Lecture

Music Processing

Chord Recognition

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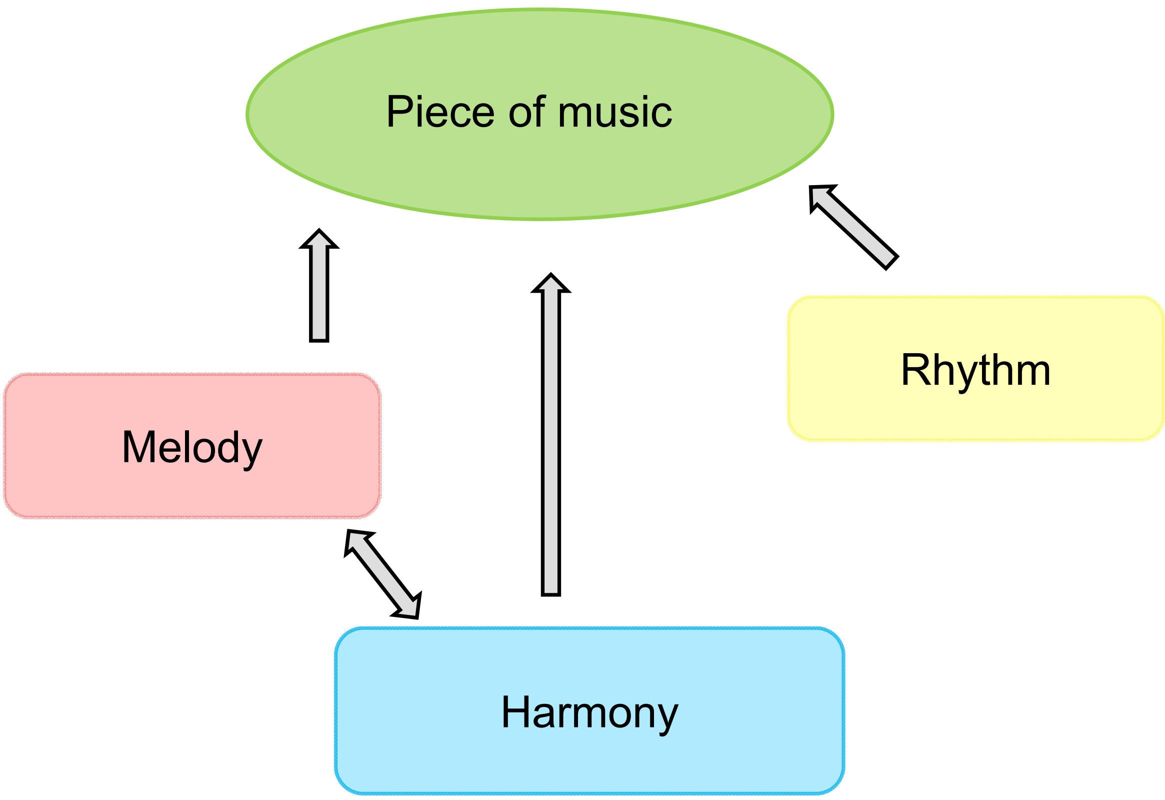
Aspects of Music



Harmony: The Basis of Music

Pachelbel's Canon

Coversong *Die Eine* (*Die Firma*)

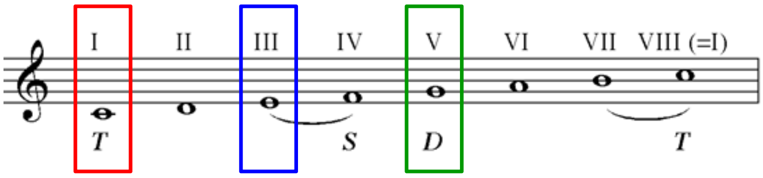
Musical Chords

- Combination of three or more tones which sound simultaneously
- Chord classes
  - Triads including major, minor, diminished, augmented chords
  - Many other more complex chords such as seventh chords
- Here: focus on major and minor triads

Musical Chords

The C **major** chord

Derived from the C **major** scale

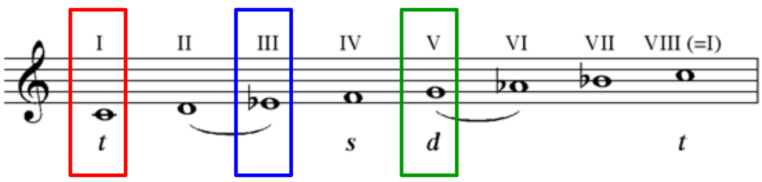


C ---- the root
E ---- the (**major**) third
G ---- the fifth

Musical Chords

The C **minor** chord

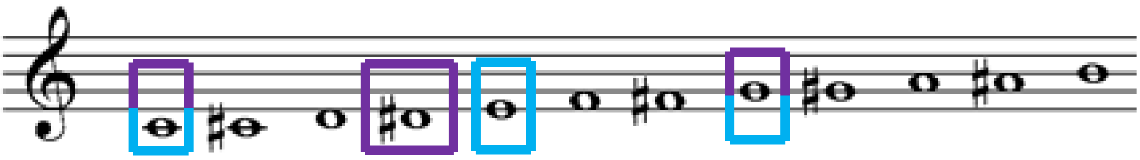
Derived from the C **minor** scale



C ---- the root
Eb ---- the (**minor**) third
G ---- the fifth

Musical Chords

Structure of the 24 major/minor chords



	0	1	2	3	4	5	6	7	8	9	10	11
	C	C#	D	D#	E	F	F#	G	G#	A	A#	B
C major	✓				✓			✓				
C minor	✓			✓				✓				

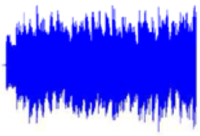
Chord Recognition

- Development of automatic methods for the harmonic analysis of audio data

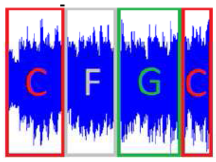
- Applications in the field of music information retrieval:
  - music segmentation
  - cover song identification
  - audio matching
  - music structure analysis
  - …

Chord Recognition

Signal



Result

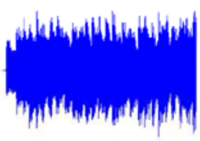


Segmentation 

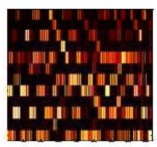
Chord label assignment C F G C

Chord Recognition

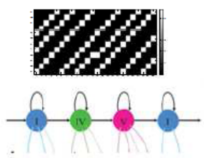
Signal



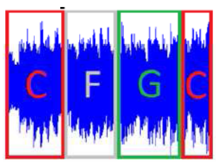
Feature Extraction



Classification



Result



Chroma features

- Type
- Resolution
- Compression
- Smoothing

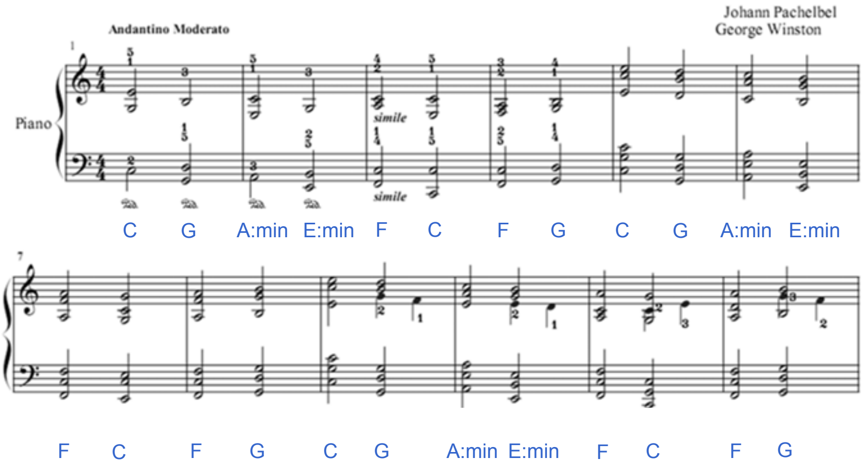
Pattern matching

- Template
- Gaussian
- Hidden Markov Models
- Graphical Models

Chord Recognition

Given: Audio file

Output: Segmentation and chord labeling



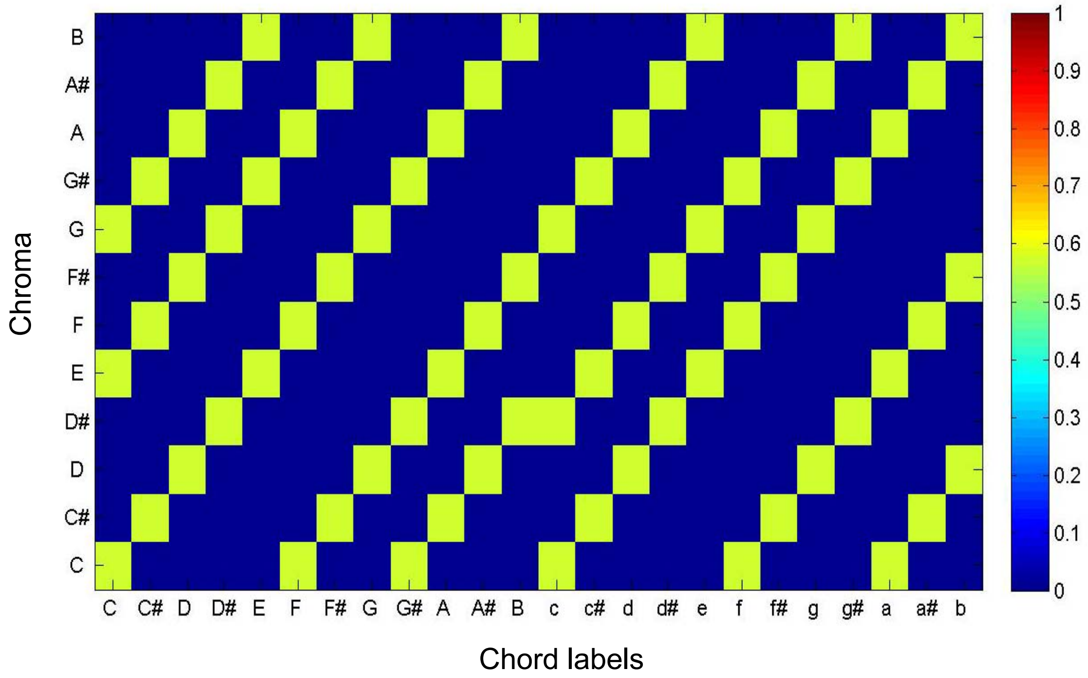
Baseline Method for Chord Recognition

Chord templates 24 major/minor chords

	C major	C# major	D major	D# major	……	C minor	C# minor	……
B	0	0	0	0	……	0	0	……
A#	0	0	0	1	……	0	0	……
A	0	0	1	0	……	0	0	……
G#	0	1	0	0	……	0	1	……
G	1	0	0	1	……	1	0	……
F#	0	0	1	0	……	0	0	……
F	0	1	0	0	……	0	0	……
E	1	0	0	0	……	0	1	……
D#	0	0	0	1	……	1	0	……
D	0	0	1	0	……	0	0	……
C#	0	1	0	0	……	0	1	……
C	1	0	0	0	……	1	0	……

Baseline Method for Chord Recognition

Chord templates 24 major/minor chords



Baseline Method for Chord Recognition

24 chord templates
(12 major, 12 minor)

Chroma feature
extraction (framewise)

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Compute for each frame the distance of
the feature vector to the 24 templates

Baseline Method for Chord Recognition

24 chord templates
(12 major, 12 minor)

Chroma feature
extraction (framewise)

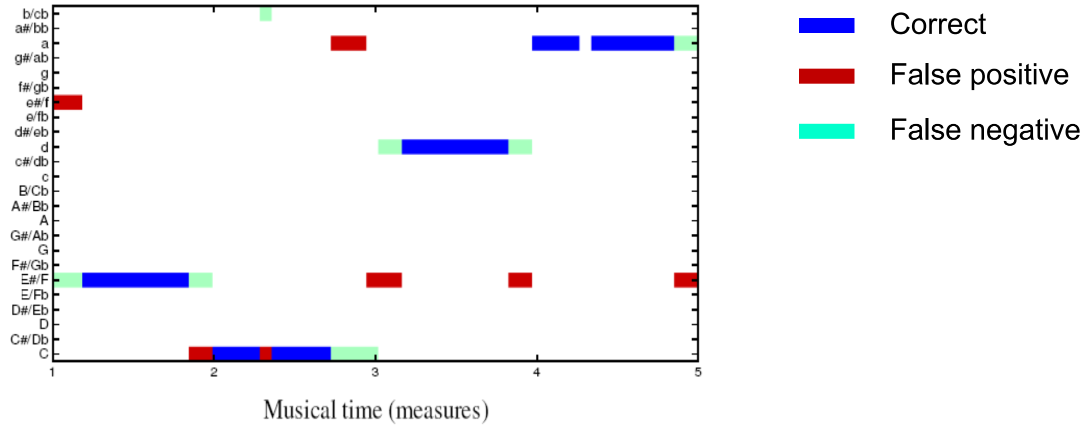
Compute for each frame the distance of
the feature vector to the 24 templates

Selected chord according to template with
minimal distance to respective feature vector

Problems in Chord Recognition

Problem: Transitions between subsequent chord

Example: Chopin Mazurka Op. 68 No.3

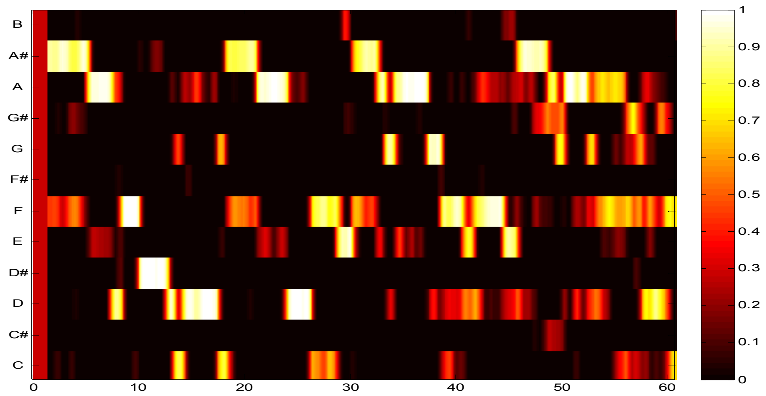


Problems in Chord Recognition

Problem: Monphonic musical passages

Example: Excerpt of Wagner's Meistersinger

Chromagram



Problems in Chord Recognition

Problem: Frame-wise chord analysis may not be meaningful

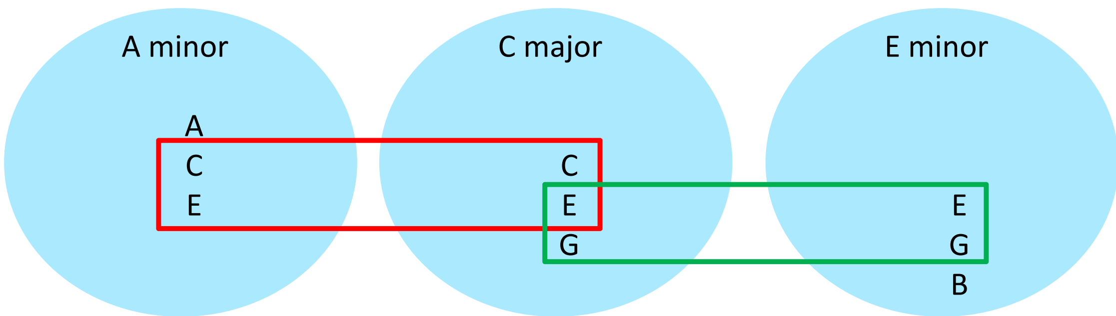
Example: Bach: Prelude C major, BWV 846

Problem: Broken chords

→ Measure-wise chord analysis necessary

Problems in Chord Recognition

Problem: Ambiguity of chords



Problems in Chord Recognition

Problem: Reduction to the 24 major/minor chords makes the recognition of more complex chords difficult/impossible!

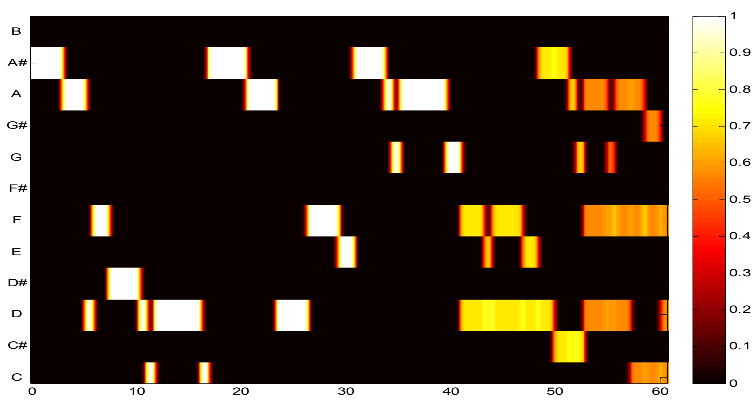
Example: Prelude C major, BWV 846, mm.19-25

Problems in Chord Recognition

Problem: Tuning problems

Example: Excerpt of Wagner's Meistersinger

Chromagram (from MIDI)

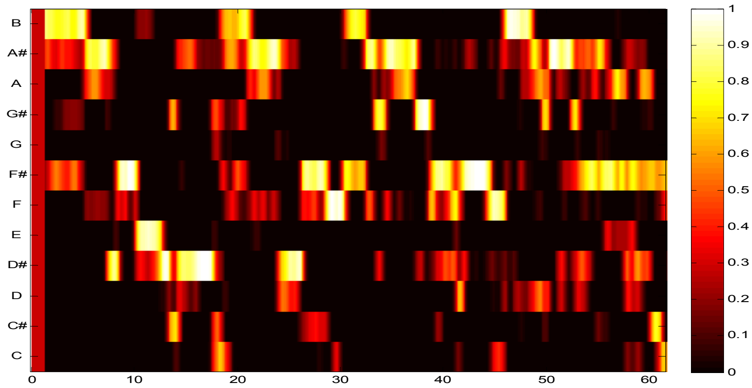


Problems in Chord Recognition

Problem: Tuning problems

Example: Excerpt of Wagner’s Meistersinger

Chromagram (from MIDI)



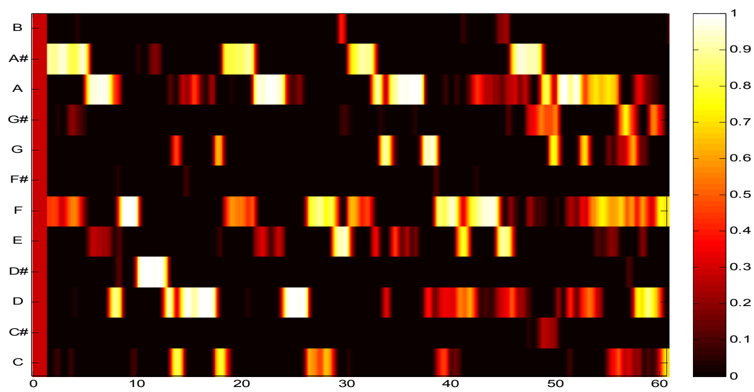
Problem:
Audio is tuned more than half a semi-tone upwards

Problems in Chord Recognition

Problem: Tuning problems

Example: Excerpt of Wagner’s Meistersinger

Chromagram (from MIDI)



Problem:
Audio is tuned more than half a semi-tone upwards

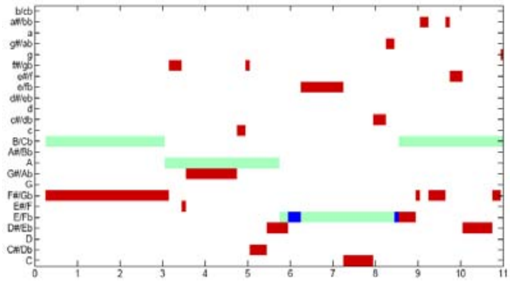
Solution:
Adjust frequency binning when computing pitch features.

Problems in Chord Recognition

Problem: Tuning problems

Example: The Beatles “Lovely Rita”

Without tuning

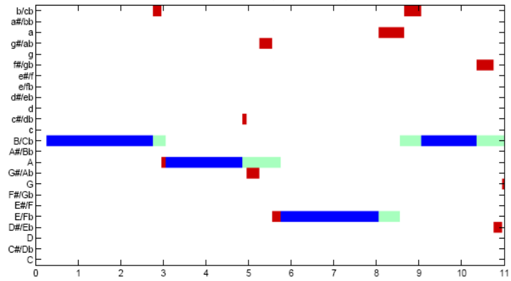


Correct

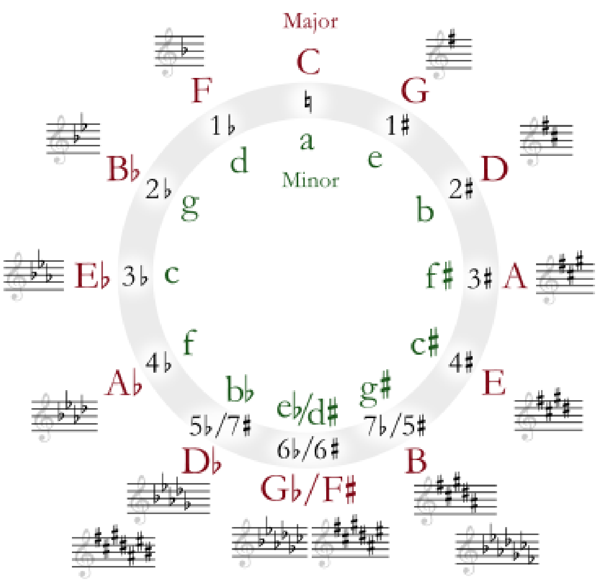
False positive

False negative

With tuning

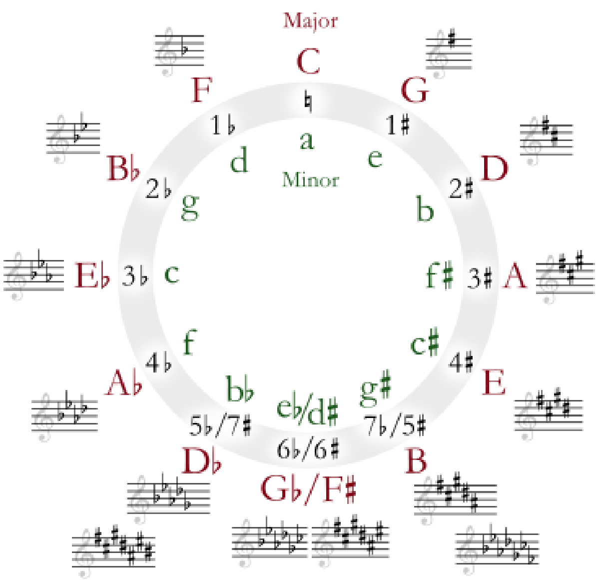


Key Relations: Circle of Fifths



From http://en.wikipedia.org/wiki/Circle_of_fifths

Key Relations: Circle of Fifths



Observation:
For tonality reasons, some chord progressions are more likely than others.

Idea:
Usage of Hidden Markov Models (HMMs) to model chord dependencies

From http://en.wikipedia.org/wiki/Circle_of_fifths

Markov Models

Description of certain stochastic processes

Andrei Markov (Wikipedia)

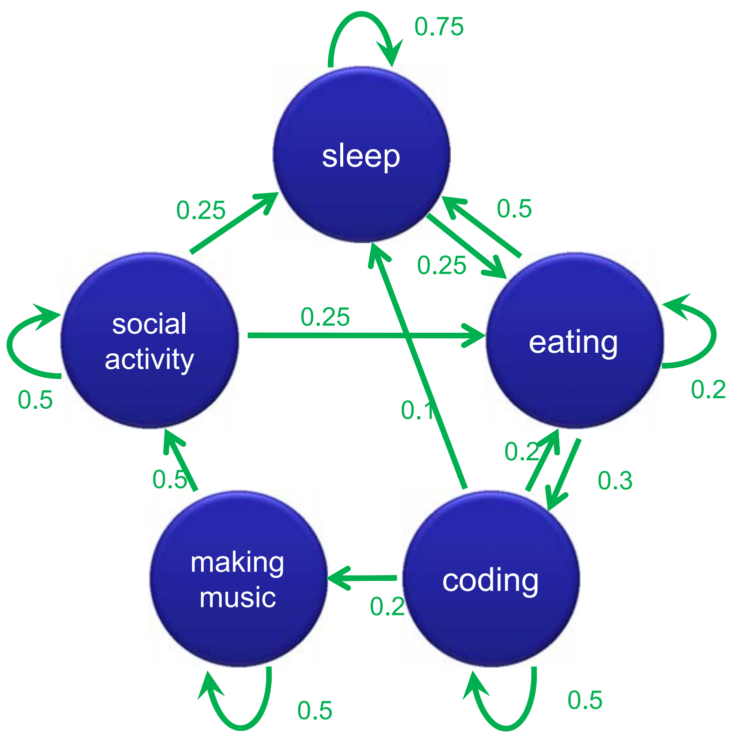
Markov Models

Description of certain stochastic processes

Andrei Markov (Wikipedia)

- Processes over discrete time
- Sequence of random variables $X_1, X_2, \ldots$
- Process has to follow Markov property:
  - no “memory”, only current state “known”
  - “ future ” depends only on “present”, not on “past”
  - $P(X_{n+1} = x \mid X_n = y) = P(X_{n+1} = x \mid X_n = y, X_{n-1} = y_2, \ldots)$

Hidden Markov Models



G = (S,E,P)

S: States

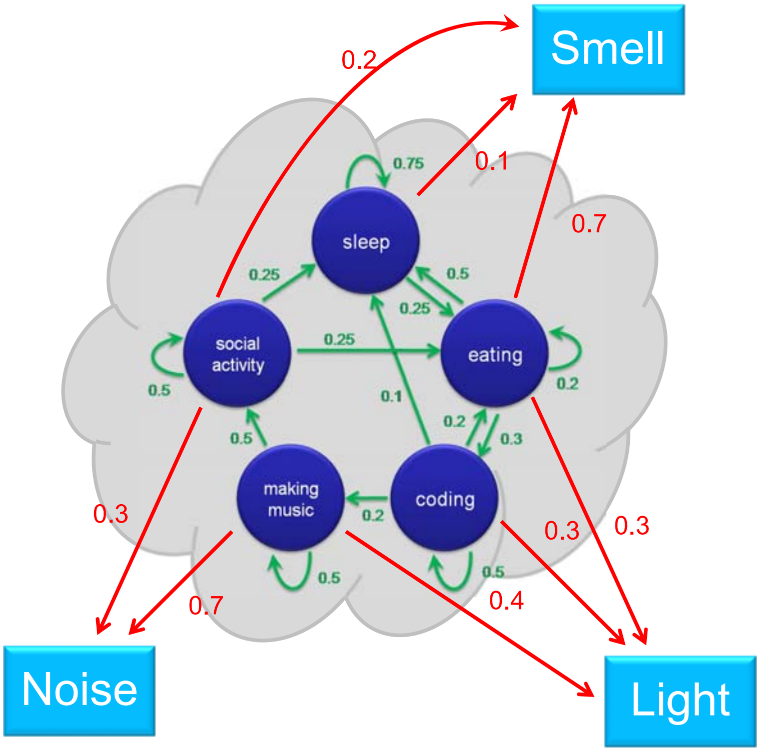
E: Transitions

P: Transition probabilities

Note: For each state, the sum of outgoing transition probabilities is equal to one.

[Radu Curticapean]

Hidden Markov Models



G = (S,P,V,B)

S: States

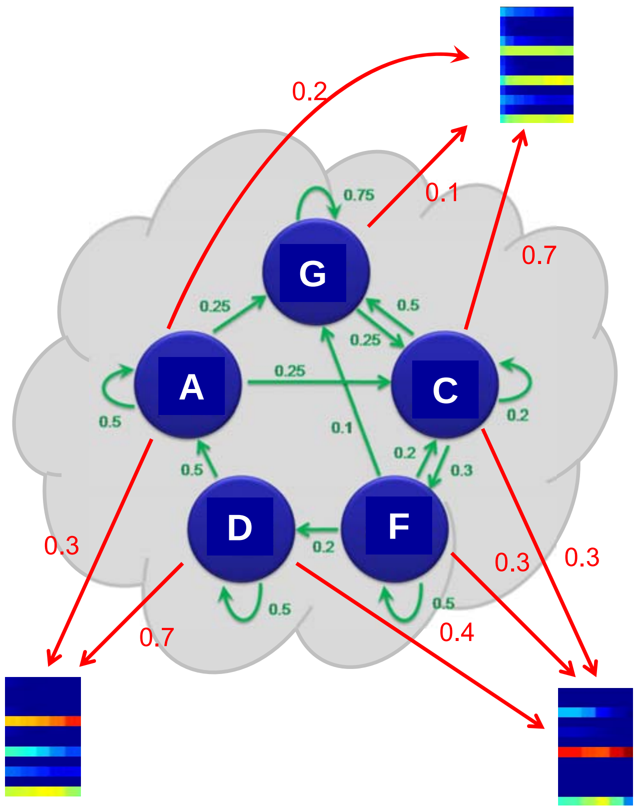
P: Transition probabilities

V: Observations

B: Emission probabilities

[Radu Curticapean]

Hidden Markov Models



G = (S,P,V,B)

S: States

P: Transition probabilities

V: Observations

B: Emission probabilities

Hidden Markov Models

G = (S,P,V,B)

24 major/minor chords — S: States

Probabilities for having a transition from one chord to another chord — P: Transition probabilities

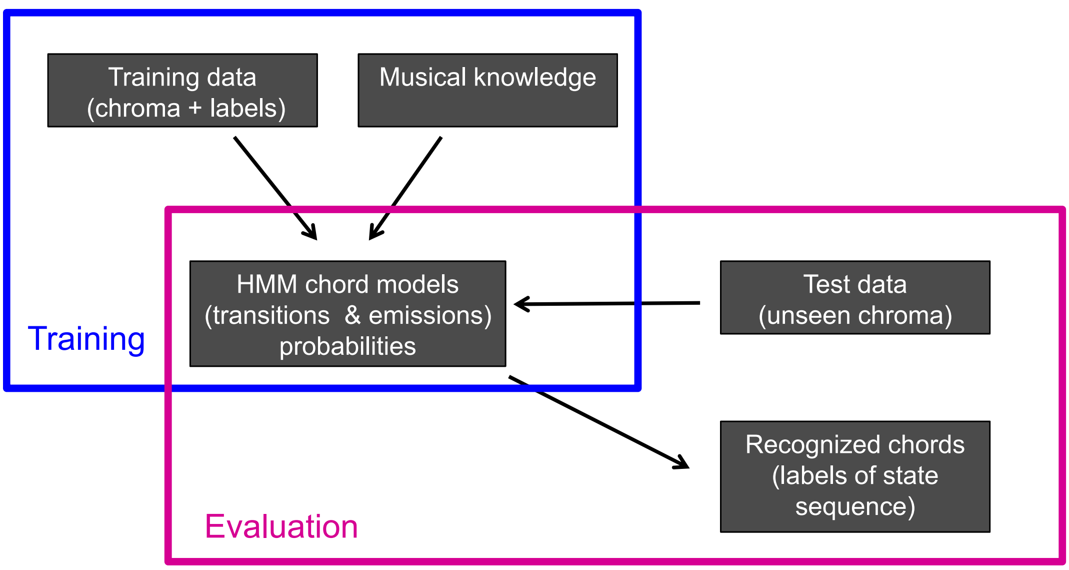
Chroma vectors — V: Observations

Probability for a chord model to produce a chorma distribution — B: Emission probabilities

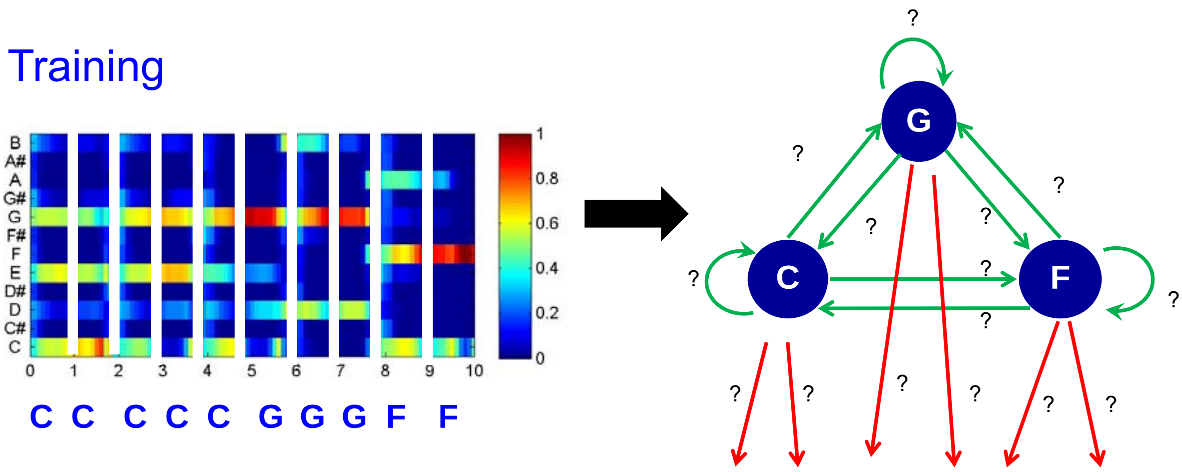
Hidden Markov Models

Two computational problems

1. Training: learn model parameters (Baum-Welch Algorithm)
2. Evaluation: find optimal state sequence (Viterbi Algorithm)



Training

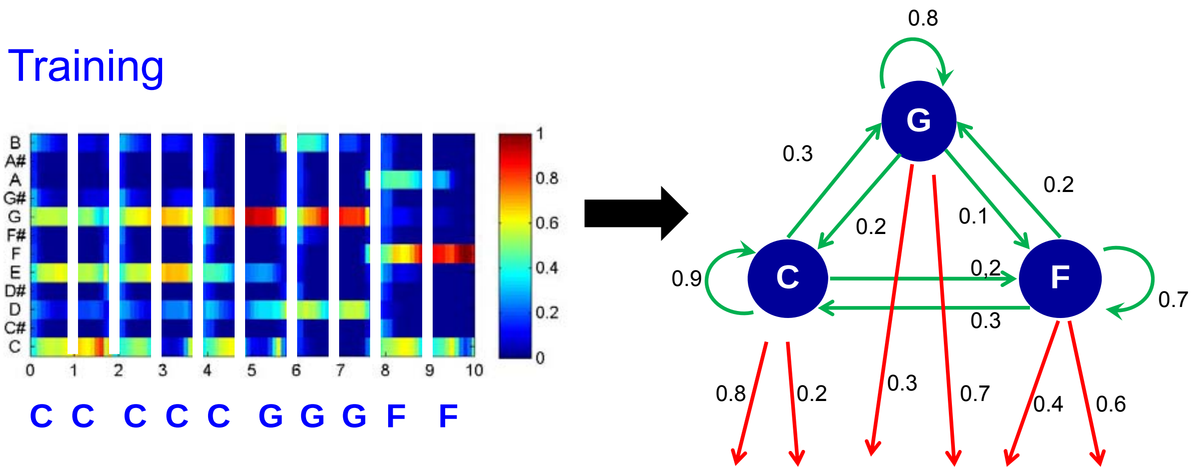


C C C C C G G G F F

Input:
Sequence of features (observations)
Corresponding ground truth chord labels

Output:
Emission probabilities
Transition probabilities

Training



C C C C C G G G F F

Input:
Sequence of features (observations)
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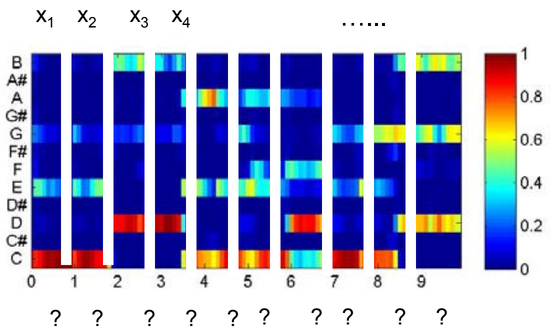
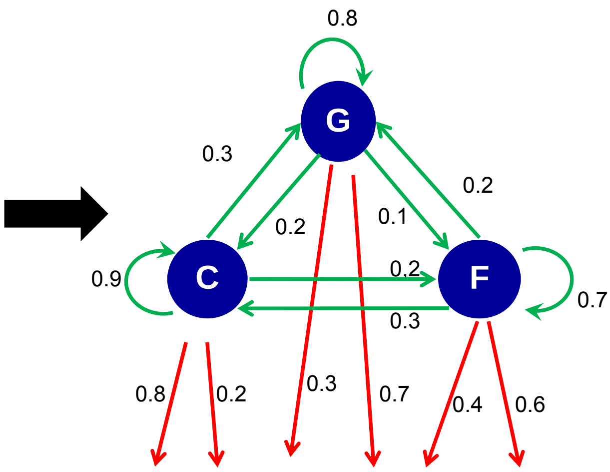
Output:
Emission probabilities
Transition probabilities

Hidden Markov Models

Evaluation



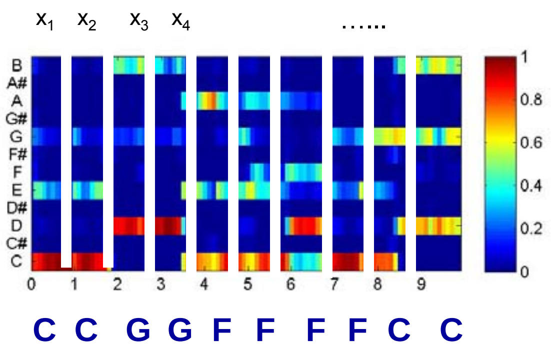


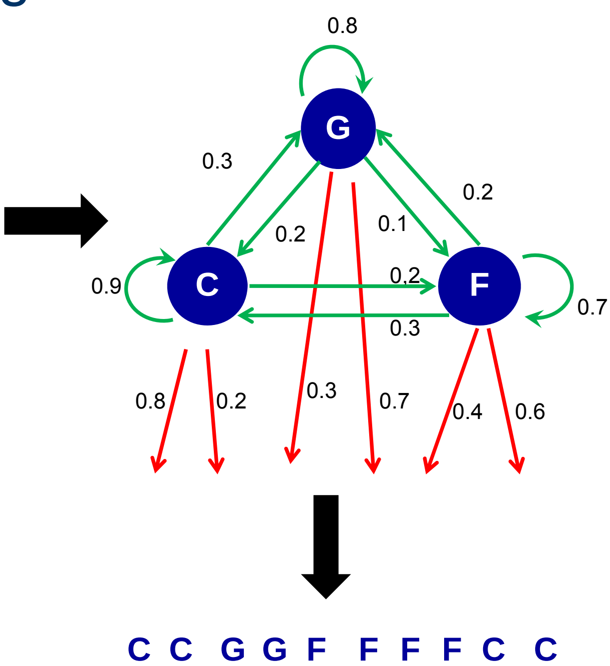
Input:
Sequence of features
Emission probabilities
Transition probabilities

Output:
Optimal state sequence (estimated chord progression)

Hidden Markov Models

Evaluation





Input:
Sequence of features
Emission probabilities
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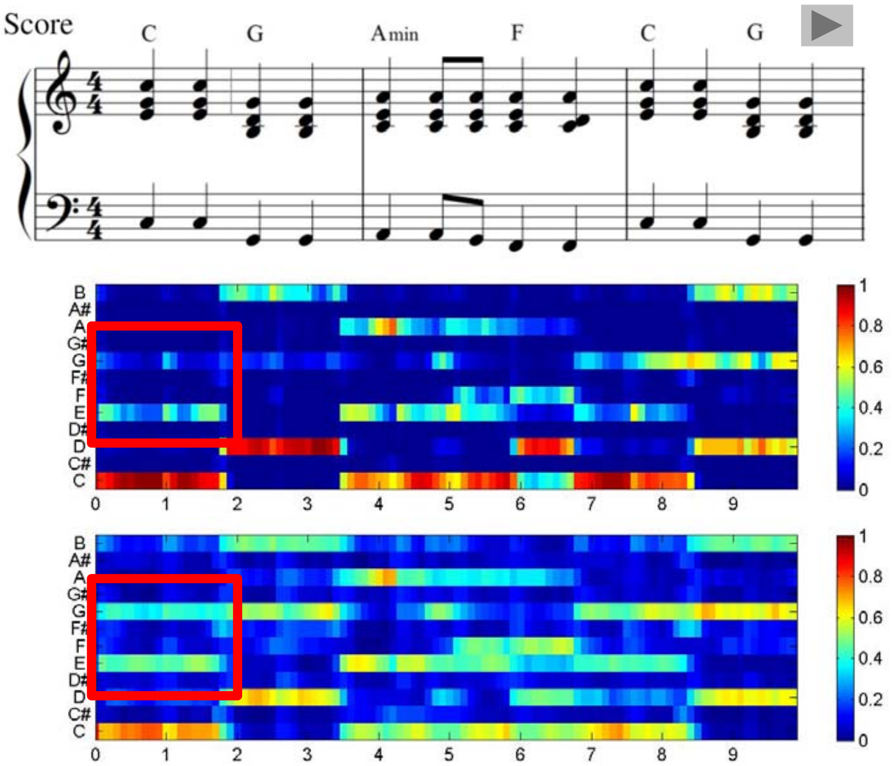
Optimal state sequence (estimated chord progression)

Importance of Chroma Feature Variant



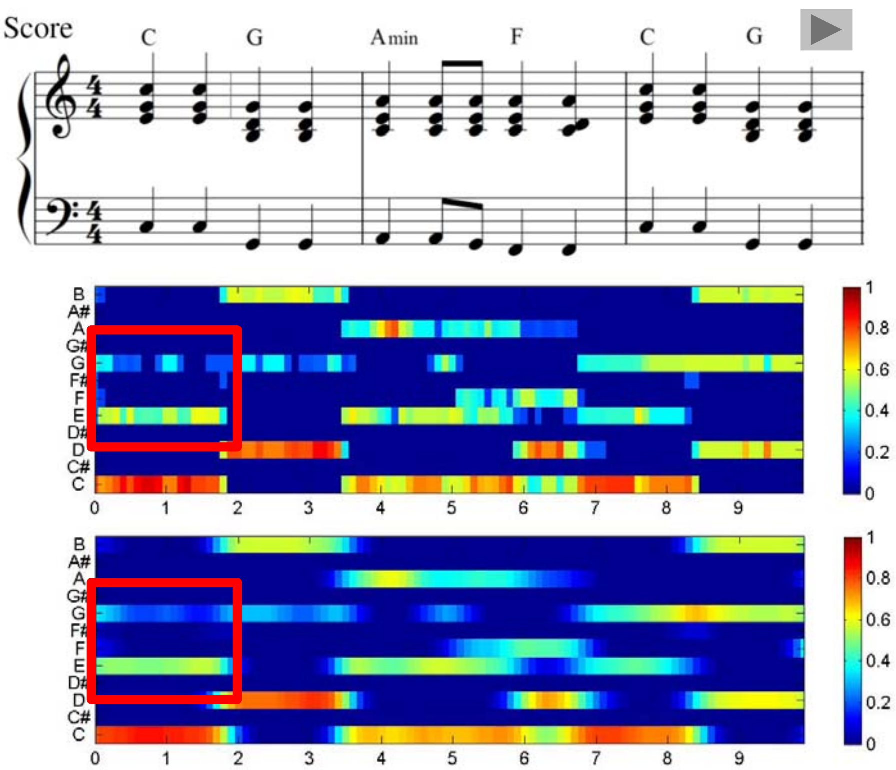
CP

Normalized chromagram

CLP

Logarithmic compression

Importance of Chroma Feature Variant



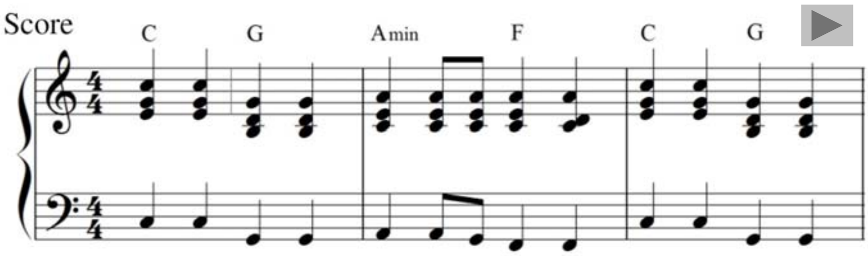
CENS[1]

Quantized chromagram

CENS[11]

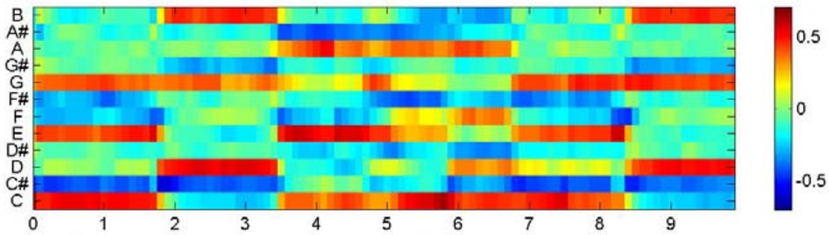
Temporal smoothing

Importance of Chroma Feature Variant



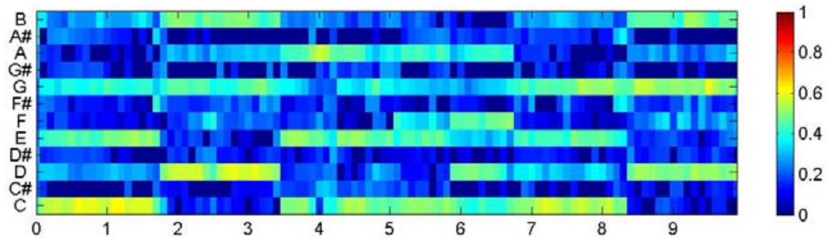
CRP

Boosting timbre invariance



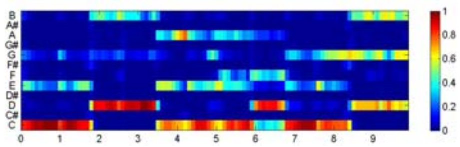
CISP

Instantaneous frequency

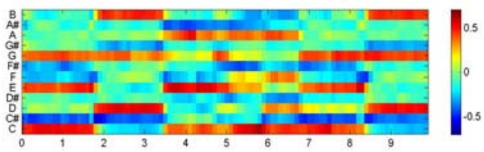


Importance of Chroma Feature Variant

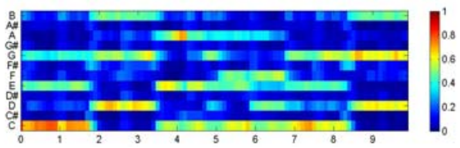
CP



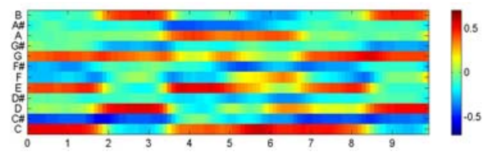
CRP[1]



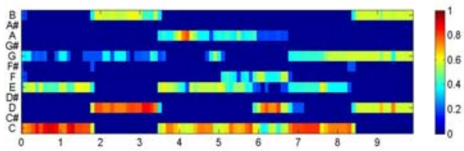
CLP



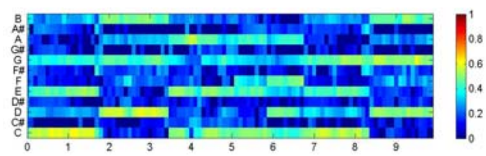
CRP[11]



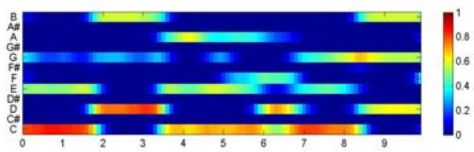
CENS[1]



CISP



CENS[11]



And many more chroma variants!

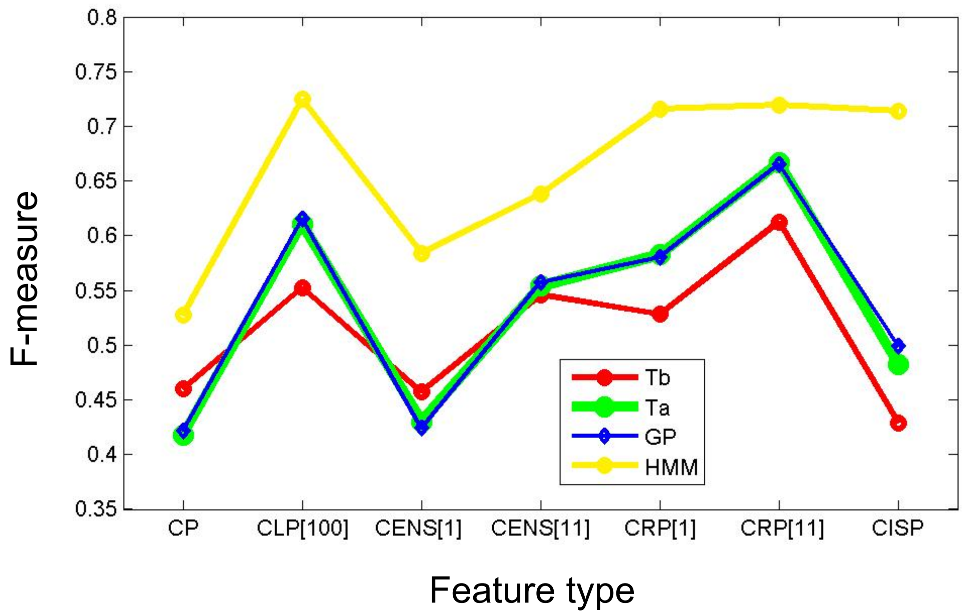
Importance of Chroma Feature Variant

Experiment

- Beatles dataset
- Three-fold cross validation
- Measurement: F-measure
- Framewise evaluation, each frame = 100 ms
- 12 major and 12 minor triads

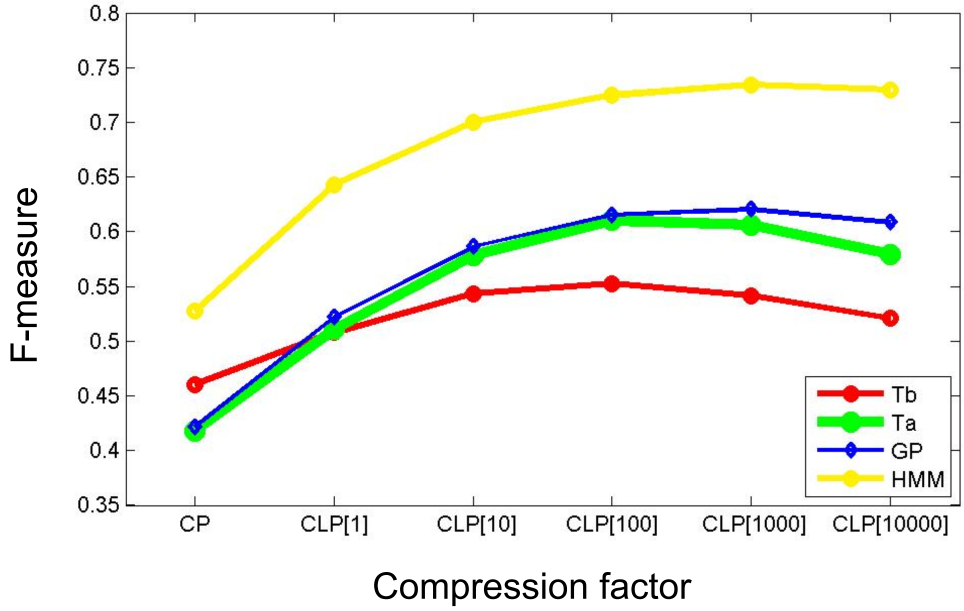
Importance of Chroma Feature Variant

Dependency on feature type



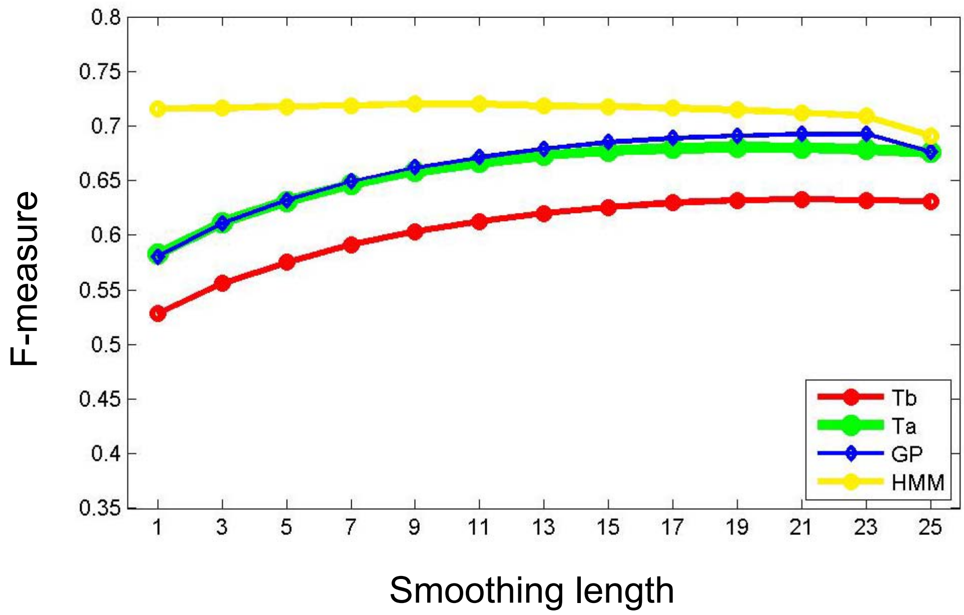
Importance of Chroma Feature Variant

Dependency on logarithmic compression

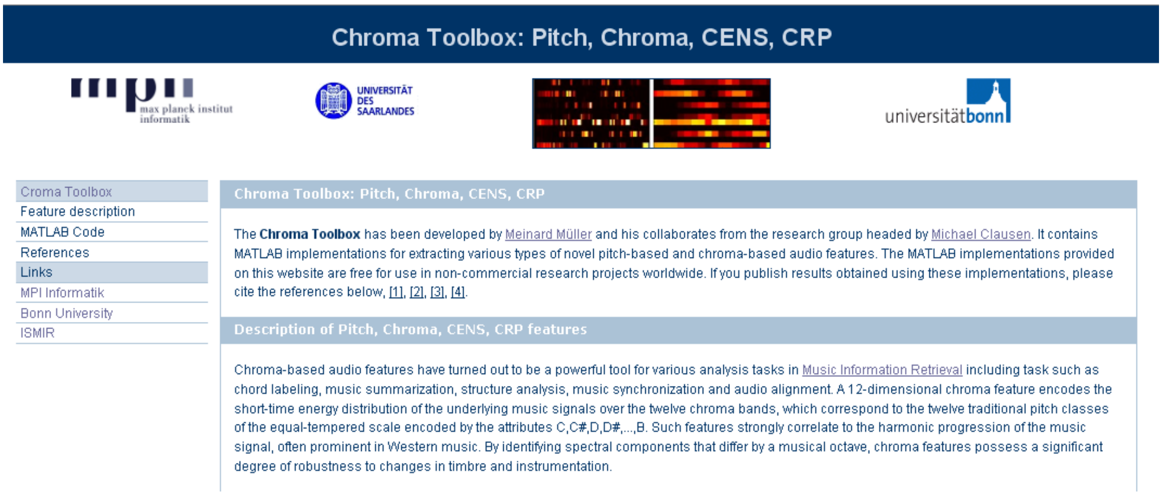


Importance of Chroma Feature Variant

Dependency on smoothing (using CRP features)



Chroma Toolbox



- Freely available Matlab toolbox
- Feature types: Pitch, Chroma, CENS, CRP
- http://www.mpi-inf.mpg.de/resources/MIR/chromatoolbox/

Cross-Version Analysis

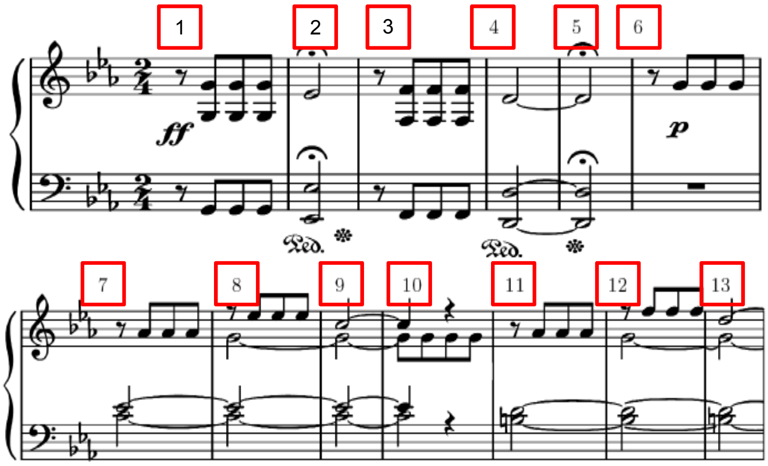
General Procedure

- Conduct analysis for multiple versions of the same object
- Relate the versions (using a reference)
- Compare analysis results accross different versions
- Look for consistencies and inconsistencies

Harmonic analysis
Different music recordings
Same piece of music

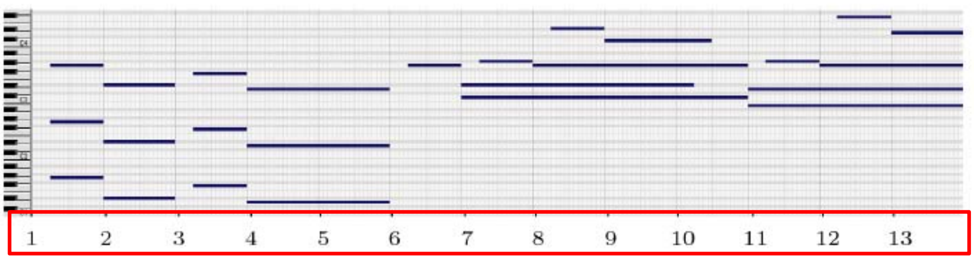
Music synchronization
Musical score

Barwise Synchronization



Barwise Synchronization

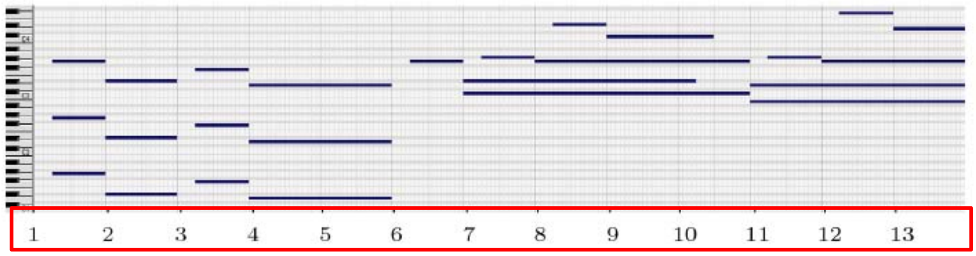
MIDI representation with bar information



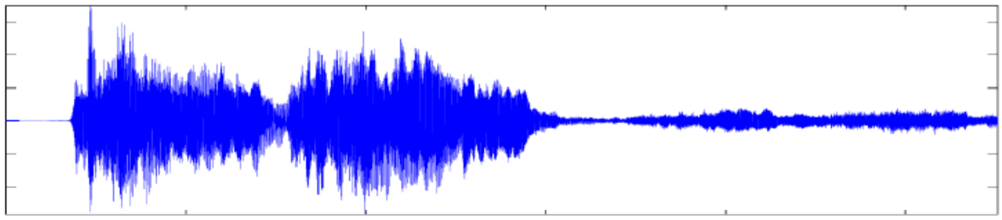
Time (bars)

Barwise Synchronization

MIDI representation with bar information



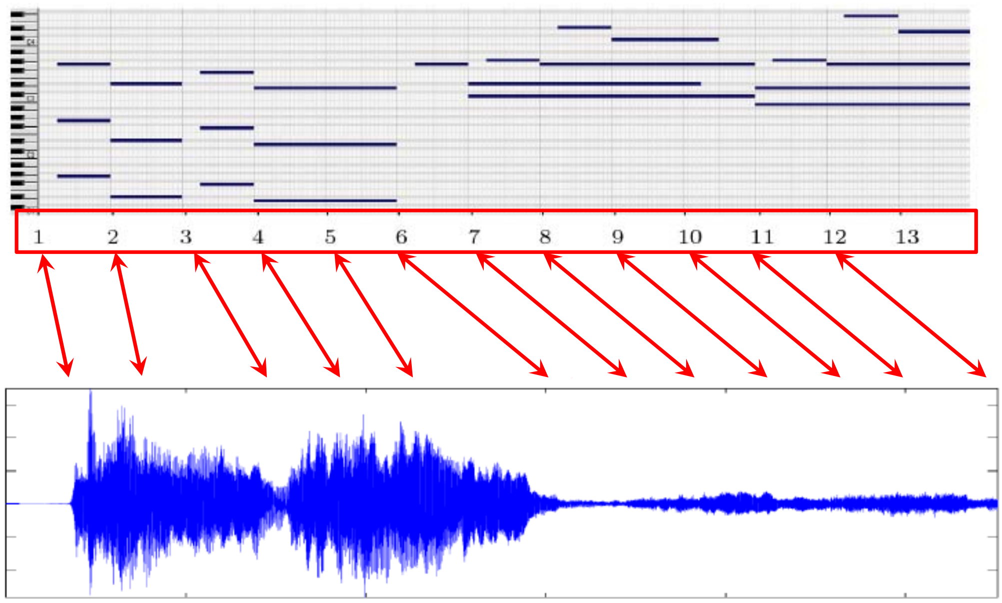
Time (bars)



Time (seconds)

Barwise Synchronization

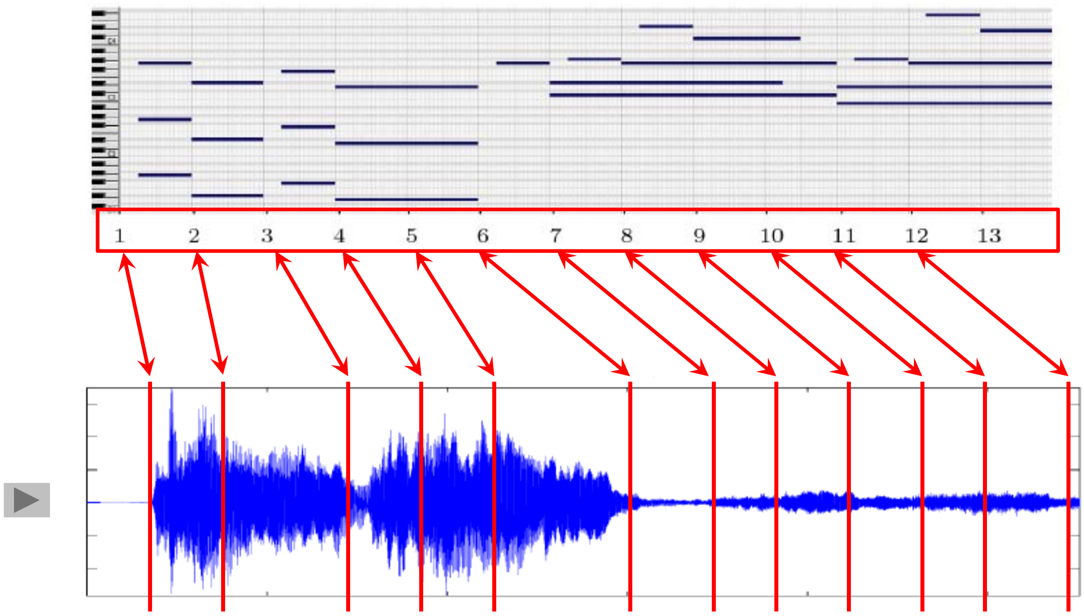
Music synchronization



Time (seconds)

Barwise Synchronization

Transfer bar information to audio domain

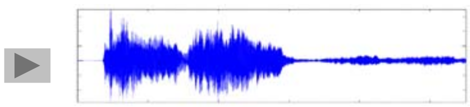


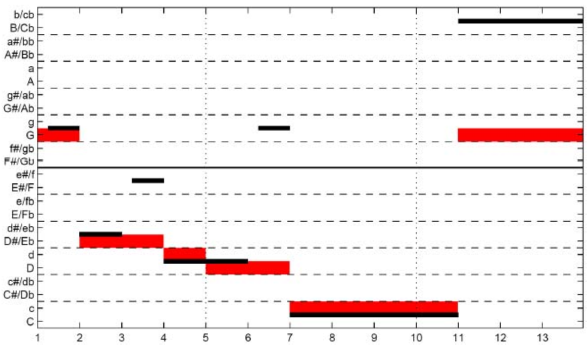
Time (seconds)

Cross-Version Harmonic Analysis

Chord recognition result

Barwise presentation of analysis results is of great benefit!





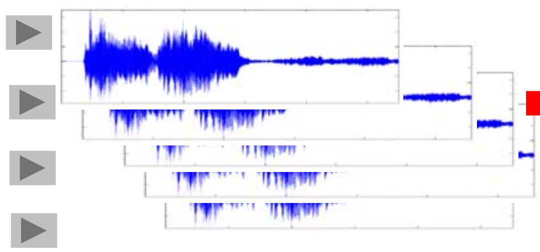
Time (seconds)

Time (bars)

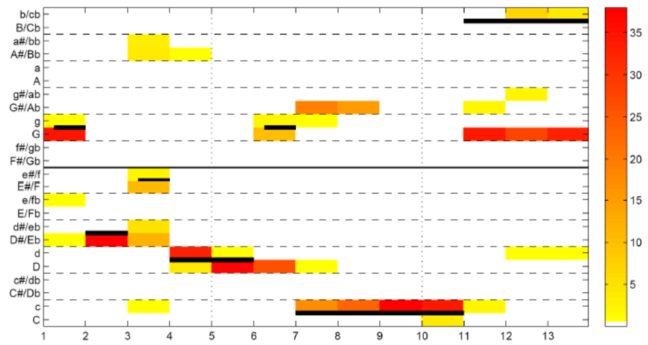
Cross-Version Harmonic Analysis

Chord recognition result

Barwise overlay across
different music recordings



Time (seconds)



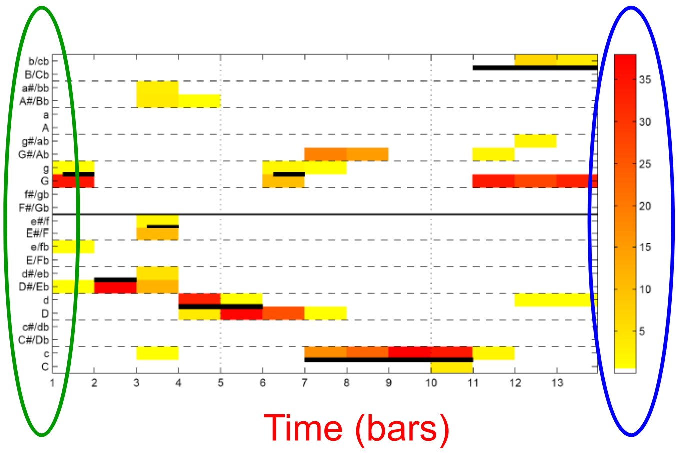
Time (bars)

Cross-Version Harmonic Analysis

Cross-version chord
recognition result

Chord labels

Consistency



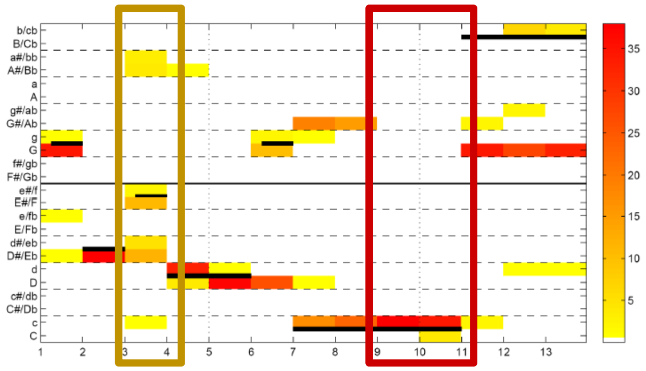
Time (bars)

Cross-Version Harmonic Analysis

Cross-version chord recognition result

Highly consistent:
C-minor

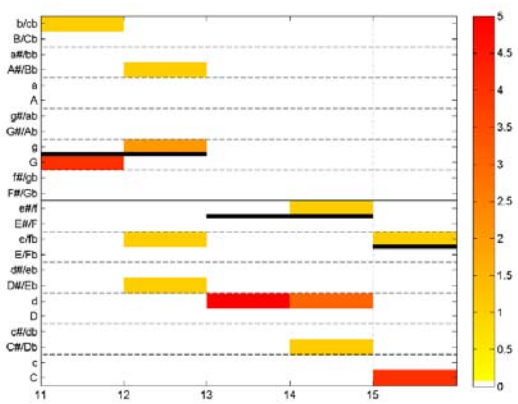
Inconsistent:
F-minor, F-major,
E^{b}-major … ???



Time (bars)

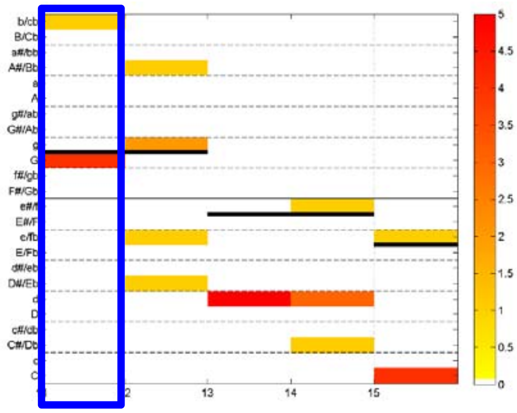
Cross-Version Visualization

Example: Bach's Prelude BWV 846 in C major (bars 11-15)



Cross-Version Visualization

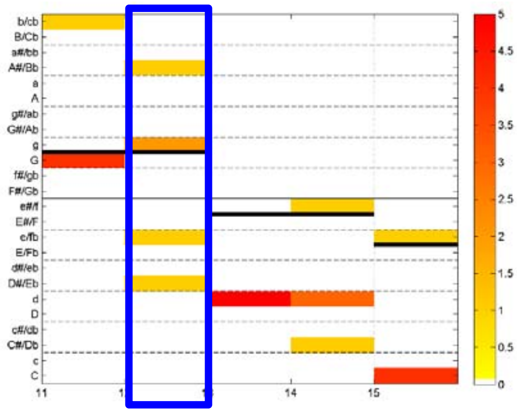
Example: Bach's Prelude BWV 846 in C major (bars 11-15)



Highly consistent: G-major

Cross-Version Visualization

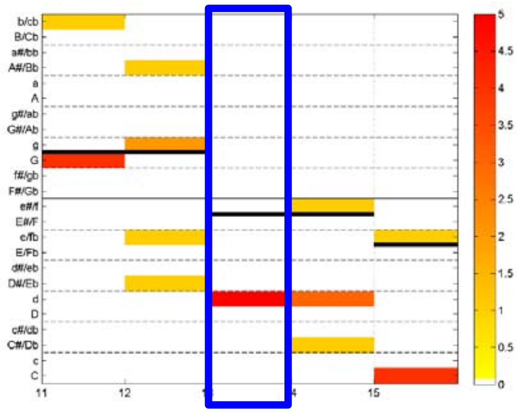
Example: Bach's Prelude BWV 846 in C major (bars 11-15)



Inconsistent!

Cross-Version Visualization

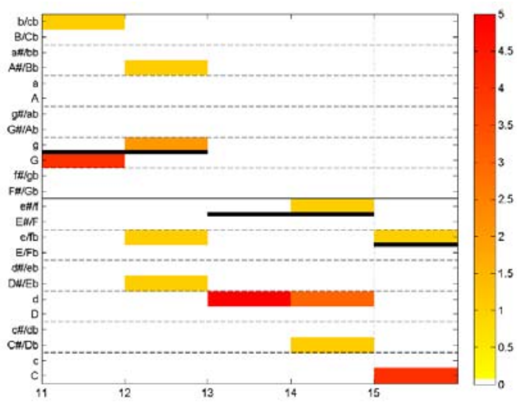
Example: Bach's Prelude BWV 846 in C major (bars 11-15)

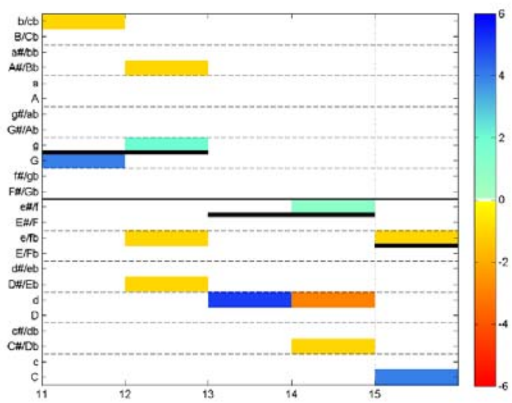


Highly consistent: D-minor

Cross-Version Visualization

Example: Bach's Prelude BWV 846 in C major (bars 11-15)



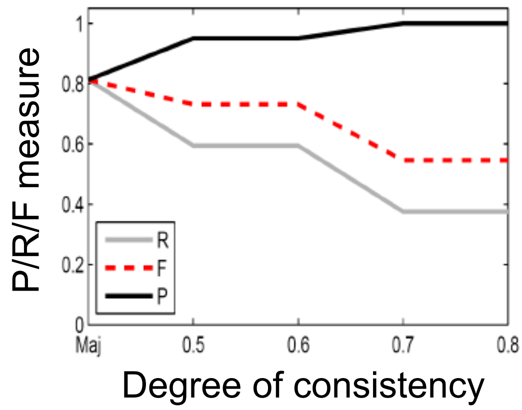


Ground-truth visualization

Convenient tool for manual error analysis and evaluation

Quantitative Evaluation

Example: Bach's Prelude BWV 846



F-measures for
individual recordings:

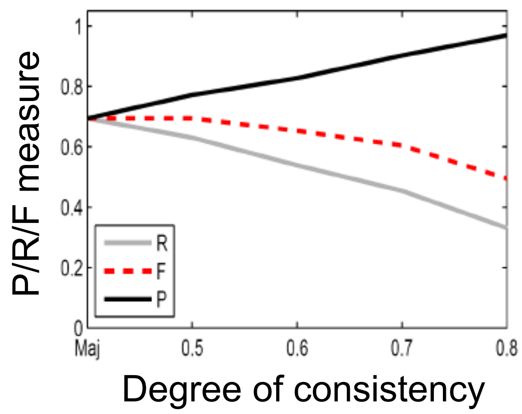
Min: 0.44
Max: 0.87
Mean: 0.70

- Consistent regions tend to be classified correctly
- Precision high
- Recall not too bad

→ Indication of harmonically stable, well-defined tonal centers

Quantitative Evaluation

Example: Beethoven's Fifth



F-measures for
individual recordings:

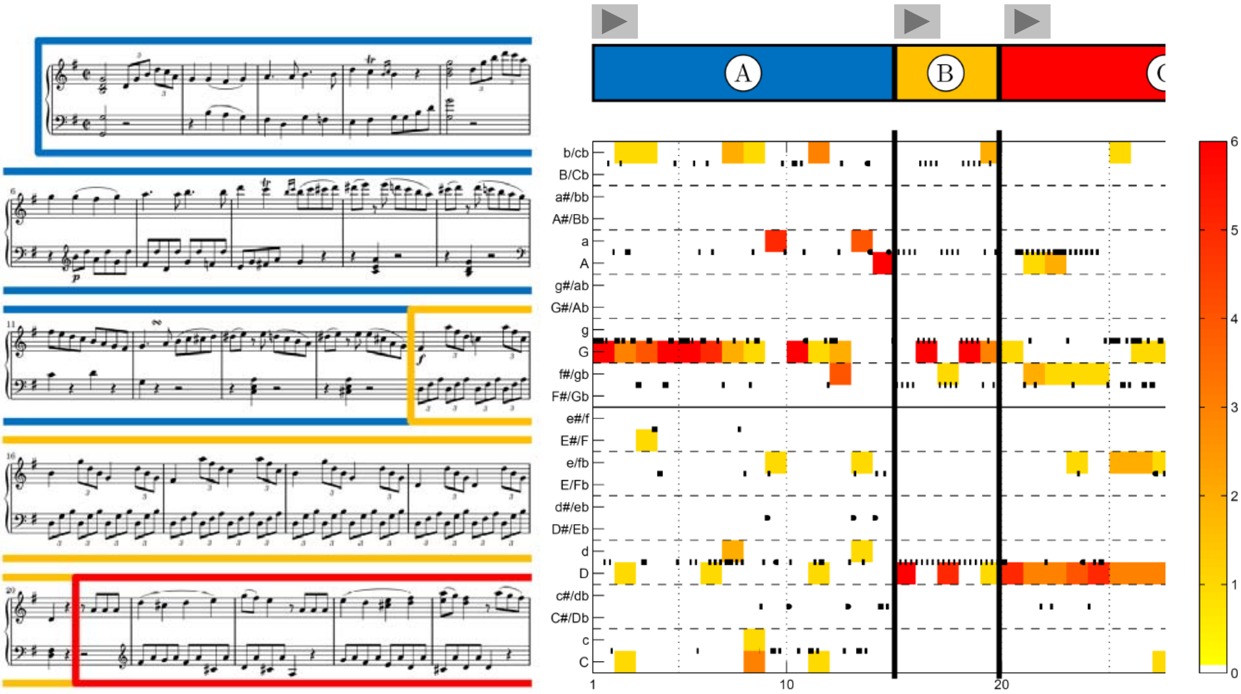
Min: 0.53
Max: 0.83
Mean: 0.60

- Consistent regions tend to be classified correctly
- Precision high
- Recall not too bad

→ Indication of harmonically stable, well-defined tonal centers

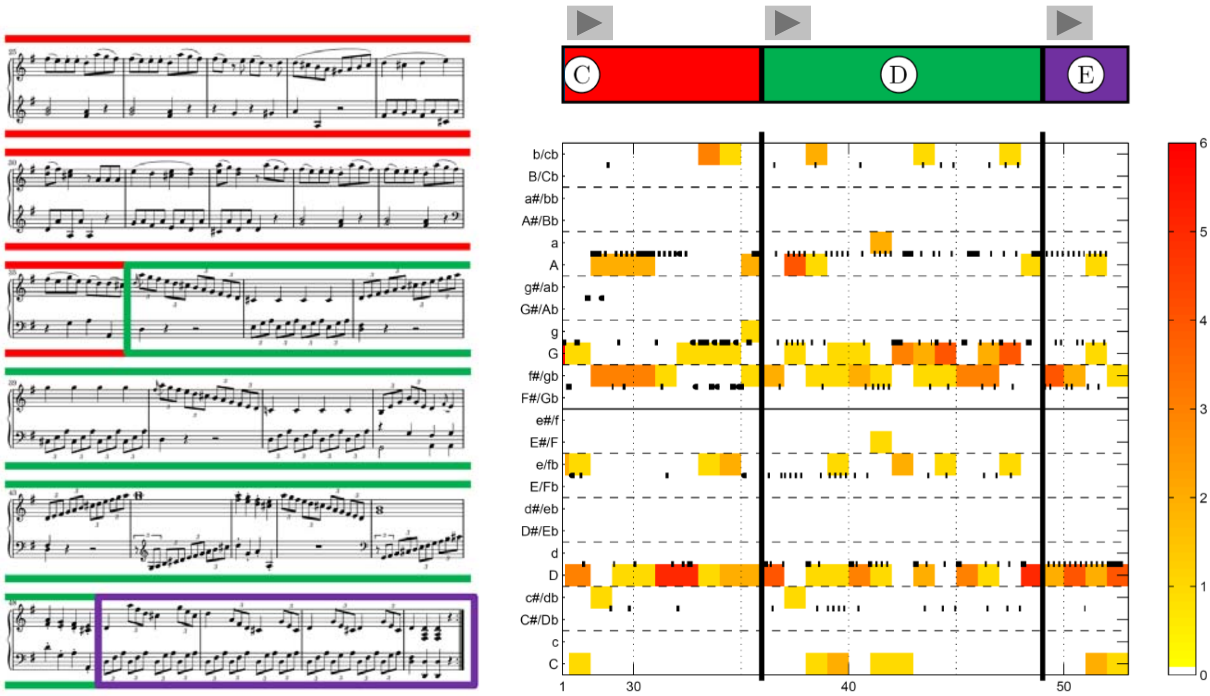
Application: Exploring Harmonic Structures

Example: Beethoven's Piano Sonata Op. 49 No. 2



Application: Exploring Harmonic Structures

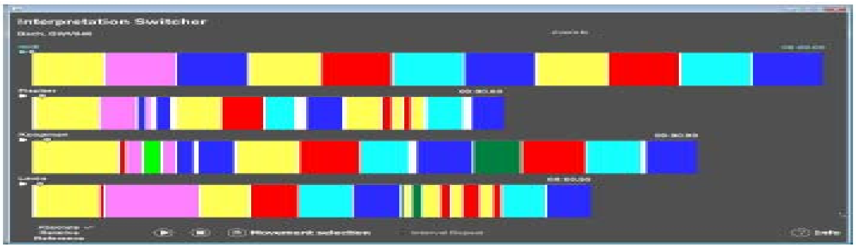
Example: Beethoven's Piano Sonata Op. 49 No. 2



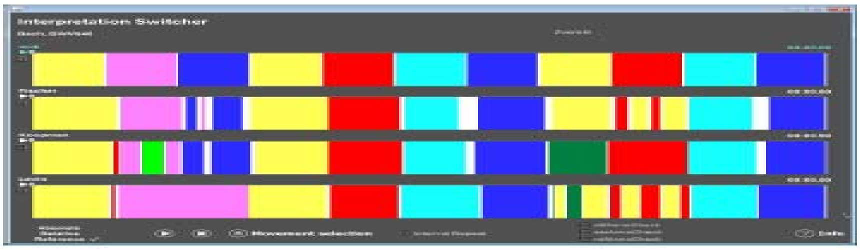
Interface: Interpretation Switcher

Chord annotations for four versions

Absolute mode



Reference mode



Simultaneous comparison of different version-dependent analysis results (here: chord labels)

Conclusions & Future Work

- Importance of feature design step
- Cross-version framework
  - Harmonic analysis
  - Tempo analysis
  - Structure analysis
- Musically meaningful timeline in bars → very convenient!
- Stabilization of analysis results
  - Consistencies seem to have musical meaning
  - Which meaning? Tonal centers?
- Towards interdisciplinary research (MIR + musicology)
  - Visualization as meanigful tool in musicology?
  - Helpful for analyis of harmonic relations across entire music corpora?

Literature

- Taemin Cho, Ron J. Weiss, and Juan Pablo Bello. Exploring common variations in state of the art chord recognition systems. Proc. Sound and Music Computing Conference (SMC), pages 1–8, Barcelona, Spain, 2010.
- Takuya Fujishima. Realtime chord recognition of musical sound: A system using common lisp music. Proc. International Computer Music Conference (ICMC), pages 464–467, Beijing, 1999.
- Nanzhu Jiang, Peter Grosche, Verena Konz, and Meinard Müller. Analyzing chroma feature types for automated chord recognition. Proc. 42nd AES Conference, 2011.
- Verena Konz, Meinard Müller, and Sebastian Ewert. A multi-perspective evaluation framework for chord recognition. Proc. ISMIR, pages 9–14, Utrecht, The Netherlands, 2010.
- Matthias Mauch and Simon Dixon. Simultaneous estimation of chords and musical context from audio. IEEE Transactions on Audio, Speech, and Language Processing, 18(6):1280–1289, 2010.
- Meinard Müller and Sebastian Ewert. Chroma Toolbox: MATLAB implementations for extracting variants of chroma-based audio features. Proc. ISMIR, pages 215–220, Miami, USA, 2011.
- Hélène Papadopoulos and Geoffroy Peeters. Joint estimation of chords and downbeats from an audio signal. IEEE Transactions on Audio, Speech, and Language Processing, 19(1):138–152, 2011.
- Alexander Sheh and Daniel P. W. Ellis. Chord segmentation and recognition using EM-trained hidden Markov models. Proc. ISMIR, pages 185–191, Baltimore, USA, 2003.
- Yushi Ueda, Yuuki Uchiyama, Takuya Nishimoto, Nobutaka Ono, and Shigeki Sagayama. HMM-based approach for automatic chord detection using refined acoustic features. Proc. ICASSP, pages 5518–5521, Dallas, USA, 2010.