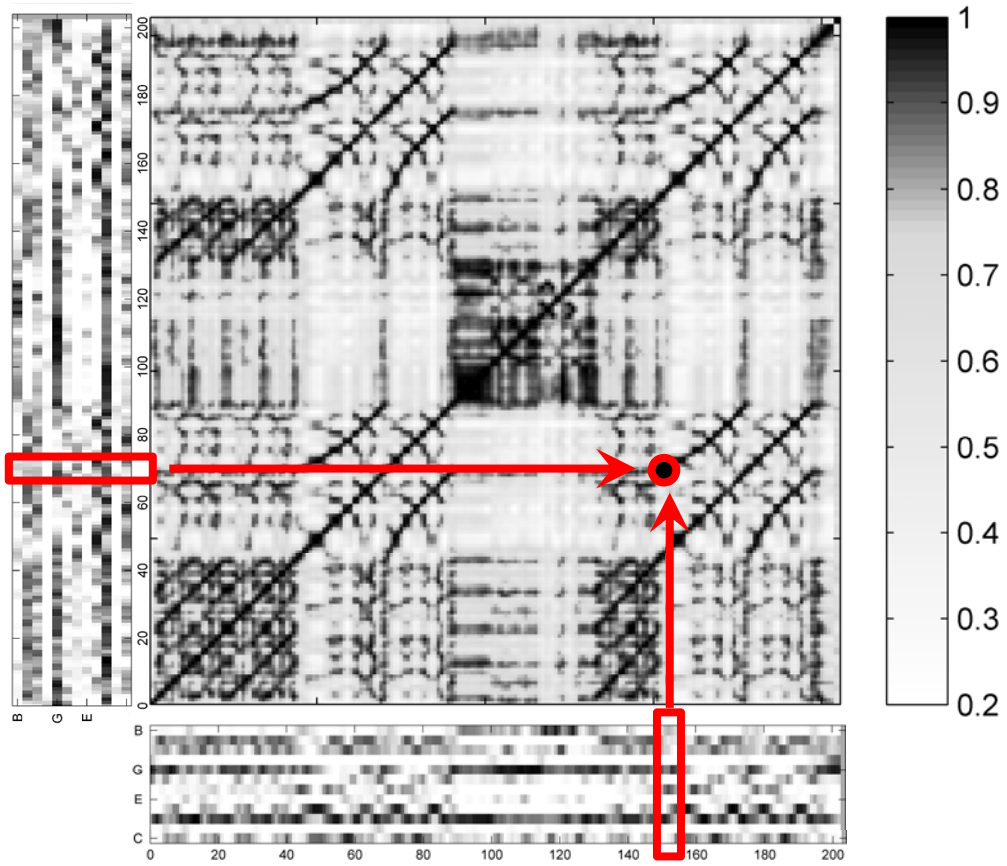

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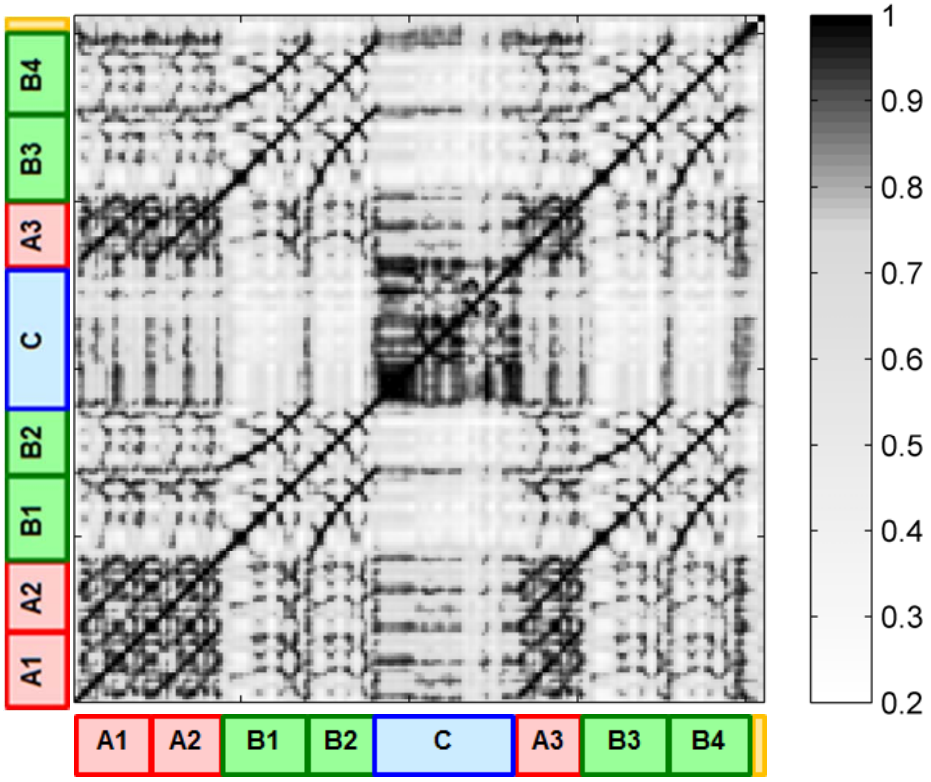

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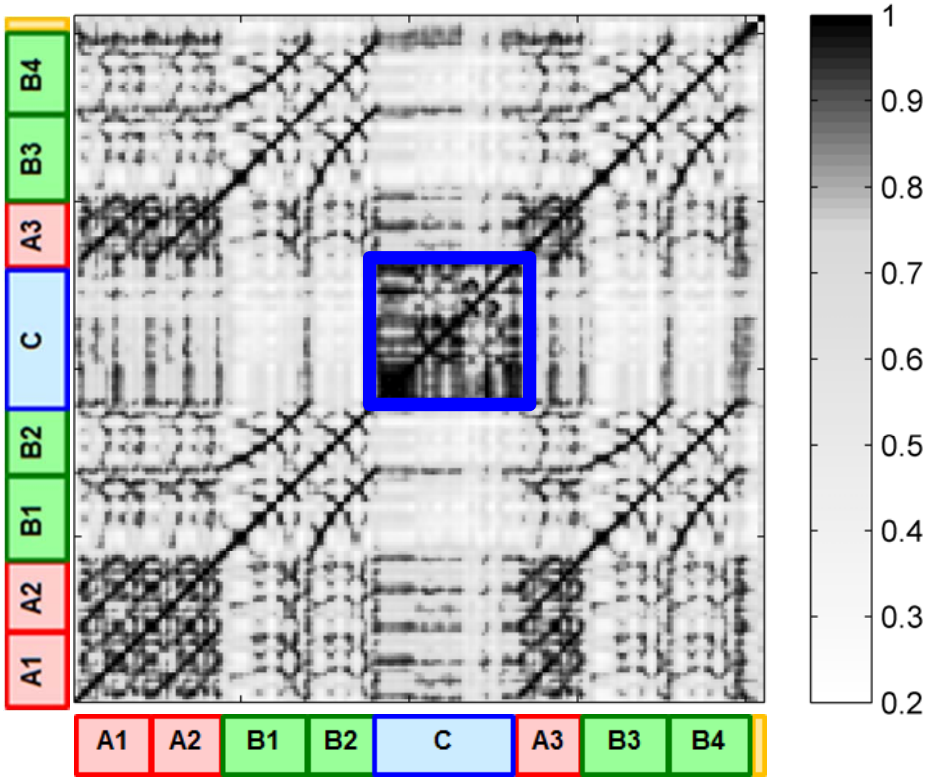

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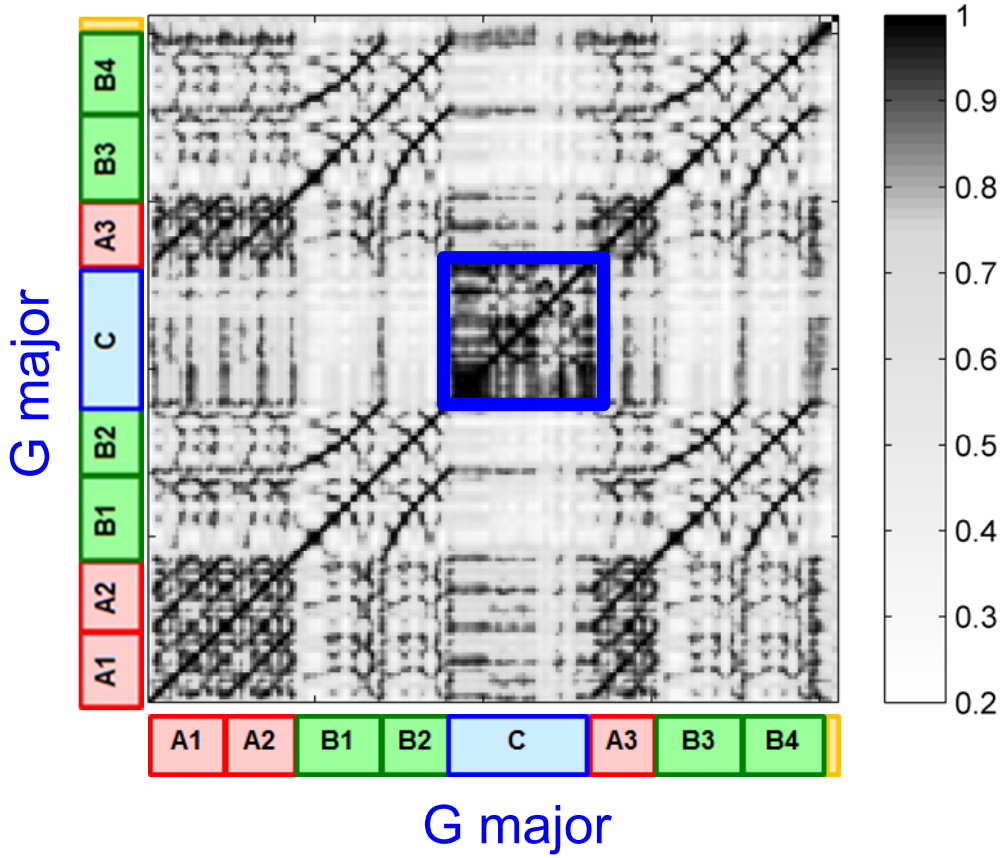

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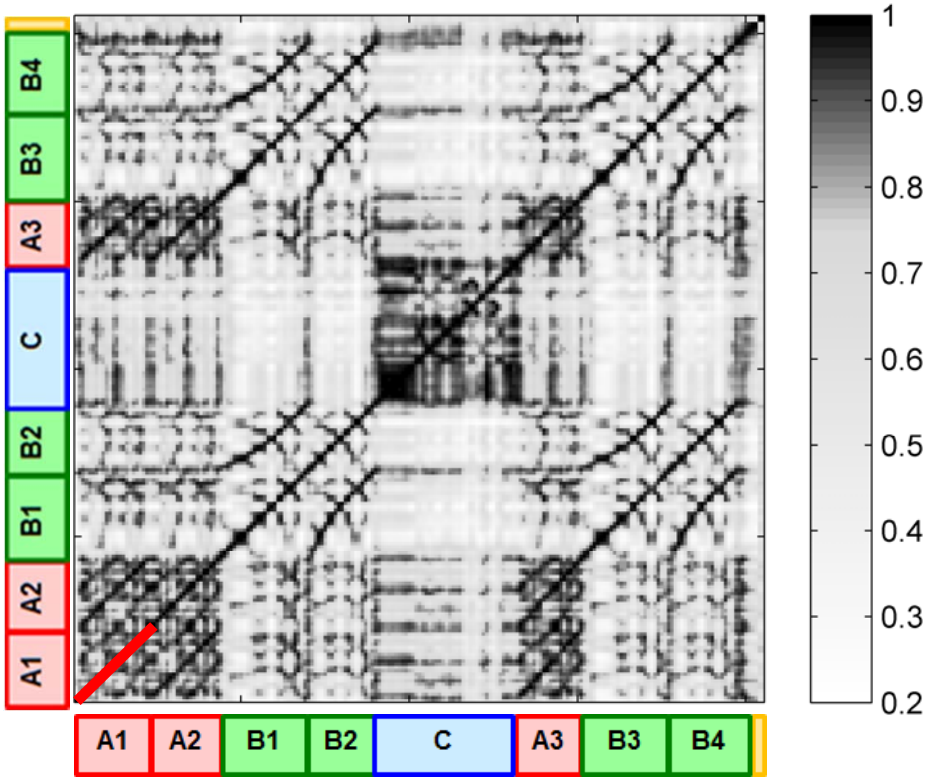

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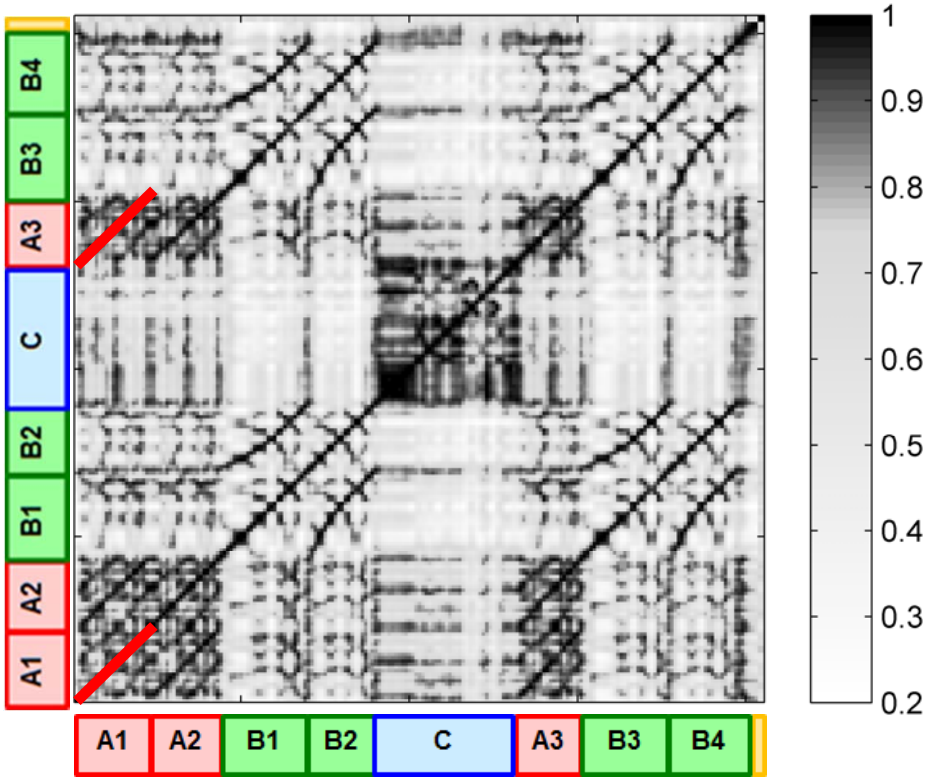

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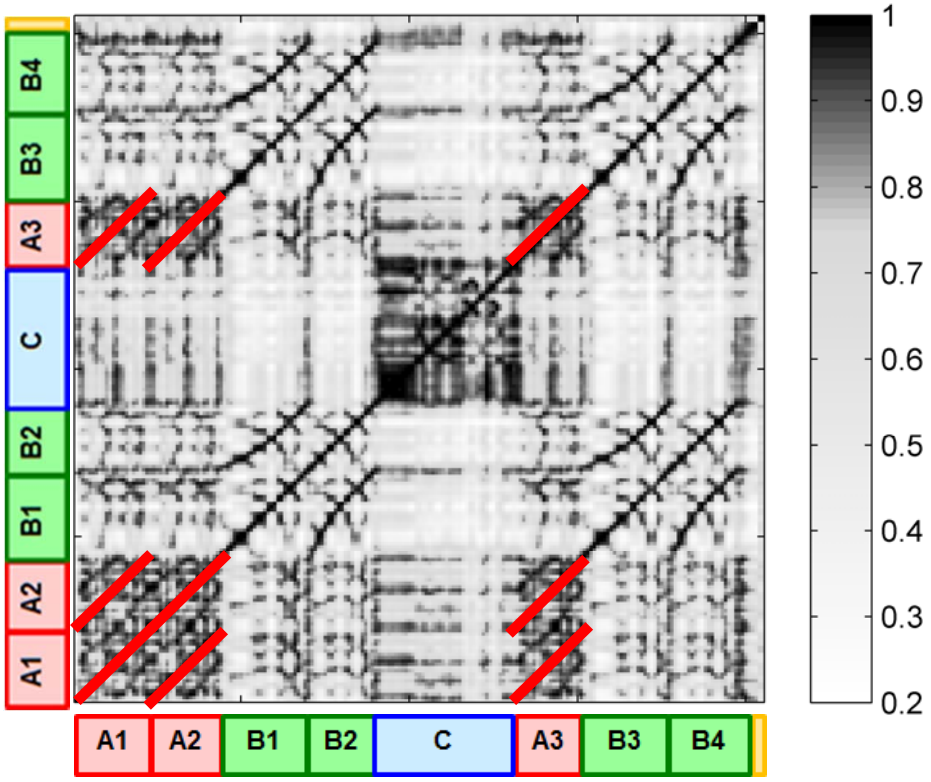

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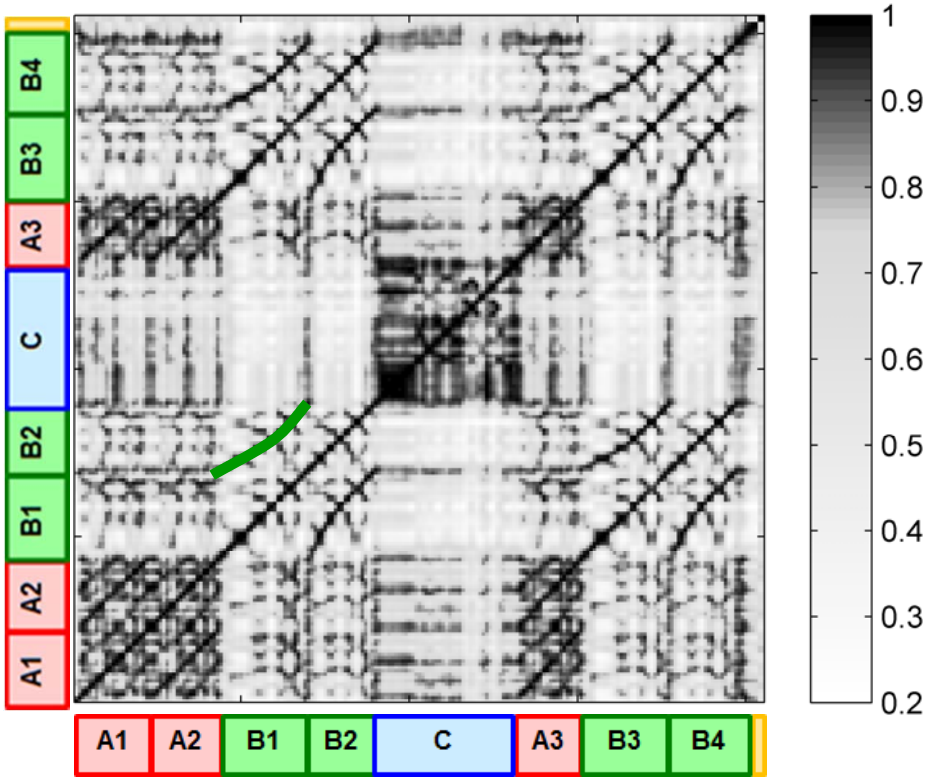

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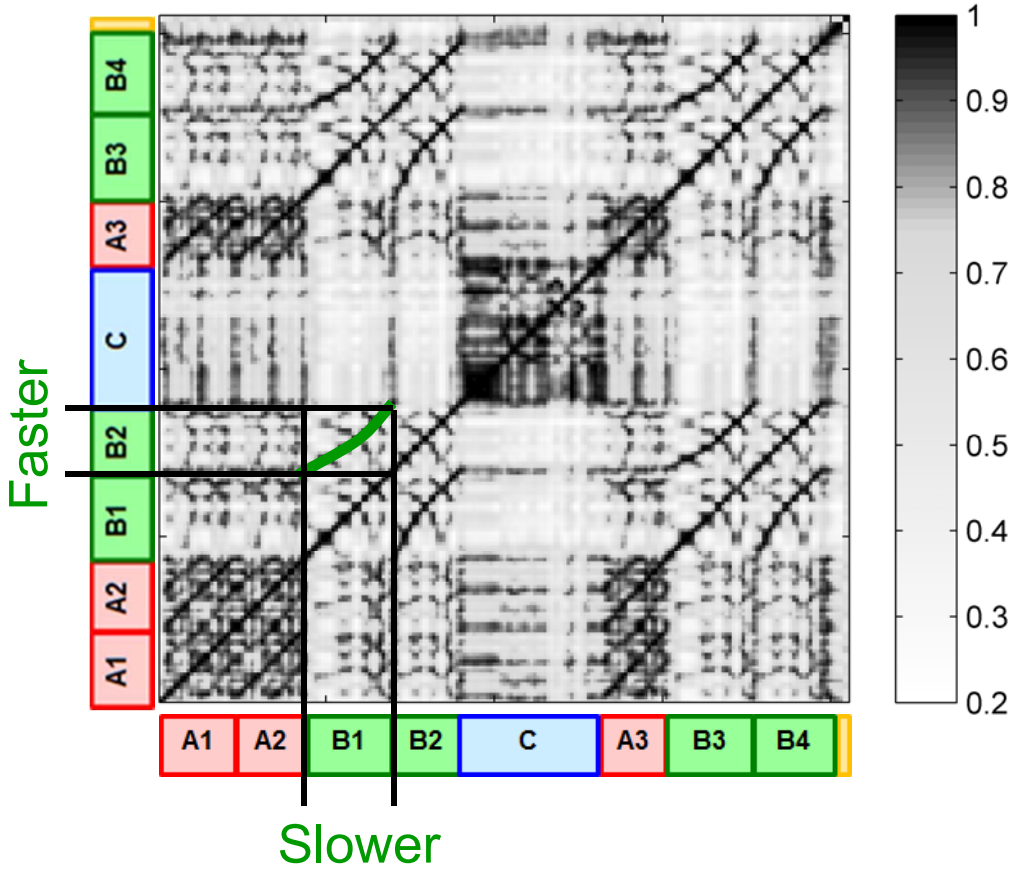

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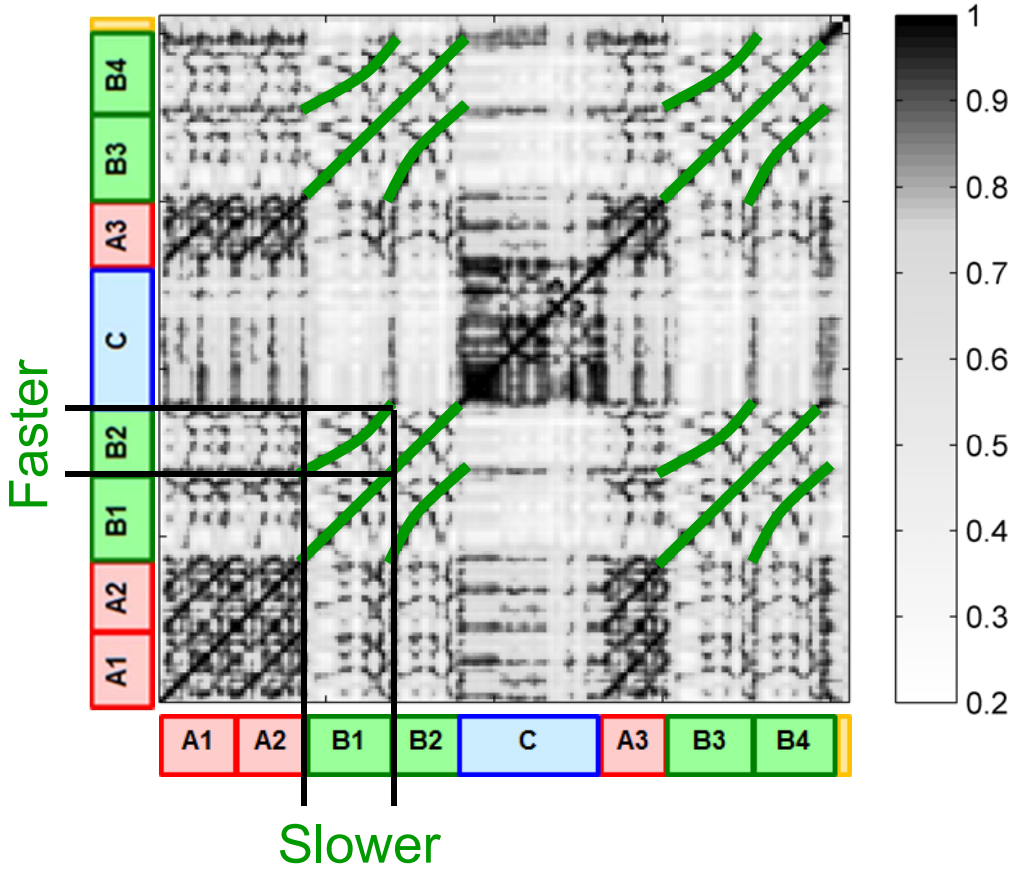

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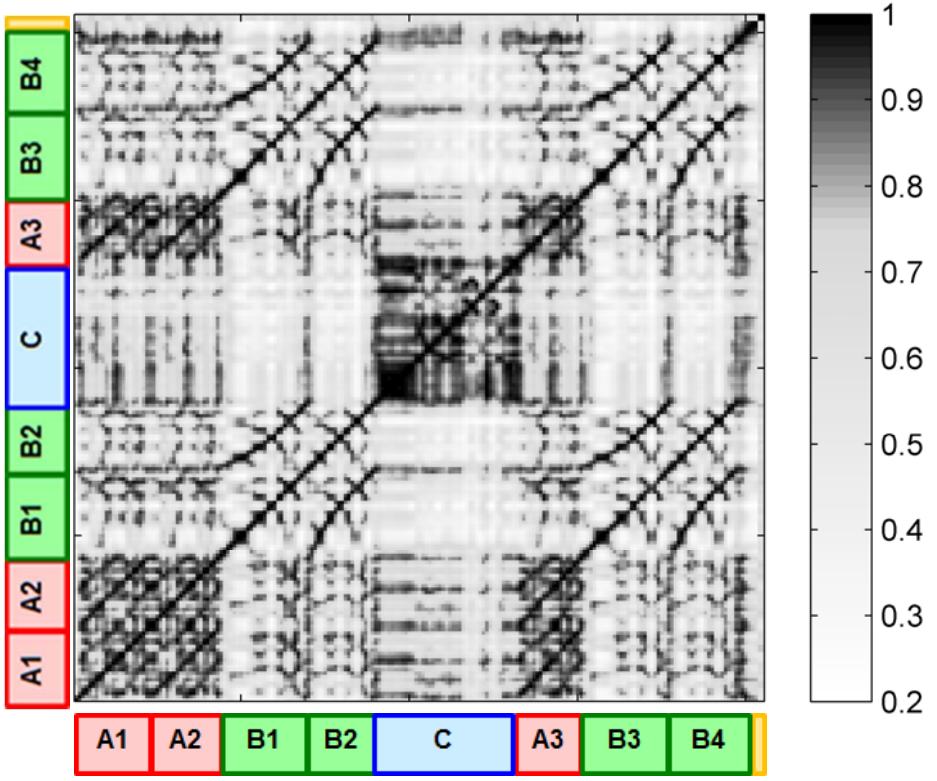
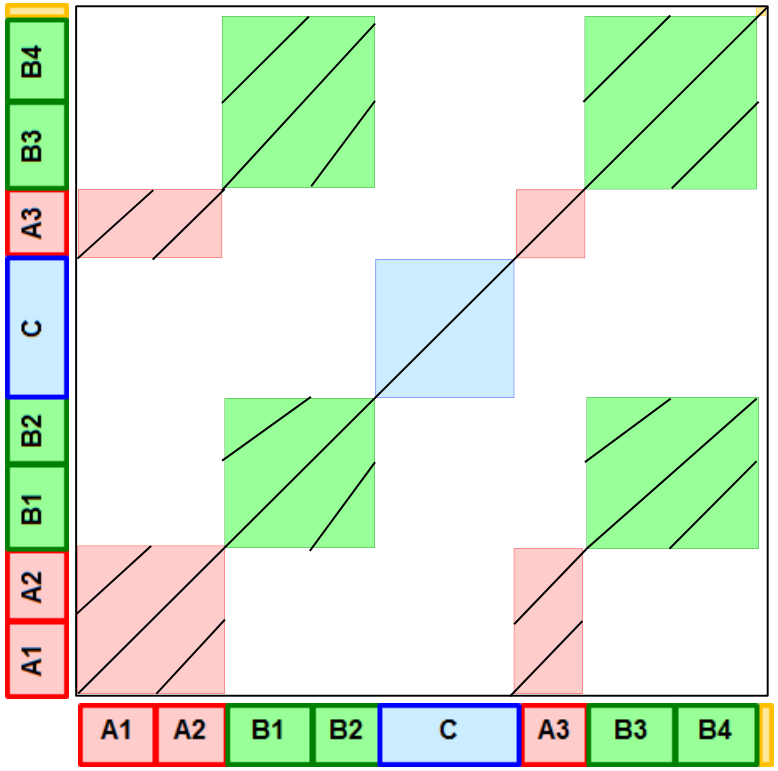


Idealized SSM



Self-Similarity Matrix (SSM)

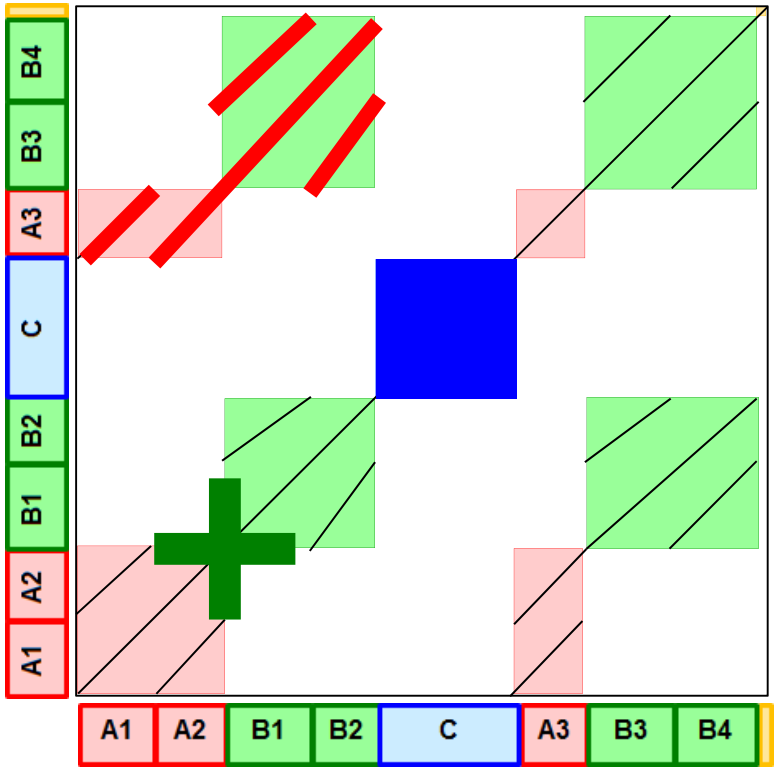
Example: Brahms Hungarian Dance No. 5 (Ormandy)

Blocks: Homogeneity

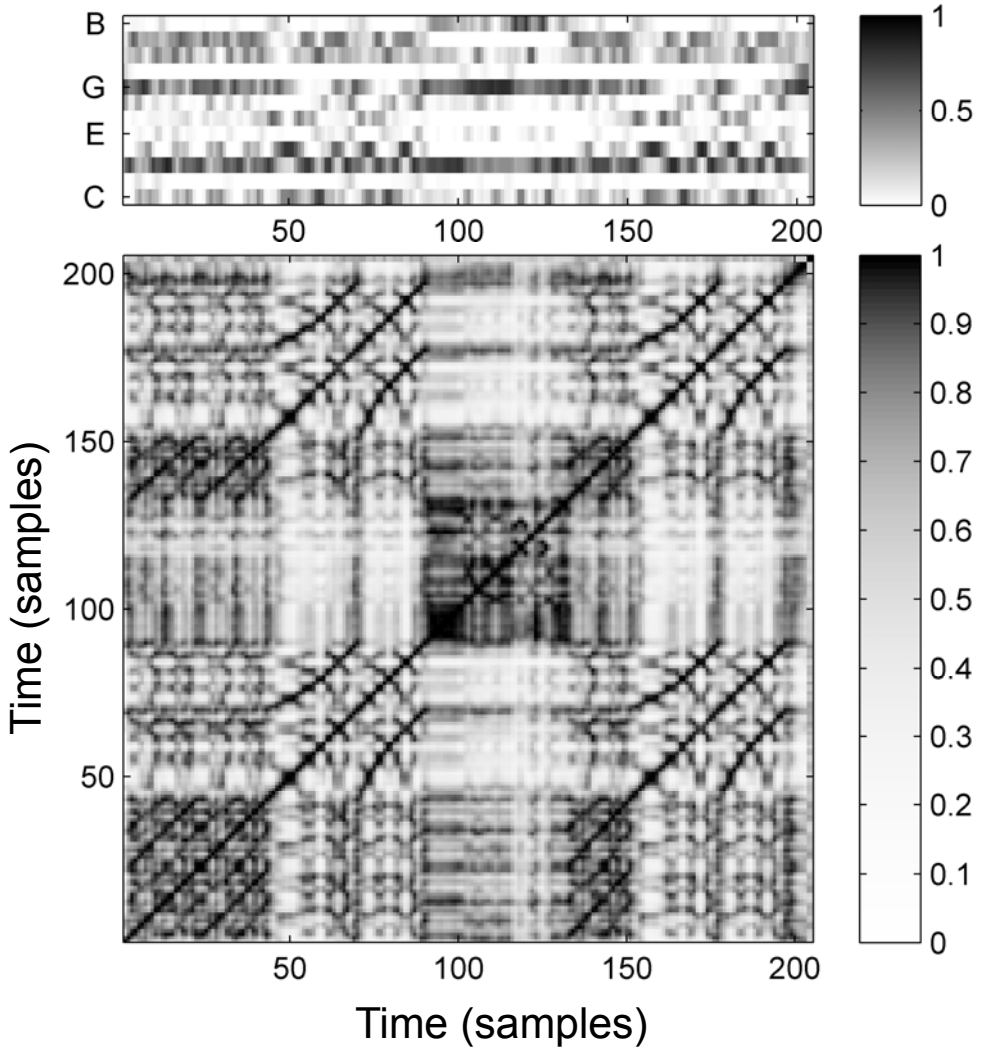
Paths: Repetition

Corners: Novelty

Idealized SSM



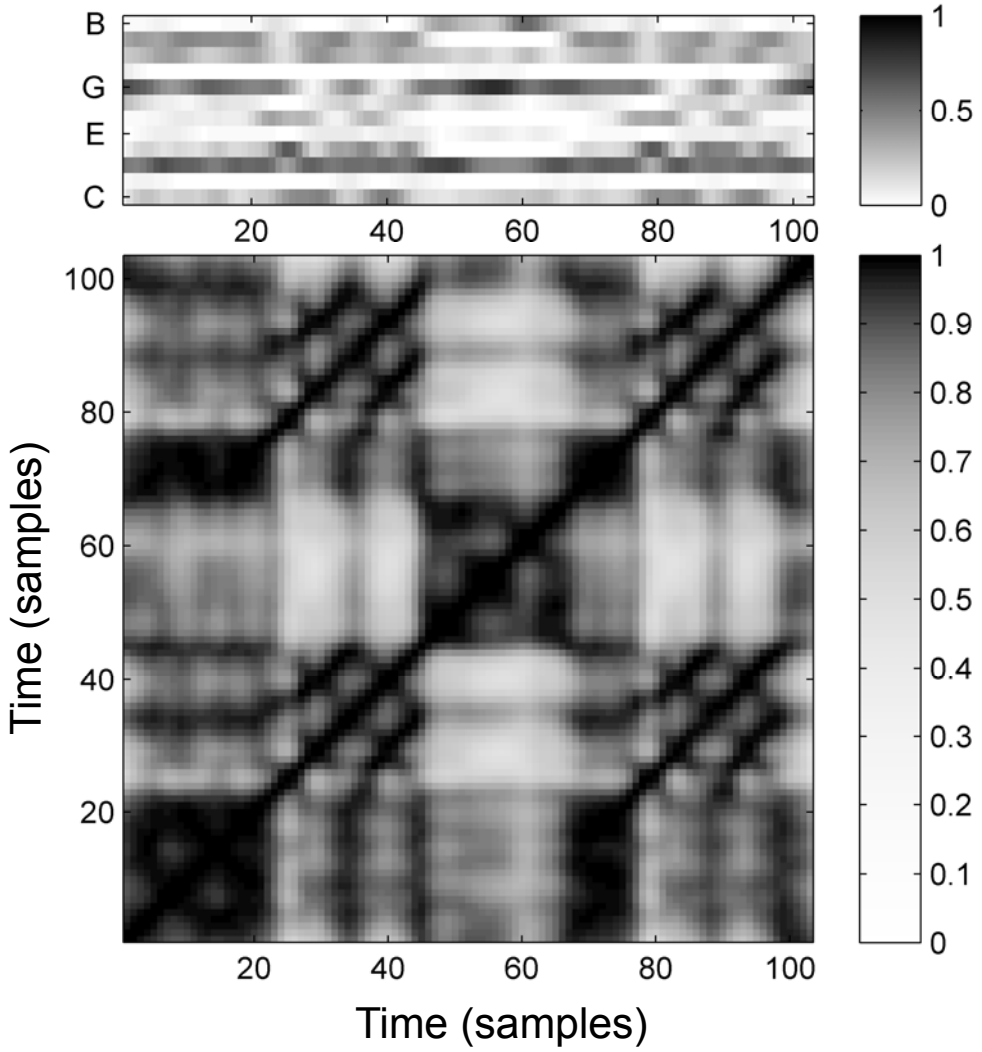
SSM Enhancement



Block Enhancement

- Feature smoothing
- Coarsening

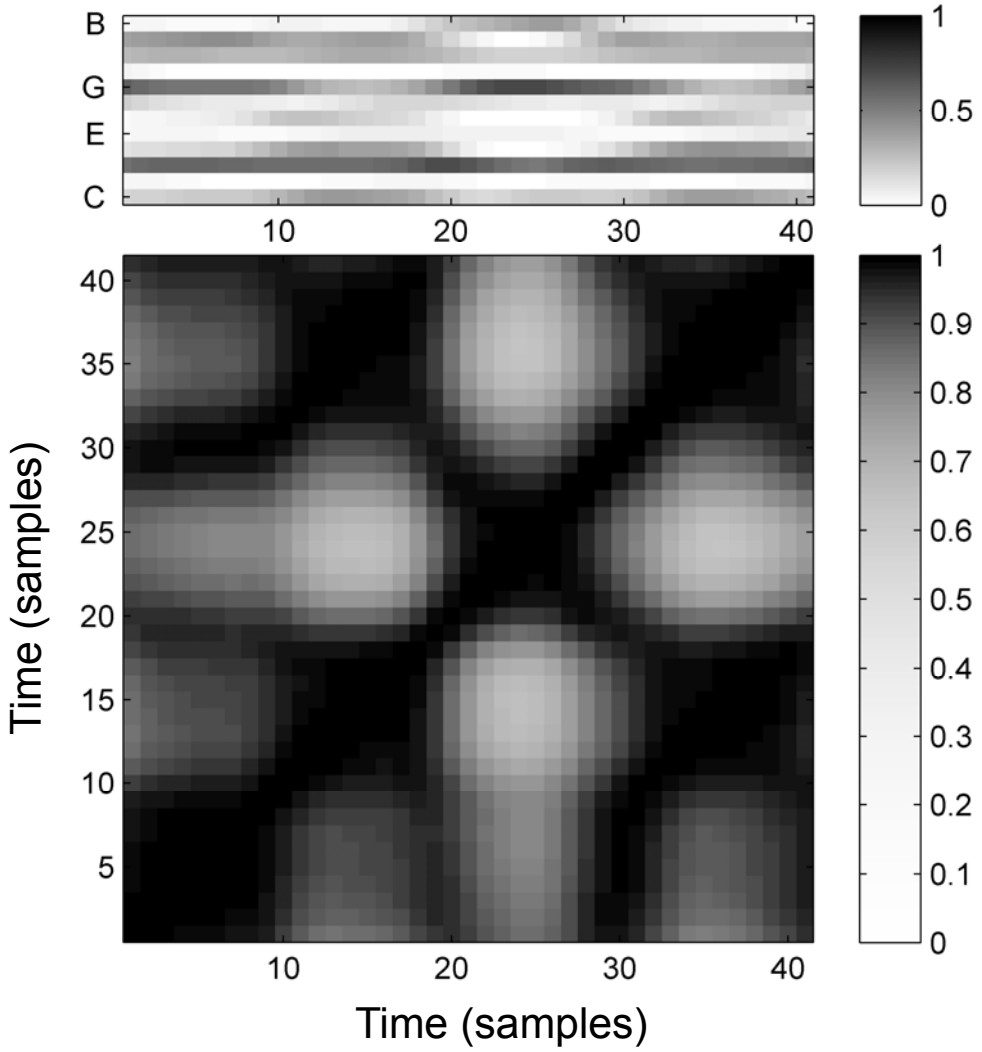
SSM Enhancement



Block Enhancement

- Feature smoothing
- Coarsening

SSM Enhancement



Block Enhancement

- Feature smoothing
- Coarsening

SSM Enhancement

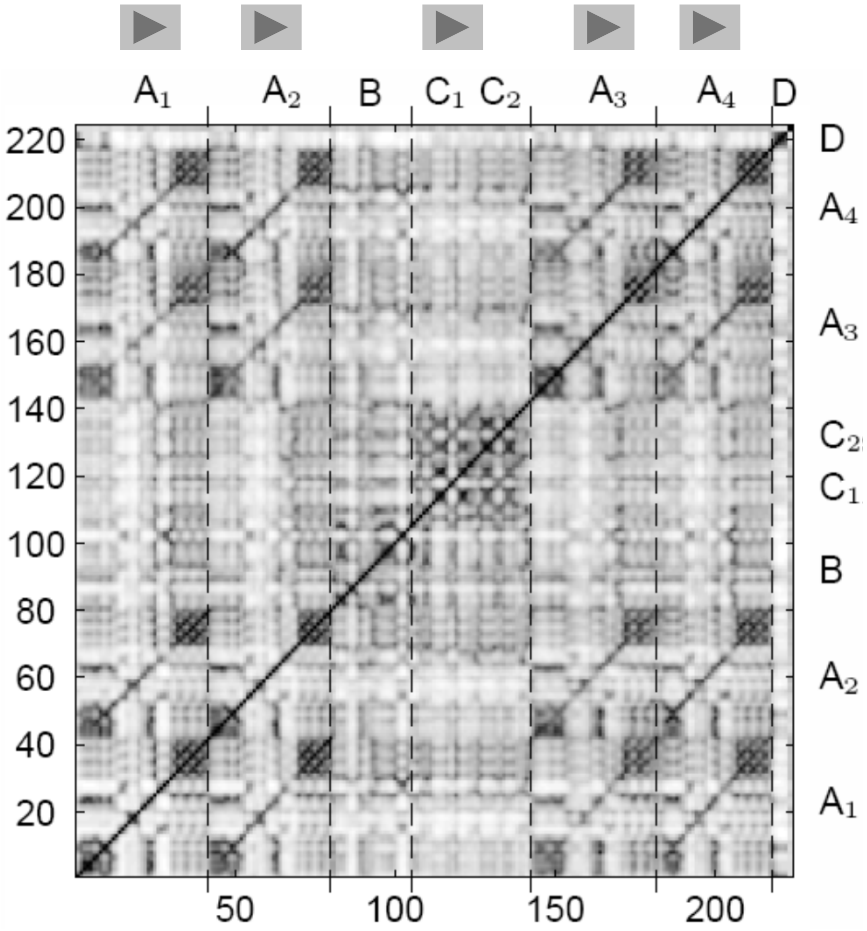
Challenge: Presence of musical variations

- Fragmented paths and gaps
- Paths of poor quality
- Regions of constant (low) cost
- Curved paths

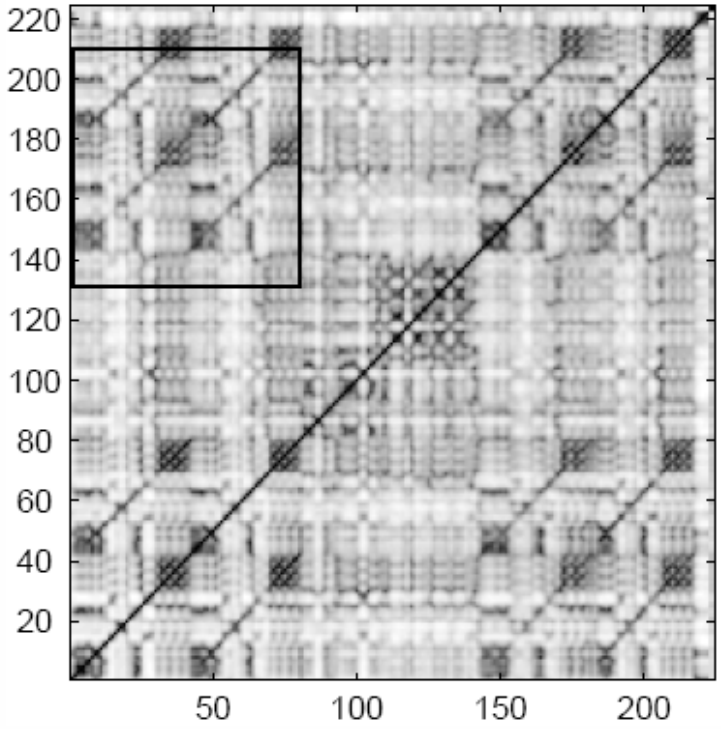
Idea: Enhancement of path structure

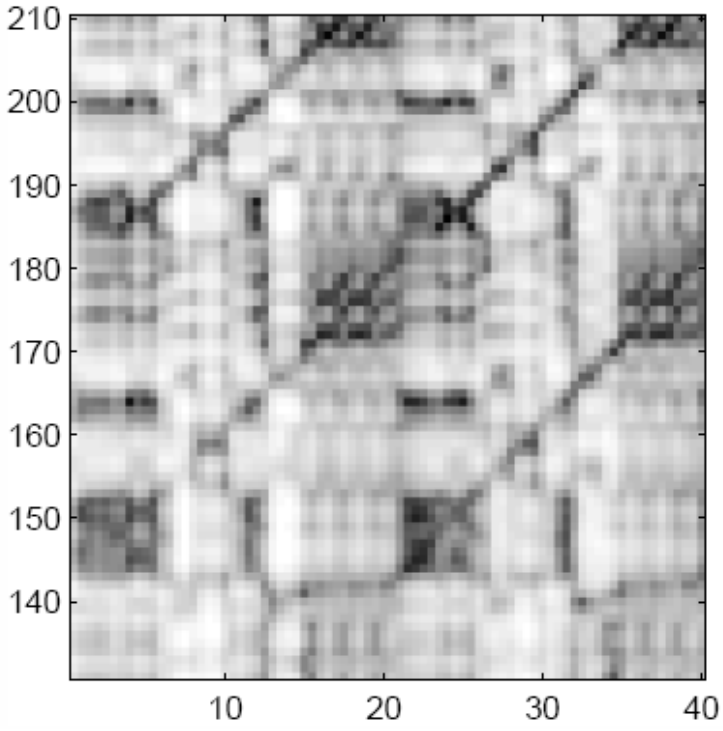
SSM Enhancement

Shostakovich Waltz 2, Jazz Suite No. 2 (Chailly)



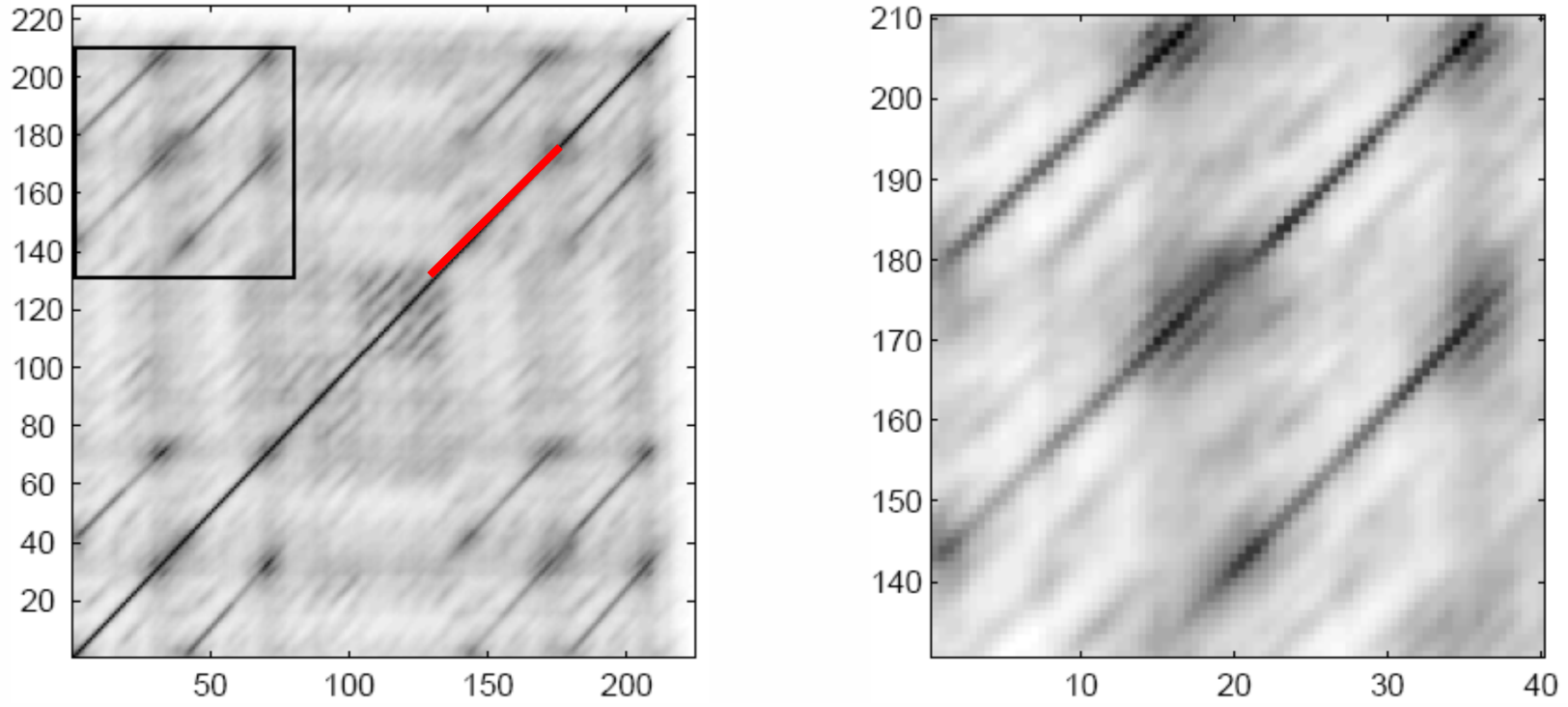
SSM Enhancement





Cost matrix C

SSM Enhancement



Enhanced cost matrix C_L

Filtering along main diagonal

SSM Enhancement

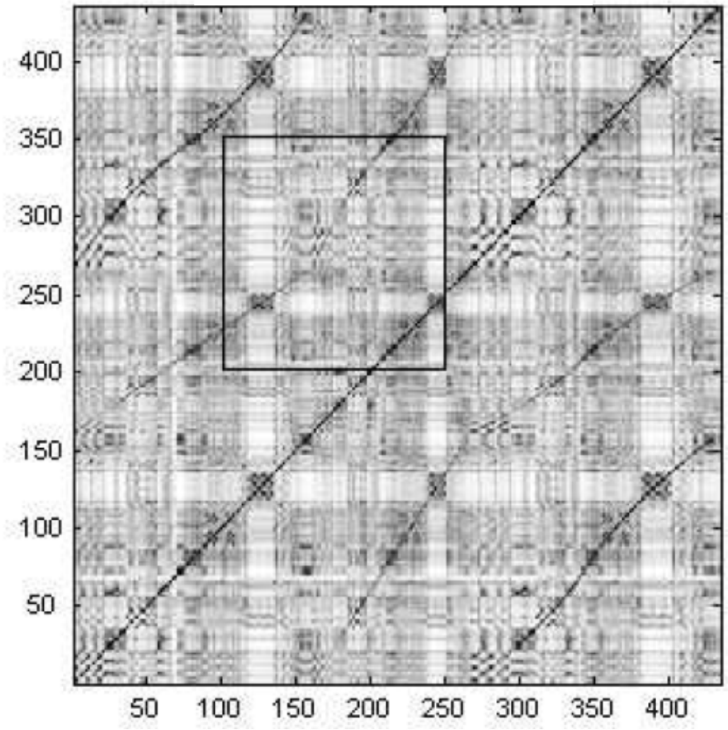
Idea: Usage of contextual information (Foote 1999)

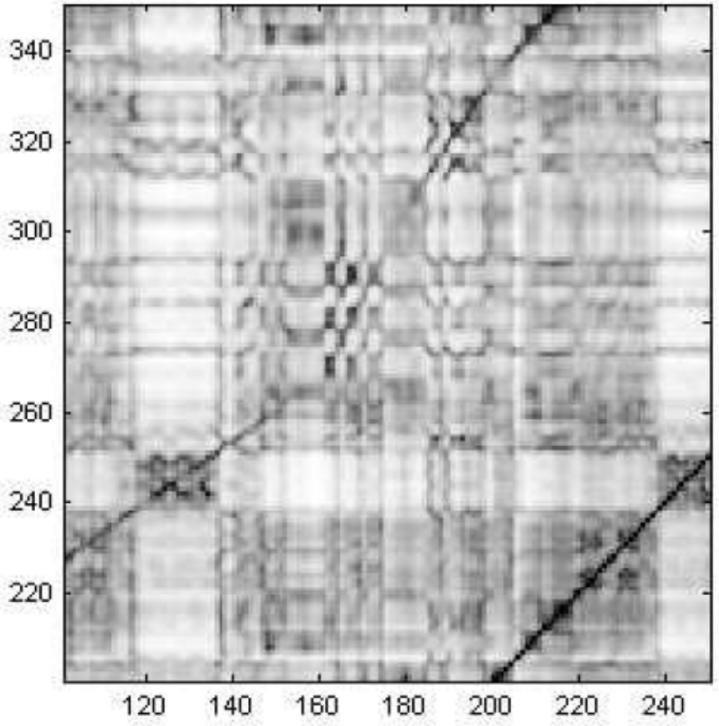
$$C_L(n,m) := \frac{1}{L} \sum_{\ell=0}^{L-1} c(v_{n+\ell}, v_{m+\ell})$$

- Comparison of entire sequences
- $L =$ length of sequences
- $C_L =$ enhanced cost matrix

$\rightsquigarrow$ smoothing effect

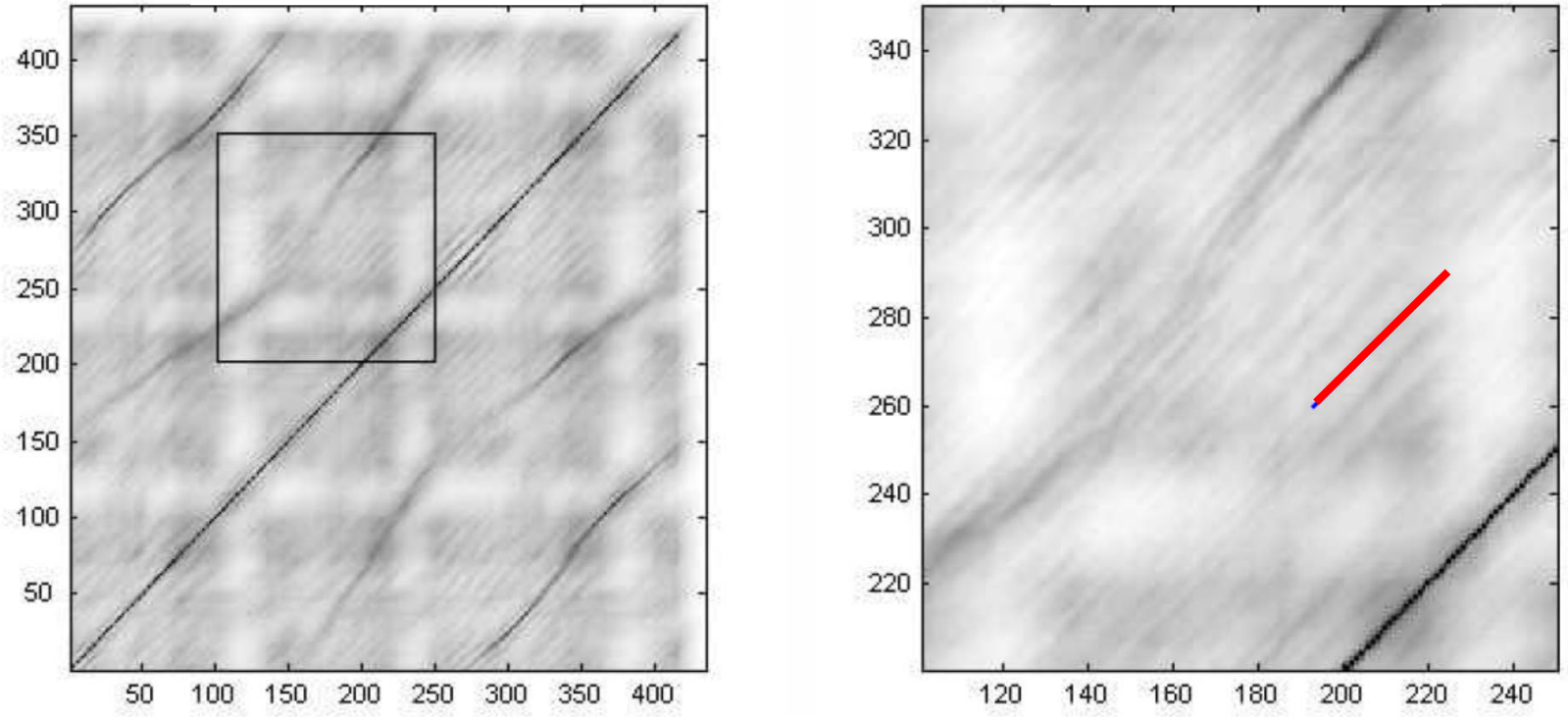
SSM Enhancement





Cost matrix C

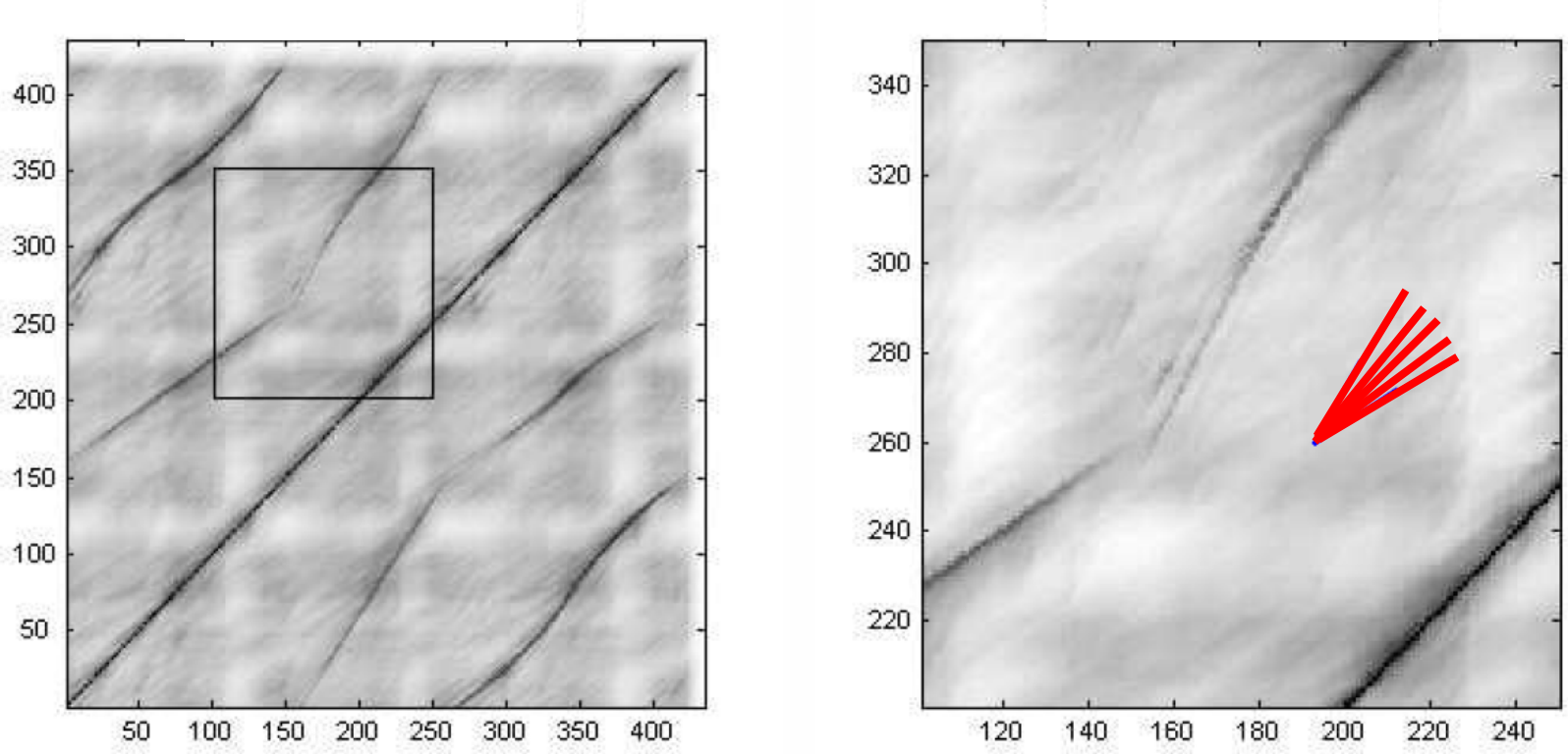
SSM Enhancement



Cost matrix C_L with $L = 20$

Filtering along main diagonal

SSM Enhancement



Cost matrix $C_L^{\min}$ with $L = 20$

Filtering along 8 different directions and minimizing

SSM Enhancement

Idea: Smoothing along various directions
and minimizing over all directions

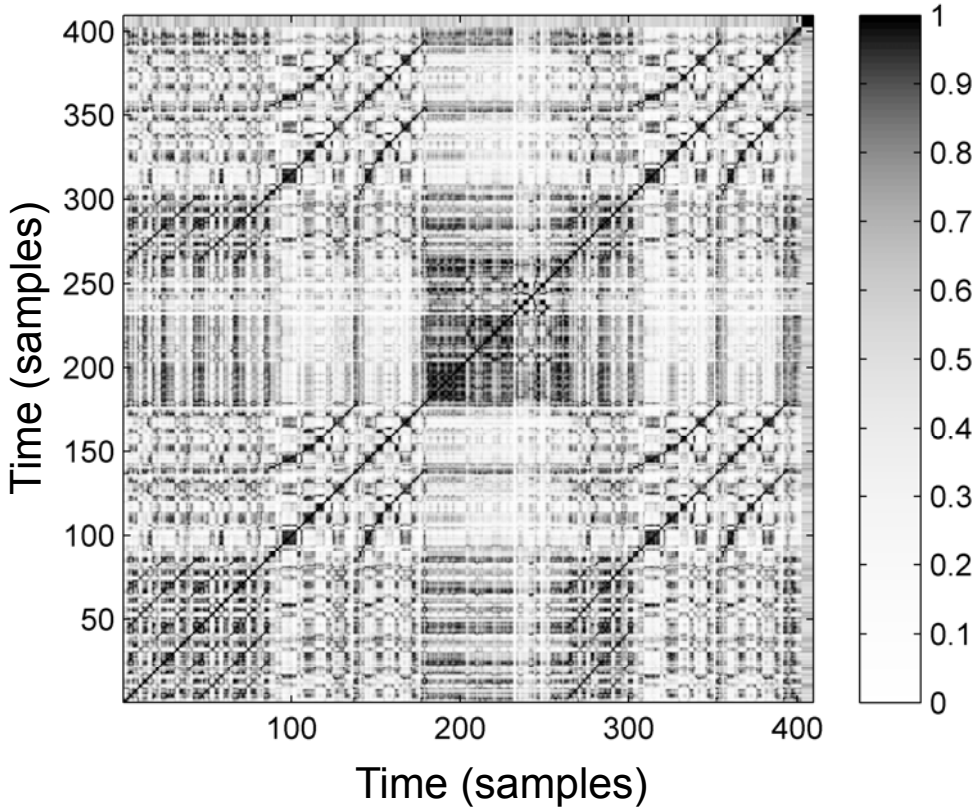
$$C_L^{\min}(n,m) := \min_k C_L^{\text{slope}_k}(n,m)$$

- $\text{slope}_k =$ kth direction of smoothing
- $C_L^{\text{slope}_k} =$ enhanced cost matrix w.r.t. slope_k
- Usage of eight slope values

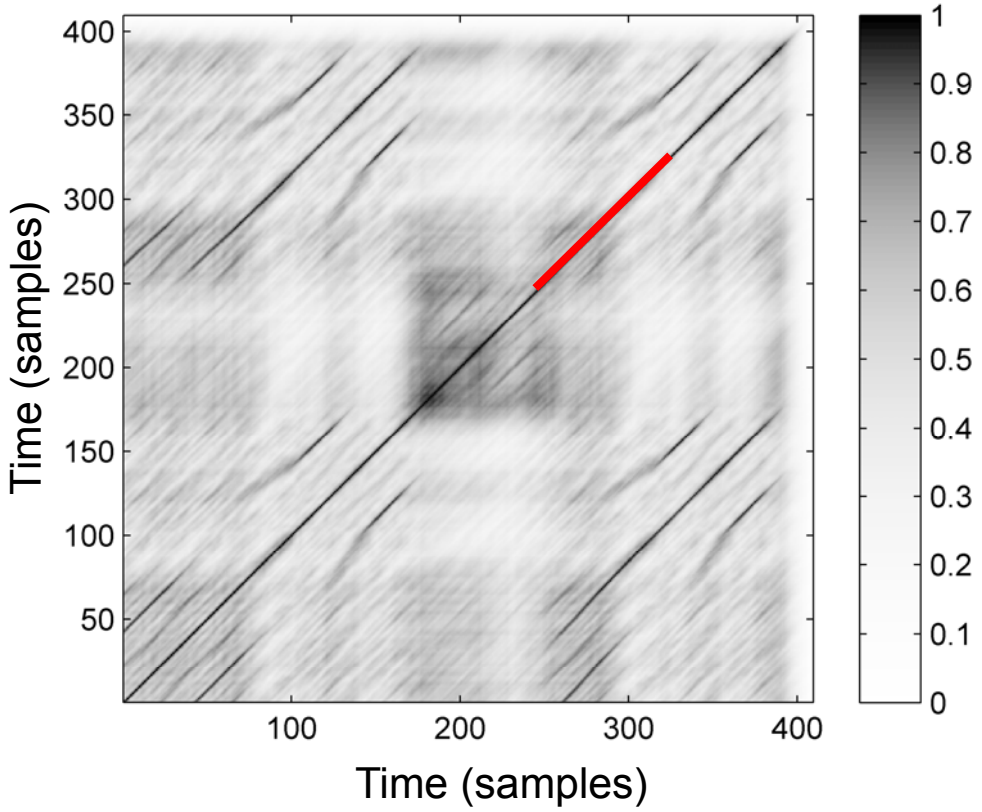
$\rightsquigarrow$ tempo changes of -30 to +40 percent

SSM Enhancement

Path Enhancement



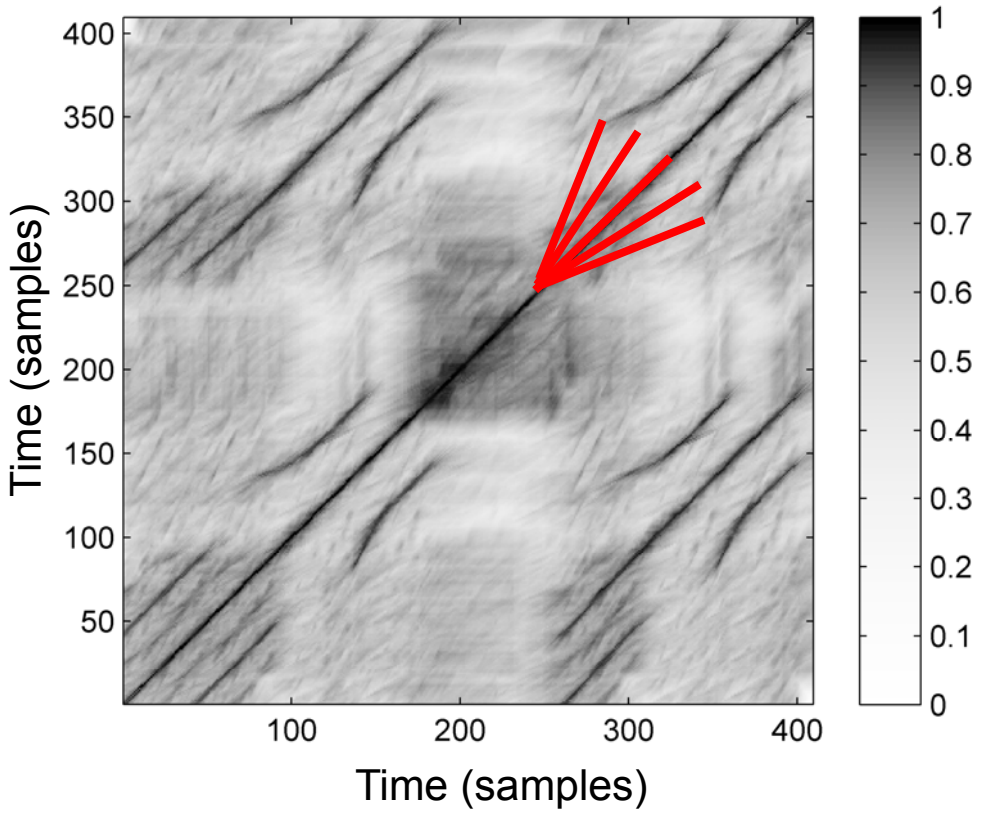
SSM Enhancement



Path Enhancement

- Diagonal smoothing

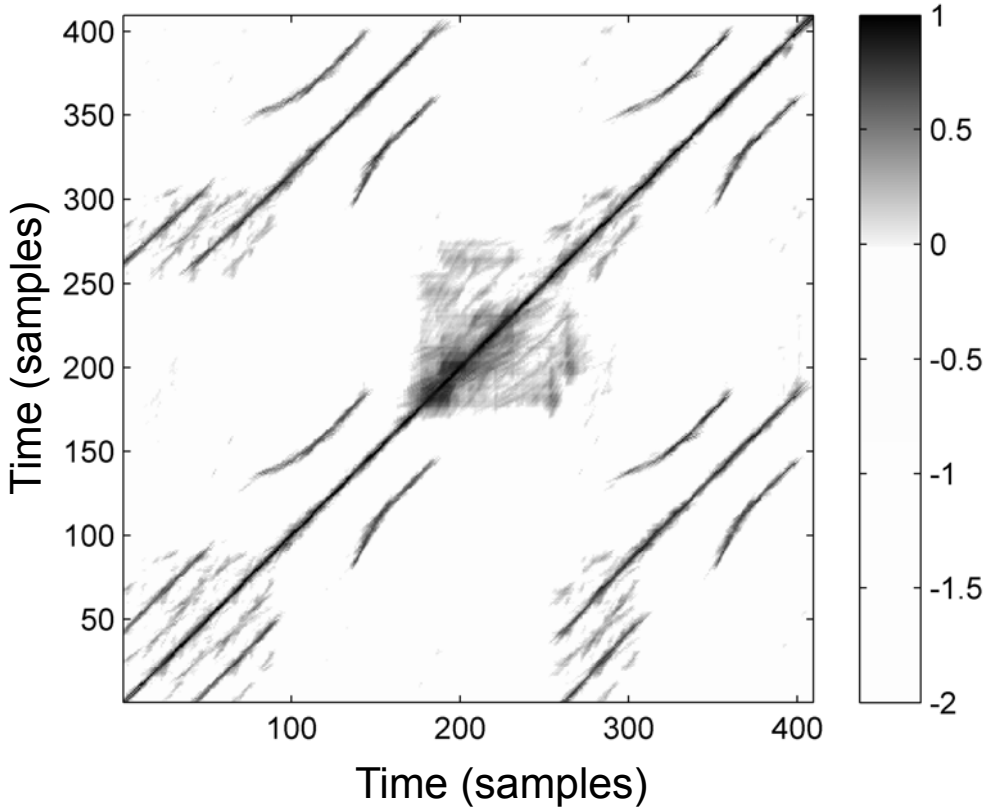
SSM Enhancement



Path Enhancement

- Diagonal smoothing
- Multiple filtering

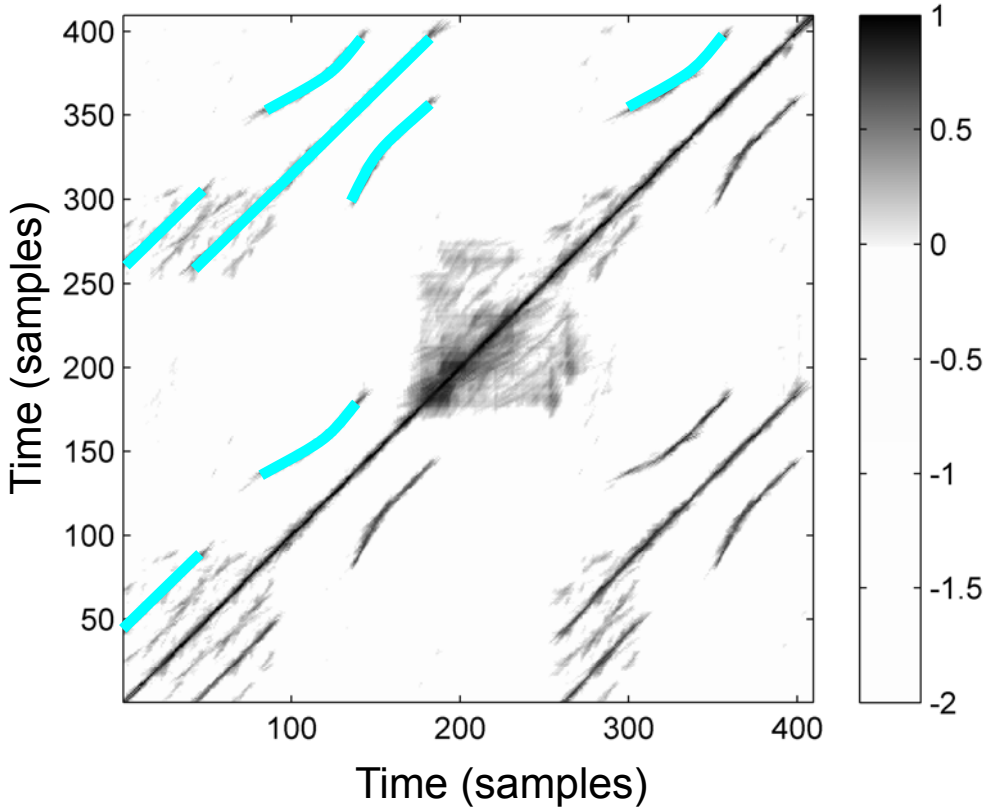
SSM Enhancement



Path Enhancement

- Diagonal smoothing
- Multiple filtering
- Thresholding (relative)
- Scaling & penalty

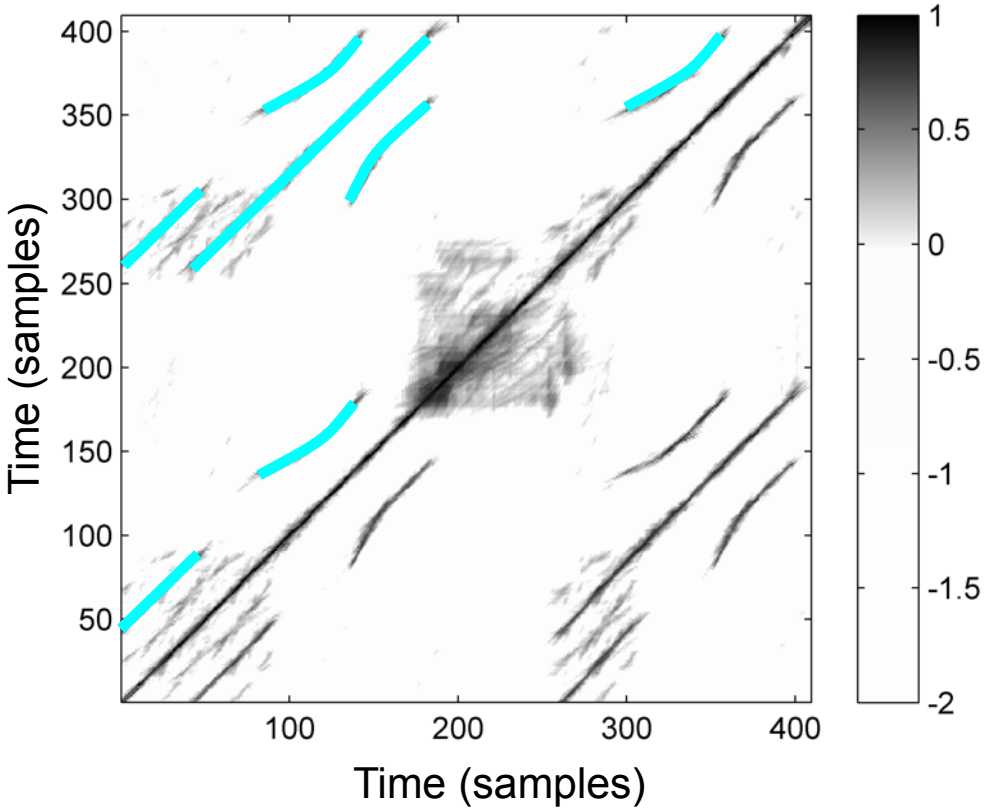
SSM Enhancement



Further Processing

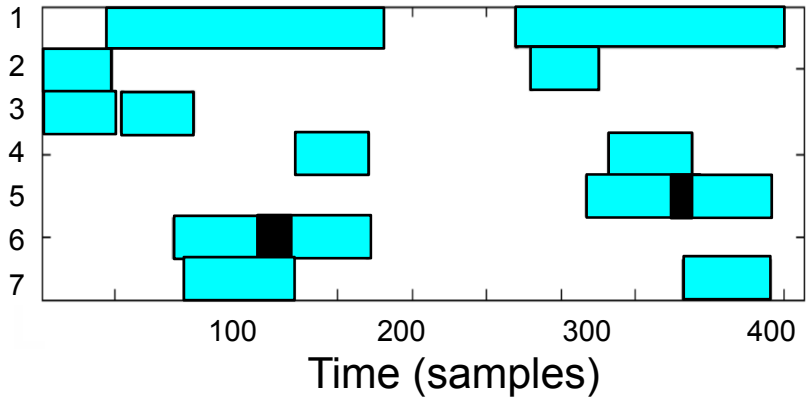
- Path extraction

SSM Enhancement

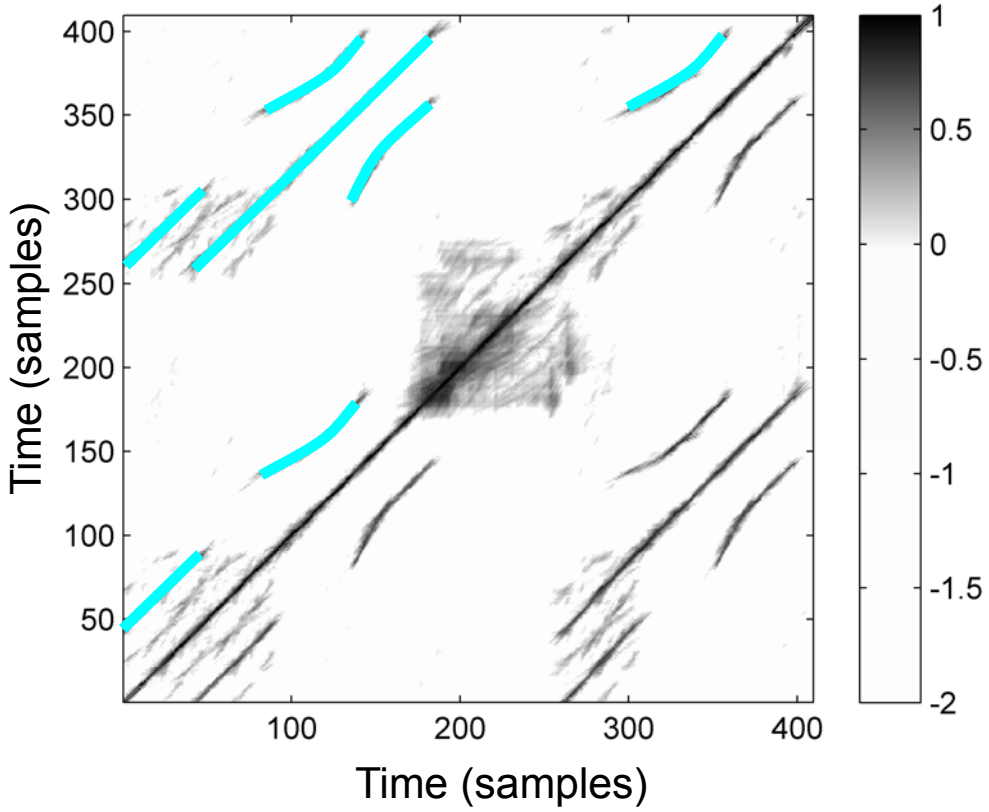


Further Processing

- Path extraction
- Pairwise relations

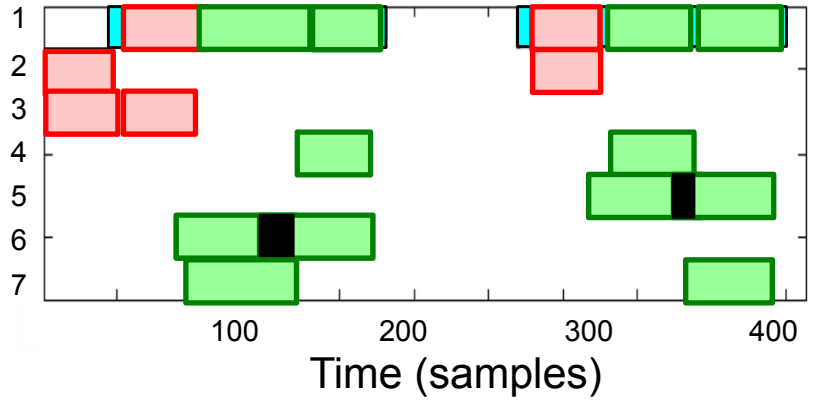


SSM Enhancement

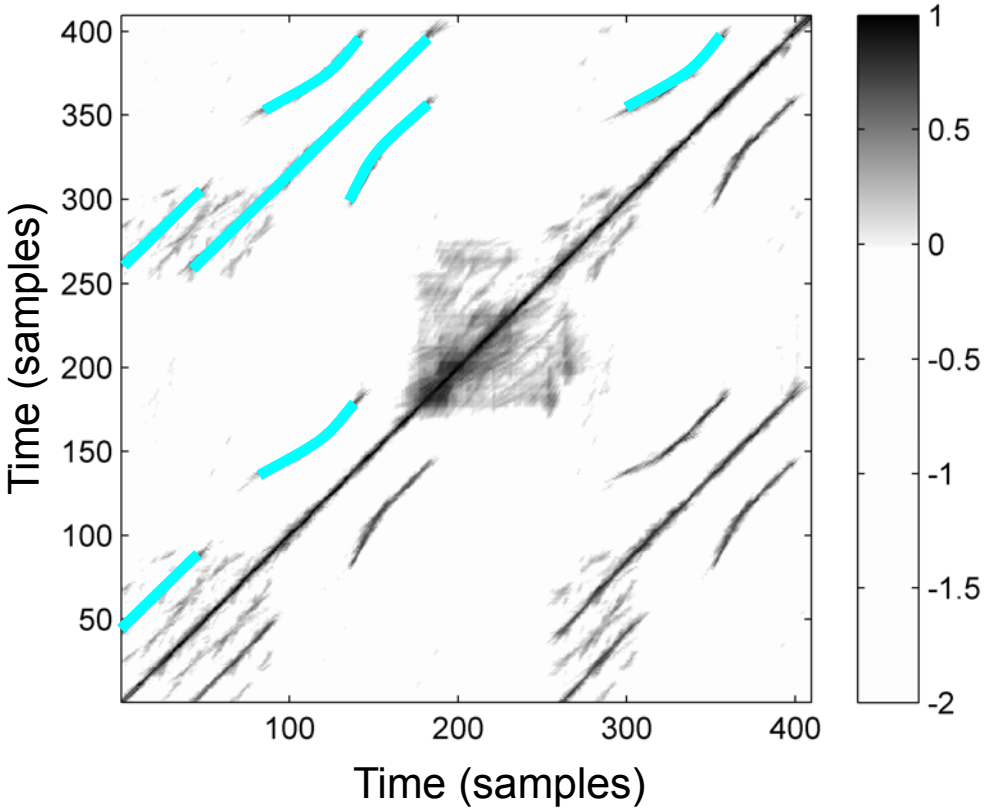


Further Processing

- Path extraction
- Pairwise relations
- Grouping (transitivity)

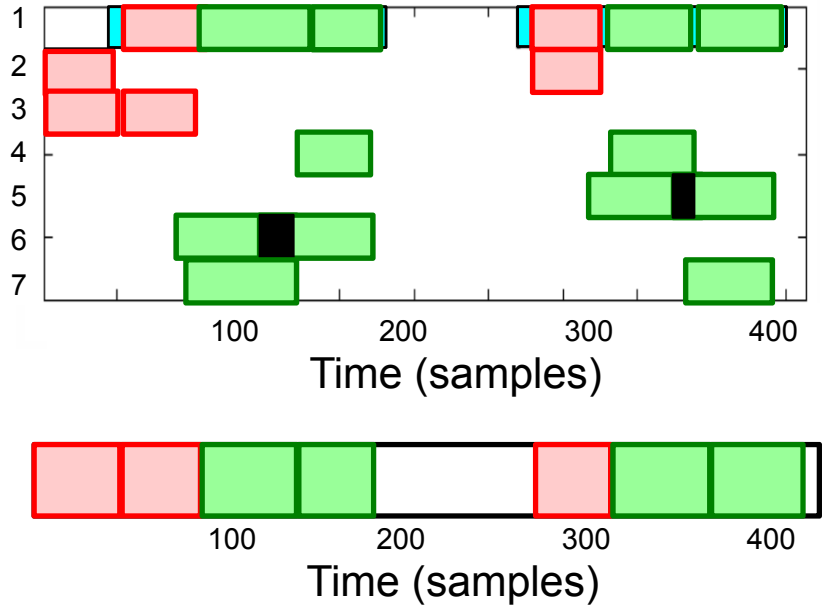


SSM Enhancement



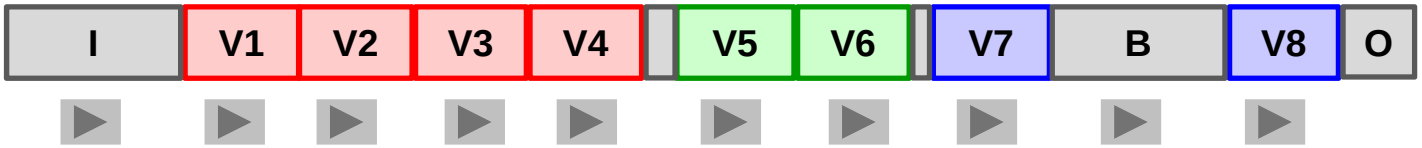
Further Processing

- Path extraction
- Pairwise relations
- Grouping (transitivity)



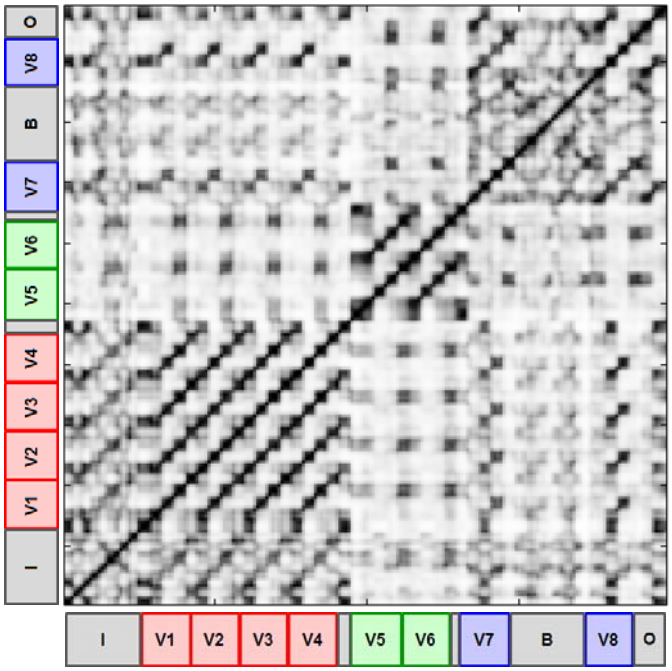
SSM Enhancement

Example: Zager & Evans “In The Year 2525”



SSM Enhancement

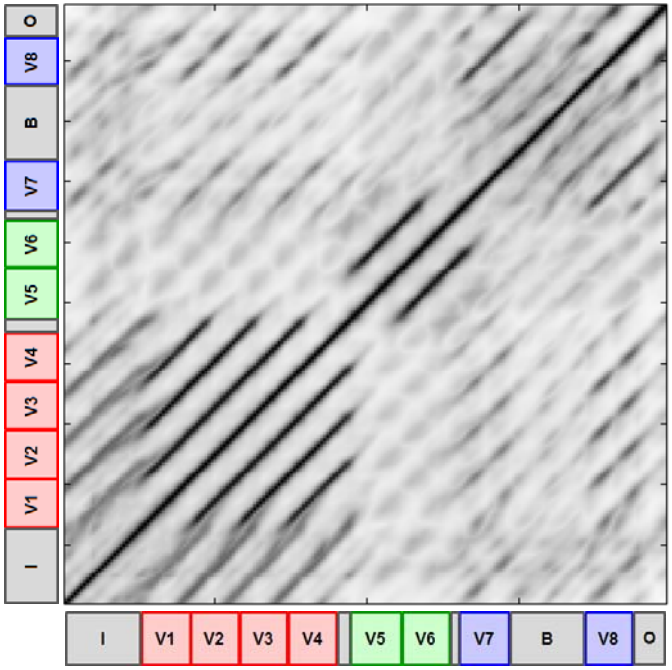
Example: Zager & Evans “In The Year 2525”



SSM Enhancement

Example: Zager & Evans “In The Year 2525”

Missing relations because of transposed sections

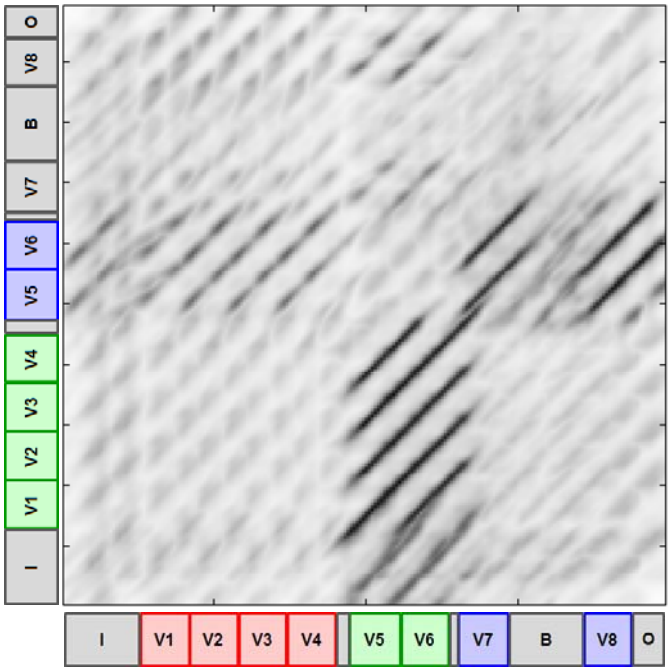


SSM Enhancement

Example: Zager & Evans “In The Year 2525”

Idea: Cyclic shift of one of the chroma sequences

One semitone up

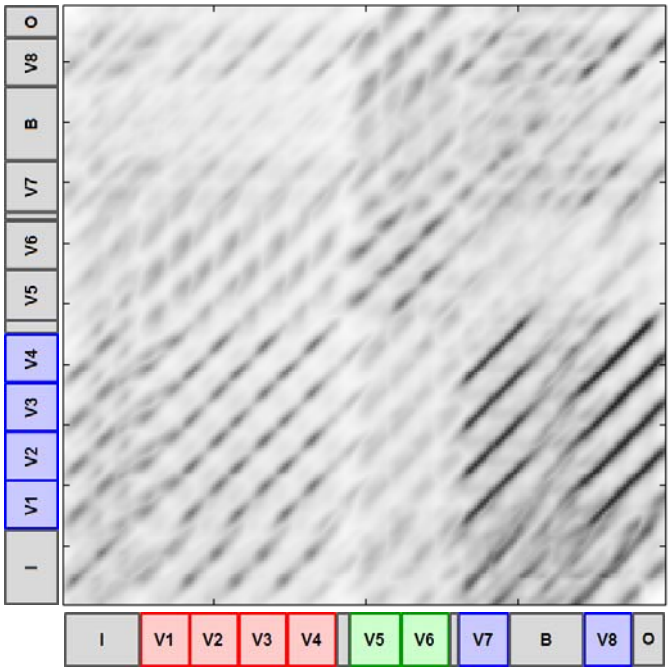


SSM Enhancement

Example: Zager & Evans “In The Year 2525”

Idea: Cyclic shift of one of the chroma sequences

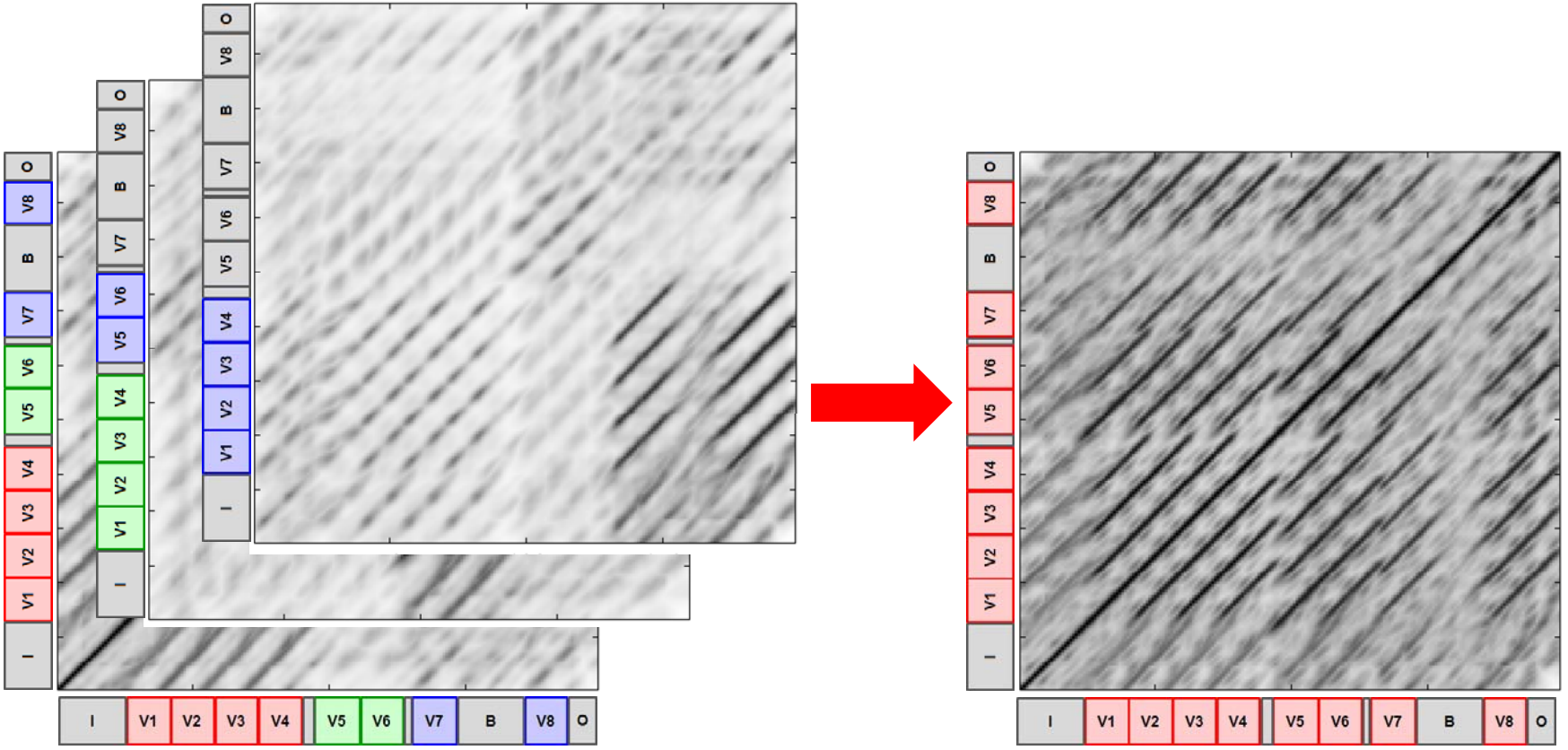
Two semitones up



SSM Enhancement

Example: Zager & Evans “In The Year 2525”

Idea: Overlay & Maximize ⟶ Transposition-invariant SSM

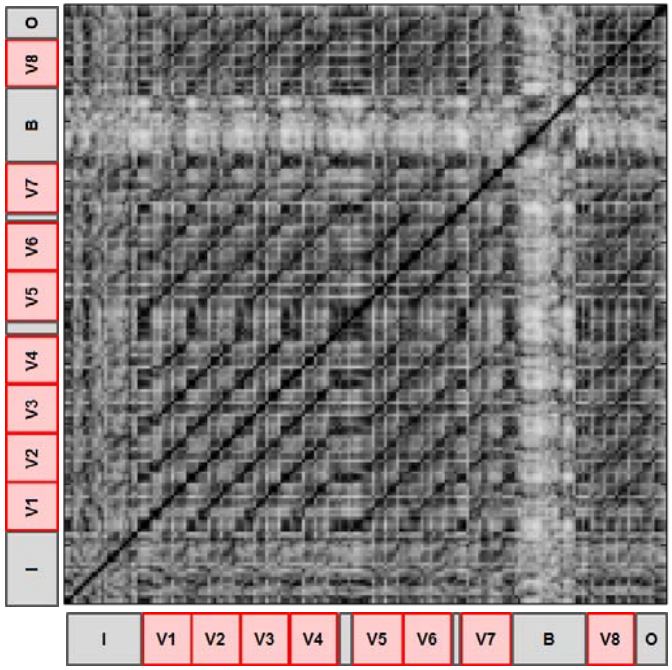


SSM Enhancement

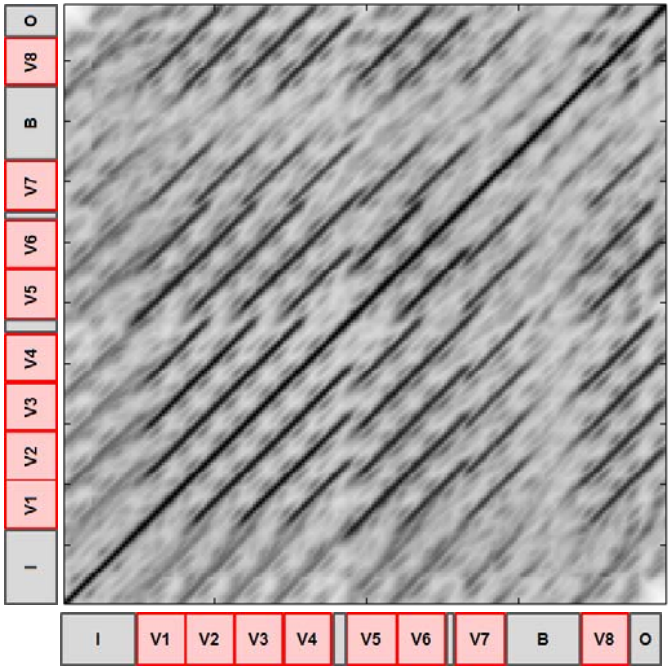
Example: Zager & Evans “In The Year 2525”

Note: Order of enhancement steps important!

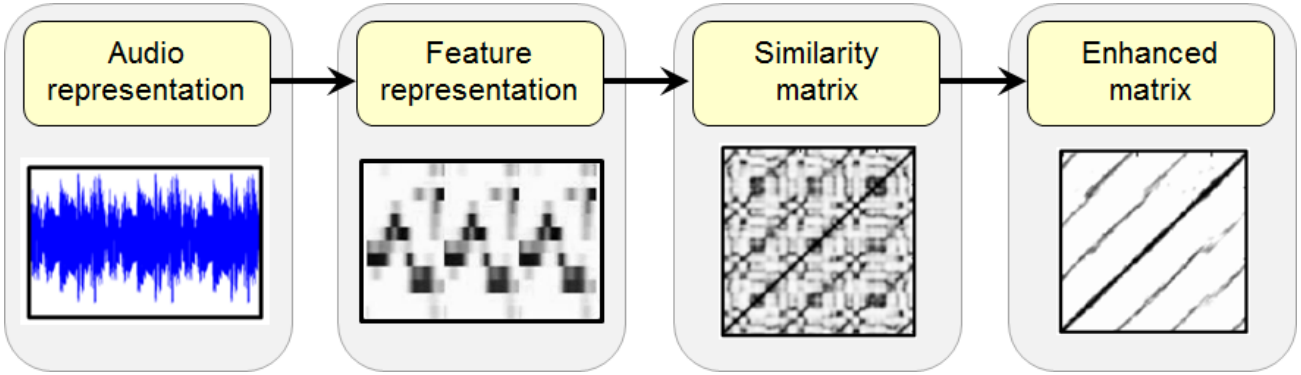
Maximization



Smoothing & Maximization



Similarity Matrix Toolbox



Meinard Müller, Nanzhu Jiang, Harald Grohganz
SM Toolbox: MATLAB Implementations for Computing and Enhancing Similarity Matrices

http://www.audiolabs-erlangen.de/resources/MIR/SMtoolbox/

Overview

- Introduction
- Feature Representations
- Self-Similarity Matrices
- Audio Thumbnailing
- Novelty-based Segmentation
- Converting Path to Block Structures

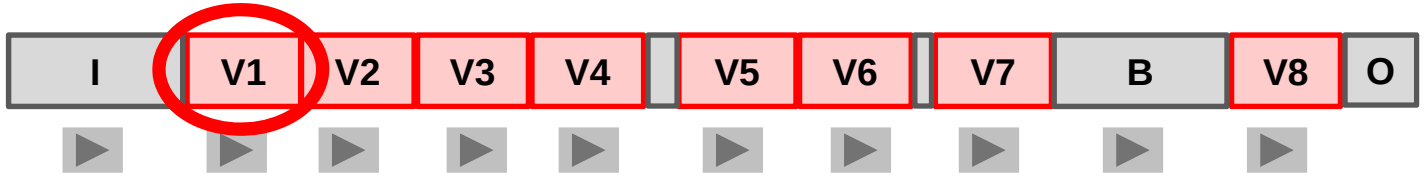
Thanks:

- Jiang, Grosche
- Peeters
- Cooper, Foote
- Goto
- Levy, Sandler
- Mauch
- Sapp

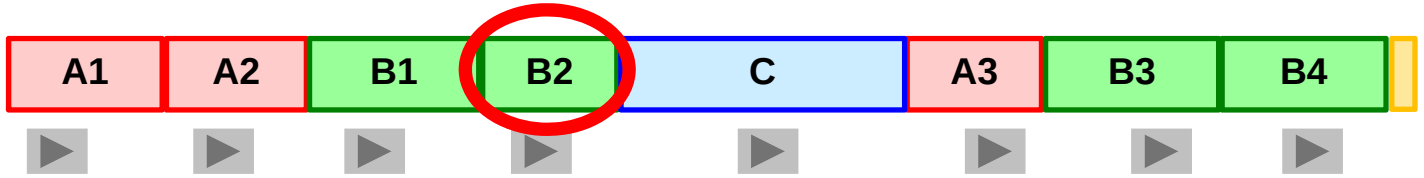
Audio Thumbnailing

General goal: Determine the most representative section ("Thumbnail") of a given music recording.

Example: Zager & Evans "In The Year 2525"



Example: Brahms Hungarian Dance No. 5 (Ormandy)



Thumbnail is often assumed to be the most repetitive segment

Audio Thumbnailing

Two steps

1. Path extraction

2. Grouping

Both steps are problematic!

- Paths of poor quality (fragmented, gaps)
- Block-like structures
- Curved paths

- Noisy relations
  (missing, distorted, overlapping)
- Transitivity computation difficult

Main idea: Do both, path extraction and grouping, jointly

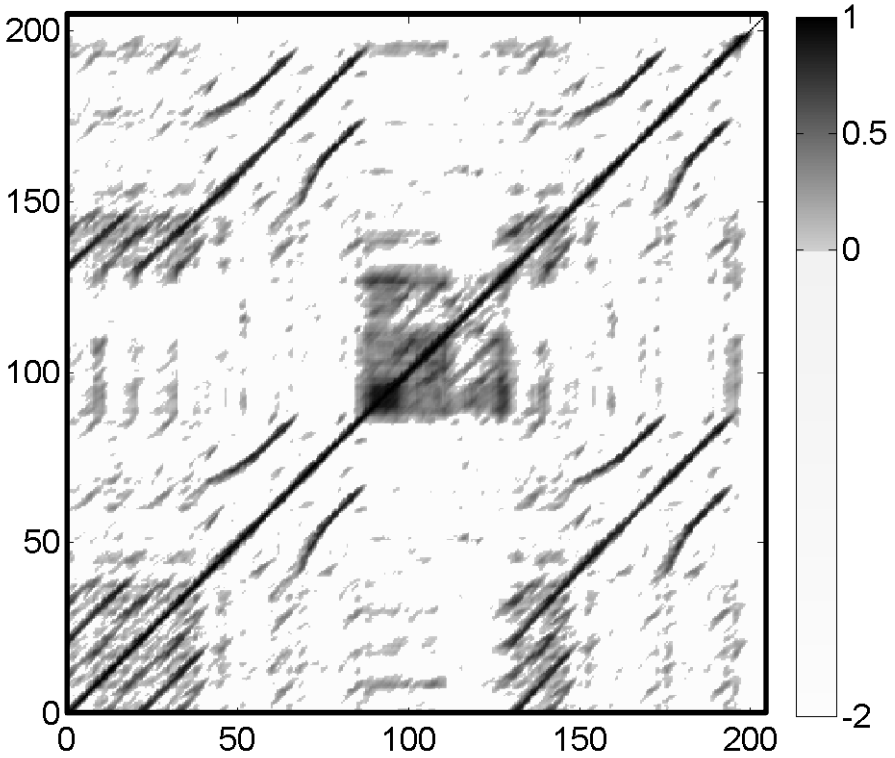
- One optimization scheme for both steps
- Stabilizing effect
- Efficient

Audio Thumbnailing

Main idea: Do both path extraction and grouping jointly

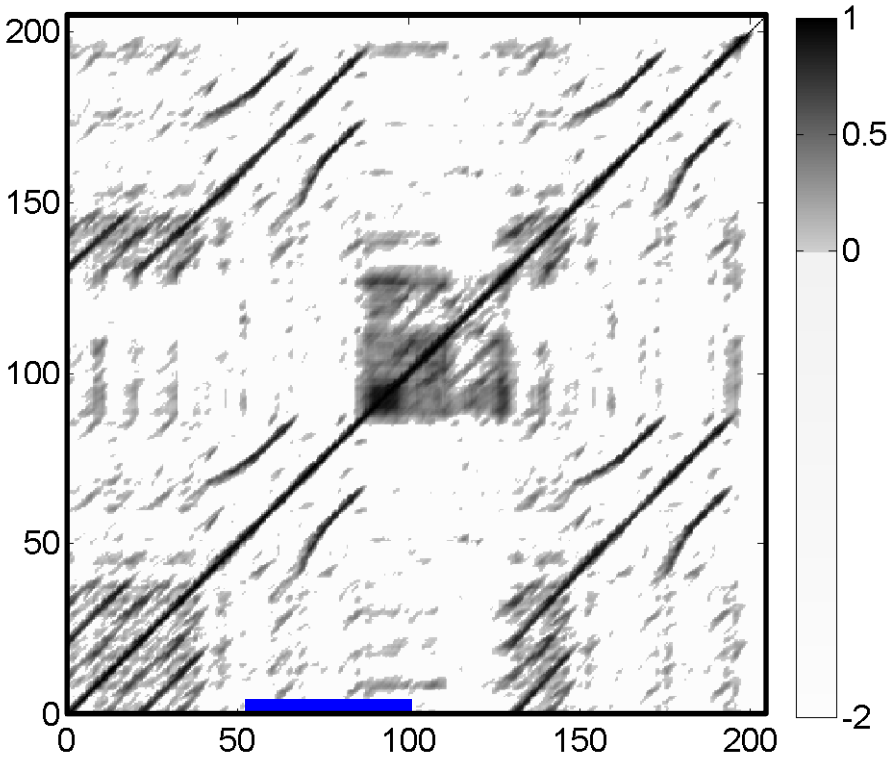
- For each audio segment we define a fitness value
- This fitness value expresses “how well” the segment explains the entire audio recording
- The segment with the highest fitness value is considered to be the thumbnail
- As main technical concept we introduce the notion of a path family

Fitness Measure



Enhanced SSM

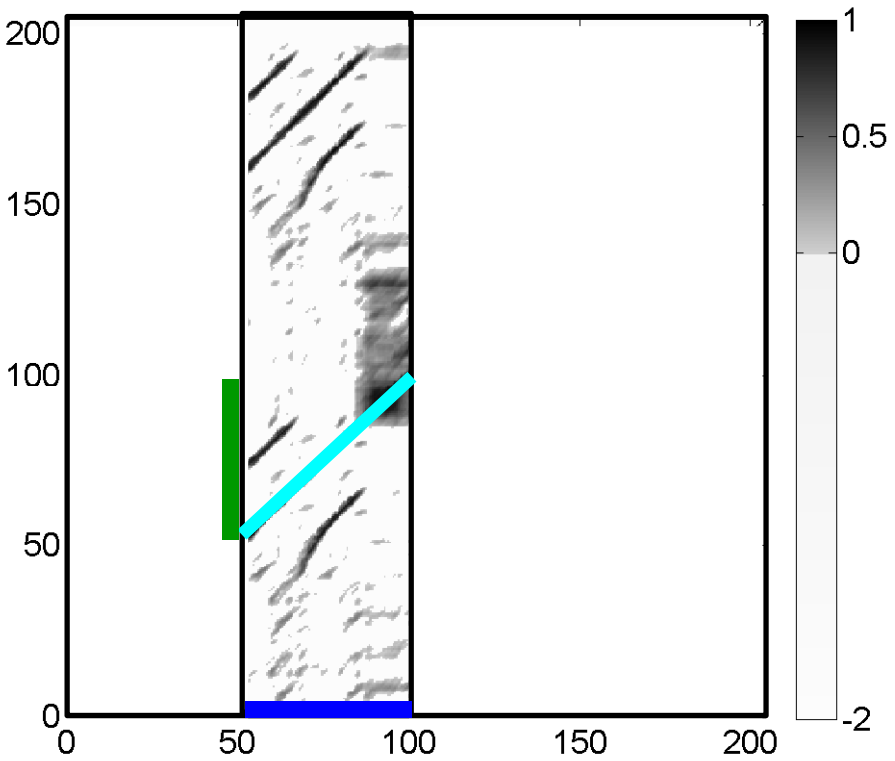
Fitness Measure



Path over segment

- Consider a fixed segment

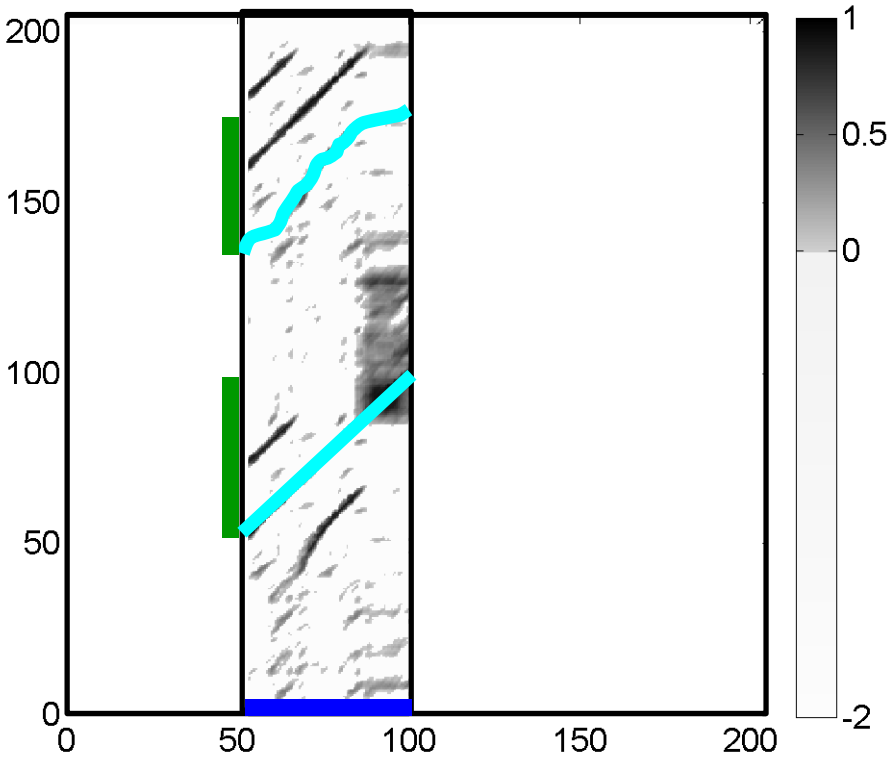
Fitness Measure



Path over segment

- Consider a fixed segment
- Path over segment
- Induced segment
- Score is high

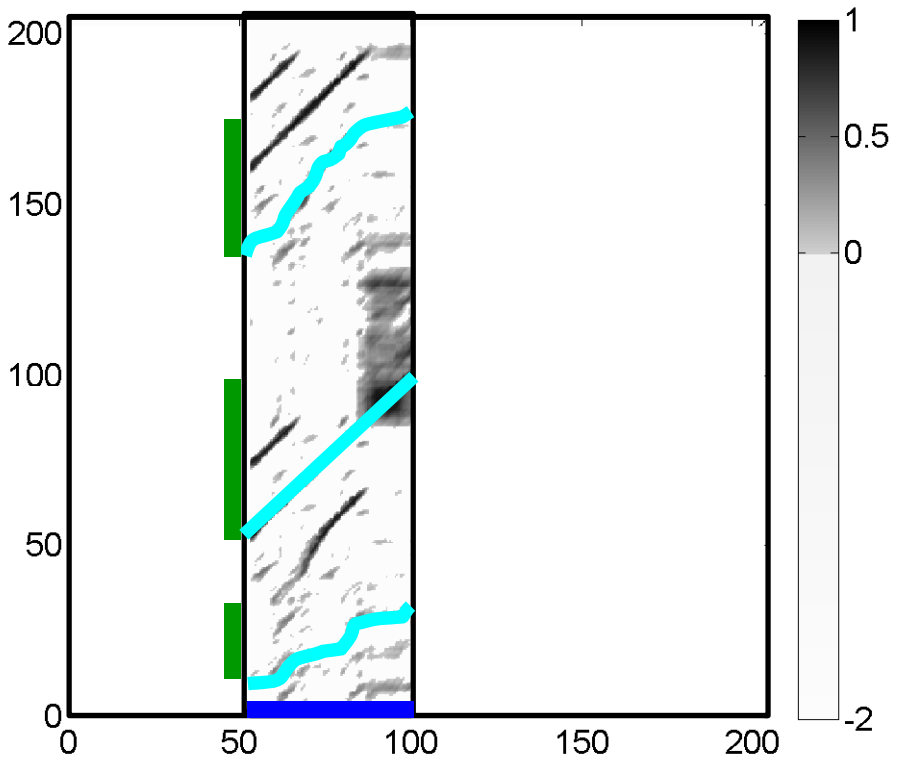
Fitness Measure



Path over segment

- Consider a fixed segment
- Path over segment
- Induced segment
- Score is high
- A second path over segment
- Induced segment
- Score is not so high

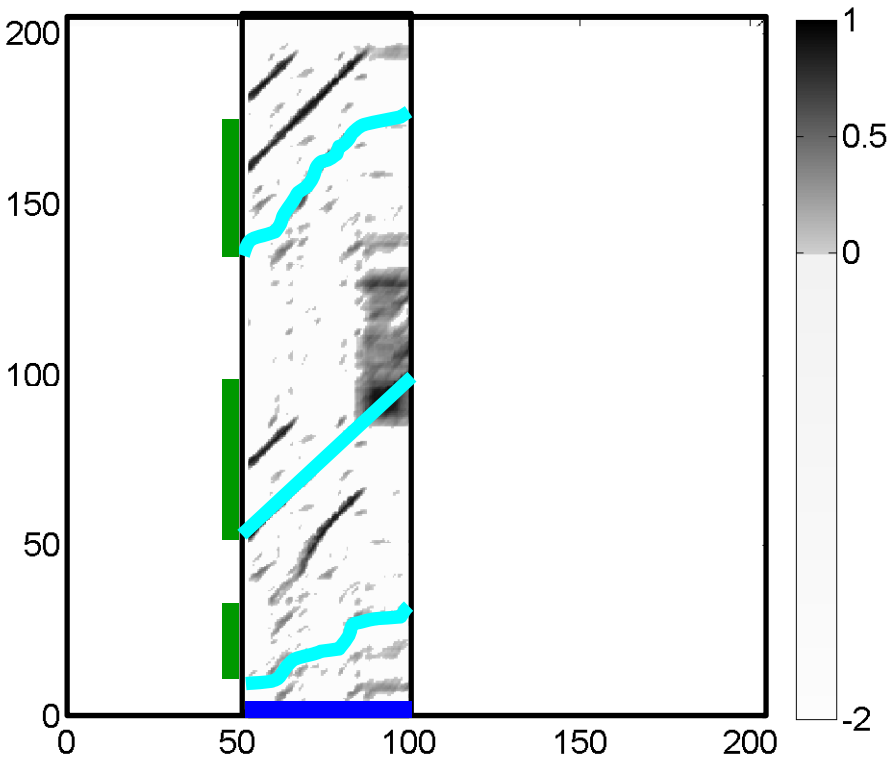
Fitness Measure



Path over segment

- Consider a fixed segment
- Path over segment
- Induced segment
- Score is high
- A second path over segment
- Induced segment
- Score is not so high
- A third path over segment
- Induced segment
- Score is very low

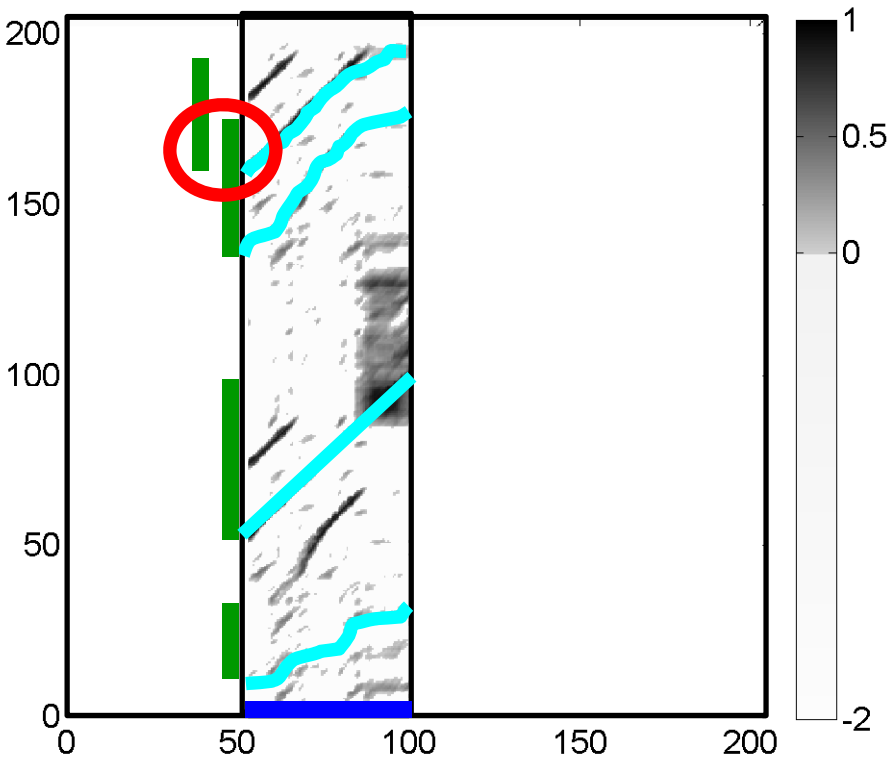
Fitness Measure



Path family

- Consider a fixed segment
- A path family over a segment is a family of paths such that the induced segments do not overlap.

Fitness Measure

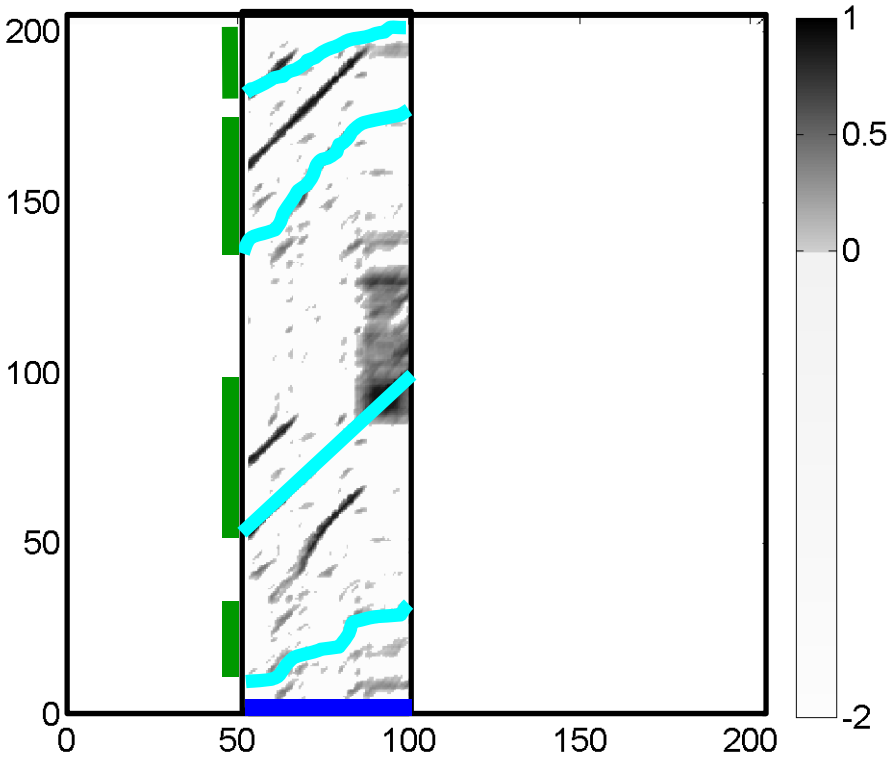


Path family

- Consider a fixed segment
- A path family over a segment is a family of paths such that the induced segments do not overlap.

This is not a path family!

Fitness Measure



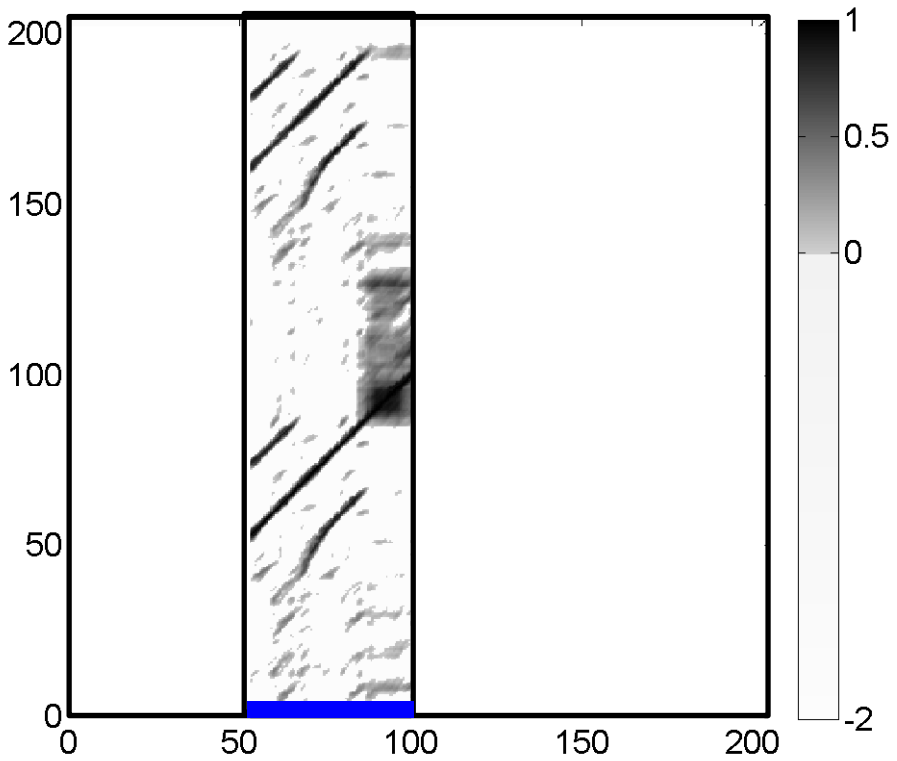
Path family

- Consider a fixed segment
- A path family over a segment is a family of paths such that the induced segments do not overlap.

This is a path family!

(Even though not a good one)

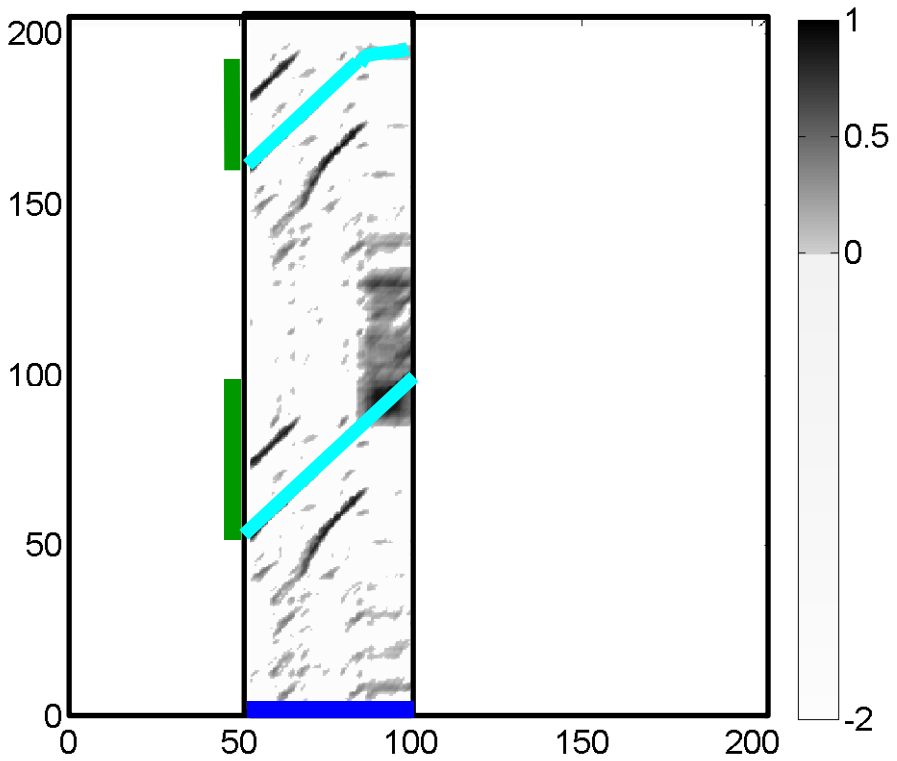
Fitness Measure



Optimal path family

- Consider a fixed segment

Fitness Measure



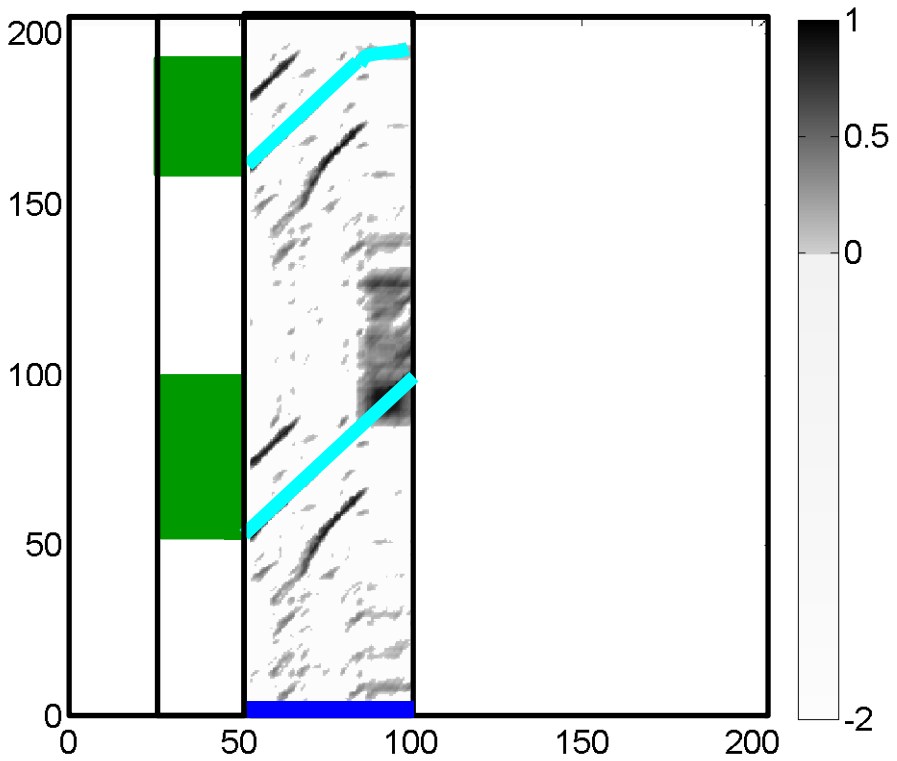
Optimal path family

- Consider a fixed segment
- Consider over the segment the optimal path family, i.e., the path family having maximal overall score.
- Call this value:

Score(segment)

Note: This optimal path family can be computed using dynamic programming.

Fitness Measure



Optimal path family

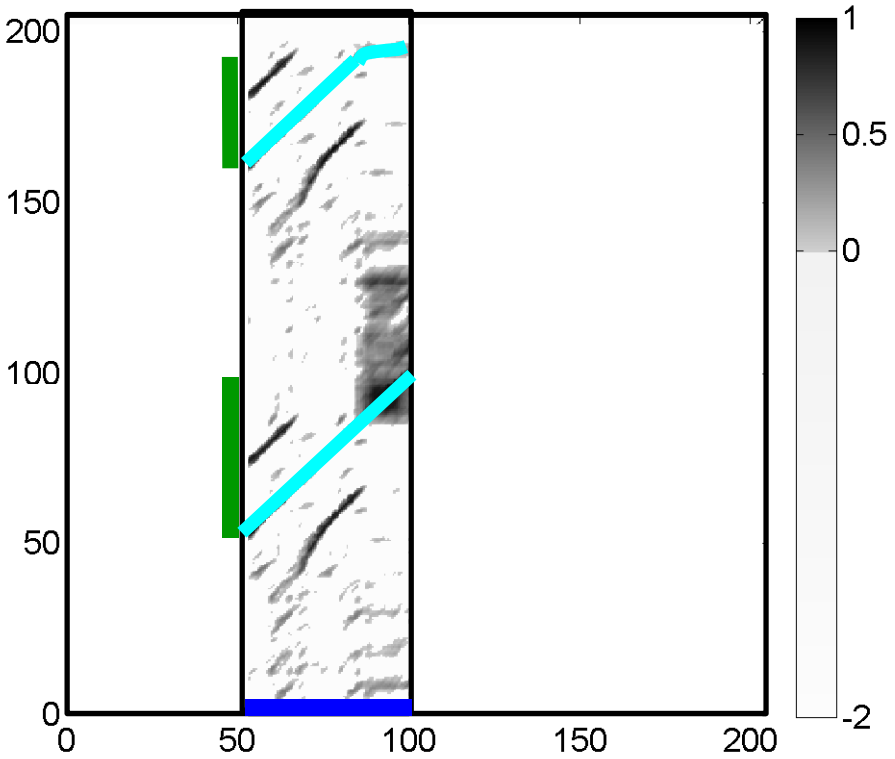
- Consider a fixed segment
- Consider over the segment the optimal path family, i.e., the path family having maximal overall score.
- Call this value:

  Score(segment)

- Furthermore consider the amount covered by the induced segments.
- Call this value:

  Coverage(segment)

Fitness Measure



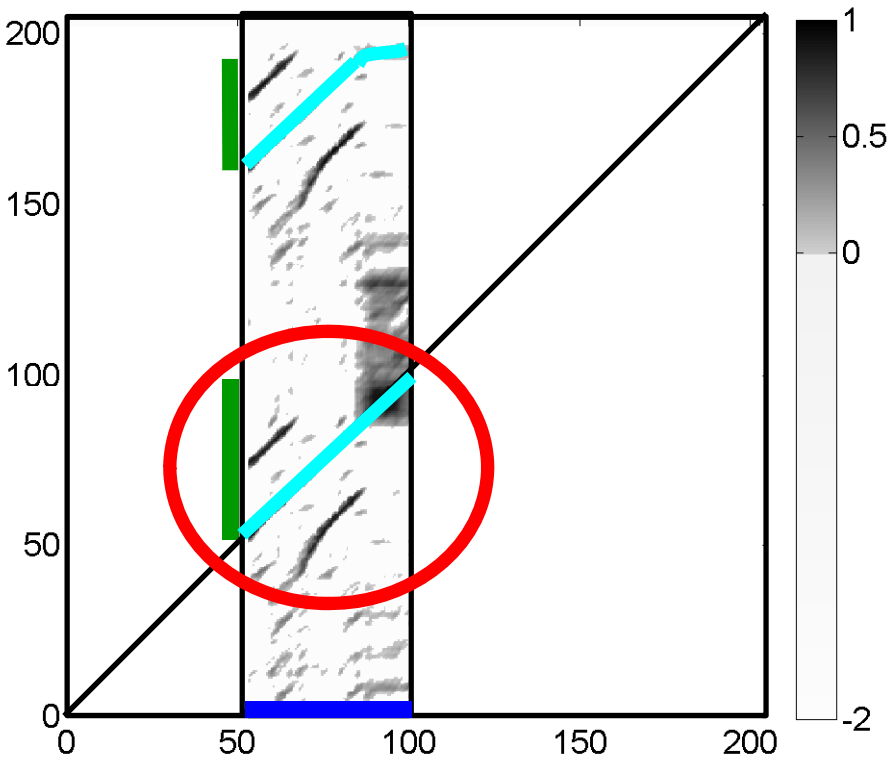
P := Score(segment)

R := Coverage(segment)

Fitness

- Consider a fixed segment

Fitness Measure



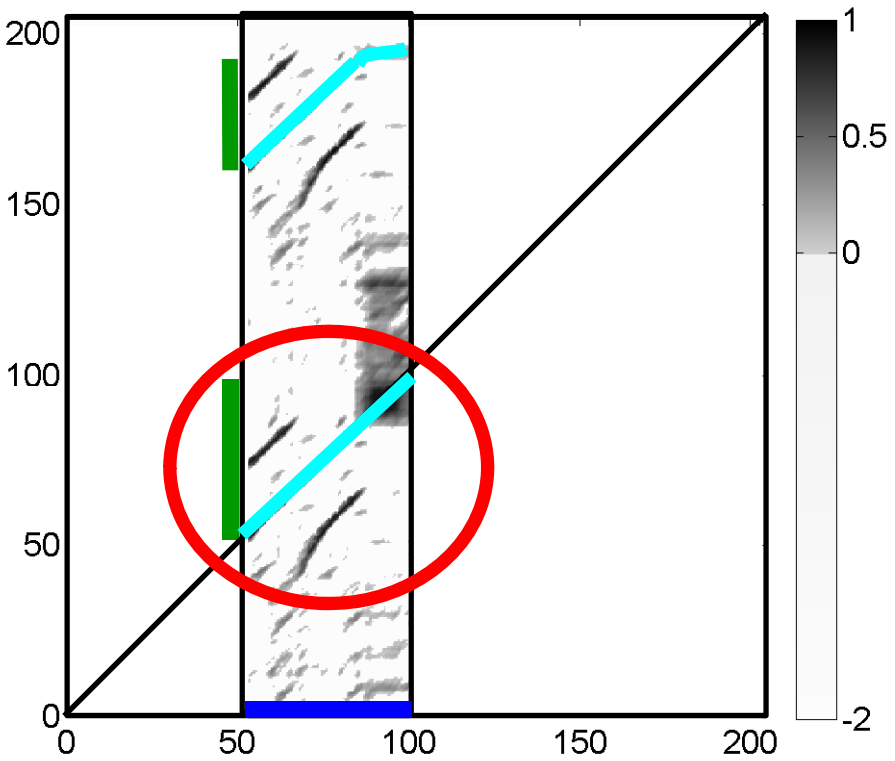
P := Score(segment)

R := Coverage(segment)

Fitness

- Consider a fixed segment
- Self-explanation are trivial!

Fitness Measure



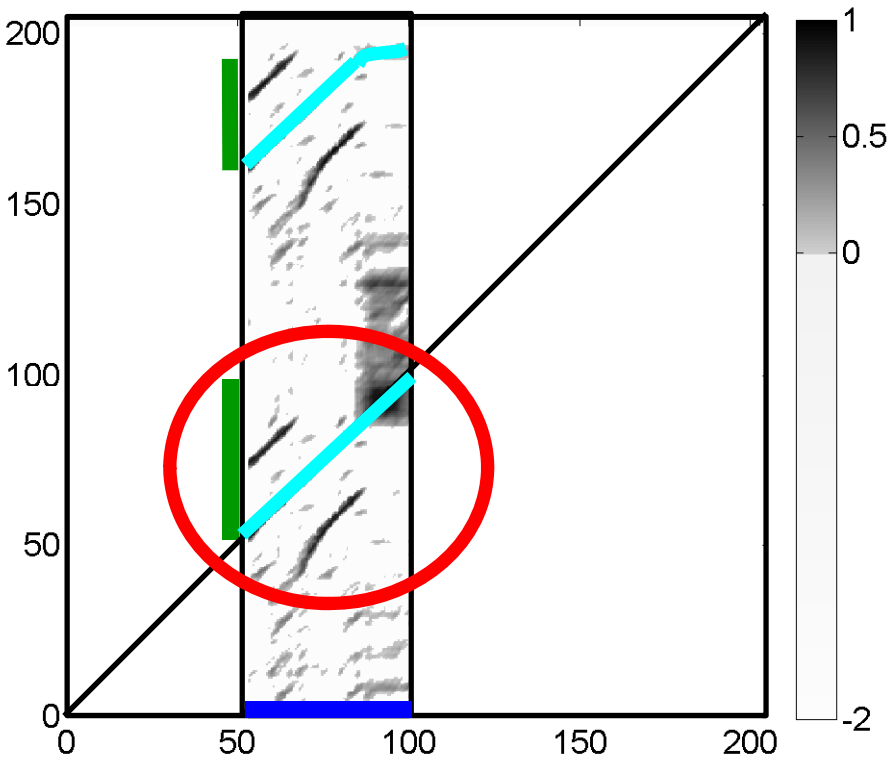
Fitness

- Consider a fixed segment
- Self-explanation are trivial!
- Subtract length of segment

P := Score(segment) - length(segment)

R := Coverage(segment) - length(segment)

Fitness Measure



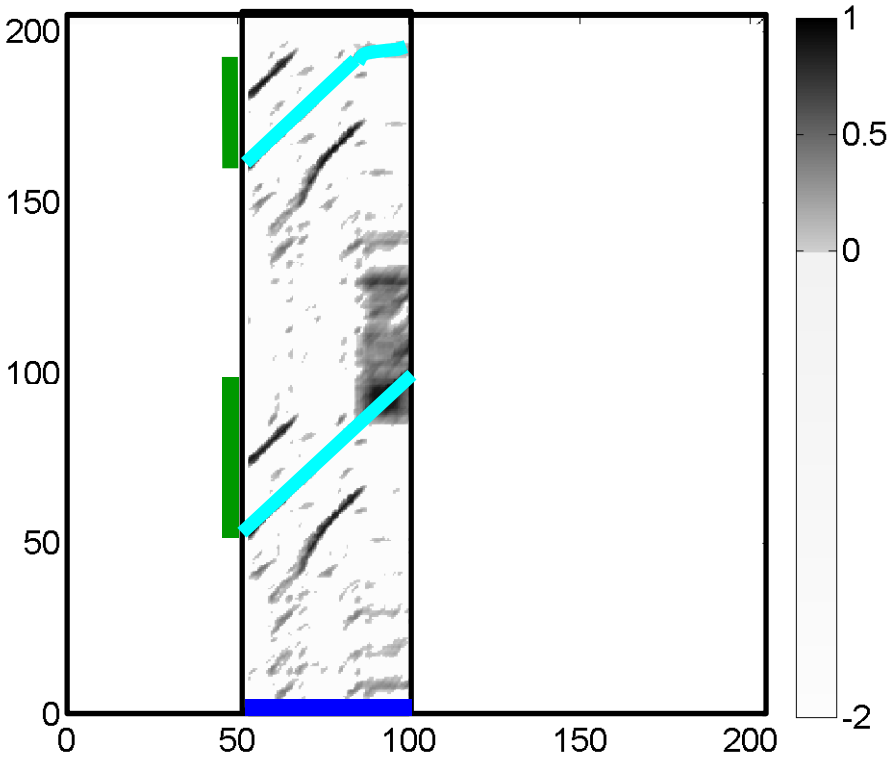
Fitness

- Consider a fixed segment
- Self-explanation are trivial!
- Subtract length of segment
- Normalization

P := Normalize(Score(segment) - length(segment)) $\in [0,1]$

R := Normalize(Coverage(segment) - length(segment)) $\in [0,1]$

Fitness Measure



Fitness

- Consider a fixed segment

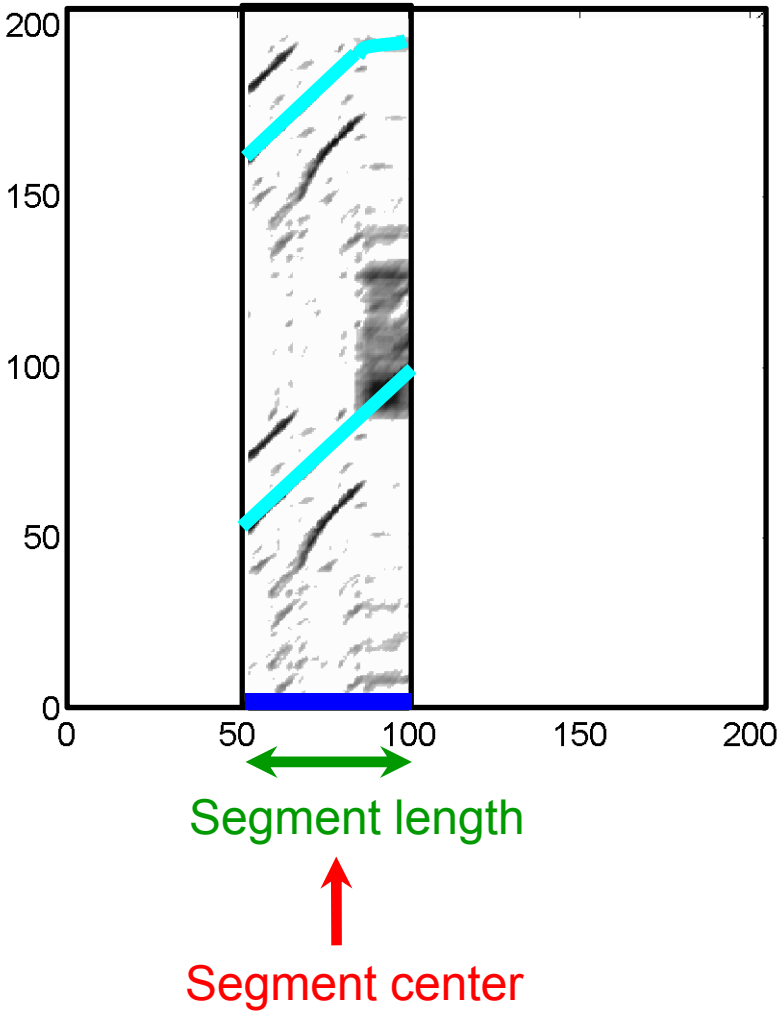
Fitness(segment)

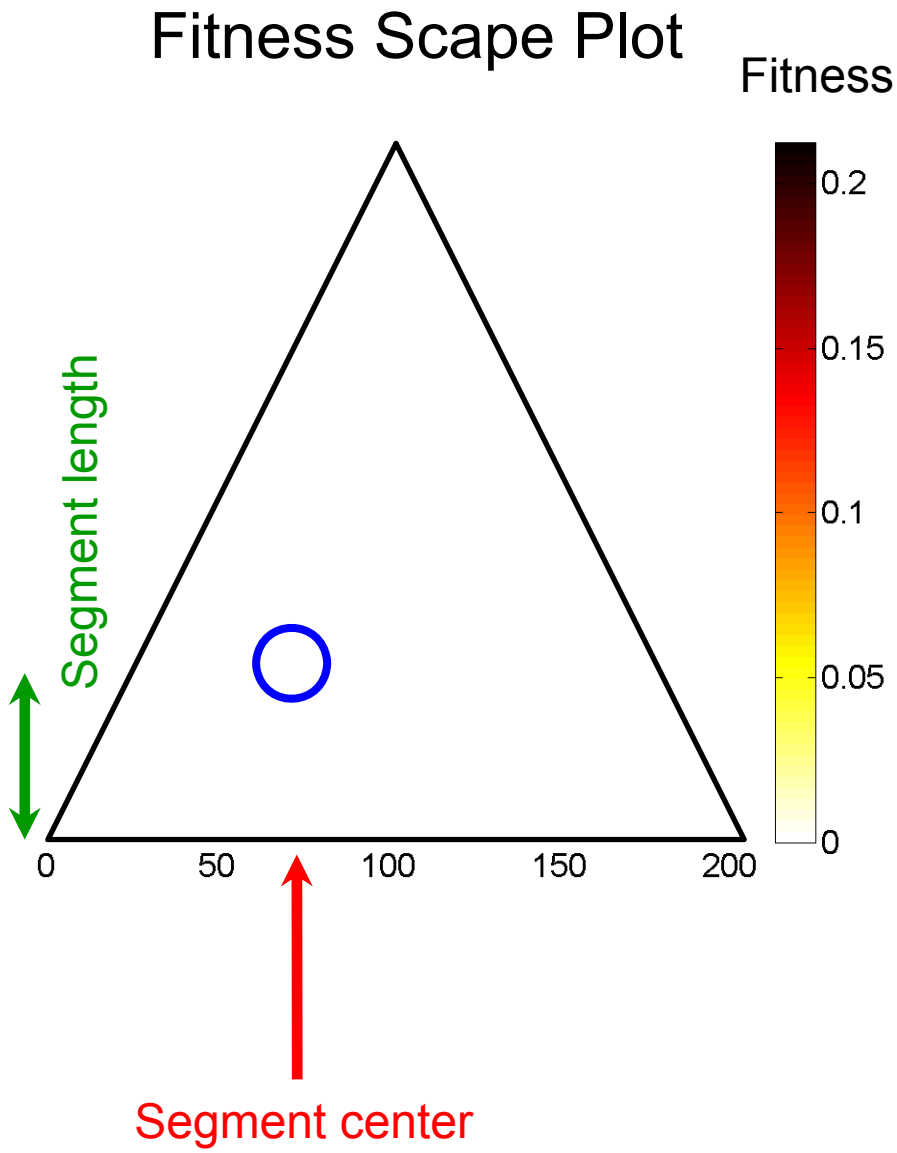
F := 2 • P • R / (P + R)

P := Normalize(Score(segment) - length(segment)) $\in [0,1]$

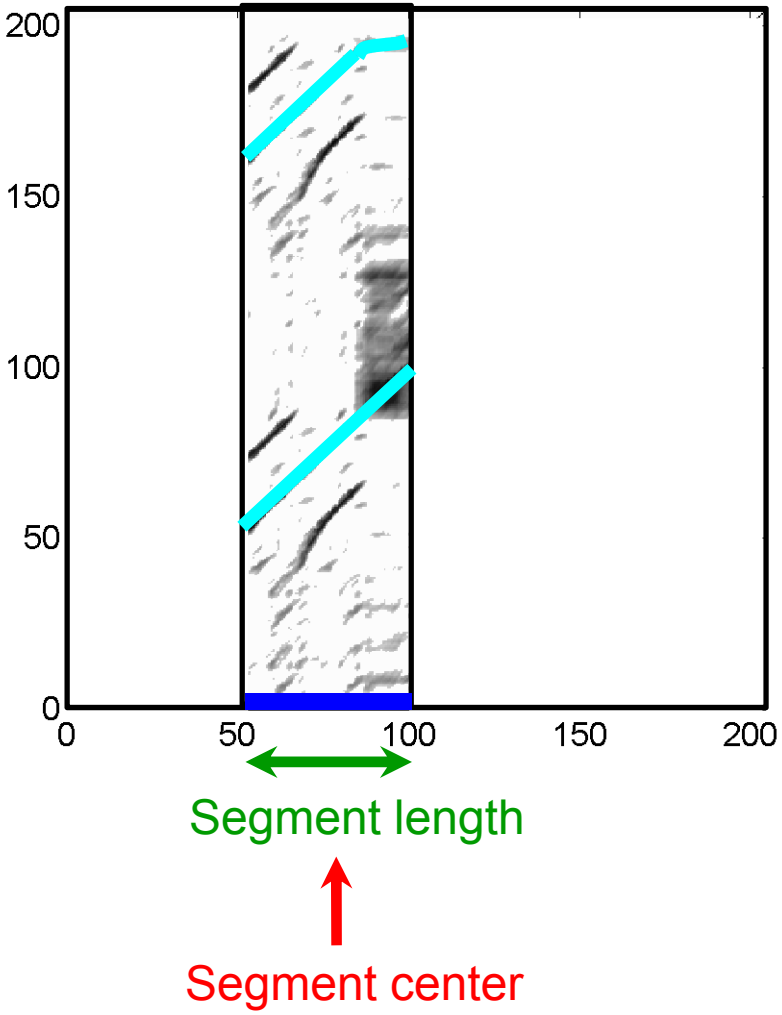
R := Normalize(Coverage(segment) - length(segment)) $\in [0,1]$

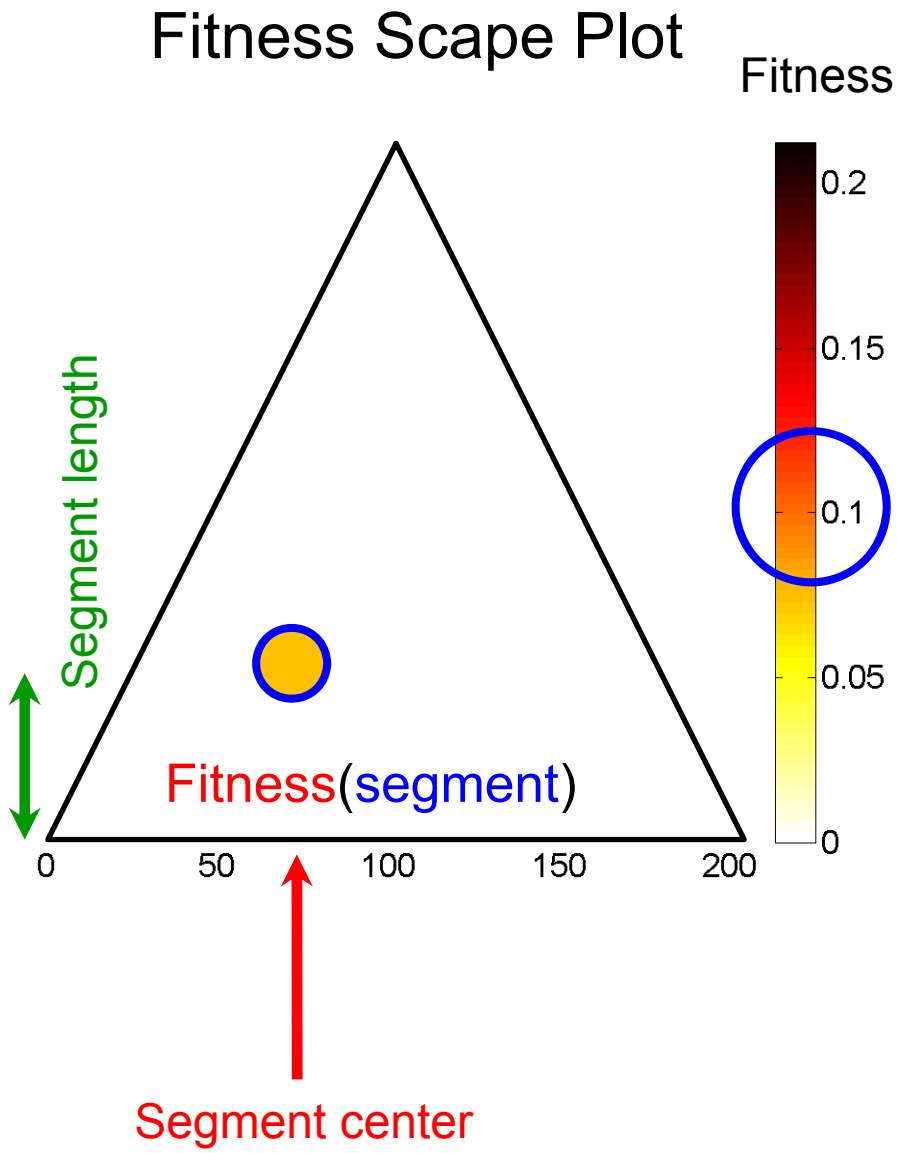
Thumbnail


200
150
100
50
0
0
50
100
150
200
Segment length
Segment center

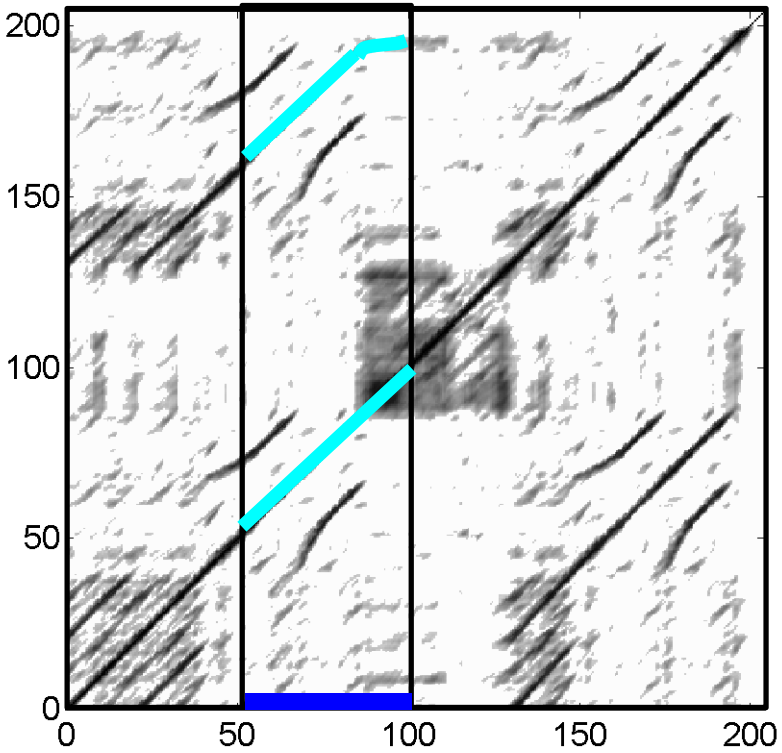

Fitness Scape Plot
Fitness
0.2
0.15
0.1
0.05
0
Segment length
0
50
100
150
200
Segment center

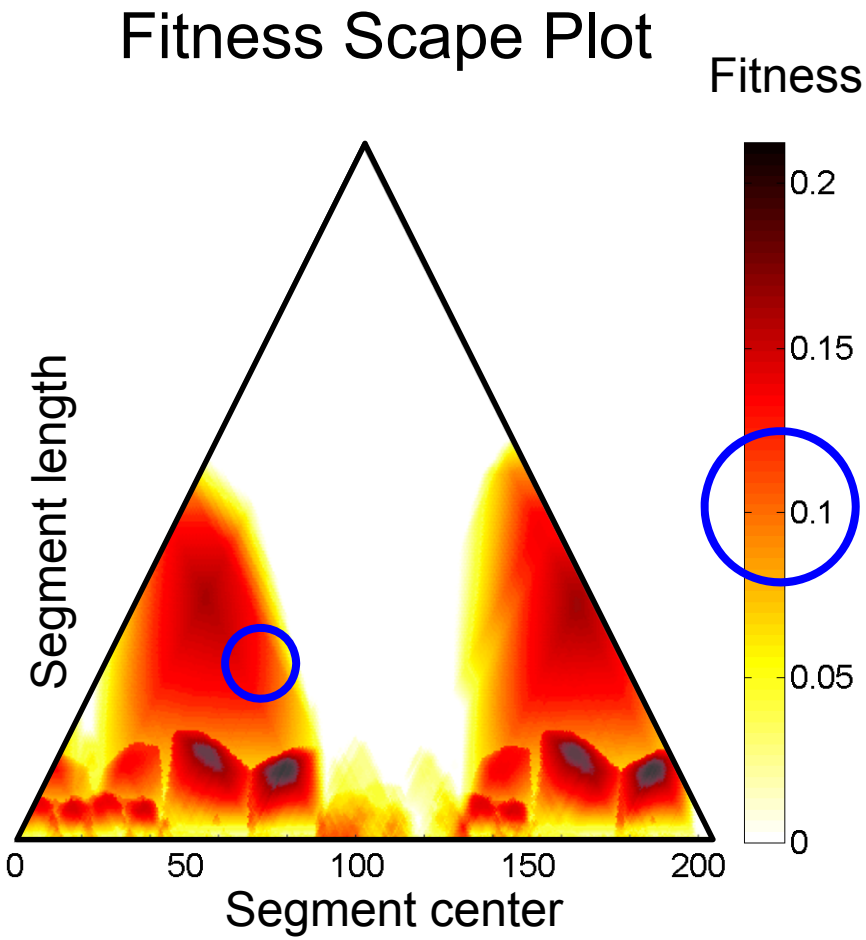
Thumbnail


200
150
100
50
0
0
50
100
150
200
Segment length
Segment center

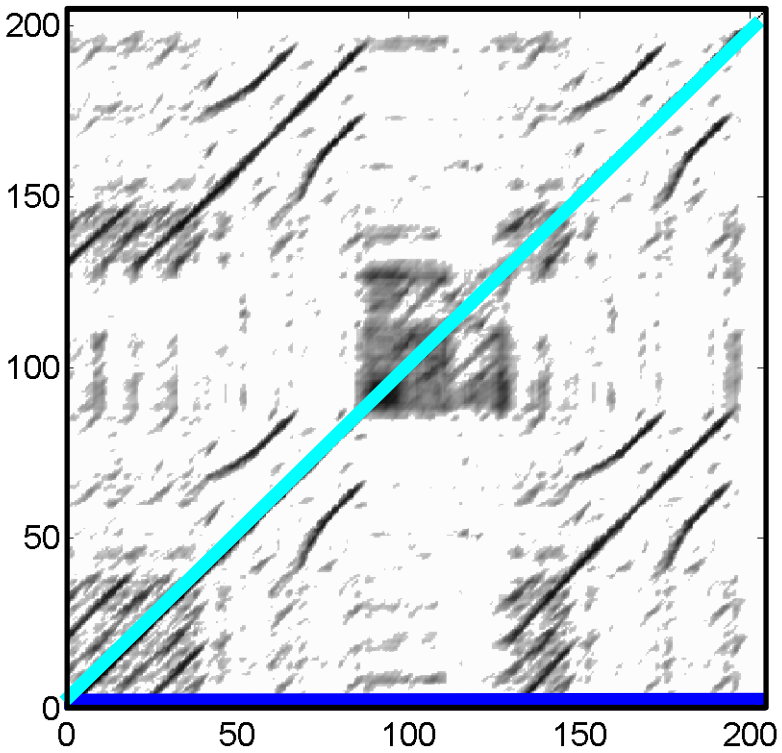

Fitness Scape Plot
Fitness
0.2
0.15
0.1
0.05
0
Segment length
Fitness(segment)
0
50
100
150
200
Segment center

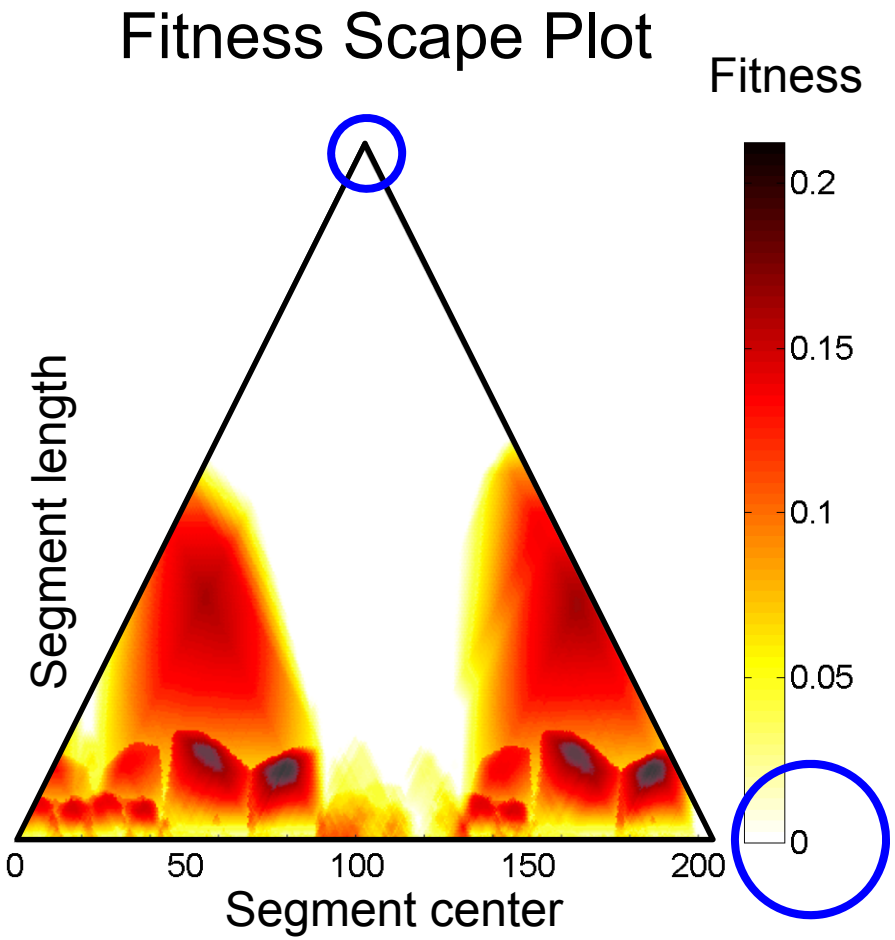
Thumbnail


200
150
100
50
0
0
50
100
150
200


Fitness Scape Plot
Fitness
0.2
0.15
0.1
0.05
0
Segment length
0
50
100
150
200
Segment center

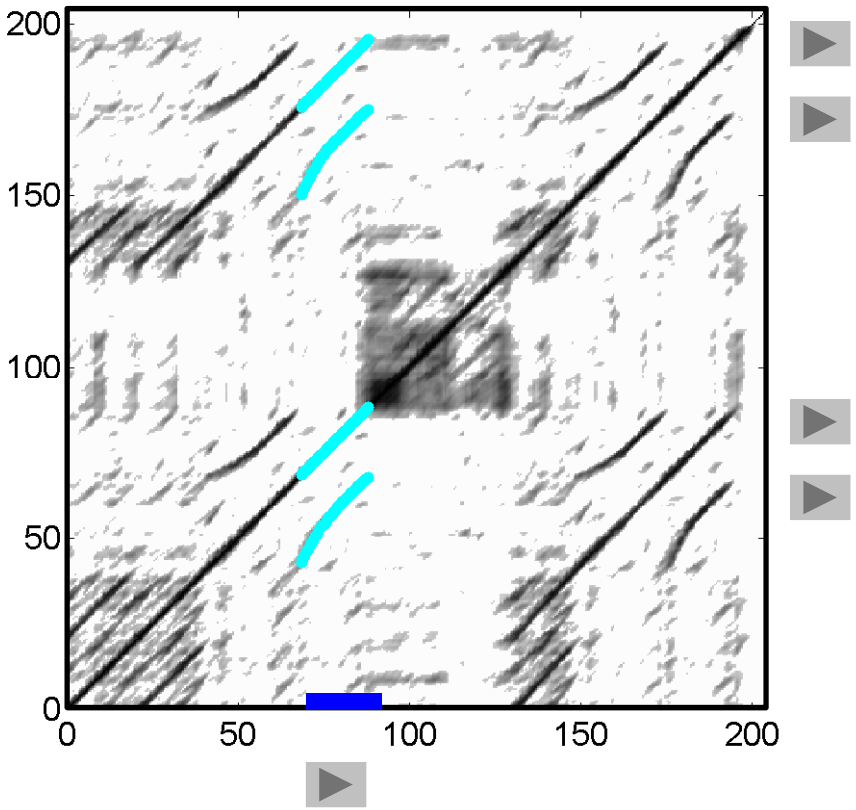
Thumbnail

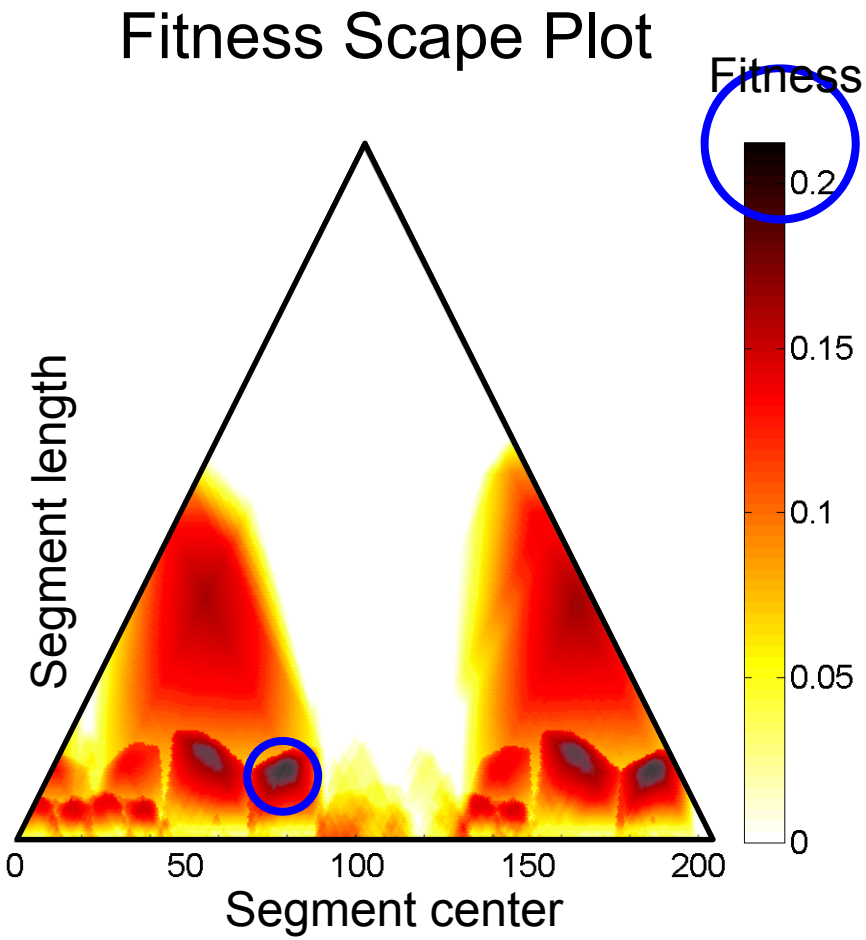




Note: Self-explanations are ignored → fitness is zero

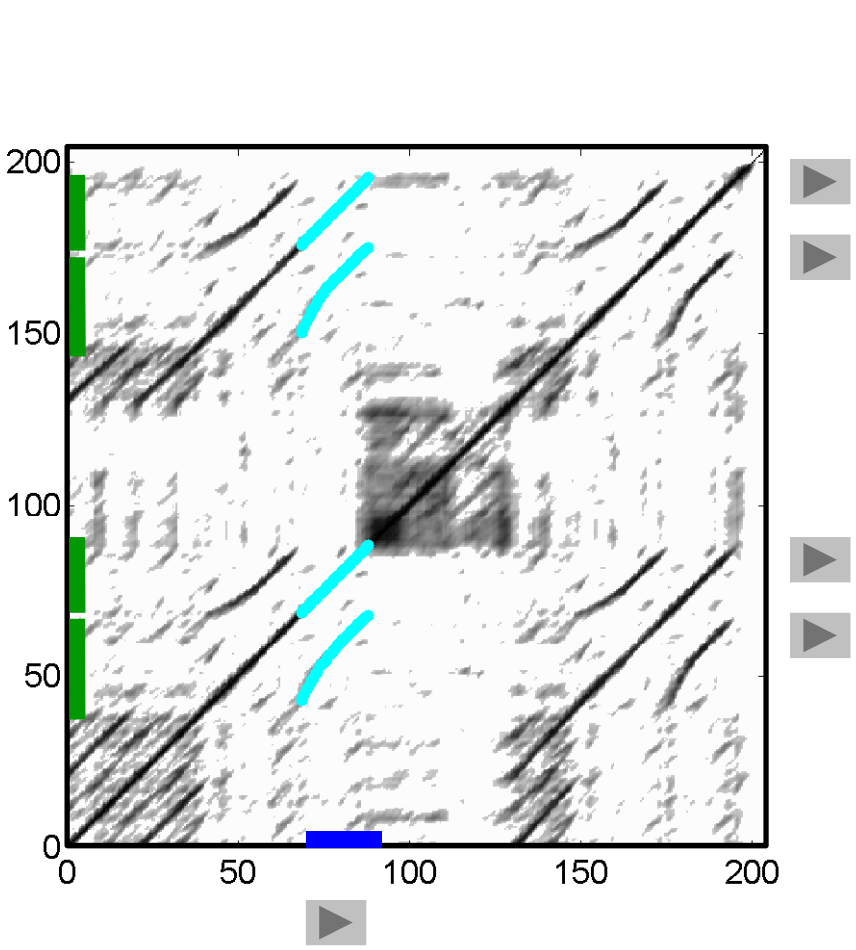
Thumbnail

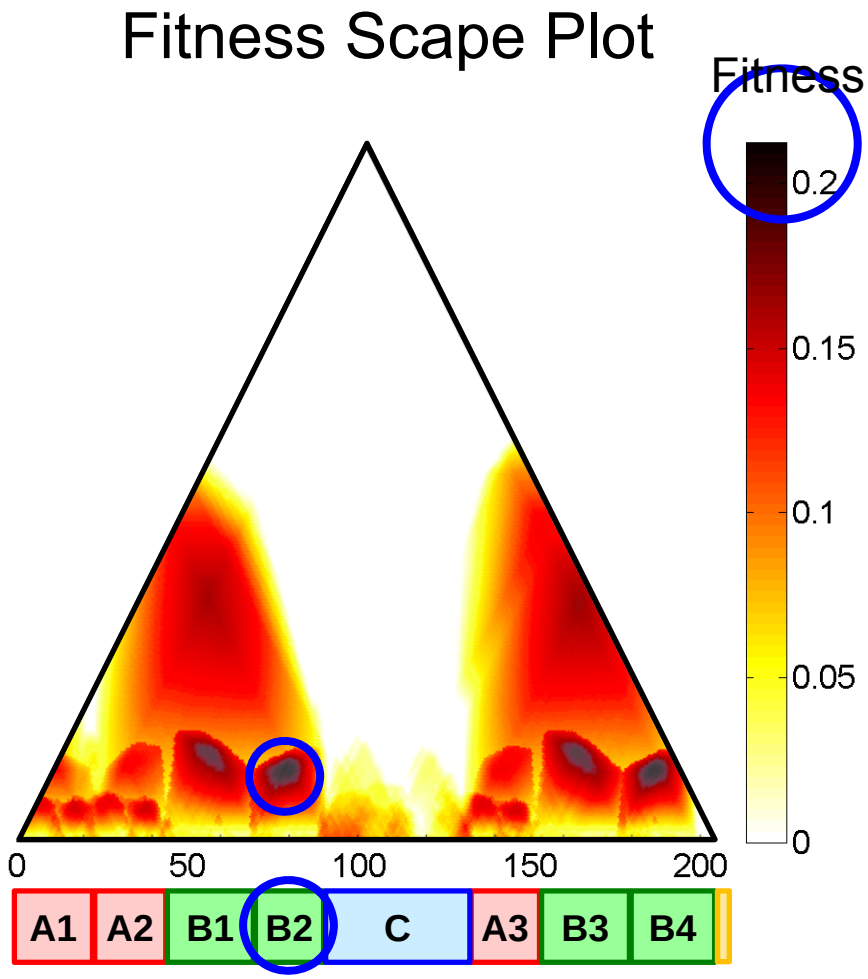




Thumbnail := segment having the highest fitness

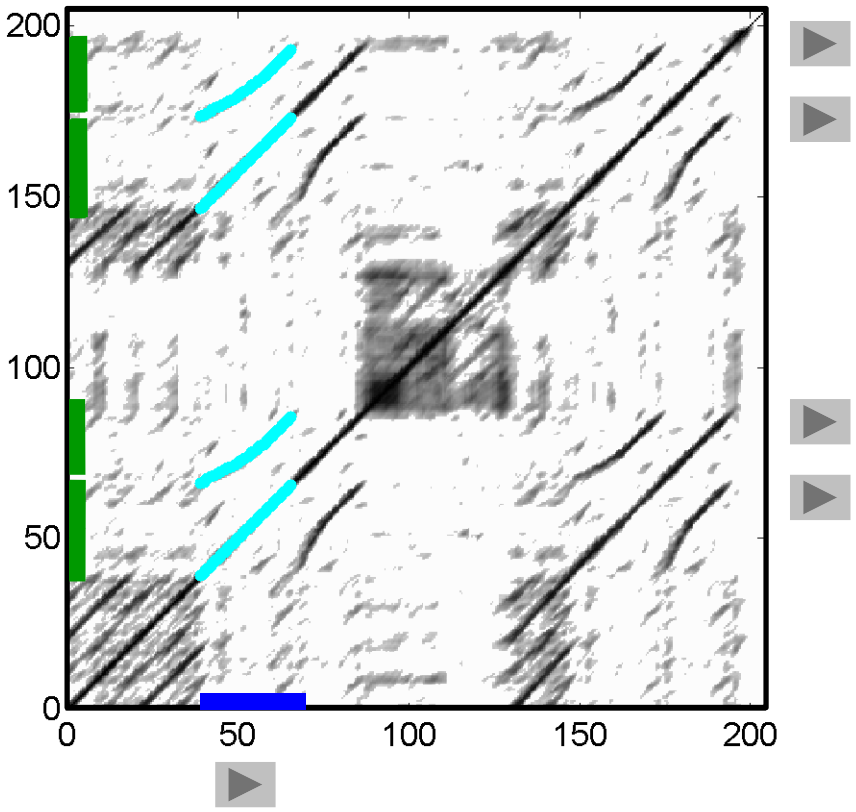
Thumbnail

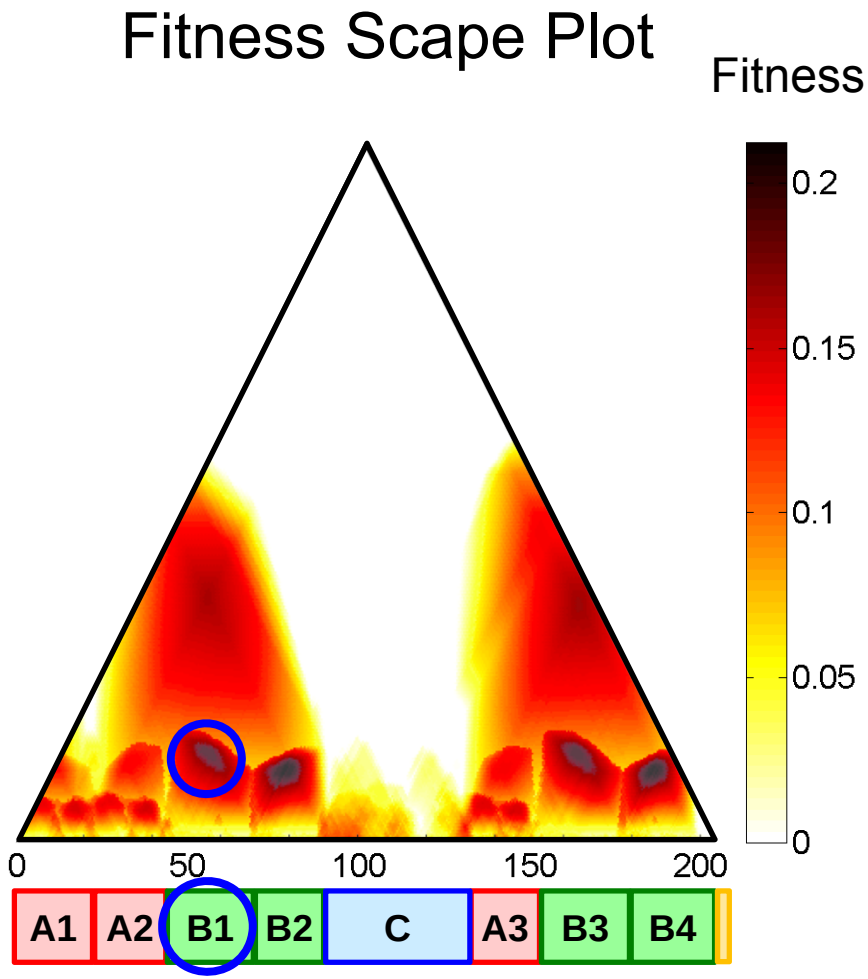




Example: Brahms Hungarian Dance No. 5 (Ormandy)

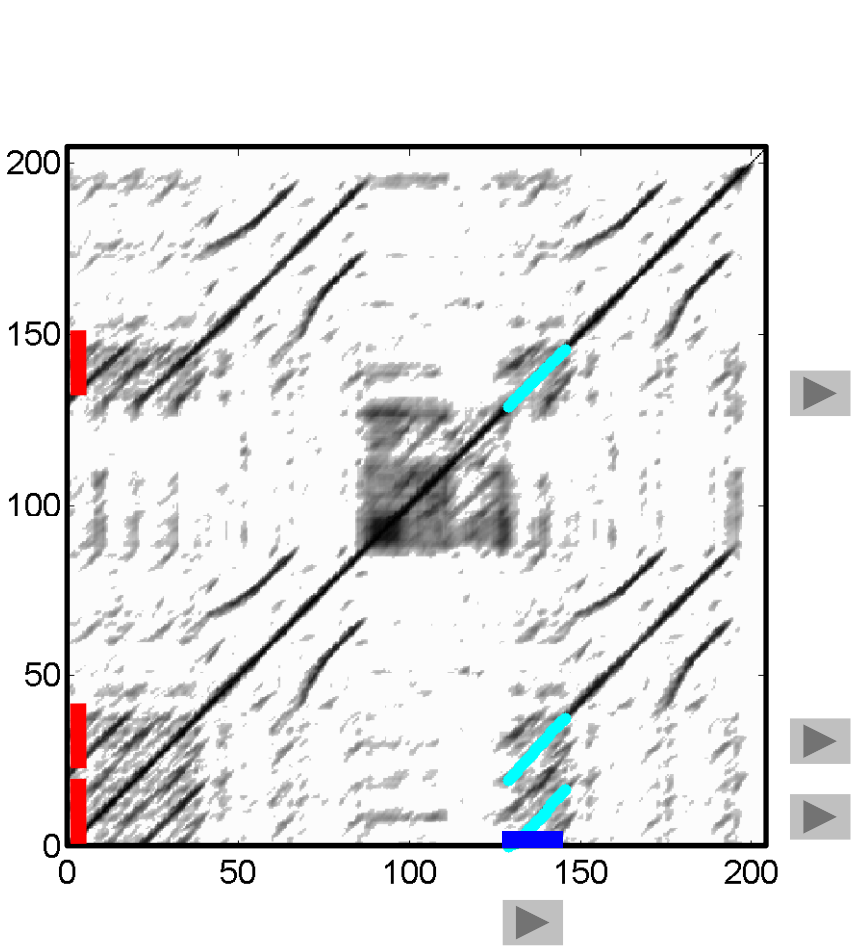
Thumbnail

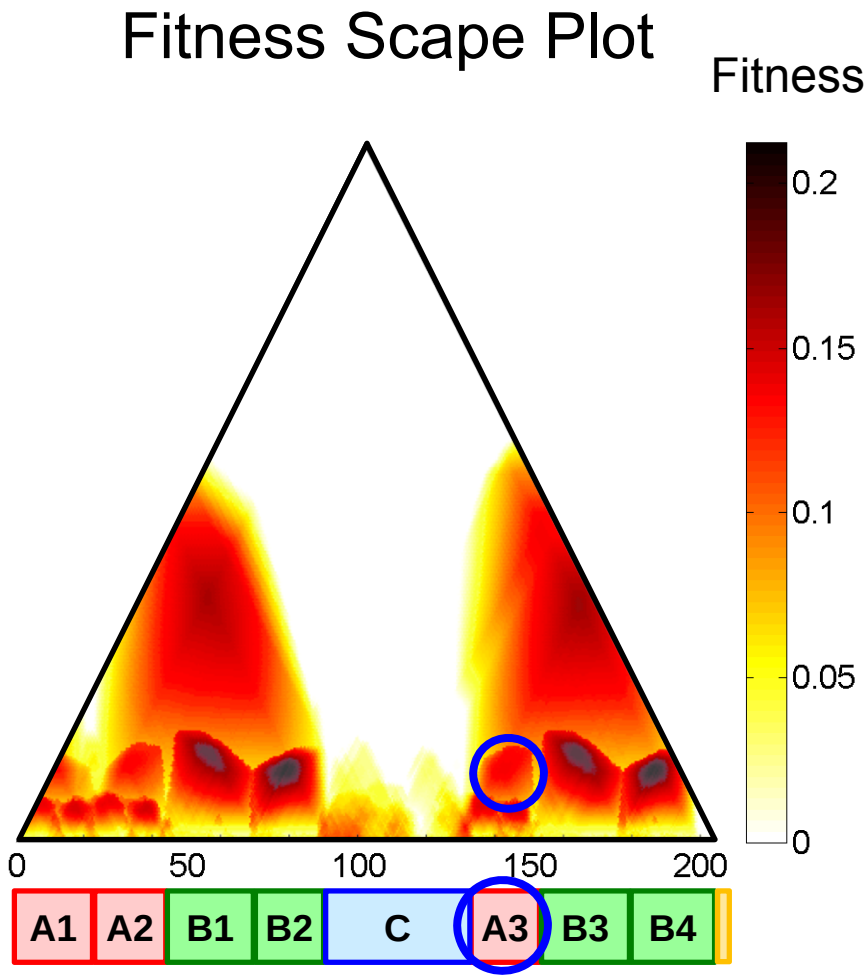




Example: Brahms Hungarian Dance No. 5 (Ormandy)

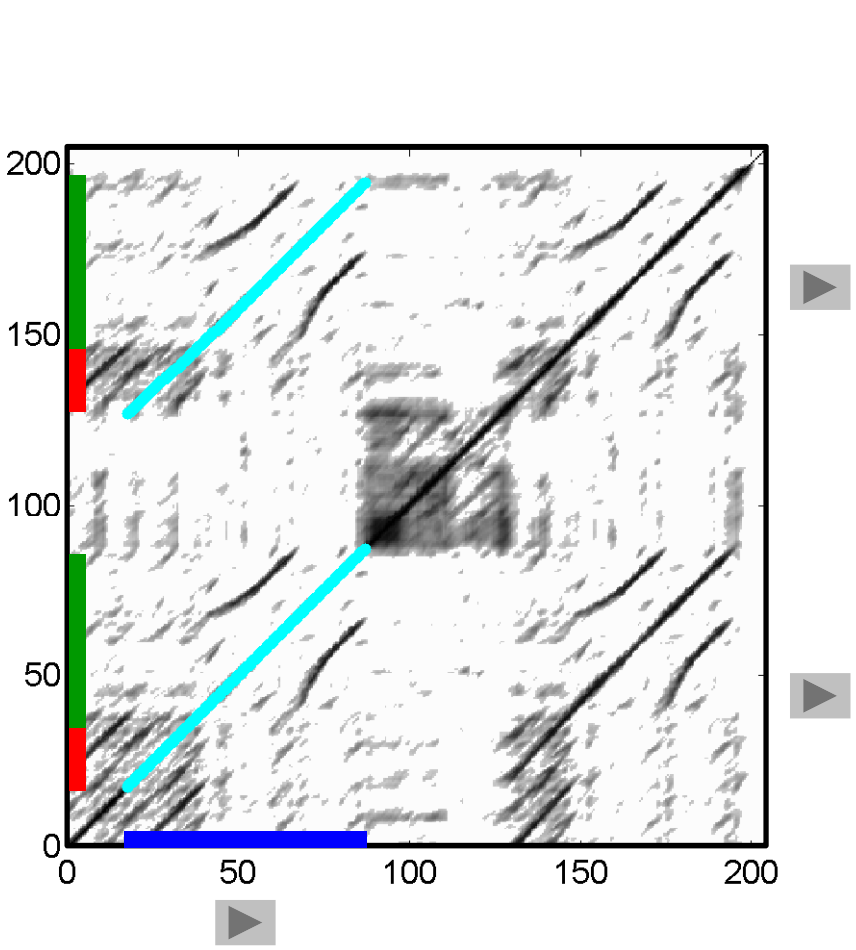
Thumbnail

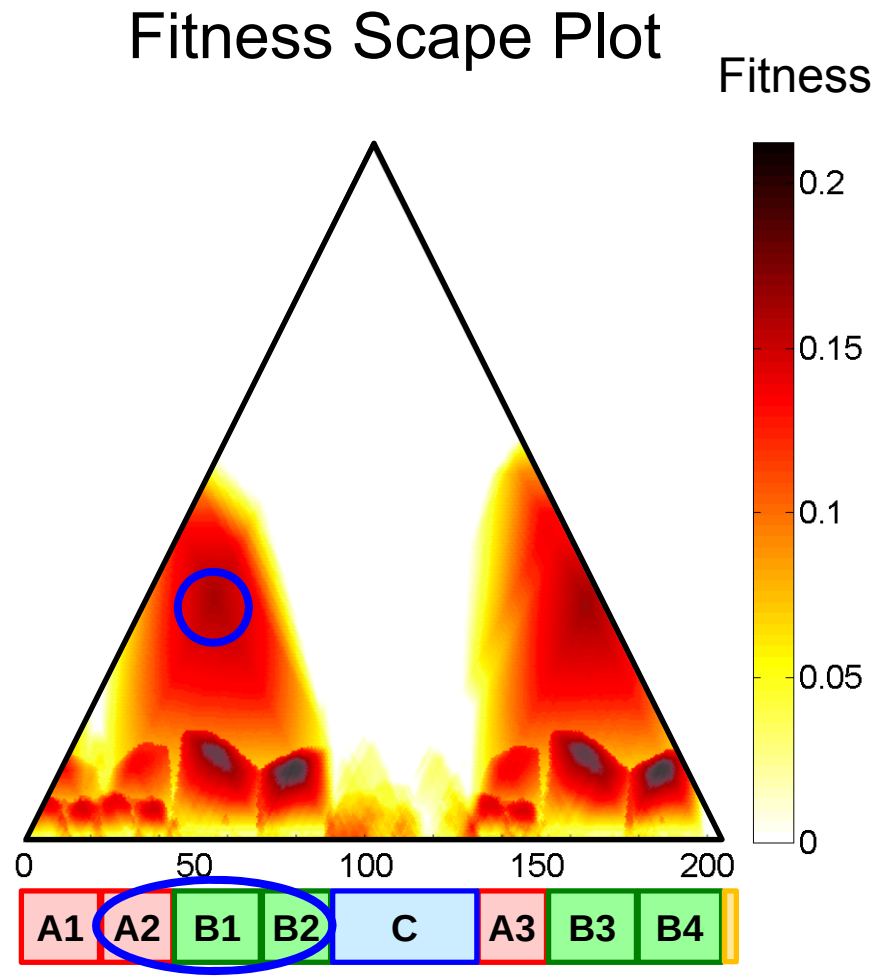




Example: Brahms Hungarian Dance No. 5 (Ormandy)

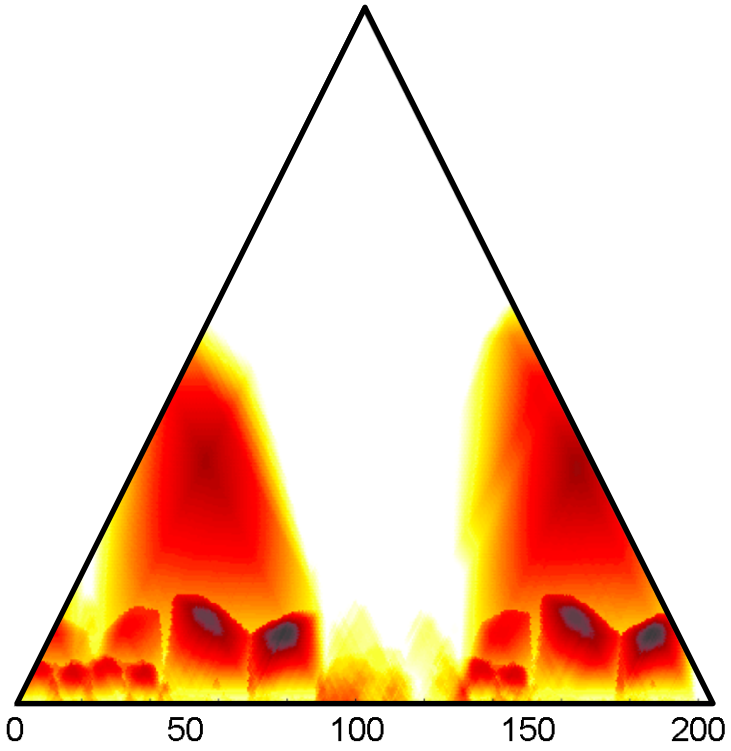
Thumbnail





Example: Brahms Hungarian Dance No. 5 (Ormandy)

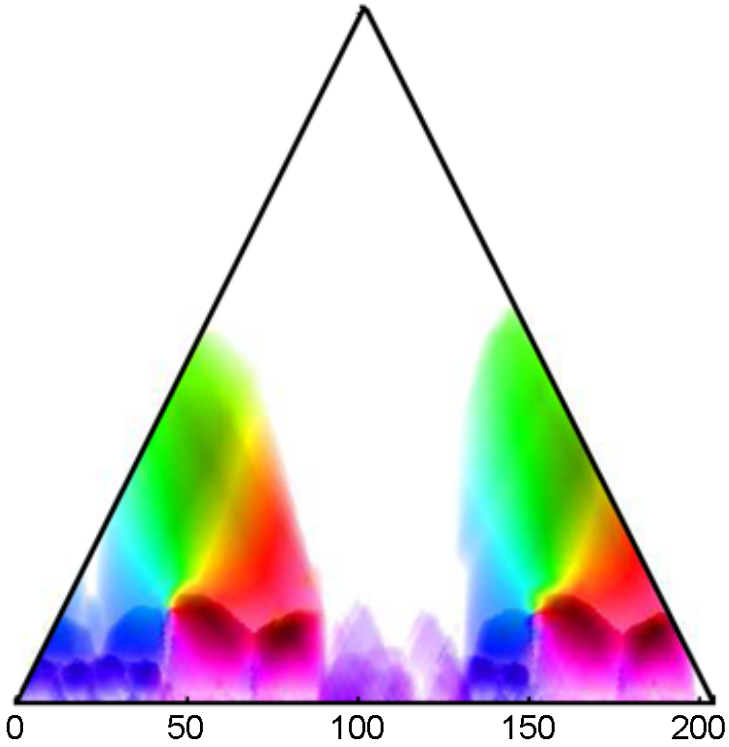
Scape Plot



Example: Brahms Hungarian Dance No. 5 (Ormandy)

Scape Plot

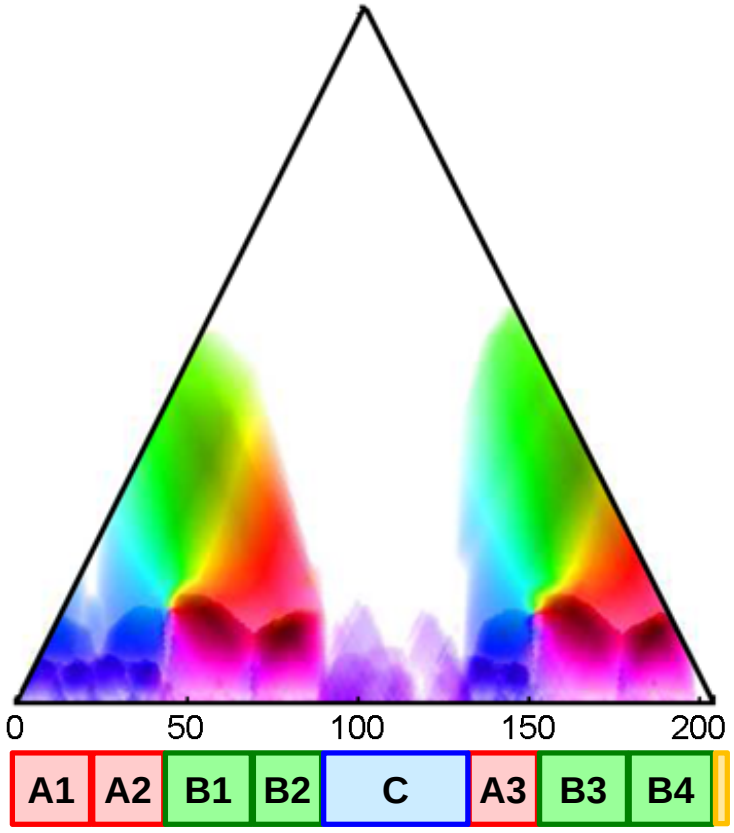
Coloring according to clustering result (grouping)



Example: Brahms Hungarian Dance No. 5 (Ormandy)

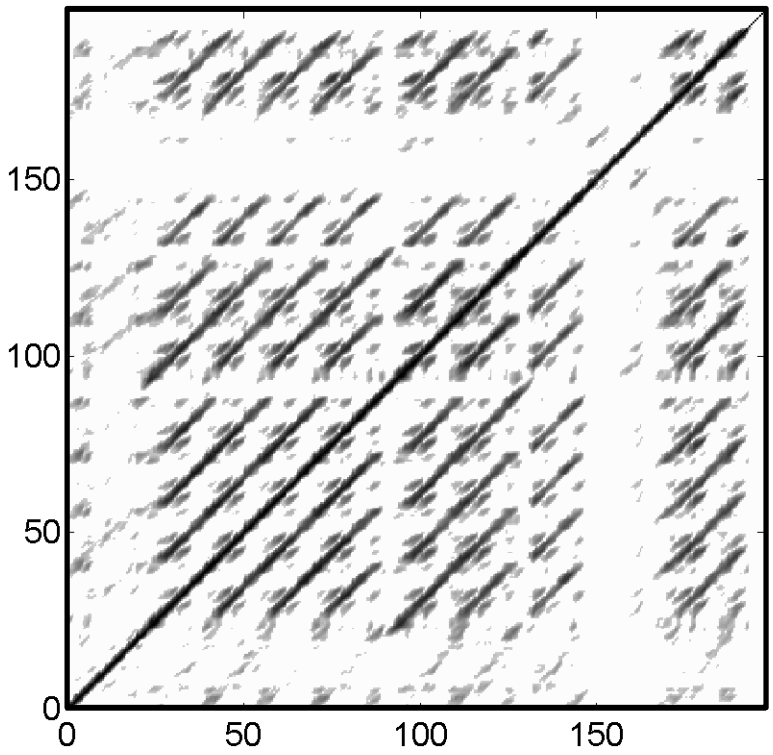
Scape Plot

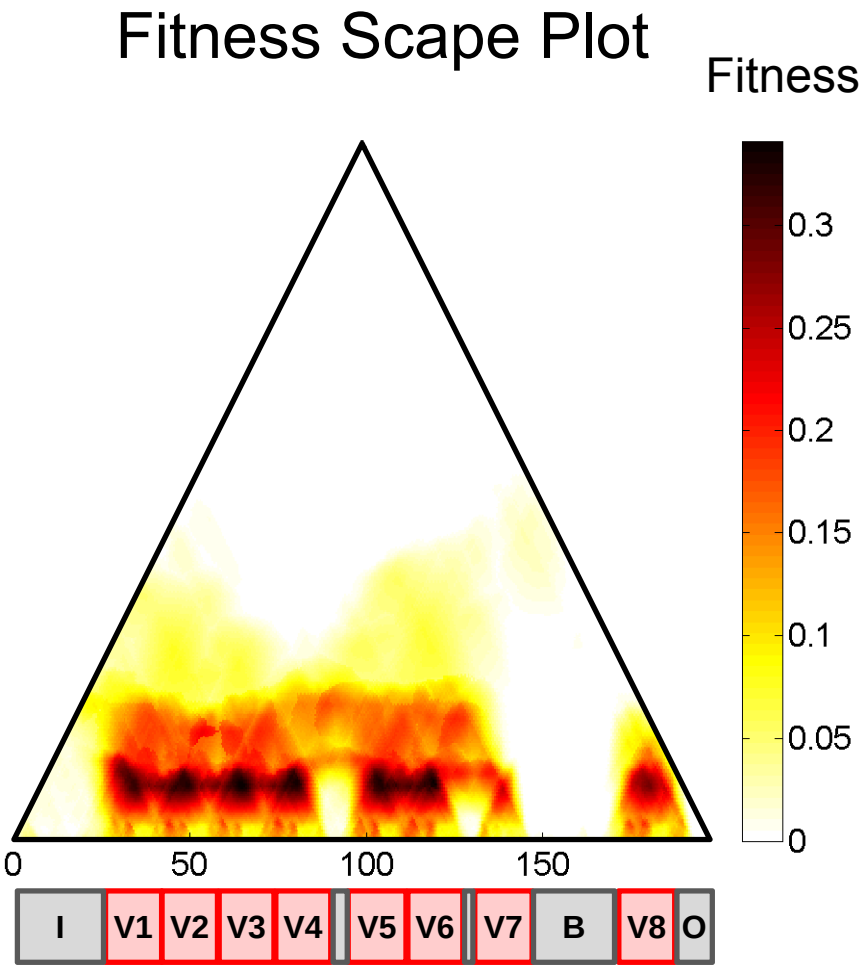
Coloring according to clustering result (grouping)



Example: Brahms Hungarian Dance No. 5 (Ormandy)

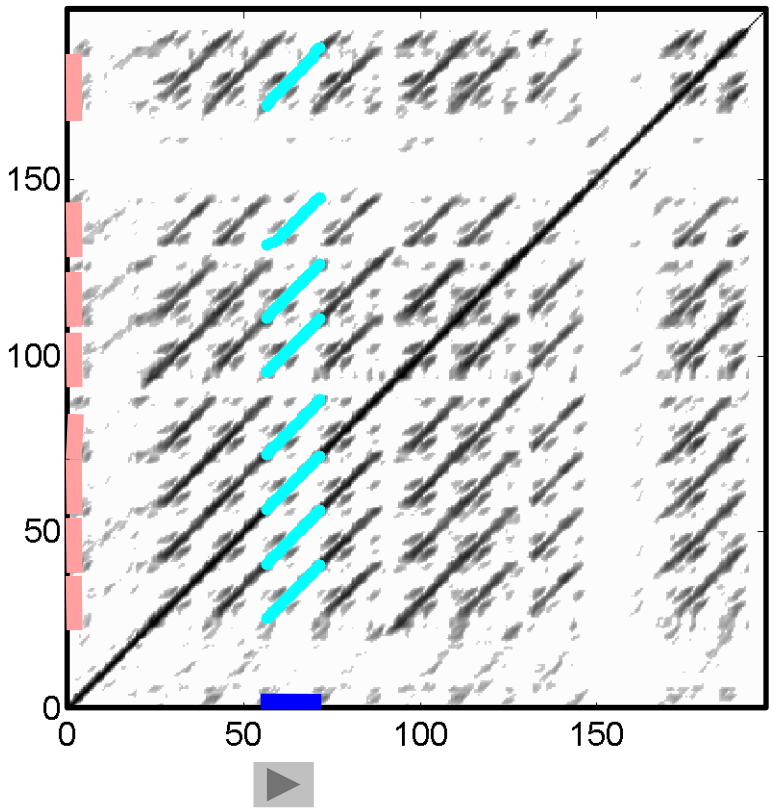
Thumbnail

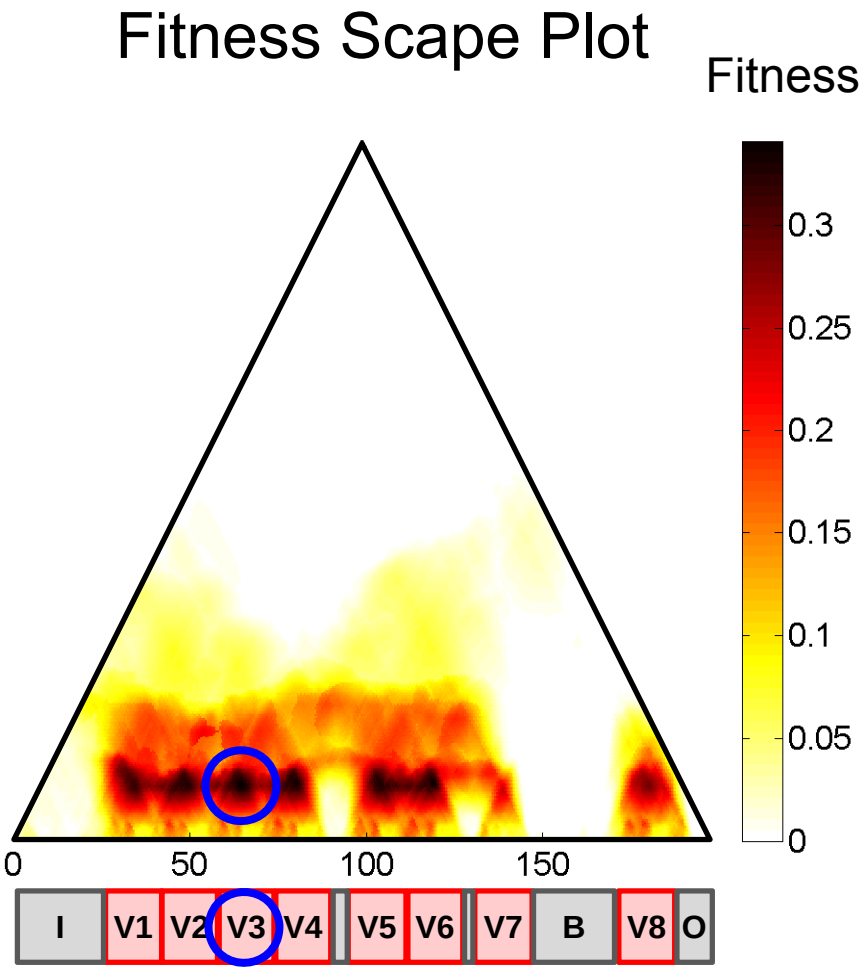




Example: Zager & Evans “In The Year 2525”

Thumbnail





Example: Zager & Evans “In The Year 2525”

Overview

- Introduction
- Feature Representations
- Self-Similarity Matrices
- Audio Thumbnailing
- Novelty-based Segmentation
- Converting Path to Block Structures

Thanks:

- Foote
- Serra, Grosche, Arcos
- Goto
- Tzanetakis, Cook

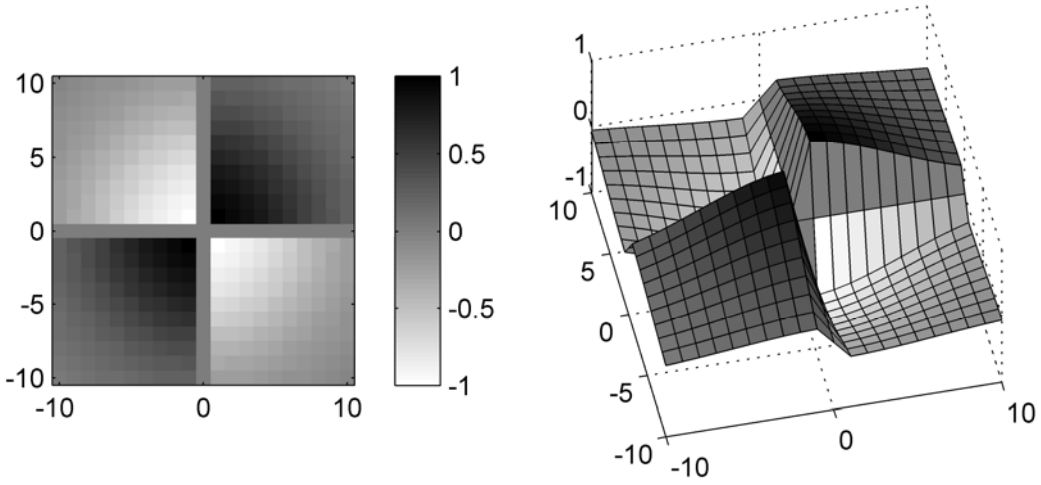
Novelty-based Segmentation

General goals:

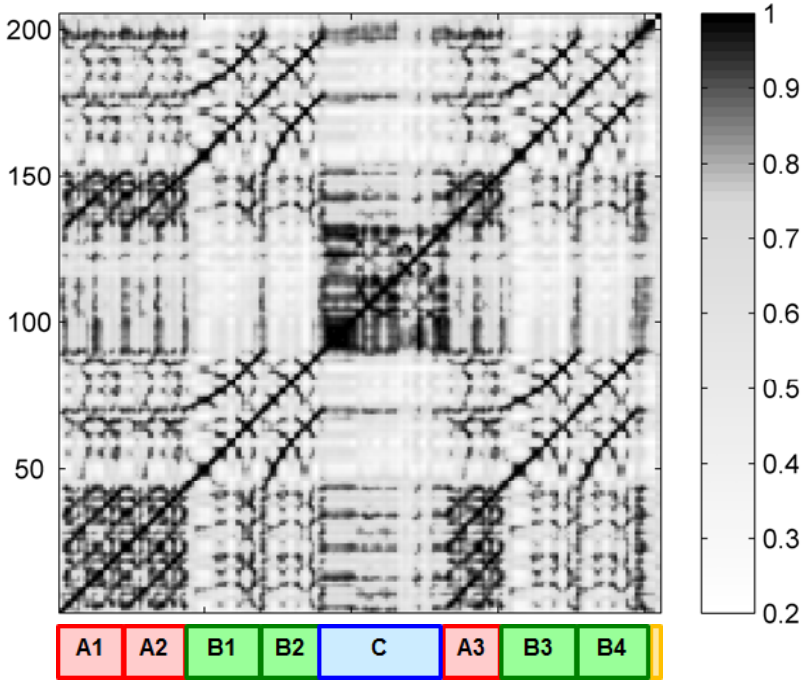
- Find instances where musical changes occur.
- Find transition between subsequent musical parts.

Idea (Foote):

Use checkerboard-like kernel function to detect corner points on main diagonal of SSM.



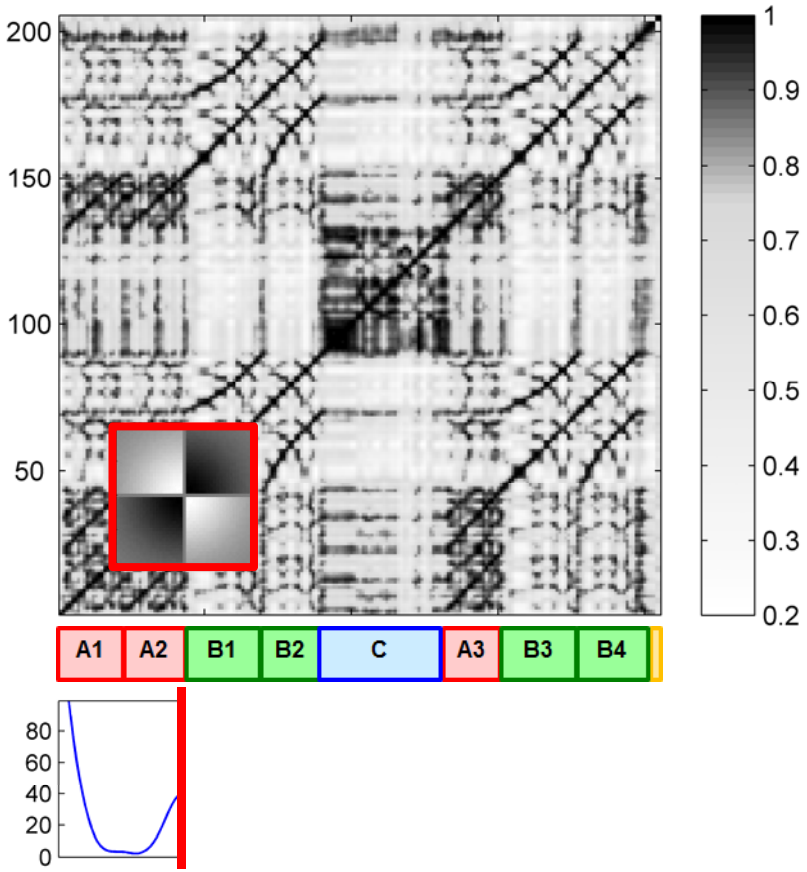
Novelty-based Segmentation



Idea (Foote):

Use checkerboard-like kernel function to detect corner points on main diagonal of SSM.

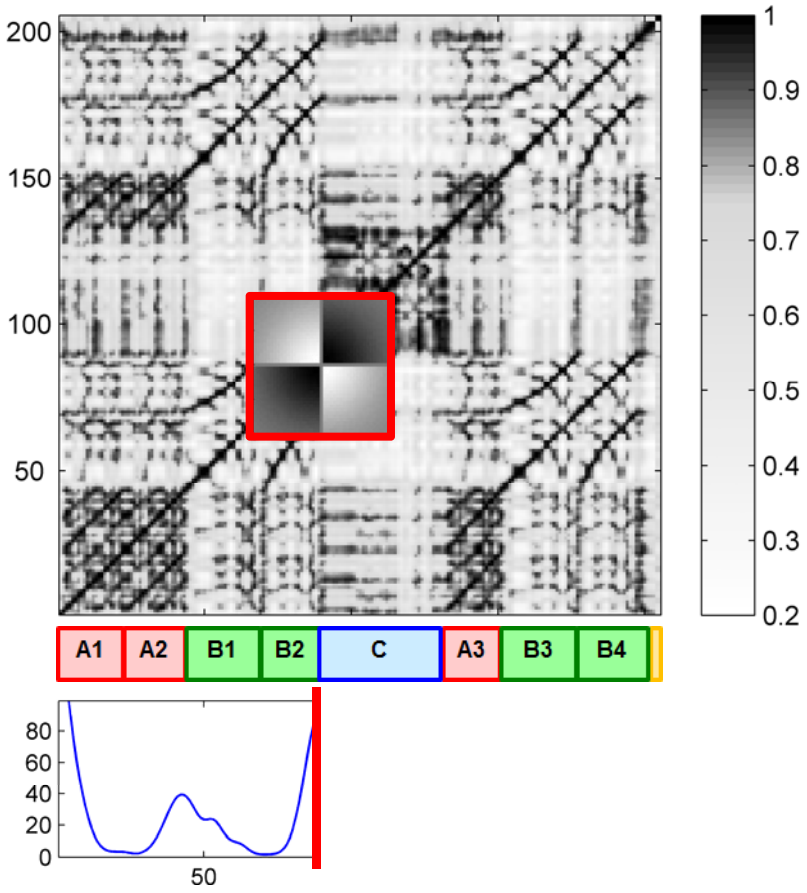
Novelty-based Segmentation



Idea (Foote):

Use checkerboard-like kernel function to detect corner points on main diagonal of SSM.

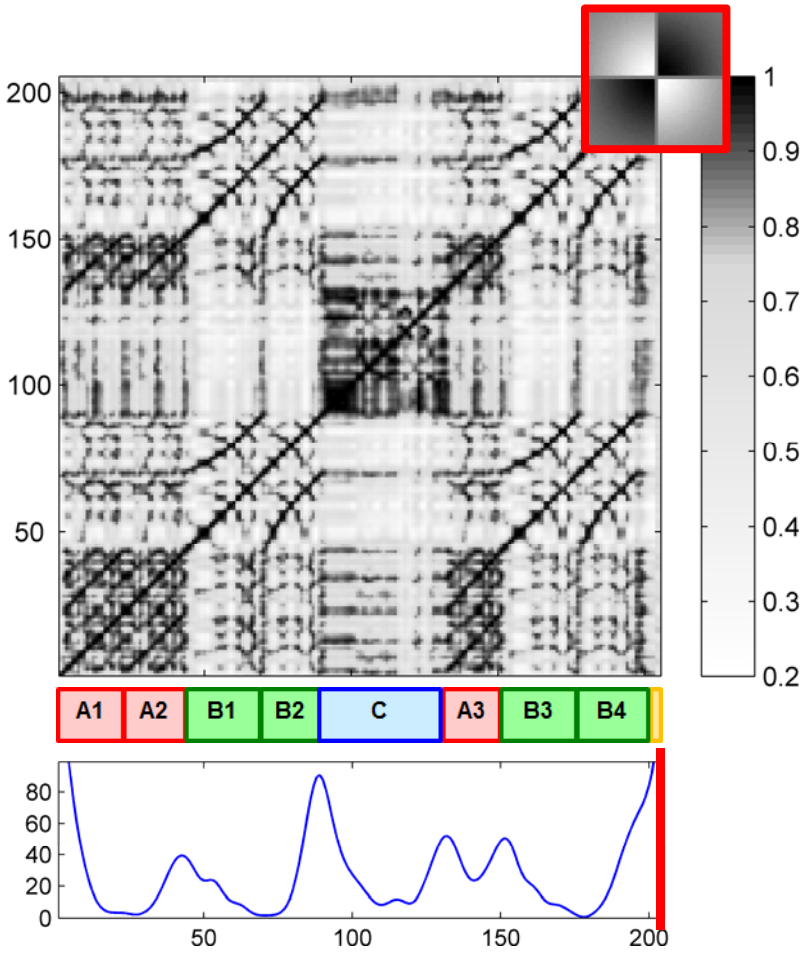
Novelty-based Segmentation



Idea (Foote):

Use checkerboard-like kernel function to detect corner points on main diagonal of SSM.

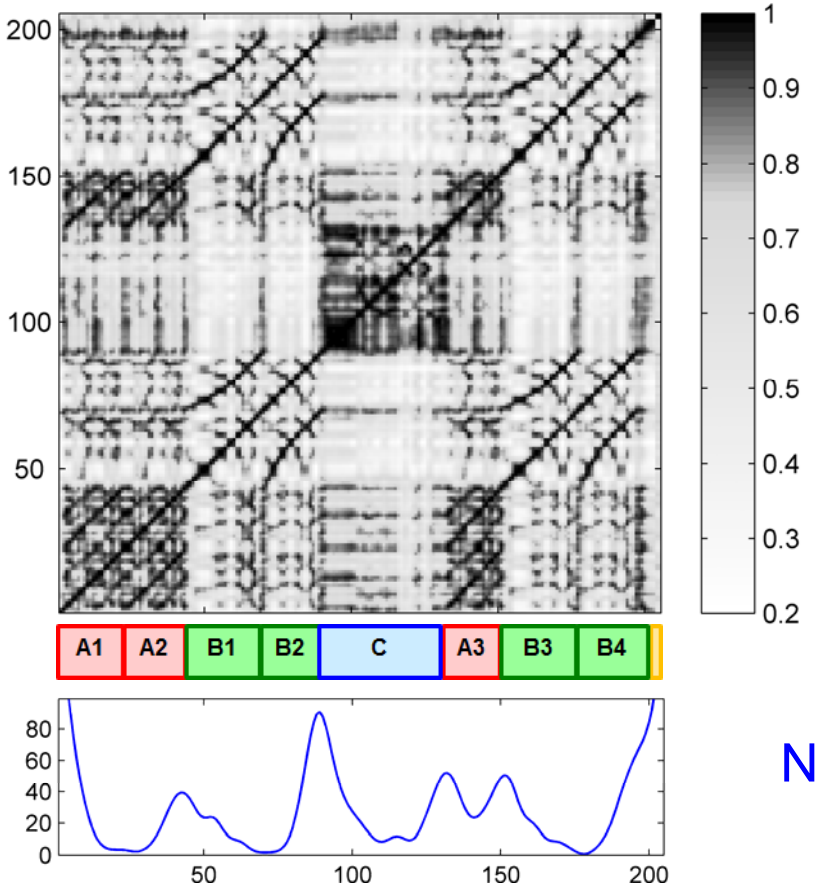
Novelty-based Segmentation



Idea (Foote):

Use checkerboard-like kernel function to detect corner points on main diagonal of SSM.

Novelty-based Segmentation

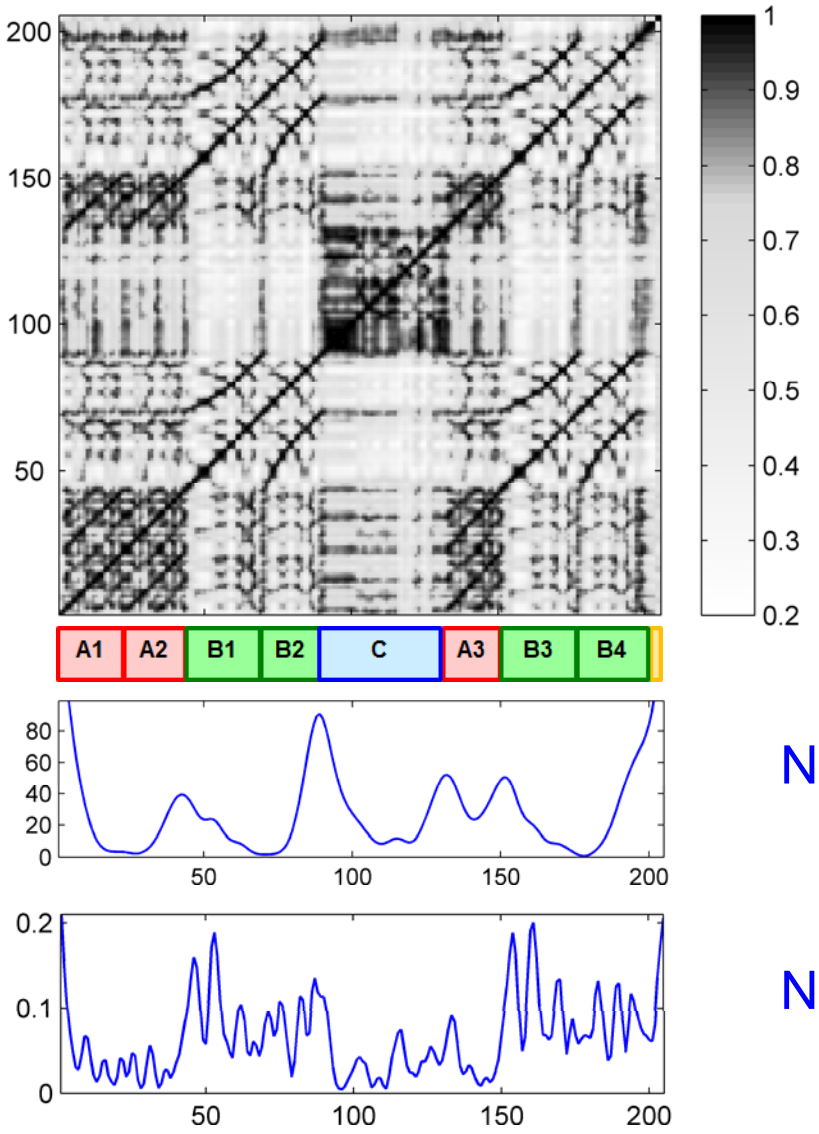


Idea (Foote):

Use checkerboard-like kernel function to detect corner points on main diagonal of SSM.

Novelty function using

Novelty-based Segmentation



Idea (Foote):

Use checkerboard-like kernel function to detect corner points on main diagonal of SSM.

Novelty function using 

Novelty function using 

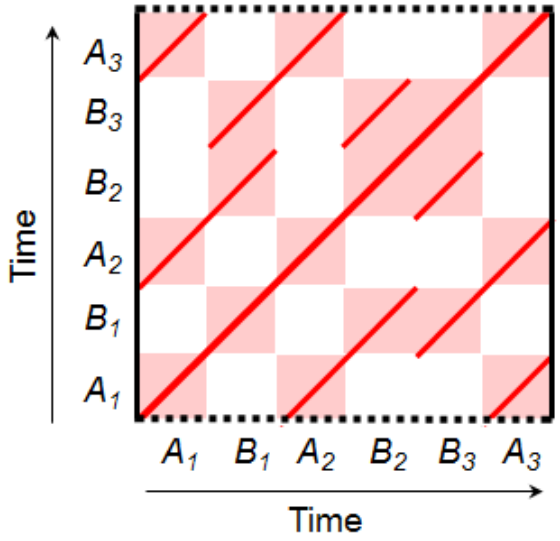
Novelty-based Segmentation

Idea:

- Find instances where structural changes occur.
- Combine global and local aspects within a unifying framework

Structure features

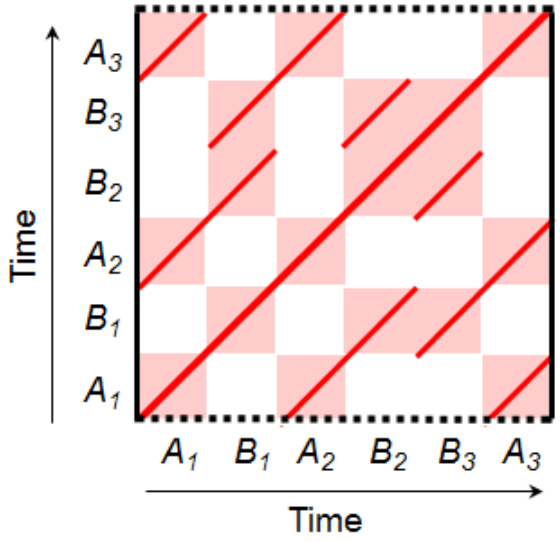
Novelty-based Segmentation

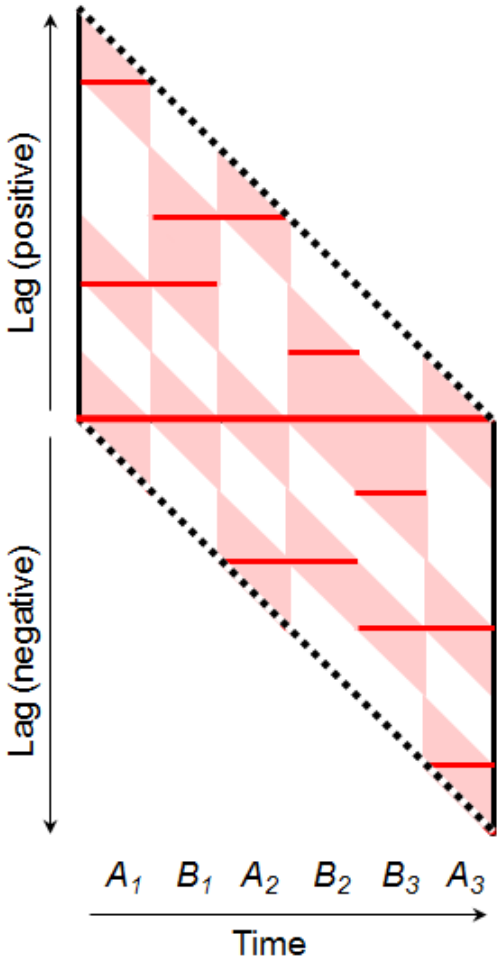


Structure features

- Enhanced SSM

Novelty-based Segmentation

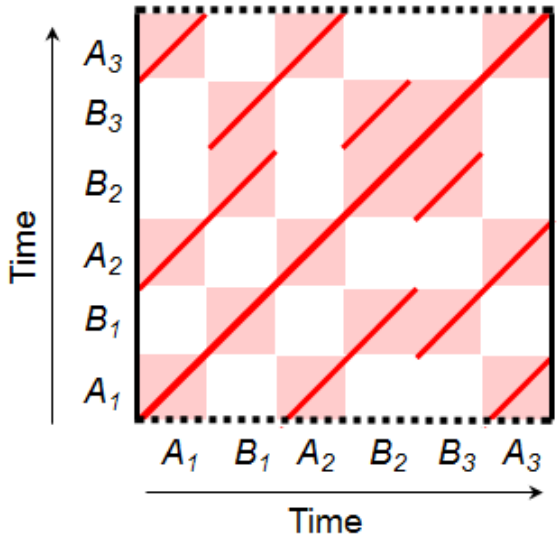


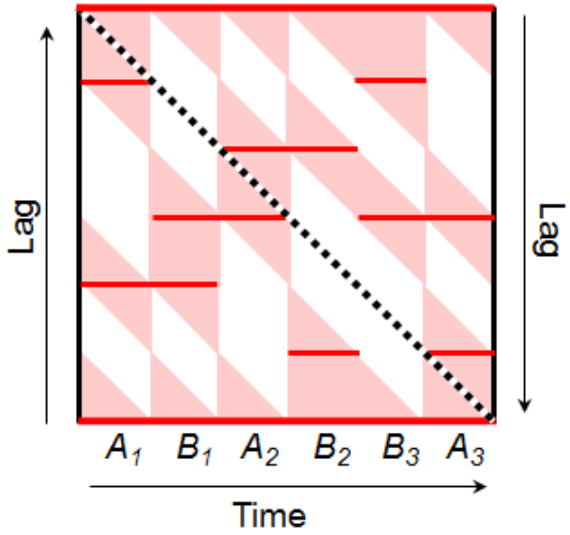


Structure features

- Enhanced SSM
- Time-lag SSM

Novelty-based Segmentation

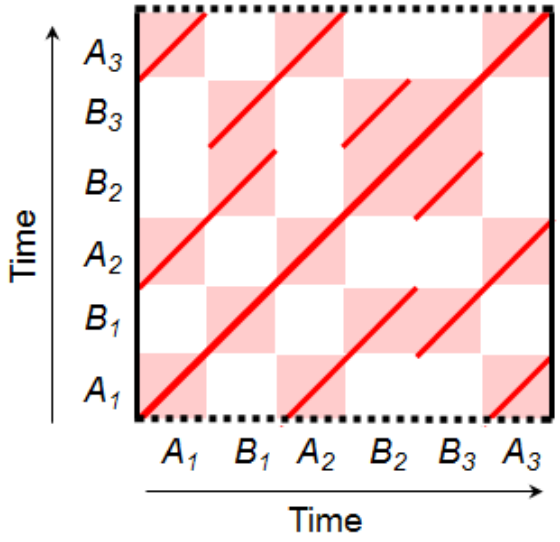


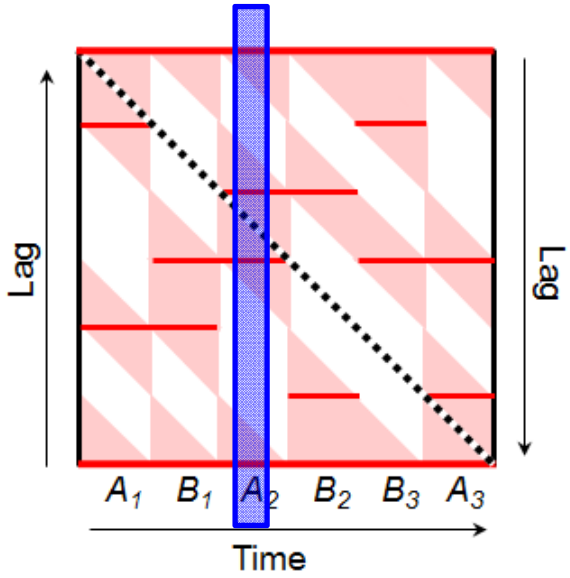


Structure features

- Enhanced SSM
- Time-lag SSM
- Cyclic time-lag SSM

Novelty-based Segmentation



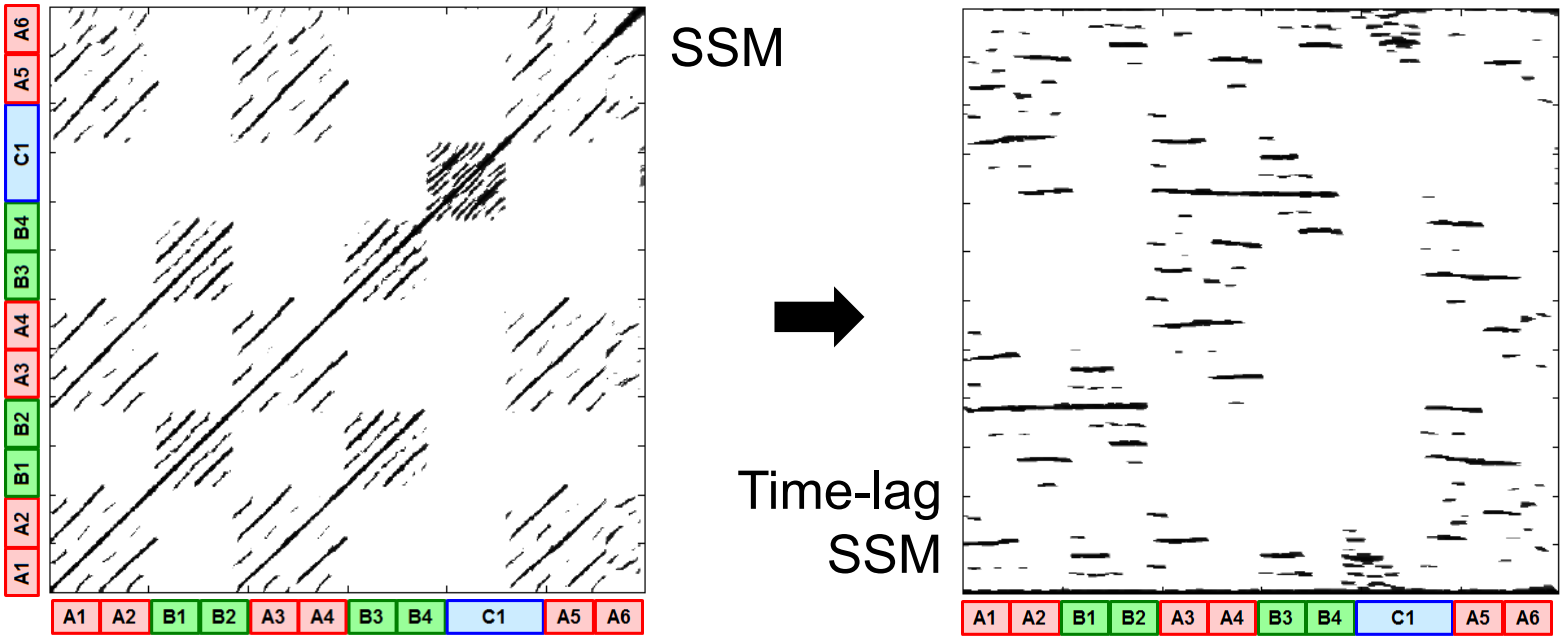


Structure features

- Enhanced SSM
- Time-lag SSM
- Cyclic time-lag SSM
- Columns as features

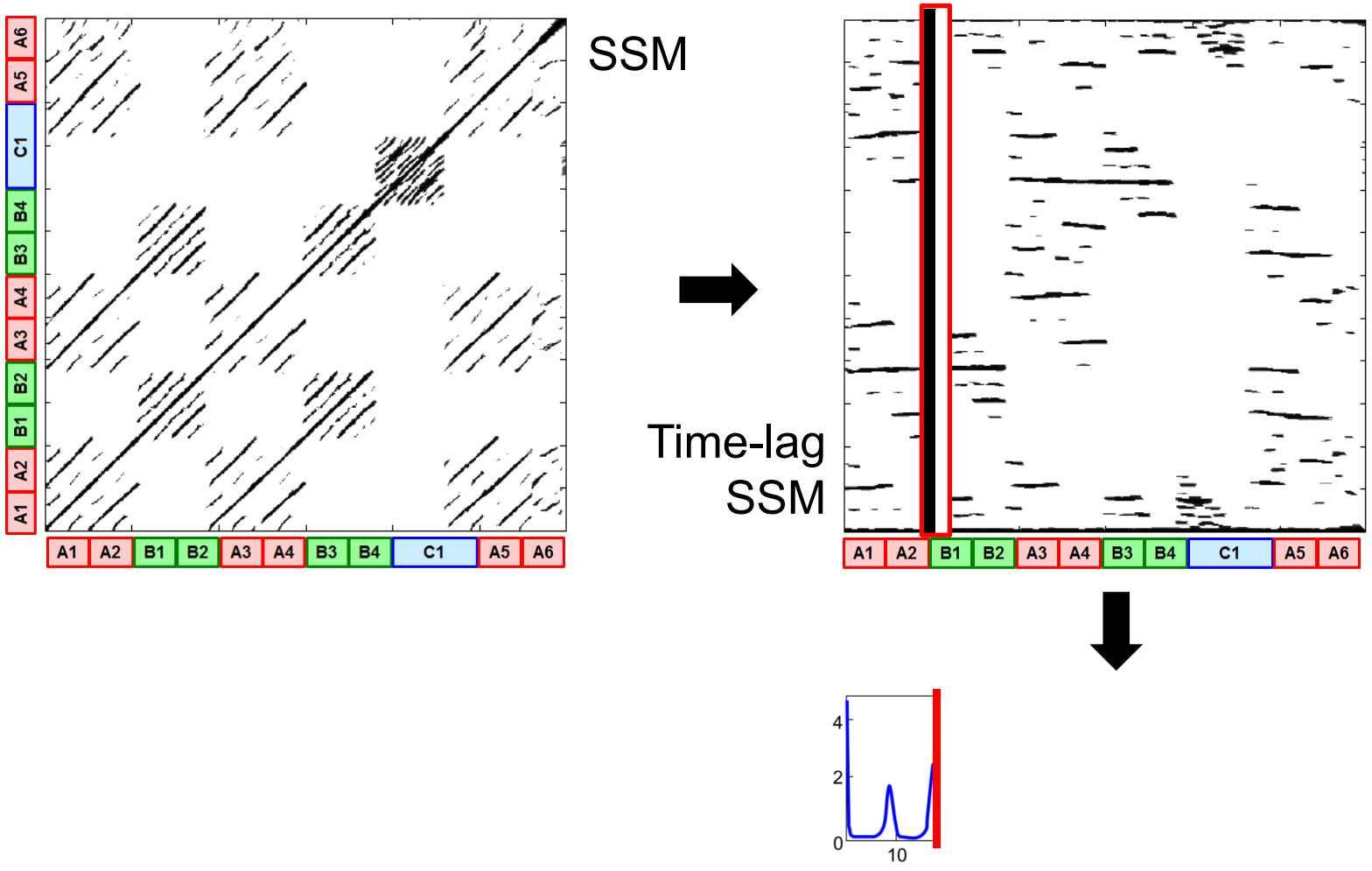
Novelty-based Segmentation

Example: Chopin Mazurka Op. 24, No. 1



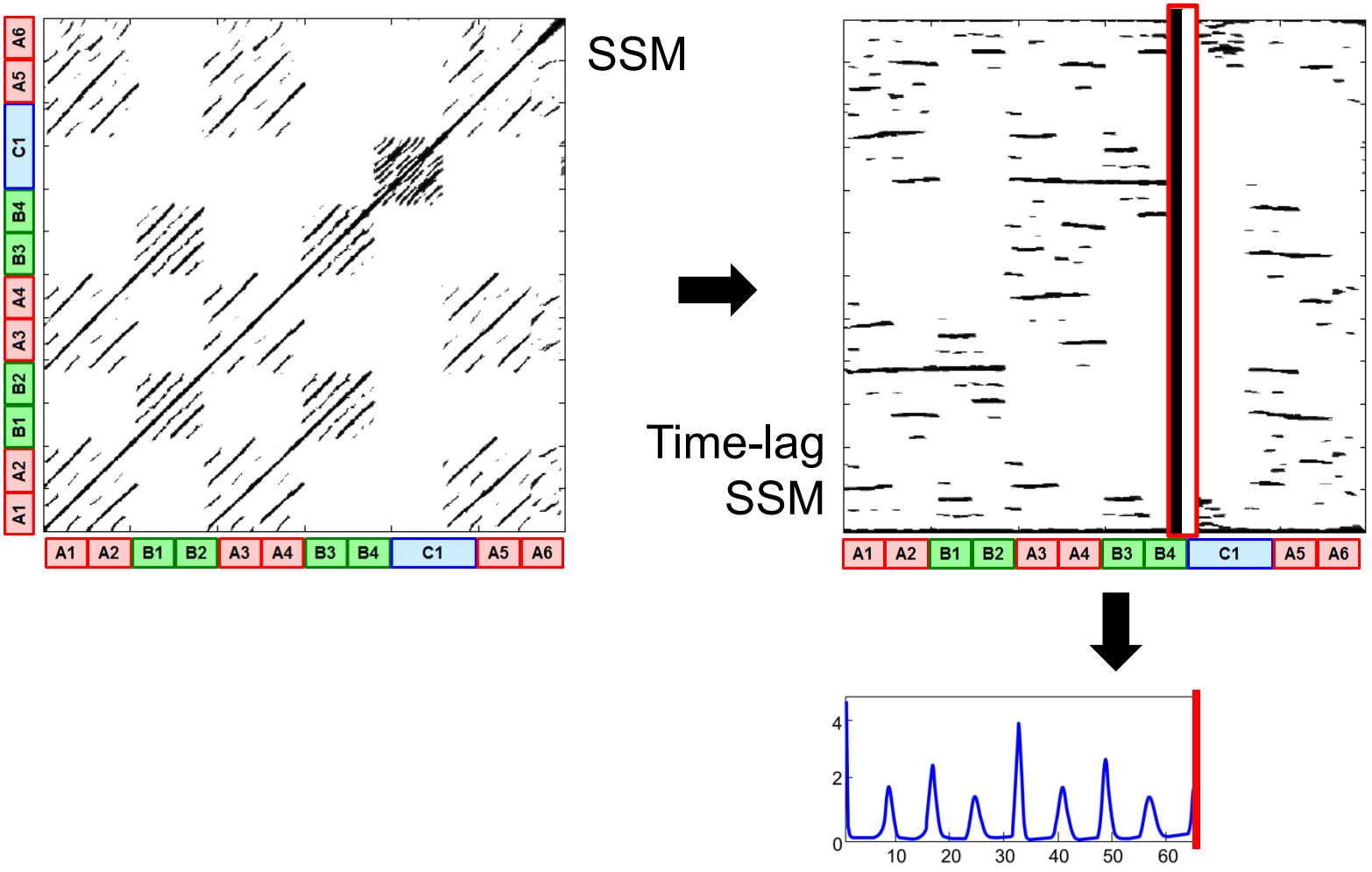
Novelty-based Segmentation

Example: Chopin Mazurka Op. 24, No. 1



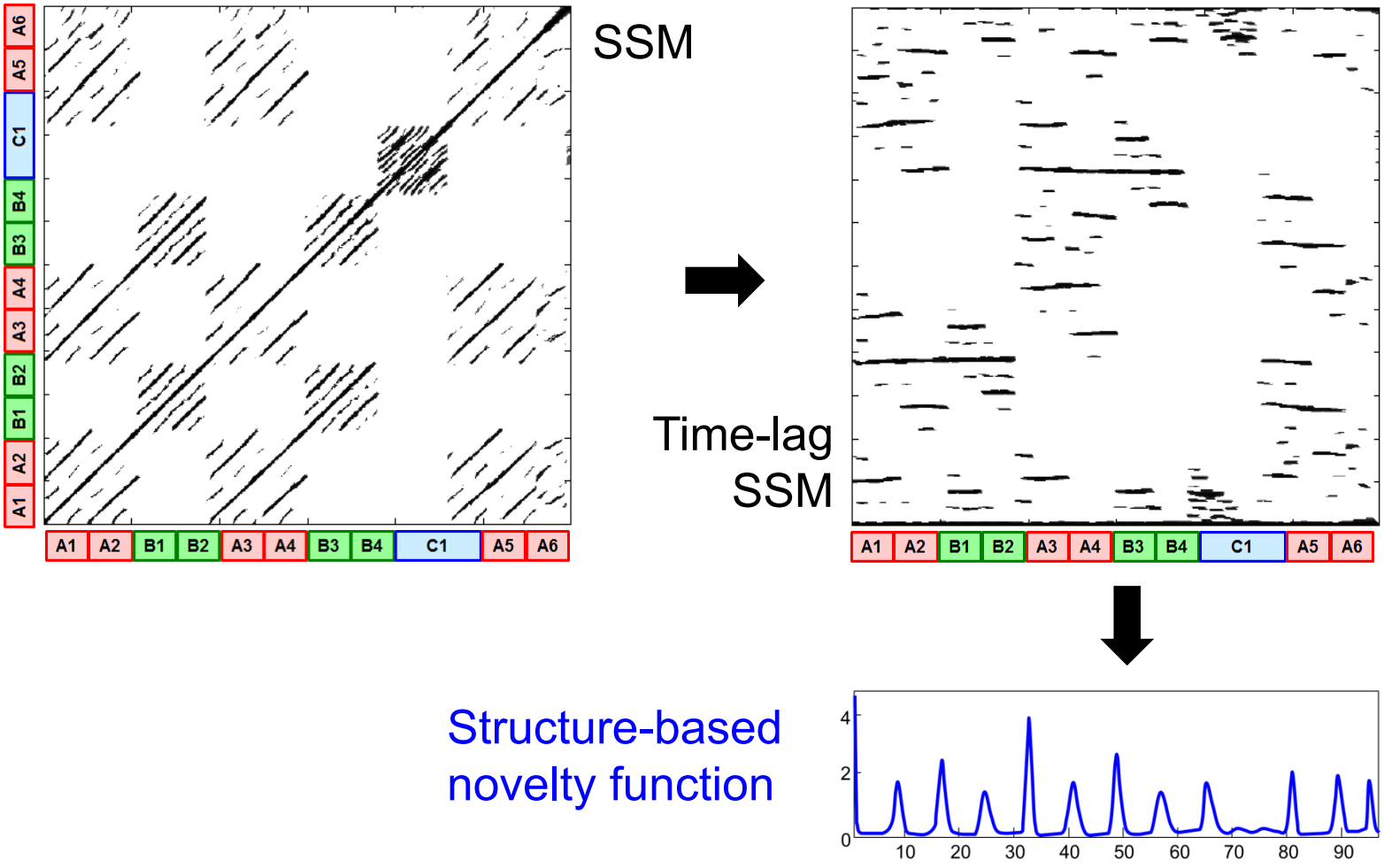
Novelty-based Segmentation

Example: Chopin Mazurka Op. 24, No. 1



Novelty-based Segmentation

Example: Chopin Mazurka Op. 24, No. 1



Overview

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- Feature Representations
- Self-Similarity Matrices
- Audio Thumbnailing
- Novelty-based Segmentation
- Converting Path to Block Structures

Thanks:

- Grohganz, Clausen
- Kaiser
- Peeters
- Dubnov, Apel
- Serra, Grosche, Arcos

Converting Path to Block Structures

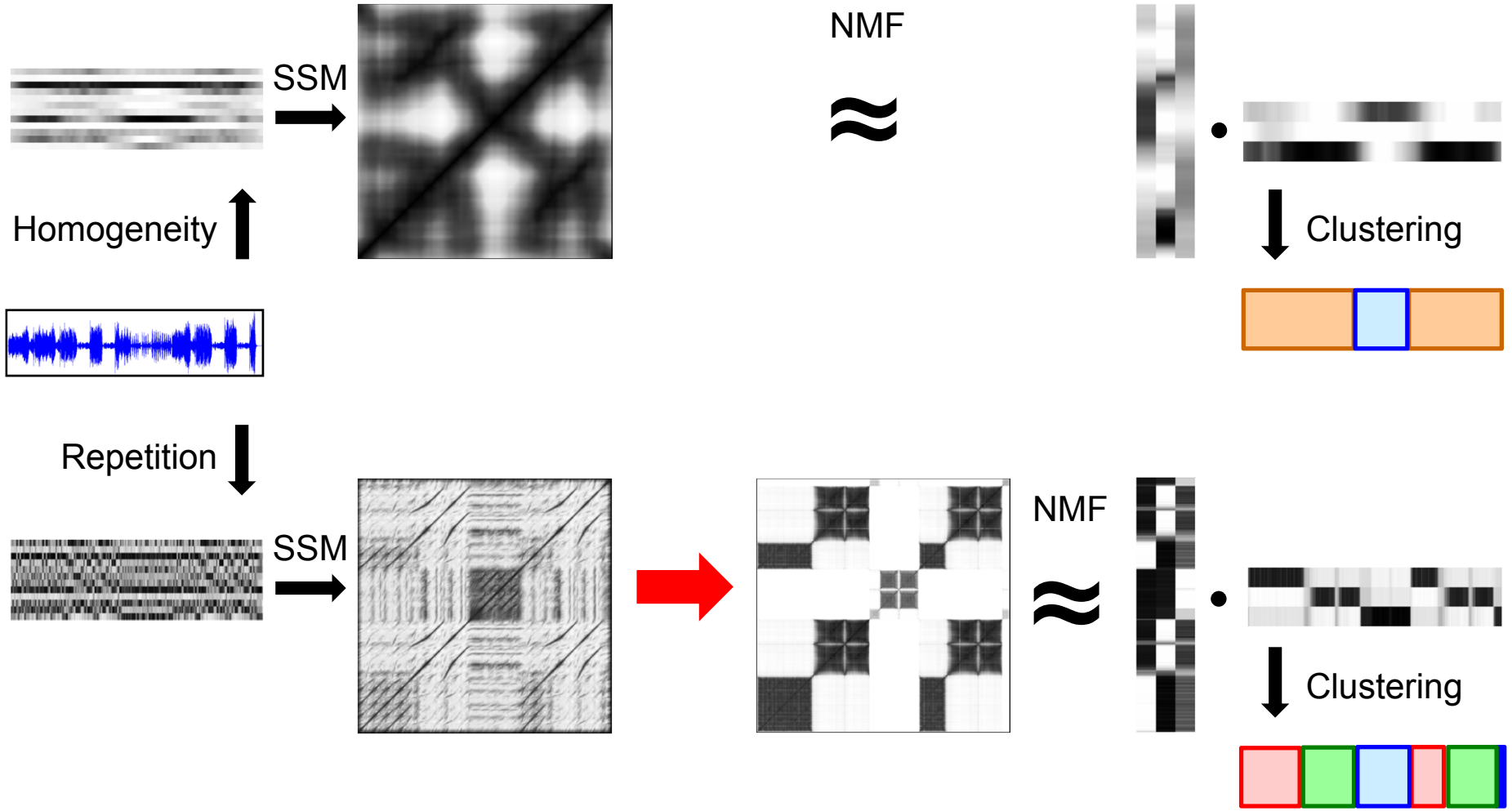
Motivation

- Perform joint analysis using repetitive as well as homogeneous aspects

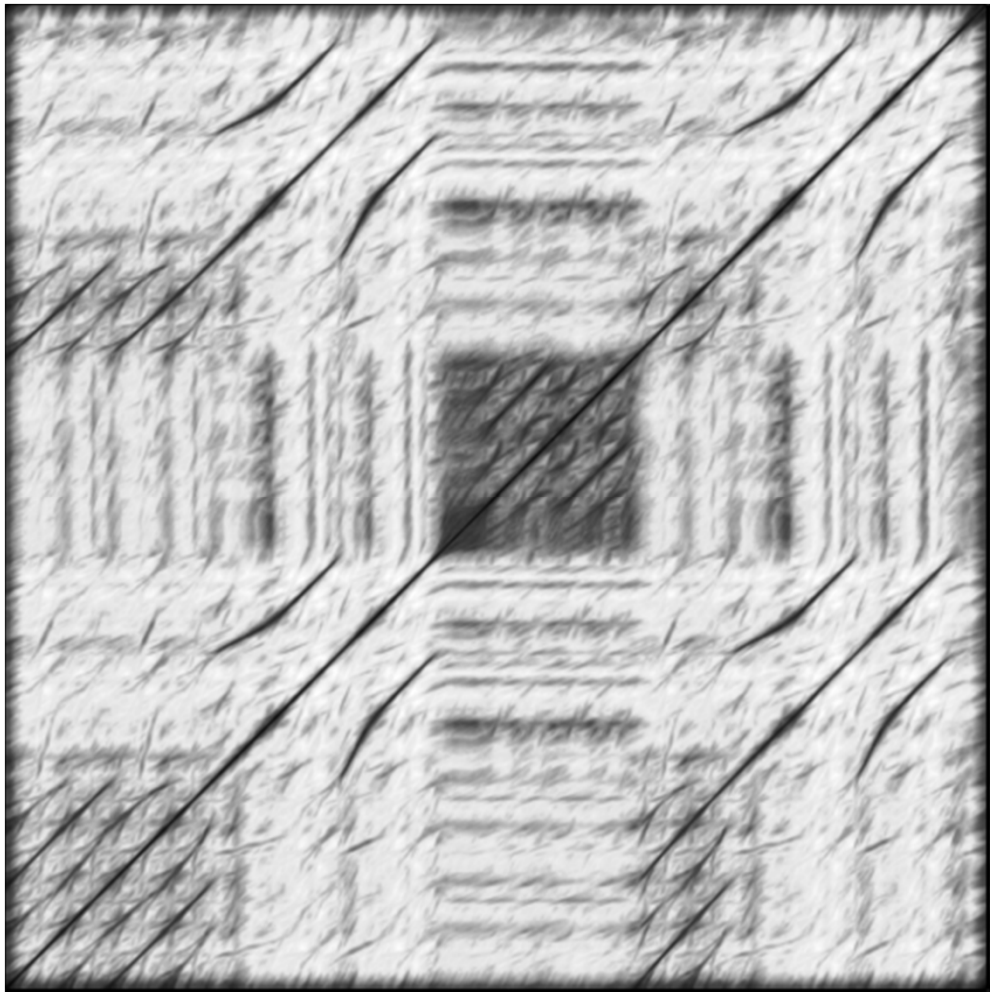
- Make homogeneity-based methods applicable to repetition-based analysis

Converting Path to Block Structures

Motivation



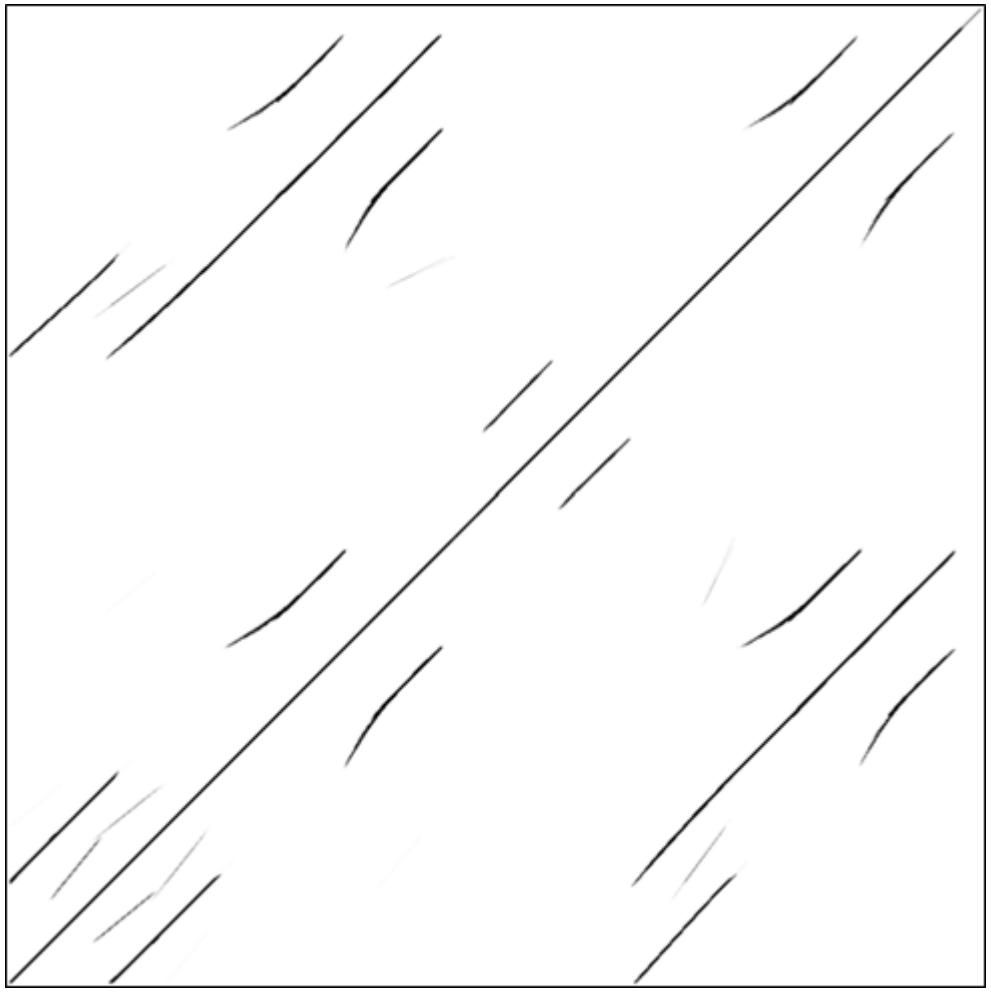
Converting Path to Block Structures



Procedure

- Enhanced SSM

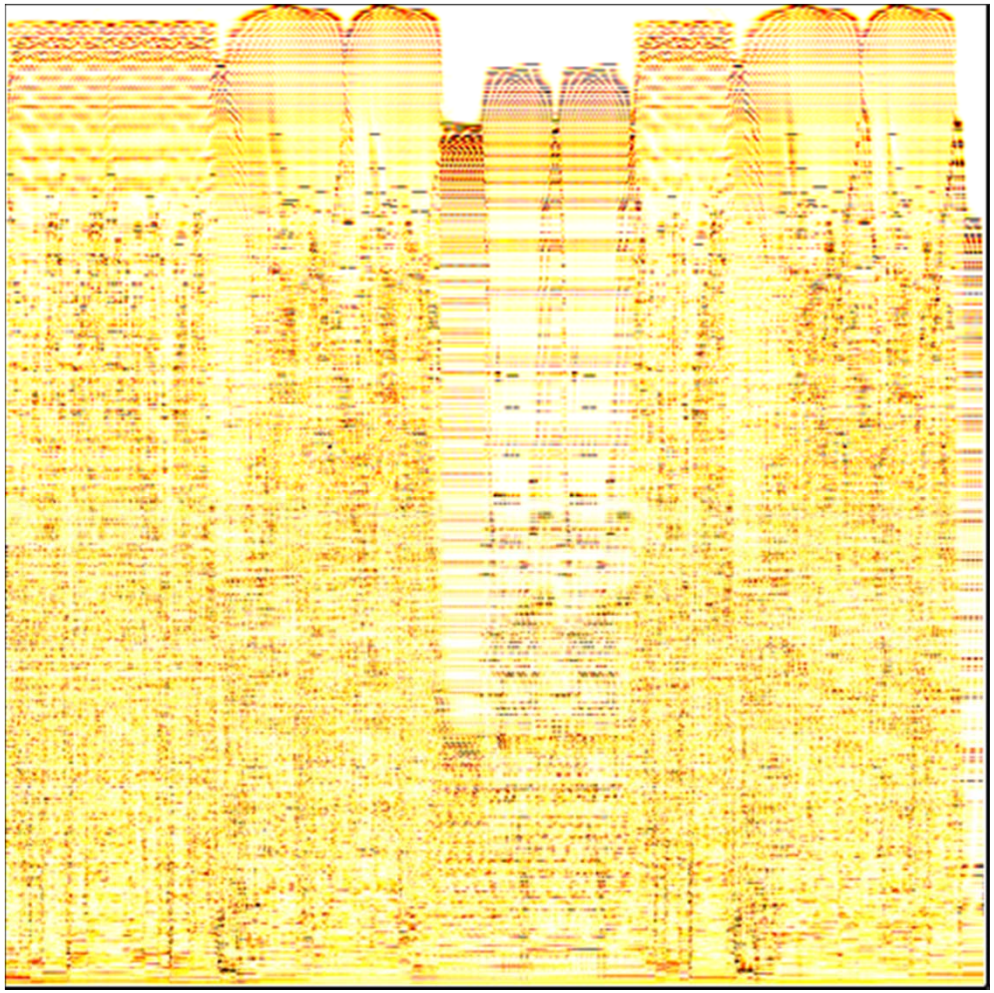
Converting Path to Block Structures



Procedure

- Enhanced SSM
- Thresholding & image processing

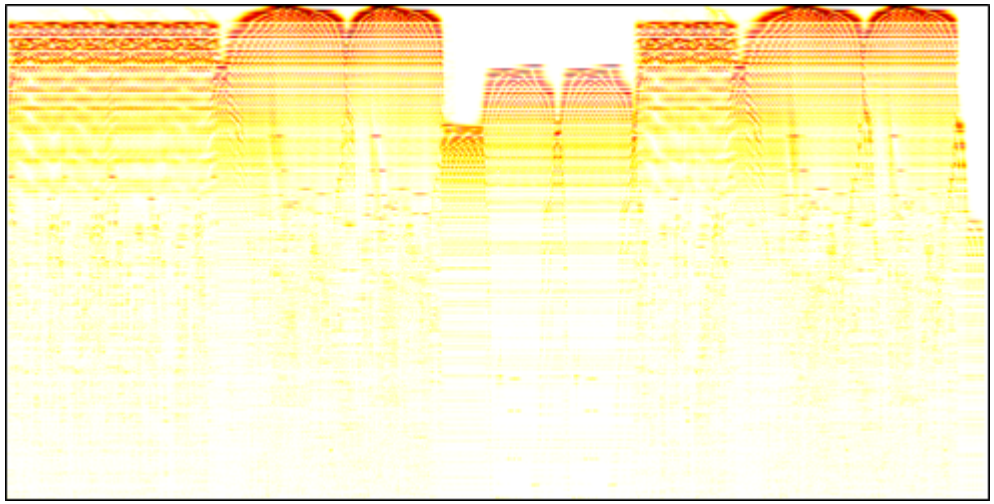
Converting Path to Block Structures



Procedure

- Enhanced SSM
- Thresholding & image processing
- Eigenvalue decomposition

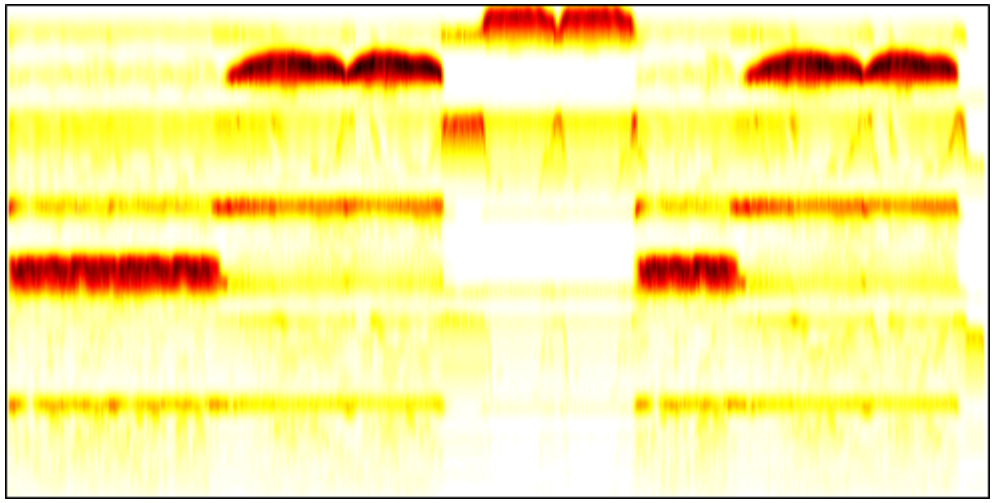
Converting Path to Block Structures



Procedure

- Enhanced SSM
- Thresholding & image processing
- Eigenvalue decomposition
- Weigthing

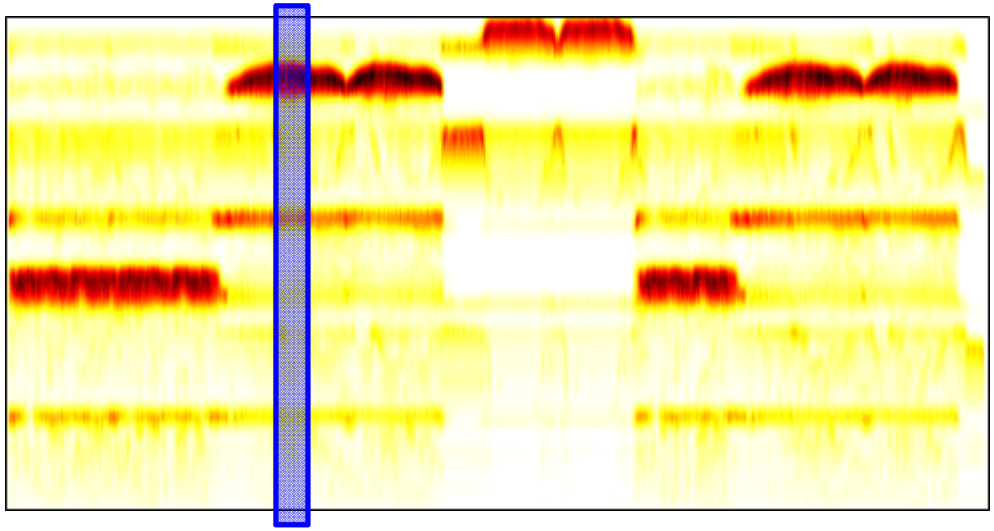
Converting Path to Block Structures



Procedure

- Enhanced SSM
- Thresholding & image processing
- Eigenvalue decomposition
- Weigthing
- Clustering & smoothing

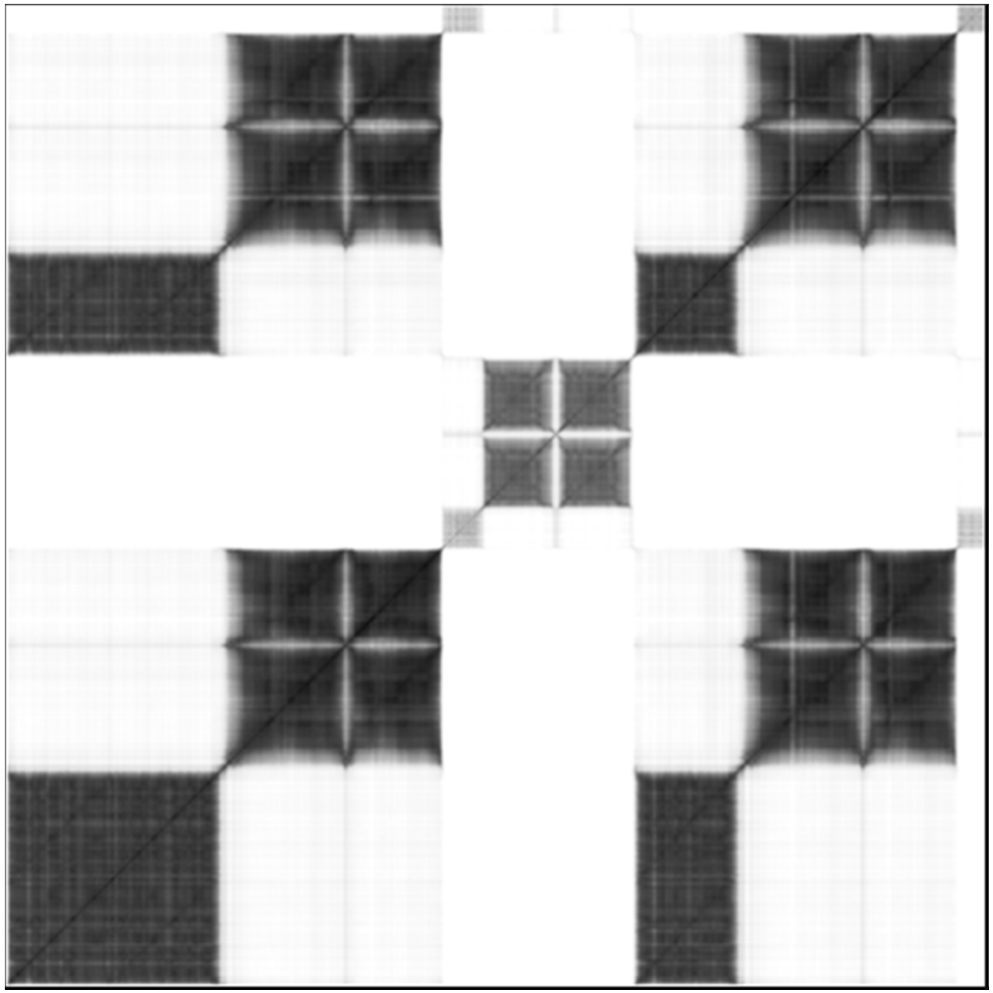
Converting Path to Block Structures



Procedure

- Enhanced SSM
- Thresholding & image processing
- Eigenvalue decomposition
- Weigthing
- Clustering & smoothing
- **Columns as features**

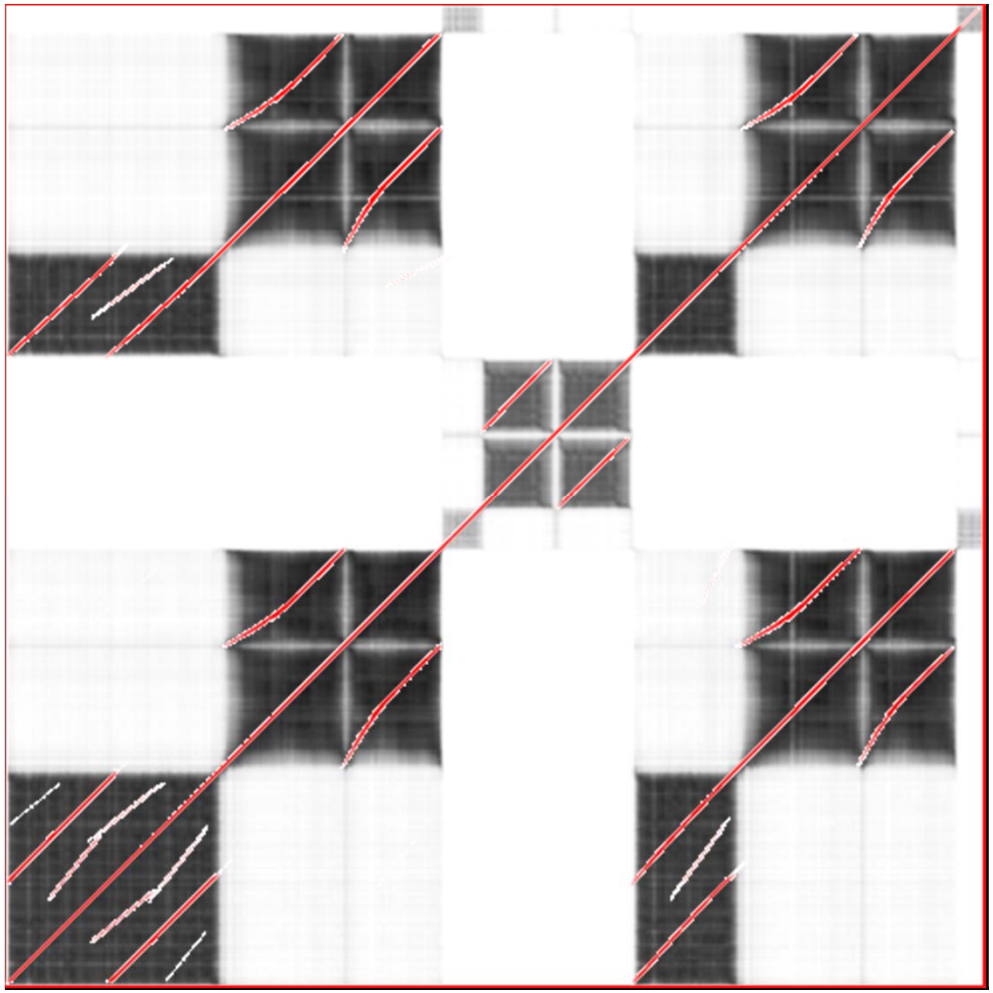
Converting Path to Block Structures



Procedure

- Enhanced SSM
- Thresholding & image processing
- Eigenvalue decomposition
- Weigthing
- Clustering & smoothing
- **Columns as features**
- SSM from these features

Converting Path to Block Structures

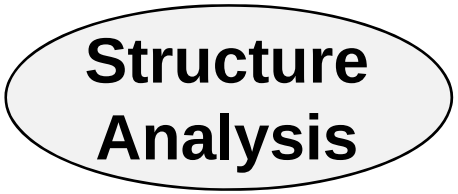


Procedure

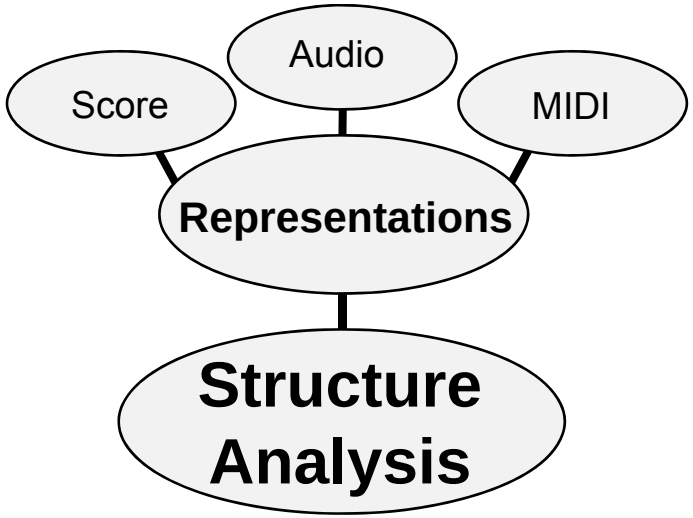
- Enhanced SSM
- Thresholding & image processing
- Eigenvalue decomposition
- Weigthing
- Clustering & smoothing
- **Columns as features**
- SSM from these features

Final matrix show paths as blocks

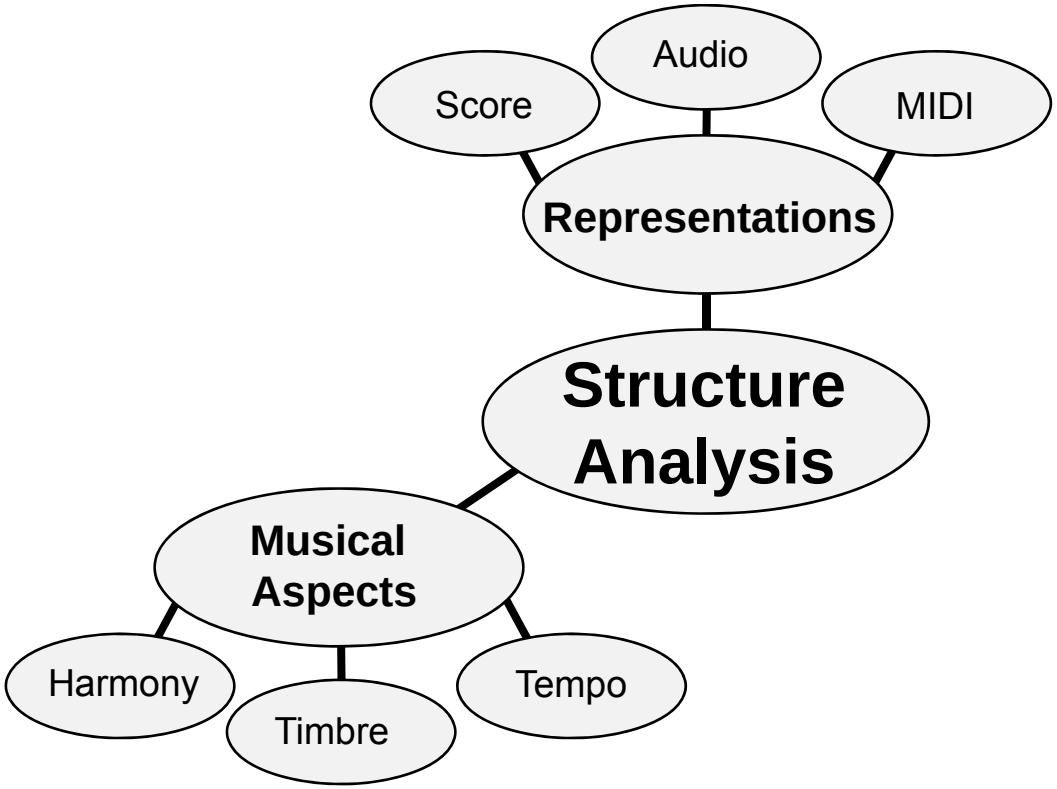
Conclusions



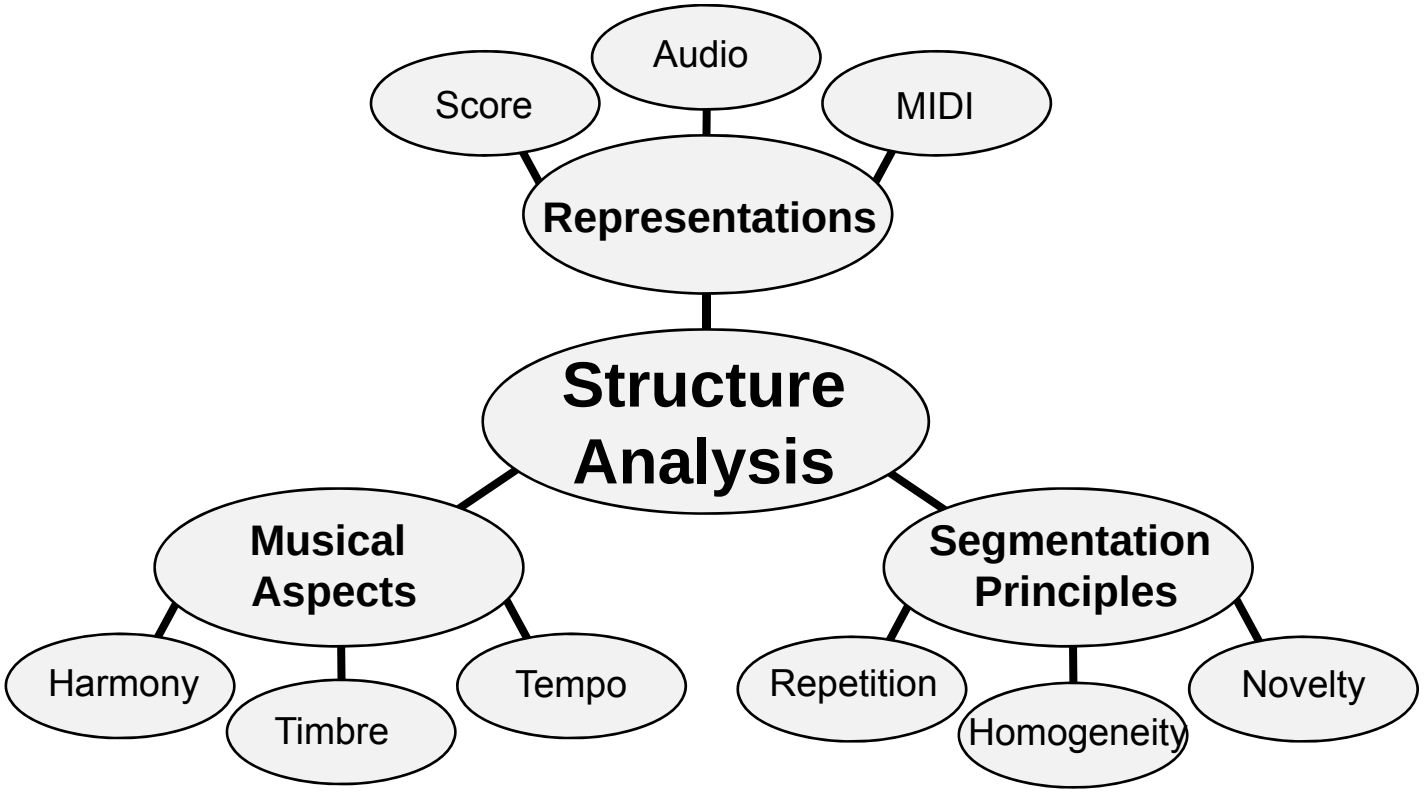
Conclusions



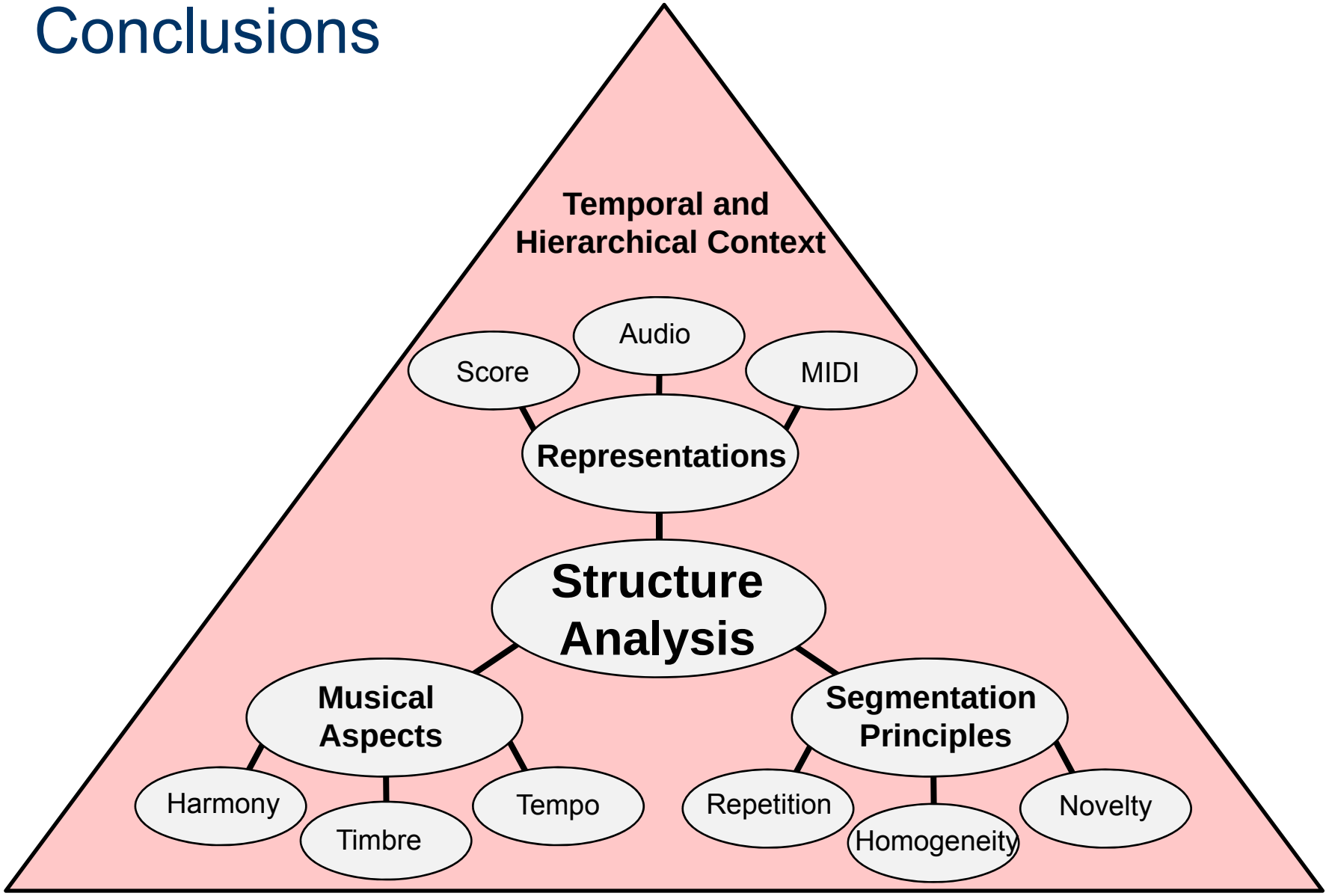
Conclusions



Conclusions

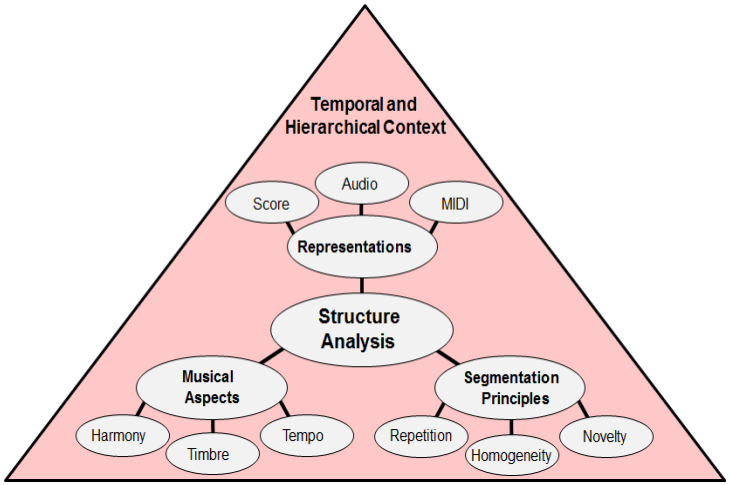


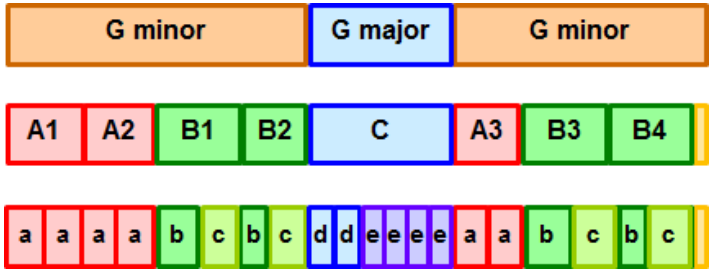
Conclusions



Conclusions

- Combined Approaches
- Hierarchical Approaches
- Evaluation
- Explaining Structure





- MIREX
- SALAMI-Project
- Smith, Chew

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