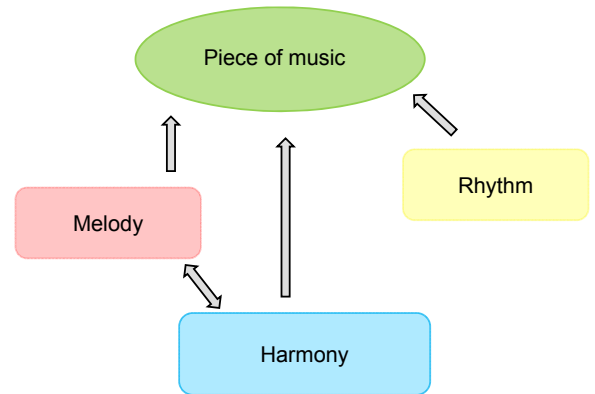


Lecture
Music Processing

Chord Recognition

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International Audio Laboratories Erlangen
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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

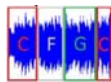
- Development of automatic methods for the harmonic analysis of audio data
- Applications in the field of music information retrieval:
 - music segmentation
 - cover song identification
 - audio matching
 - music structure analysis
 - ...

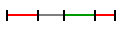
Chord Recognition

Signal



Result



Segmentation 
 Chord label assignment C F G C

Chord Recognition

Signal



Feature Extraction



Chroma features

- Type
- Resolution
- Compression
- Smoothing

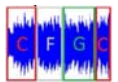
Classification



Pattern matching

- Template
- Gaussian
- Hidden Markov Models
- Graphical Models

Result



Chord Recognition

Given: Audio file

Output: Segmentation and chord labeling

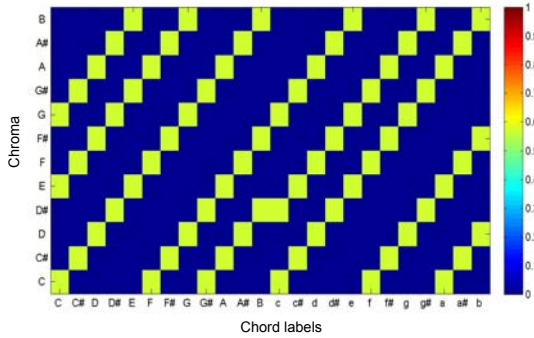
Baseline Method for Chord Recognition

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)

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

Baseline Method for Chord Recognition

24 chord templates
(12 major, 12 minor)

Chroma feature
extraction (framewise)

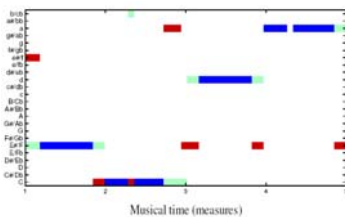
Compute for each frame the distance of
the feature vector to the 24 templates

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



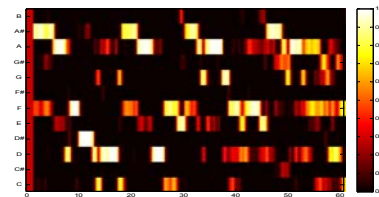
Problems in Chord Recognition

Problem: Monophonic musical passages

Example: Excerpt of Wagner's Meistersinger



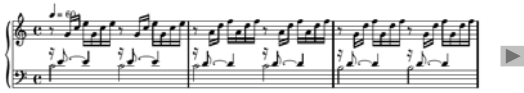
Chromagram



Problems in Chord Recognition

Problem: Frame-wise chord analysis may not be meaningful

Example: Bach: Prelude C major, BWV 846

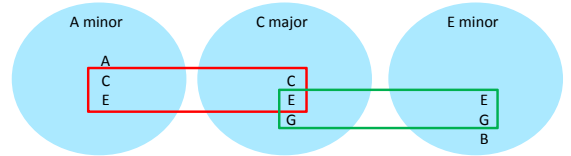


Problem: Broken chords

→ Measure-wise chord analysis necessary

Problems in Chord Recognition

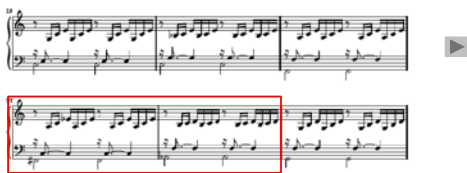
Problem: Ambiguity of chords



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



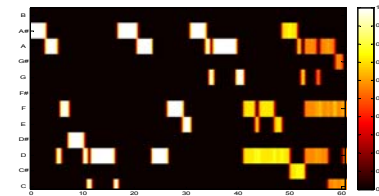
Problems in Chord Recognition

Problem: Tuning problems

Example: Excerpt of Wagner's Meistersinger



Chromagram (from MIDI)



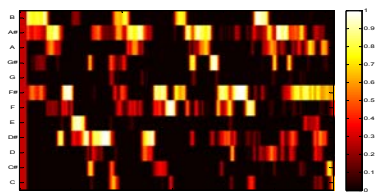
Problems in Chord Recognition

Problem: Tuning problems

Example: Excerpt of Wagner's Meistersinger



Chromagram (from MIDI)



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

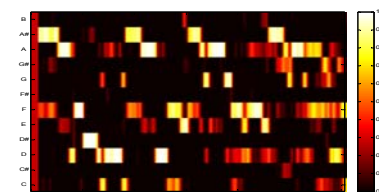
Problems in Chord Recognition

Problem: Tuning problems

Example: Excerpt of Wagner's Meistersinger



Chromagram (from MIDI)



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

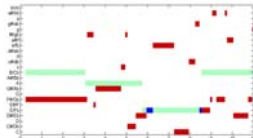
Solution: Adjust frequency binning when computing pitch features.

Problems in Chord Recognition

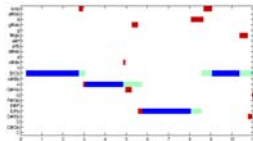
Problem: Tuning problems

Example: The Beatles "Lovely Rita" ▶

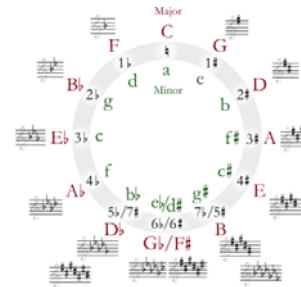
Without tuning



With tuning

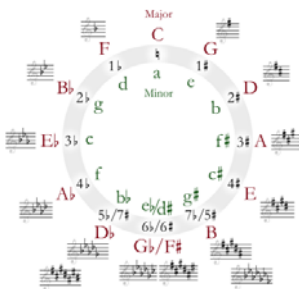


Key Relations: Circle of Fifths



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

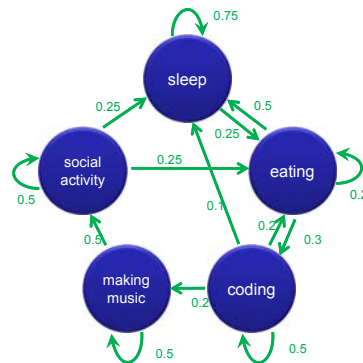
Description of certain
stochastic processes



Andrei Markov
(Wikipedia)

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

Hidden Markov Models



$G = (S, E, P)$

S: States

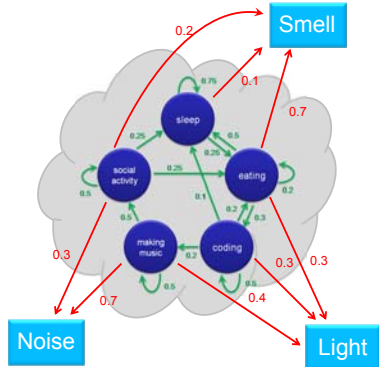
E: Transitions

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

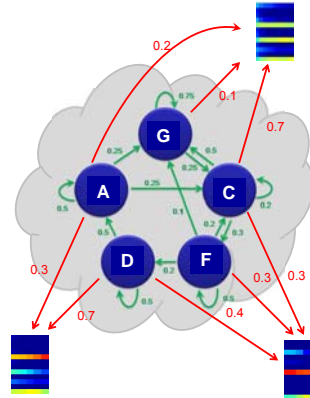
P: Transition probabilities

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

24 major/minor chords

Probabilities for having a transition from one chord to another chord

Chroma vectors

Probability for a chord model to produce a chroma distribution

$$G = (S, P, V, B)$$

S: States

P: Transition probabilities

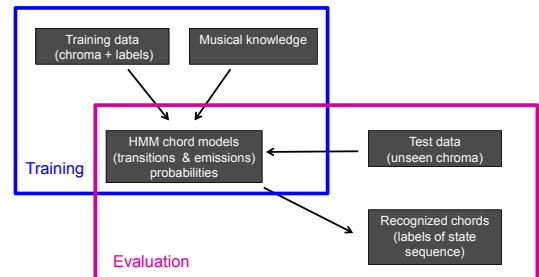
V: Observations

B: Emission probabilities

Hidden Markov Models

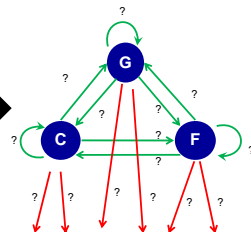
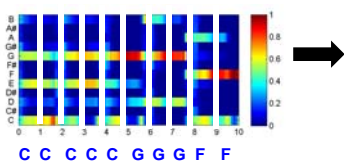
Two computational problems

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



Hidden Markov Models

Training

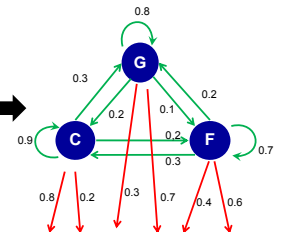
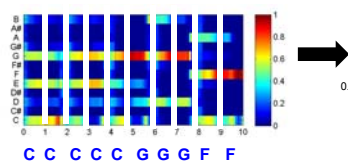


Input:
Sequence of features (observations)
Corresponding ground truth chord labels

Output:
Emission probabilities
Transition probabilities

Hidden Markov Models

Training

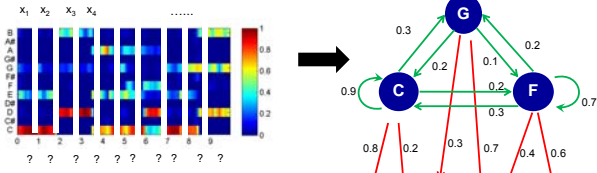


Input:
Sequence of features (observations)
Corresponding ground truth chord labels

Output:
Emission probabilities
Transition probabilities

Hidden Markov Models

Evaluation



Input:

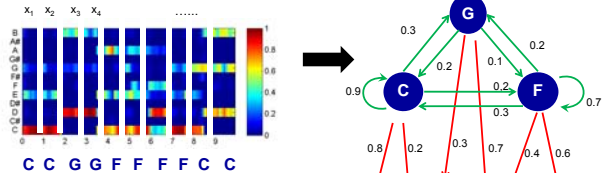
- Sequence of features
- Emission probabilities
- Transition probabilities

Output:

Optimal state sequence (estimated chord progression)

Hidden Markov Models

Evaluation



Input:

- Sequence of features
- Emission probabilities
- Transition probabilities

Output:

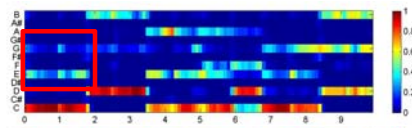
Optimal state sequence (estimated chord progression)

Importance of Chroma Feature Variant



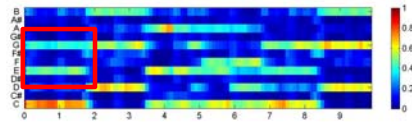
CP

Normalized chromagram



CLP

Logarithmic compression

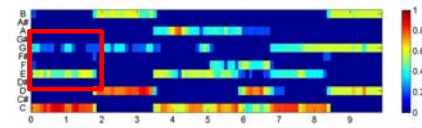


Importance of Chroma Feature Variant



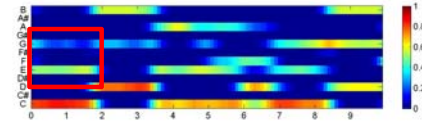
CENS[1]

Quantized chromagram



CENS[11]

Temporal smoothing

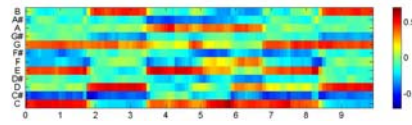


Importance of Chroma Feature Variant



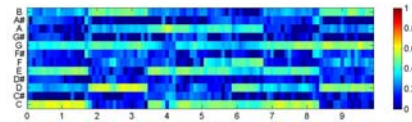
CRP

Boosting timbre invariance

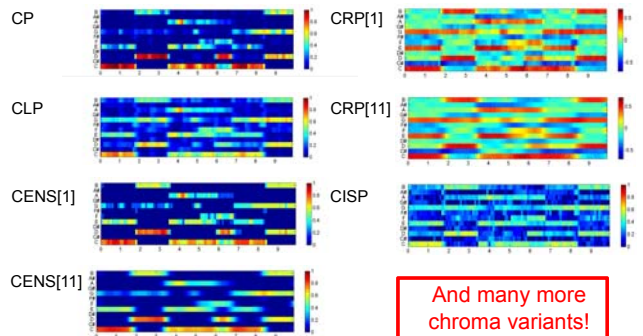


CISP

Instantaneous frequency



Importance of Chroma Feature Variant



And many more chroma variants!

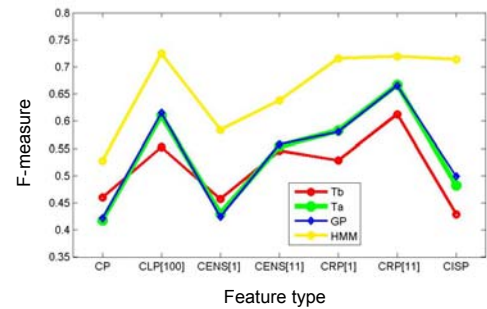
Importance of Chroma Feature Variant

Experiment

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

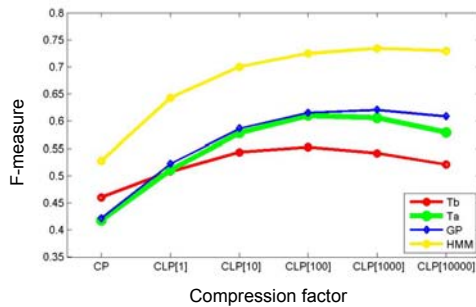
Importance of Chroma Feature Variant

Dependency on feature type



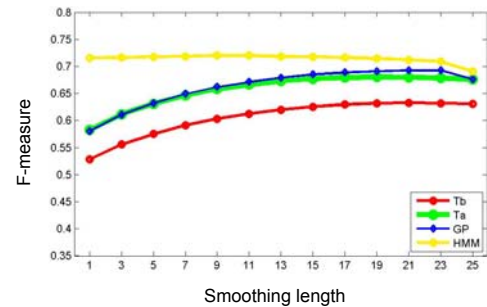
Importance of Chroma Feature Variant

Dependency on logarithmic compression



Importance of Chroma Feature Variant

Dependency on smoothing (using CRP features)



Chroma Toolbox

Chroma Toolbox: Pitch, Chroma, CENS, CRP

The **Chroma Toolbox** has been developed by [Marius Müller-Peterson] and his collaborators from the research group headed by [Gerrit Heinrich]. It contains MATLAB implementations for extracting various types of novel pitch-based and chroma-based audio features. The MATLAB implementations provided on this website are free for use in non-commercial research projects worldwide. If you publish results obtained using these implementations, please cite the references below: [1], [2], [3], [4].

Description of Pitch, Chroma, CENS, CRP Features

Chroma-based audio features have turned out to be a powerful tool for various analysis tasks in [audio processing], including task such as chord labeling, music summarization, structure analysis, music synchronization and audio alignment. A 12-dimensional chroma feature encodes the short-time energy distribution of the underlying music signals over the twelve chroma bands, which correspond to the twelve traditional pitch classes of the equal-tempered scale encoded by the abbreviations C, F, G, D, E, A. Each feature strongly correlates to the harmonic progression of the music signal, often perceived as triadic music. Its underlying spectral components that differ by a musical octave, chroma features possess a significant degree of robustness to changes in timbre and instrumentation.

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

Cross-Version Analysis

General Procedure

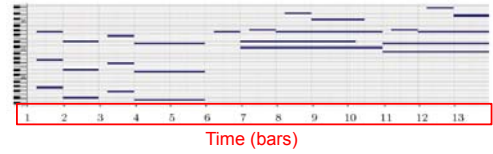
- Conduct **analysis** for **multiple versions** of the **same object**
 - Harmonic analysis
 - Different music recordings
 - Same piece of music
- Relate** the versions (using a **reference**)
 - Music synchronization
 - Musical score
- Compare analysis results across different versions
- Look for consistencies and inconsistencies

Barwise Synchronization



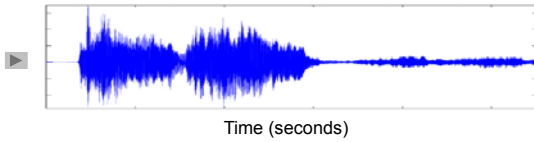
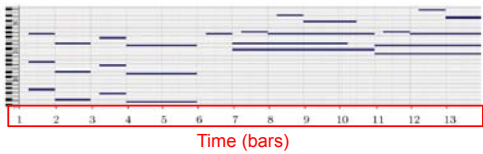
Barwise Synchronization

MIDI representation with bar information



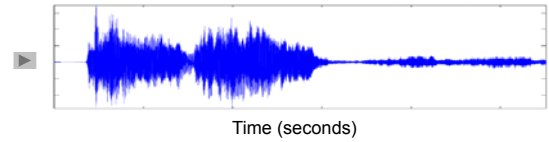
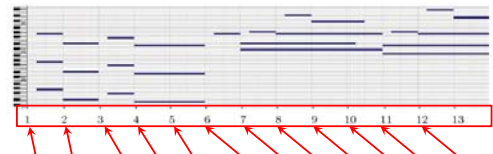
Barwise Synchronization

MIDI representation with bar information



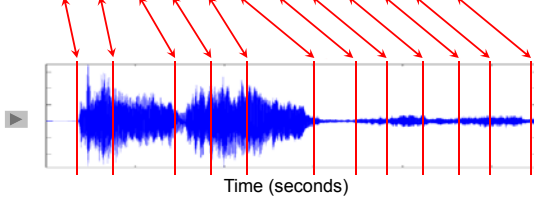
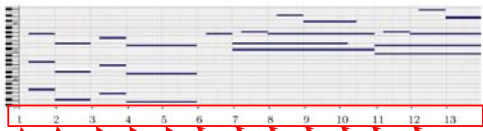
Barwise Synchronization

Music synchronization



Barwise Synchronization

Transfer bar information to audio domain

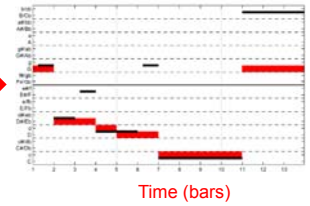
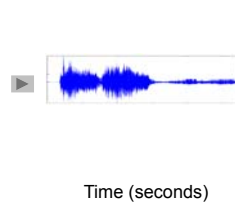


Cross-Version Harmonic Analysis

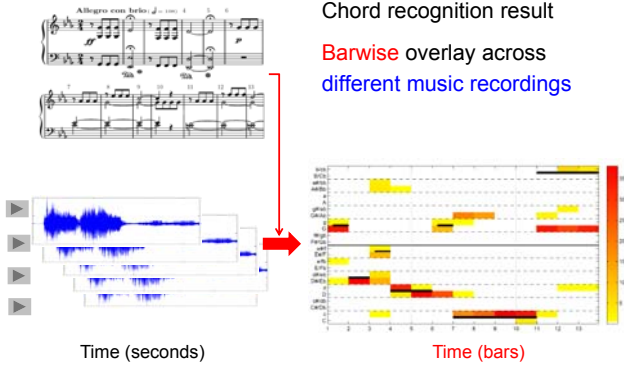
Chord recognition result



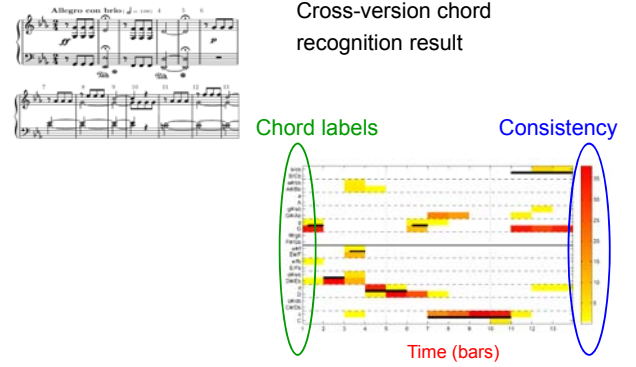
Barwise presentation of analysis results is of great benefit!



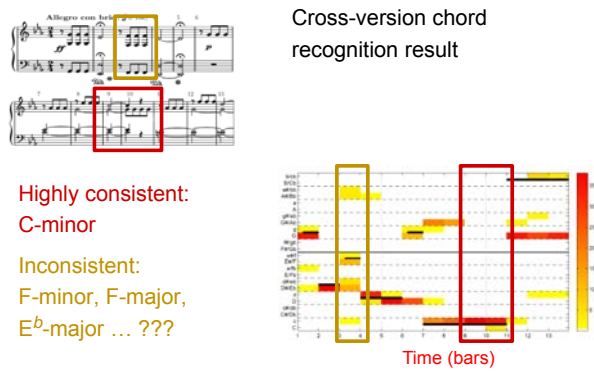
Cross-Version Harmonic Analysis



Cross-Version Harmonic Analysis



Cross-Version Harmonic Analysis



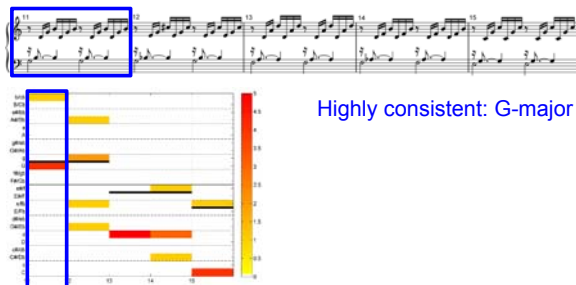
Cross-Version Visualization

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)



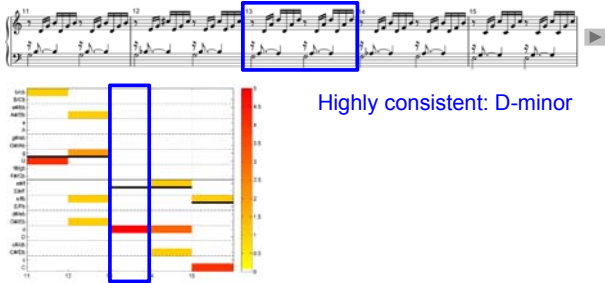
Cross-Version Visualization

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



Cross-Version Visualization

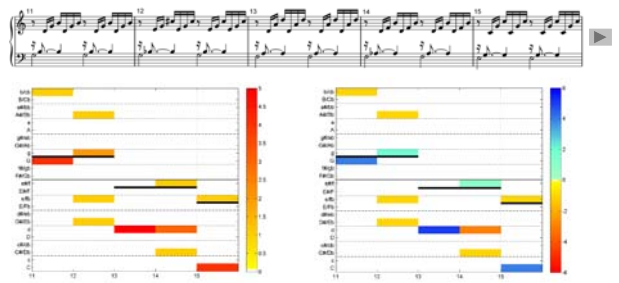
Example: Bach's Prelude BWV 846 in C major (bars 11-15)



Highly consistent: D-minor

Cross-Version Visualization

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

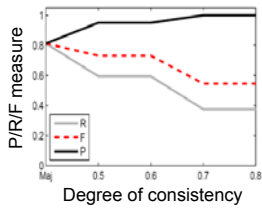


Ground-truth visualization

Convenient tool for manual error analysis and evaluation

Quantitative Evaluation

Example: Bach's Prelude BWV 846



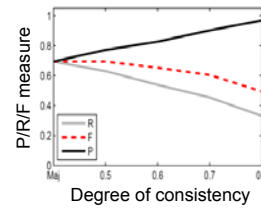
F-measures for individual recordings:

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



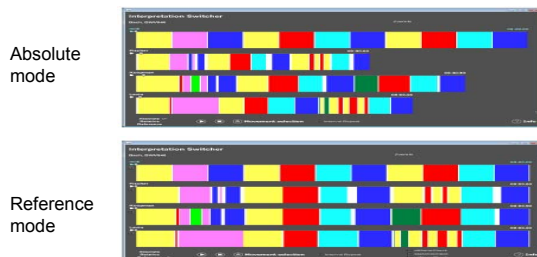
Application: Exploring Harmonic Structures

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



Interface: Interpretation Switcher

Chord annotations for four versions



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 meaningful tool in musicology?
 - Helpful for analysis 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.
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