INTERNATIONAL AUDIO LABORATORIES ERLANGEN

AUDIO LABS

Tutorial
Automatisierte Methoden der Musikverarbeitung
47. Jahrestagung der Gesellschaft für Informatik

Harmony Analysis

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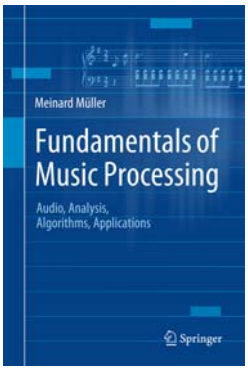
Book: Fundamentals of Music Processing



Meinard Müller
Fundamentals of Music Processing
Audio, Analysis, Algorithms, Applications
483 p., 249 illus., hardcover
ISBN: 978-3-319-21944-8
Springer, 2015

Accompanying website:
www.music-processing.de

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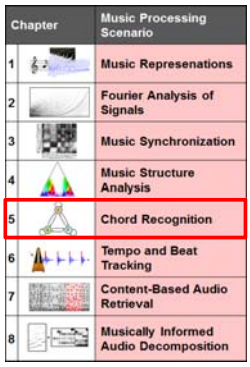

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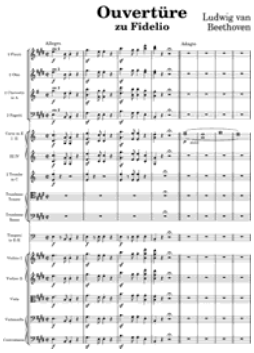
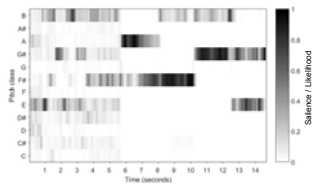
Dissertation: Tonality-Based Style Analysis

Christof Weiß
Computational Methods for Tonality-Based Style Analysis of Classical Music Audio Recordings
PhD thesis, Technical University of Ilmenau, 2017

Chapter 5: Analysis Methods for Key and Scale Structures
Chapter 6: Design of Tonal Features

Recall: Chroma Representations



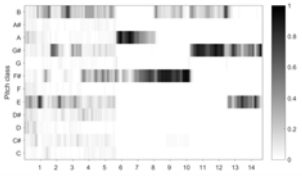


L. van Beethoven,
Fidelio, Overture,
Slovak Philharmonic

Recall: Chroma Representations

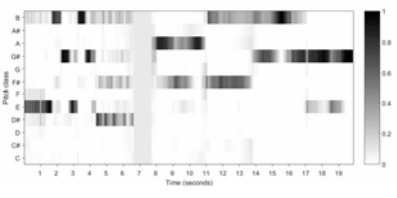
- Orchestra

L. van Beethoven,
Fidelio, Overture,
Slovak Philharmonic



- Piano

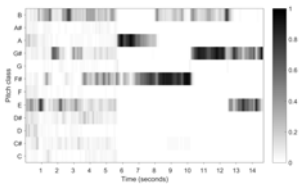
Fidelio, Overture,
arr. Alexander Zemlinsky
M. Namekawa, D.R. Davies
piano four hands



Recall: Chroma Representations

- Orchestra

L. van Beethoven, *Fidelio*, Overture, Slovak Philharmonic

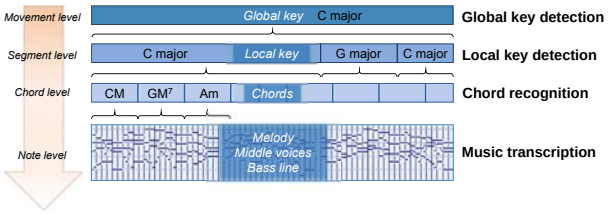


Gómez, *Tonal Description of Polyphonic Audio*, PhD thesis, Barcelona 2006

Müller / Ewert, *Towards Timbre-Invariant Audio Features for Harmony-Based Music*, IEEE TASLP, 2010

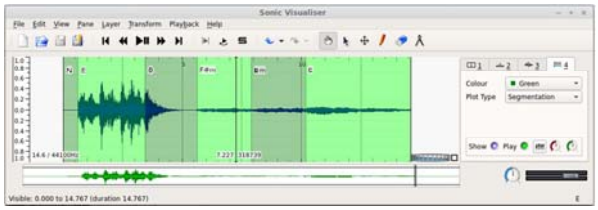
Mauch / Dixon, *Approximate Note Transcription for the Improved Identification of Difficult Chords*, ISMIR 2010

Tonal Structures



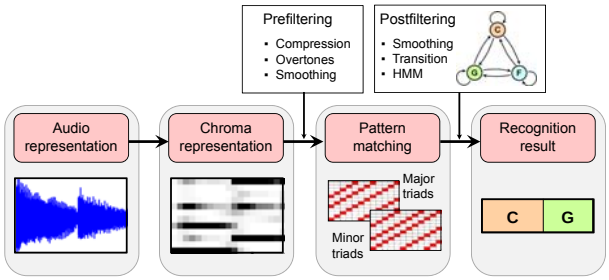
Chord Recognition

- Chord recognition
  - Typically: Feature extraction, pattern matching, filtering
  - "Out-of-the-box" solutions

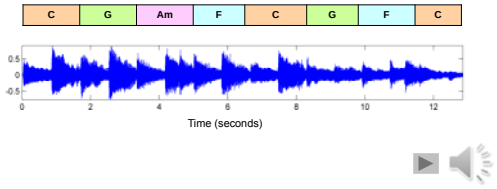


Sonic Visualizer, Chordino Vamp Plugin (Queen Mary University of London)

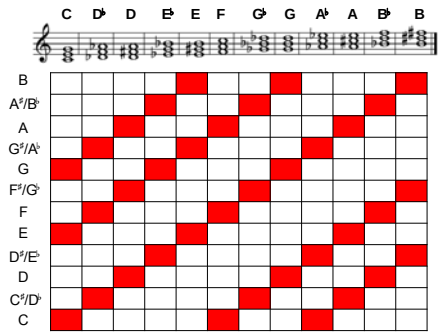
Chord Recognition



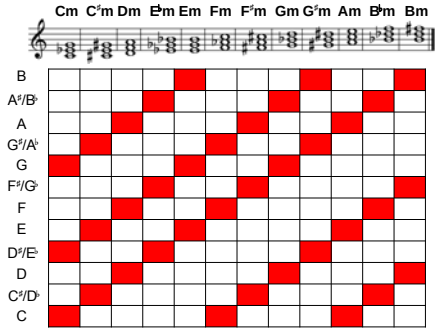
Chord Recognition



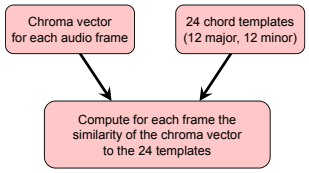
Chord Recognition: Basics



Chord Recognition: Basics

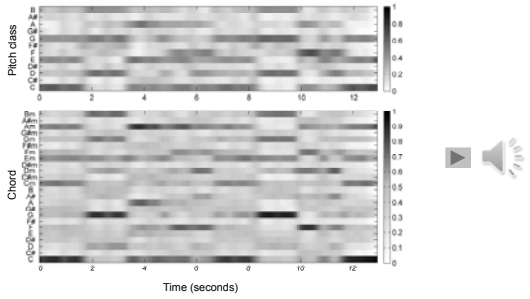


Chord Recognition: Template Matching

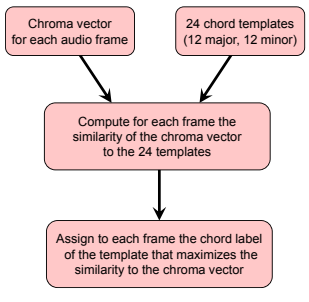


	C	C♯	D	…	Cm	C♯m	Dm	…
B	0	0	0	…	0	0	0	…
A♯	0	0	0	…	0	0	0	…
A	0	0	1	…	0	0	1	…
G♯	0	1	0	…	0	1	0	…
G	1	0	0	…	1	0	0	…
F♯	0	0	1	…	0	0	0	…
F	0	1	0	…	0	0	1	…
E	1	0	0	…	0	1	0	…
D♯	0	0	0	…	1	0	0	…
D	0	0	1	…	0	0	1	…
C♯	0	1	0	…	0	1	0	…
C	1	0	0	…	1	0	0	…

Chord Recognition: Template Matching

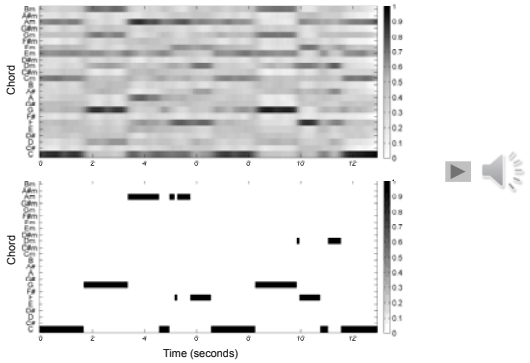


Chord Recognition: Label Assignment

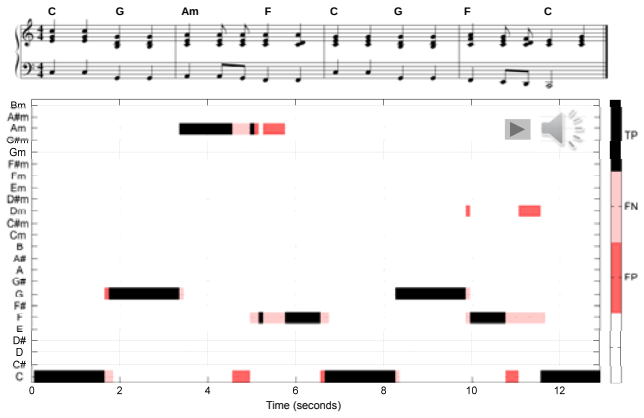


	C	C♯	D	…	Cm	C♯m	Dm	…
B	0	0	0	…	0	0	0	…
A♯	0	0	0	…	0	0	0	…
A	0	0	1	…	0	0	1	…
G♯	0	1	0	…	0	1	0	…
G	1	0	0	…	1	0	0	…
F♯	0	0	1	…	0	0	0	…
F	0	1	0	…	0	0	1	…
E	1	0	0	…	0	1	0	…
D♯	0	0	0	…	1	0	0	…
D	0	0	1	…	0	0	1	…
C♯	0	1	0	…	0	1	0	…
C	1	0	0	…	1	0	0	…

Chord Recognition: Label Assignment

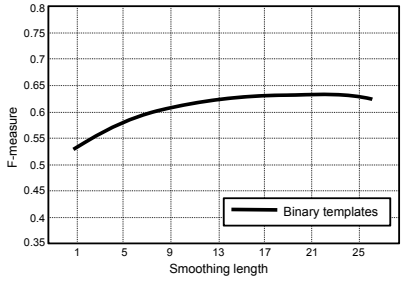


Chord Recognition: Evaluation



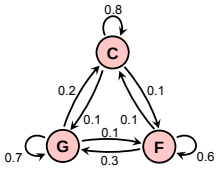
Chord Recognition: Evaluation

- Frame-wise approach: Too many / too rapid changes of output label
- Improvement strategies:
  - Pre-filtering: Average chroma features over several frames (**smoothing**)
  - Evaluation on all Beatles songs



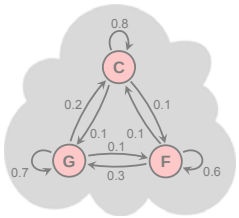
Chord Recognition: Markov Chains

- Probabilistic model for sequential data
- Markov property: Next state depends only on current state (no "memory")
- Consist of:
  - Set of states
  - State transition probabilities
  - *Initial state probabilities*



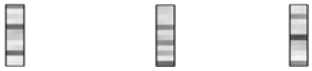
Chord Recognition: Hidden Markov Models

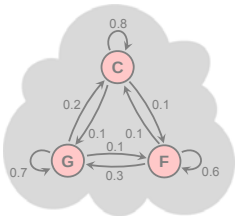
- States as **hidden** variables
- Consist of:
  - Set of states (hidden)
  - State transition probabilities
  - *Initial state probabilities*



Chord Recognition: Hidden Markov Models

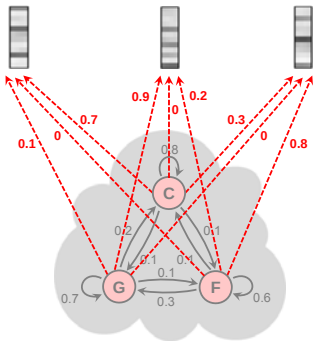
- States as **hidden** variables
- Consist of:
  - Set of states (hidden)
  - State transition probabilities
  - *Initial state probabilities*
  - Observations (visible)





Chord Recognition: Hidden Markov Models

- States as **hidden** variables
- Consist of:
  - Set of states (hidden)
  - State transition probabilities
  - *Initial state probabilities*
  - Observations (visible)
  - Emission probabilities

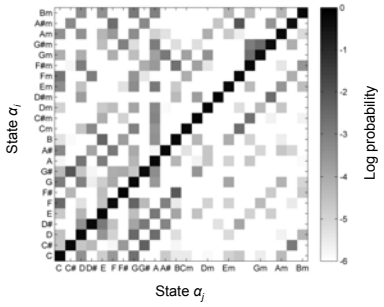


Chord Recognition: Hidden Markov Models

- Different algorithmic problems
- **Estimation problem:**
  - Given an observation sequence, determine the *model parameters*
  - „Training" the HMM on given data
  - Baum-Welch algorithm (Expectation-Maximization)
- **Uncovering problem:**
  - Given the model, find the optimal *hidden state sequence*
  - Use Viterbi algorithm based on dynamic programming
  - Corresponds to chord estimation task!

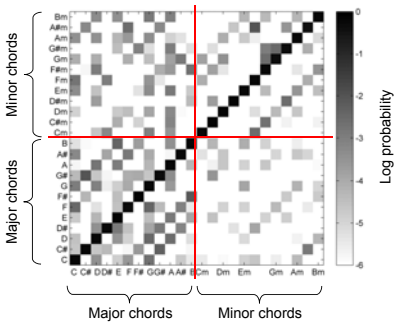
Chord Recognition: Hidden Markov Models

- Parameters: **Transition probabilities**
- Estimated from data



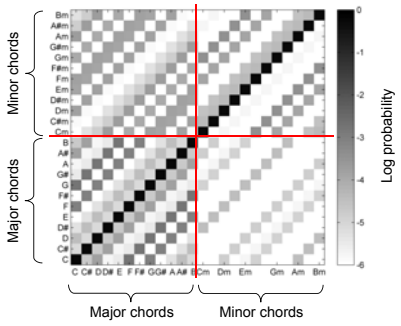
Chord Recognition: Hidden Markov Models

- Parameters: **Transition probabilities**
- Estimated from data



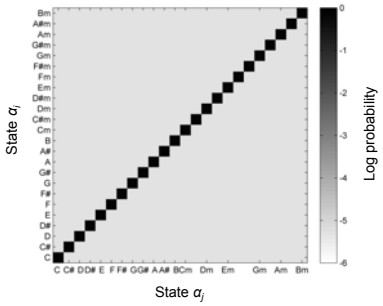
Chord Recognition: Hidden Markov Models

- Parameters: **Transition probabilities**
- Transposition-invariant



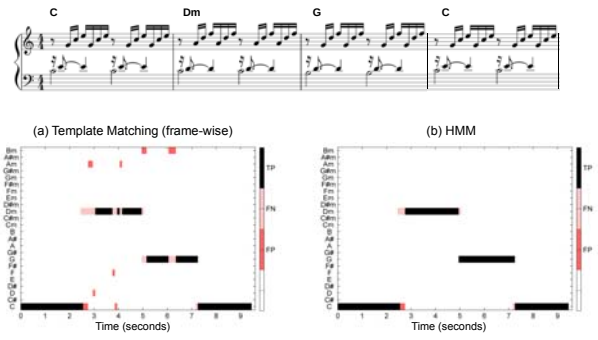
Chord Recognition: Hidden Markov Models

- Parameters: **Transition probabilities**
- Uniform transition matrix (only smoothing)



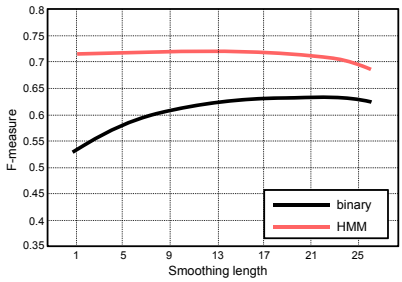
Chord Recognition: Evaluation

- Effect of HMM-based chord estimation and smoothing:

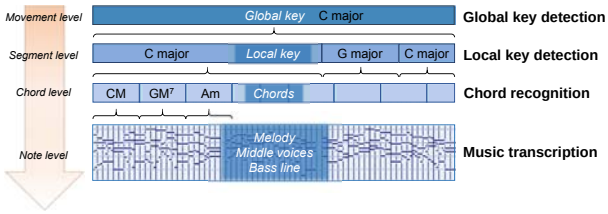


Chord Recognition: Evaluation

- Evaluation on all Beatles songs

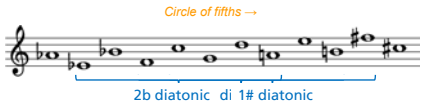


Tonal Structures



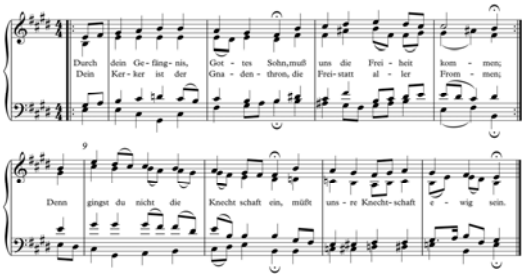
Local Key Detection

- Key as an important musical concept (*"Symphony in C major"*)
- Modulations → Local approach
- Diatonic Scales
  - Simplification of keys
  - Perfect-fifth relation



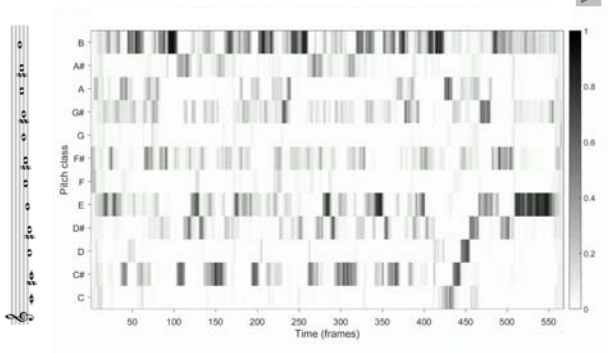
Local Key Detection

- Example: J.S. Bach, Choral "Durch Dein Gefängnis" (*Johannespassion*)
- **Score** – Piano reduction



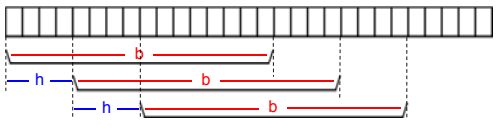
Local Key Detection: Chroma Features

- Example: J.S. Bach, Choral "Durch Dein Gefängnis" (*Johannespassion*)
- **Audio** – Chroma features (Scholars Baroque Ensemble, Naxos 1994)



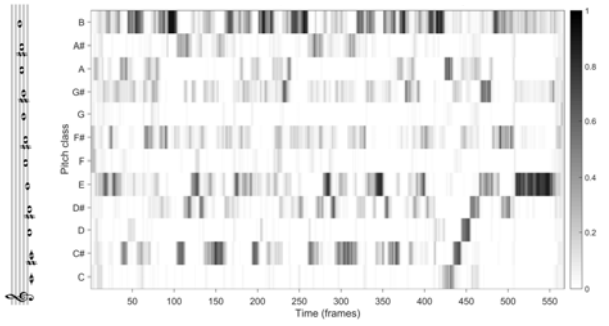
Local Key Detection: Chroma Smoothing

- Summarize pitch classes over a certain time
  - **Chroma smoothing**
  - Parameters: blocksize b and hopsize h



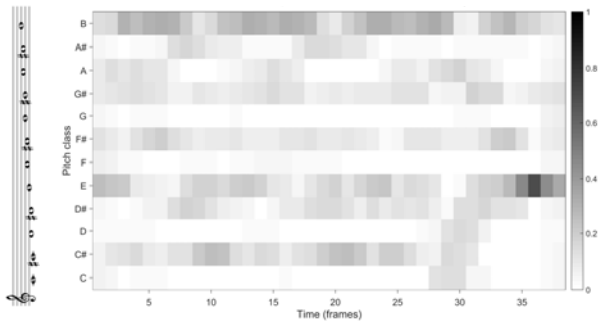
Local Key Detection: Chroma Smoothing

- Choral (Bach)



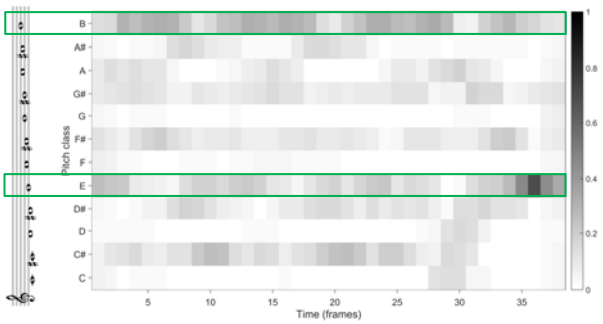
Local Key Detection: Chroma Smoothing

- Choral (Bach) — smoothed with b = 42 seconds and h = 15 seconds



Local Key Detection: Diatonic Scales

- Choral (Bach) — Re-ordering to **perfect fifth** series



Local Key Detection: Diatonic Scales

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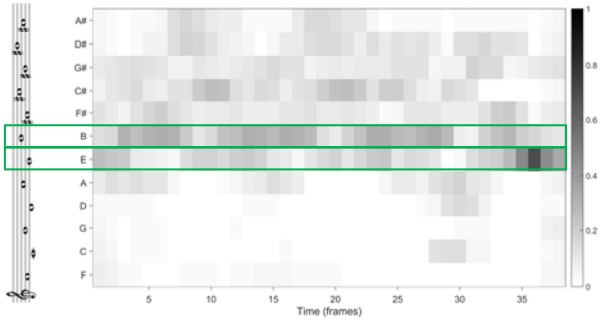
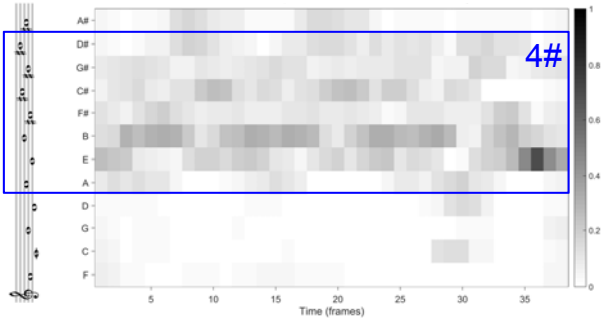


Local Key Detection: Diatonic Scales

- Choral (Bach) — Diatonic Scale Estimation (7 fifths)



Local Key Detection: Diatonic Scales

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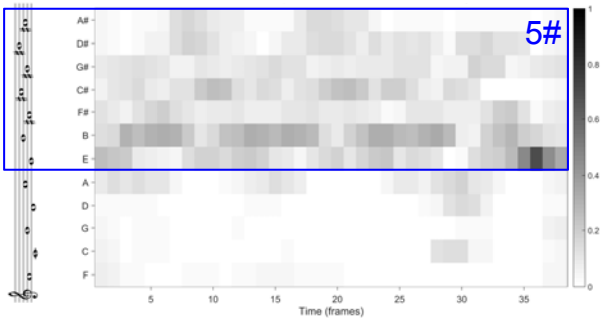
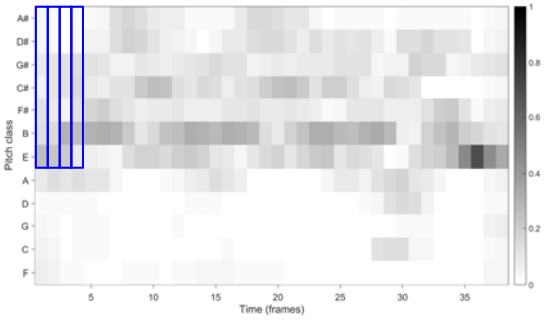


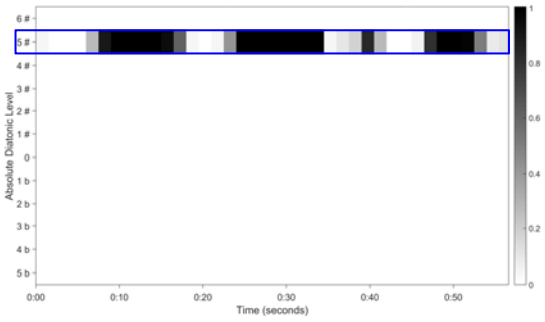
Local Key Detection: Diatonic Scales

- Choral (Bach) — Diatonic Scale Estimation: Multiply chroma values*



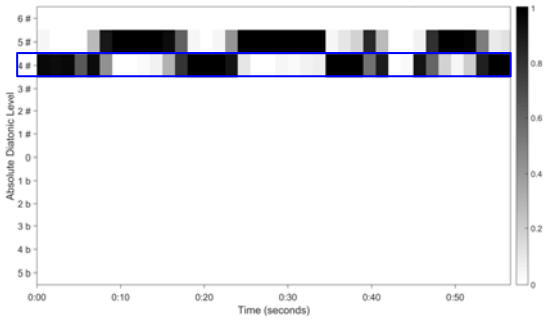
Local Key Detection: Diatonic Scales

- Choral (Bach) — Diatonic Scale Estimation: Multiply chroma values



Local Key Detection: Diatonic Scales

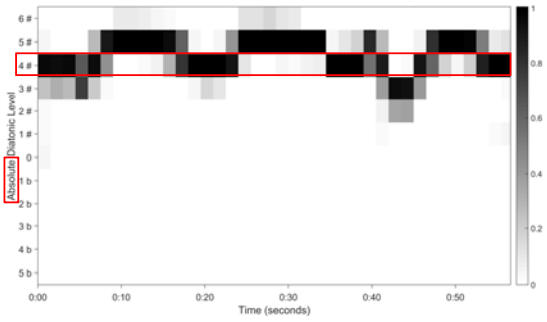
- Choral (Bach) — Diatonic Scale Estimation



Local Key Detection: Diatonic Scales

- Choral (Bach) — Diatonic Scale Estimation

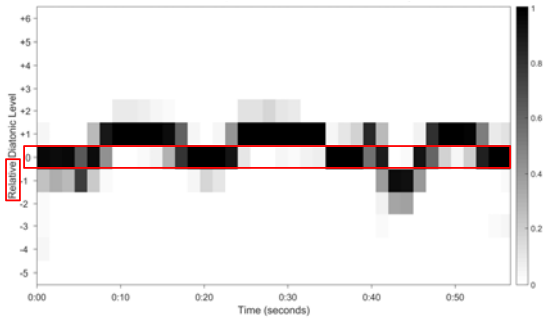
4 #
(E major)



Local Key Detection: Diatonic Scales

- Choral (Bach) — Diatonic Scale Estimation: Shift to **global key**

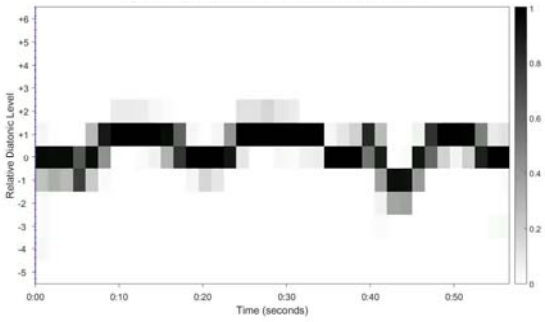
4 #
(E major)



Local Key Detection: Diatonic Scales

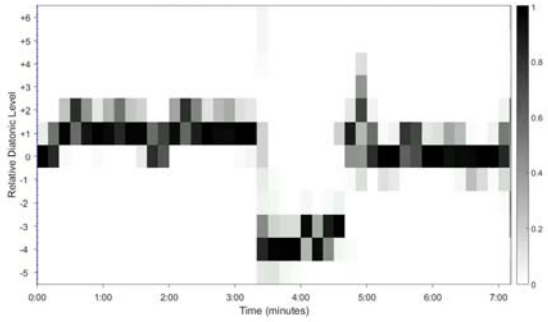
- Choral (Bach) — 0 ≙ 4#

Weiss / Habryka, *Chroma-Based Scale Matching for Audio Tonality Analysis*, CIM 2014



Local Key Detection: Examples

- L. v. Beethoven – Sonata No. 10 op. 14 Nr. 2, 1. Allegro — 0 ≙ 1
(Barenboim, EMI 1998)



Local Key Detection: Examples

- R. Wagner, *Die Meistersinger von Nürnberg*, Vorspiel — 0 ≙ 0
  (Polish National Radio Symphony Orchestra, J. Wildner, Naxos 1993)