Lecture
Music Processing

Audio Structure Analysis

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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

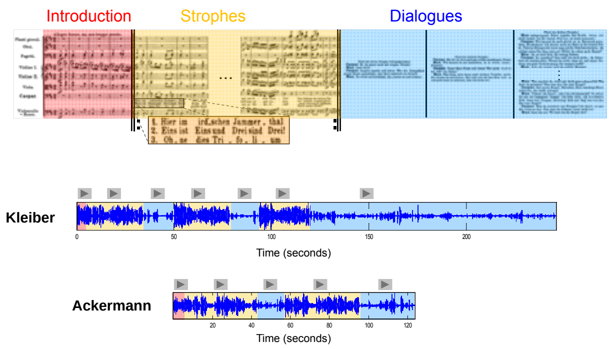
General goal: Divide an audio recording into temporal segments corresponding to musical parts and group these segments into musically meaningful categories.

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

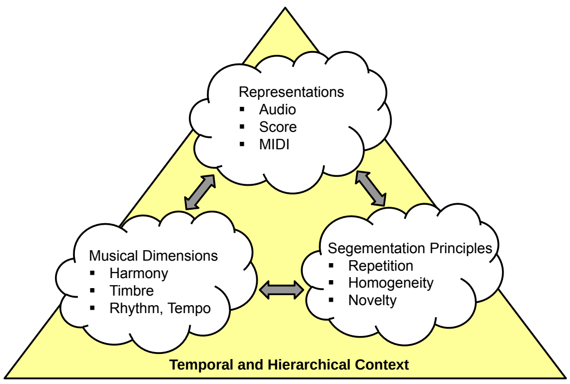
- Repetition: Repeating themes, motives, rhythmic patterns,…
- Contrast: Surprising elements, sudden changes, …
- Variation: Changes in melody, harmony, rhythm, …
- Homogeneity: Consistency in tempo, orchestration, key, …

Music Structure Analysis

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



Music Structure Analysis



Repetition-Based Audio Structure Analysis

- Extract the repetitive structure of a given audio recording
- Often corresponds to musical form of the underlying piece
- The thumbnail is the most repetitive segment

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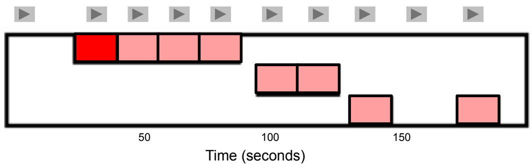
Example: Zager & Evans “In The Year 2525”



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Example: Folk Song Field Recording (Nederlandse Liederenbank)

Repetition-Based Audio Structure Analysis

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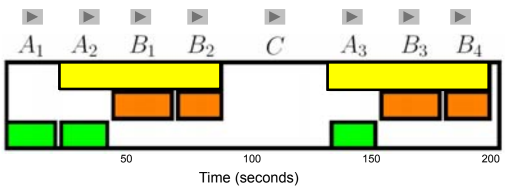
Example: Brahms Hungarian Dance No. 5 (Ormandy)



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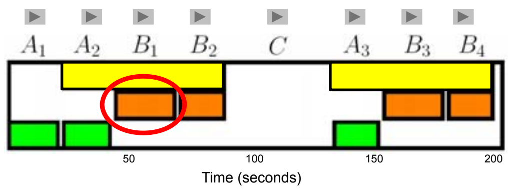

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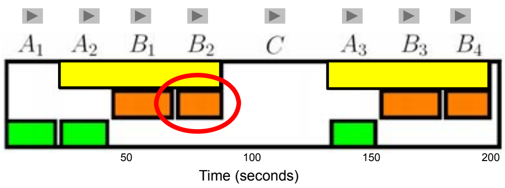


Basic Procedure

- Transform music signal into feature sequence
- Compare all elements of feature sequence in a pairwise fashion to obtain a self-distance matrix (SDM)
- Extract paths from SDM (pairwise similarity of segments)
- Derive global structure from path relations (clustering, grouping)

Basic Procedure

- Audio $\rightsquigarrow$ $V := (v^1, v^2, \ldots, v^N)$
- v^n = 12-dimensional normalized chroma vector
- Local cost measure $c : \mathbb{R}^{12} \times \mathbb{R}^{12} \to \mathbb{R}$

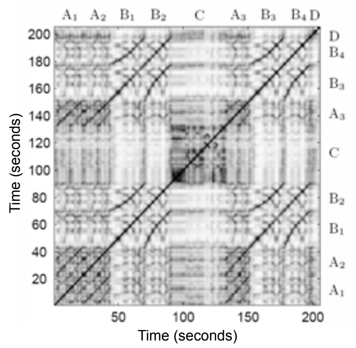
$$c(v^n, w^m) := 1 - \langle v^n, w^m \rangle$$

- $N \times N$ cost matrix $C(n,m) := c(v^n, w^m)$

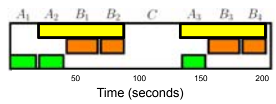
$\rightsquigarrow$ Quadratic self-distance matrix (SDM)

Basic Procedure

Self-distance matrix

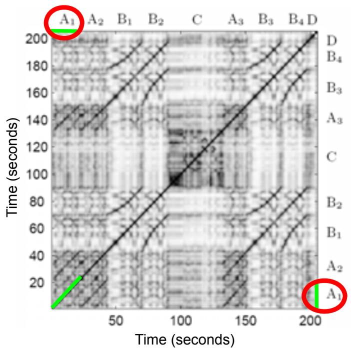


Similarity structure



Basic Procedure

Self-distance matrix



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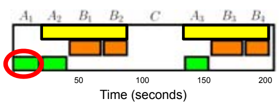
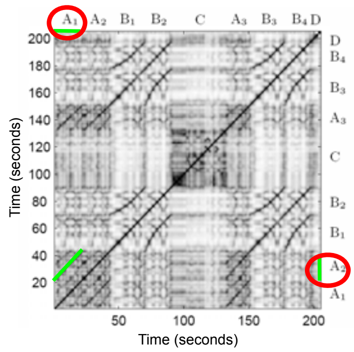
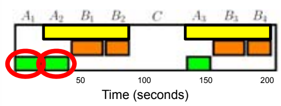


Basic Procedure

Self-distance matrix

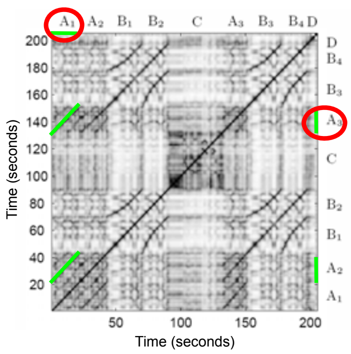


Similarity structure

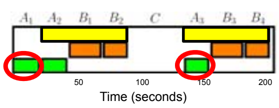


Basic Procedure

Self-distance matrix

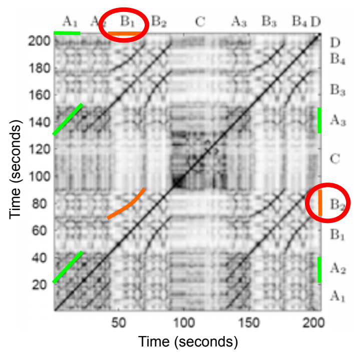


Similarity structure



Basic Procedure

Self-distance matrix



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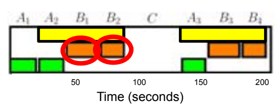

Basic Procedure

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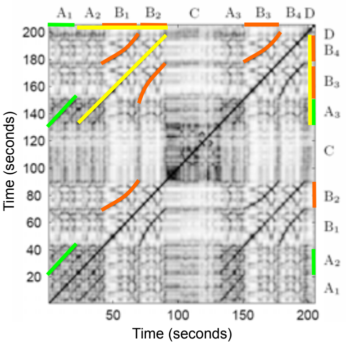
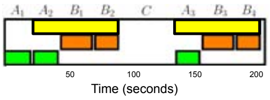
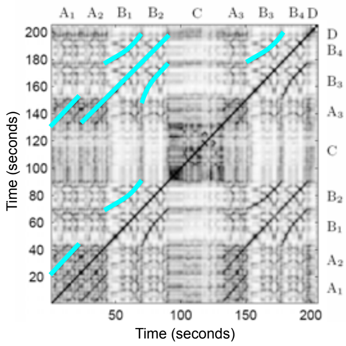


Similarity structure

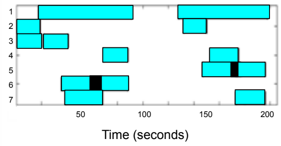


Basic Procedure

Self-distance matrix

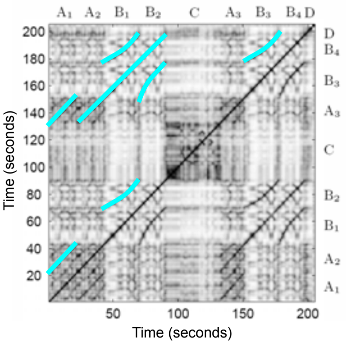


Path relations

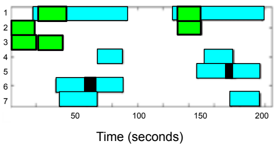


Basic Procedure

Self-distance matrix



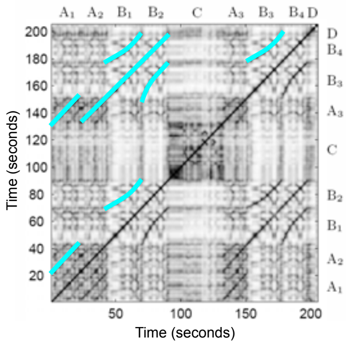
Path relations



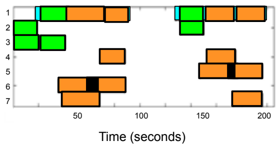
Grouping / Transitivity

Basic Procedure

Self-distance matrix



Path relations



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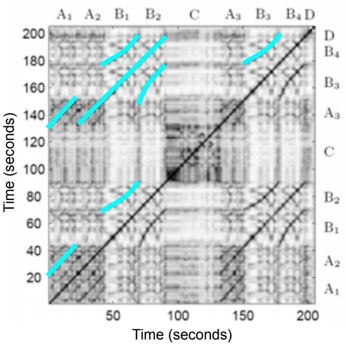

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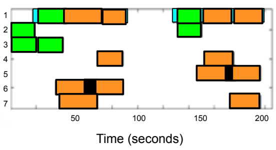

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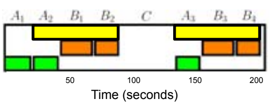


Matrix Enhancement

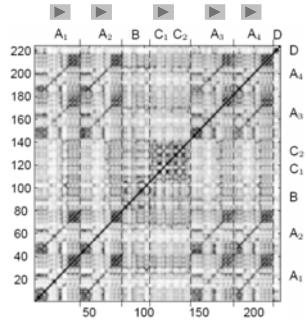
Challenge: Presence of musical variations

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

Idea: Enhancement of path structure

Matrix Enhancement

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



Matrix Enhancement

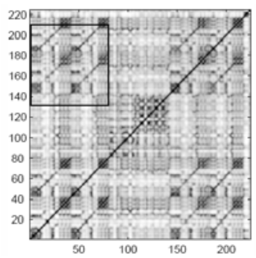
Idea: Usage of contextual information (Foote 1999)

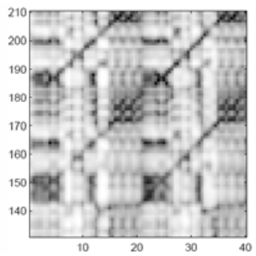
$$C_L(n,m) := \frac{1}{L}\sum_{\ell=0}^{L-1} c(v_{n+\ell}, v_{m+\ell})$$

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

$\rightsquigarrow$ smoothing effect

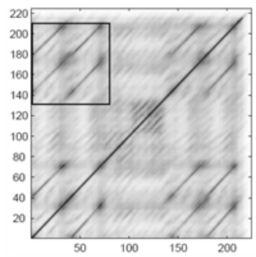
Matrix Enhancement (Shostakovich)

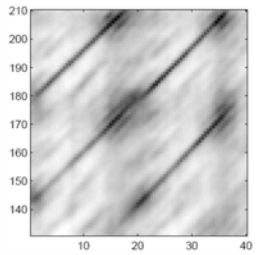




Cost matrix C

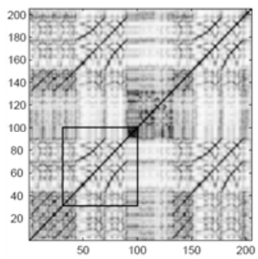
Matrix Enhancement (Shostakovich)

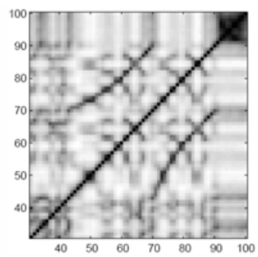




Enhanced cost matrix C_L

Matrix Enhancement (Brahms)





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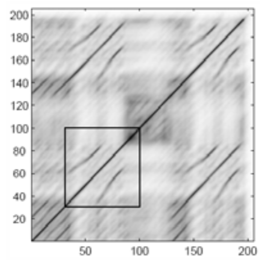
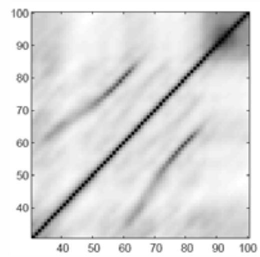




Enhanced cost matrix C_L

Problem: Relative tempo differences are smoothed out

Matrix Enhancement

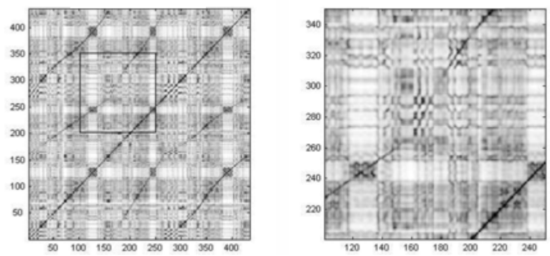
Idea: Smoothing along various directions
and minimizing over all directions

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

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

⇝ tempo changes of -30 to +40 percent

Matrix Enhancement



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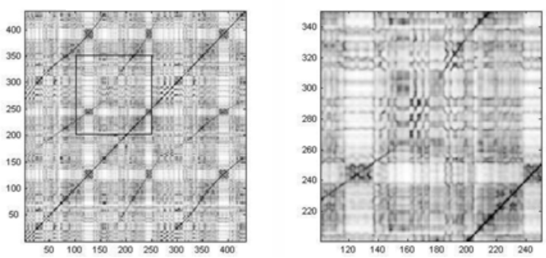
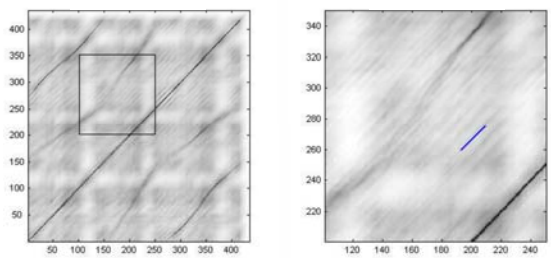


Cost matrix C

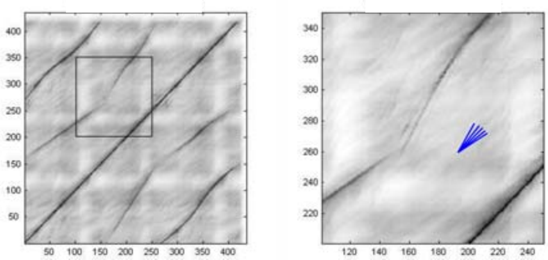
Matrix Enhancement



Cost matrix C_L with $L = 20$

Filtering along main diagonal

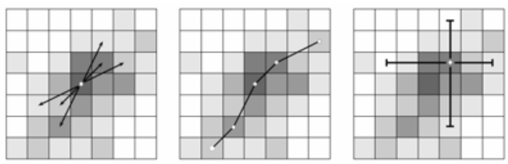
Matrix Enhancement



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

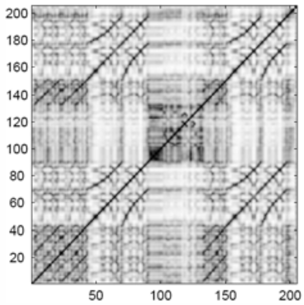
Filtering along 8 different directions and minimizing

Path Extraction



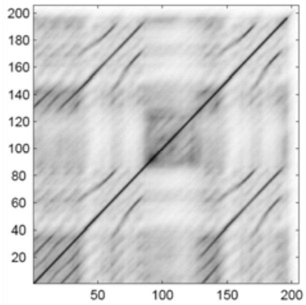
- Start with initial point
- Extend path in greedy fashion
- Remove path neighborhood

Path Extraction



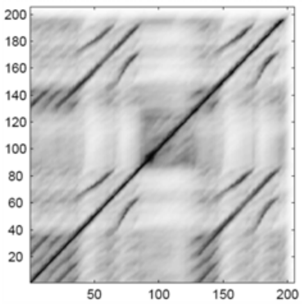
Cost matrix C

Path Extraction



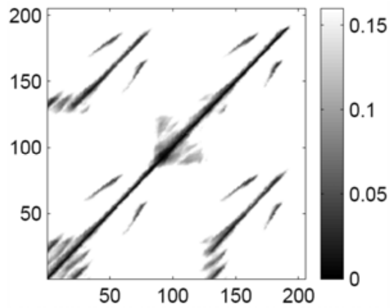
Enhanced cost matrix C_L

Path Extraction



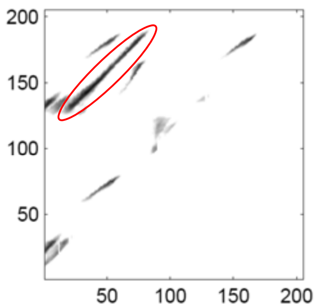
Enhanced cost matrix $C_L^{\min}$

Path Extraction



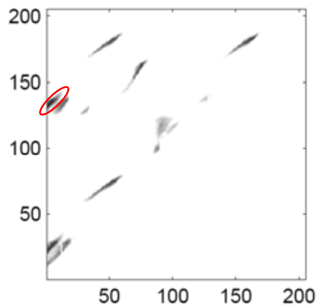
Thresholded $C_L^{\min}$

Path Extraction



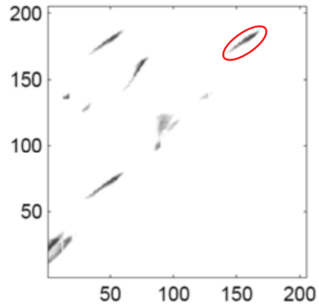
Thresholded $C_L^{\min}$, upper left

Path Extraction



Path removal

Path Extraction



Path removal

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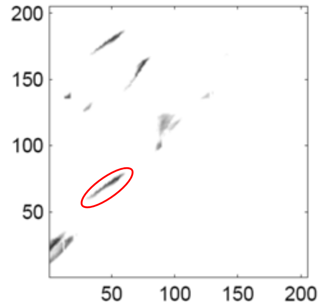

Path removal

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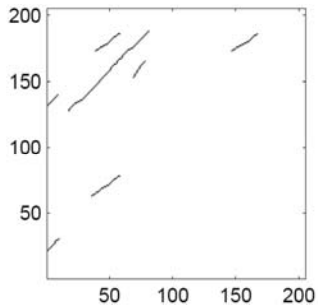
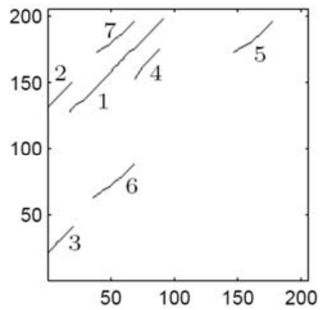


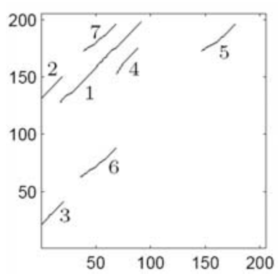
Extracted paths

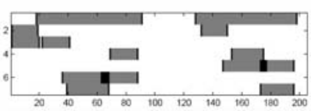
Path Extraction



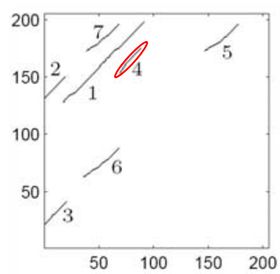
Extracted paths after postprocessing

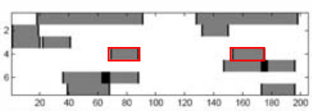
Global Structure





Global Structure





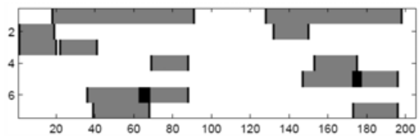
How can one derive the global structure from pairwise relations?

Global Structure

- Taks: Computation of similarity clusters
- Problem: Missing and inconsistent path relations
- Strategy: Approximate “transitive hull”

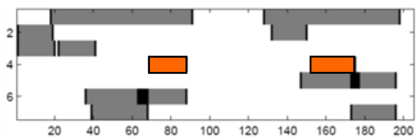
Global Structure

Path relations



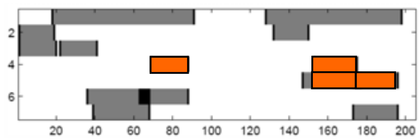
Global Structure

Path relations



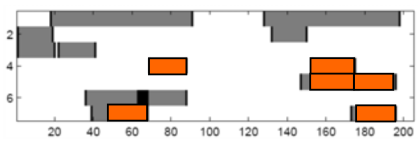
Global Structure

Path relations



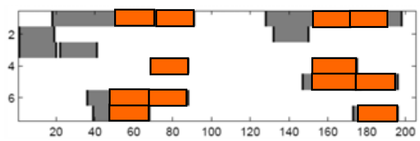
Global Structure

Path relations

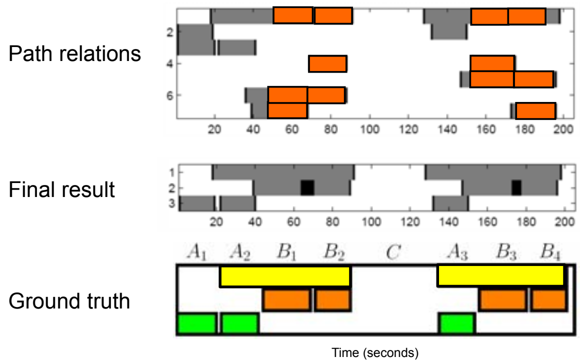


Global Structure

Path relations

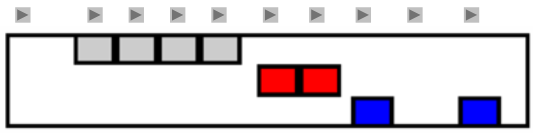


Global Structure



Transposition Invariance

Example: Zager & Evans “In The Year 2525”



Transposition Invariance

Goto (ICASSP 2003)

- Cyclically shift chroma vectors in one sequence
- Compare shifted sequence with original sequence
- Perform for each of the twelve shifts a separate structure analysis
- Combine the results

Transposition Invariance

Goto (ICASSP 2003)

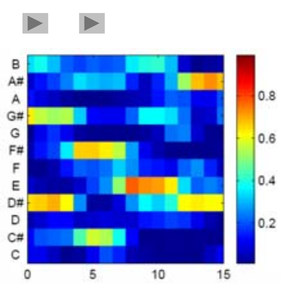
- Cyclically shift chroma vectors in one sequence
- Compare shifted sequence with original sequence
- Perform for each of the twelve shifts a separate structure analysis
- Combine the results

Müller/Clausen (ISMIR 2007)

- Integrate all cyclic information in one transposition-invariant self-distance matrix
- Perform one joint structure analysis

Transposition Invariance

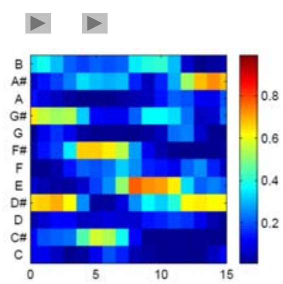
Example: Zager & Evans “In The Year 2525”



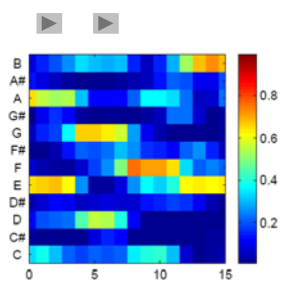
Original: $(v^1, \ldots, v^N)$

Transposition Invariance

Example: Zager & Evans “In The Year 2525”

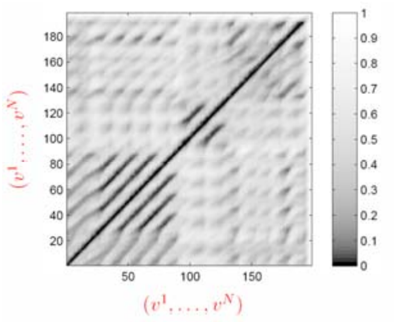


Original: $(v^1, \ldots, v^N)$

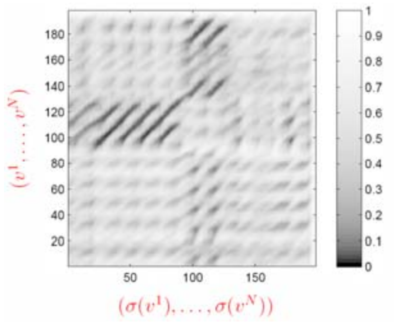


Shifted: $(\sigma(v^1), \ldots, \sigma(v^N))$

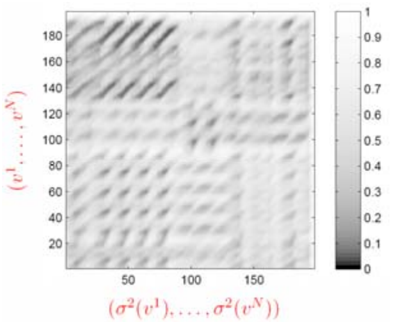
Transposition Invariance



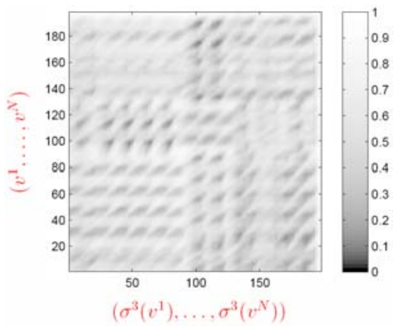
Transposition Invariance



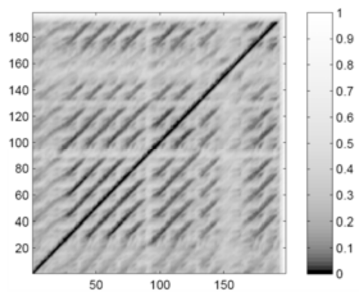
Transposition Invariance



Transposition Invariance

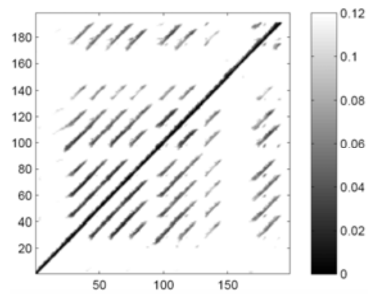


Transposition Invariance



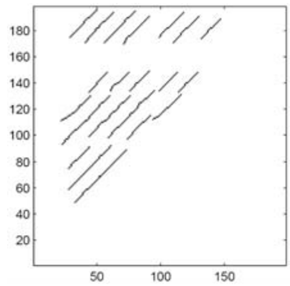
Minimize over all twelve matrices

Transposition Invariance



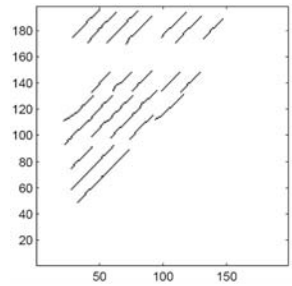
Thresholded self-distance matrix

Transposition Invariance

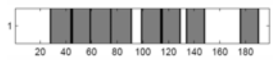


Path extraction

Transposition Invariance



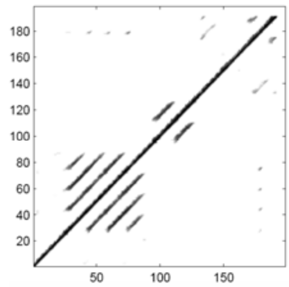
Path extraction

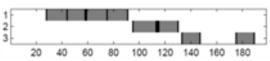


Computation of similarity clusters

Transposition Invariance

Stabilizing effect

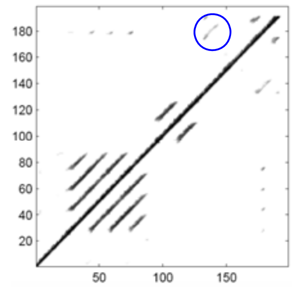


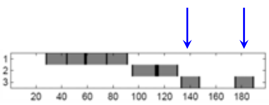


Self-distance matrix (thresholded)

Transposition Invariance

Stabilizing effect

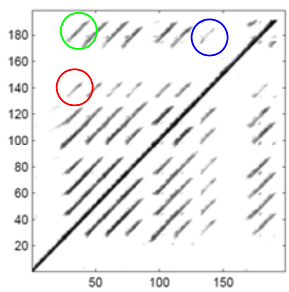


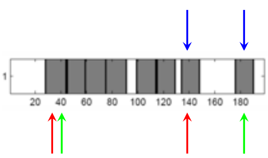


Self-distance matrix (thresholded)

Transposition Invariance

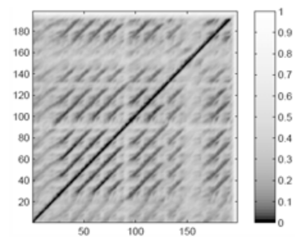
Stabilizing effect



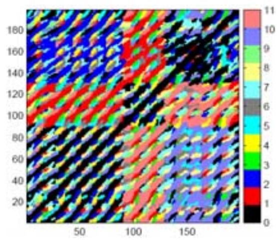


Transposition-invariant self-distance matrix (thresholded)

Transposition Invariance

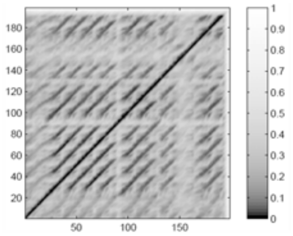


Transposition-invariant matrix

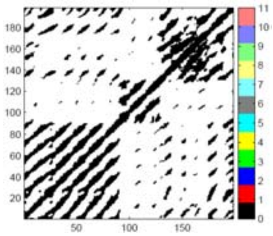


Minimizing shift index

Transposition Invariance

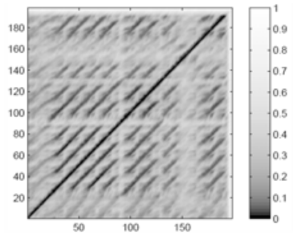


Transposition-invariant matrix

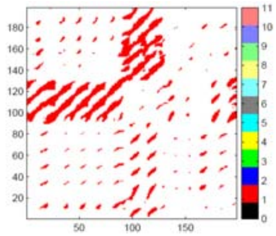


Minimizing shift index = 0

Transposition Invariance

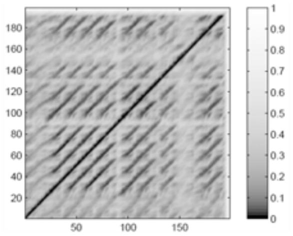


Transposition-invariant matrix

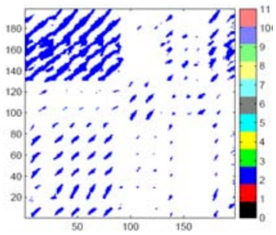


Minimizing shift index = 1

Transposition Invariance

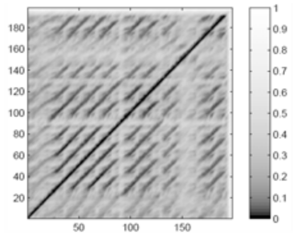


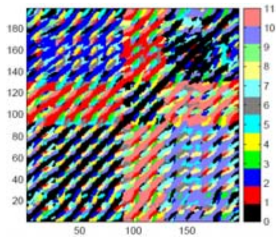
Transposition-invariant matrix



Minimizing shift index = 2

Transposition Invariance



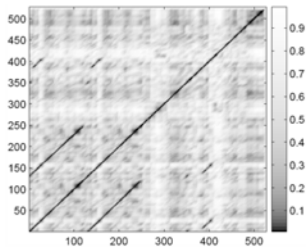


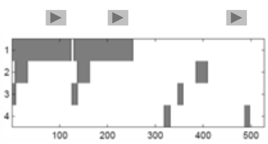
Serra/Gomez (ICASSP 2008): Used for Cover Song ID

Discrete structure $\rightsquigarrow$ suitable for indexing?

Transposition Invariance

Example: Beethoven “Tempest”

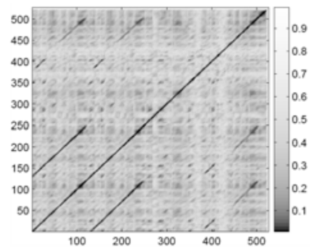


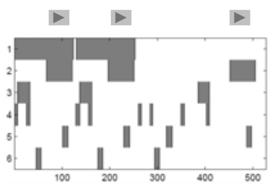


Self-distance matrix

Transposition Invariance

Example: Beethoven “Tempest”





Transposition-invariant self-distance matrix

Novel Approach for Audio Thumbnailing

Original approach: Two steps

1. Path extraction
   - Paths of poor quality (fragmented, gaps)
   - Regions of constant (low) cost
   - Curved paths
2. Grouping:
   - Noisy relations (missing, distorted, overlapping)
   - Transitivity computation difficult

Both steps are problematic!

Our main idea: Do both, path extraction and grouping, jointly

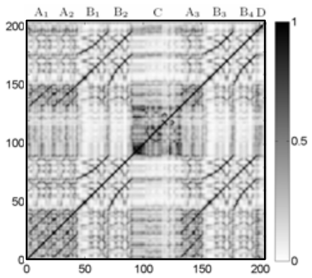
- One optimization scheme for both steps
- Stabilizing effect
- Efficient

Novel Approach for Audio Thumbnailing

Our main idea: Do both path extraction and grouping jointly

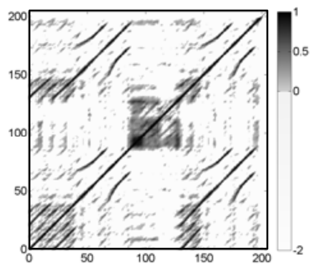
- For each audio segment we define a fitness value
- This fitness value expresses "how well" the segment explains the entire audio recording
- The segment with the highest fitness value is considered to be the thumbnail
- As main technical concept we introduce the notion of a path family

Fitness Measure



Self-similarity matrix

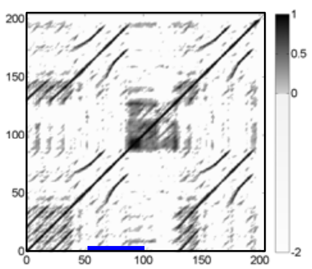
Fitness Measure



Self-similarity matrix

- Smoothing
- Transposition-Invariance
- Normalization
- Thresholding
- Negative score

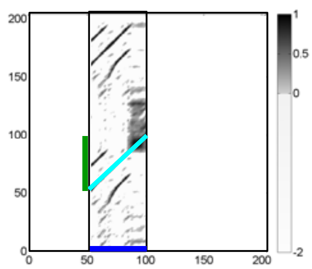
Fitness Measure



Path over segment

- Consider a fixed segment

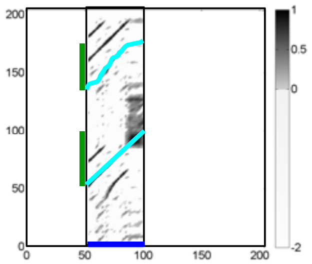
Fitness Measure



Path over segment

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

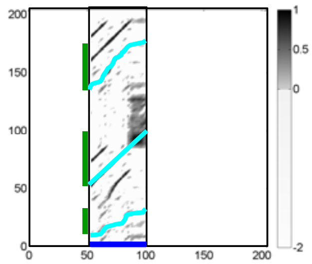
Fitness Measure



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

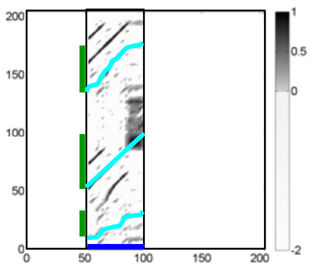
Fitness Measure



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

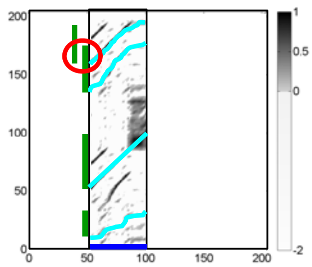
Fitness Measure



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

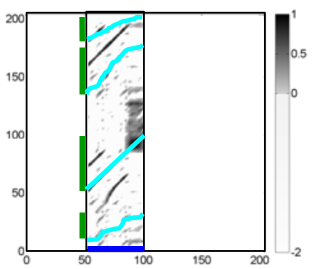


Path family

- 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



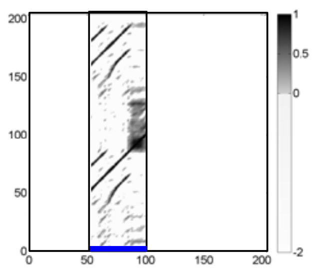
Path family

- 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)

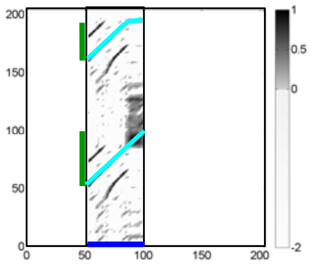
Fitness Measure



Optimal path family

- Consider a fixed segment

Fitness Measure



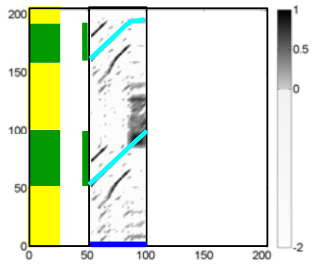
Optimal path family

- 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

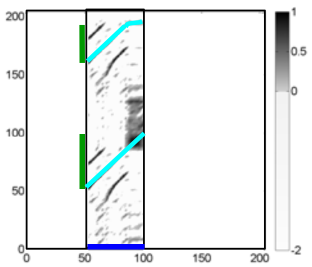
- Consider a fixed segment
- Consider over the segment the optimal path family, i.e., the path family having maximal overall score.
- Call this value:

  Score(segment)

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

  Coverage(segment)

Fitness Measure



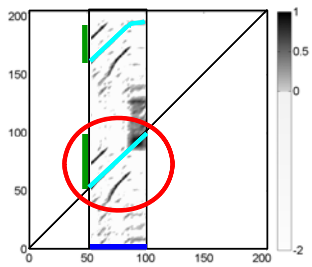
Fitness

- Consider a fixed segment

P := Score(segment)

R := Coverage(segment)

Fitness Measure



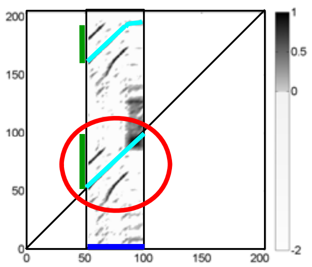
Fitness

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

P := Score(segment)

R := Coverage(segment)

Fitness Measure



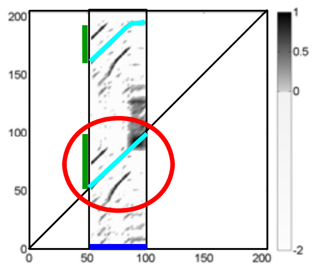
Fitness

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

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

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

Fitness Measure



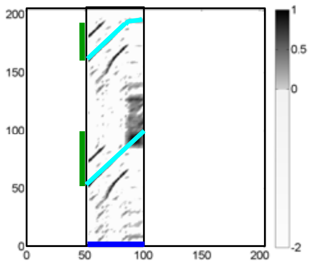
Fitness

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

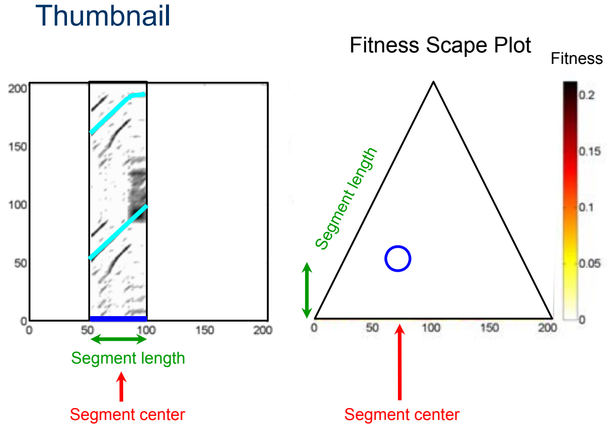
Fitness(segment)

F := 2 • P • R / (P + R)

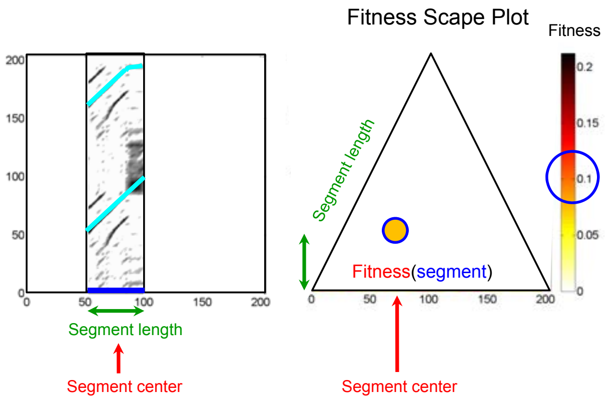
P := Normalize(Score(segment) - length(segment)) $\in [0,1]$

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

Thumbnail



Thumbnail



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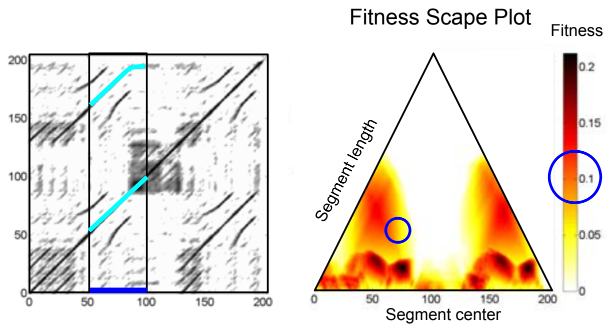
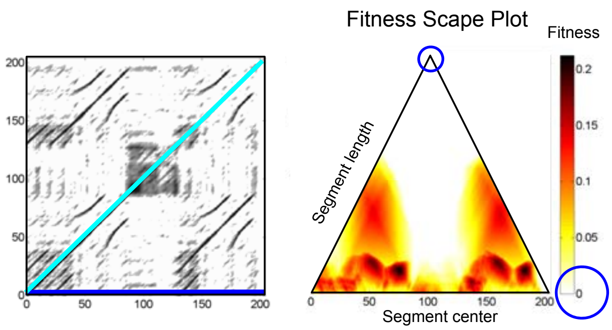
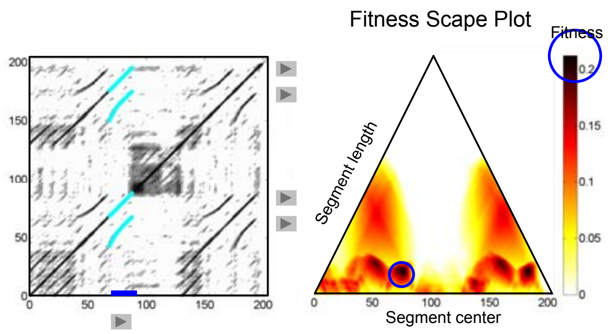


Thumbnail



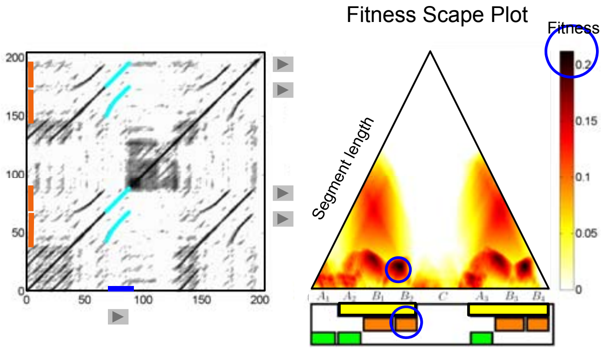
Note: Self-explanations are ignored → fitness is zero

Thumbnail



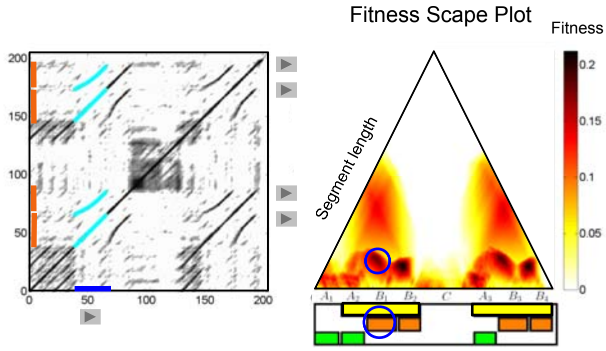
Thumbnail := segment having the highest fitness

Thumbnail



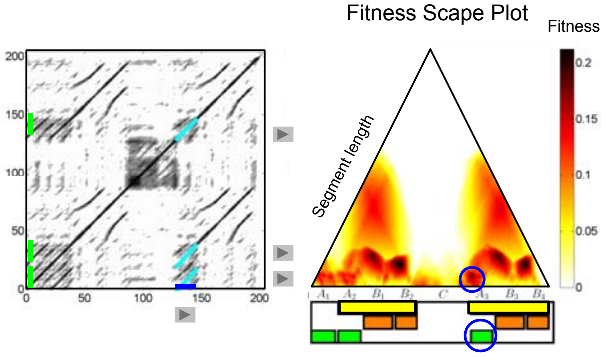
Example: Brahms Hungarian Dance No. 5 (Ormandy)

Thumbnail



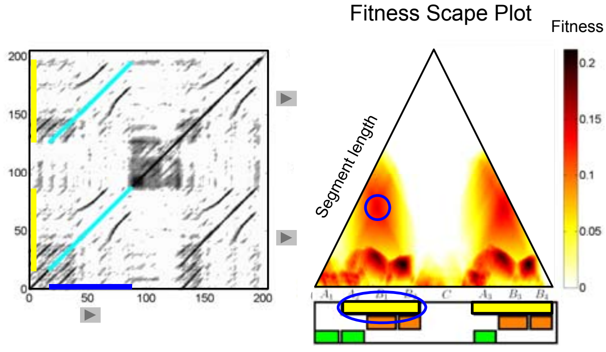
Example: Brahms Hungarian Dance No. 5 (Ormandy)

Thumbnail



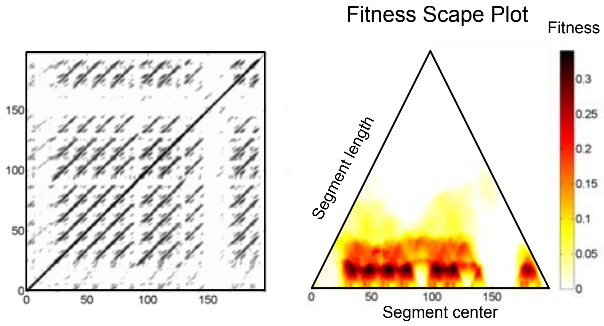
Example: Brahms Hungarian Dance No. 5 (Ormandy)

Thumbnail



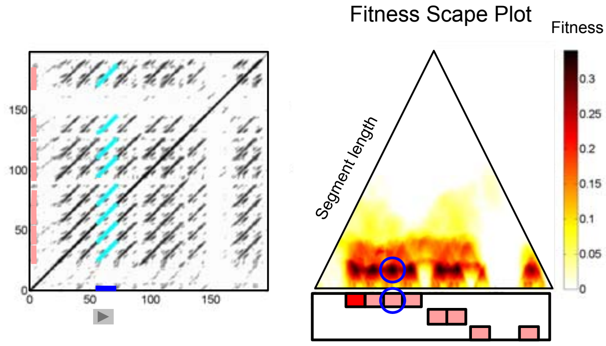
Example: Brahms Hungarian Dance No. 5 (Ormandy)

Thumbnail



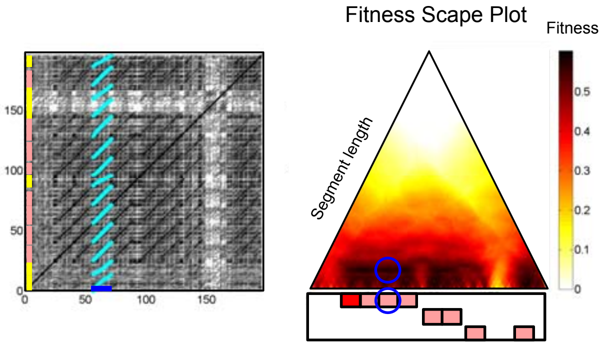
Example: Zager & Evans “In The Year 2525”

Thumbnail



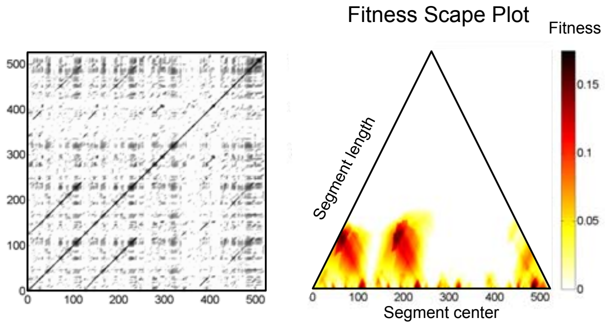
Example: Zager & Evans “In The Year 2525”

Thumbnail



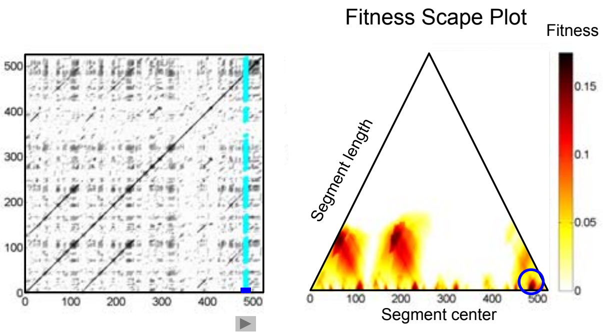
Example: Zager & Evans “In The Year 2525”

Thumbnail



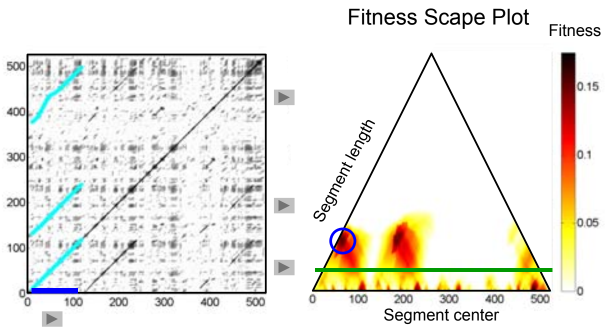
Example: Beethoven “Tempest”, Pollini

Thumbnail



Example: Beethoven “Tempest”, Pollini

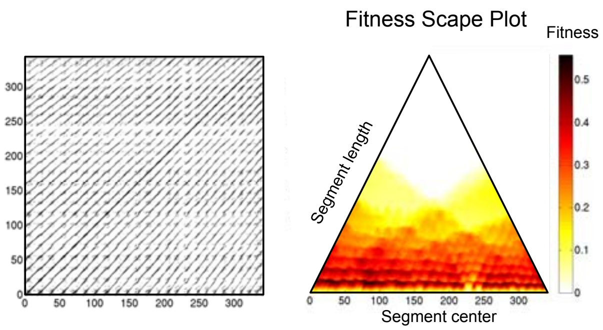
Thumbnail



Example: Beethoven “Tempest”, Pollini

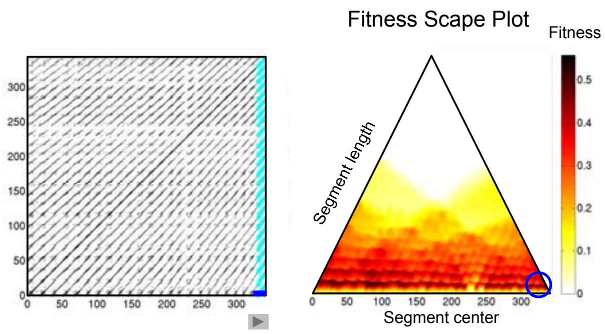
Musical knowledge: Minimum length for thumbnail

Thumbnail



Example: NLB72246

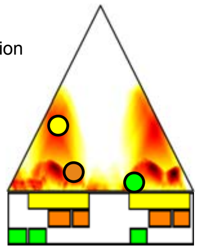
Thumbnail



Example: NLB72246

Conclusions

- Path family: Couples path extraction and grouping
- Fitness: Quality of segment in context of entire recording
  - Combination of score and coverage
  - Trivial self-explanation are disregarded
- Thumbnail: Segment of maximal fitness
- Fintness scape plot: Global structure visualization



Future work:

- Multiscale approach
- Combination with novelty detection
- Interface for structure navigation