INTERNATIONAL AUDIO LABORATORIES ERLANGEN
A joint institution of Fraunhofer IIS and Universität Erlangen-Nürnberg

AUDIO LABS

Tutorial 5, ISMIR
Milan, November 5, 2023

ISMIR 2023

Learning with Music Signals: Technology Meets Education

Music Retrieval

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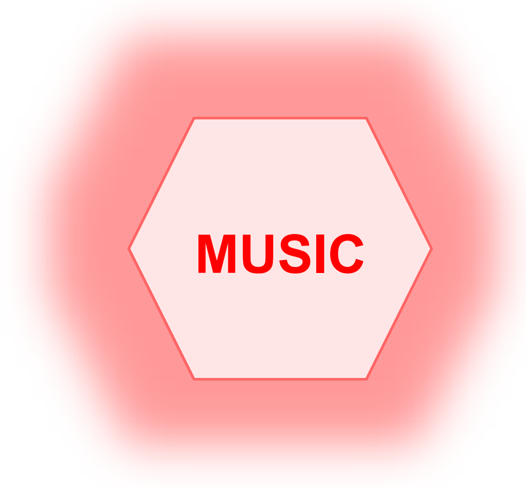
Fraunhofer IIS

Music Representations

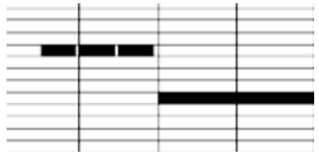


Music Representations

Recording (Audio)

Sheet Music (Image)

Piano Roll (MIDI)



Singing (Audio)

MUSIC

Literature (Text)

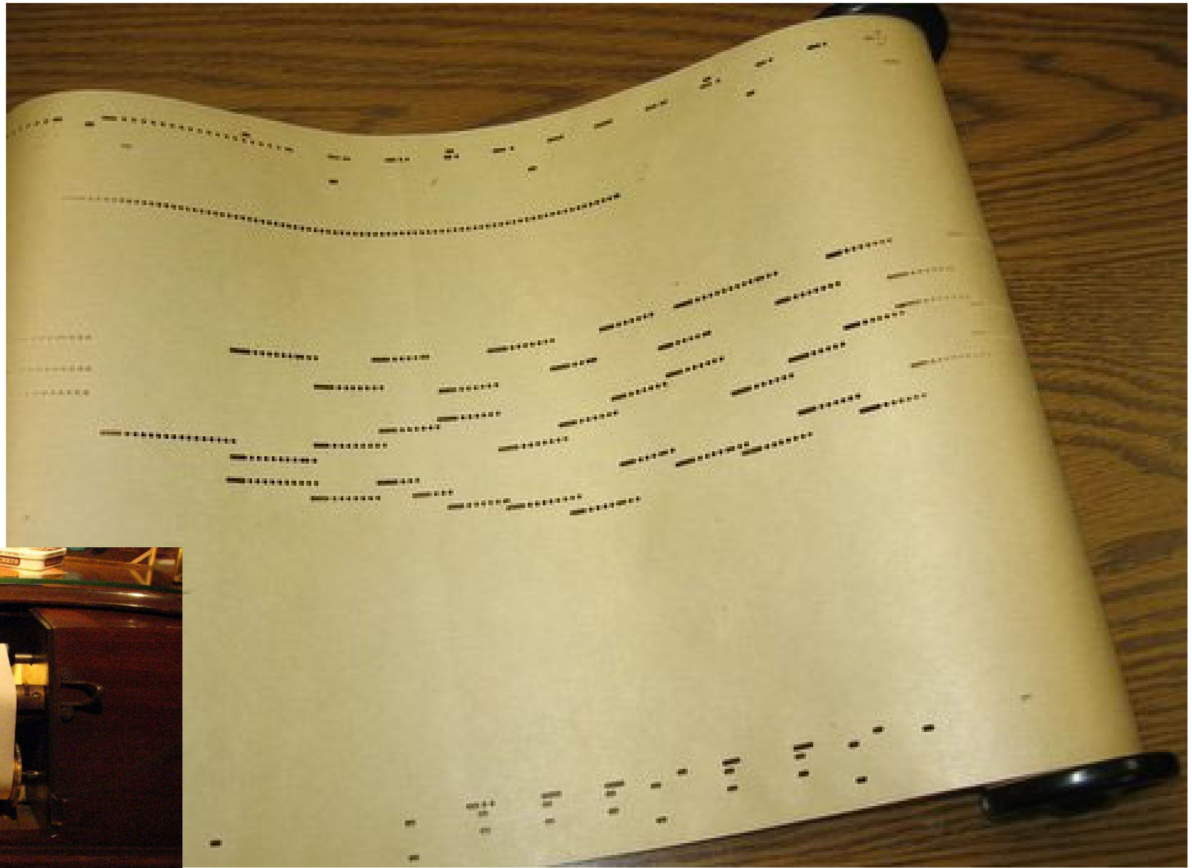
Dance (Mocap)

Film (Video)

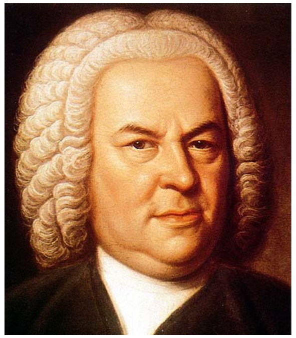
MusicXML (Symbolic)

```
<pitch>
  <step>E</step>
  <alter>-1</alt
```

Piano Roll Representation (1900)

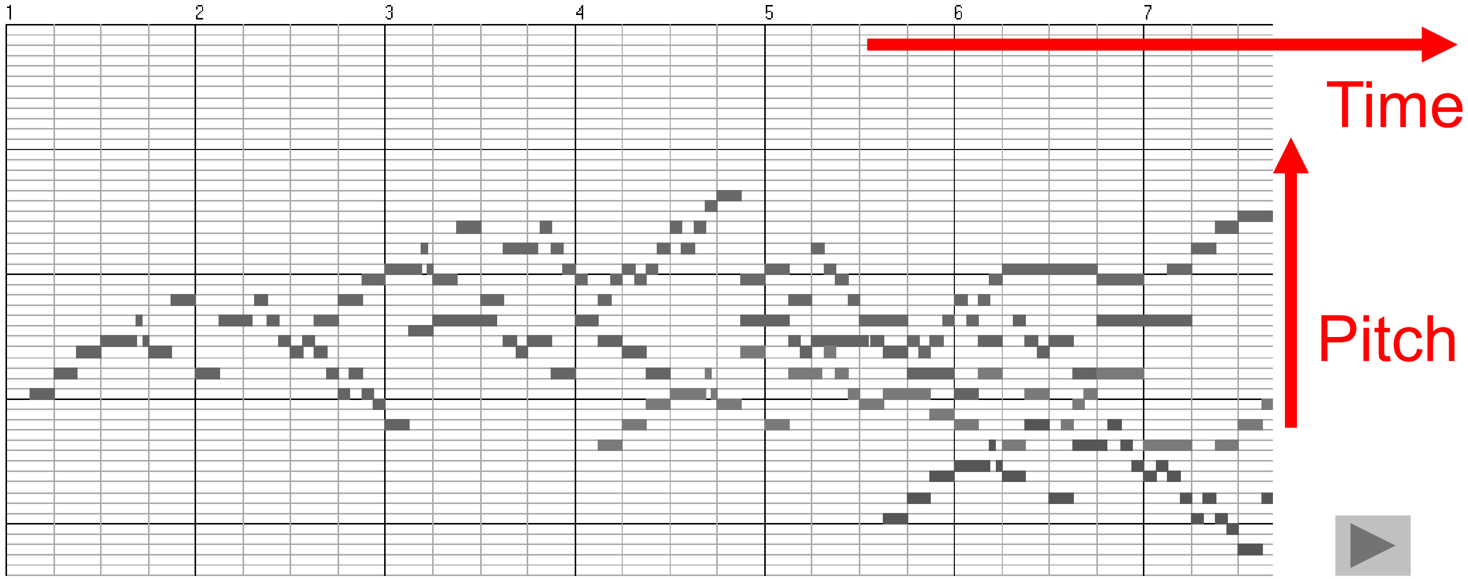


Piano Roll Representation

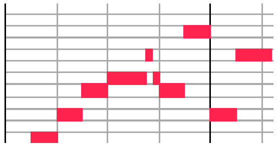


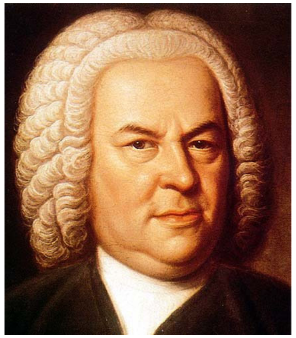
J.S. Bach, C-Major Fuge

(Well Tempered Piano, BWV 846)

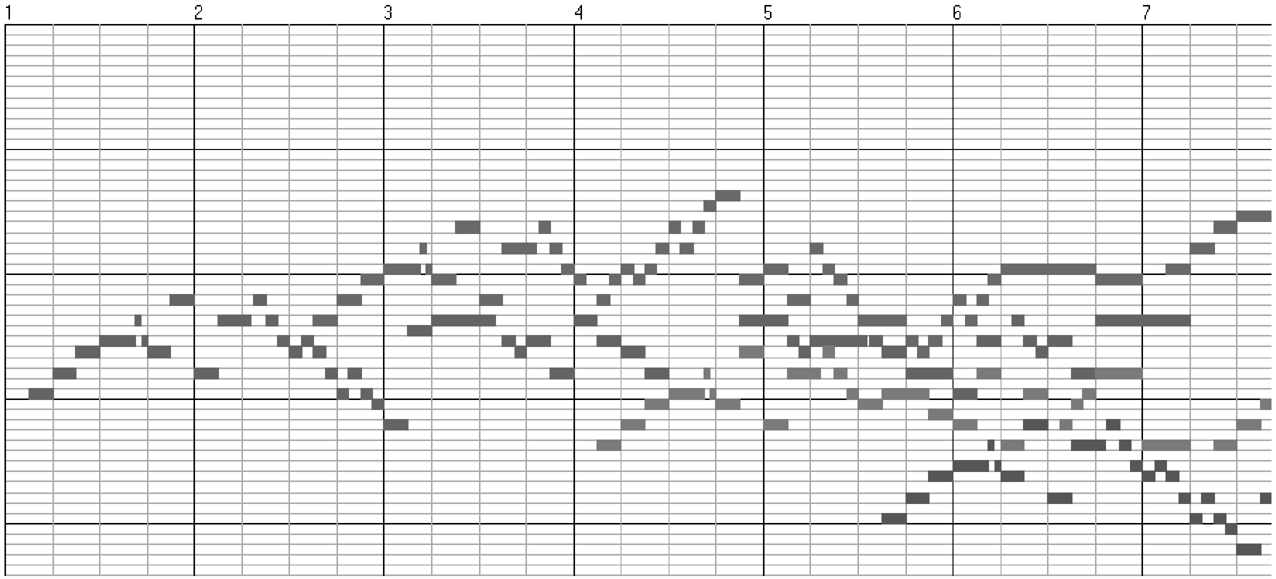


Piano Roll Representation

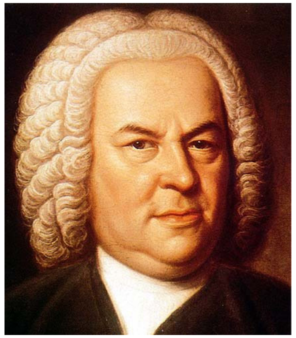
Query: 

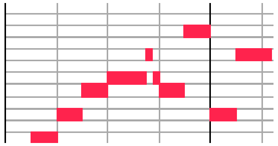


Goal: Find all occurrences of the query



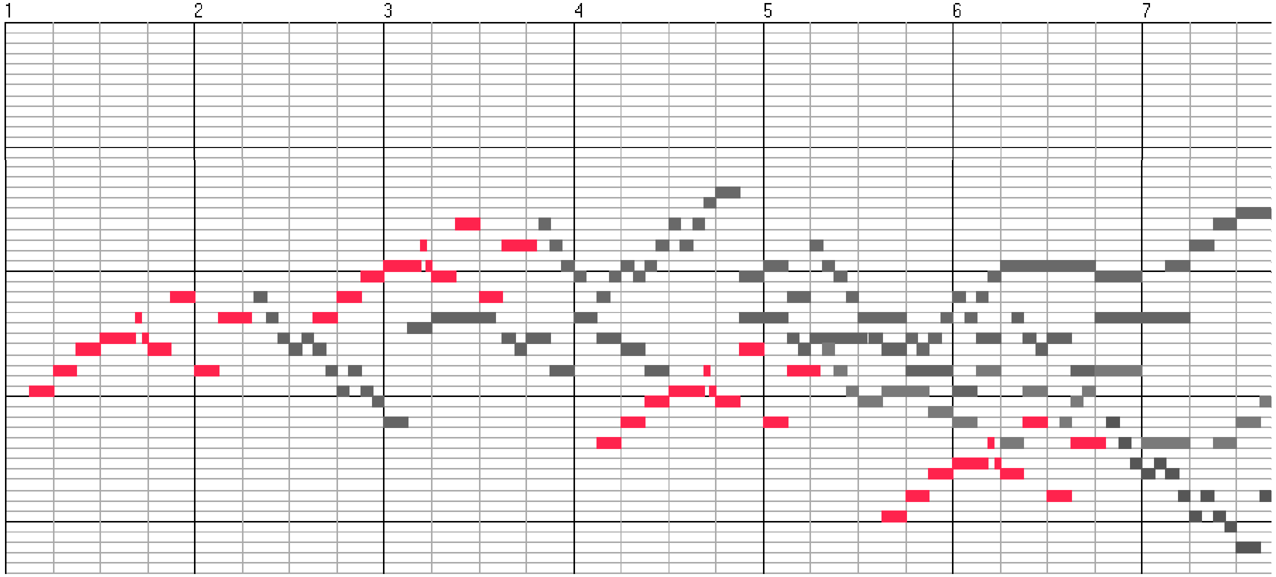
Piano Roll Representation



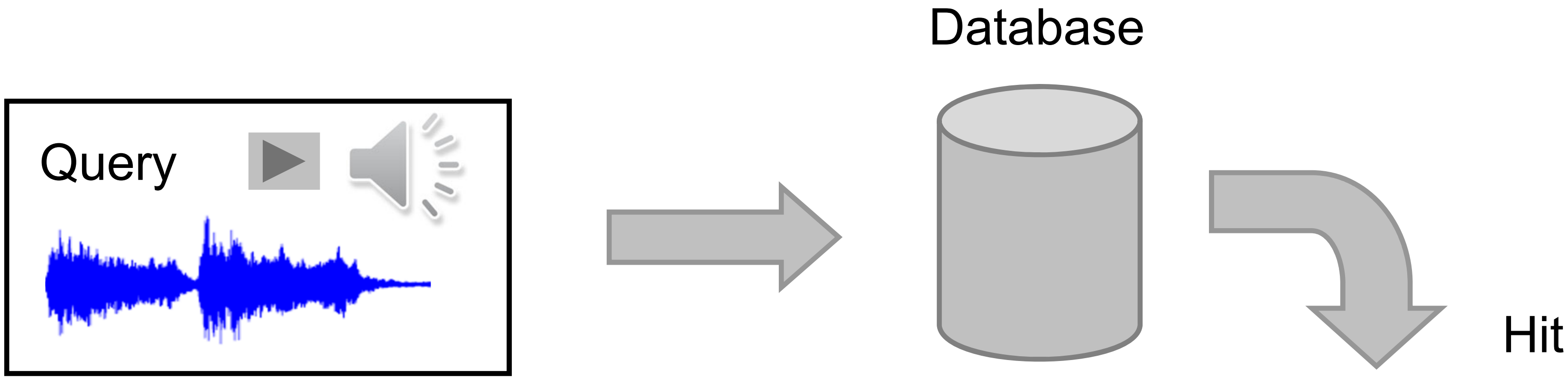
Query: 

Goal: Find all occurrences of the query

Matches:



Music Retrieval



Audio ID

Bernstein (1962)
Beethoven, Symphony No. 5

Version ID

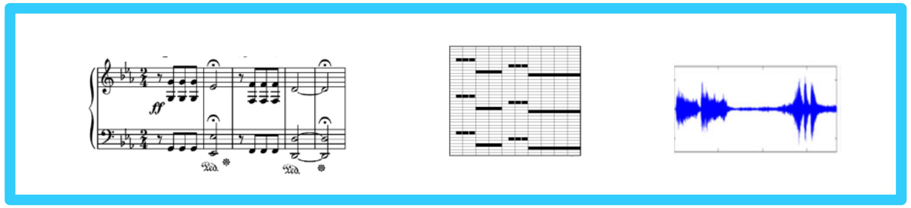
Beethoven, Symphony No. 5:
- Bernstein (1962)
- Karajan (1982)
- Gould (1992)

Category ID

- Beethoven, Symphony No. 9
- Beethoven, Symphony No. 3
- Haydn Symphony No. 94

Music Retrieval

Modalities



Retrieval tasks:

Audio ID

Version ID

Category ID

Specificity

High specificity

↕

Low specificity

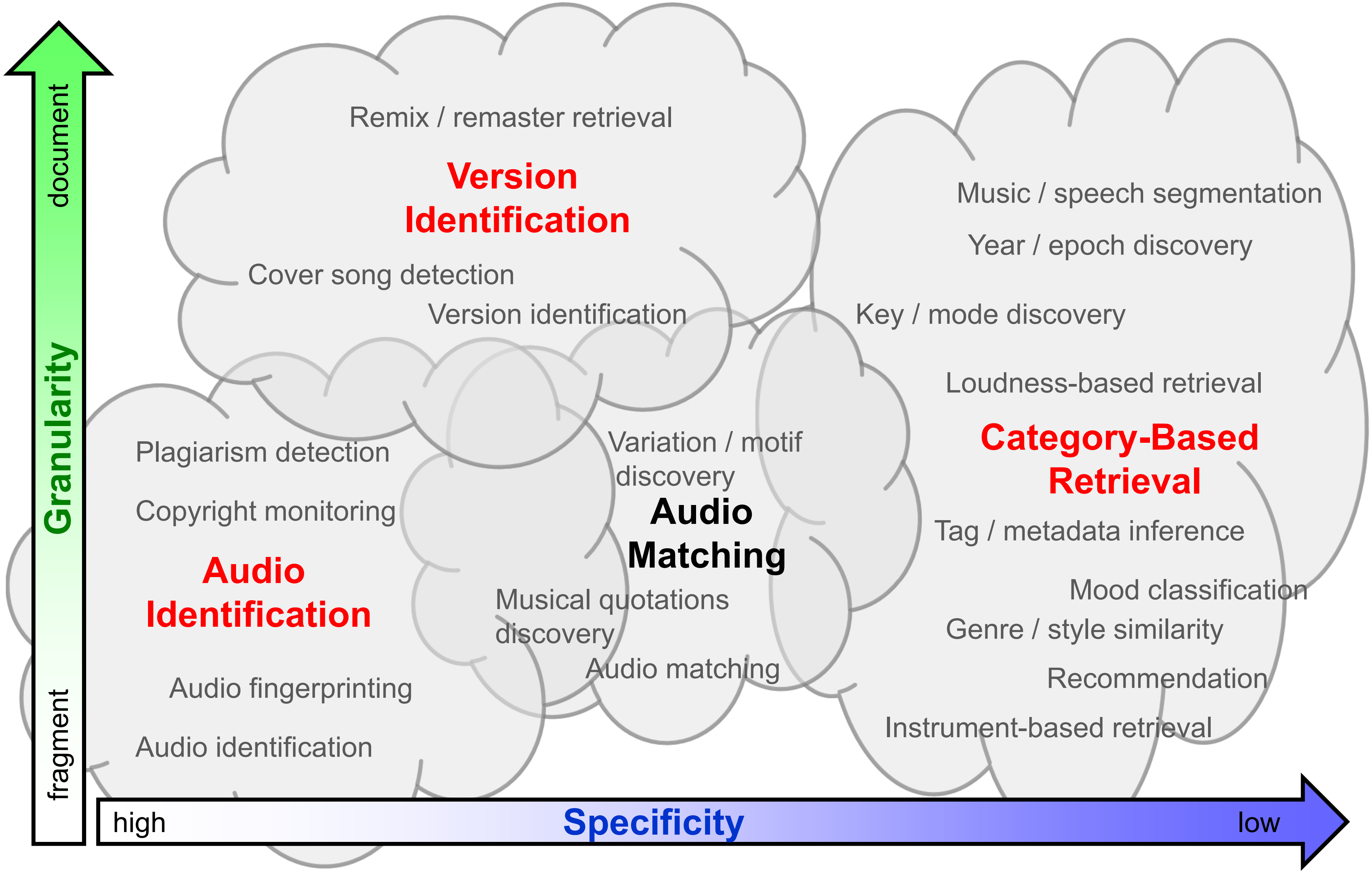
Granularity

Fragment-based retrieval

↕

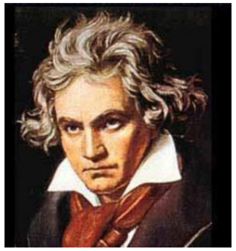
Document-based retrieval

Music Retrieval



Music Synchronization: Audio-Audio

Beethoven’s Fifth



Music Synchronization: Audio-Audio

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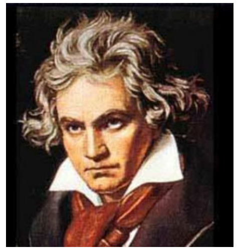
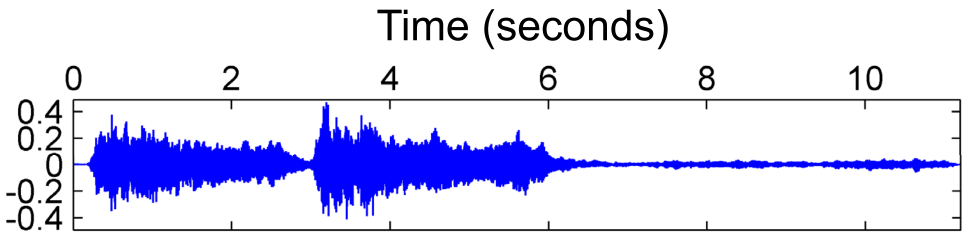
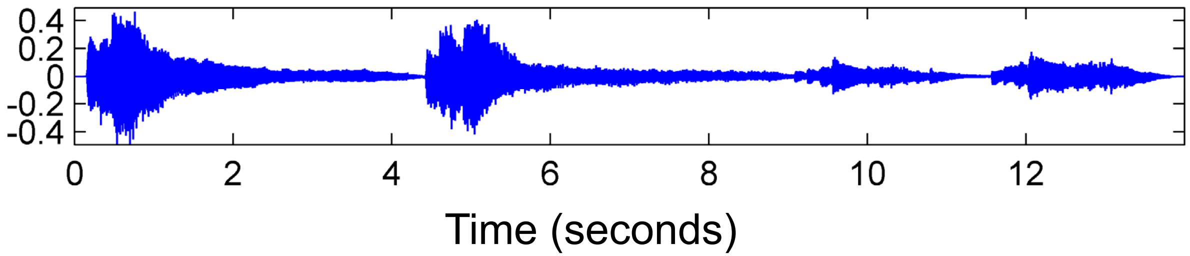


Karajan
(Orchester)

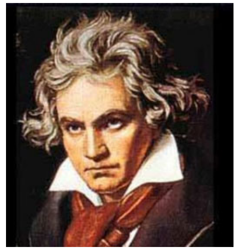


Gould
(Piano)



Music Synchronization: Audio-Audio

Beethoven's Fifth



Karajan
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Gould
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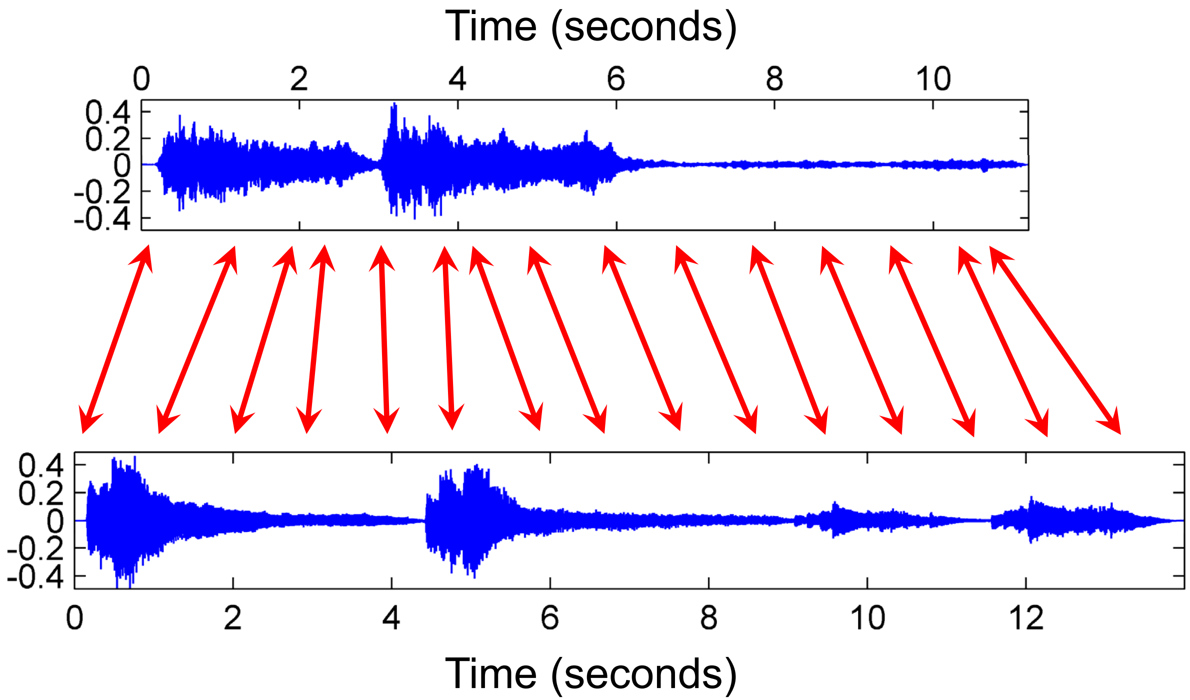


Application: Interpretation Switcher

Music Synchronization: Audio-Audio

Task

Given: Two different audio recordings (two versions) of the same underlying piece of music.

Goal: Find for each position in one audio recording the musically corresponding position in the other audio recording.

Music Synchronization: Audio-Audio

Traditional Engineering Approach:

1.) Feature extraction

- Robust to variations (e.g., instrumentation, timbre, dynamics)
- Discriminative (e.g., capturing harmonic, melodic, tonal aspects)

➡ **Chroma features**

2.) Temporal alignment

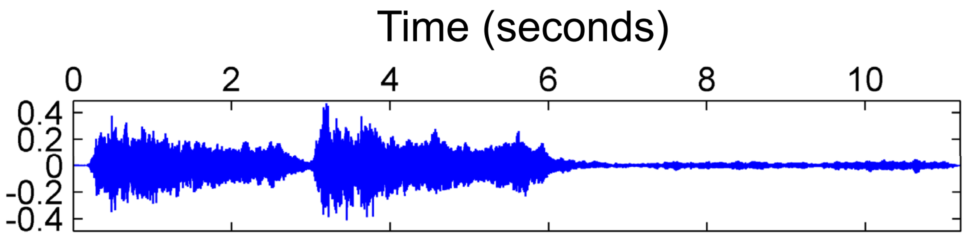
- Capturing local and global tempo variations
- Trade-off: Robustness vs. accuracy
- Efficiency

➡ **Dynamic time warping (DTW)**

Music Synchronization: Audio-Audio

Beethoven's Fifth

Karajan
(Orchester)



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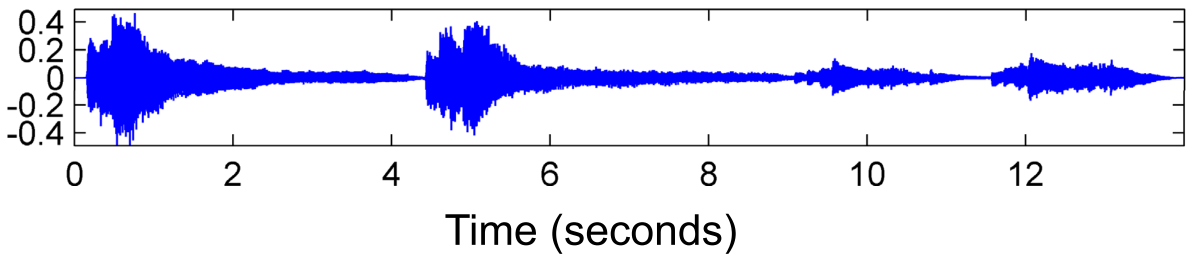
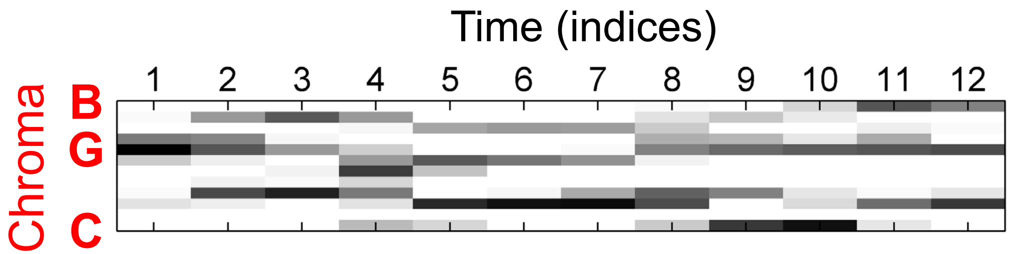


Music Synchronization: Audio-Audio

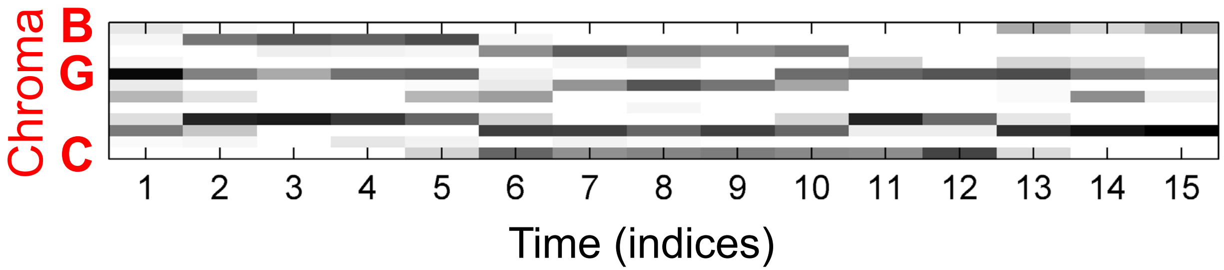
Beethoven's Fifth

Karajan (Orchester)



Time–chroma representations

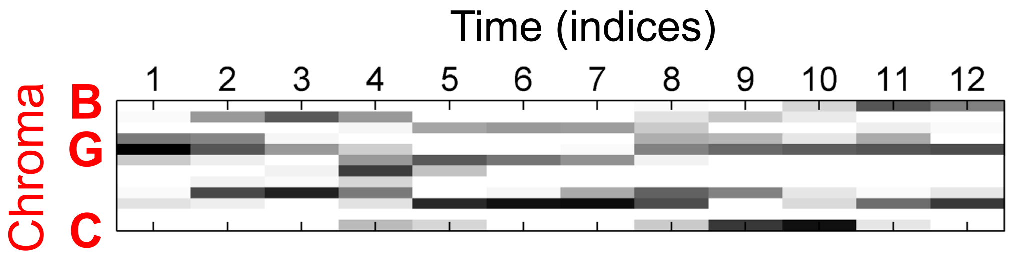
Gould (Piano)



Music Synchronization: Audio-Audio

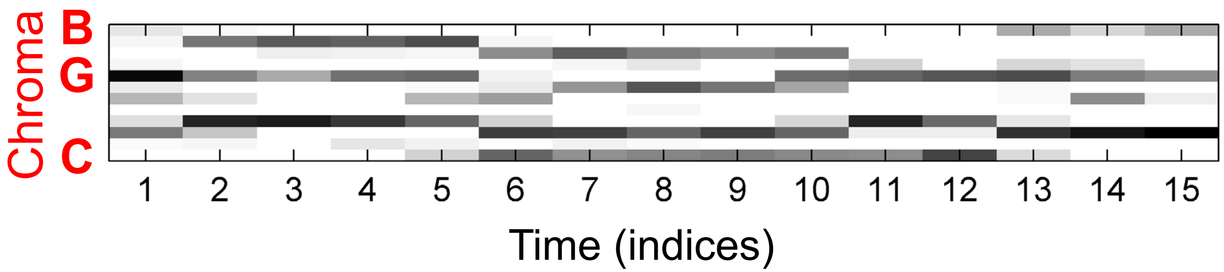
Beethoven's Fifth

Karajan
(Orchester)

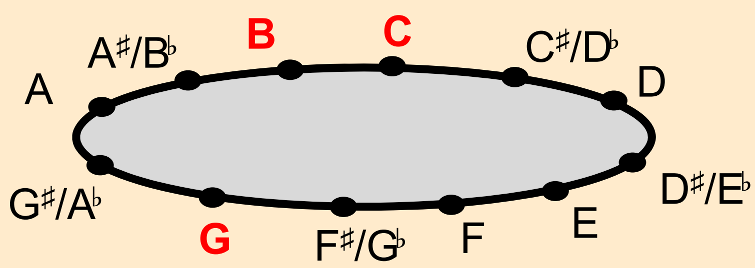


Time–chroma representations

Gould
(Piano)



Chromatic circle



Music Synchronization: Audio-Audio

Beethoven's Fifth

Karajan
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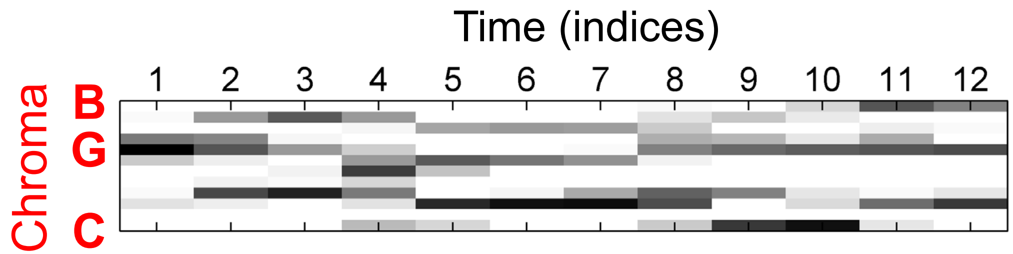

Time–chroma representations

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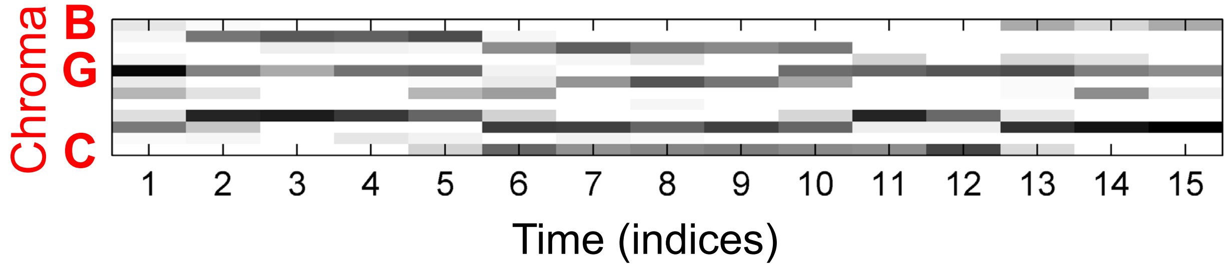

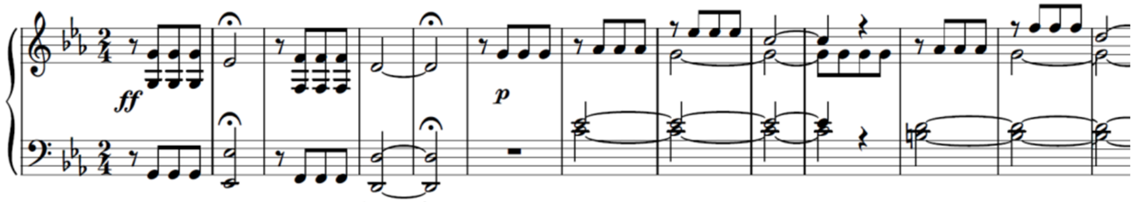

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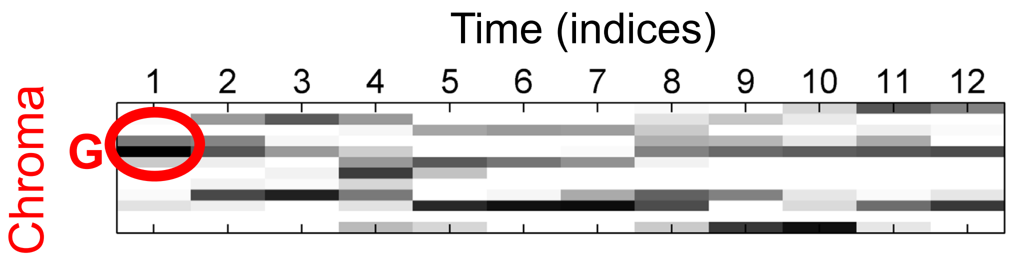
Music Synchronization: Audio-Audio

Beethoven's Fifth

Karajan
(Orchester)



Time–chroma representations

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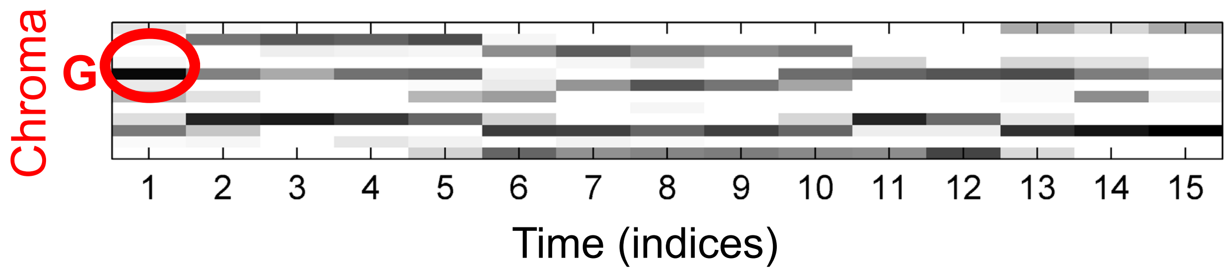
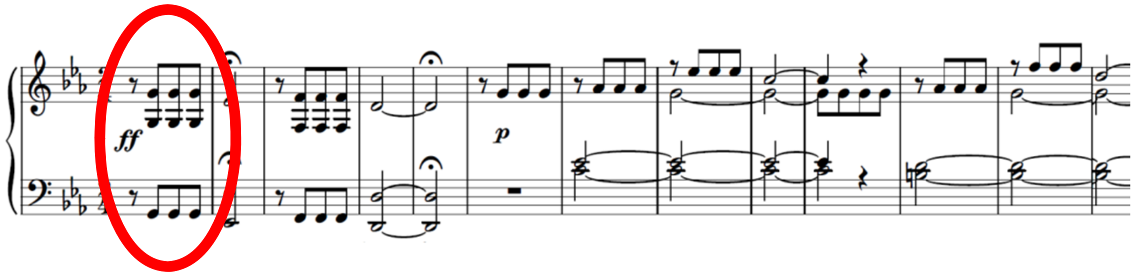
(Piano)





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Music Synchronization: Audio-Audio

Beethoven's Fifth

Karajan
(Orchester)

Gould
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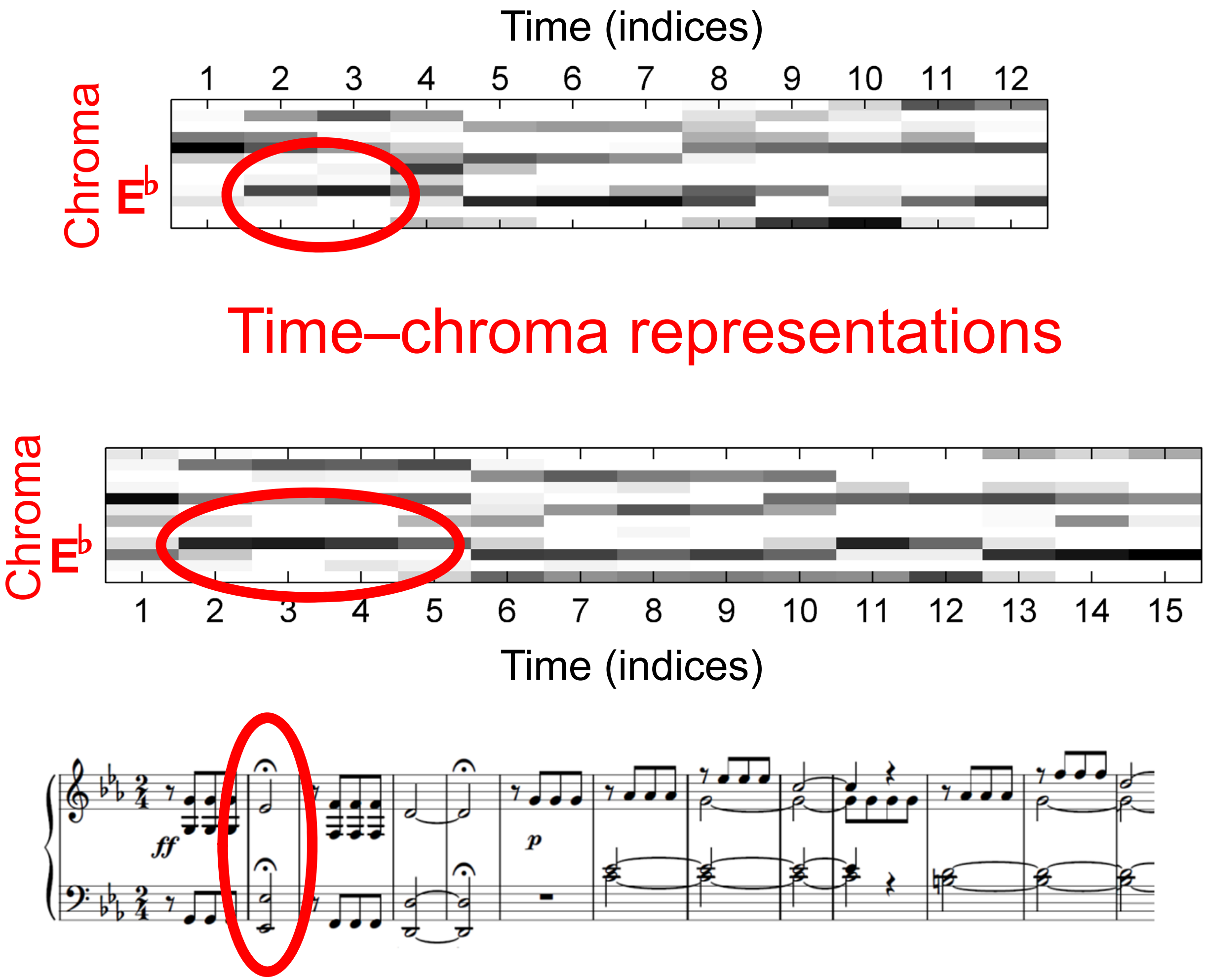
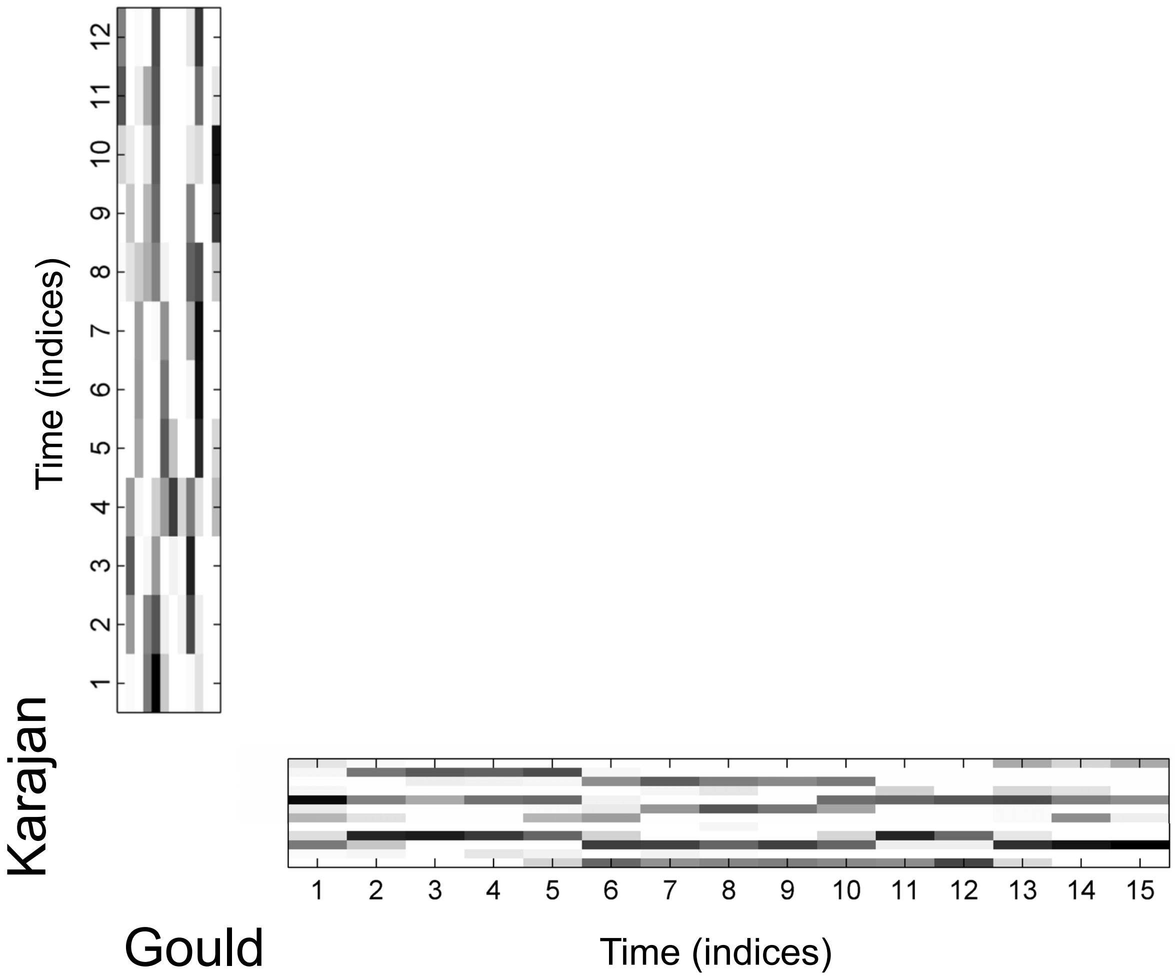
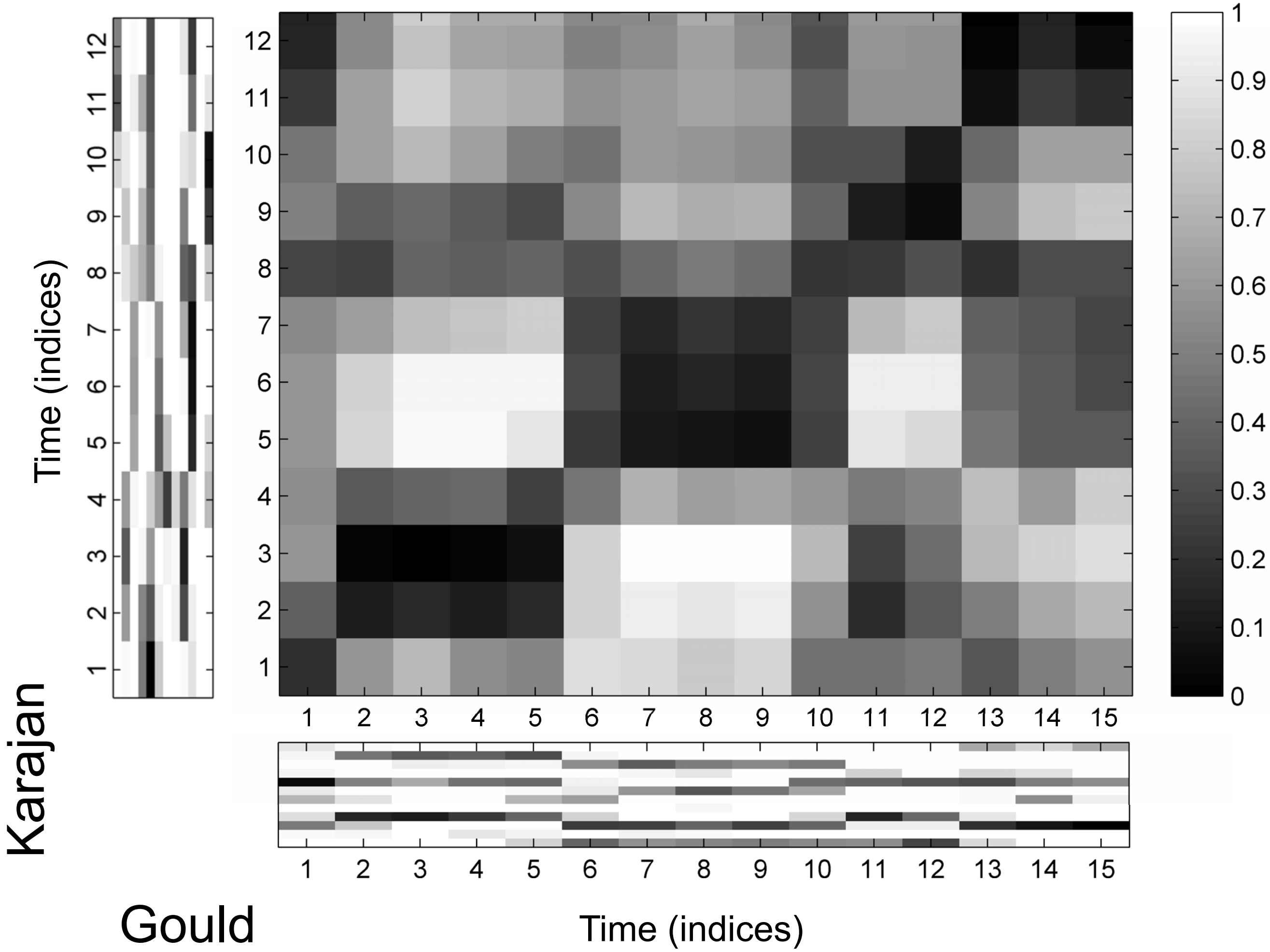


Music Synchronization: Audio-Audio



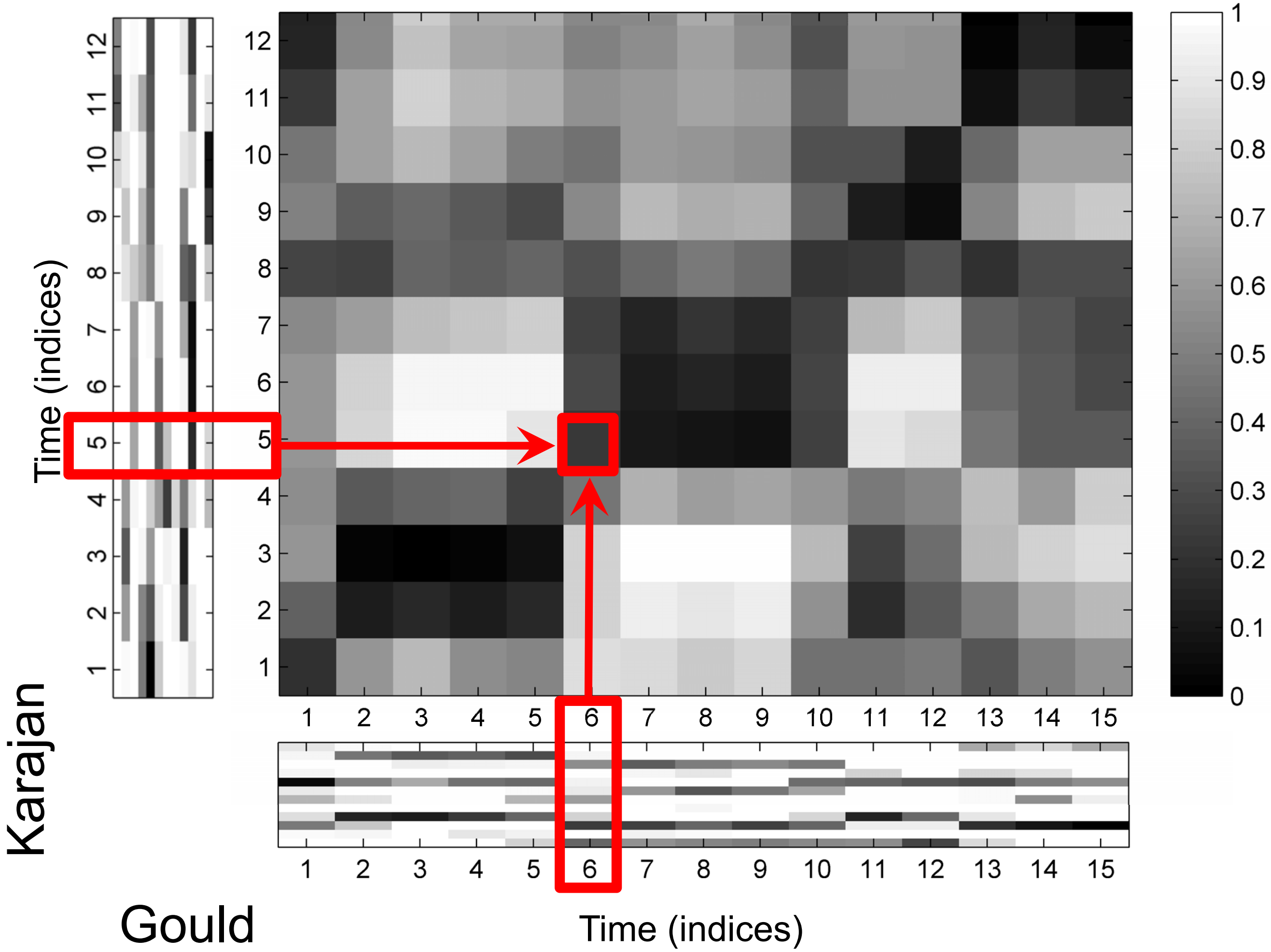
Music Synchronization: Audio-Audio

Cost matrix



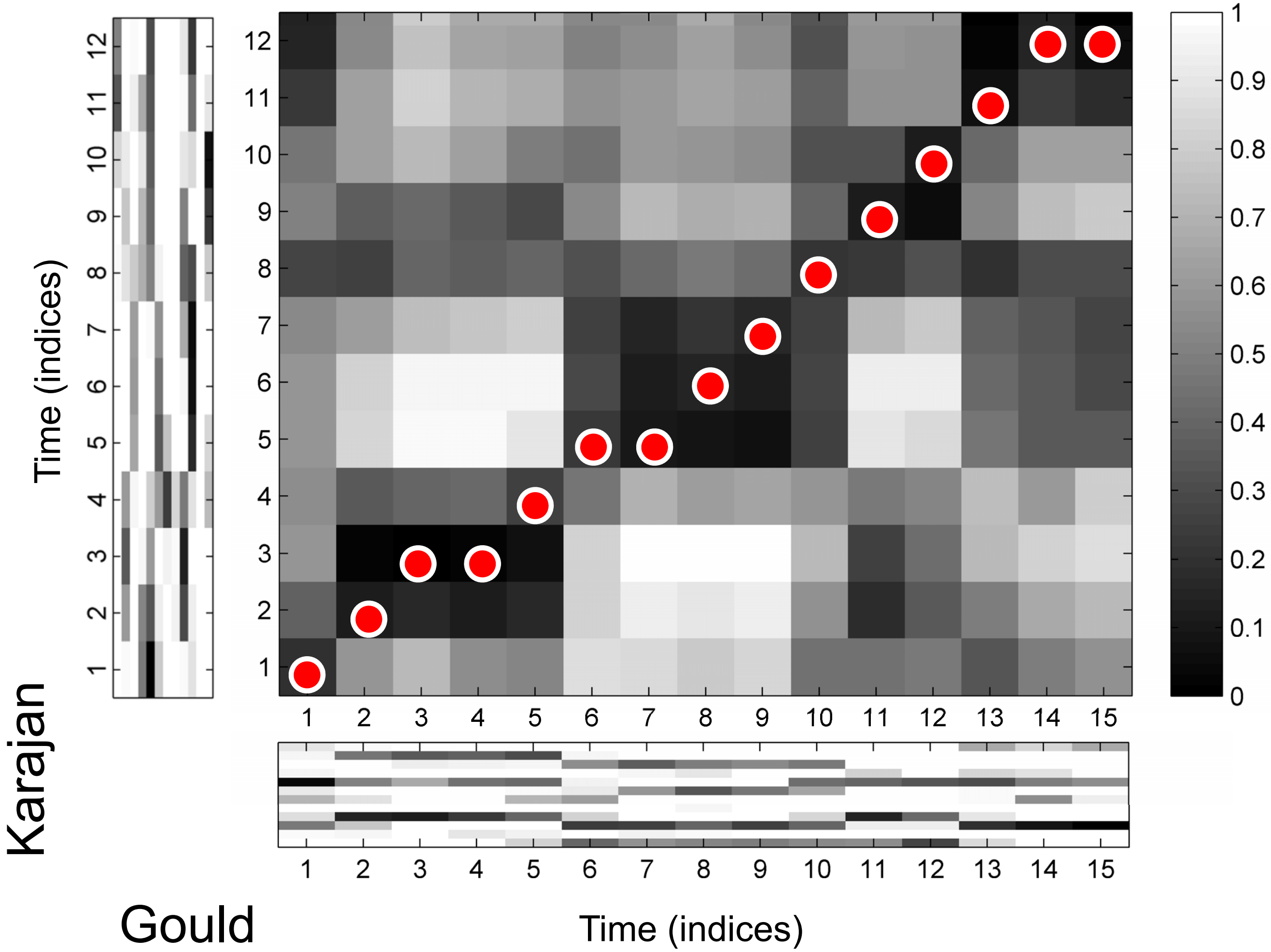
Music Synchronization: Audio-Audio

Cost matrix



Music Synchronization: Audio-Audio

Cost-minimizing warping path



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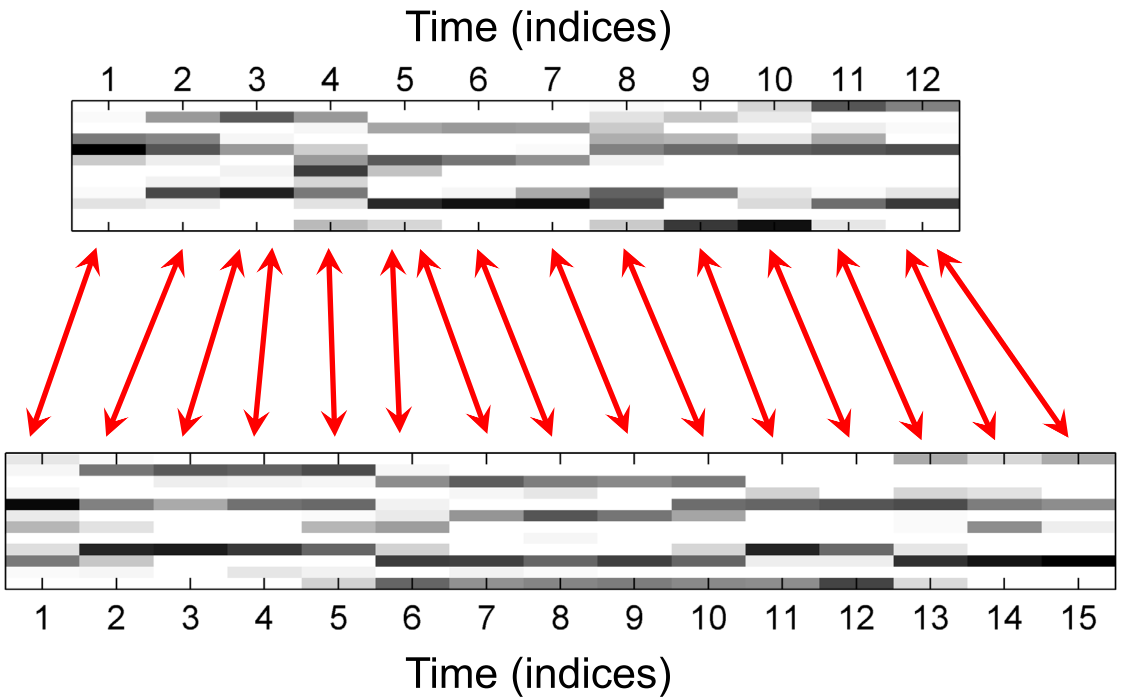
Music Synchronization: Audio-Audio

Cost-minimizing warping path = Optimal alignment

Karajan
(Orchester)

Gould
(Piano)



Music Synchronization: Audio-Audio

Deep Learning Approaches

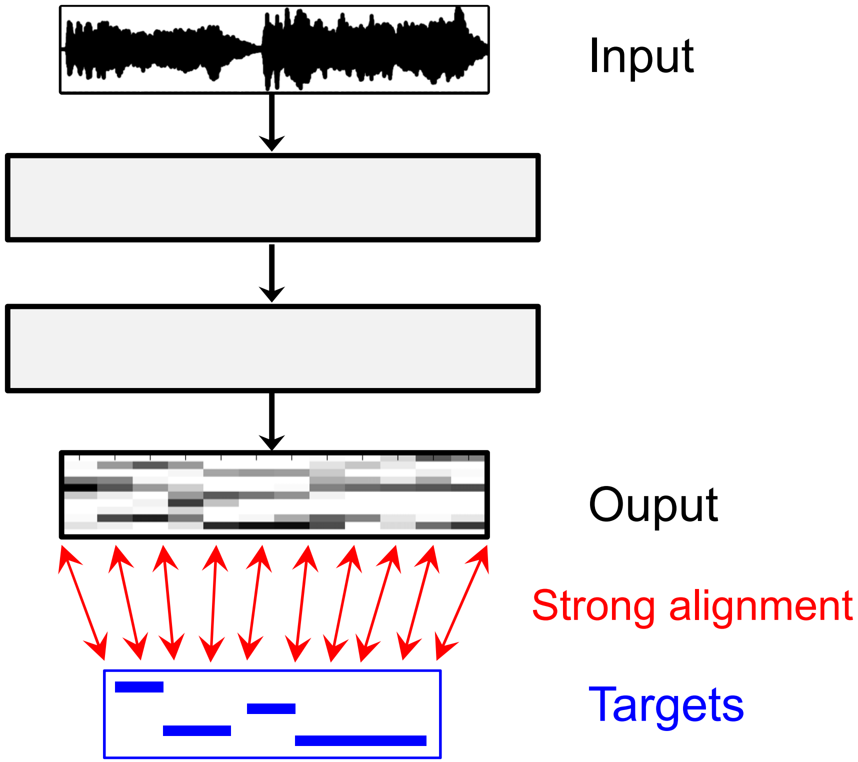
- Learn audio features from data
  - Should be robust to performance variations
  - Should yield high alignment accuracy
  - Should have musical relevance

- Alignment problem
  - Pre-aligned data for training
  - Part of loss function → differentiability?

CTC-Loss
Graves et al.: Connectionist Temporal Classification: Labelling Unsegmented Sequence Data with Recurrent Neural Networks. ICML, 2006

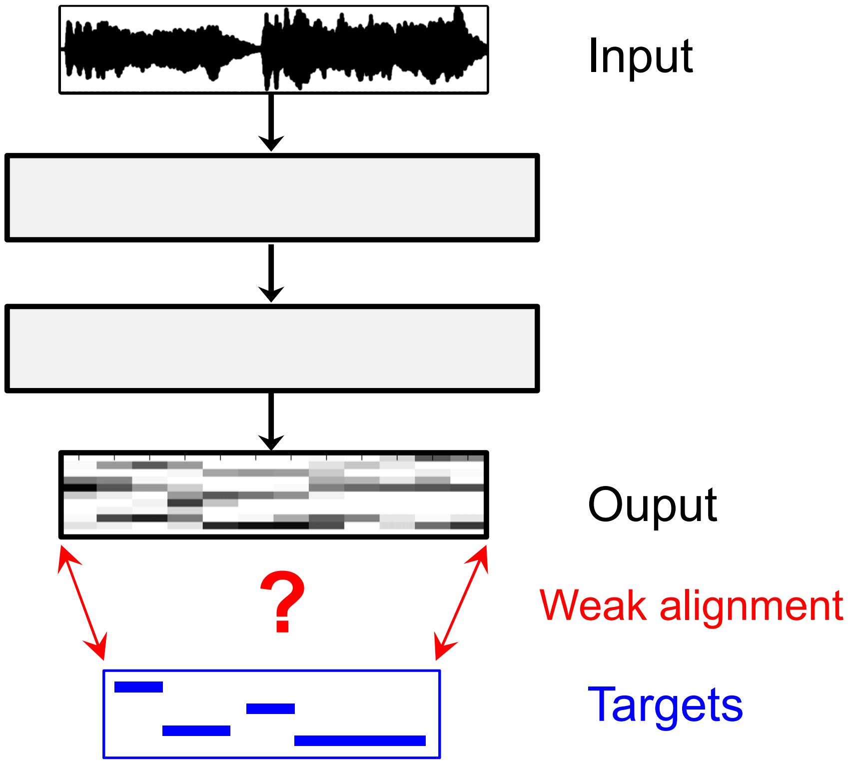
Soft-DTW
Cuturi, Blondel: Soft-DTW: A Differentiable Loss Function for Time-Series. ICML, 2017

Feature Learning



- Task: Learn audio features using a neural network
- Loss: Binary cross-entropy
  - framewise loss
  - requires strongly aligned targets
  - hard to obtain

Feature Learning



- Task: Learn audio features using a neural network
- Loss: Binary cross-entropy
  - framewise loss
  - requires strongly aligned targets
  - hard to obtain
- Alignment as part of loss function
  - requires only weakly aligned targets
  - needs to be differentiable
- Problem: DTW is not differentiable → Soft DTW

Dynamic Time Warping (DTW)

$$X := (x_1, x_2, \ldots, x_N)$$

$$Y := (y_1, y_2, \ldots, y_M)$$

$$x_n, y_m \in \mathcal{F},\ n \in [1:N],\ m \in [1:M]$$

$\mathcal{F}$ = Feature space

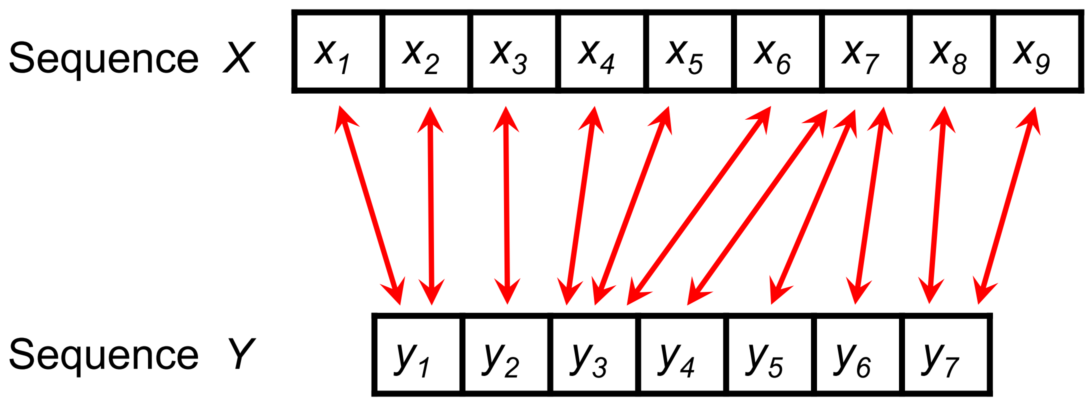
Alignment matrix

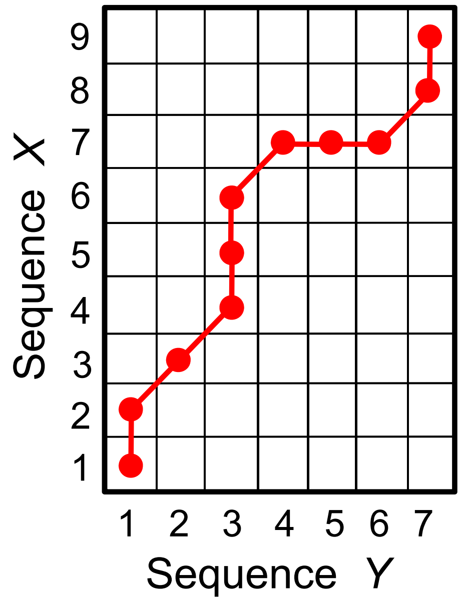
$$A \in \{0,1\}^{N \times M}$$

Set of all possible alignment matrices

$$\mathcal{A}_{N,M} \subset \{0,1\}^{N \times M}$$

Alignment





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$\mathcal{F}$ = Feature space

Alignment matrix

$A \in \{0,1\}^{N \times M}$

Set of all possible alignment matrices

$\mathcal{A}_{N,M} \subset \{0,1\}^{N \times M}$

Cost measure: $c : \mathcal{F} \times \mathcal{F} \to \mathbb{R}_{\geq 0}$

Cost matrix: $C \in \mathbb{R}^{N \times M}$ with $C(n,m) := c(x_n, y_m)$

Cost of alignment: $\langle A, C \rangle$

DTW cost: $\mathrm{DTW}(C) = \min\left(\{\langle A, C \rangle \mid A \in \mathcal{A}_{N,M}\}\right)$

Optimal alignment: $A^* = \mathrm{argmin}\left(\{\langle A, C \rangle \mid A \in \mathcal{A}_{N,M}\}\right)$

Dynamic Time Warping (DTW)

DTW cost: $$\mathrm{DTW}(C) = \min\left(\{\langle A, C\rangle \mid A \in \mathcal{A}_{N,M}\}\right)$$

- Efficient computation via Bellman's recursion in O(*NM*)

$$D(n,m) = \min\{D(n-1,m), D(n,m-1), D(n,m)\} + C(n,m)$$

for *n>1* and *m>1* and suitable initialization.

$$\mathrm{DTW}(C) = D(N,M)$$

- Problem: DTW(*C*) is not differentiable with regard to *C*
- Idea: Replace min-function by a smooth version

$$\min^{\gamma}(\mathcal{S}) = -\gamma \log \sum_{s\in\mathcal{S}} \exp\left(-s/\gamma\right)$$

for set $\mathcal{S} \subset \mathbb{R}$ and temperature parameter $\gamma \in \mathbb{R}$

AUDIO LABS

Soft Dynamic Time Warping (SDTW)

SDTW cost: $\mathrm{SDTW}^{\gamma}(C) = \min^{\gamma}\left(\{\langle A, C\rangle \mid A \in \mathcal{A}_{N,M}\}\right)$

- Efficient computation via Bellman's recursion in O(*NM*) still works:

  $$D^{\gamma}(n,m) = \min^{\gamma}\{D^{\gamma}(n-1,m), D^{\gamma}(n,m-1), D^{\gamma}(n,m)\} + C(n,m)$$

  for *n>1* and *m>1* and suitable initialization.

  $$\mathrm{SDTW}^{\gamma}(C) = D^{\gamma}(N,M)$$

- Limit case: $\mathrm{SDTW}^{\gamma}(C) \xrightarrow{\gamma\to 0} \mathrm{DTW}(C)$

- SDTW(*C*) is differentiable with regard to *C*

- Questions:
  - How does the gradient look like?
  - Can it be computed efficiently?
  - How does SDTW generalize the alignment concept?

Soft Dynamic Time Warping (SDTW)

SDTW cost: $\mathrm{SDTW}^{\gamma}(C) = \min^{\gamma}\left(\{\langle A, C\rangle \mid A \in \mathcal{A}_{N,M}\}\right)$

- Define $p^{\gamma}(C)$ as the following "probability" distribution over $\mathcal{A}_{N,M}$:

$$p^{\gamma}(C)_A = \frac{\exp\left(-\langle A, C\rangle/\gamma\right)}{\sum_{A' \in \mathcal{A}_{N,M}} \exp\left(-\langle A', C\rangle/\gamma\right)} \qquad \text{for } A \in \mathcal{A}_{N,M}$$

- The expected alignment with respect to $p^{\gamma}(C)$ is given by:

$$E^{\gamma}(C) = \sum_{A \in \mathcal{A}_{N,M}} p^{\gamma}(C)_A A \quad \in \mathbb{R}^{N \times M}$$

- The gradient is given by:

$$\nabla_C \mathrm{SDTW}^{\gamma}(C) = E^{\gamma}(C)$$

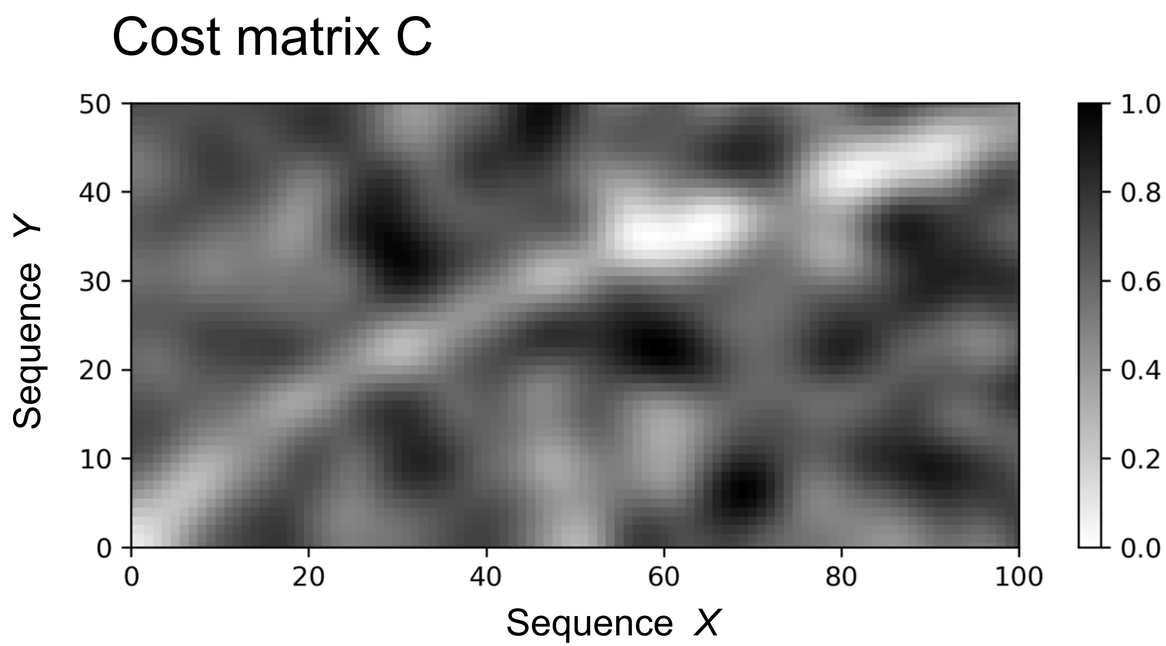
- The gradient can be computed efficiently in O(*NM*) via a recursive algorithm.

Soft-DTW
Cuturi, Blondel: Soft-DTW: A Differentiable Loss Function for Time-Series. ICML, 2017

Soft Dynamic Time Warping (SDTW)

Expected alignment : $E^\gamma(C) = \sum_{A \in \mathcal{A}_{N,M}} p^\gamma(C)_A A \quad \in \mathbb{R}^{N \times M}$

- Can be interpreted as a smoothed version of an alignment
- Degree of smoothing depends on temperature parameter γ



Soft Dynamic Time Warping (SDTW)

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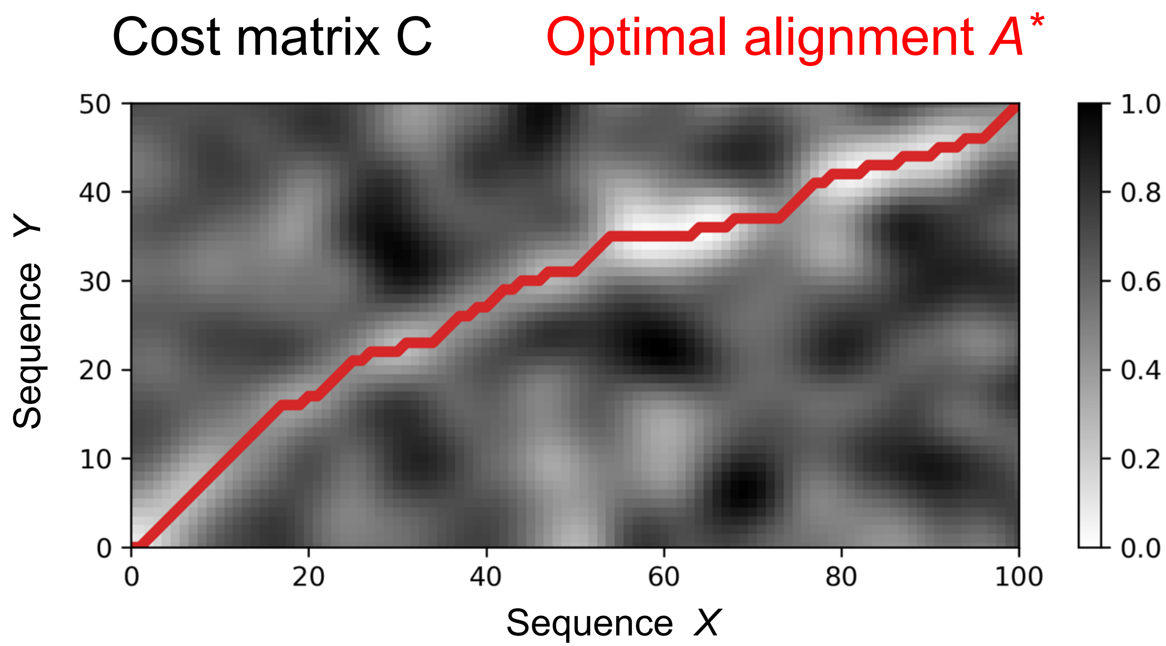

Soft Dynamic Time Warping (SDTW)

Expected alignment : $E^{\gamma}(C) = \sum_{A \in \mathcal{A}_{N,M}} p^{\gamma}(C)_A A \quad \in \mathbb{R}^{N \times M}$

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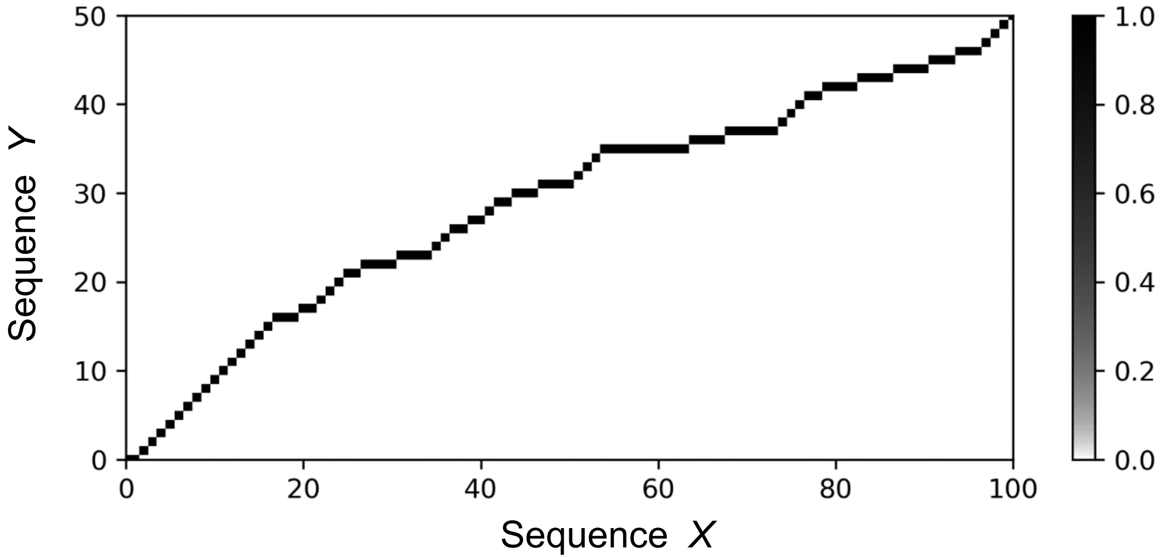
$E^{\gamma}(C)$ with $\gamma = 0$ ($= A^*$)

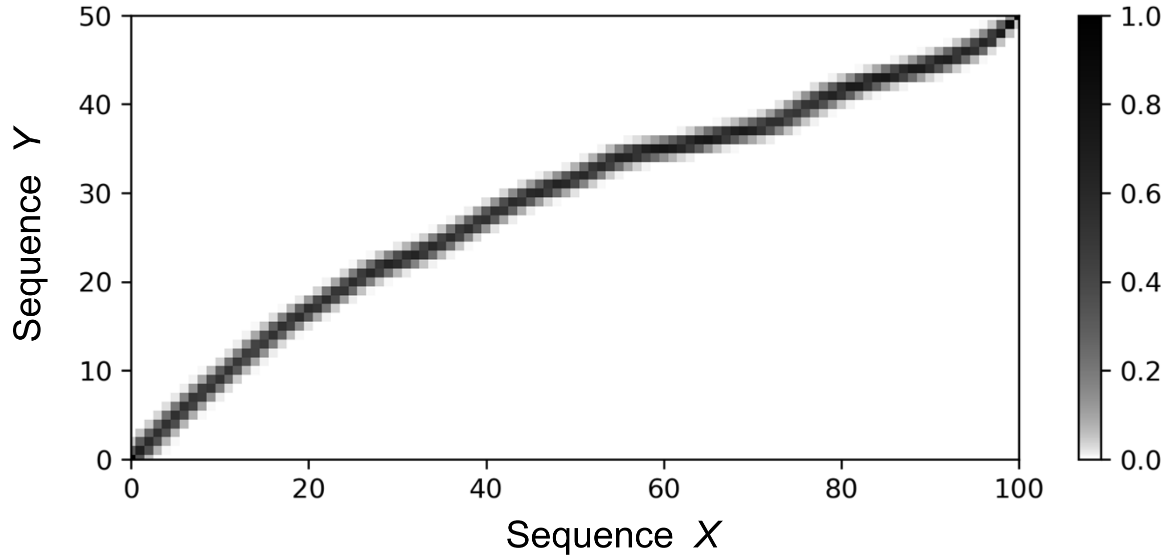


Soft Dynamic Time Warping (SDTW)

Expected alignment : $E^{\gamma}(C) = \sum_{A \in \mathcal{A}_{N,M}} p^{\gamma}(C)_A A \quad \in \mathbb{R}^{N \times M}$

- Can be interpreted as a smoothed version of an alignment
- Degree of smoothing depends on temperature parameter γ

$E^{\gamma}(C)$ with γ = 0.1

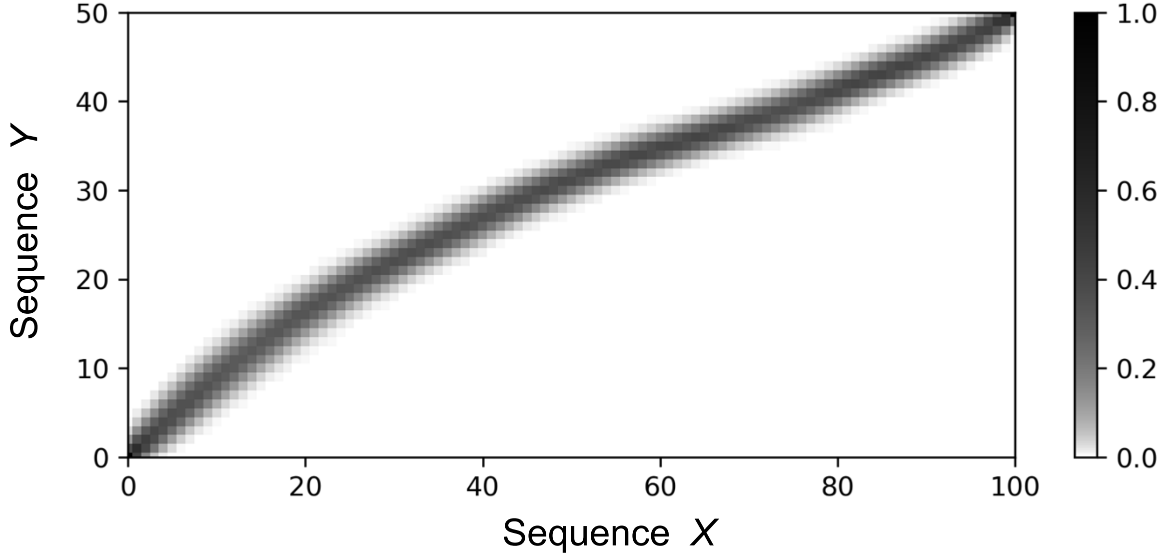


Soft Dynamic Time Warping (SDTW)

Expected alignment : $E^{\gamma}(C) = \sum_{A \in \mathcal{A}_{N,M}} p^{\gamma}(C)_A A \quad \in \mathbb{R}^{N \times M}$

- Can be interpreted as a smoothed version of an alignment
- Degree of smoothing depends on temperature parameter γ

$E^{\gamma}(C)$ with γ = 1

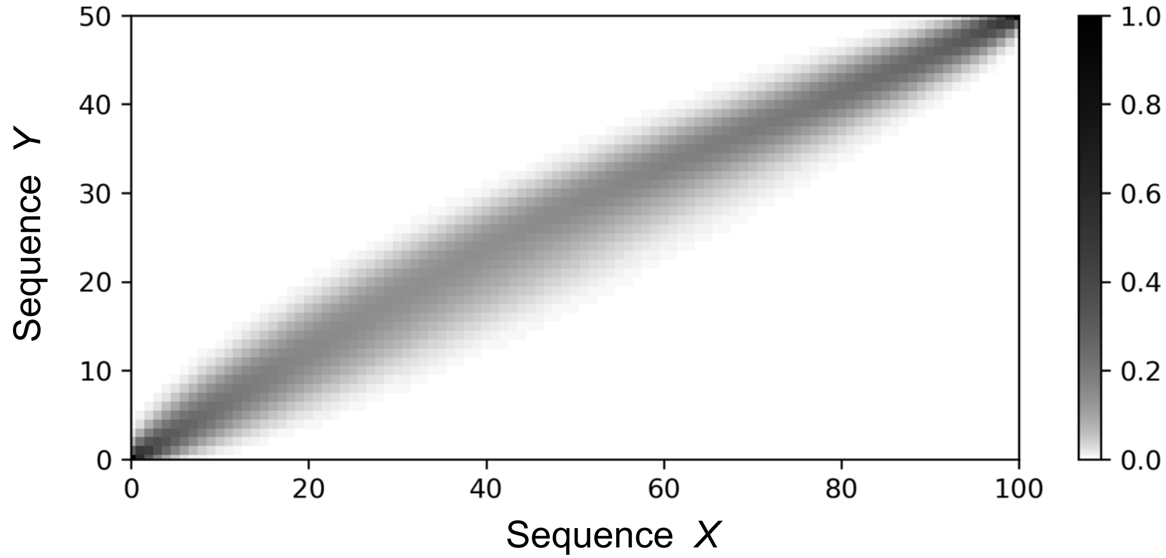


Soft Dynamic Time Warping (SDTW)

Expected alignment : $E^\gamma(C) = \sum_{A\in\mathcal{A}_{N,M}} p^\gamma(C)_A A \quad \in \mathbb{R}^{N\times M}$

- Can be interpreted as a smoothed version of an alignment
- Degree of smoothing depends on temperature parameter γ

$E^\gamma(C)$ with γ = 10

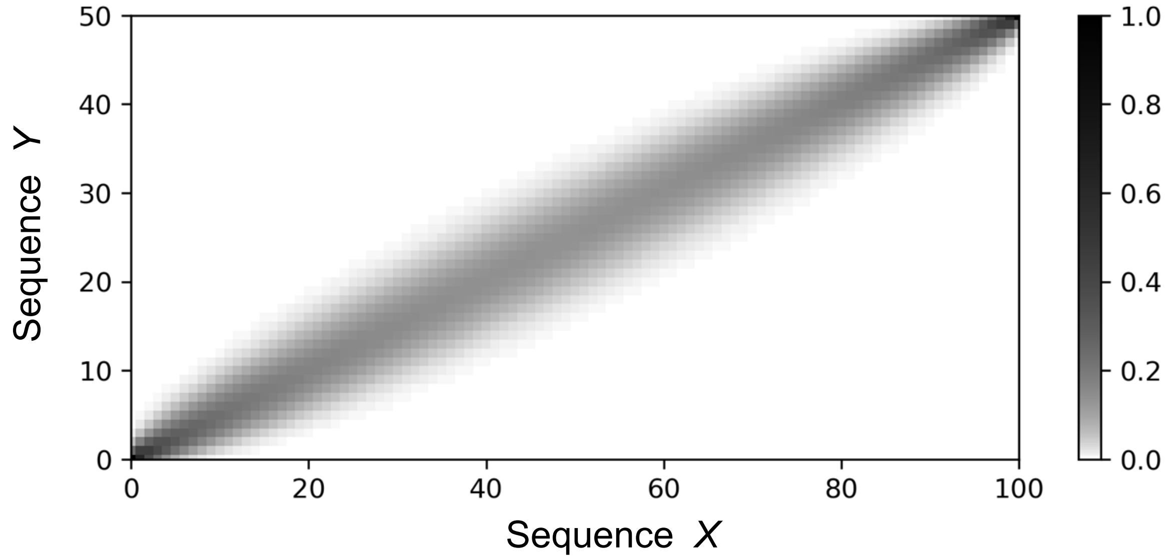


Soft Dynamic Time Warping (SDTW)

Expected alignment : $E^\gamma(C) = \sum_{A \in \mathcal{A}_{N,M}} p^\gamma(C)_A A \quad \in \mathbb{R}^{N \times M}$

- Can be interpreted as a smoothed version of an alignment
- Degree of smoothing depends on temperature parameter γ

$E^\gamma(C)$ with γ = 100



Soft Dynamic Time Warping (SDTW)

Conclusions

- Direct generalization of DTW (replacing min by smooth variant)
- Gradient is given by expected alignment
- Fast forward algorithm: O(NM)
- Fast gradient computation: O(NM)
- SDTW yields a (typically) poor lower bound for DTW
- Can be used as loss function to learn from weakly aligned sequences

Soft Dynamic Time Warping (SDTW)

References

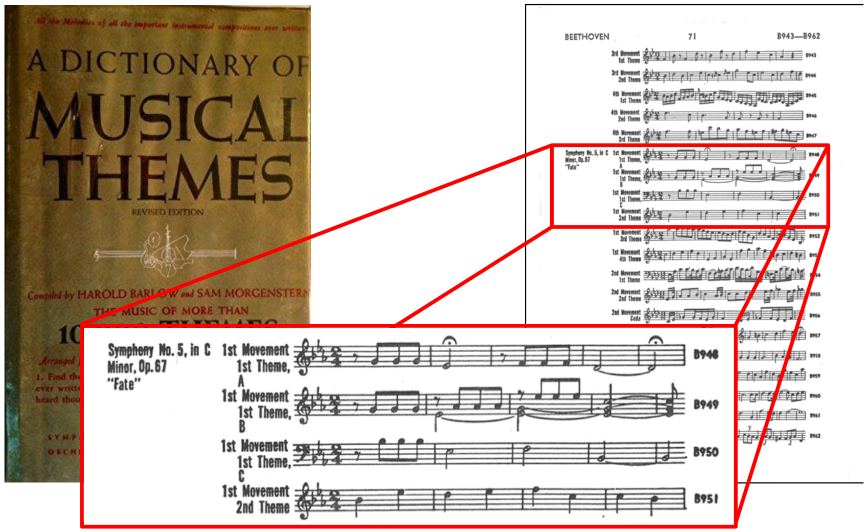
- Marco Cuturi, Mathieu Blondel: Soft-DTW: A Differentiable Loss Function for Time-Series. ICML, pages 894–903, 2017.
- Mathieu Blondel, Arthur Mensch, Jean-Philippe Vert: Differentiable Divergences Between Time Series. AISTATS, pages 3853 – 3861, 2021.
- Michael Krause, Christof Weiß, Meinard Müller: Soft Dynamic Time Warping for Multi-Pitch Estimation and Beyond. IEEE ICASSP, 2023.

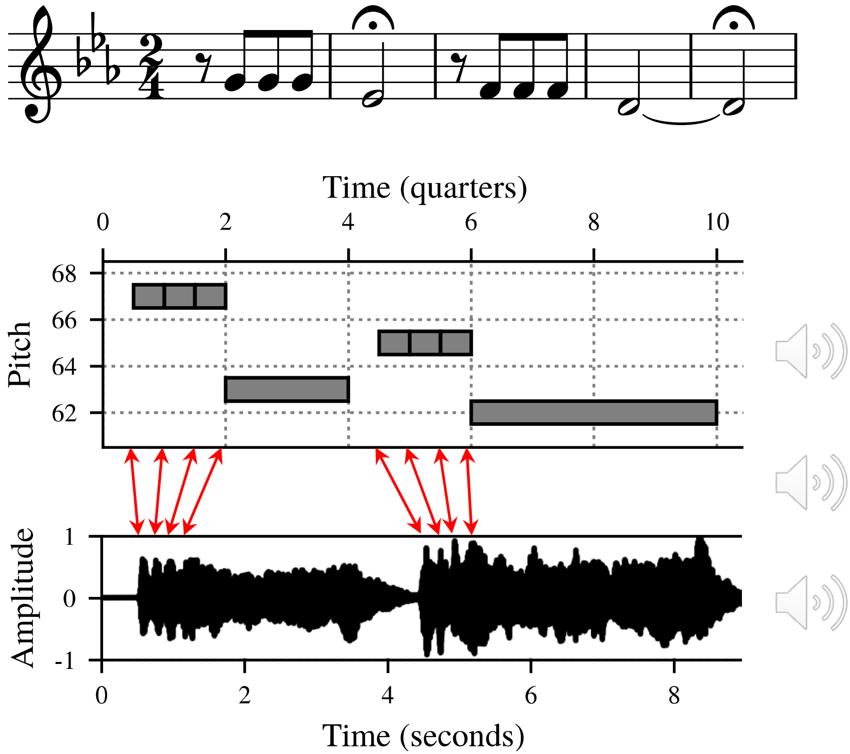
Thanks:
Michale Krause (Ph.D. 2023)
Johannes Zeitler (Ph.D.)

Theme-Based Audio Retrieval

Theme-Based Audio Retrieval

Barlow & Morgenstern (1949): A Dictionary of Musical Themes



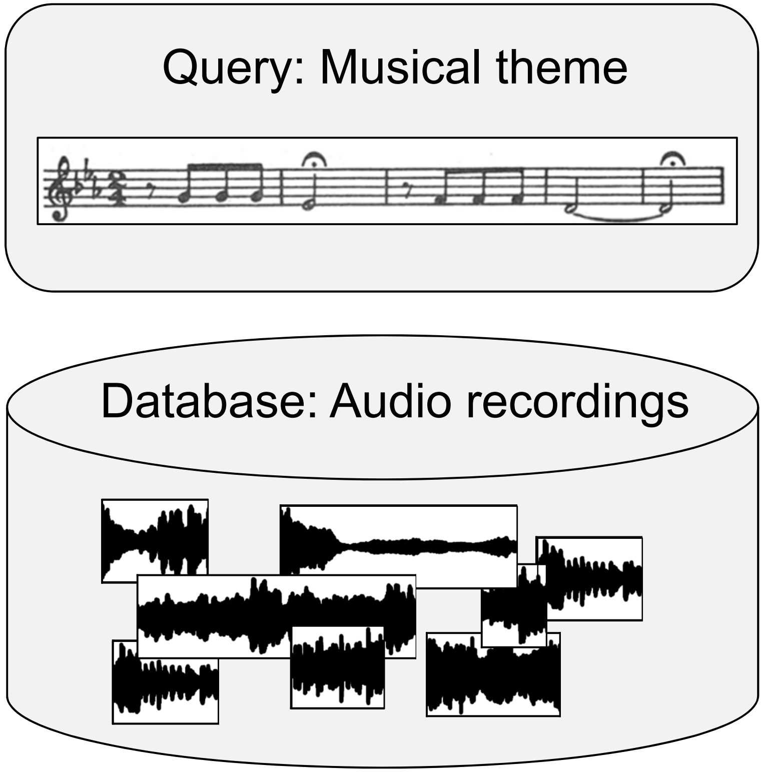


- 2067 themes by 54 different composers
- Recordings (1126 recordings, ~ 120 hours)
- Theme occurences (~ 5 hours)

Meinard Müller

Theme-Based Audio Retrieval

Barlow & Morgenstern (1949): A Dictionary of Musical Themes



Challenges

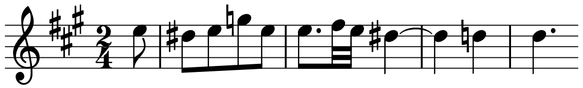
- **Cross-modality**
  Symbolic vs. audio data
- **Tuning**
  Deviations from standard tuning
- **Transposition**
  Played key vs. written key
- **Tempo**
  Local & global tempo deviations
- **Polyphony**
  Monophonic query vs. polyphonic audio

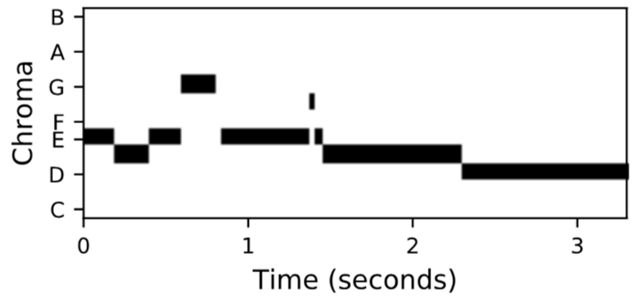
Theme-Based Audio Retrieval

Monophony–Polyphony Challenge

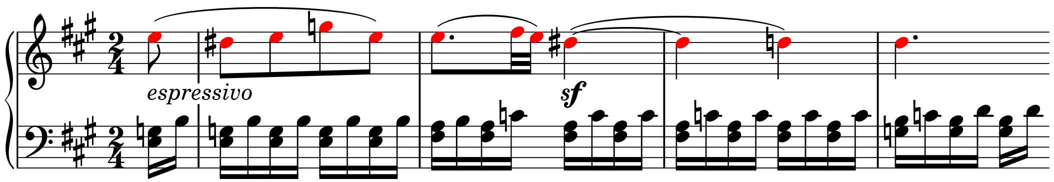
Chromagram

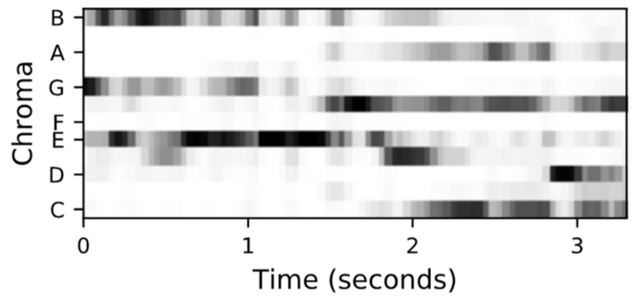
Monophonic symbolic musical theme





Audio recording of polyphonic music

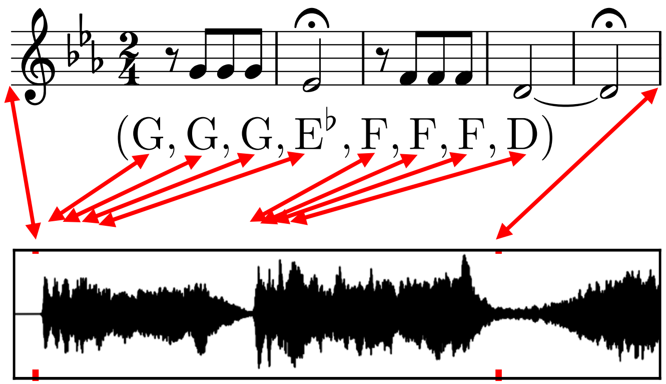




Goal: Compute "enhanced" chromagram from polyphonic audio recording that better matches the symbolic monophonic theme

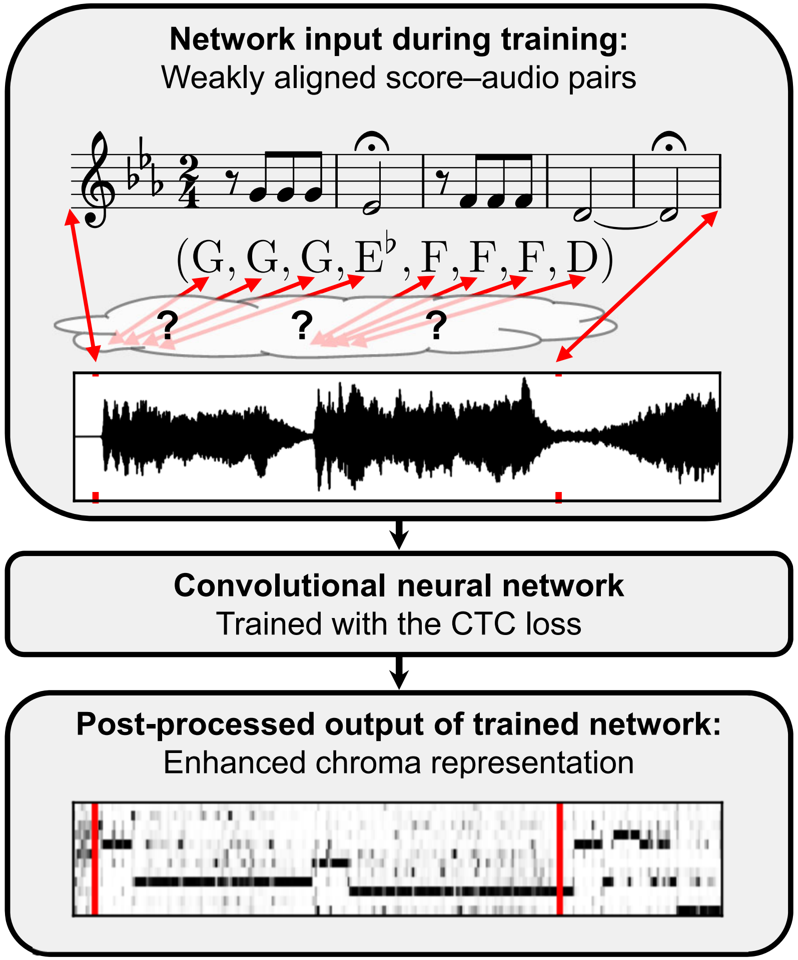
Theme-Based Audio Retrieval

Strongly Aligned Training Data

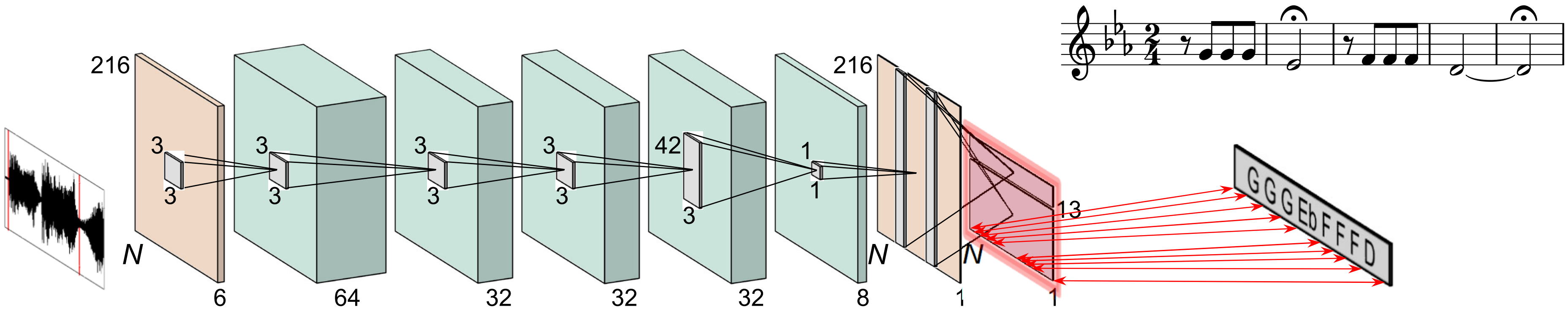


Theme-Based Audio Retrieval

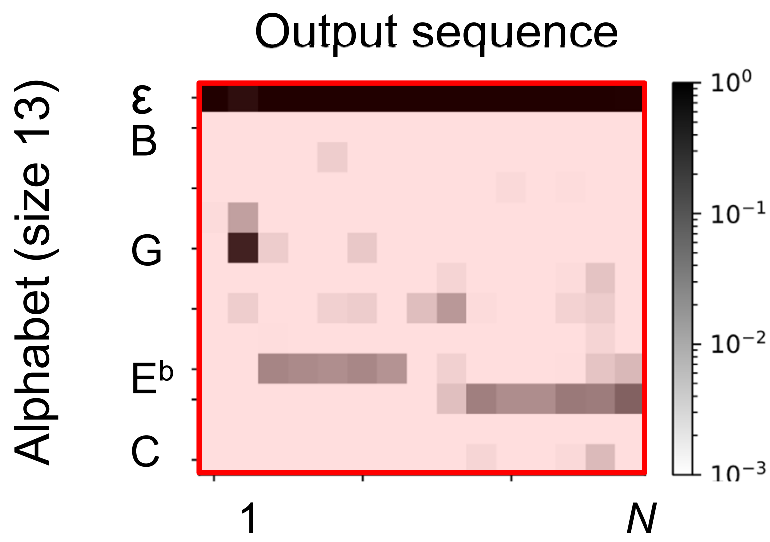
Weakly Aligned Training Data



Theme-Based Audio Retrieval

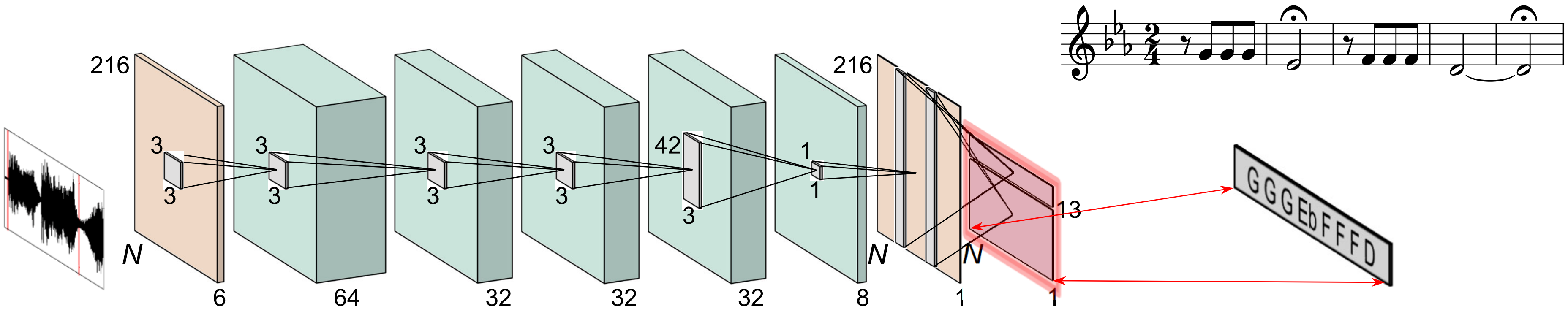


Framewise loss
(strong annotations)



Salience Computation
Bittner, McFee, Salamon, Li, Bello: Deep salience representations for F0 tracking in polyphonic music. ISMIR, 2017.

Theme-Based Audio Retrieval



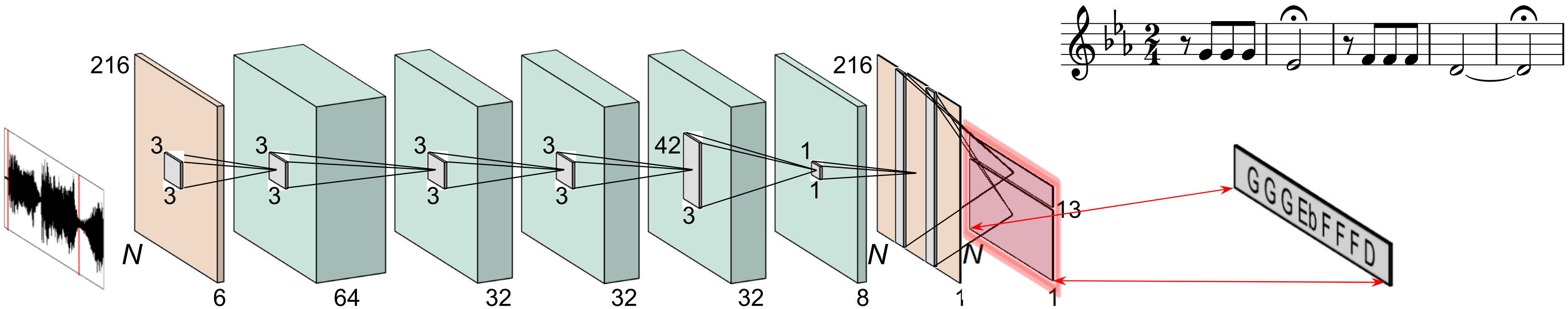
CTC loss
(weak annotations)

- Idea of CTC loss similar to SDTW
- Theme is given as label sequence over finite alphabet (size 13 including blank symbol)
- Expand label sequence to match audio feature sequence → valid alignment
- CTC loss considers probability over **all** valid alignments → differentiable

CTC Loss
Graves, Fernández, Gomez, Schmidhuber: Connectionist temporal classification: Labelling unsegmented sequence data with recurrent neural networks. ICML, 2006.

Theme-Based Audio Retrieval

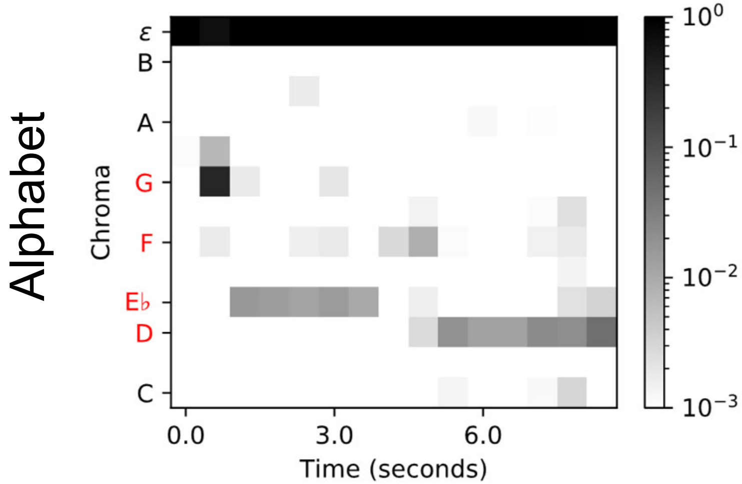
CTC-Based Training



Label sequence Y

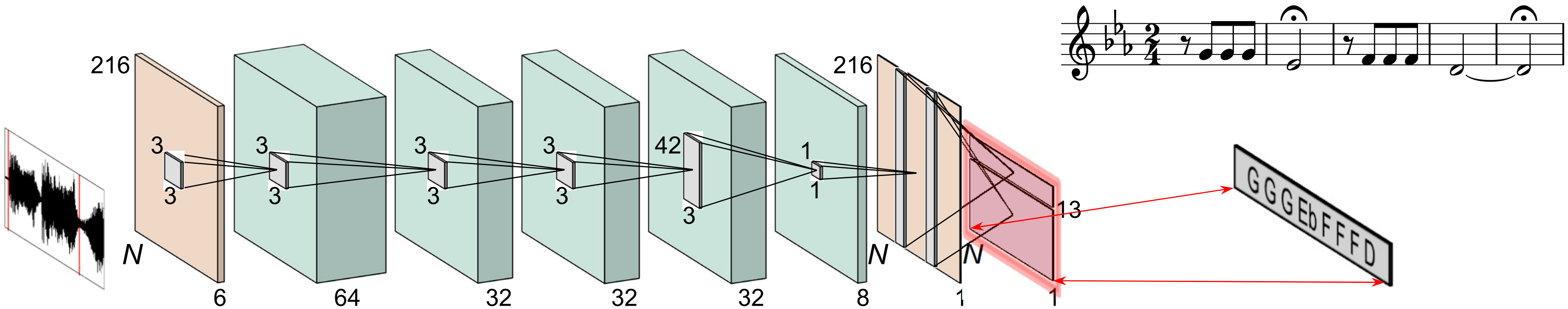
G G G E^b F F F D

Output sequence X



Theme-Based Audio Retrieval

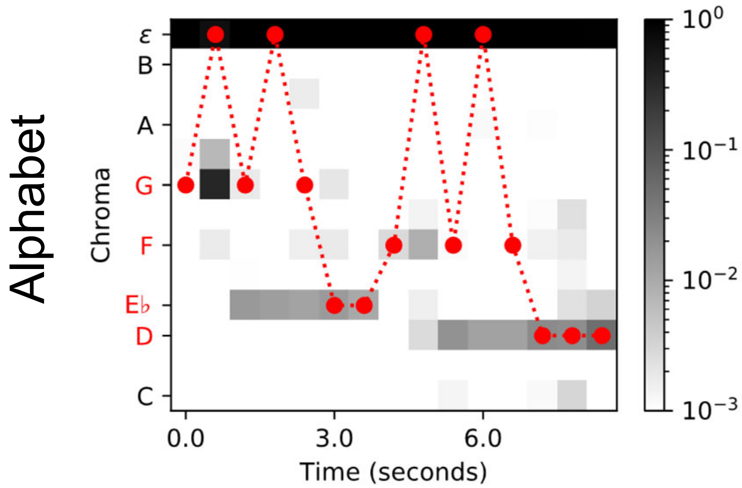
CTC-Based Training



Label sequence Y

G G G E^b F F F D

Output sequence X



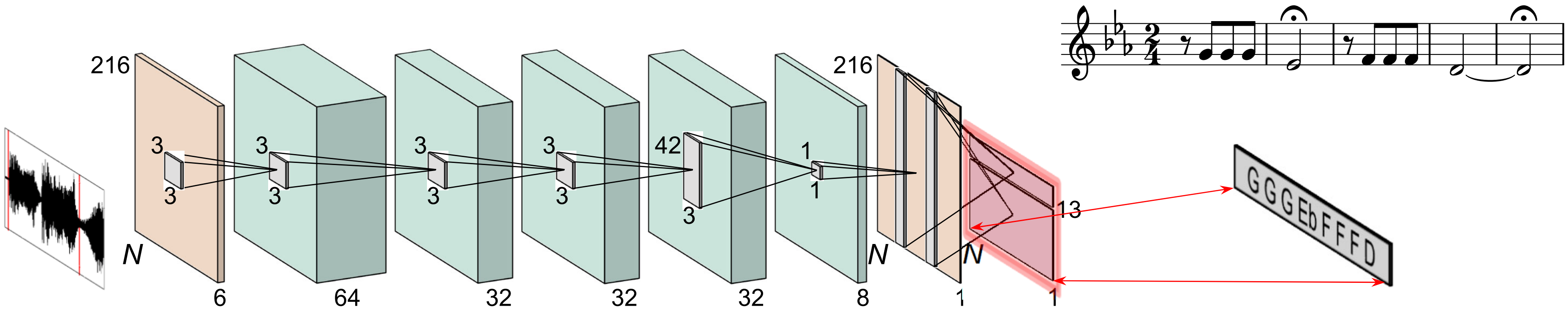
Valid alignment

G ε G ε G E^b E^b F ε F ε F D D D

→ matches sequence X

Theme-Based Audio Retrieval

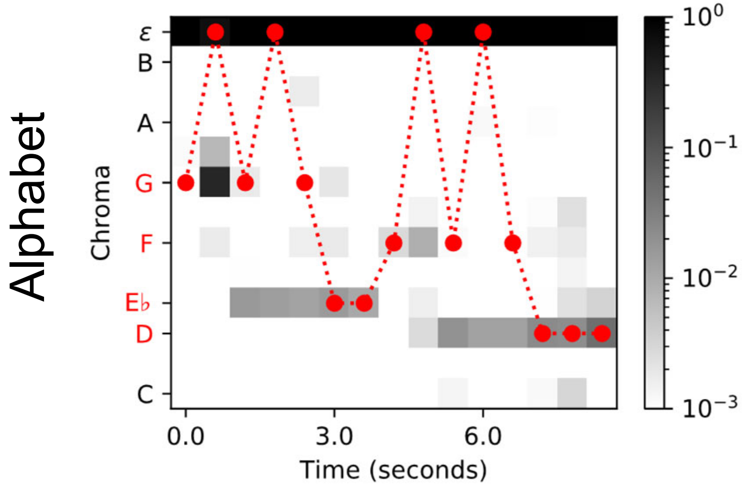
CTC-Based Training



Label sequence Y

G G G E^{b} F F F D

Output sequence X



- Set of all valid alignments

$$\mathbb{K}_{X,Y} = \{A \in (\mathbb{A}')^N : \kappa(A) = Y\}$$

- Probability of label sequence

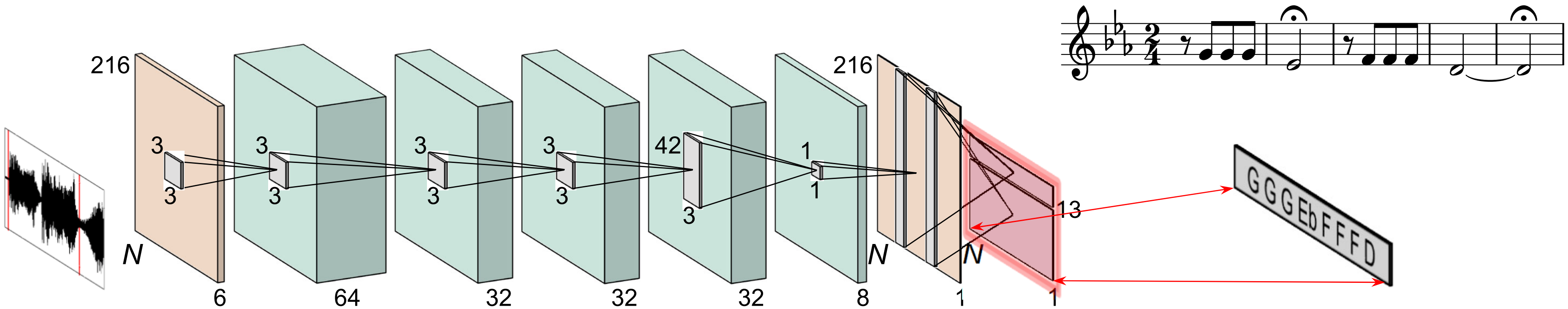
$$P(Y \mid X) = \sum_{A \in \mathbb{K}_{X,Y}} P(A \mid X)$$

- CTC loss

$$L_\theta(X,Y) = -\log P(Y \mid X)$$

Theme-Based Audio Retrieval

CTC-Based Training

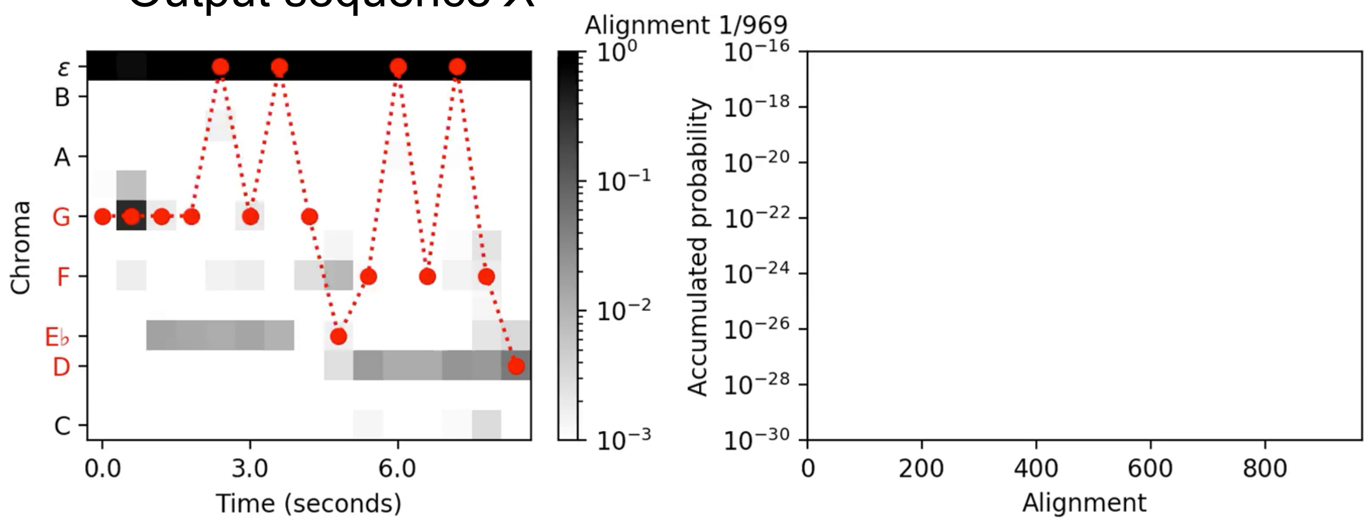


Label sequence *Y*

G G G E♭ F F F D

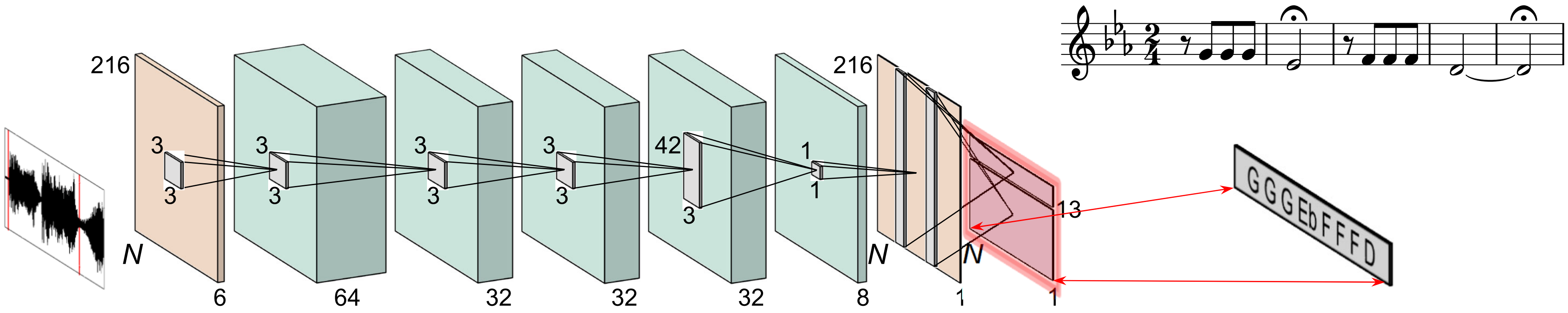
Output sequence *X*

Alphabet



Theme-Based Audio Retrieval

CTC-Based Training

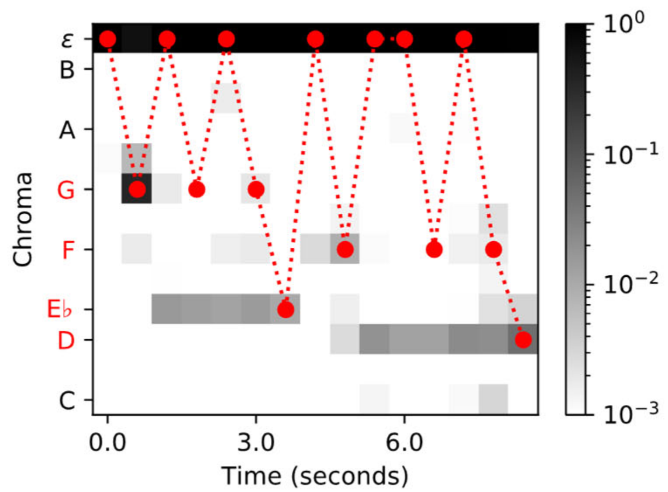


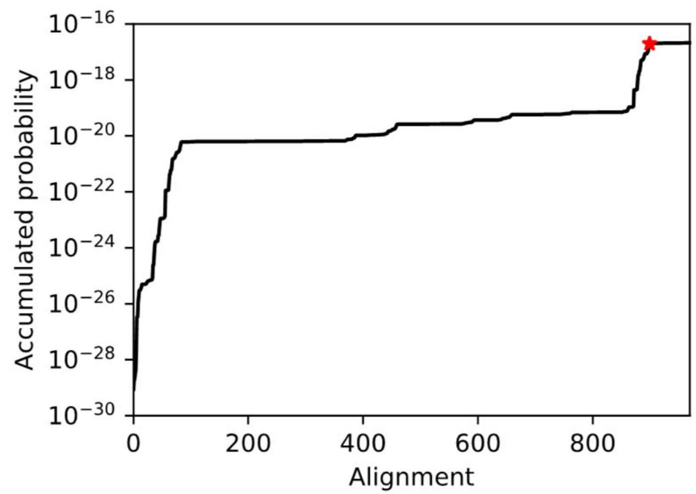
Label sequence *Y*

G G G E^{b} F F F D

Output sequence *X*

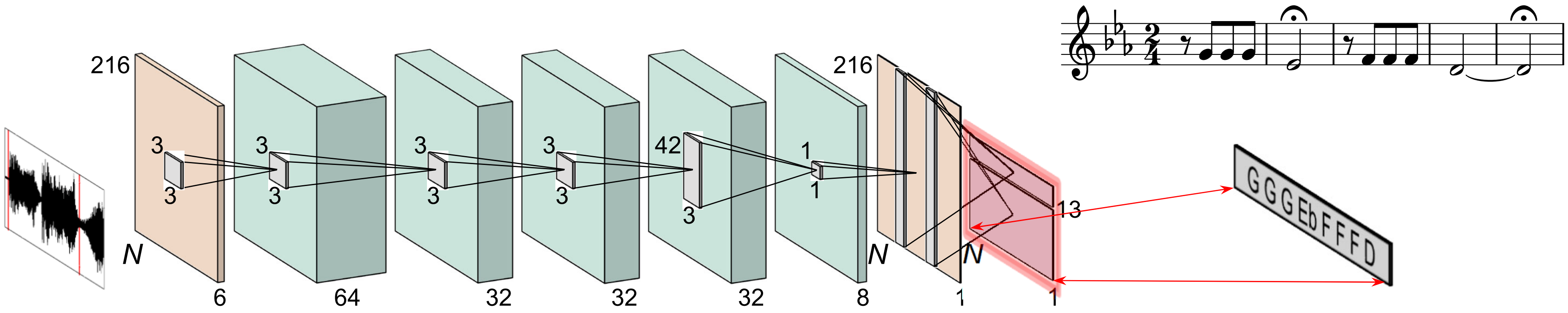
Alphabet

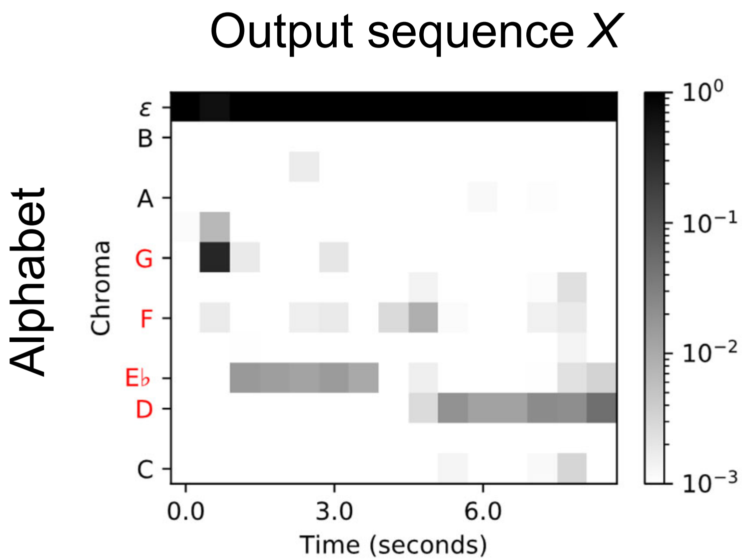




Theme-Based Audio Retrieval

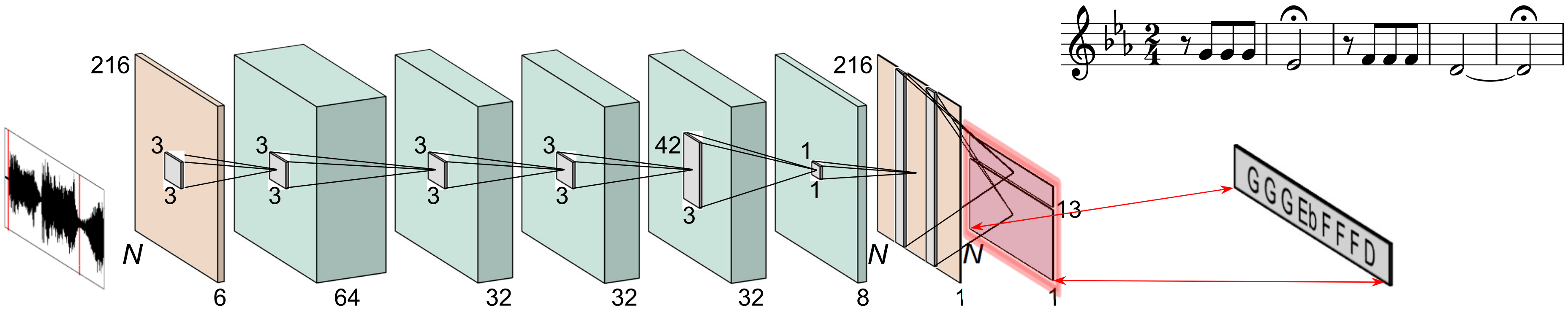
CTC-Based Training

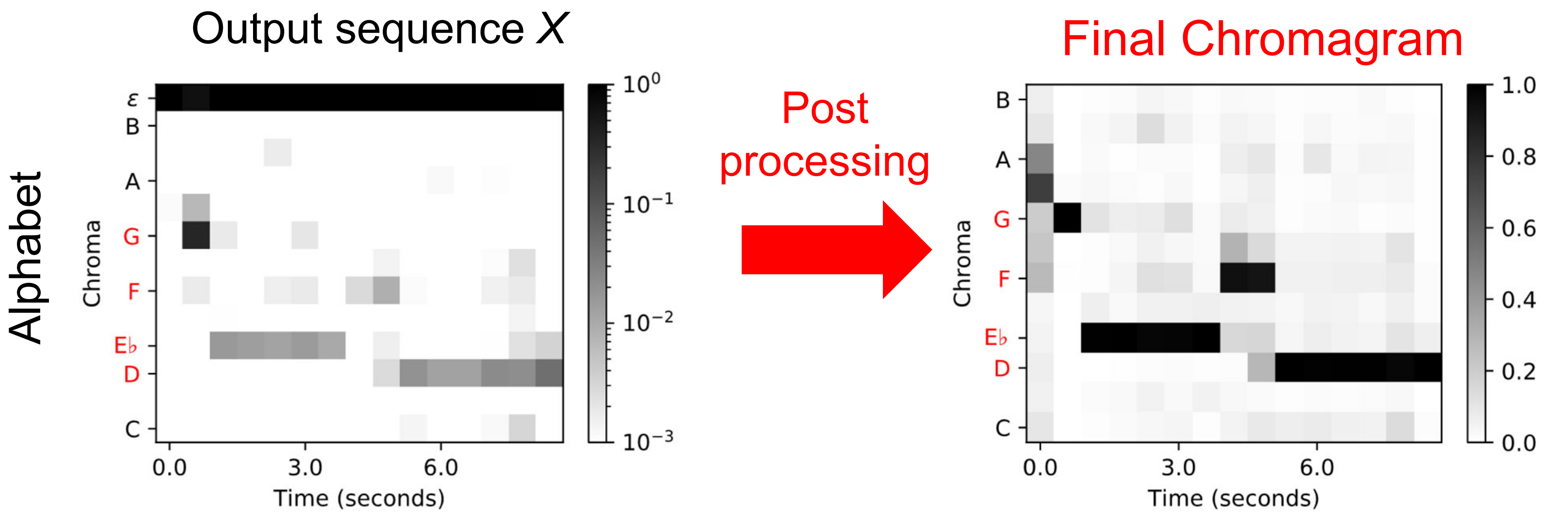




Theme-Based Audio Retrieval

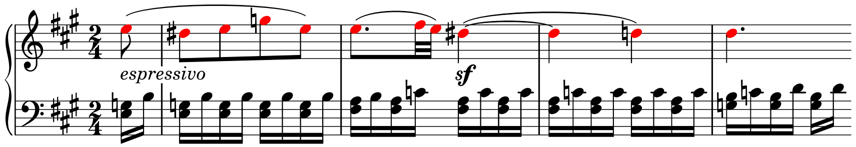
CTC-Based Training





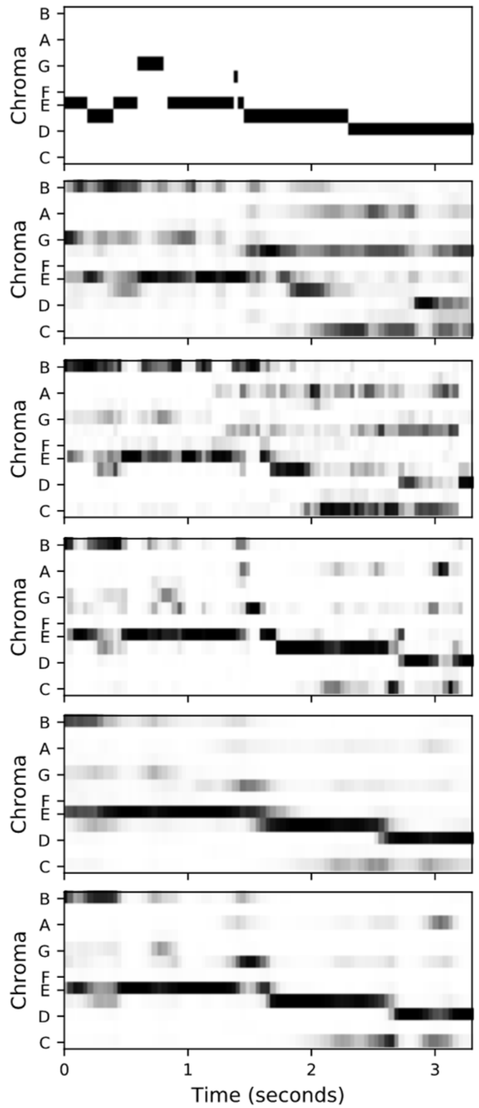
Theme-Based Audio Retrieval

Evaluation Results



$(\mathrm{E}, \mathrm{D}^\sharp, \mathrm{E}, \mathrm{G}, \mathrm{E}, \mathrm{E}, \mathrm{F}^\sharp, \mathrm{E}, \mathrm{D}^\sharp, \mathrm{D}, \mathrm{D})$

Chroma Variant	**Top-1**	**Top-10**
Standard chromagram	0.561	0.723
Enhanced chromagram (baseline)	0.824	0.861
DNN-based chromagram (CTC)	0.867	0.942
DNN-based chromagram (linear scaling)	0.829	0.914
DNN-based chromagram (strong alignment)	0.882	0.939



Theme-Based Audio Retrieval

References

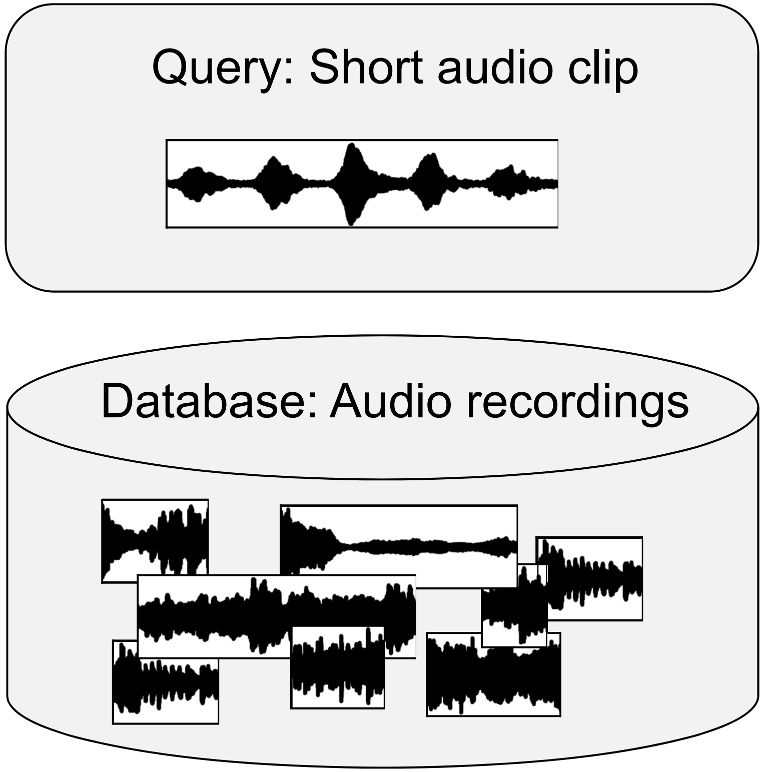
- R. Bittner, B. McFee, J. Salamon, P. Li, and J. Bello: Deep salience representations for F0 tracking in polyphonic music. Proc. ISMIR, pages 63–70, 2017.
- A. Graves, S. Fernández, F. J. Gomez, and J. Schmidhuber: Connectionist temporal classification: Labelling unsegmented sequence data with recurrent neural networks. ICML, 2006.
- F. Zalkow, S. Balke, V. Arifi-Müller, and M. Müller. MTD: A multimodal dataset of musical themes for MIR research. TISMIR, 3(1), 2020.
- F. Zalkow, S. Balke, and M. Müller. Evaluating salience representations for cross-modal retrieval of Western classical music recordings. Proc. ICASSP, 2019.
- F. Zalkow and M. Müller. CTC-based learning of deep chroma features for score-audio music retrieval. 2021. IEEE/ACM Trans. on Audio, Speech, and Language Processing, 29, pages 2957–2971, 2021.

Thanks:
Frank Zalkow (Ph.D. 2021)
Stefan Balke (Ph.D. 2018)

Audio Matching

Task

Given a short query audio clip, find corresponding audio clips of similar musical content.



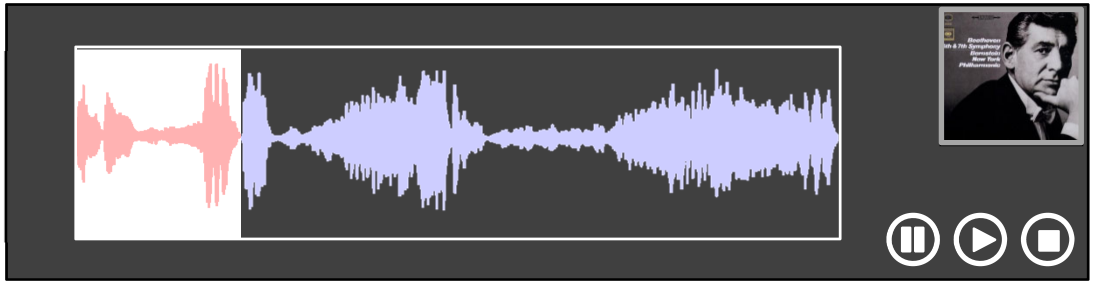
Challenges

- Similarity measure
  - Different performances
  - Instrumentation may change
  - Similar harmonic progression
- Local comparison
  - Query is short
  - Database recordings are long
- Efficiency
  - Database may be huge

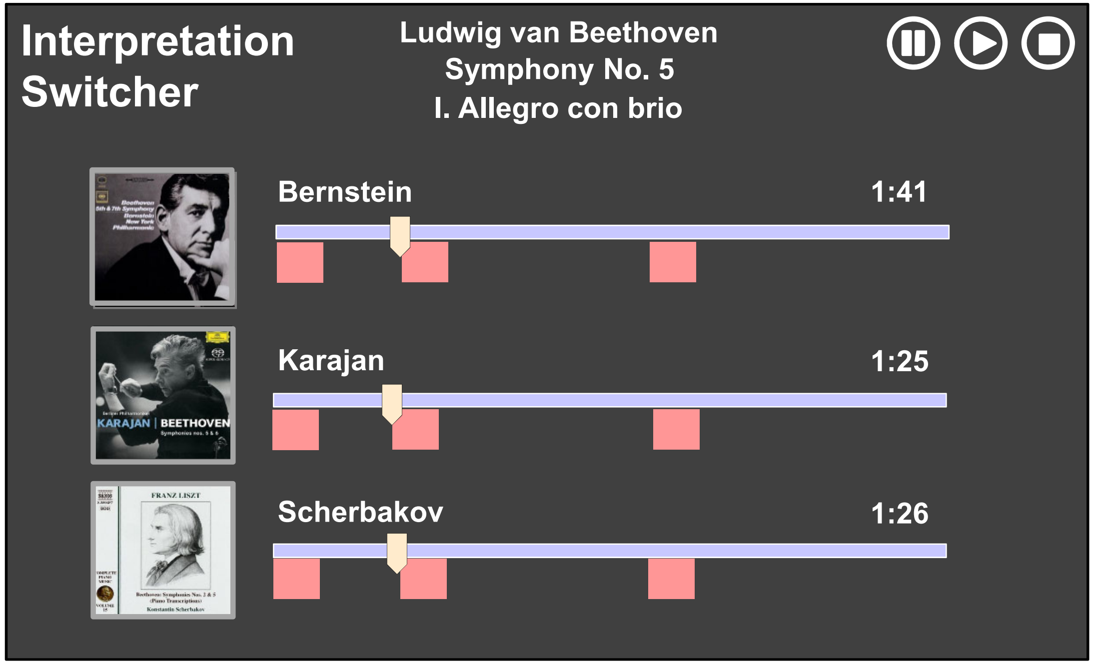
Audio Matching

Task

Query:



Database: Matches

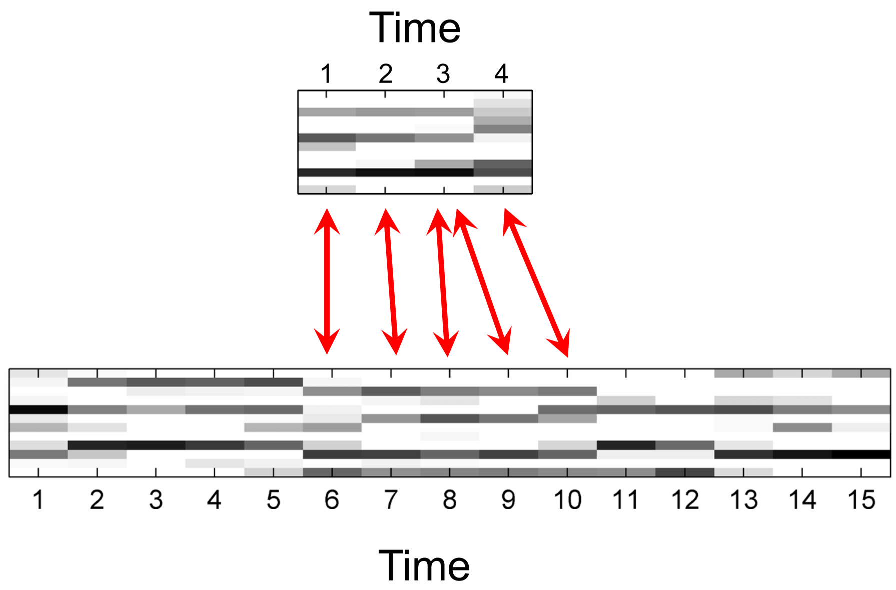


Audio Matching

Task

Query: Sequence X

Database: Sequence Y

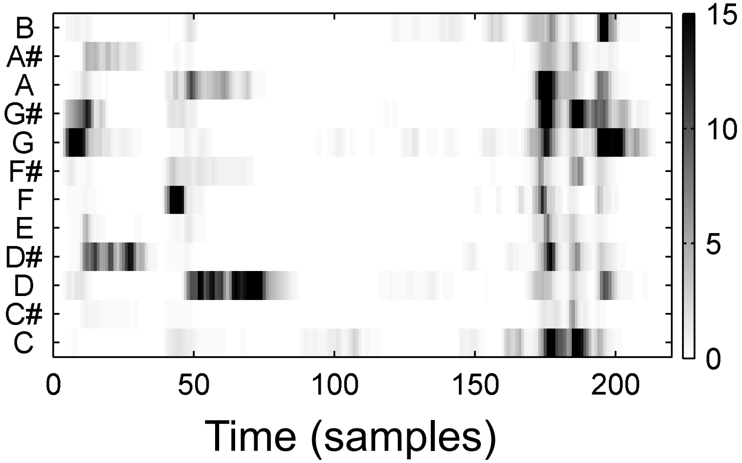


Subsequence matching

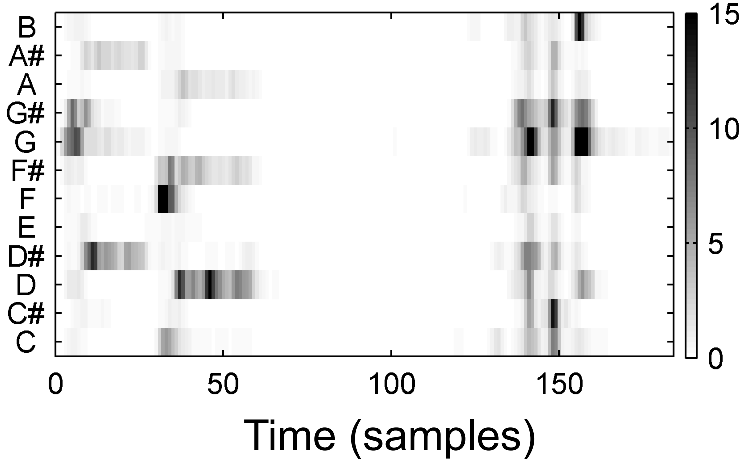
Audio Features

Example: Beethoven's Fifth

Bernstein



Karajan

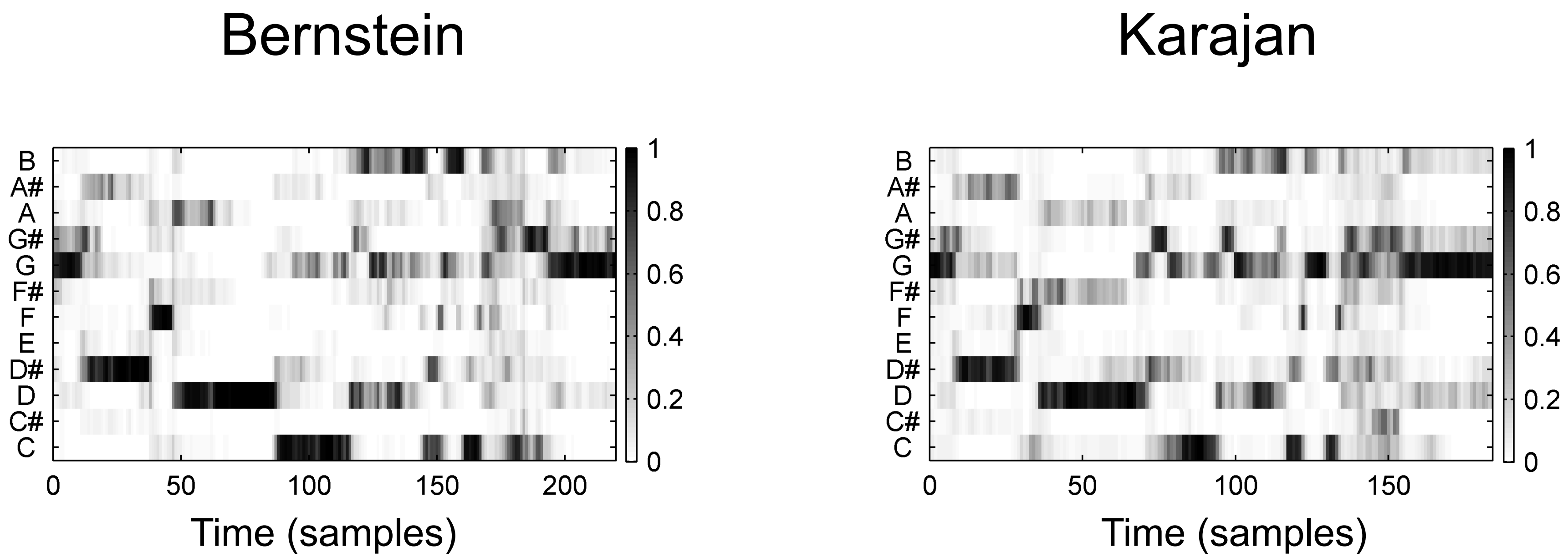


Chroma representation (10 Hz)

Chroma Features
Müller, Kurth, Clausen: Audio Matching via Chroma-Based Statistical Features. ISMIR, 2005

Audio Features

Example: Beethoven's Fifth



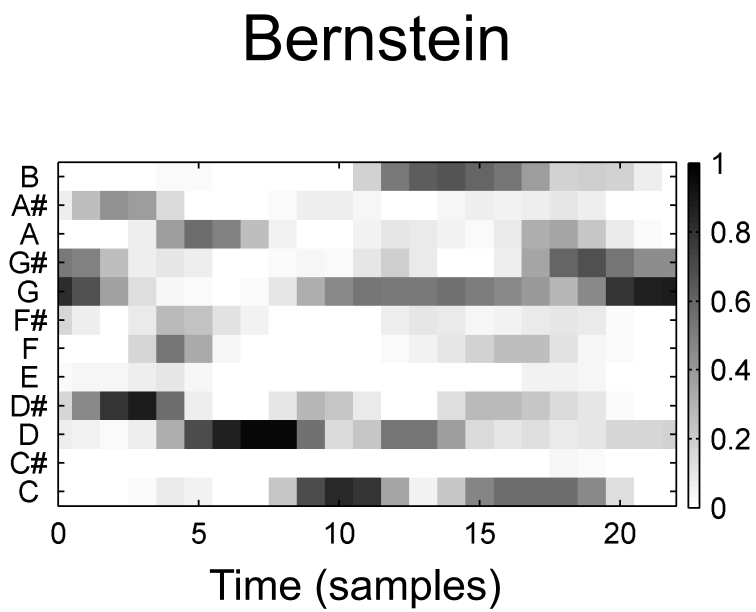
Chroma representation (10 Hz)

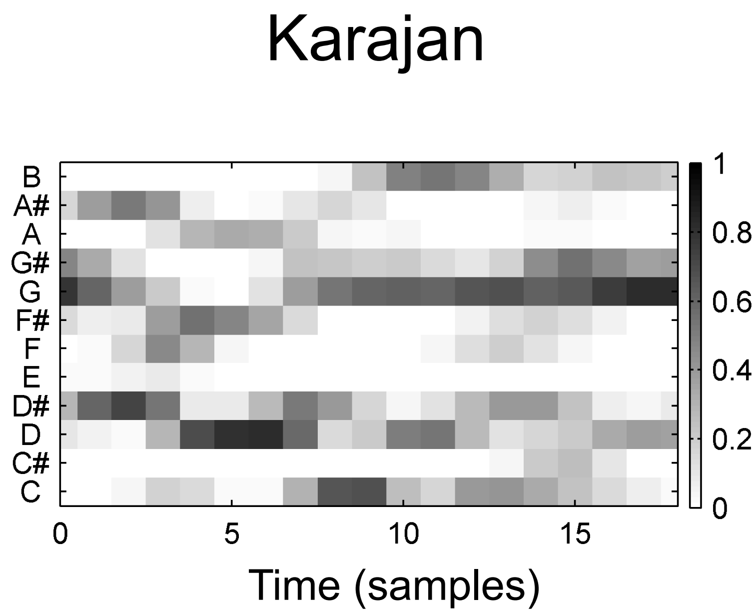
- Normalization

Chroma Features
Müller, Kurth, Clausen: Audio Matching via Chroma-Based Statistical Features. ISMIR, 2005

Audio Features

Example: Beethoven's Fifth



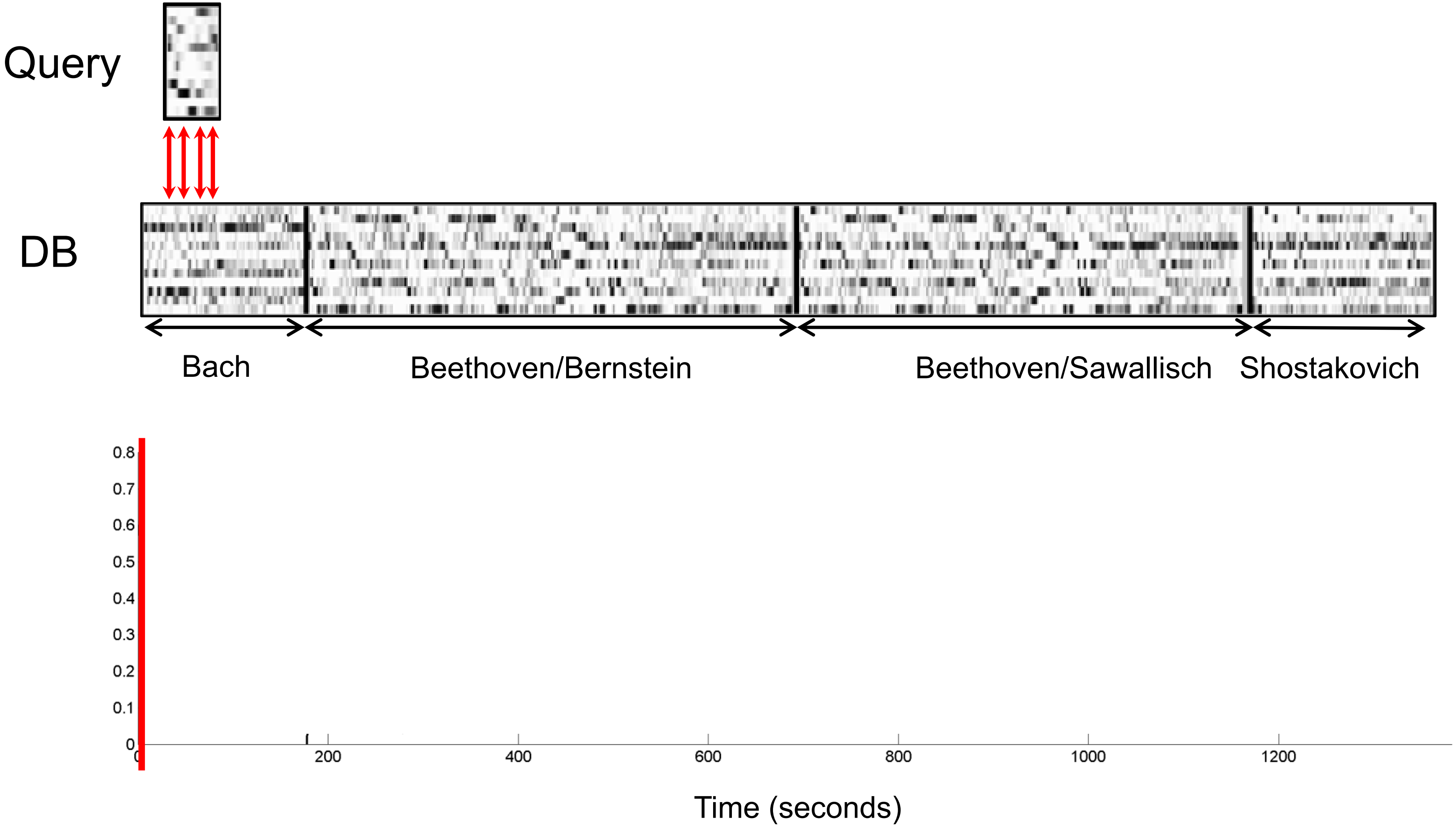


Chroma representation (1 Hz)

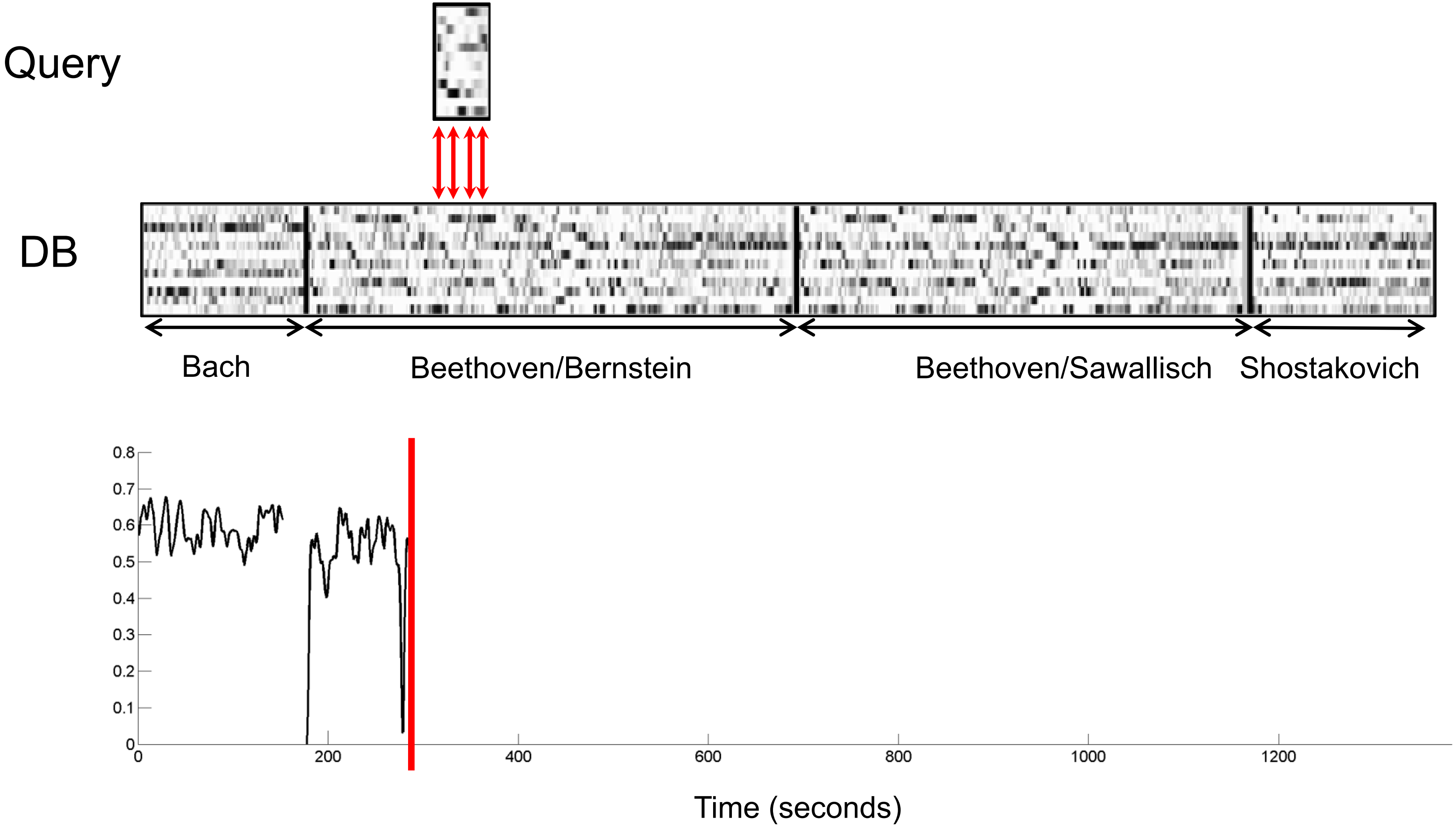
- Normalization
- Smoothing & downsampling

Chroma Features
Müller, Kurth, Clausen: Audio Matching via Chroma-Based Statistical Features. ISMIR, 2005

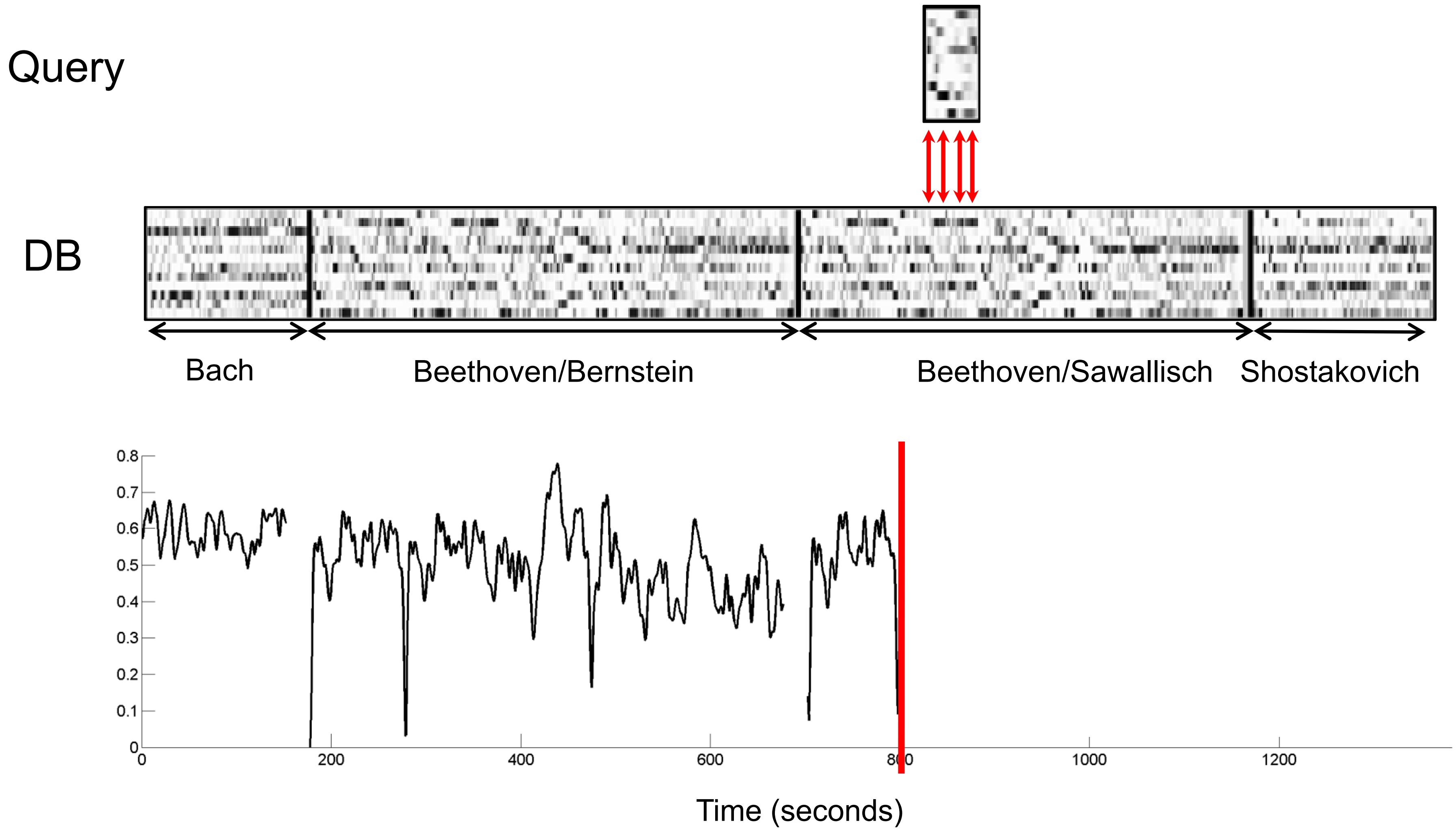
Matching Procedure



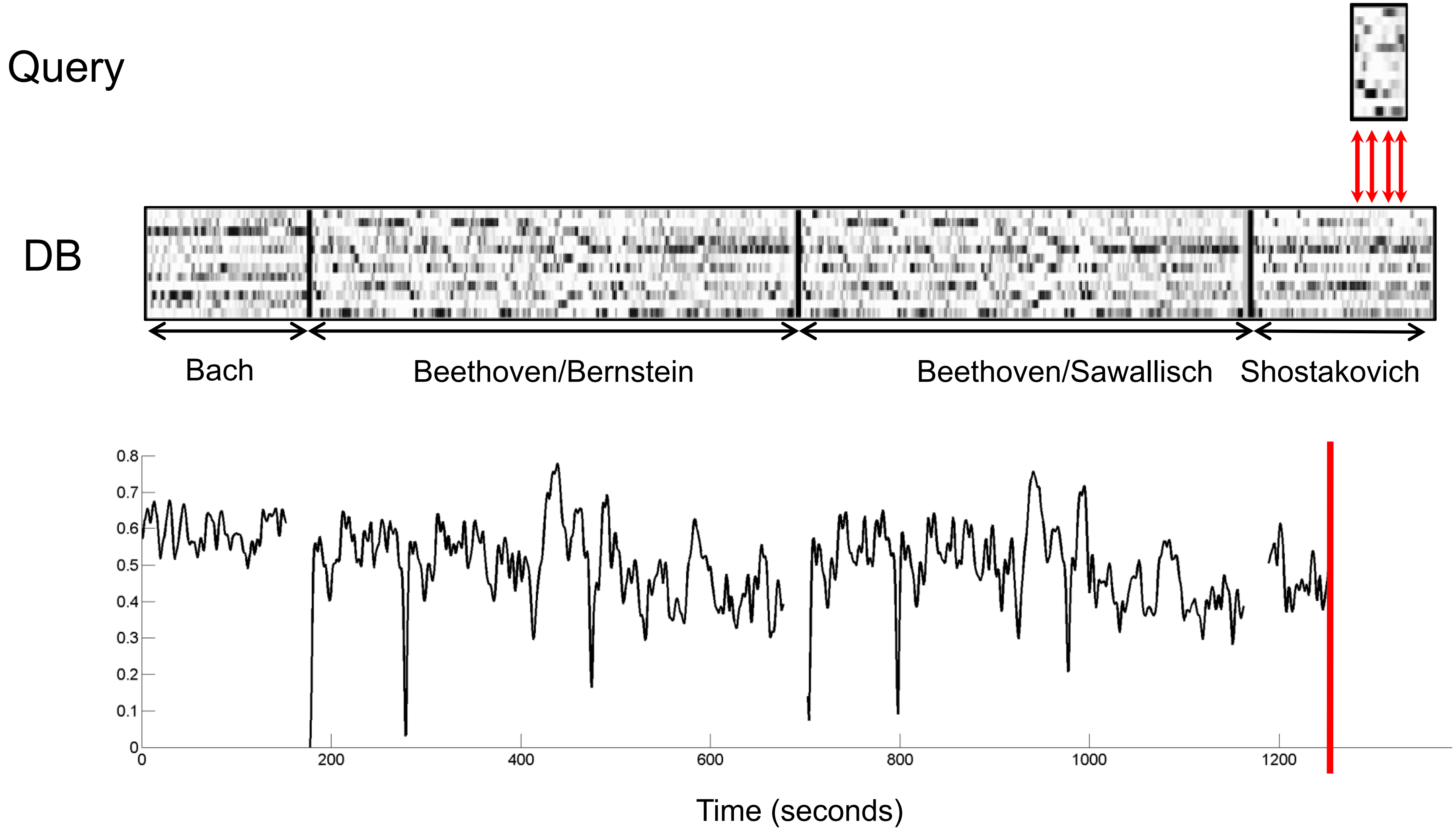
Matching Procedure



Matching Procedure



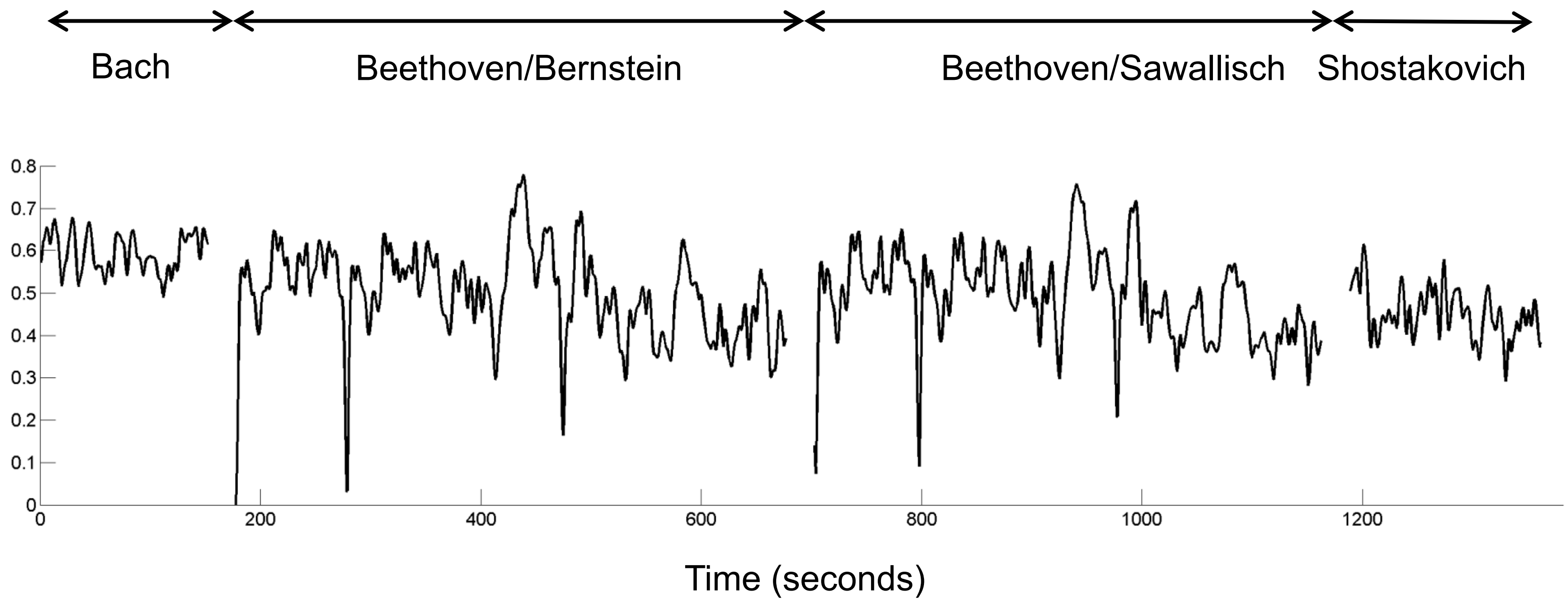
Matching Procedure



Matching Procedure

Matching curve

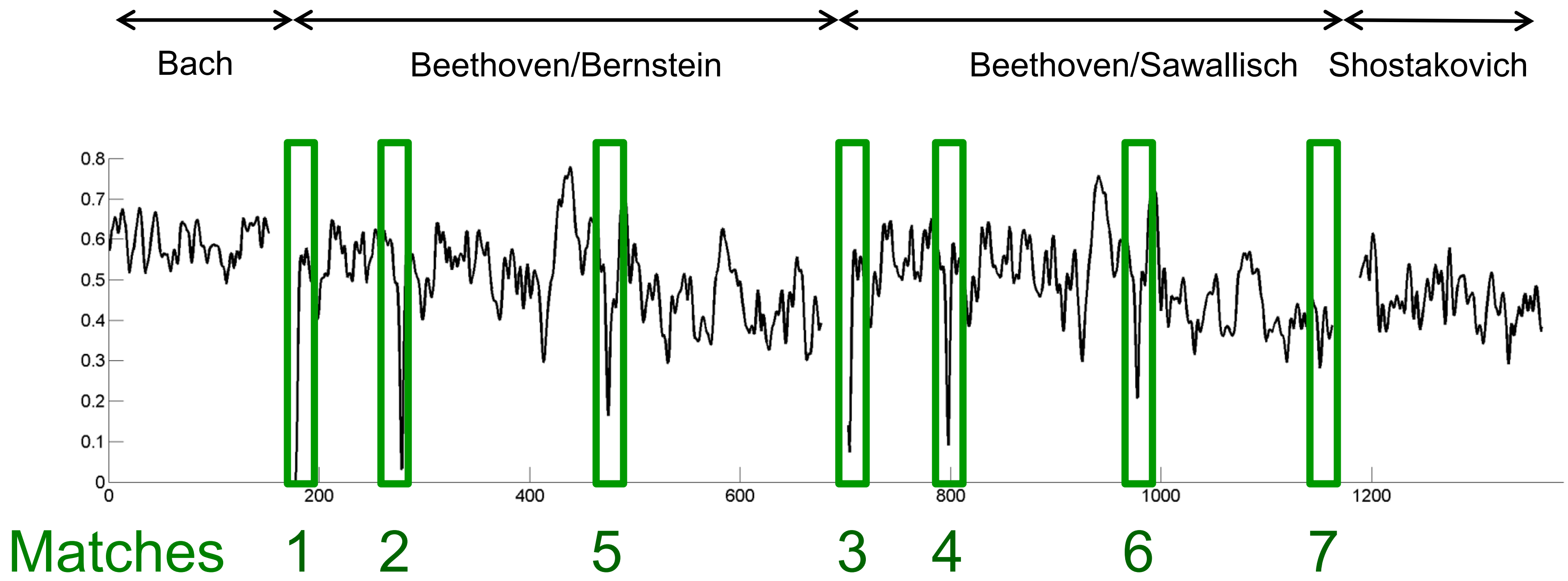
Query: Beethoven's Fifth / Bernstein (first 20 seconds)



Matching Procedure

Matching curve

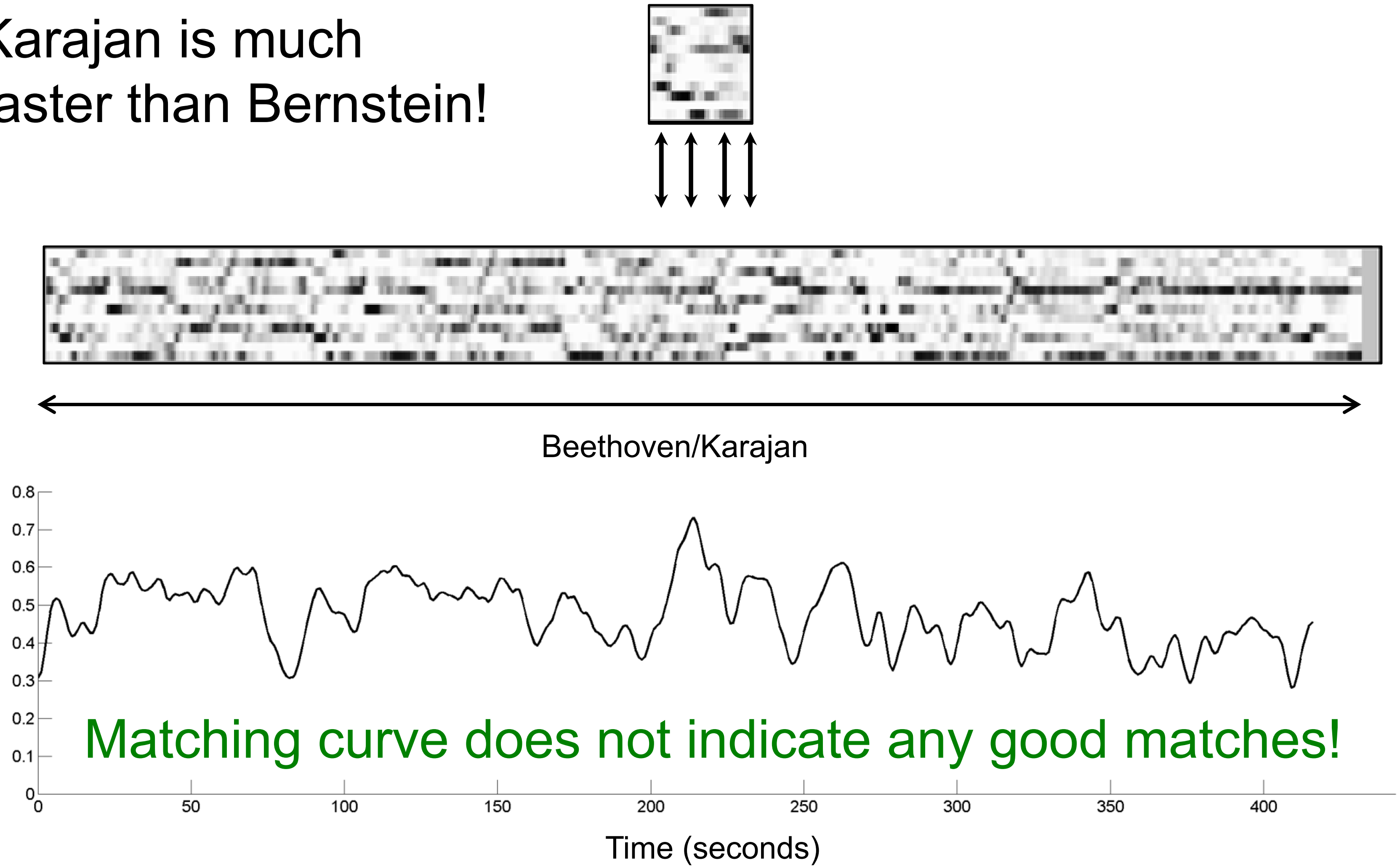
Query: Beethoven's Fifth / Bernstein (first 20 seconds)



Matching Procedure

Problem: How to deal with tempo differences?

Karajan is much faster than Bernstein!



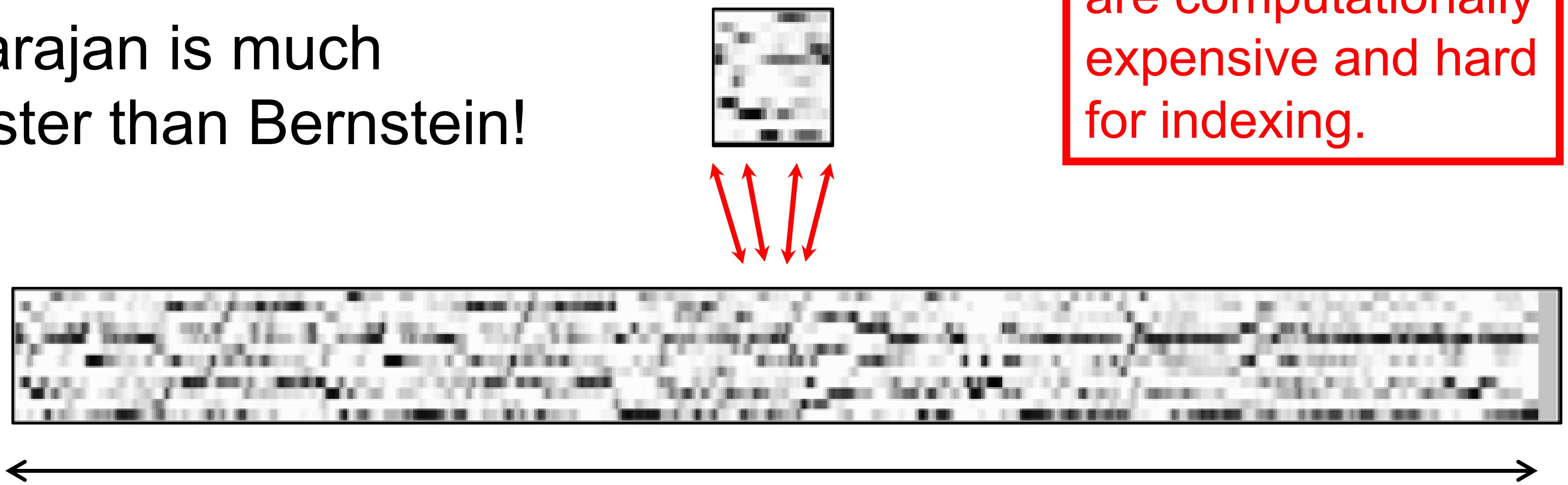
Matching curve does not indicate any good matches!

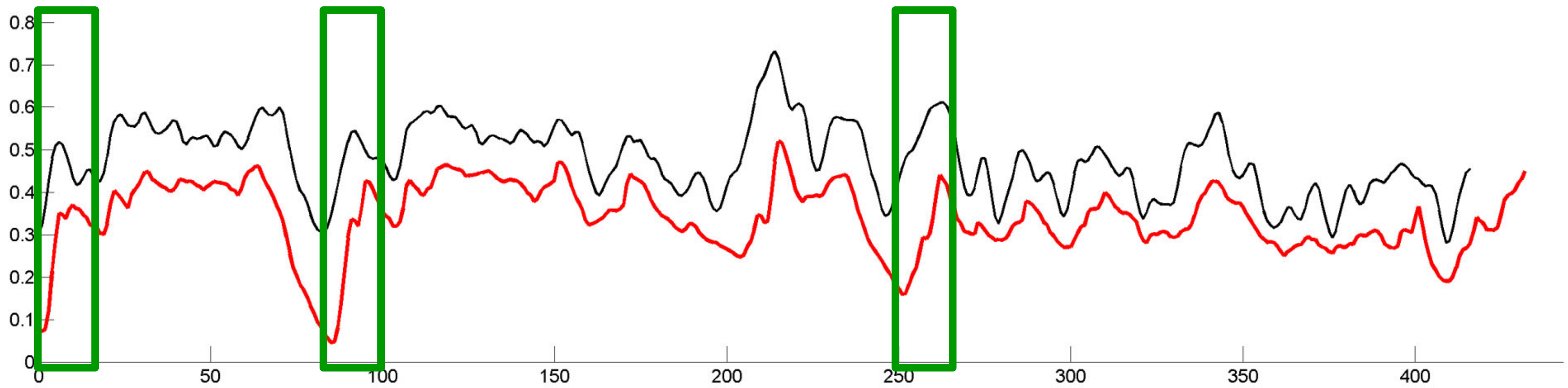
Matching Procedure

1. Strategy: Usage of local warping

Karajan is much faster than Bernstein!

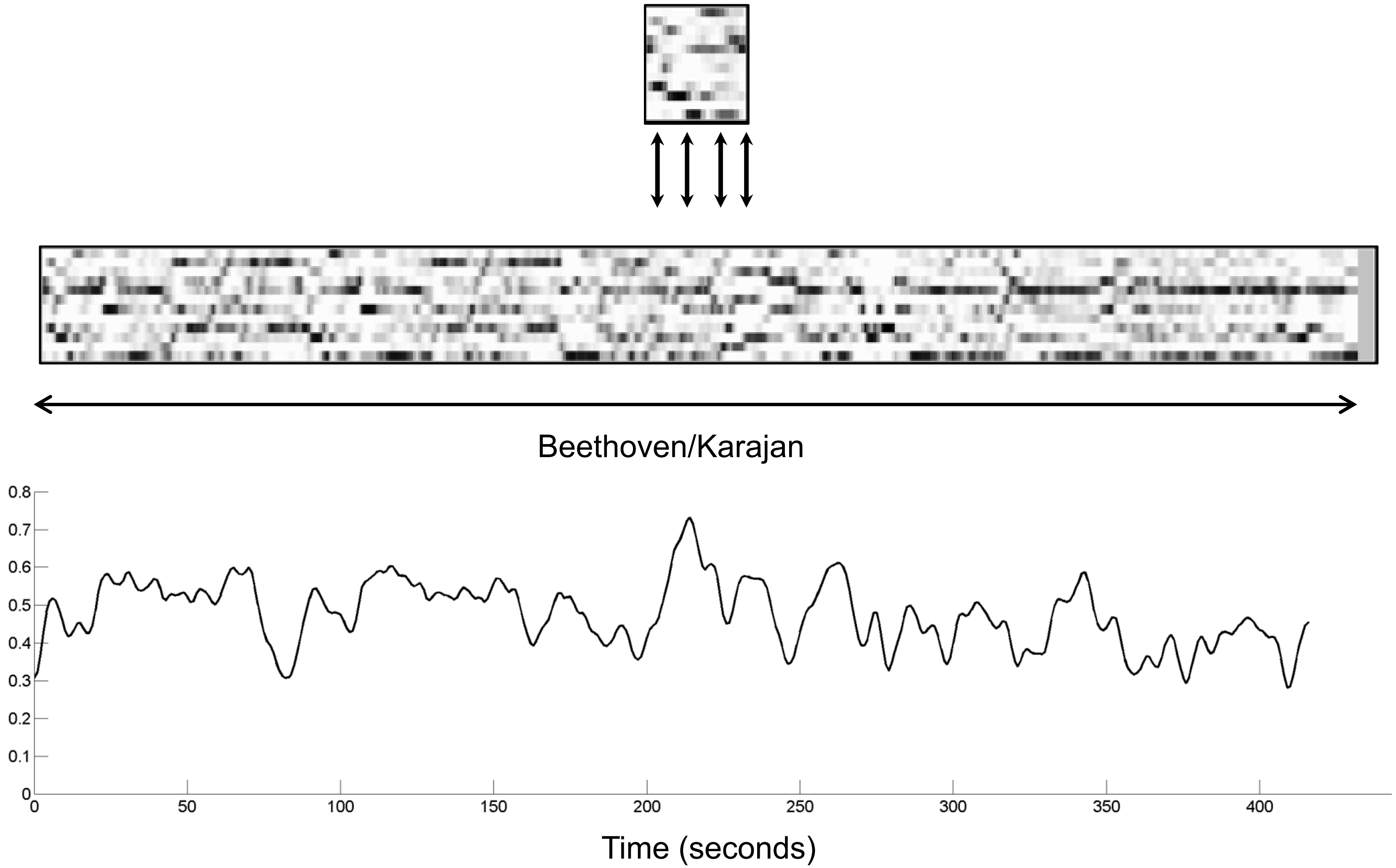
Warping strategies are computationally expensive and hard for indexing.





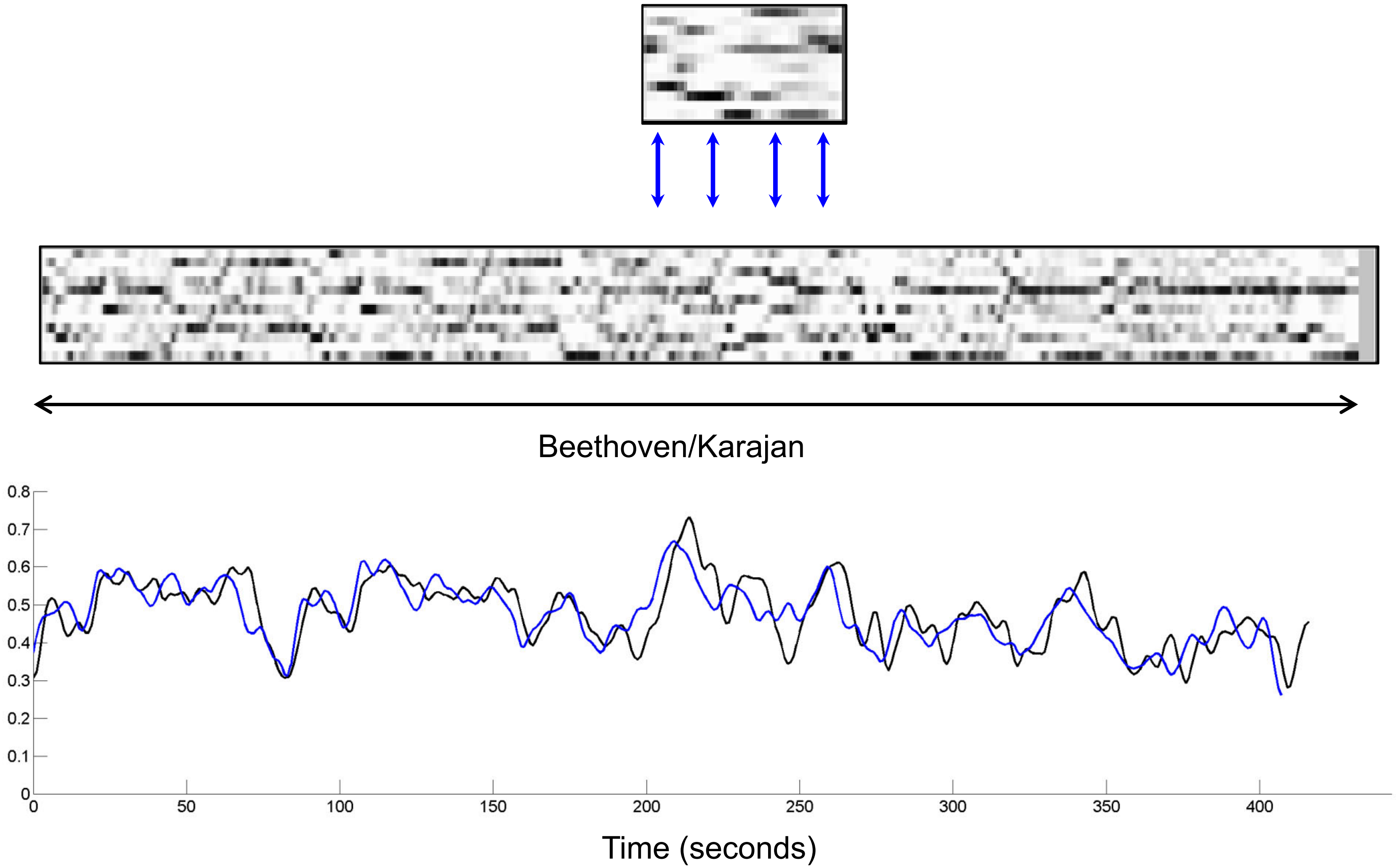
Matching Procedure

2. Strategy: Usage of multiple scaling



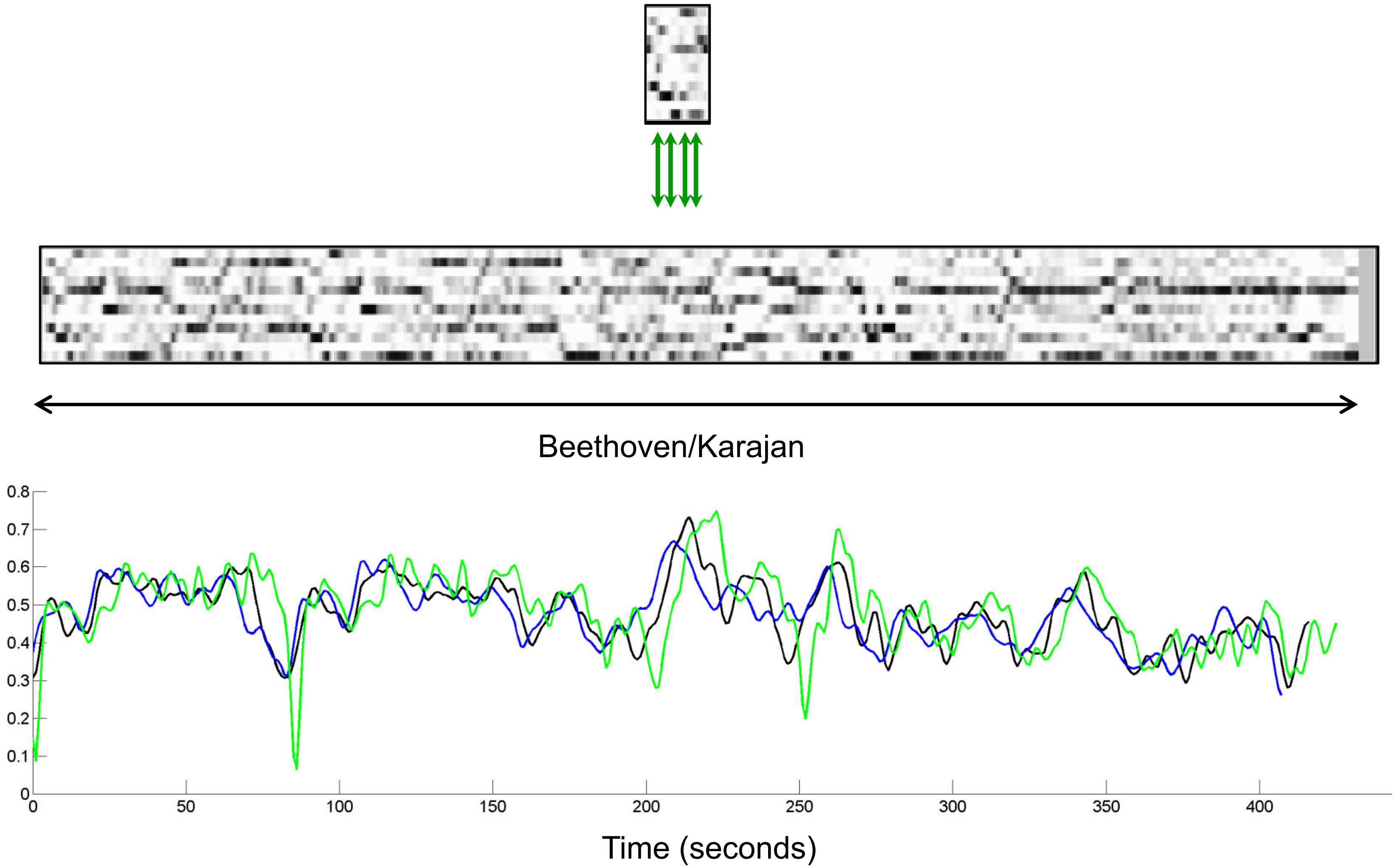
Matching Procedure

2. Strategy: Usage of multiple scaling



Matching Procedure

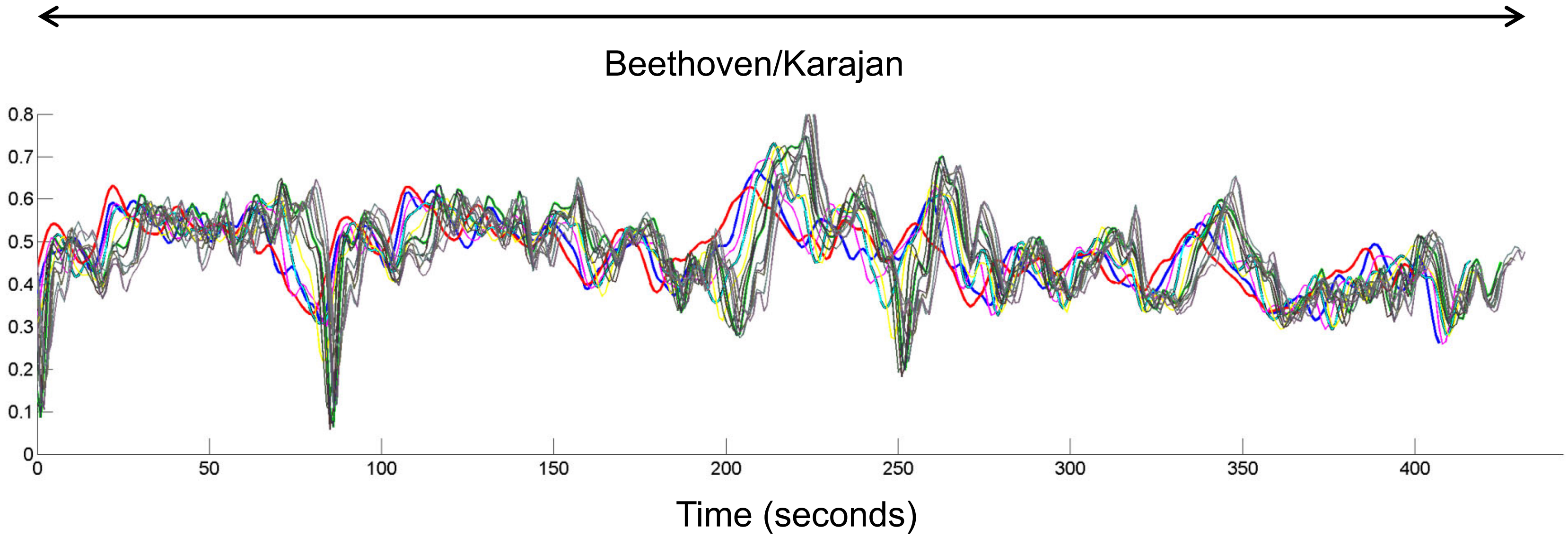
2. Strategy: Usage of multiple scaling



Matching Procedure

2. Strategy: Usage of multiple scaling

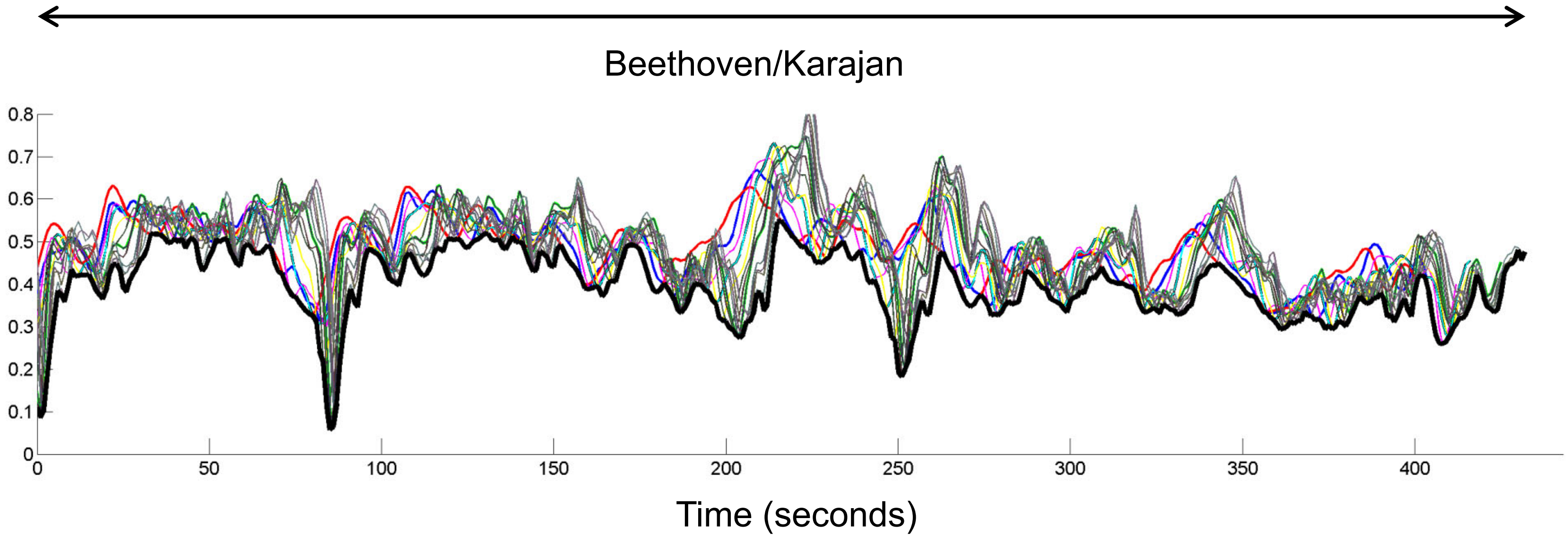
- Query resampling simulates tempo changes



Matching Procedure

2. Strategy: Usage of multiple scaling

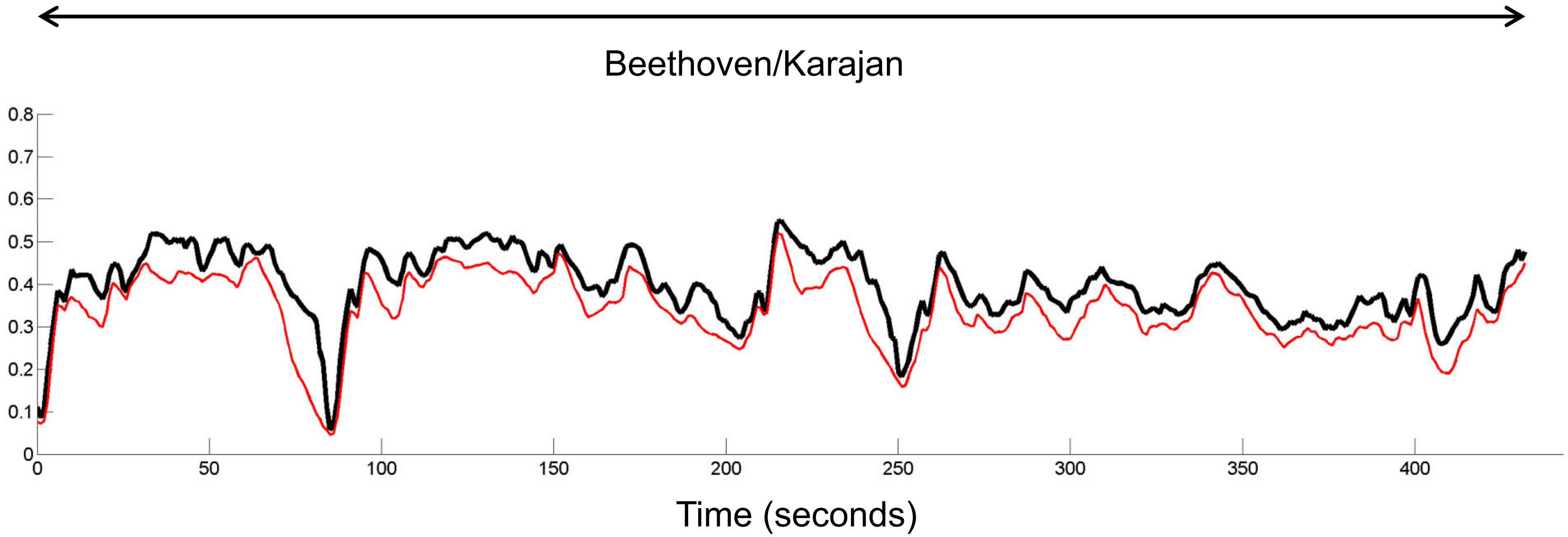
- Query resampling simulates tempo changes
- Minimize over all curves



Matching Procedure

2. Strategy: Usage of multiple scaling

- Query resampling simulates tempo changes
- Minimize over all curves
- Resulting curve is similar to warping curve



Audio Matching

Query: Beethoven's Fifth / Bernstein (first 20 seconds)

Rank	Piece	Position
1	Beethoven's Fifth/Bernstein	0 - 21
2	Beethoven's Fifth/Bernstein	101- 122
3	Beethoven's Fifth/Karajan	86 - 103
⋮	⋮	⋮
⋮	⋮	⋮
10	Beethoven's Fifth/Karajan	252 - 271
11	Beethoven's Fifth/Scherbakov	0 - 19
12	Beethoven's Fifth/Sawallisch	275 - 296
13	Beethoven's Fifth/Scherbakov	86 - 103
14	Schumann Op. 97,1/Levine	28 - 43

Audio Matching

Strategy: Handle variations at various levels

- Chroma → invariance to timbre
- Normalization → invariance to dynamics
- Smoothing → invariance to local time deviations
- Multiple queries → invariance to global tempo

Audio Matching
Müller, Kurth, Clausen: Audio Matching via Chroma-Based Statistical Features. ISMIR, 2005

Notes:

- There is no "standard" chroma feature.
  → Variants can make a huge difference!
- Learn invariance from examples
  → "Deep Chroma"
- Temporal warping makes problem hard
- Efficiency

Deep Chroma
Korzeniowski, Widmer: Feature Learning for Chord Recognition: The Deep Chroma Extractor. ISMIR, 2016

Shingle-Based Retrieval

Idea

- Query and database are split up into small overlapping shingles that consist of short feature subsequences.
- Shingles can be matched using efficient nearest neighbor retrieval.
- Trade-off:
  - Large shingles have high musical relevance
  - High shingle dimensionality makes indexing difficult

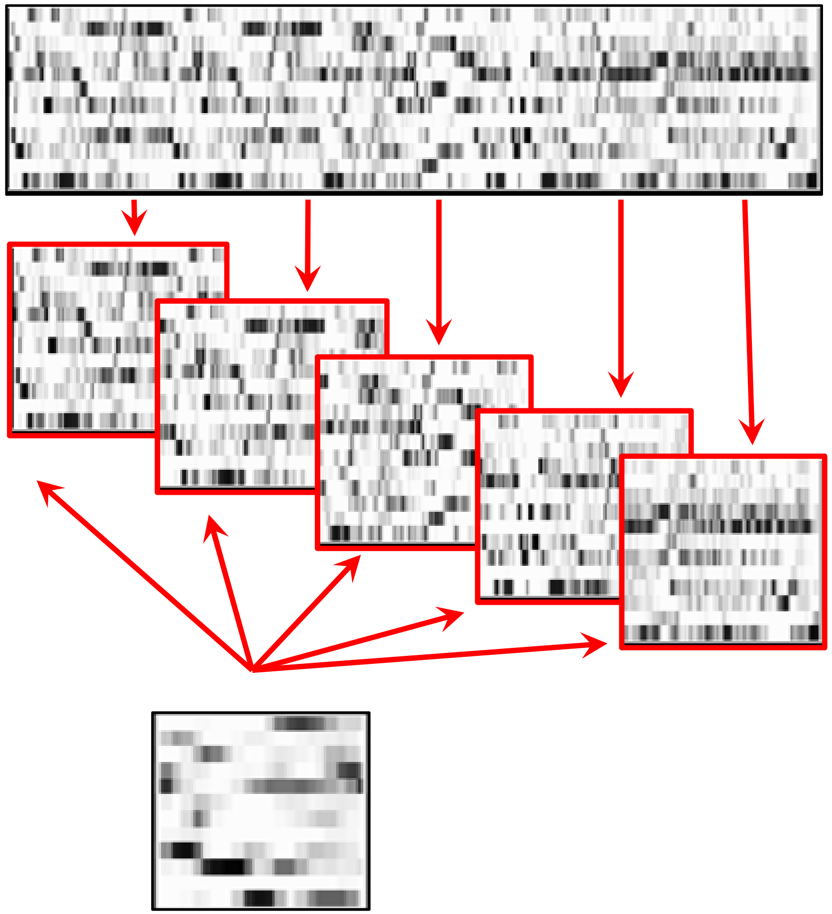
Shingle-Based Retrieval

Database
Chroma sequence

Chroma shingles

Retrieval
(index-based)

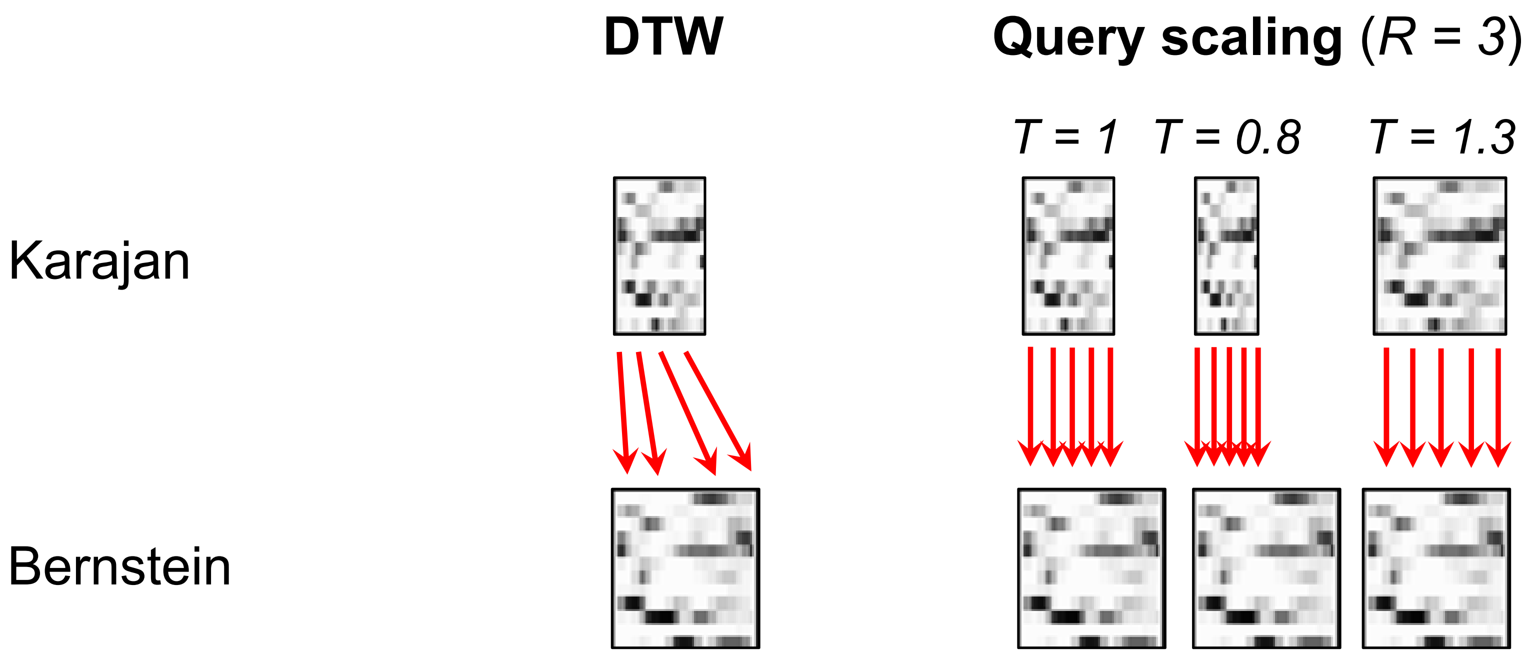
Query
Chroma sequence
(ca. 10 to 30 seconds)



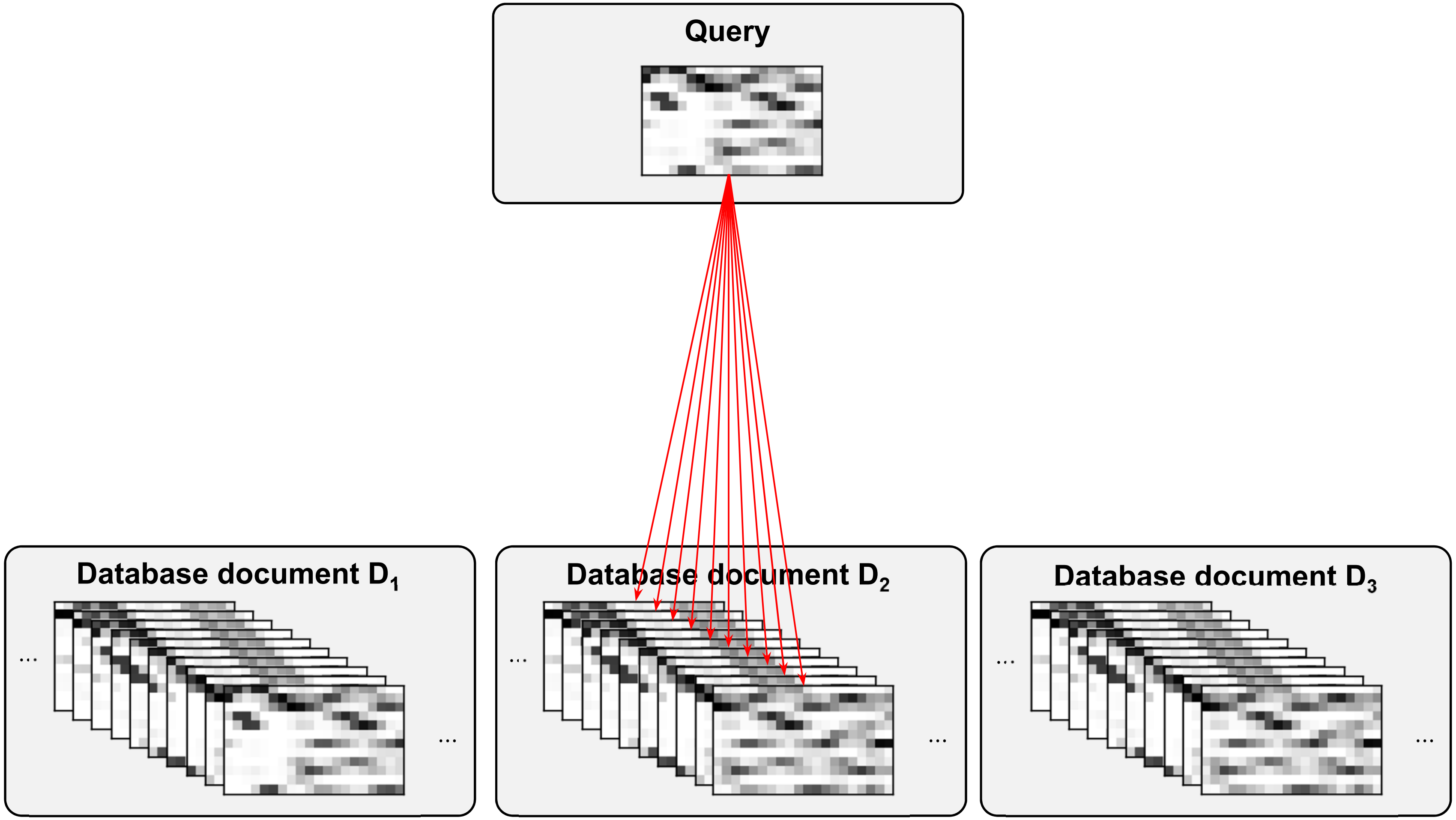
Shingle-Based Retrieval

Tempo-invariant matching

Avoiding expensive temporal warping, tempo differences are handled by creating *R* scaled variants of the query, each simulating a global change in tempo of up to ± 50 %.



Shingle-Based Retrieval



Shingle-Based Retrieval

Query

Ranked list

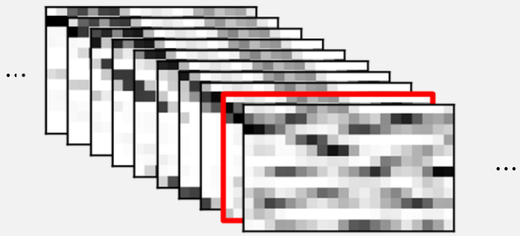
1. Database document D_1
2. Database document D_3
3. Database document D_2

distance ≈ 0.001

Database document D_1

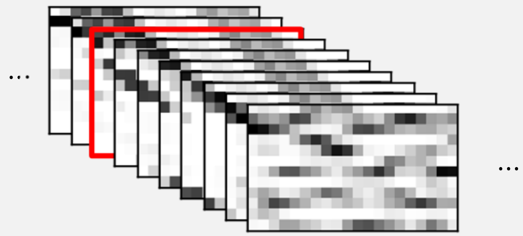
distance ≈ 0.651

Database document D_2



distance ≈ 0.289

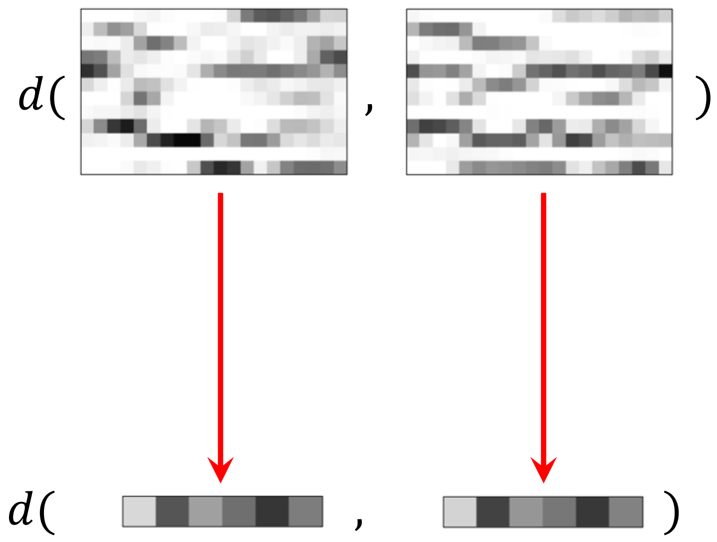
Database document D_3



Shingle-Based Retrieval

Dimensionality Reduction

Retrieval based on distance computation between shingles



Expensive for high shingle dimensions

Strategy: dimensionality reduction

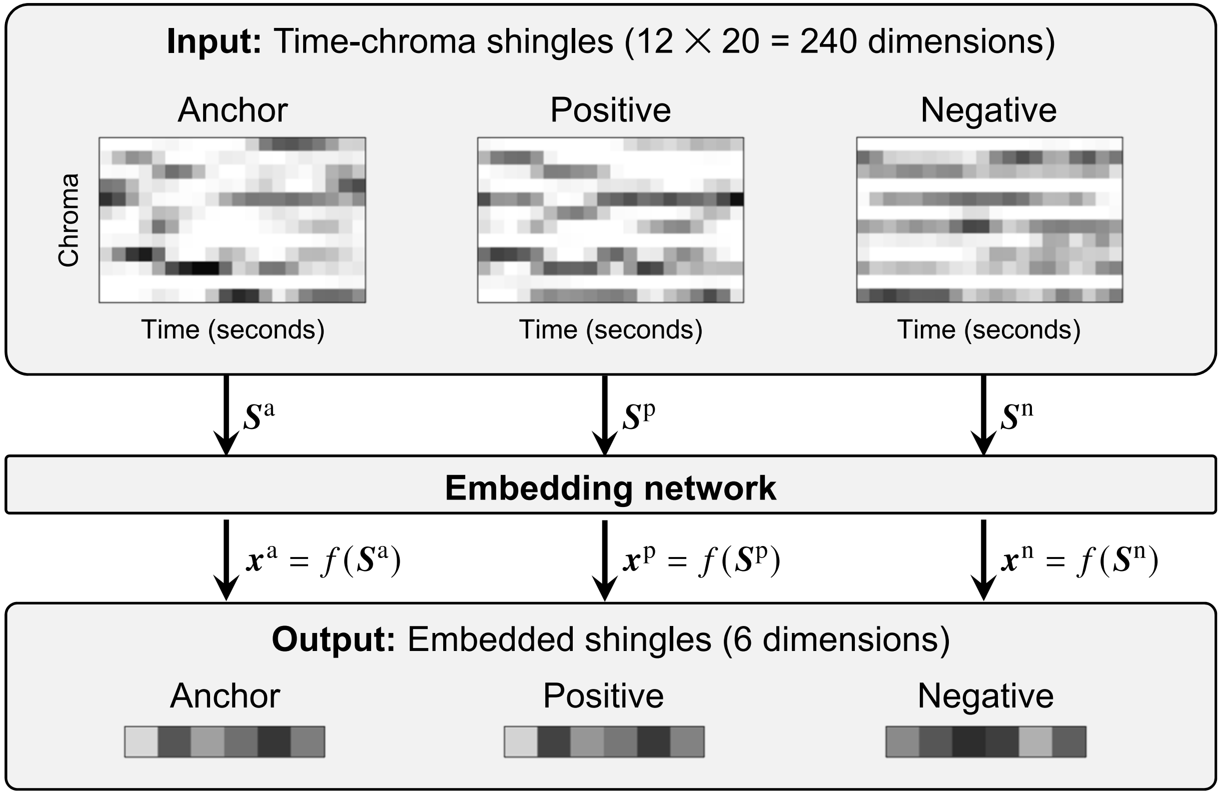
1. Using classical PCA

2. Using a neural network trained with triplet loss

Triplet Loss
F. Schroff, D. Kalenichenko, J. Philbin: FaceNet: A unified embedding for face recognition and clustering. CVPR, 2015.

Shingle-Based Retrieval

Triplet-Based Embedding

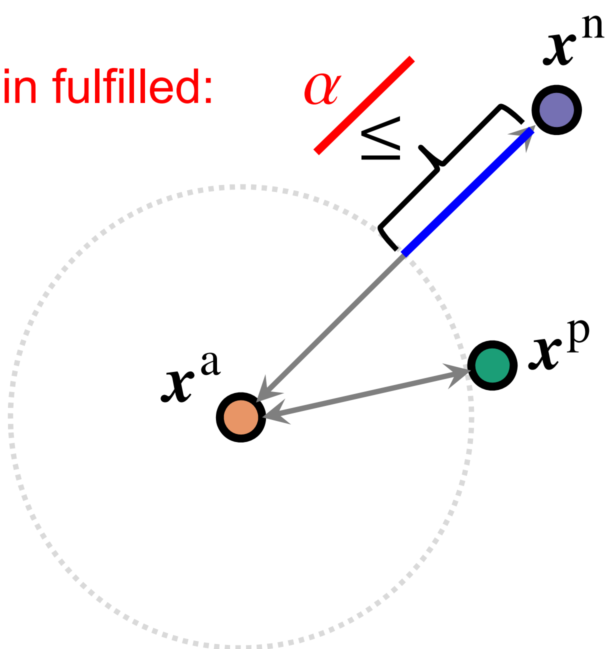


Shingle-Based Retrieval

Triplet Loss

$$\mathcal{L}(\boldsymbol{X}) = \max\left(0, d(\boldsymbol{x}^{\mathrm{a}}, \boldsymbol{x}^{\mathrm{p}}) - d(\boldsymbol{x}^{\mathrm{a}}, \boldsymbol{x}^{\mathrm{n}}) + \alpha\right)$$

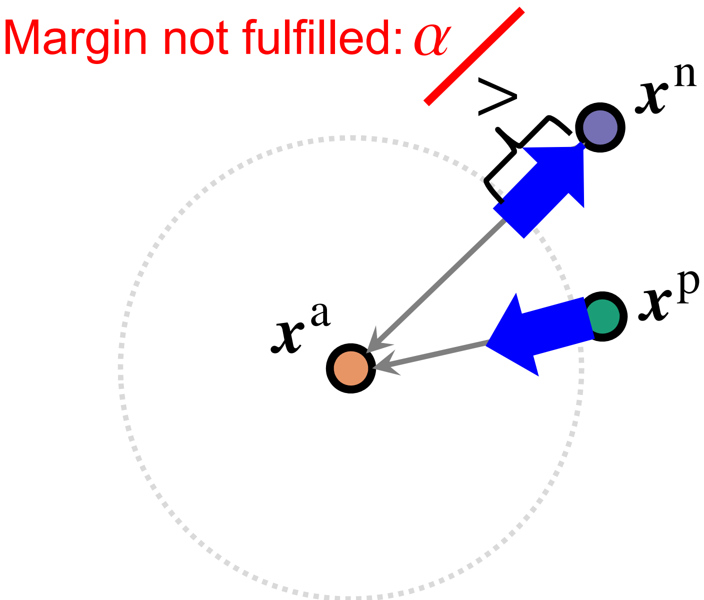
Margin fulfilled:



Shingle-Based Retrieval

Triplet Loss

$$\mathcal{L}(X) = \max\left(0, d(\boldsymbol{x}^{\mathrm{a}}, \boldsymbol{x}^{\mathrm{p}}) - d(\boldsymbol{x}^{\mathrm{a}}, \boldsymbol{x}^{\mathrm{n}}) + \alpha\right)$$



Loss tries to

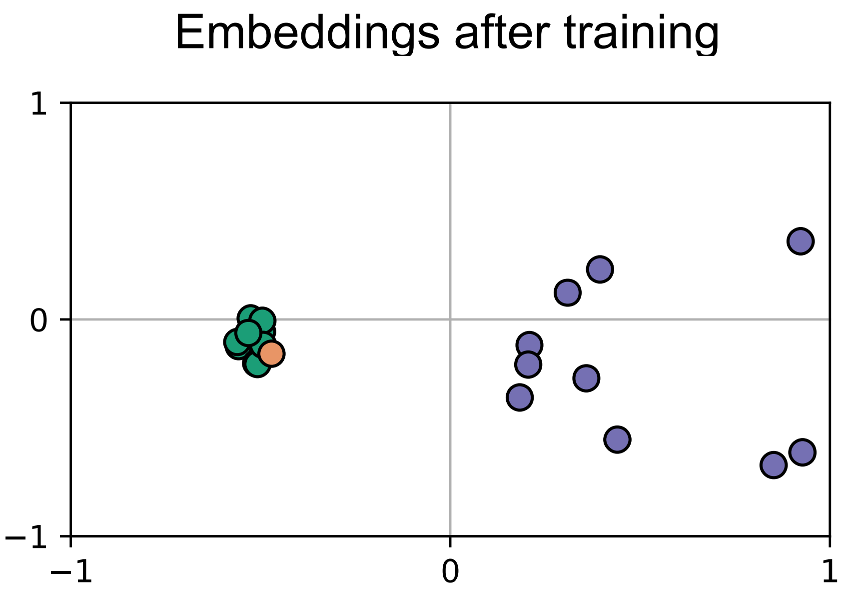
- **push** $\boldsymbol{x}^{\mathrm{n}}$ from anchor $\boldsymbol{x}^{\mathrm{a}}$
- **pull** $\boldsymbol{x}^{\mathrm{p}}$ towards anchor $\boldsymbol{x}^{\mathrm{a}}$

until margin α is fulfilled

Shingle-Based Retrieval

Triplet Loss

$$\mathcal{L}(\boldsymbol{X}) = \max\left(0, d(\boldsymbol{x}^{\mathrm{a}}, \boldsymbol{x}^{\mathrm{p}}) - d(\boldsymbol{x}^{\mathrm{a}}, \boldsymbol{x}^{\mathrm{n}}) + \alpha\right)$$



Shingle-Based Retrieval

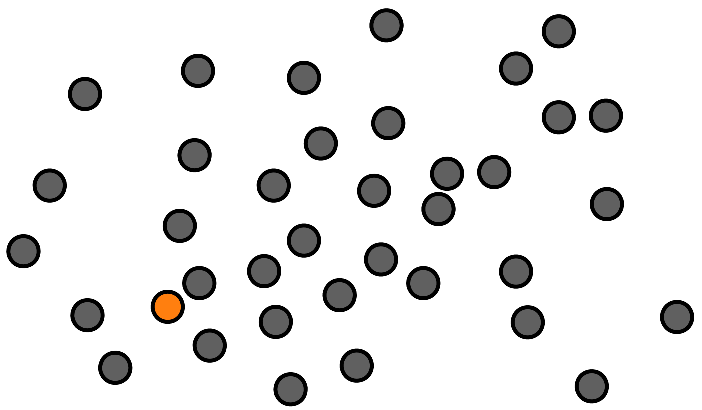
Experiment

- Training set: 357 recordings of different pieces by Beethoven, Chopin, and Vivaldi (~ 19 hours)
- Test set: 330 different recordings of different pieces by the same composers (~ 16 hours)

Shingle Reduction	Dimensionality	Retrieval Quality P@1	Retrieval Quality MAP	Retrieval Time (seconds)
No reduction	240	0.996	0.972	23.0
DNN	30	0.981	0.959	3.4
DNN	12	0.964	0.928	1.8
DNN	6	0.890	0.856	1.2

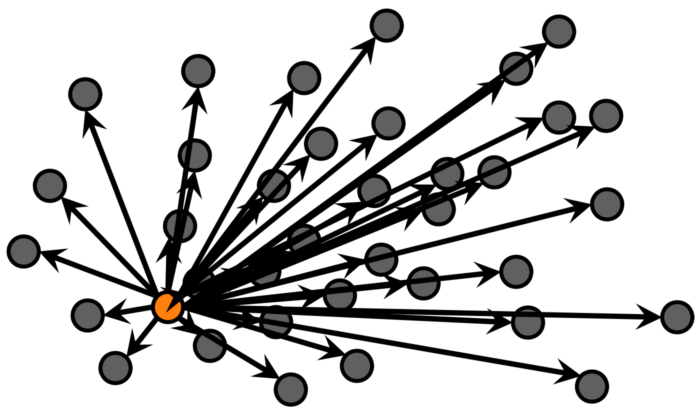
Shingle-Based Retrieval

Nearest Neighbor Search



Shingle-Based Retrieval

Nearest Neighbor Search



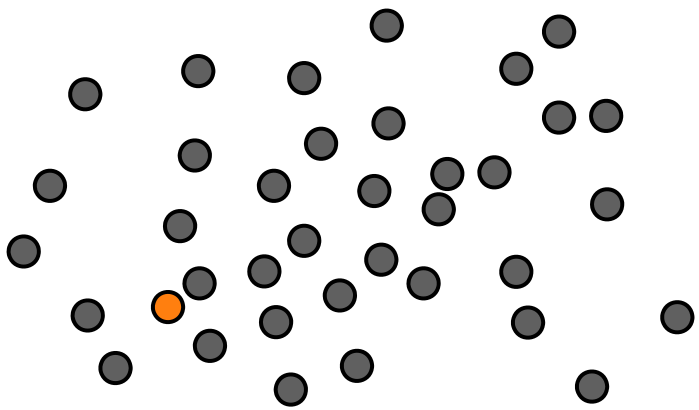
Strategies

- Brute force

AUDIO LABS

Shingle-Based Retrieval

Nearest Neighbor Search



Strategies

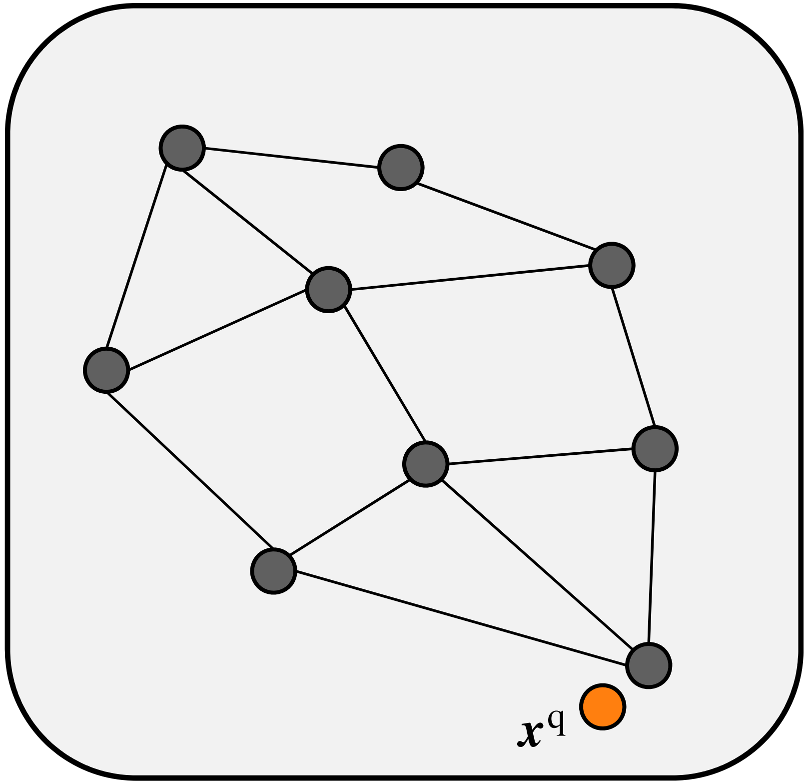
- Brute force
- K-D trees
- HNSW graphs

HNSW Graphs
Y. Malkov and D. Yashunin. Efficient and robust approximate nearest neighbor search using hierarchical navigable small world graphs. IEEE Transactions on PAMI, 2020.

Shingle-Based Retrieval

Graph-Based Nearest Neighbor Search

Initial situation



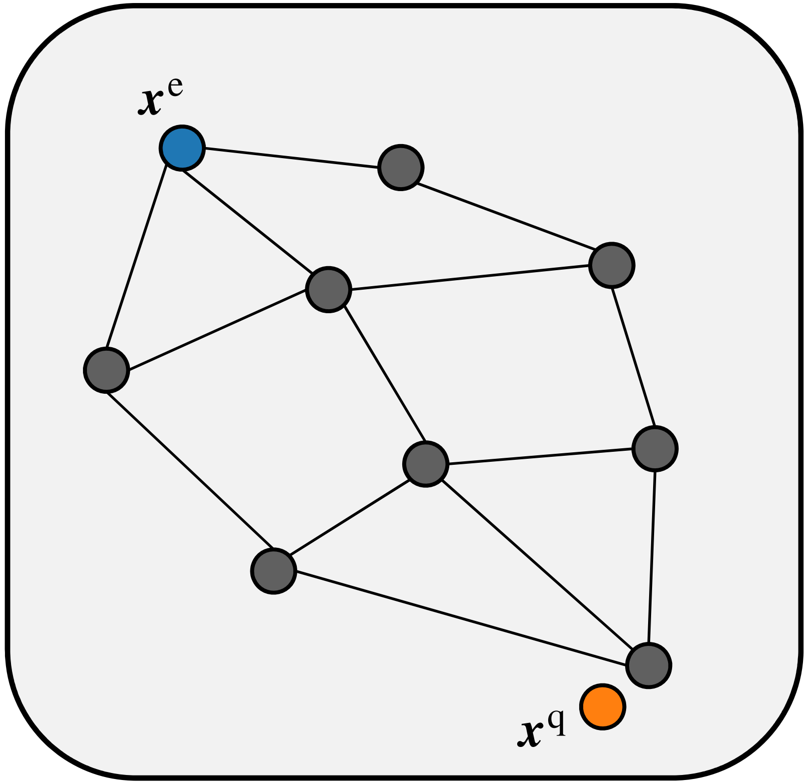
- Given: query node $\boldsymbol{x}^{\mathrm{q}}$

HNSW Graphs
Y. Malkov and D. Yashunin. Efficient and robust approximate nearest neighbor search using hierarchical navigable small world graphs. IEEE Transactions on PAMI, 2020.

Shingle-Based Retrieval

Graph-Based Nearest Neighbor Search

Step 1



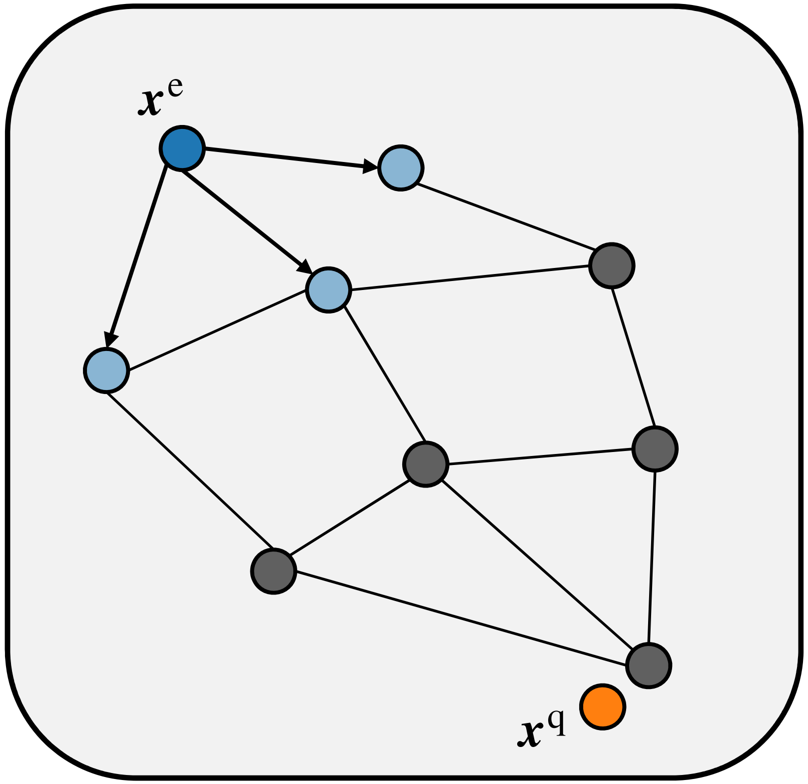
- Given: query node $\boldsymbol{x}^{\mathrm{q}}$
- Start with (random) entry node $\boldsymbol{x}^{\mathrm{e}}$

HNSW Graphs
Y. Malkov and D. Yashunin. Efficient and robust approximate nearest neighbor search using hierarchical navigable small world graphs. IEEE Transactions on PAMI, 2020.

Shingle-Based Retrieval

Graph-Based Nearest Neighbor Search

Step 1



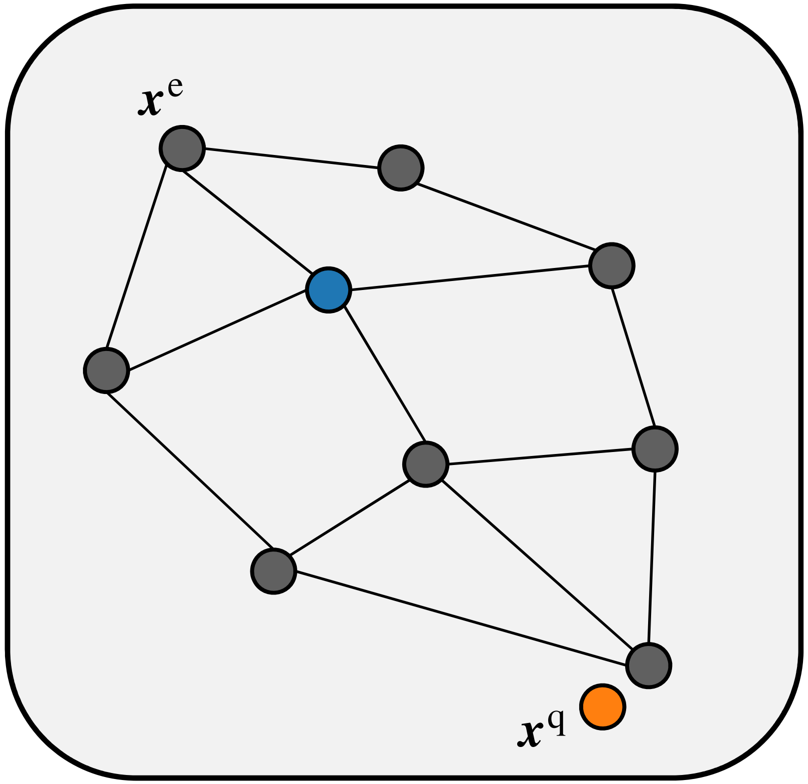
- Given: query node $\boldsymbol{x}^{\mathrm{q}}$
- Start with (random) entry node $\boldsymbol{x}^{\mathrm{e}}$
- Traverse graph along edges and compare nodes with $\boldsymbol{x}^{\mathrm{q}}$

HNSW Graphs
Y. Malkov and D. Yashunin. Efficient and robust approximate nearest neighbor search using hierarchical navigable small world graphs. IEEE Transactions on PAMI, 2020.

Shingle-Based Retrieval

Graph-Based Nearest Neighbor Search

Step 2



- Given: query node $\boldsymbol{x}^{\mathrm{q}}$
- Start with (random) entry node $\boldsymbol{x}^{\mathrm{e}}$
- Traverse graph along edges and compare nodes with $\boldsymbol{x}^{\mathrm{q}}$
- Continue with closest node

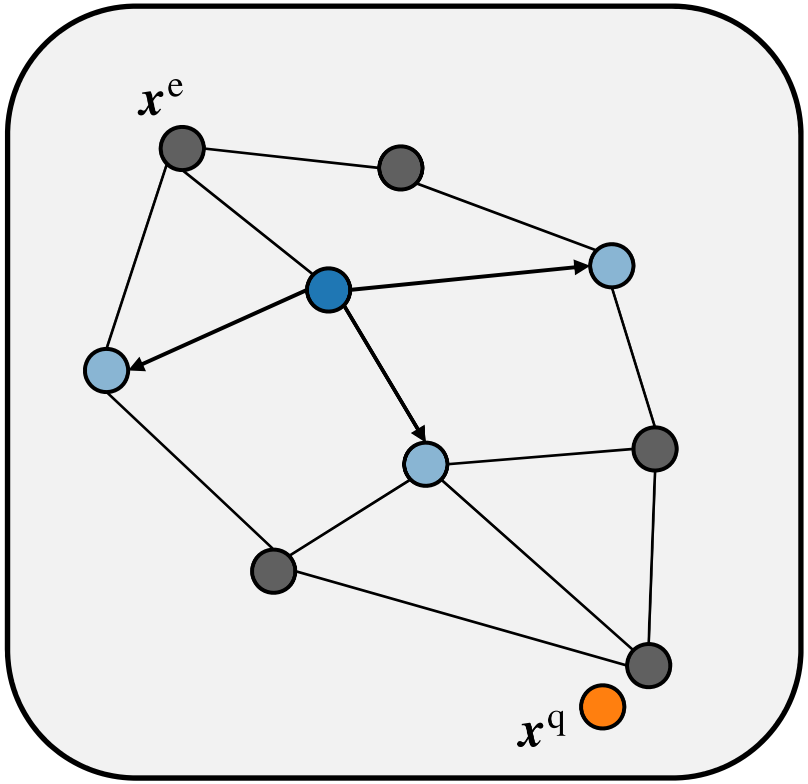
HNSW Graphs

Y. Malkov and D. Yashunin. Efficient and robust approximate nearest neighbor search using hierarchical navigable small world graphs. IEEE Transactions on PAMI, 2020.

Shingle-Based Retrieval

Graph-Based Nearest Neighbor Search

Step 2

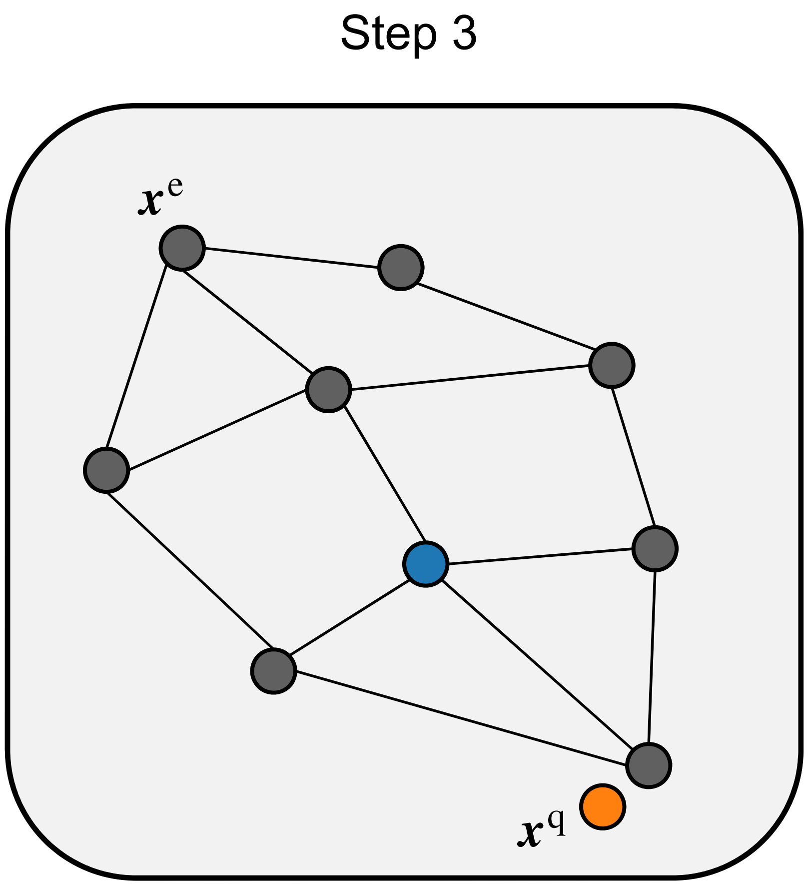


- Given: query node x^q
- Start with (random) entry node x^e
- Traverse graph along edges and compare nodes with x^q
- Continue with closest node

HNSW Graphs
Y. Malkov and D. Yashunin. Efficient and robust approximate nearest neighbor search using hierarchical navigable small world graphs. IEEE Transactions on PAMI, 2020.

Shingle-Based Retrieval

Graph-Based Nearest Neighbor Search



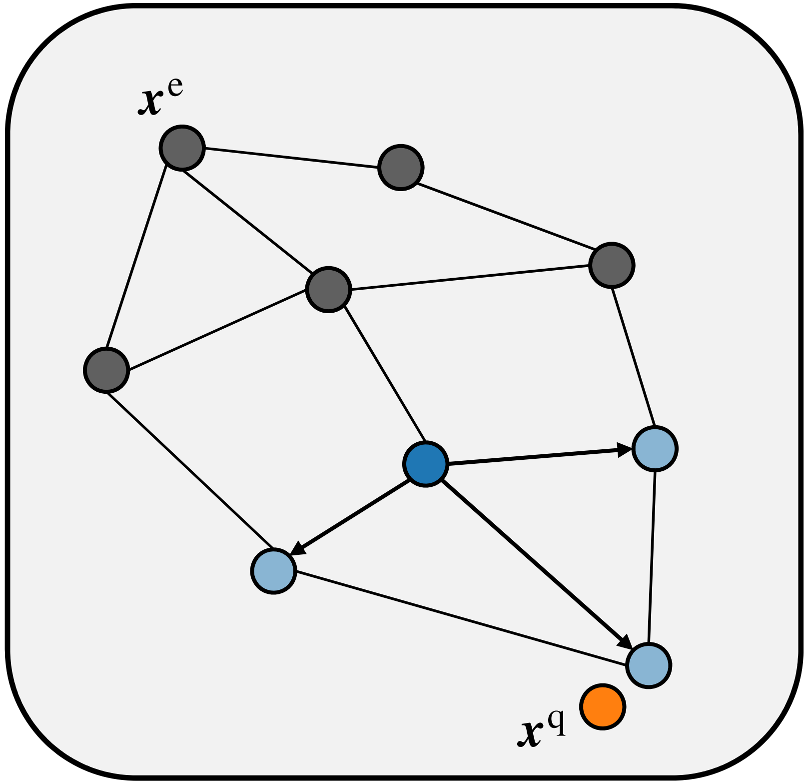
- Given: query node $\boldsymbol{x}^{\mathrm{q}}$
- Start with (random) entry node $\boldsymbol{x}^{\mathrm{e}}$
- Traverse graph along edges and compare nodes with $\boldsymbol{x}^{\mathrm{q}}$
- Continue with closest node

HNSW Graphs
Y. Malkov and D. Yashunin. Efficient and robust approximate nearest neighbor search using hierarchical navigable small world graphs. IEEE Transactions on PAMI, 2020.

Shingle-Based Retrieval

Graph-Based Nearest Neighbor Search

Step 3



- Given: query node x^q
- Start with (random) entry node x^e
- Traverse graph along edges and compare nodes with x^q
- Continue with closest node

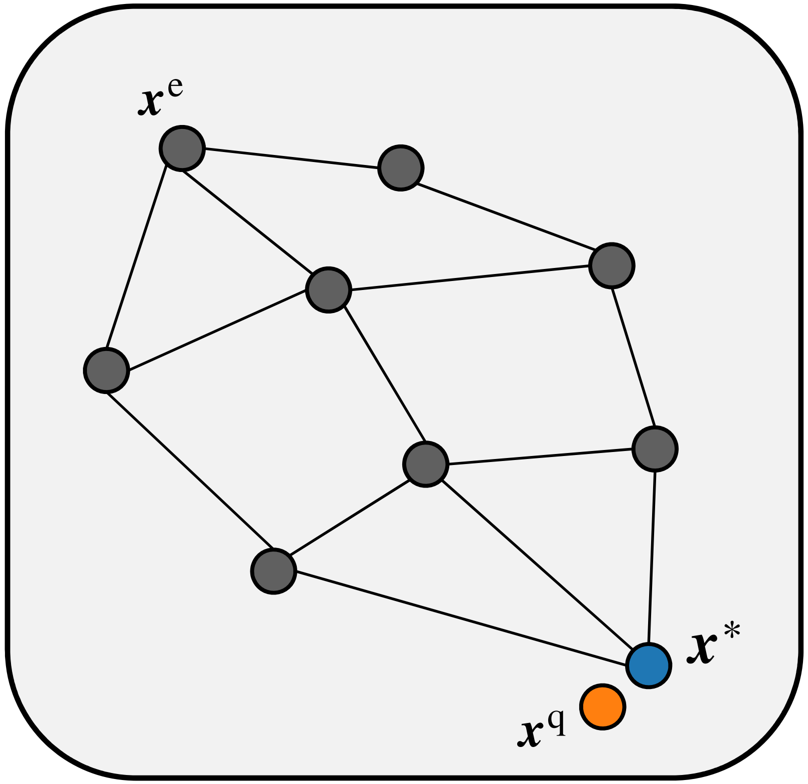
HNSW Graphs

Y. Malkov and D. Yashunin. Efficient and robust approximate nearest neighbor search using hierarchical navigable small world graphs. IEEE Transactions on PAMI, 2020.

Shingle-Based Retrieval

Graph-Based Nearest Neighbor Search

Step 4

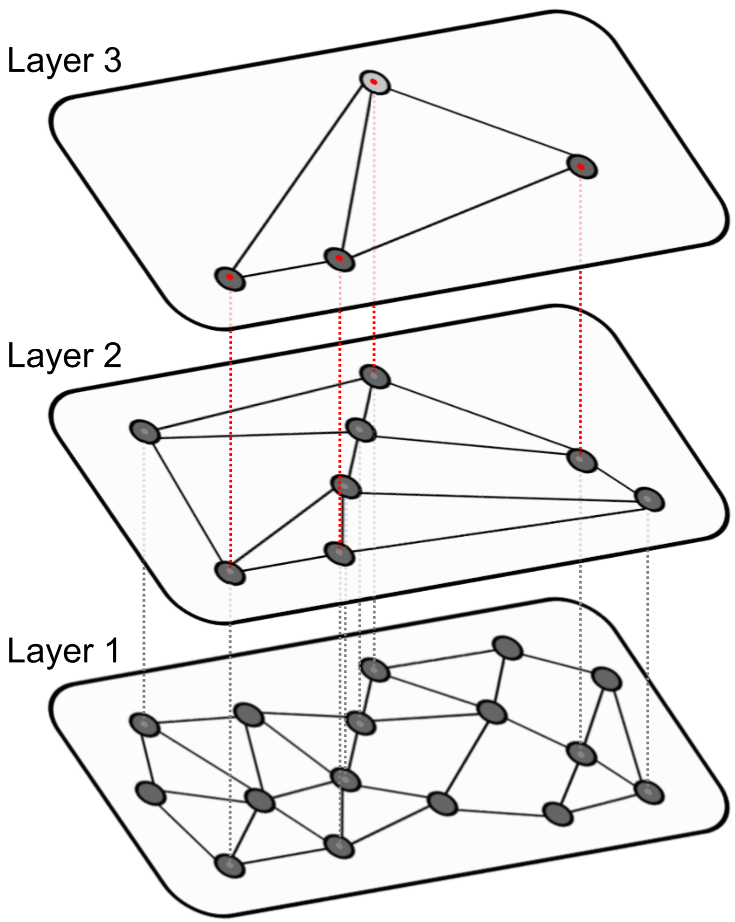


- Given: query node $\boldsymbol{x}^{\mathrm{q}}$
- Start with (random) entry node $\boldsymbol{x}^{\mathrm{e}}$
- Traverse graph along edges and compare nodes with $\boldsymbol{x}^{\mathrm{q}}$
- Continue with closest node
- Stop when distances increase

HNSW Graphs
Y. Malkov and D. Yashunin. Efficient and robust approximate nearest neighbor search using hierarchical navigable small world graphs. IEEE Transactions on PAMI, 2020.

Shingle-Based Retrieval

HNSW Graphs



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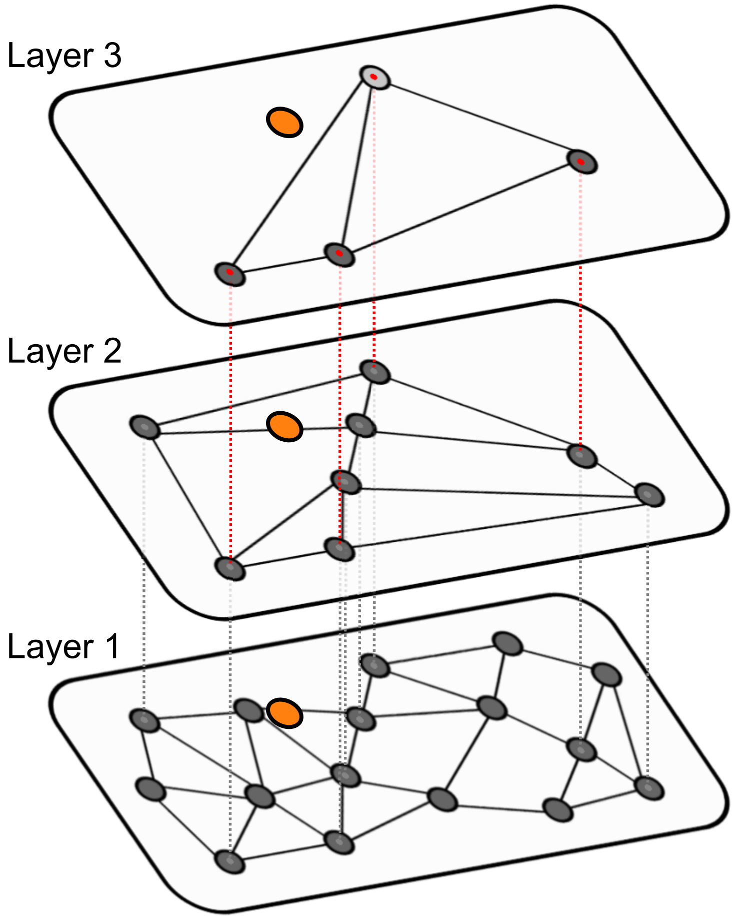
Y. Malkov and D. Yashunin. Efficient and robust approximate nearest neighbor search using hierarchical navigable small world graphs. IEEE Transactions on PAMI, 2020.

Shingle-Based Retrieval

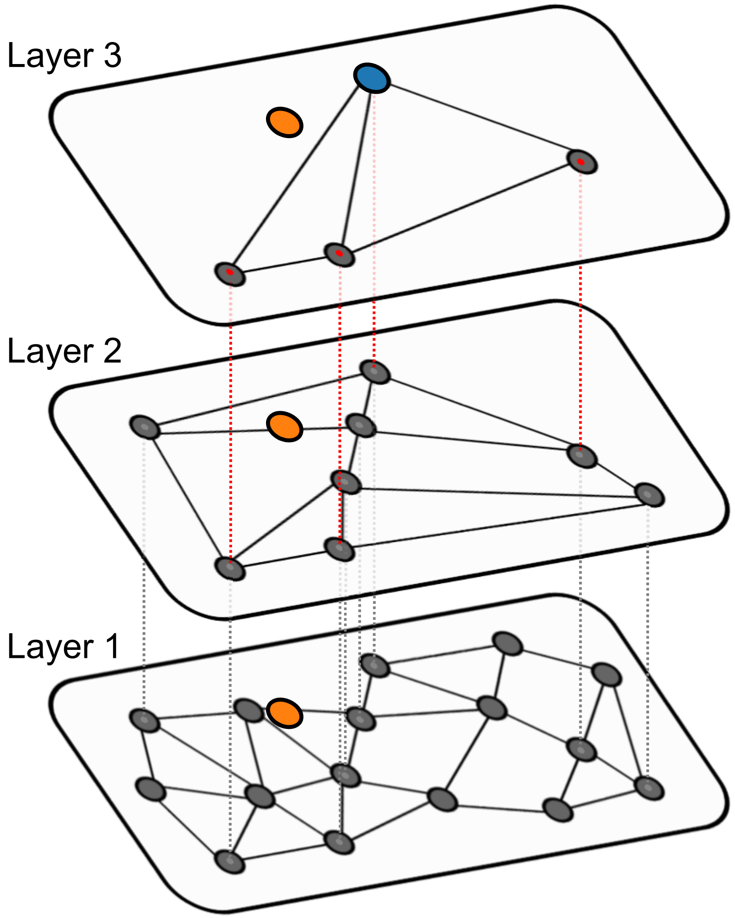
HNSW Graphs



HNSW Graphs
Y. Malkov and D. Yashunin. Efficient and robust approximate nearest neighbor search using hierarchical navigable small world graphs. IEEE Transactions on PAMI, 2020.

Shingle-Based Retrieval

HNSW Graphs



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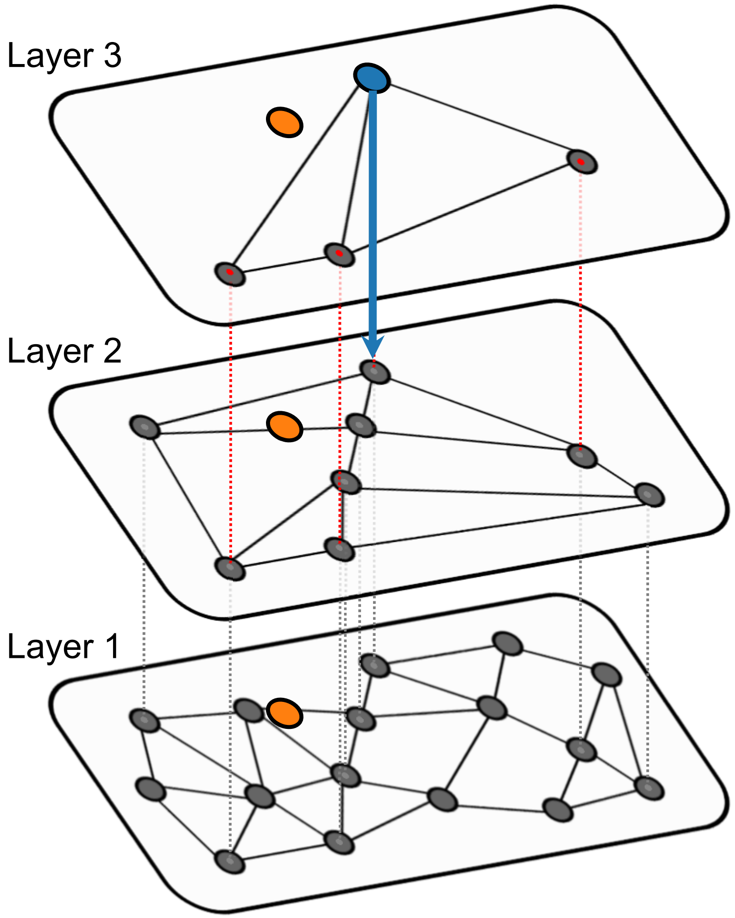
Shingle-Based Retrieval

HNSW Graphs



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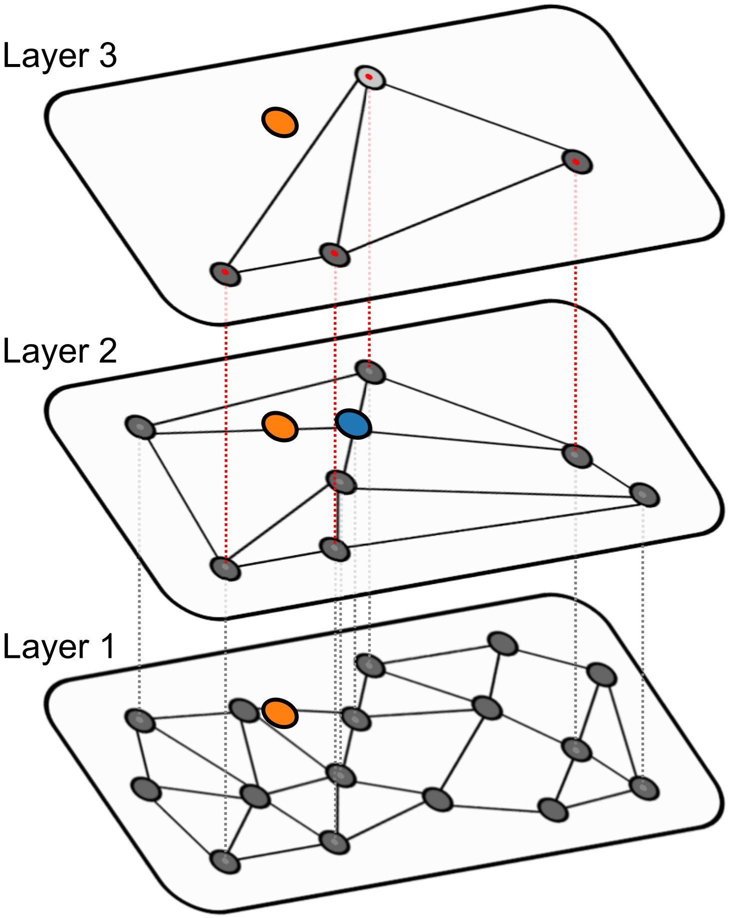
Shingle-Based Retrieval

HNSW Graphs



HNSW Graphs
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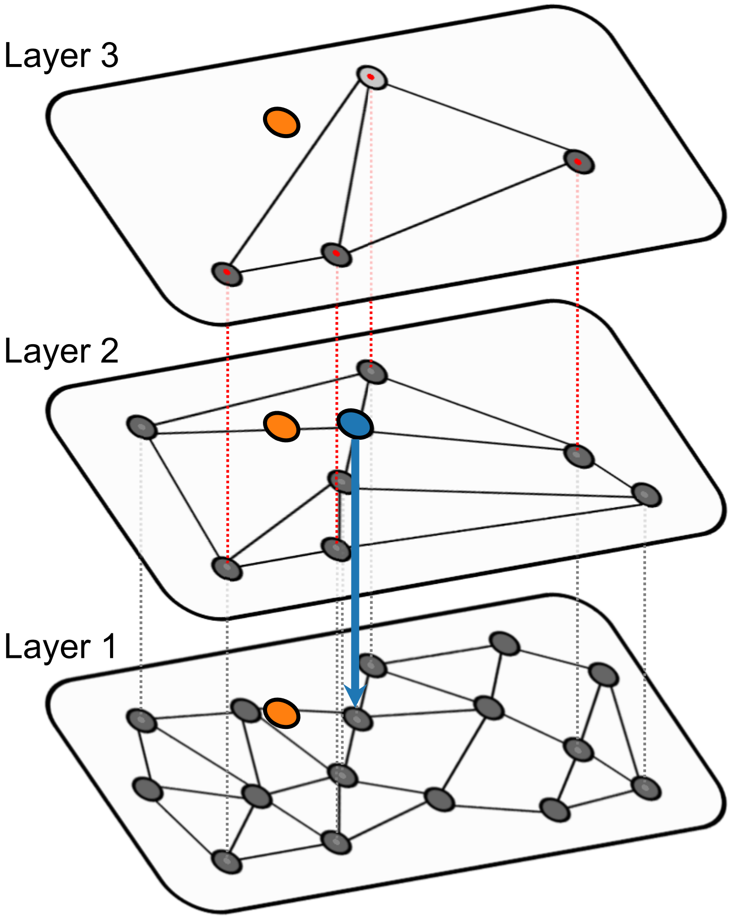
Shingle-Based Retrieval

HNSW Graphs



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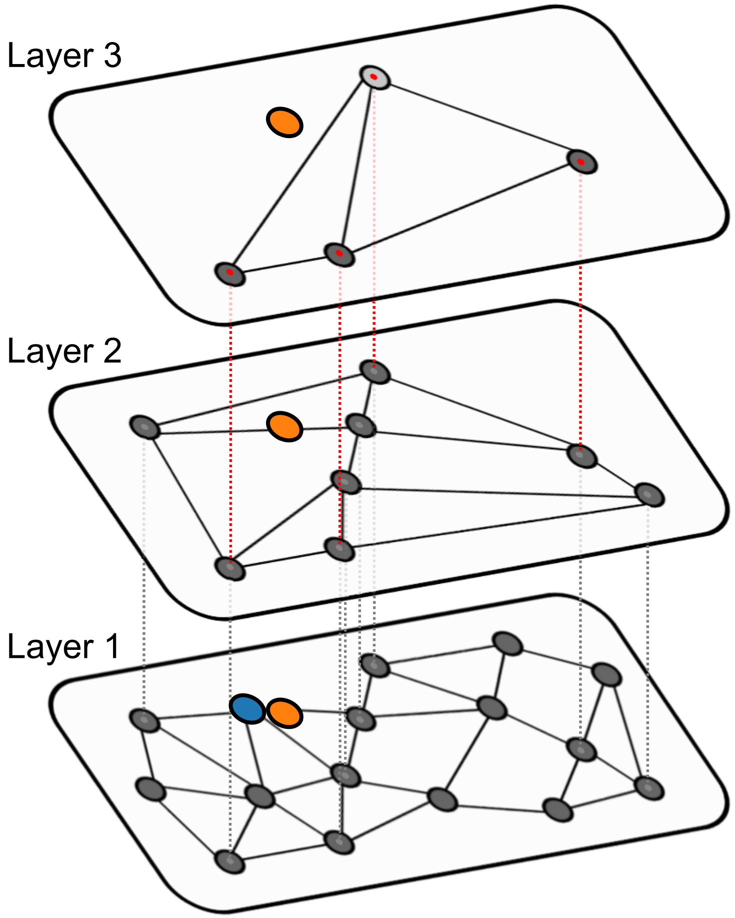
Shingle-Based Retrieval

HNSW Graphs



Properties

- Approximate nearest neighbor search
- Search runtime logarithmic in dataset size
- Works well with high dimensional data
- Efficient algorithm to build graph structure

HNSW Graphs
Y. Malkov and D. Yashunin. Efficient and robust approximate nearest neighbor search using hierarchical navigable small world graphs. IEEE Transactions on PAMI, 2020.

Shingle-Based Retrieval

Experiment

- Approximate search yields nearly same results as exact search
- Dataset: Entire audio catalogue by Carus publisher
(7115 recordings, ~ 390 hours, > 1,25 million shingles)
- Runtime for brute force approach: ~ 100 ms to 300 ms per query

Search	Shingle Reduction	Dimensionality	Time (ms)
KD	No reduction	240	772.95
KD	DNN	30	117.54
KD	DNN	12	7.24
KD	DNN	6	0.66
HNSW	No reduction	240	0.20
HNSW	DNN	30	0.08
HNSW	DNN	12	0.06
HNSW	DNN	6	0.06

Shingle-Based Retrieval

References

- P. Grosche, M. Müller: Toward characteristic audio shingles for efficient cross-version music retrieval. IEEE ICASSP, pages 473-476, 2012
- Y. Malkov and D. Yashunin. Efficient and robust approximate nearest neighbor search using hierarchical navigable small world graphs. IEEE Transactions on PAMI, 2020.
- F. Schroff, D. Kalenichenko, J. Philbin: FaceNet: A unified embedding for face recognition and clustering. CVPR, 2015.
- F. Zalkow and M. Müller: Learning low-dimensional embeddings of audio shingles for cross-version retrieval of classical music. Applied Sciences, 10(1), 2020.
- F. Zalkow, J. Brandner, and M. Müller: Efficient retrieval of music recordings using graph-based index structures. Signals, 2(2), 2021.

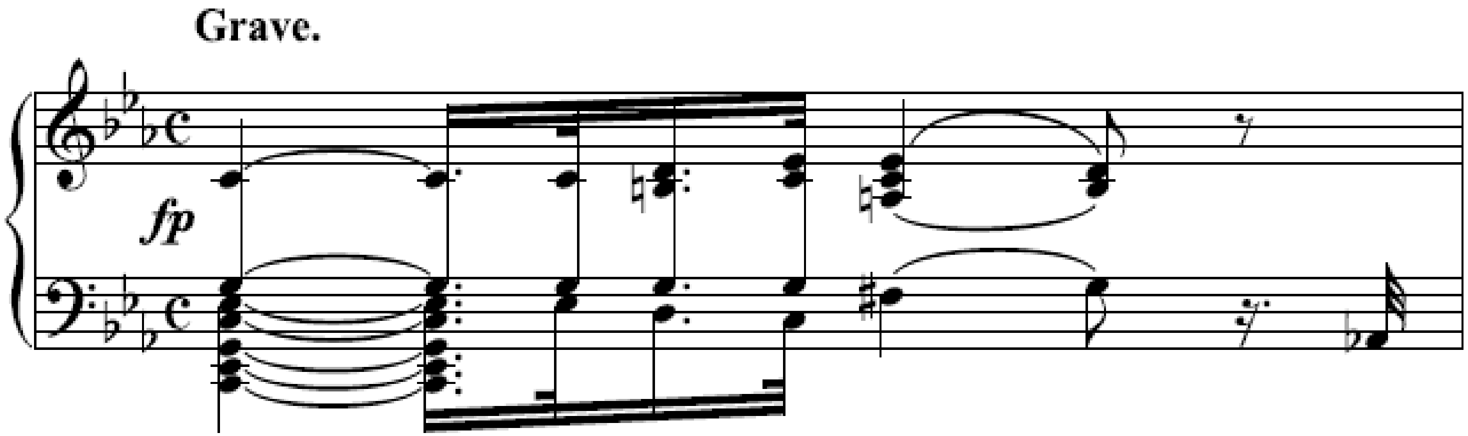
Thanks:

Frank Zalkow (Ph.D. 2021)

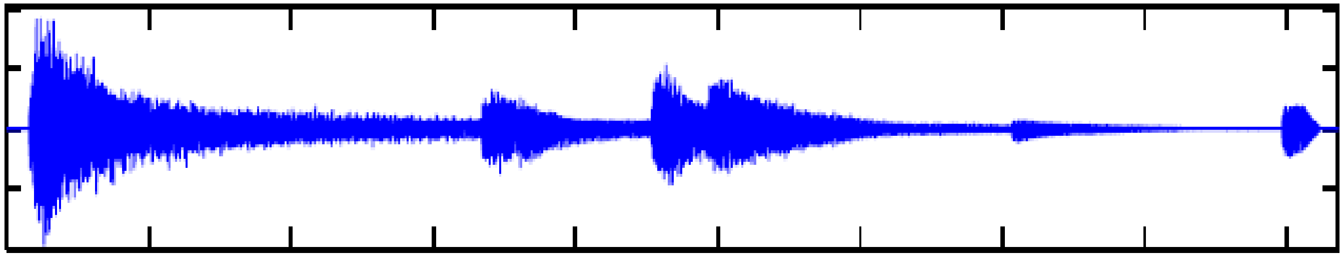
Music Synchronization: Image-Audio

Music Synchronization: Image-Audio

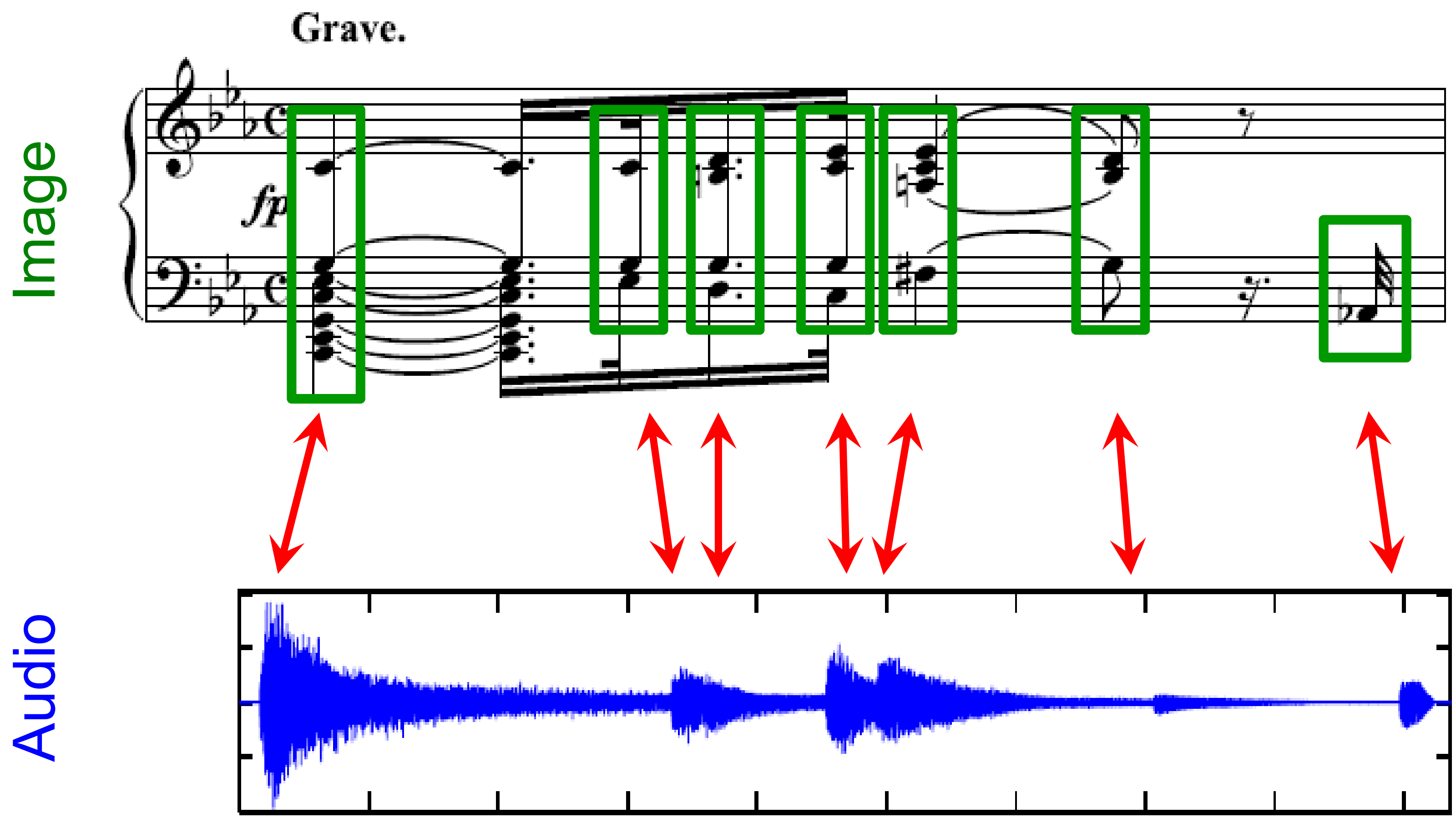
Image



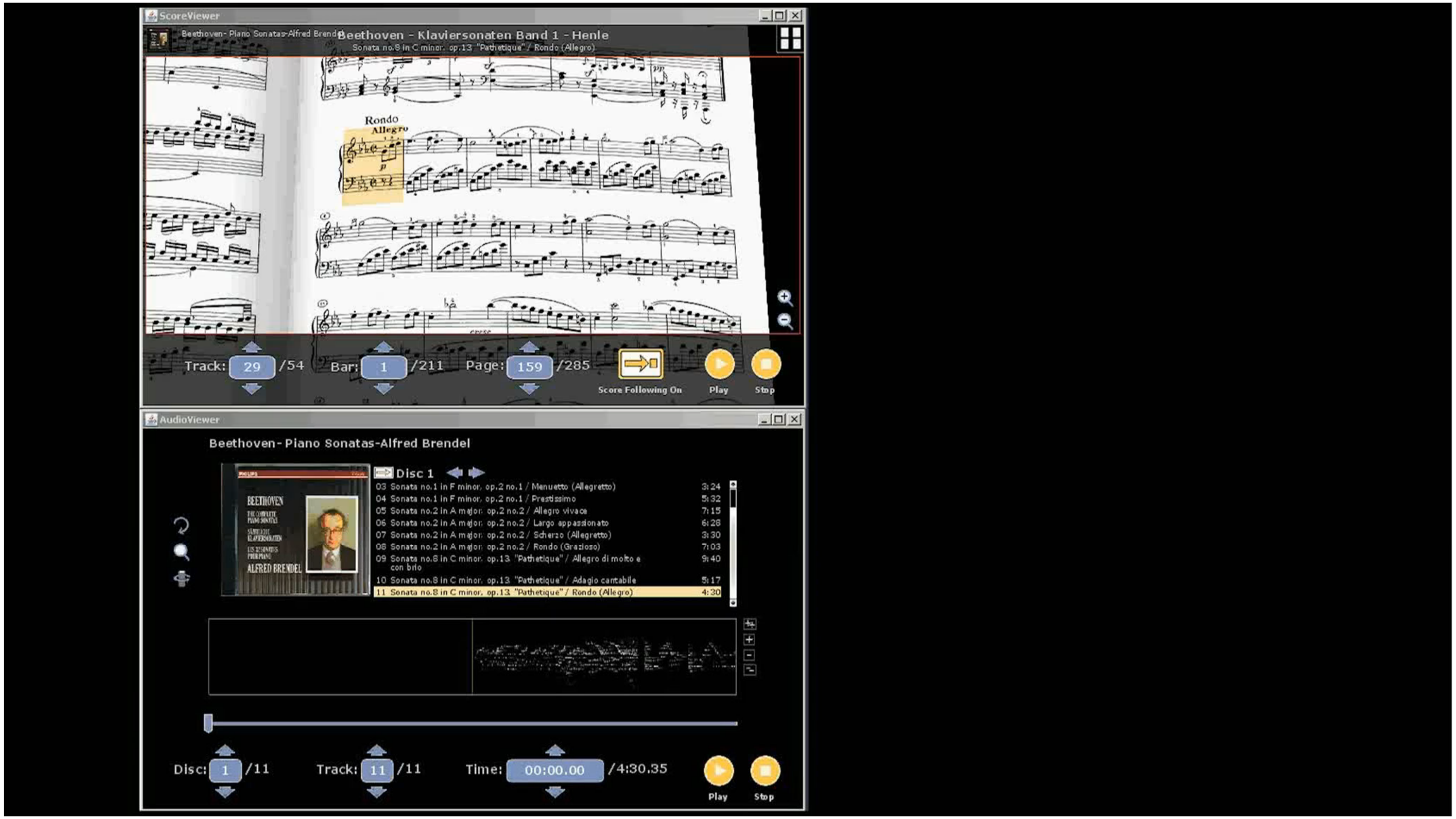
Audio



Music Synchronization: Image-Audio



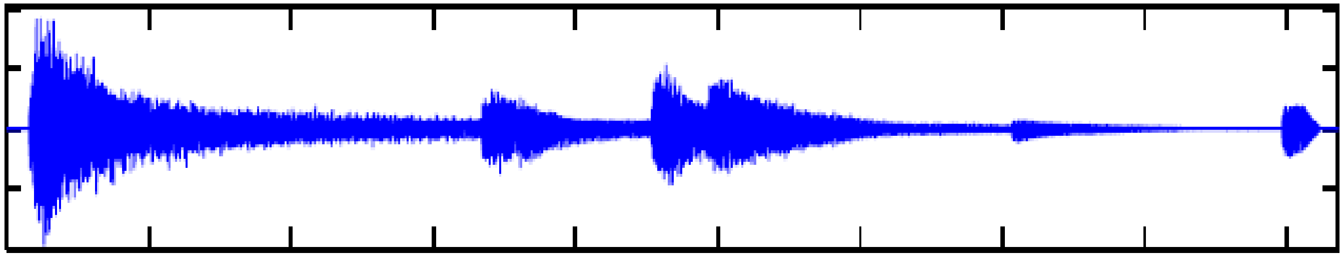
Application: Score Viewer



Music Synchronization: Image-Audio

Image

Audio

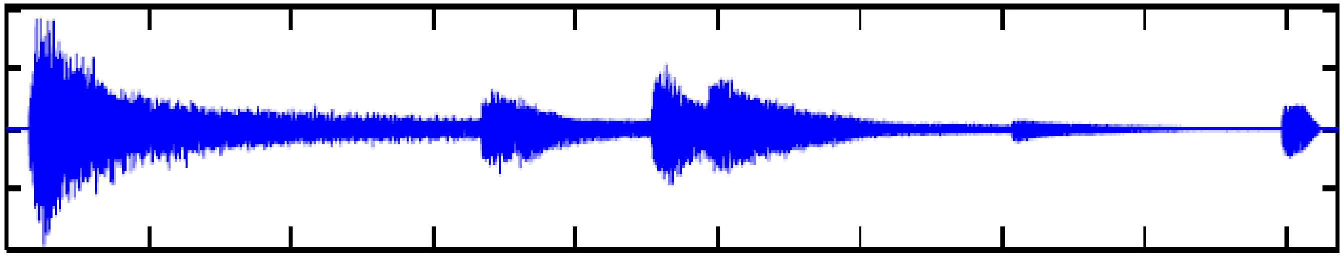


Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition

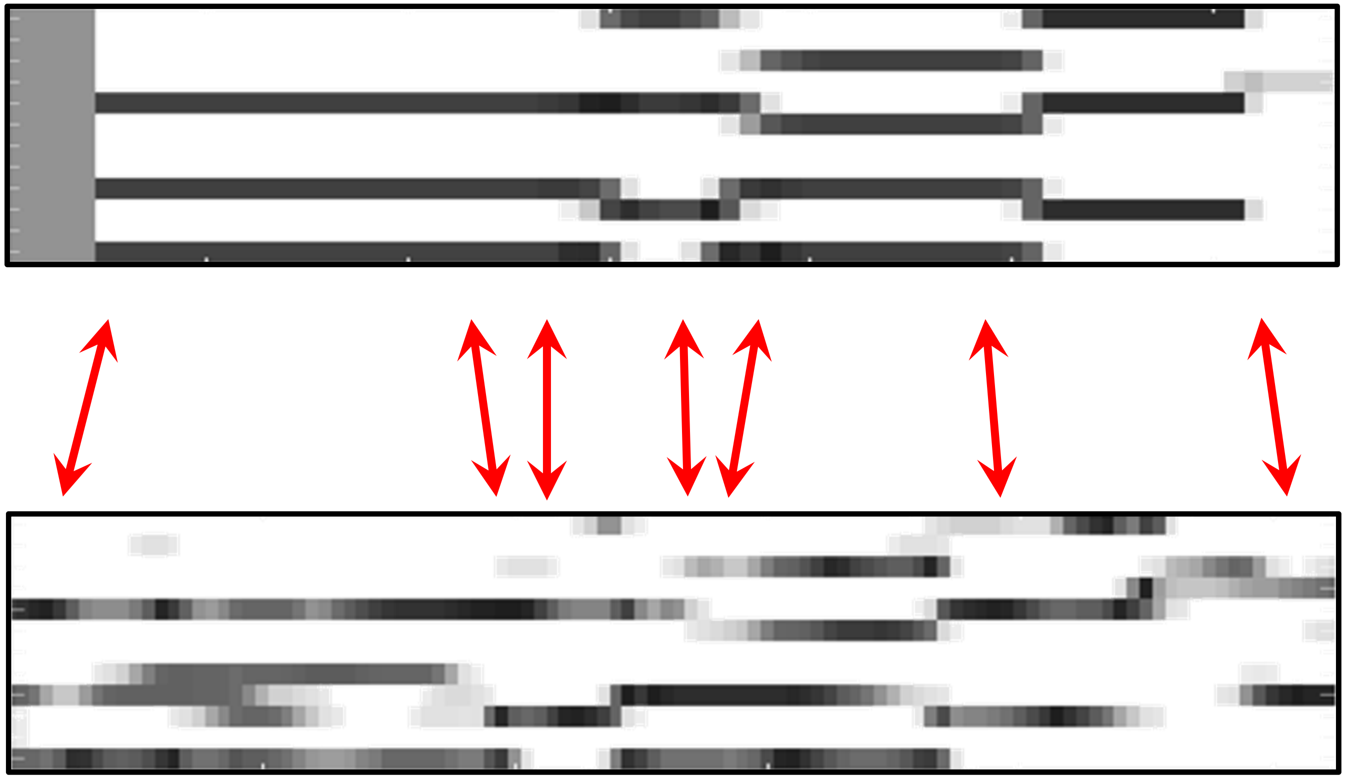
Image

Audio



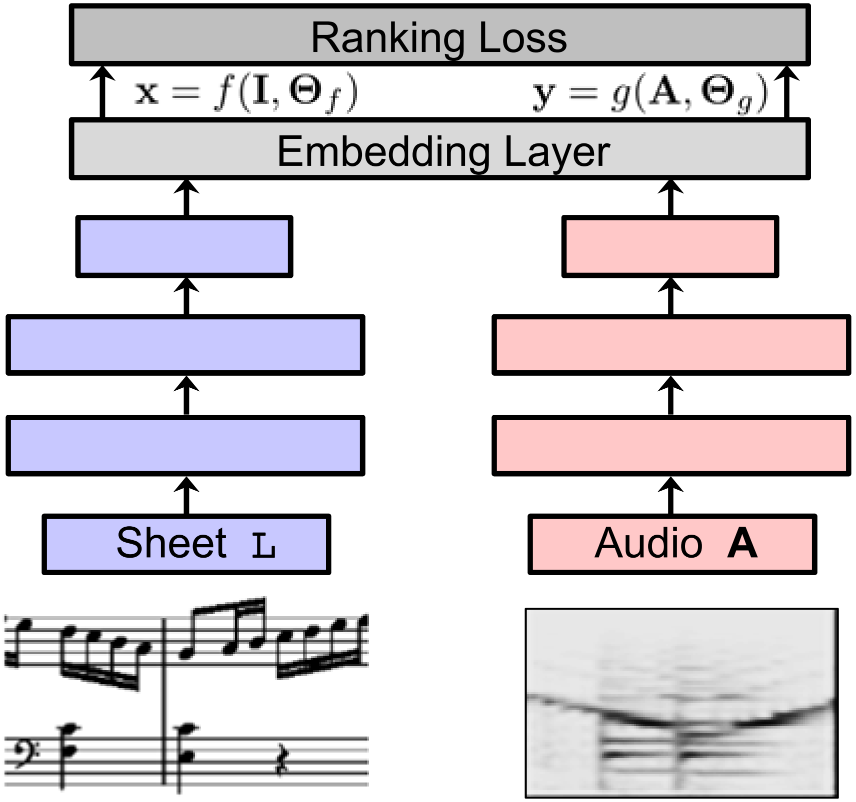
Music Synchronization: Image-Audio

Image Processing: Optical Music Recognition



Audio Processing: Fourier Analysis

Music Synchronization: Image-Audio



- Representation learning
- Embedding techniques
- Weak annotations
- Loss functions
- …

Cross-Modal Retrieval
Dorfer et al.: End-to-End Cross-Modality Retrieval with CCA Projections and Pairwise Ranking Loss. International Journal of Multimedia Information Retrieval, 2018.

Music Retrieval