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

AUDIO LABS

Seminar

Wie gut können Computer hören? – Über die Anwendung musiktheoretischer Konzepte auf Audiodaten

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12.12.2018

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

Fraunhofer IIS

Christof Weiß

- 2006: Abitur, Max-Reger-Gymnasium Amberg
- 2006-2012: Studium **Physik** Diplom, Universität Würzburg
- 2006-2011: Studium **Komposition**, HfM Würzburg (Prof. Heinz Winbeck)
- 2011-2012: Fortbildungsklasse Komposition (Tobias Schneid)
- 2012-2015: **Promotion** Fraunhofer Institut für Digitale Medientechnologie (IDMT), Ilmenau, Thüringen, gefördert von Stiftung der Dt. Wirtschaft (sdw)

Computational Methods for Tonality-Based Style Analysis of Classical Music Audio Recordings

- Seit 09/2015: AudioLabs Erlangen / freischaffender Komponist
- 2018: KlarText-Preis für Wissenschaftskommunikation

UNIVERSITÄT WÜRZBURG
Hochschule für Musik Würzburg
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Fraunhofer IDMT
TECHNISCHE UNIVERSITÄT ILMENAU
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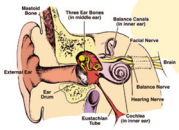
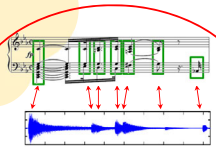
Audio Coding

3D Audio

Audio



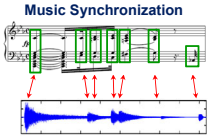


Psychoacoustics

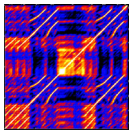
Music Processing

Music Processing / Music Information Retrieval (MIR)

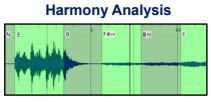
Music Synchronization



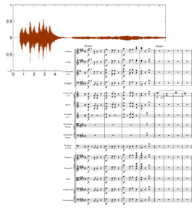
Structure Analysis



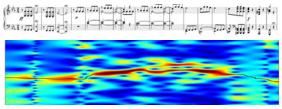
Harmony Analysis



Automatic Music Transcription



Tempo Estimation and Beat Tracking



AUDIO LABS

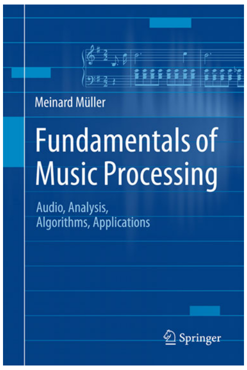
Outline

Teil 1 (16:15–17:45)
- Frequenzmessung und Spektralanalyse: Die Fourier-Transformation
- Gemessene Tonhöhen: Chromamerkmale, Akkord- und Skalenvisualisierung
- Hands-On: Extraktion von Chromamerkmalen mit Sonic Visualizer
- Programmierbeispiel: Tonart-Visualisierung mit Python
- Versionsübergreifende Harmonieanalyse
- Analyse in der Praxis: Wagners *Ring*

Teil 2 (18:00–19:30)
- Quantitativer Ansatz: Authentische und plagale Akkordfortschreitungen als Stilmerkmale
- Realisierung weiterer musiktheoretischer Konzepte: Skalentypen, Pitch Class Sets und tonale Komplexität
- Historischer Kontext: musiktheoretische Beobachtungen in großen Korpora

AUDIO LABS

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

Book: Fundamentals of Music Processing

Chapter		Music Processing Scenario
1		Music Representations
2		Fourier Analysis of Signals
3		Music Synchronization
4		Music Structure Analysis
5		Chord Recognition
6		Tempo and Beat Tracking
7		Content-Based Audio Retrieval
8		Musically Informed Audio Decomposition

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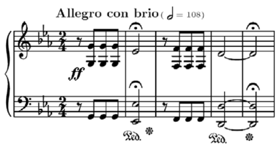
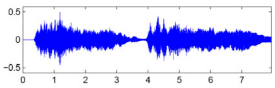
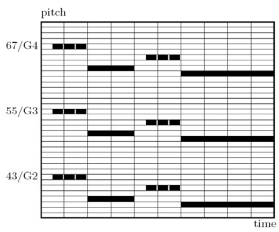
Music Representations

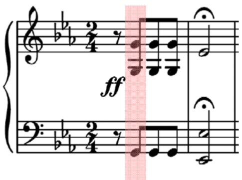






Symbolic Representation

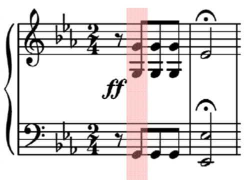
MIDI representation

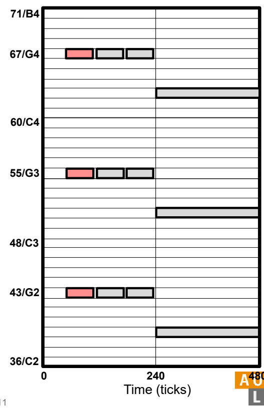


Time (Ticks)	Message	Channel	Note Number	Velocity
60	NOTE ON	1	67	100
0	NOTE ON	1	55	100
0	NOTE ON	2	43	100
55	NOTE OFF	1	67	0
0	NOTE OFF	1	55	0
0	NOTE OFF	2	43	0
5	NOTE ON	1	67	100
0	NOTE ON	1	55	100
0	NOTE ON	2	43	100
55	NOTE OFF	1	67	0
0	NOTE OFF	1	55	0
0	NOTE OFF	2	43	0
5	NOTE ON	1	67	100
0	NOTE ON	1	55	100
0	NOTE ON	2	43	100
55	NOTE OFF	1	67	0
0	NOTE OFF	1	55	0
0	NOTE OFF	2	43	0
5	NOTE ON	1	63	100
0	NOTE ON	2	51	100
0	NOTE ON	2	39	100
240	NOTE OFF	1	63	0
0	NOTE OFF	2	51	0
0	NOTE OFF	2	39	0

Symbolic Representation

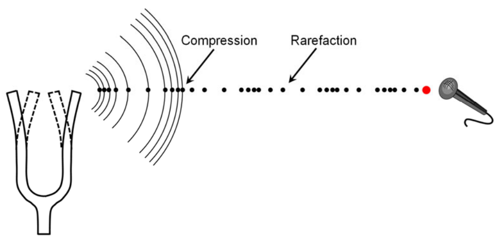
MIDI representation





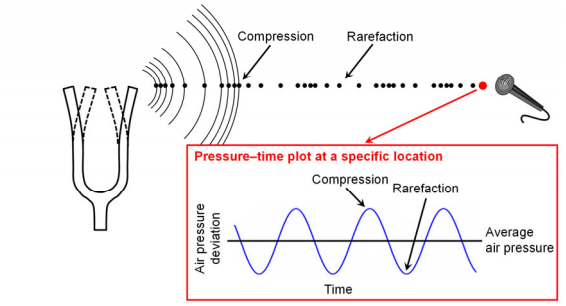
Audio Representation

Waveform



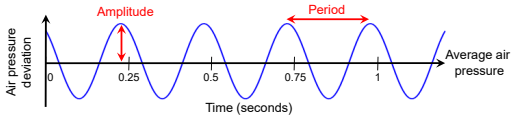
Audio Representation

Waveform



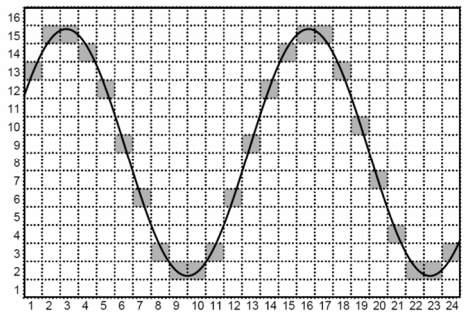
Audio Representation

Waveform



Audio Representation

Digitization



Audio Representation

Digitization

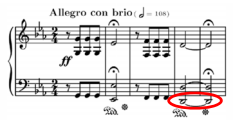
- Convertion of continuous-time (analog) signal into a discrete signal
- Sampling (discretization of time axis)
- Quantization (discretization of amplitudes)

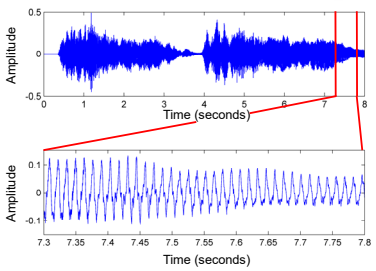
Examples:

- Audio CD: 44100 Hz sampling rate
  16 bits (65536 values) used for quantization
- Telephone: 8000 Hz sampling rate
  8 bits (256 values) used for quantization

Audio Representation

Waveform

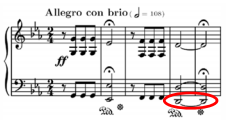


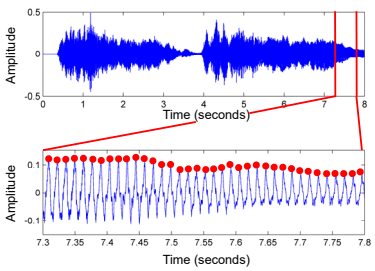


D2 (73.4 Hz)

Audio Representation

Waveform





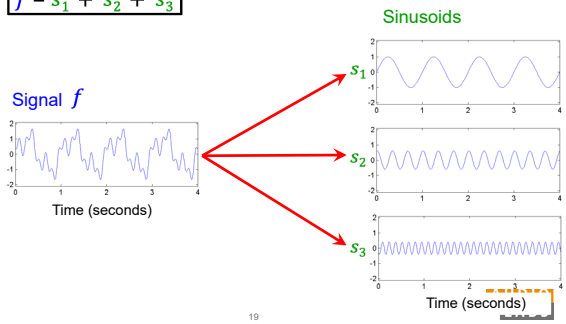
D2 (73.4 Hz)

37 periods within 500 ms section

Fourier Transform

Idea: Decompose a given signal into a superposition of sinusoids (elementary signals).

$f = s_1 + s_2 + s_3$



Fourier Transform

Each sinusoid has a physical meaning and can be described by three parameters:

$s_{(A,\omega,\varphi)}(t) = A \cdot \sin(2\pi(\omega t - \varphi))$

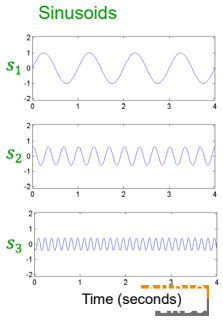
ω = frequency
A = amplitue
φ = phase

Interpretation:
The amplitude A reflects the intensity at which the sinusoidal of frequency ω appears in f.
The phase φ reflects how the sinusoidal has to be shifted to best correlate with f.

$A_1 = 1$, $\omega_1 = 1$, $\varphi_1 = 0$

$A_2 = 0.6$, $\omega_2 = 3$, $\varphi_2 = -0.2$

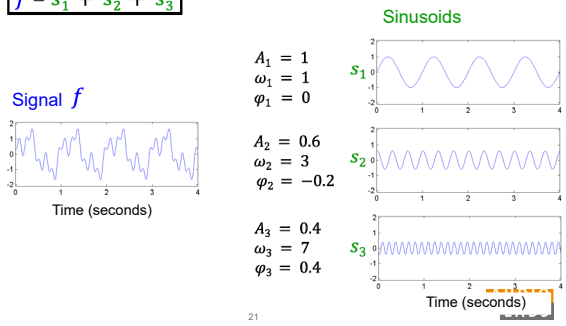
$A_3 = 0.4$, $\omega_3 = 7$, $\varphi_3 = 0.4$



Fourier Transform

Each sinusoid has a physical meaning and can be described by three parameters:

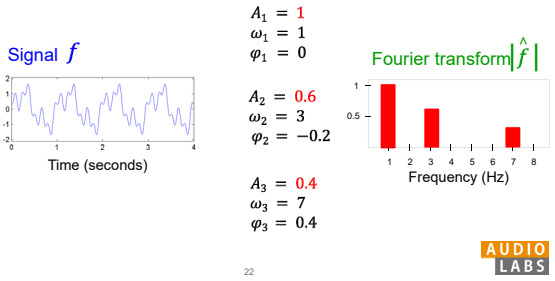
$f = s_1 + s_2 + s_3$



Fourier Transform

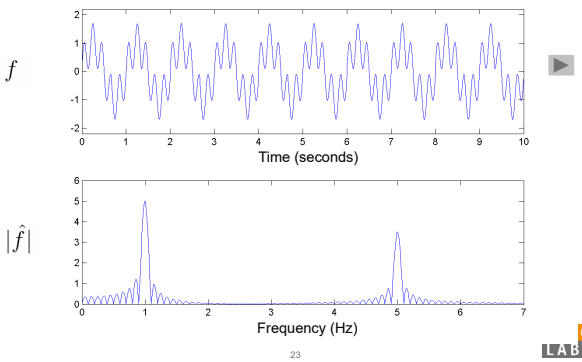
Each sinusoid has a physical meaning and can be described by three parameters:

$f = s_1 + s_2 + s_3$



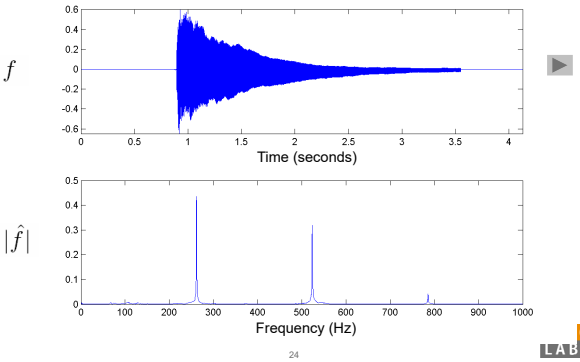
Fourier Transform

Example: Superposition of two sinusoids



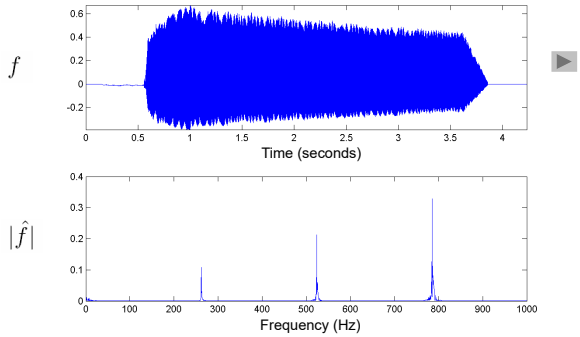
Fourier Transform

Example: C4 played by piano



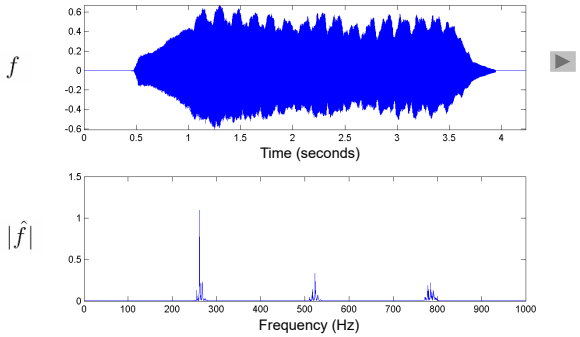
Fourier Transform

Example: C4 played by trumpet



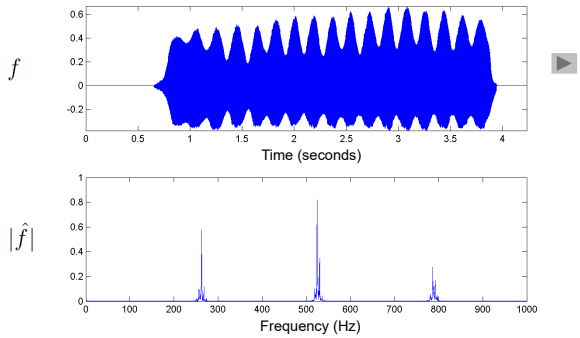
Fourier Transform

Example: C4 played by violine



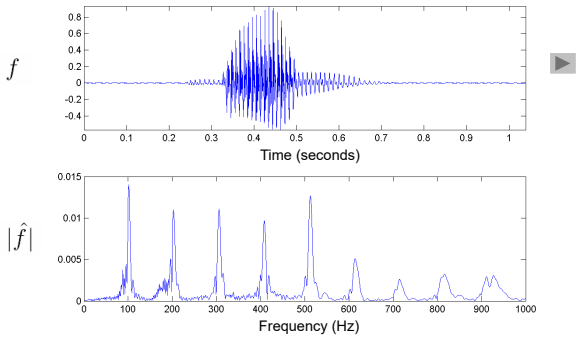
Fourier Transform

Example: C4 played by flute



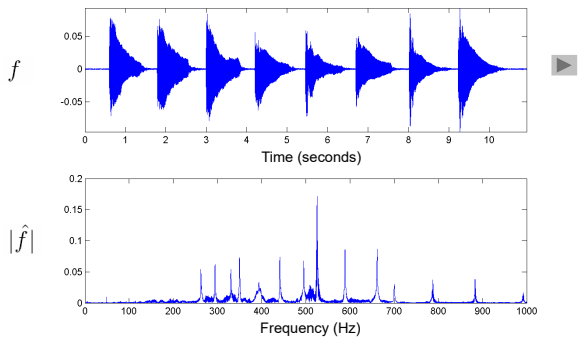
Fourier Transform

Example: Speech “Bonn”



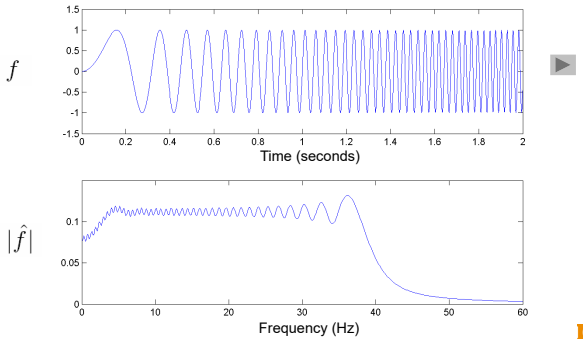
Fourier Transform

Example: C-major scale (piano)



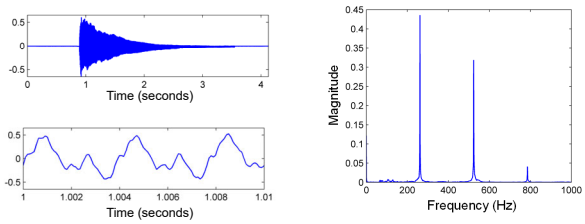
Fourier Transform

Example: Chirp signal



Fourier Transform

Example: Piano tone (C4, 261.6 Hz)



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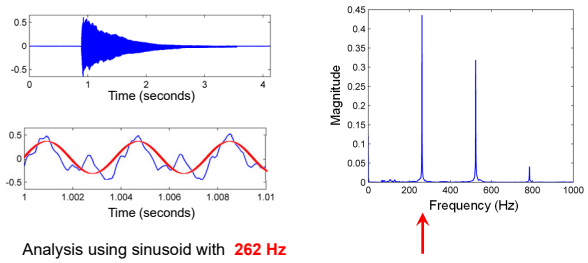
Fourier Transform

Example: Piano tone (C4, 261.6 Hz)



Analysis using sinusoid with **262 Hz**

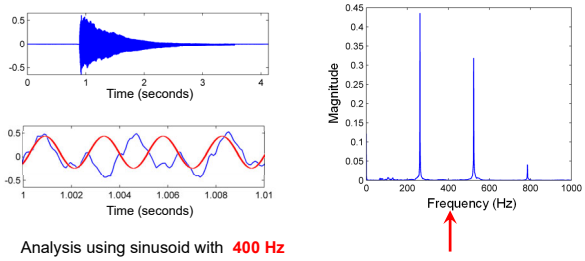
→ high correlation

→ large Fourier coefficient

AUDIO LABS

Fourier Transform

Example: Piano tone (C4, 261.6 Hz)



Analysis using sinusoid with **400 Hz**

→ low correlation

→ small Fourier coefficient

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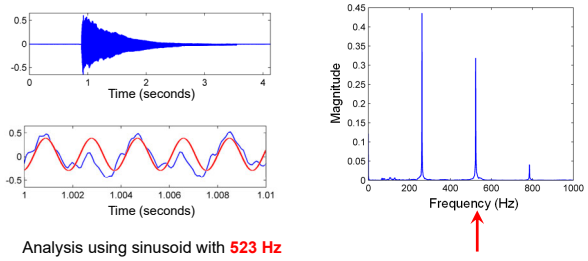
Fourier Transform

Example: Piano tone (C4, 261.6 Hz)



Analysis using sinusoid with **523 Hz**

→ high correlation

→ large Fourier coefficient

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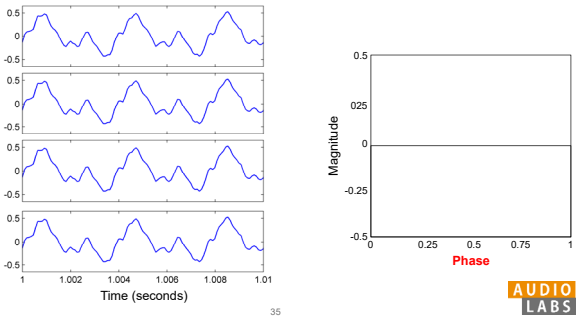
Fourier Transform

Role of phase



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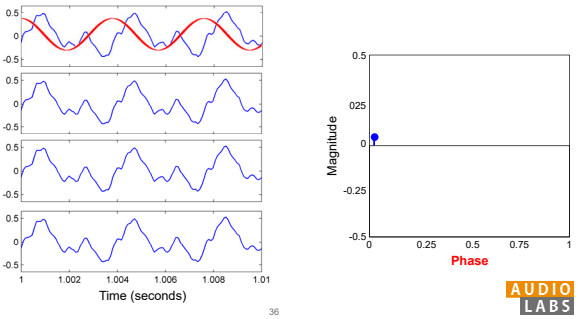
Fourier Transform

Role of phase

Analysis with sinusoid having frequency 262 Hz and phase $\varphi = 0.05$



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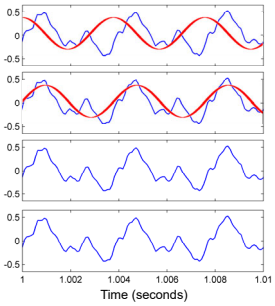
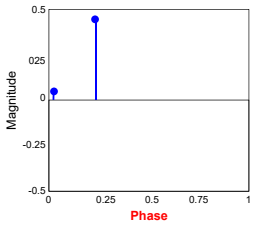
Fourier Transform

Role of phase

Analysis with sinusoid having frequency 262 Hz and phase $\varphi = 0.24$

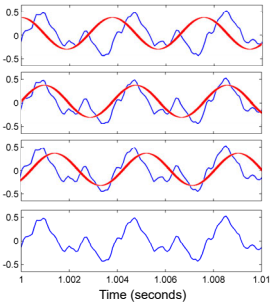


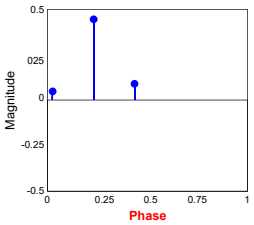


Fourier Transform

Role of phase

Analysis with sinusoid having frequency 262 Hz and phase $\varphi = 0.45$

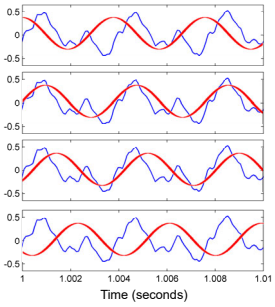


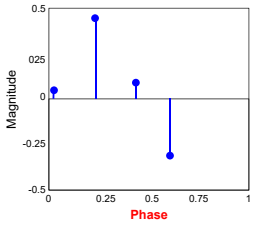


Fourier Transform

Role of phase

Analysis with sinusoid having frequency 262 Hz and phase $\varphi = 0.6$





Fourier Transform

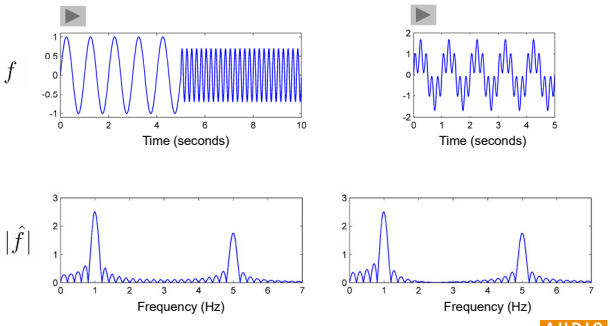
Signal $f: \mathbb{R} \to \mathbb{R}$

Fourier representation $f(t) = \int_{\omega \in \mathbb{R}} c_\omega \exp(2\pi i \omega t) d\omega$

Fourier transform $c_\omega = \hat{f}(\omega) = \int_{t \in \mathbb{R}} f(t) \exp(-2\pi i \omega t) dt$

- Tells which frequencies occur, but does not tell when the frequencies occur.
- Frequency information is averaged over the entire time interval.
- Time information is hidden in the phase

Fourier Transform



Short Time Fourier Transform

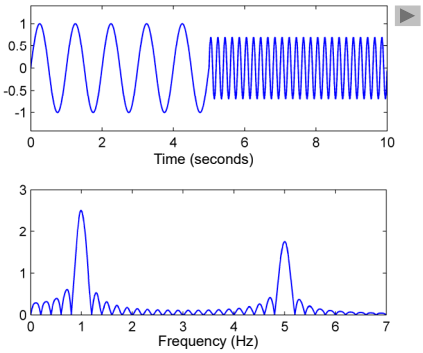
Idea (Dennis Gabor, 1946):

- Consider only a small section of the signal for the spectral analysis

  → recovery of time information

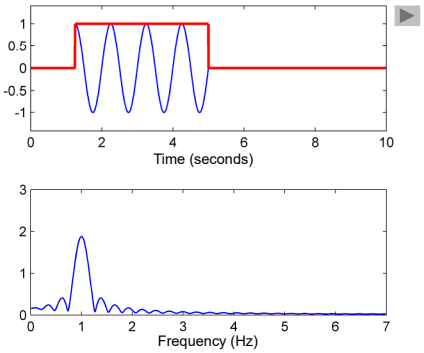
- Short Time Fourier Transform (STFT)
- Section is determined by pointwise multiplication of the signal with a localizing window function

Short Time Fourier Transform



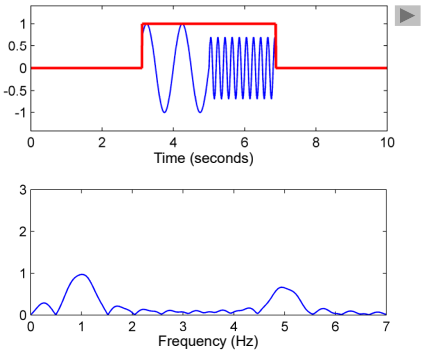
AUDIO LABS

Short Time Fourier Transform



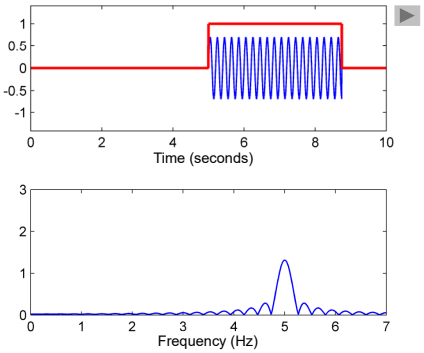
AUDIO LABS

Short Time Fourier Transform



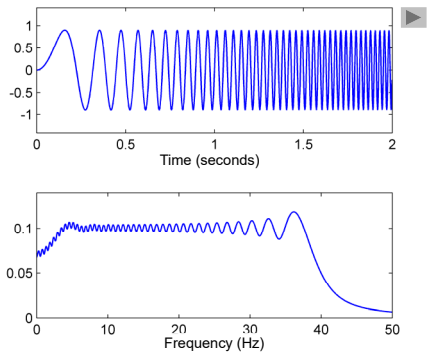
AUDIO LABS

Short Time Fourier Transform



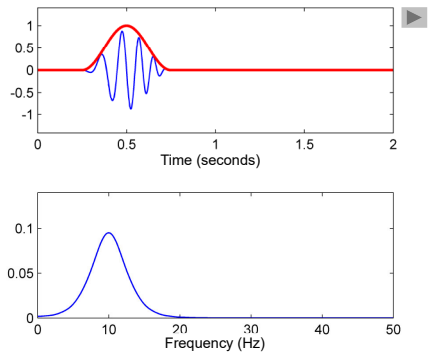
AUDIO LABS

Short Time Fourier Transform



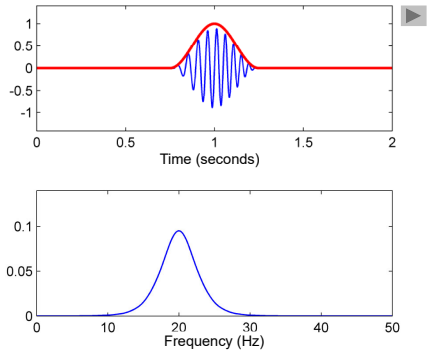
AUDIO LABS

Short Time Fourier Transform



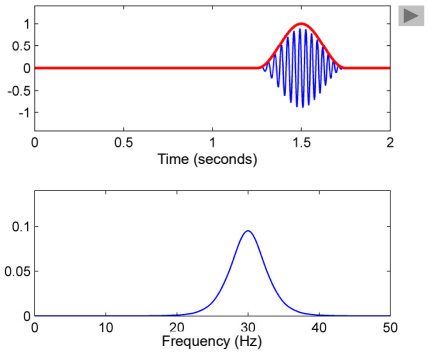
AUDIO LABS

Short Time Fourier Transform



AUDIO LABS

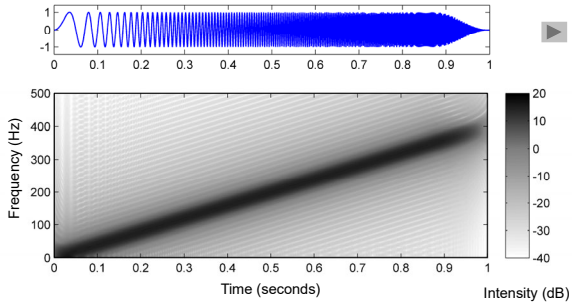
Short Time Fourier Transform



AUDIO LABS

Time–Frequency Representation

Spectrogram



AUDIO LABS

Time–Frequency Representation

Time–Frequency Localization

- Size of window constitutes a trade-off between time resolution and frequency resolution:

  Large window : poor time resolution
  good frequency resolution

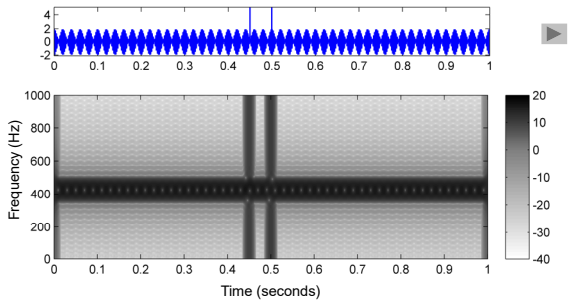
  Small window : good time resolution
  poor frequency resolution

- Heisenberg Uncertainty Principle: there is no window function that localizes in time and frequency with arbitrary precision.

AUDIO LABS

Time–Frequency Representation

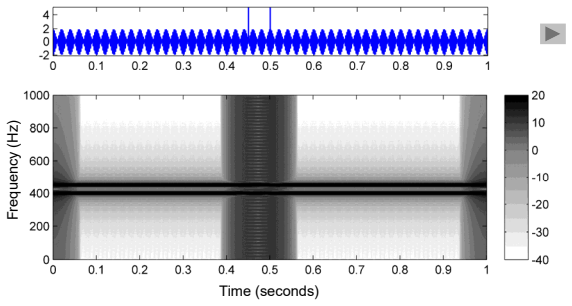
Signal and STFT with Hann window of length 20 ms



AUDIO LABS

Time–Frequency Representation

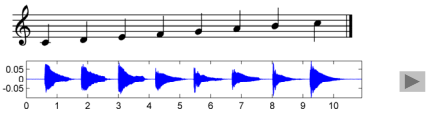
Signal and STFT with Hann window of length 100 ms



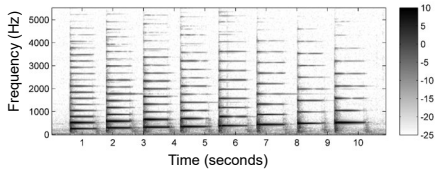
AUDIO LABS

Audio Features

Example: C-major scale (piano)



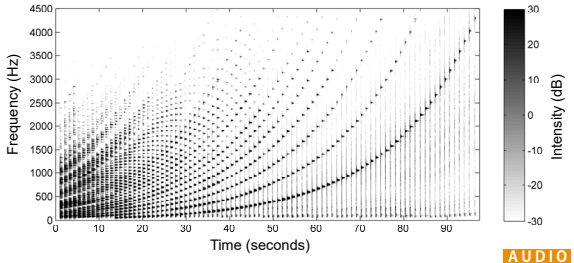
Spectrogram



Audio Features

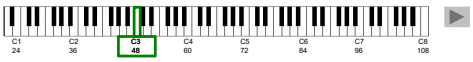
Example: Chromatic scale

Spectrogram

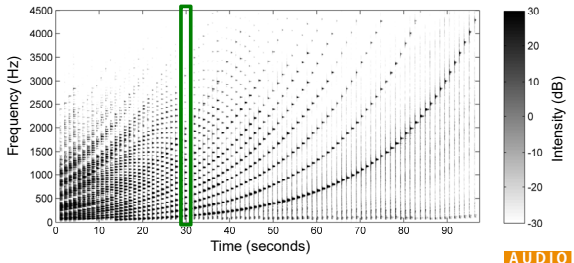


Audio Features

Example: Chromatic scale



Spectrogram



Audio Features

Model assumption: Equal-tempered scale

- MIDI pitches: $p \in [1:128]$
- Piano notes: p = 21 (A0) to p = 108 (C8)
- Concert pitch: p = 69 (A4) ≙ 440 Hz
- Center frequency: $F_{\text{pitch}}(p) = 2^{(p-69)/12} \cdot 440$ Hz

→ Logarithmic frequency distribution
Octave: doubling of frequency

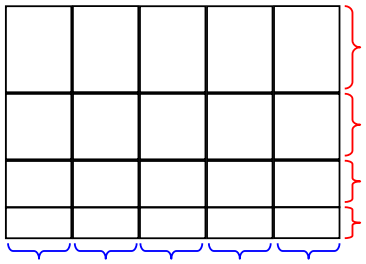
Audio Features

Idea: Binning of Fourier coefficients

Divide up the fequency axis into logarithmically spaced “pitch regions” and combine spectral coefficients of each region to a single pitch coefficient.

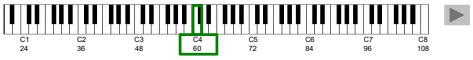
Audio Features

Time-frequency representation

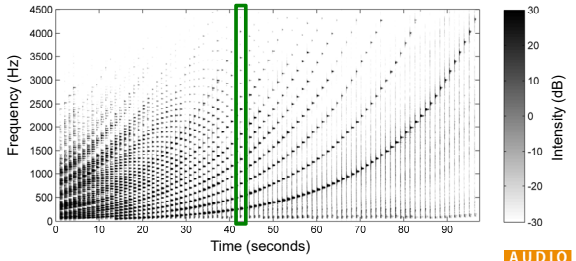


Audio Features

Example: Chromatic scale



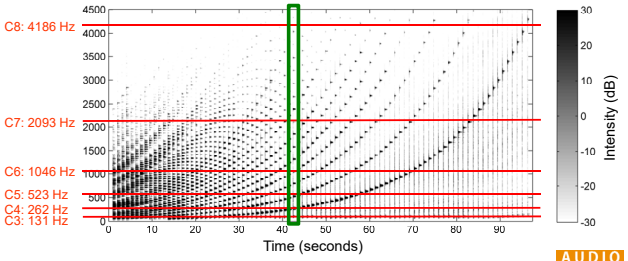
Spectrogram



Audio Features

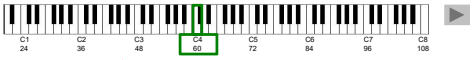
Example: Chromatic scale

Spectrogram

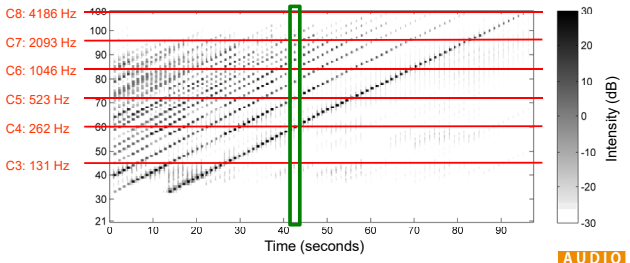


Audio Features

Example: Chromatic scale



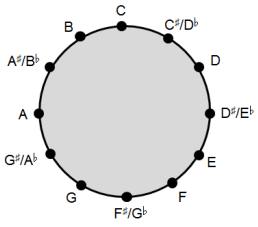
Log-frequency spectrogram



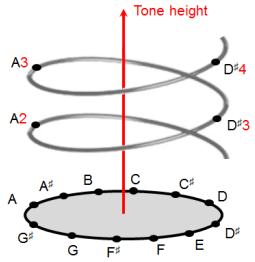
Audio Features

Chroma features

Chromatic circle

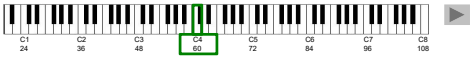


Shepard's helix of pitch

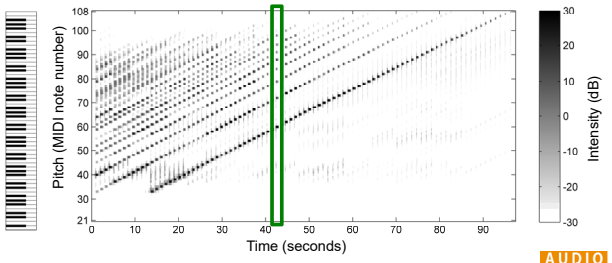


Audio Features

Example: Chromatic scale



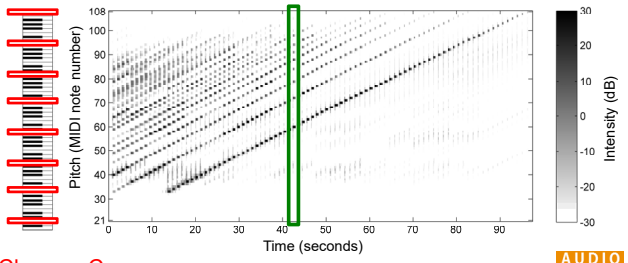
Log-frequency spectrogram



Audio Features

Example: Chromatic scale

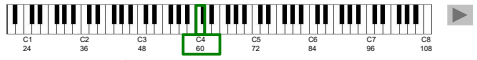
Log-frequency spectrogram



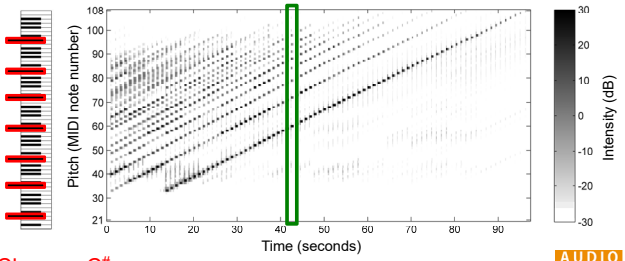
Chroma C

Audio Features

Example: Chromatic scale



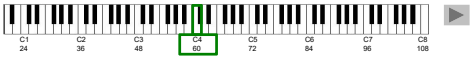
Log-frequency spectrogram



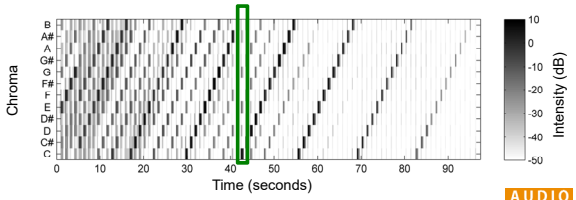
Chroma $C^{\sharp}$

Audio Features

Example: Chromatic scale

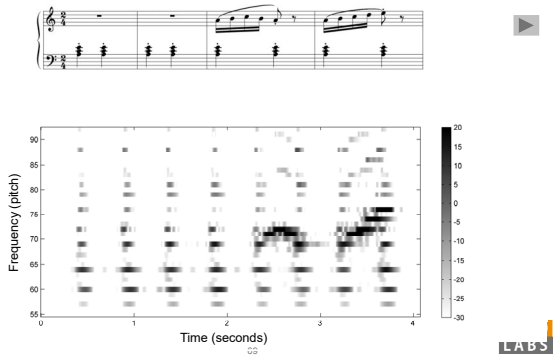


Chromagram



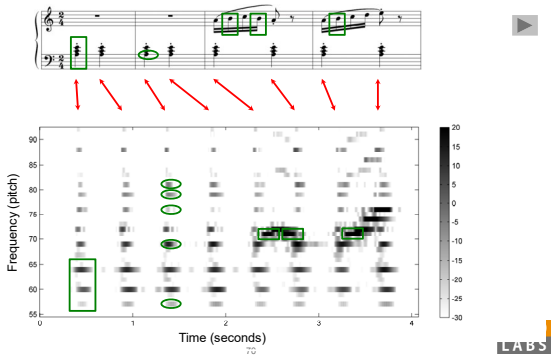
Audio Features

Chroma features



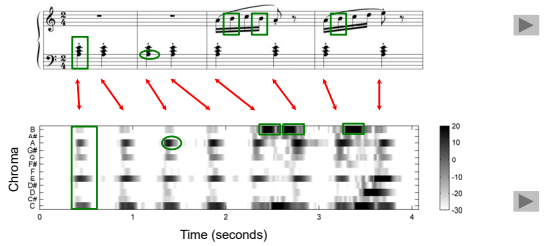
Audio Features

Chroma features



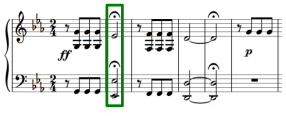
Audio Features

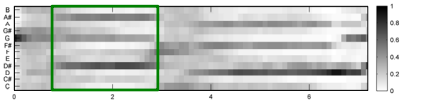
Chroma features



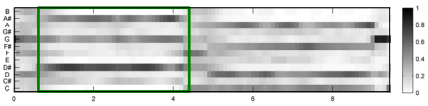
Audio Features

Chroma features (normalized)





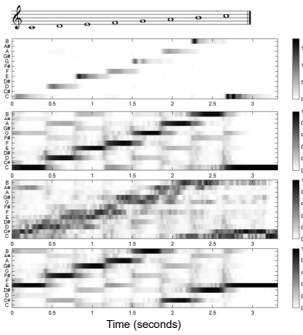
Karajan



Scherbakov

Audio Features

Chroma features



Chromagram

Chromagram after logarithmic compression and normalization

Chromagram based on a piano tuned 40 cents upwards

Chromagram after applying a cyclic shift of four semitones upwards

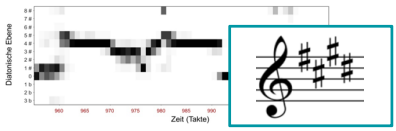
Audio Features

Practical Example:
Extracting Chroma Features with free software

- Sonic Visualizer
  https://www.sonicvisualiser.org
- NNLS / Chordino Vamp Plugin
  http://isophonics.net/nnls-chroma

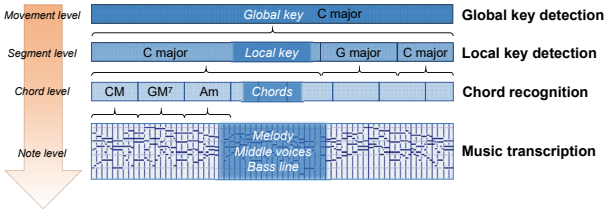
Programming Example:
Extracting Chroma Features with Python

Local Tonality Analysis Based on Diatonic Scales



Motivation

- **Harmony analysis** of music:
  - Different concepts
  - Concepts relate to different **temporal granularity**



Motivation

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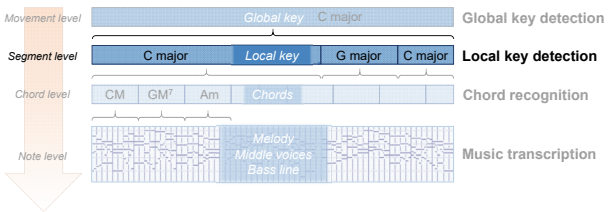
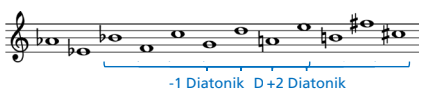


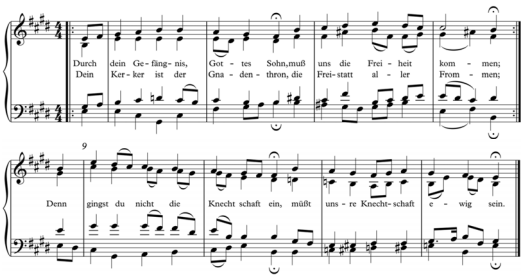
Musicological Foundations

- Method: estimate **diatonic scales – 7** fifth-related pitches
- Relationship of diatonic scales:
  - Fifth-neighbouring scales share 6 of 7 notes
  - Ordering of scales according to the **circle of fifths:**



Visualization of Diatonic Scales

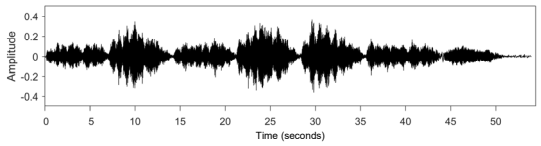
- Example: J.S. Bach, Choral "Durch Dein Gefängnis" (*Johannespassion*)
- **Score** – Piano reduction



AUDIO LABS

Visualization of Diatonic Scales

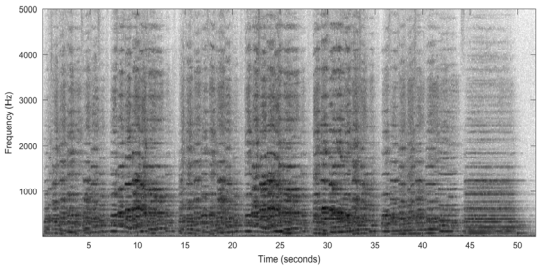
- Example: J.S. Bach, Choral "Durch Dein Gefängnis" (*Johannespassion*)
- **Audio** – Waveform (Scholars Baroque Ensemble, Naxos 1994)



AUDIO LABS

Visualization of Diatonic Scales

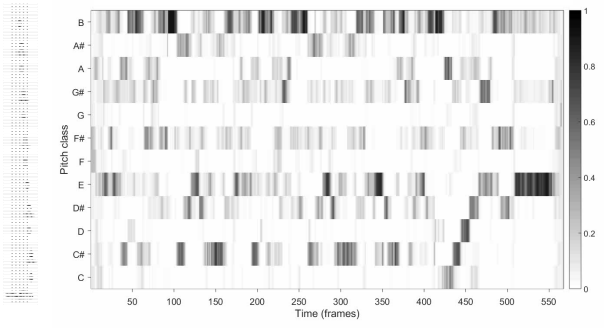
- Example: J.S. Bach, Choral "Durch Dein Gefängnis" (*Johannespassion*)
- **Audio** – Spectrogram (Scholars Baroque Ensemble, Naxos 1994)



AUDIO LABS

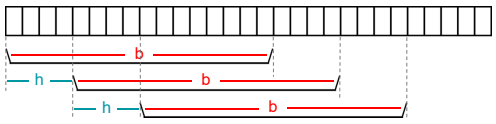
Visualization of Diatonic Scales

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



Visualization of Diatonic Scales

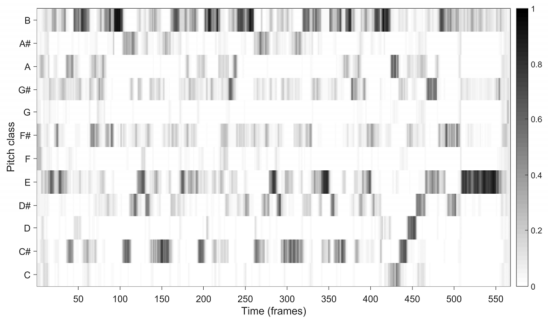
- Summarize pitch classes over a certain time
  - **Chroma smoothing**
  - Parameters: blocksize b and hopsize h



AUDIO LABS

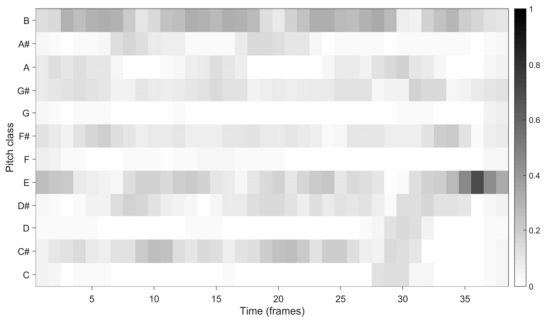
Visualization of Diatonic Scales

- Choral (Bach)



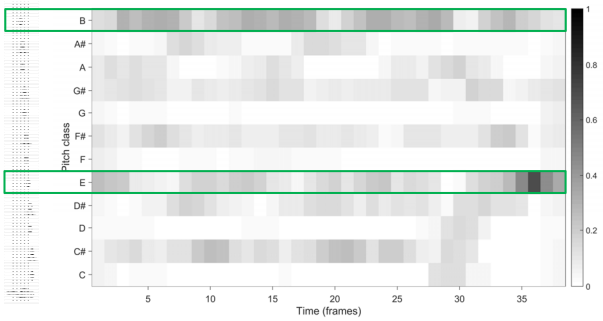
Visualization of Diatonic Scales

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



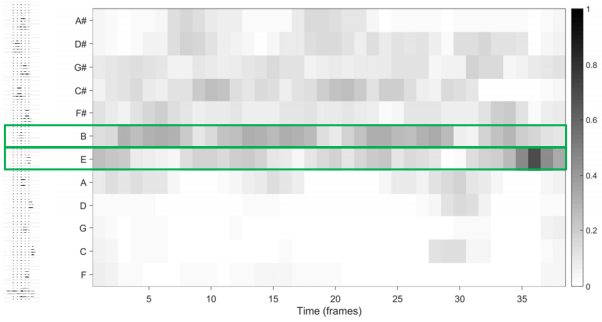
Visualization of Diatonic Scales

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



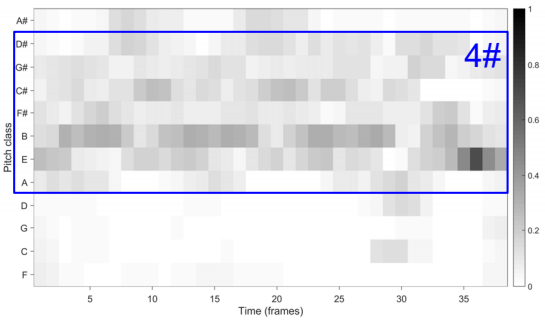
Visualization of Diatonic Scales

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



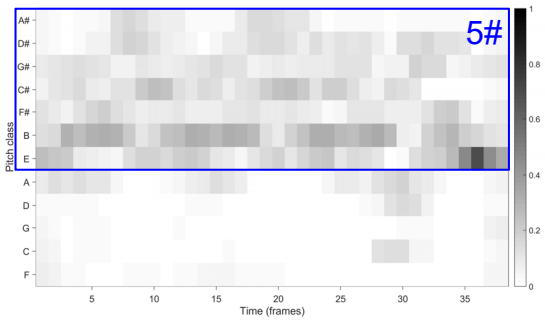
Visualization of Diatonic Scales

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



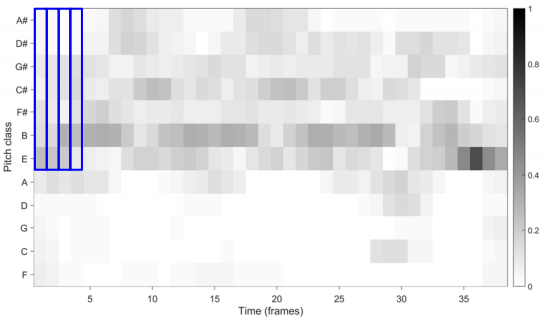
Visualization of Diatonic Scales

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



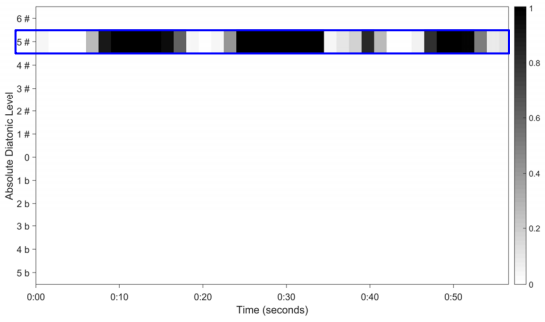
Visualization of Diatonic Scales

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



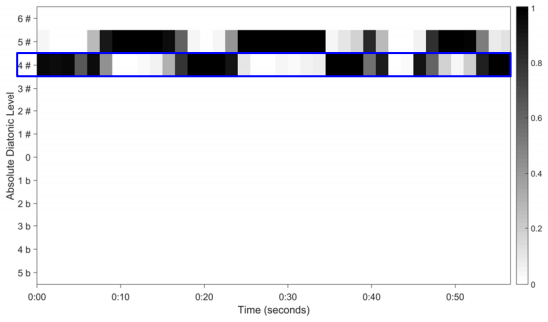
Visualization of Diatonic Scales

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



Visualization of Diatonic Scales

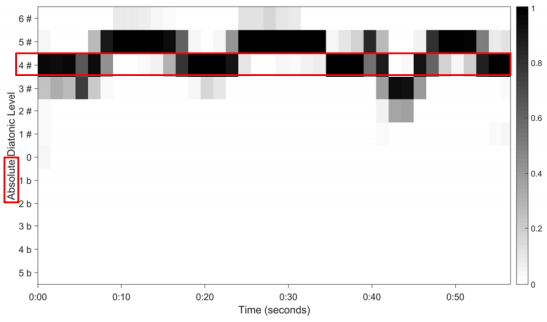
- Choral (Bach) — Diatonic Scale Estimation



Visualization of Diatonic Scales

- Choral (Bach) — Diatonic Scale Estimation

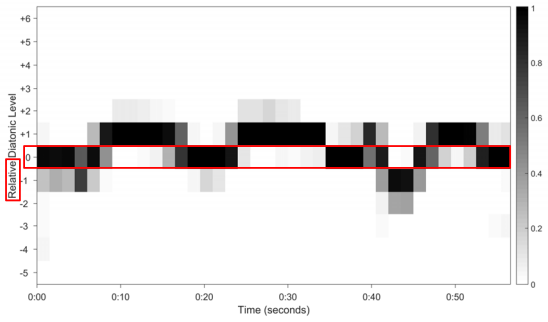
4 #
(E major)



Visualization of Diatonic Scales

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

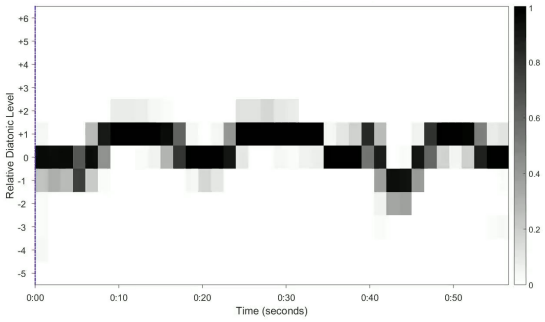
4 #
(E major)



Visualization of Diatonic Scales

- Choral (Bach) — 0 ≙ 4#

C. Weiß, J. Habryka, "Chroma-Based Scale Matching for Audio Tonality Analysis" In: *Proceedings of the 9th Conference on Interdisciplinary Musicology*, Berlin 2014.



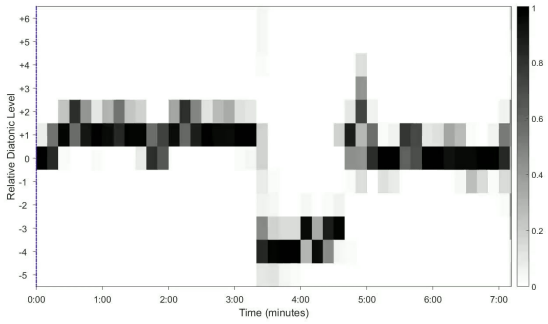
Visualization of Diatonic Scales

Programming Example:
Tonal Analysis with Python

AUDIO LABS

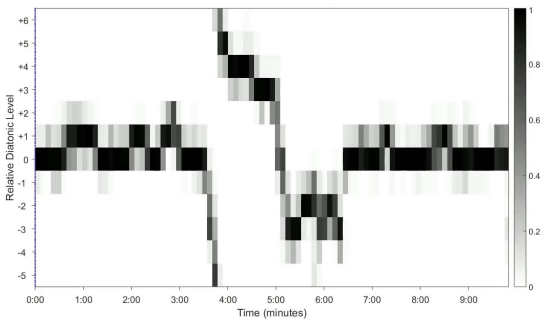
Visualization of Diatonic Scales

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

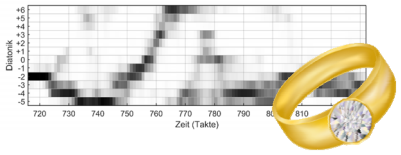


Visualization of Diatonic Scales

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



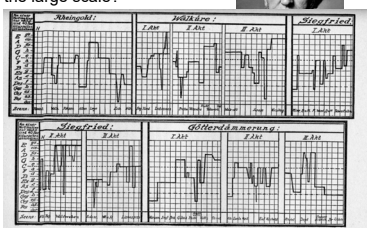
Cross-Version Tonality Analysis of the *Ring*



DFG-funded Project: Computational Analysis of Harmonic Structures

- With Prof. Rainer Kleinertz, Musicology, Uni Saarland

- Richard Wagner, *Der Ring des Nibelungen*
  - Four operas, up to 15 hours of music
  - How is harmony organized at the large scale?
  - Analyses by A. Lorenz 1924



Music Scenario

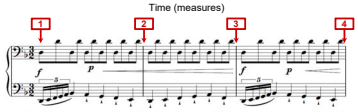
- Richard Wagner, *Die Walküre* (opera)
  - Long work (1st act: ~70 minutes)
  - No interruptions of acts

- Different data types
  - Libretto (**text**)
  - Score / piano reduction (**sheet music**)
  - Recorded performance (**audio**)


Source: Wikipedia

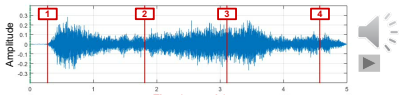
Music Scenario

Score:

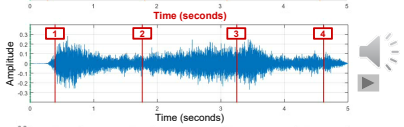


Performance (Karajan 1966):

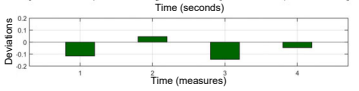
- Annotation 1



- Annotation 2

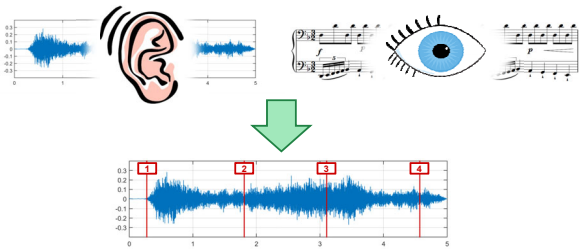


- Deviations



Manual Measure Annotations

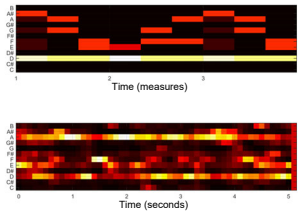
- 5 students with musical background
- Procedure: Listening while reading the vocal score
- Tool: *Sonic Visualiser*



AUDIO LABS

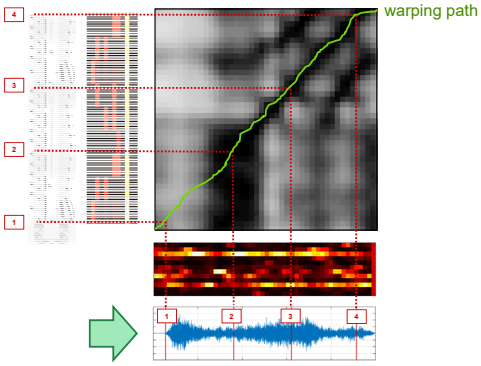
Computed Measure Annotations

- Synchronization (score-to-audio alignment)
- Based on *chroma features*



AUDIO LABS

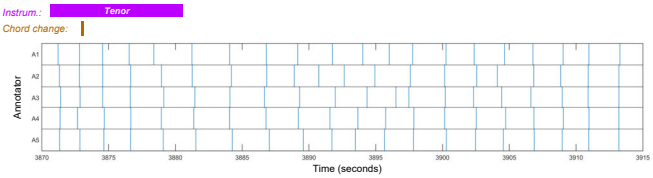
Computed Measure Annotations



AUDIO LABS

Analysis of Manual Annotations

- Compare 5 different annotators
- Questions:
  - Accuracy?
  - Typical errors?
  - Systematic offsets?
- Example passage (Karajan 1966)



AUDIO LABS

Analysis of Manual Annotations

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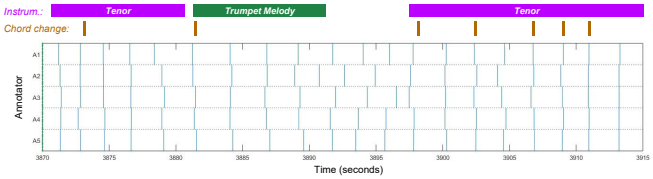
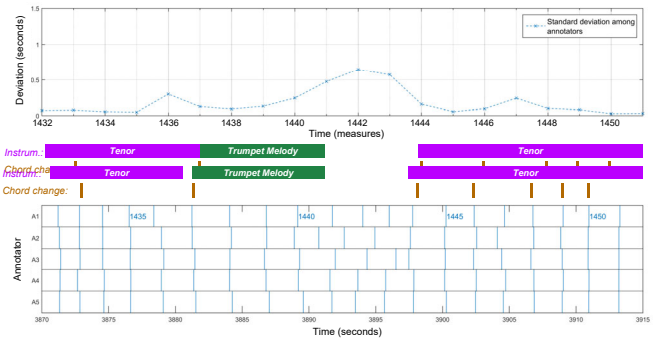
  - Typical errors?
  - Systematic offsets?
- Example passage (Karajan 1966)



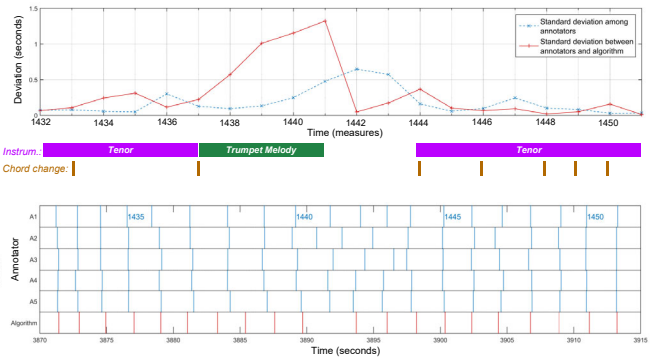
AUDIO LABS

Analysis of Manual Annotations



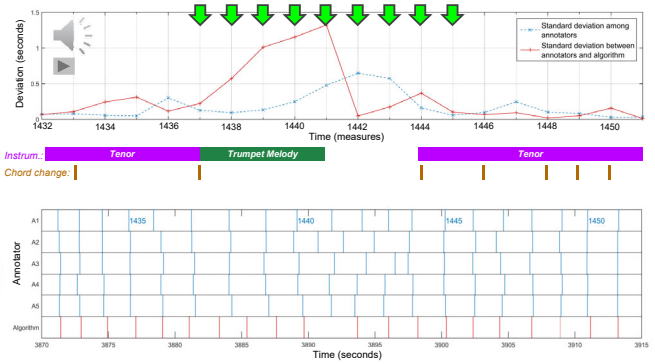
AUDIO LABS

Analysis of Computed Annotations



AUDIO LABS

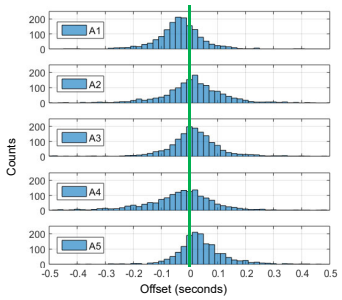
Analysis of Computed Annotations



AUDIO LABS

Analysis of Manual Annotations

Dataset: Full act (*67 minutes*, *1523 measures*)

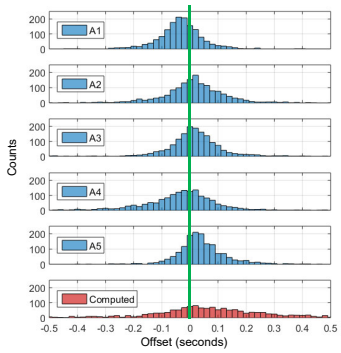


0 s = mean position of A1 … A5

AUDIO LABS

Analysis of Computed Annotations

Dataset: Full act (*67 minutes*, *1523 measures*)

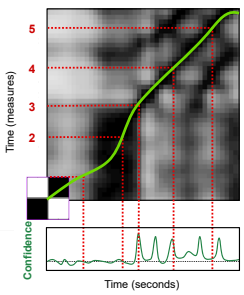


0 s = mean position of A1 … A5

AUDIO LABS

Confidences for Computed Annotations

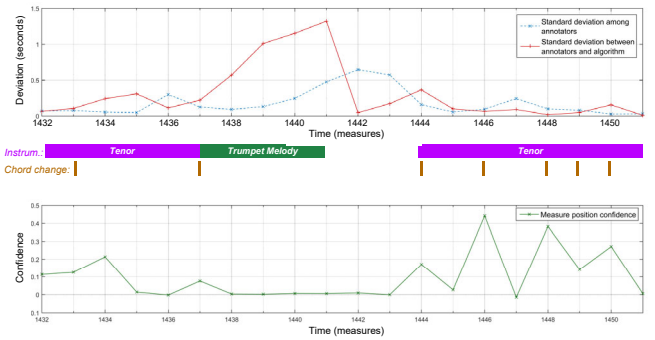
- Use information from **similarity matrix**
- Shift checkerboard kernel **along the warping path**



J. Foote (2000):
Shift checkerboard kernel **along the main diagonal of a self-similarity matrix**

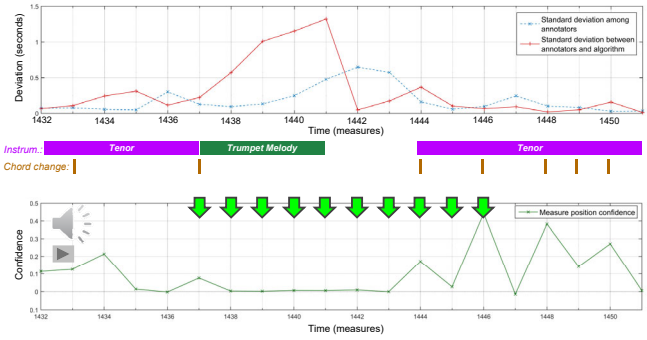
AUDIO LABS

Confidences for Computed Annotations



AUDIO LABS

Confidences for Computed Annotations



Towards Confidence-based Measure Annotations

High confidence implies high reliability (quantitative evaluation, full act)

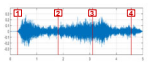
Future work:

- Reliable measures → anchor points
- → improve computed annotations
- Other types of features

C. Weiß, V. Arifi-Müller, T. Prätzlich, R. Kleinertz, M. Müller
"Analyzing Measure Annotations for Western Classical Music Recordings"
In: *Proceedings of the 17th International Society for Music Information Retrieval Conference (ISMIR)*, New York, USA 2016.

Cross-Version Analysis: Wagners Ring

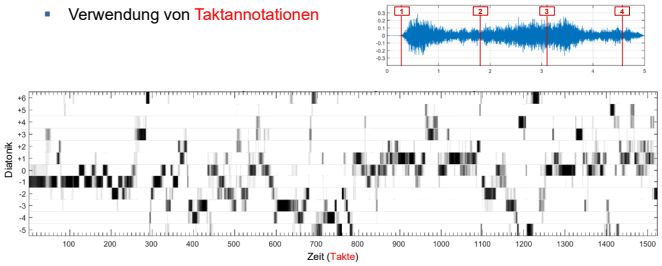
- Up to 18 versions
- 3 versions manually annotated



No.	Conductor	Recording	hh:mm:ss
1	Barenboim	1991–92	14:54:55
2	Boulez	1980–81	13:44:38
3	Böhm	1967–71	13:39:28
4	Furtwängler	1953	15:04:22
5	Haitink	1988–91	14:27:10
6	Janowski	1980–83	14:08:34
7	Karajan	1967–70	14:58:08
8	Keilberth/Furtwängler	1952–54	14:19:56
9	Krauss	1953	14:12:27
10	Levine	1987–89	15:21:52
11	Neuhold	1993–95	14:04:35
12	Sawallisch	1989	14:06:50
13	Solti	1958–65	14:36:58
14	Swarowsky	1968	14:56:34
15	Thielemann	2011	14:31:13
16	Weigle	2010–12	14:48:46

Cross-Version Analysis: Wagners Ring

- *Die Walküre*, 1. Akt (Berliner Philharmoniker, H. von Karajan, DG 1966)
- Verwendung von Taktannotationen



R. Kleinertz,
„Richard Wagners Begriff der ‚dichterisch-musikalischen Periode'"
Die Musikforschung, 67 (2014), S. 26–47

67. Jahrgang 2014
Heft 1

gfm
GESELLSCHAFT FÜR MUSIKFORSCHUNG

DIE MUSIKFORSCHUNG

Oswald Panagl
„Die Tonsprache ist Anfang und Ende der Wortsprache".
Zur Diktion der Opern und Musikdramen Richard Wagners

Rainer Kleinertz
Richard Wagners Begriff der „dichterisch-musikalischen Periode"

Gerhard Poppe
Neue Ermittlungen zur Geschichte des sogenannten „Dresdner Amen"

Besprechungen · Mitteilungen

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Bärenreiter

26

Rainer Kleinertz (Saarbrücken)

Richard Wagners Begriff der „dichterisch-musikalischen Periode"

Gemessen am Gesamtumfang des Schrifttums über Richard Wagner nehmen Studien zu grundsätzlichen Fragen der Analyse von „Form" (oder „Formen") seiner Musik immer noch einen zahlenmäßig untergeordneten Rang ein. Trotz neuer Ansätze zu weiterführenden Aspekten der Wagner-Forschung und zur wissenschaftlichen Auseinandersetzung mit seinen Notentexten[1] hat sich in den letzten Jahrzehnten wenig daran geändert, dass es kaum Analysen größerer Einheiten wie ganzer Szenen oder Akte gibt.[2] Dies könnte nicht zuletzt auch ein Problem der Begrifflichkeit sein, mit der sich das Spezifische der Musik Wagners überhaupt beschreiben ließe.

Auch wenn der Komponist selbst und die ihm zur Verfügung stehenden Begriffe sicher nicht die entscheidende und letzte Instanz für die Analyse seiner Werke darstellen, so sind doch – will man nicht einem völlig unbewussten, „dumpfen" Schaffen das Wort reden – der Rückgriff auf ihm zur Verfügung stehende oder von ihm geprägte Begriffe oder der Versuch, ein entsprechendes Vokabular aus überlieferten Dokumenten heraus zu entwickeln, zumindest denkbare Ansätze. Versucht man, Wagners Schriften und Briefe in diesem Sinne fruchtbar zu machen, so fällt auf, dass neben seinen Ausführungen zum „Motiv", dem sogenannten „Leitmotiv",[3] der Begriff der „dichterisch-musikalischen Periode" der einzige von Wagner geprägte Begriff ist, der für die Analyse seiner Werke folgenreich werden sollte. Ihm sind im dritten Teil von *Oper und Drama* (Leipzig 1852, erschienen Ende November 1851) immerhin sieben Seiten gewidmet.[4] Für Wagner, der zu nicht nur aus heutiger Sicht nicht immer besonders glücklichen Geschlechtermetaphern neigte, war im Musikdrama (er selbst spricht immer nur von „Drama") die Musik das Weib, das der Begattung durch die Sprache

1 Vgl. u. a. Reinhold Brinkmann, „Drei der Fragen stellt' ich mir frei'. Zur Wanderer-Szene im I. Akt von Wagners *Siegfried*", in: *JbSIMPK* 1972, S. 120–162; Anthony Newcomb, „The Birth of Music out of the Spirit of Drama. An Essay in Wagnerian Formal Analysis", in: *19th-Century Music* 5 (1981), S. 38–66; Patrick Phillip McCreless, *Wagner's Siegfried. Its Drama, Its History, And Its Music*, Diss. Rochester 1982; *Das Drama Richard Wagners als musikalischer Kunstwerk*, hrsg. von Carl Dahlhaus, Regensburg 1970; ders., *Wagners Konzeption des musikalischen Dramas*, Regensburg 1971; ders., *Richard Wagners Musikdramen*, Velber 1971; *Analysing Opera. Verdi and Wagner*, hrsg. von Carolyn Abbate und Roger Parker, Berkeley u. a. 1989; Thomas S. Grey, *Wagner's Musical Prose. Texts and Contexts*, Cambridge 1995, hier insbesondere das Kapitel „The 'poetic-musical period' and the 'evolution' of Wagnerian form", S. 181–241; Tobias Janz, *Klangdramaturgie. Studien zur theatralen Orchesterkomposition in Wagners „Ring des Nibelungen"*, Würzburg 2006; Rainer Kleinertz, „Liszt, Wagner, and Unfolding Form: *Orpheus* and the Genesis of *Tristan und Isolde*", in: *Franz Liszt and His World*, hrsg. von Christopher H. Gibbs und Dana Gooley, Princeton und Oxford 2006, S. 231–254.

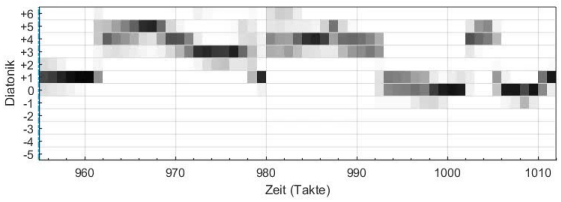
2 Vgl. Egon Voss, „Versuch der Musikwissenschaft vor der Musik Richard Wagners?", in: *Der „Komponist" Richard Wagner im Blick der aktuellen Musikwissenschaft. Symposion Würzburg 2000*, hrsg. von Ulrich Konrad und Egon Voss, Wiesbaden u. a. 2003, S. 15–24.

3 Vgl. hierzu insbesondere die Arbeit von Christian Thorau, *Semantisierte Sinnlichkeit. Studien zu Rezeption und Zeichenstruktur der Leitmotivtechnik Richard Wagners*, Stuttgart 2003.

4 Richard Wagner, *Oper und Drama*, Leipzig 1852, Teil 3: *Dichtkunst und Tonkunst im Drama der Zukunft*, S. 98–104.

Anwendungsbeispiel: Wagners Ring

- *Die Walküre*, 1. Akt (Berliner Philharmoniker, H. von Karajan, DG 1966)
- Erzählung der Sieglinde
- Beispiel für „Dichterisch-musikalische Periode"



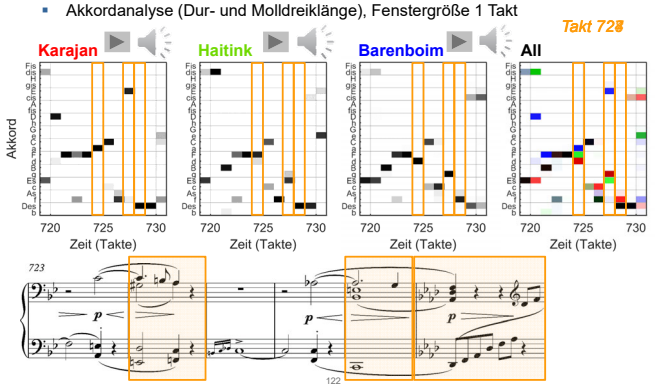
C. Weiß, R. Kleinertz, M. Müller,
„Möglichkeiten der computergestützten Erkennung und Visualisierung harmonischer Strukturen – eine Fallstudie zu Richard Wagners *Die Walküre*."
In: *Bericht zur Jahrestagung der GfM 2015*, Schott Campus 2016.

Versionsübergreifende Harmonieanalyse

- Idee: Vergleiche Analyseergebnisse basierend auf unterschiedlichen Interpretationen (*Versionen*)
- Erwartung: Harmonische Eigenschaften sind robust
- Visualisierung der Konsistenz durch ein additives Farbschema (RGB):
  - **Rot**: Herbert von Karajan, Berliner Philharmoniker 1966-70, DG
  - **Grün**: Bernard Haitink, Symphonieorchester des BR, 1988-91, EMI
  - **Blau**: Daniel Barenboim, Bayreuther Festspiele, 1991-92, Warner
  - **Schwarz**: Hohe Konsistenz über alle Versionen

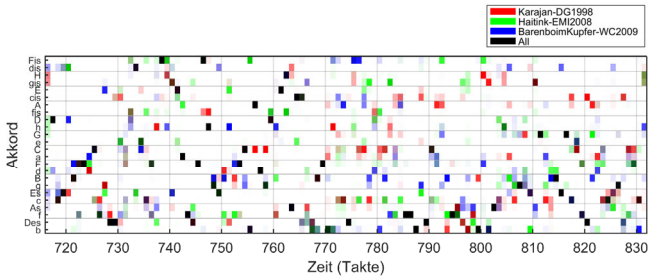
Versionsübergreifende Harmonieanalyse

- Beispiel: *Die Walküre*, Act III, Measures 720–730
- Akkordanalyse (Dur- und Molldreiklänge), Fenstergröße 1 Takt



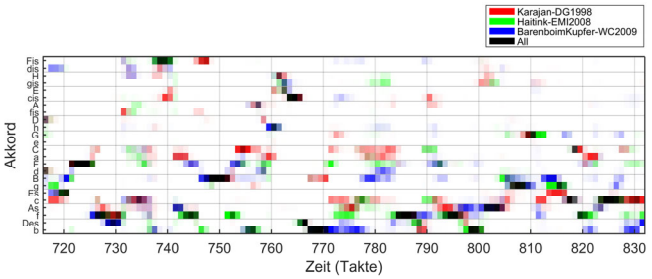
Harmonieanalyse: Parameter

- Größe des Analysefensters: 1 Takt



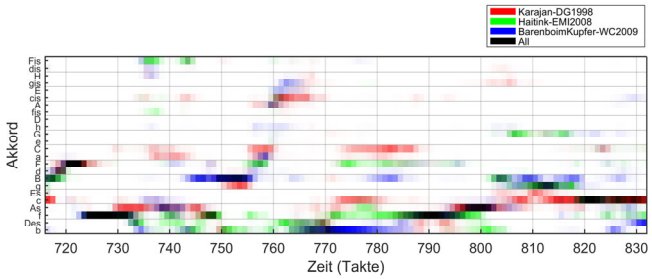
Harmonieanalyse: Parameter

- Größe des Analysefensters: 4 Takte



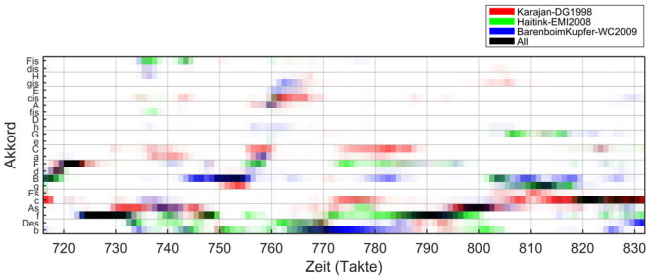
Harmonieanalyse: Parameter

- Größe des Analysefensters: 12 Takte



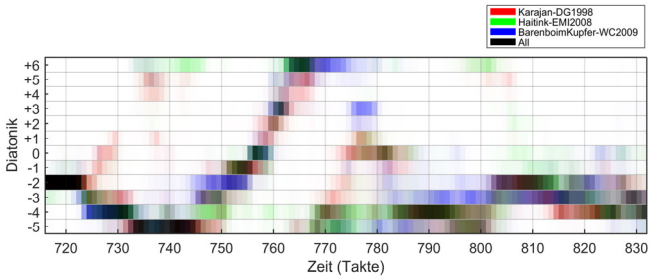
Harmonieanalyse: Parameter

- Harmonisches Konzept: Akkorde (Dur-/Molldreiklänge)



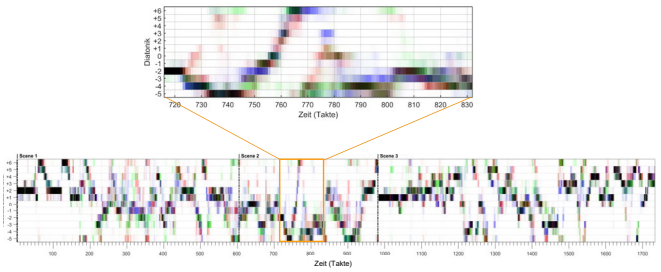
Harmonieanalyse: Parameter

- Harmonisches Konzept: Diatonische Skalen



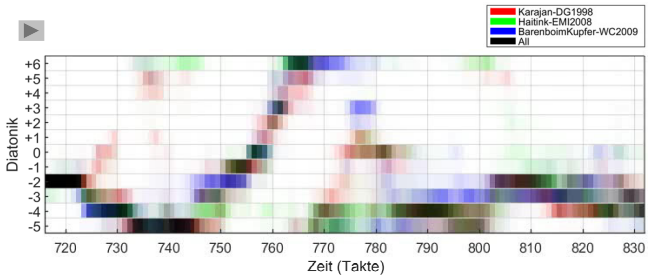
Harmonieanalyse: Parameter

- *Die Walküre*, 3. Akt
- Diatonische Skalen, Fenstergröße 12 Takte



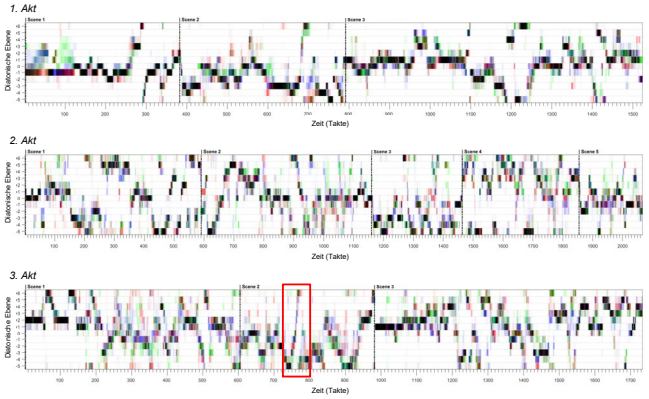
Harmonieanalyse: Parameter

- Harmonisches Konzept: Diatonische Skalen

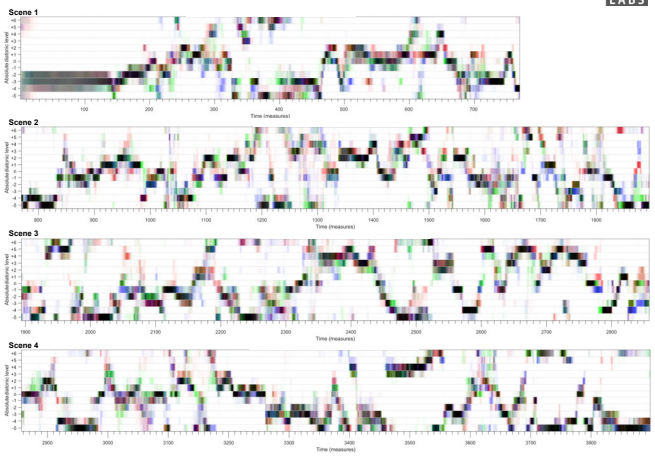


(Audio: H. von Karajan 1966, DG)

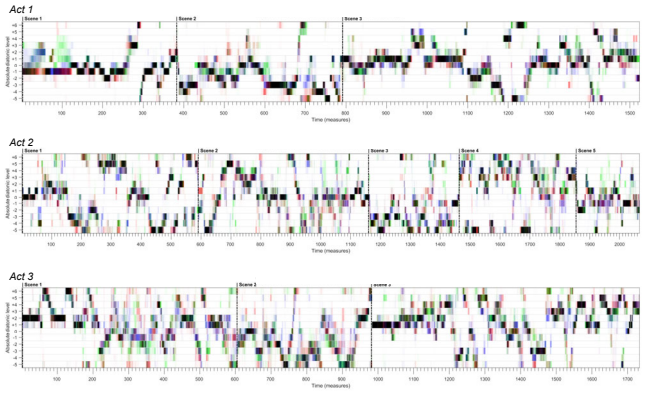
Die Walküre WWV 86 B



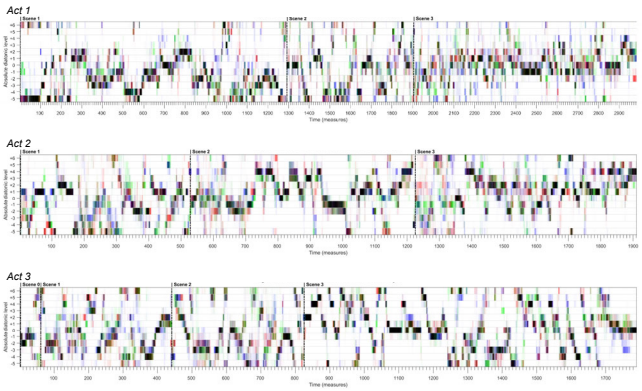
Das Rheingold WWV 86 A



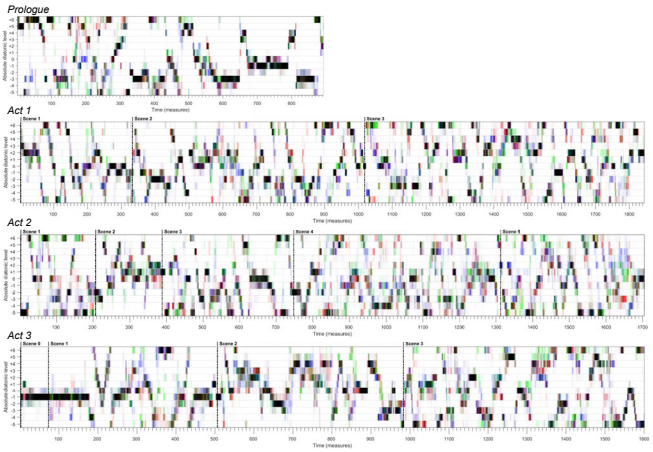
Die Walküre WWV 86 B



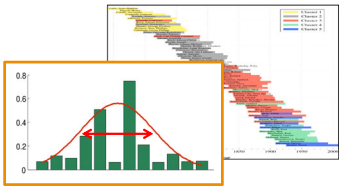
Siegfried WWV 86 C



Götterdämmerung WWV 86 D



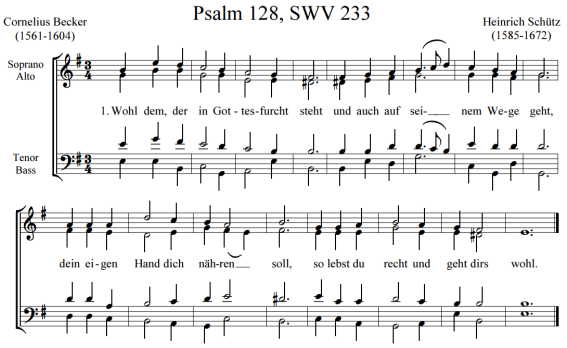
Computational Methods for Analyzing Composer Styles



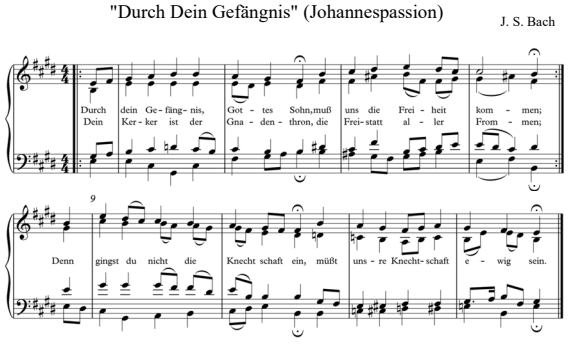
Chord transitions: Plagal vs. Authentic

- Analysis of Chorals:
- „Kantionalsatz“ (16.-17. Jh.) vs Bach-Chroal

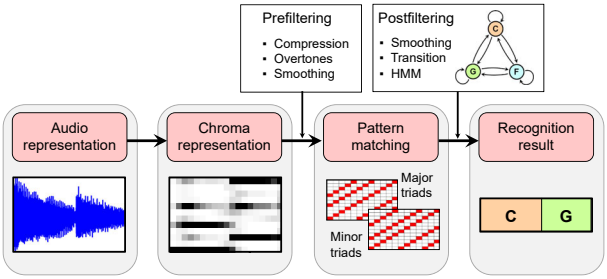
Chord transitions: Plagal vs. Authentic



Chord transitions: Plagal vs. Authentic

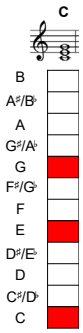


Chord transitions: Automatic Chord Recognition



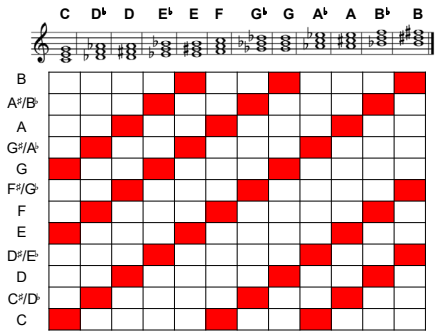
Chord transitions: Automatic Chord Recognition

- Templates: **Major Triads**



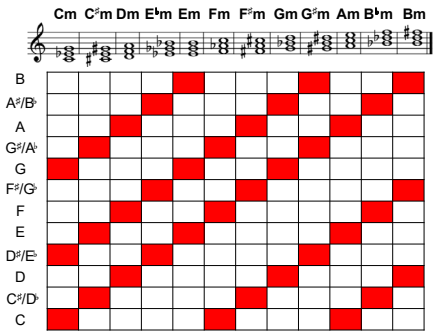
Chord transitions: Automatic Chord Recognition

- Templates: **Major Triads**

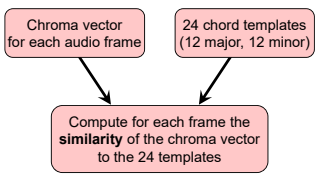


Chord transitions: Automatic Chord Recognition

- Templates: **Minor Triads**

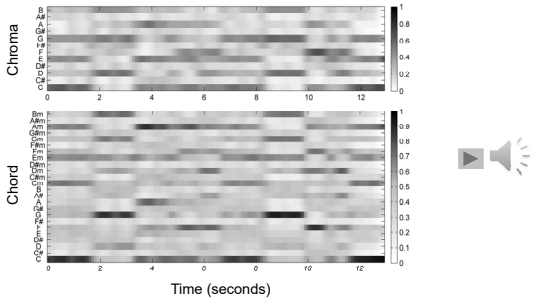


Chord transitions: Automatic Chord Recognition

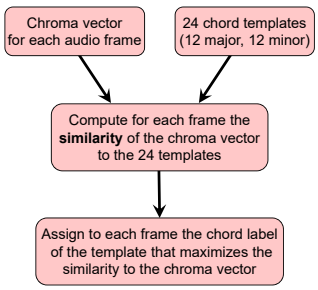


	C	C♯	D	…	Cm	C♯m	Dm	…
B	0	0	0	…	0	0	0	…
A♯	0	0	0	…	0	0	0	…
A	0	0	1	…	0	0	1	…
G♯	0	1	0	…	0	1	0	…
G	1	0	0	…	1	0	0	…
F♯	0	0	1	…	0	0	0	…
F	0	1	0	…	0	0	1	…
E	1	0	0	…	0	1	0	…
D♯	0	0	0	…	1	0	0	…
D	0	0	1	…	0	0	1	…
C♯	0	1	0	…	0	1	0	…
C	1	0	0	…	1	0	0	…

Chord transitions: Automatic Chord Recognition

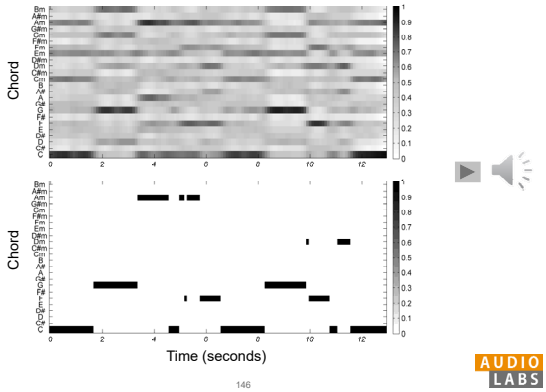


Chord transitions: Automatic Chord Recognition



	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	…

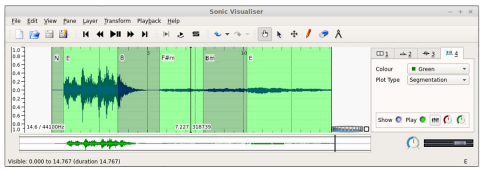
Chord transitions: Automatic Chord Recognition



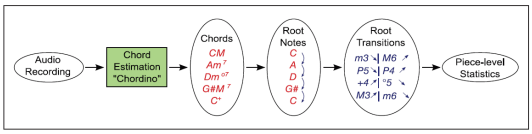
Chord transitions: Automatic Chord Recognition

Practical Example:
Extracting chord progressions with free software

- Sonic Visualizer
  https://www.sonicvisualiser.org
- NNLS / Chordino Vamp Plugin
  http://isophonics.net/nnls-chroma



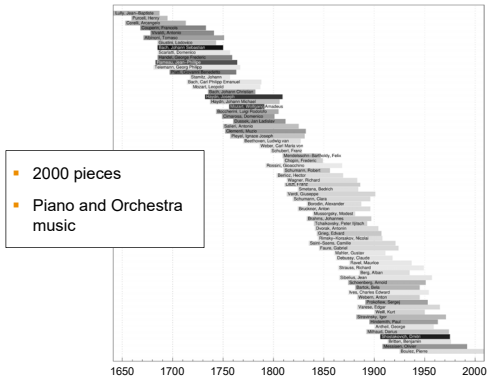
Chord transitions: Plagal vs. Authentic



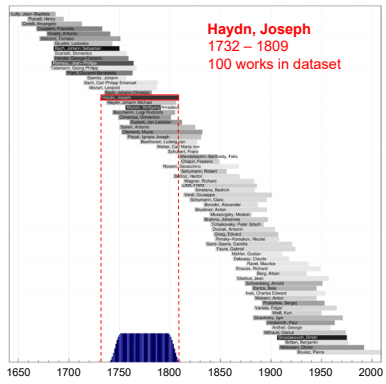
Chord transitions: Plagal vs. Authentic

Interval	Δ	Complementary	Δ	Quality
Perfect unison	0	Perfect octave ↘	−12	None
Minor second ↗	+1	Major seventh ↘	−11	Authentic
Major second ↗	+2	Minor seventh ↘	−10	Authentic
Minor third ↗	+3	Major sixth ↘	−9	Plagal
Major third ↗	+4	Minor sixth ↘	−8	Plagal
Perfect fourth ↗	+5	Perfect fifth ↘	−7	Authentic
Augmented fourth ↗	+6	Diminished fifth ↘	−6	None
Perfect fifth ↗	+7	Perfect fourth ↘	−5	Plagal
Minor sixth ↗	+8	Major third ↘	−4	Authentic
Major sixth ↗	+9	Minor third ↘	−3	Authentic
Minor seventh ↗	+10	Major second ↘	−2	Plagal
Major seventh ↗	+11	Minor second ↘	−1	Plagal
Perfect octave ↗	+12	Perfect unison	0	None

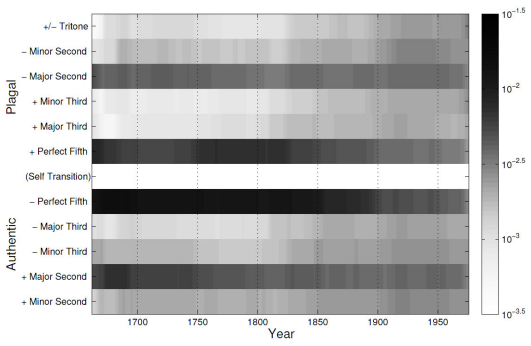
Chord transitions: Plagal vs. Authentic



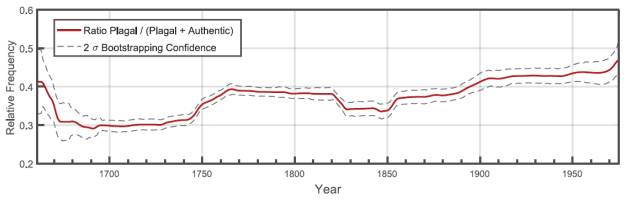
Chord transitions: Plagal vs. Authentic



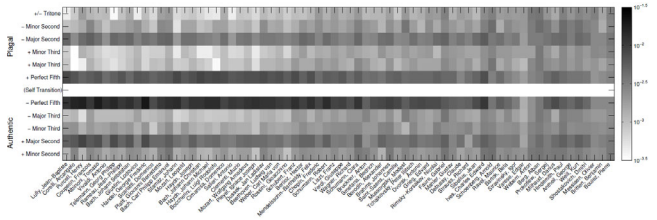
Chord transitions: Plagal vs. Authentic



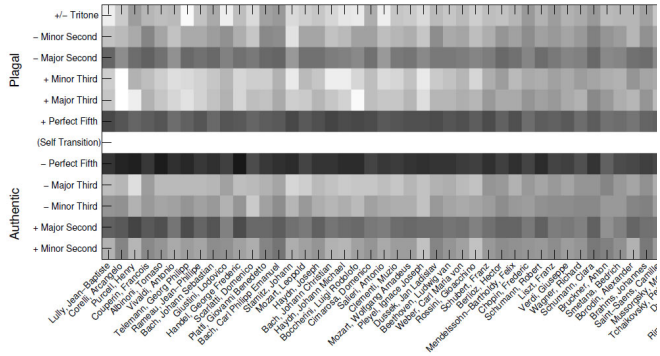
Chord transitions: Plagal vs. Authentic



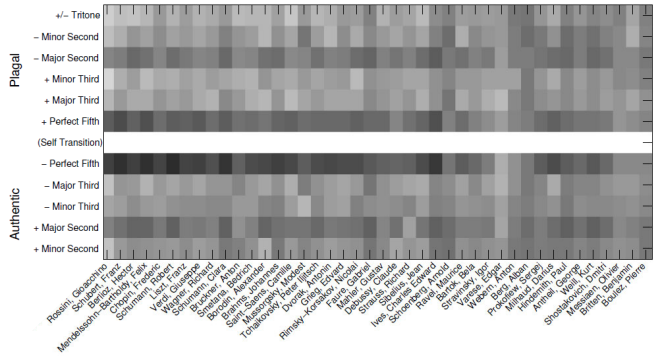
Chord transitions: Plagal vs. Authentic



Chord transitions: Plagal vs. Authentic

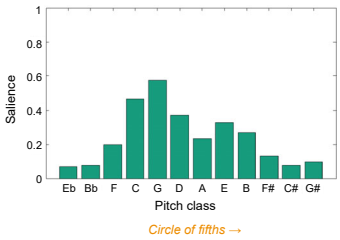


Chord transitions: Plagal vs. Authentic



Tonal Complexity

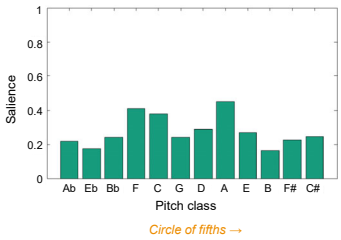
- Global chroma statistics (audio)
- **1783** – W. A. Mozart, „Linz“ symphony KV 425, 1. Adagio / Allegro (C major)



Circle of fifths →

Tonal Complexity

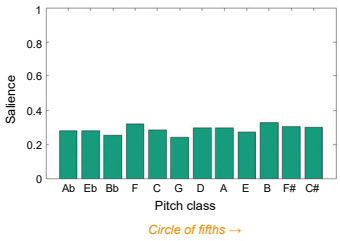
- Global chroma statistics (audio)
- **1883** – J. Brahms, Symphony No. 3, 1. Allegro con brio (F major)



Circle of fifths →

Tonal Complexity

- Global chroma statistics (audio)
- **1940** – A. Webern, Variations for Orchestra op. 30



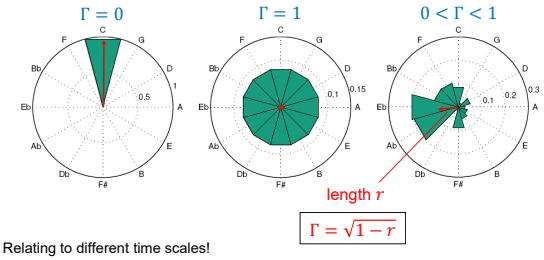
Circle of fifths →

Tonal Complexity

- Realization of complexity measure Γ

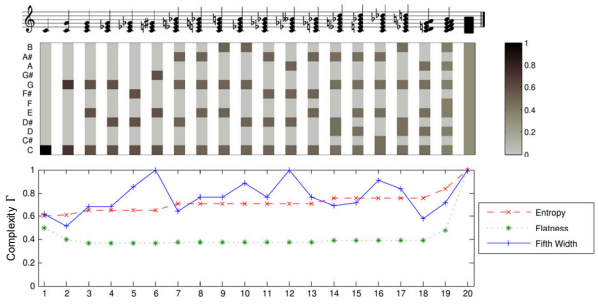
  Entropy / Flatness measures

  Distribution over *Circle of Fifths*



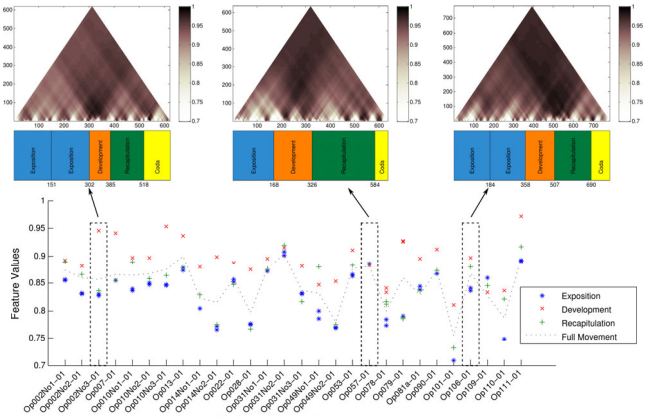
- Relating to different time scales!

Tonal Complexity – Chords

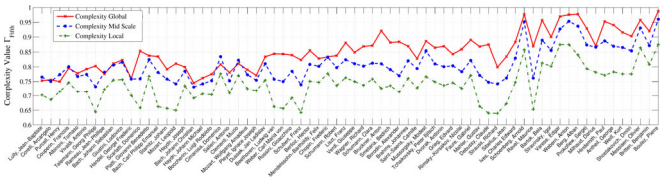


[8] Weiss / Müller, *Quantifying and Visualizing Tonal Complexity*, CIM 2014

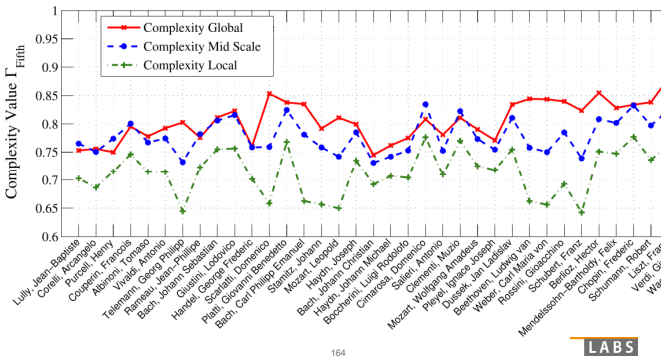
Tonal Complexity – Beethoven's Sonatas



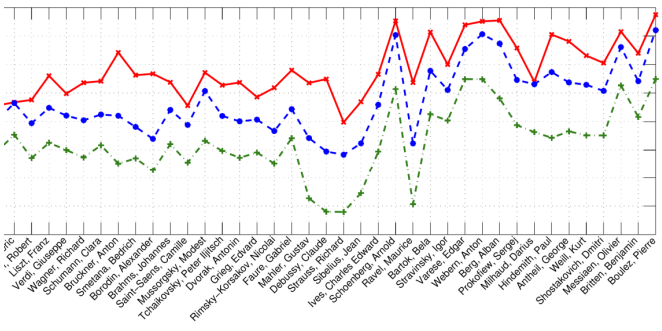
Tonal Complexity – Composers



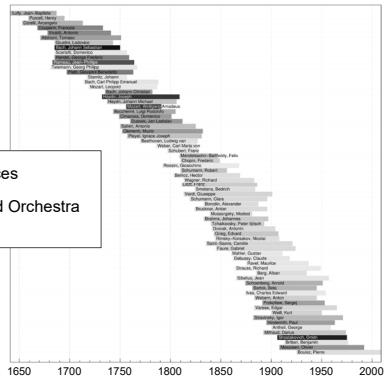
Tonal Complexity – Composers



Tonal Complexity – Composers

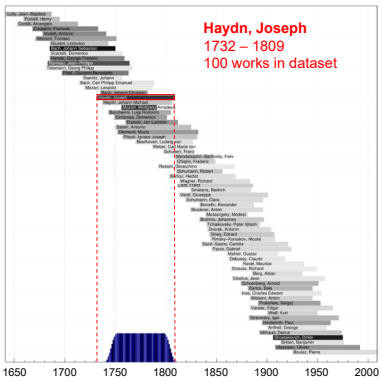


Analyzing Composer Styles

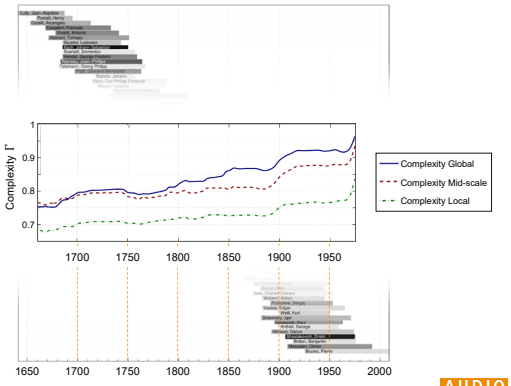


- 2000 pieces
- Piano and Orchestra music

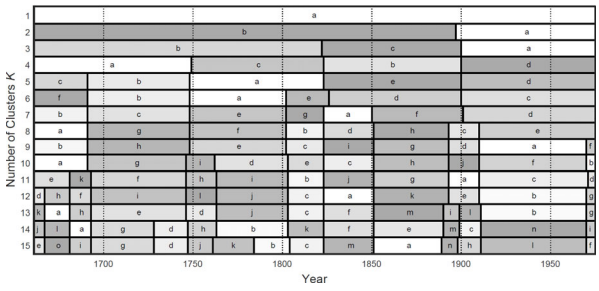
Analyzing Composer Styles



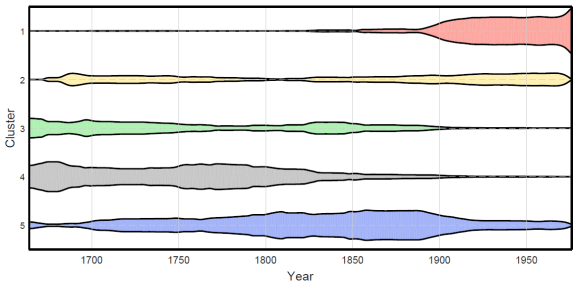
Analyzing Composer Styles



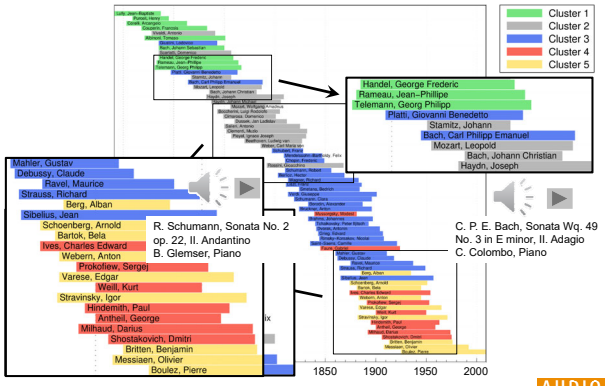
Clustering Composition Years



Clustering Individual Pieces



Clustering Composers



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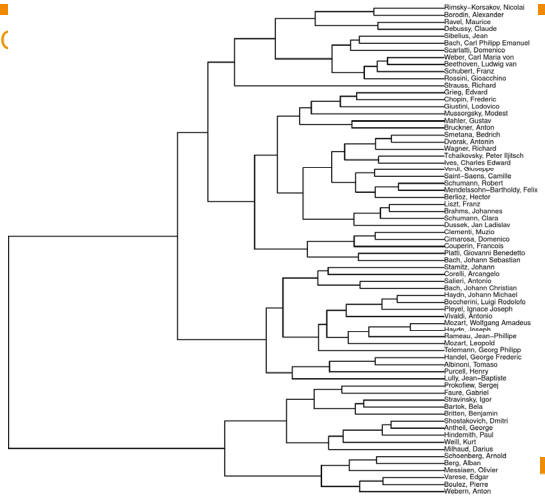
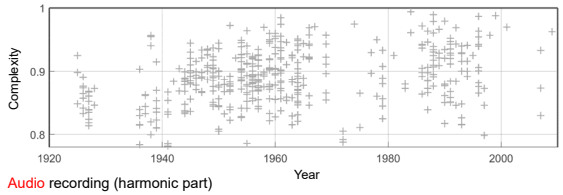
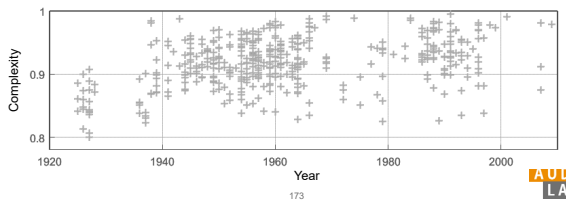


Tonal Complexity: Jazz Solos

- Symbolic transcription

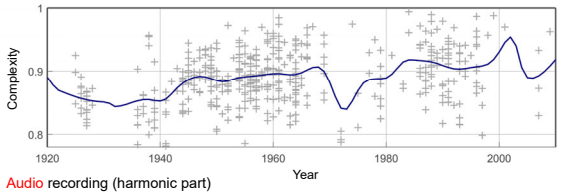


- Audio recording (harmonic part)

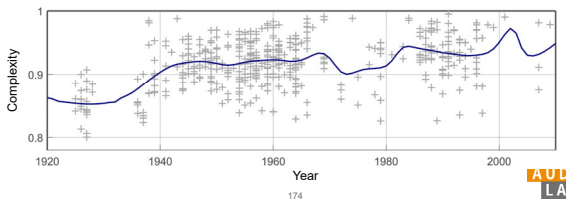


Tonal Complexity: Jazz Solos

- Symbolic transcription



- Audio recording (harmonic part)

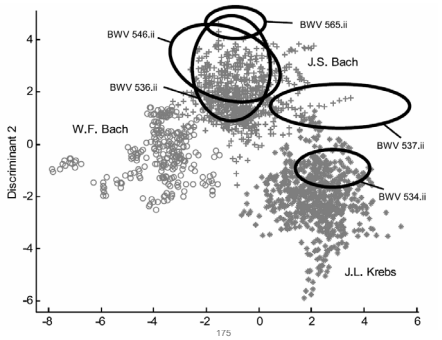


Clustering Composers

- Was interessiert das einen Musikwissenschaftler?

  Beispiel: Authentizitäts-Forschung

  Vgl. Orgelfugen von J.S. Bach, W.F. Bach (Sohn) und J.L. Krebs (Schüler)



AUDIO LABS