INTERNATIONAL AUDIO LABORATORIES ERLANGEN

AUDIO LABS

Ringvorlesung TechTalk

Philosophische Fakultät, FAU, WS 2019/20

Neue Wege für die Musikforschung mittels Digitaler Signalverarbeitung

Christof Weiß, Meinard Müller

International Audio Laboratories Erlangen

christof.weiss@audiolabs-erlangen.de, meinard.mueller@audiolabs-erlangen.de

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

Fraunhofer IIS

Christof Weiß

- Physics Diploma
  - Universität Würzburg
- Composition
  - HfM Würzburg
- Ph. D. in Media Technology
  - Fraunhofer IDMT, Ilmenau
- Postdoc in Music Processing & Composer
  - AudioLabs / Erlangen-Nürnberg University
- 2018: KlarText award for science communication

Julius-Maximilians-UNIVERSITÄT WÜRZBURG

Hochschule für Musik Würzburg university of music

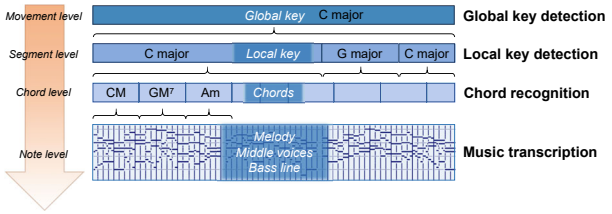
Fraunhofer IDMT

AUDIO LABS

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

Harmony Analysis

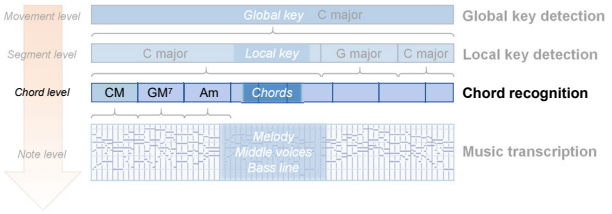
- Different concepts
- Concepts relate to different **temporal granularity**



AUDIO LABS

Harmony Analysis

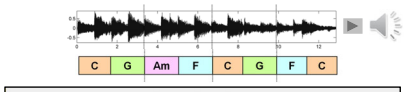
- Different concepts
- Concepts relate to different **temporal granularity**



AUDIO LABS

Harmony Analysis

- The Beatles, *Let it be* – **Chords**



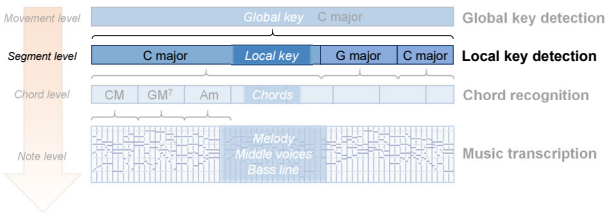

```
Let It Be chords
The Beatles 1970  (Let It Be)

[Intro]

C G Am F C G
F C Dm C

[Verse 1]

      C                G                  Am          F
When I find myself in times of trouble, Mother Mary comes to me
C                G                F C Dm C
Speaking words of wisdom, let it be
```

Source: www.ultimate-guitar.com

AUDIO LABS

Harmony Analysis

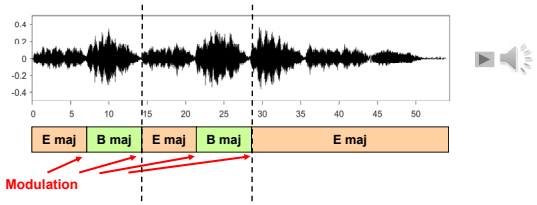
- Different concepts
- Concepts relate to different **temporal granularity**



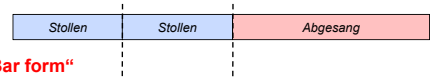
AUDIO LABS

Harmony Analysis: Local Keys

- Johann Sebastian Bach, Choral “Durch Dein Gefängnis” (*St. John’s Passion*) – **Local keys**



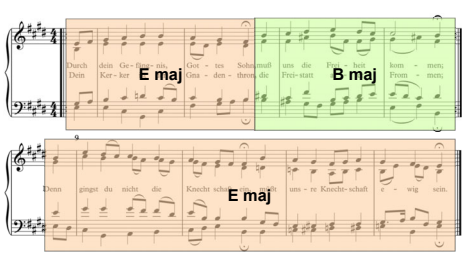
- Musical form:



„Bar form“

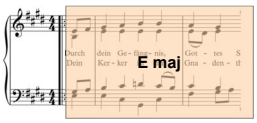
Harmony Analysis: Local Keys

- Johann Sebastian Bach, Choral “Durch Dein Gefängnis” (*St. John’s Passion*) – **Local keys**

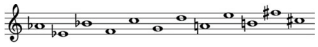


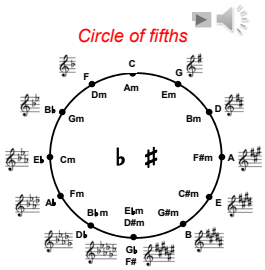
Harmony Analysis: Local Keys

- Johann Sebastian Bach, Choral “Durch Dein Gefängnis” (*St. John’s Passion*) – **Local keys**



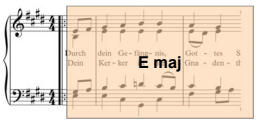
Series of fifths



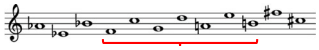


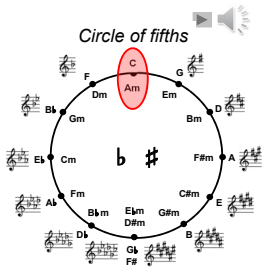
Harmony Analysis: Local Keys

- Johann Sebastian Bach, Choral “Durch Dein Gefängnis” (*St. John’s Passion*) – **Local keys**



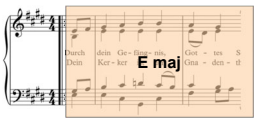
Series of fifths



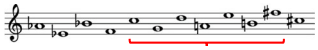


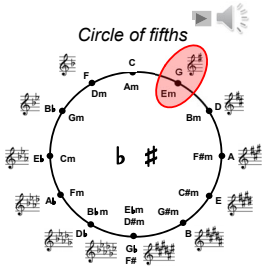
Harmony Analysis: Local Keys

- Johann Sebastian Bach, Choral “Durch Dein Gefängnis” (*St. John’s Passion*) – **Local keys**



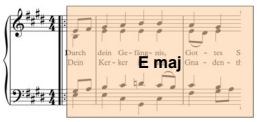
Series of fifths



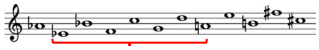


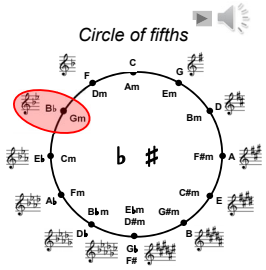
Harmony Analysis: Local Keys

- Johann Sebastian Bach, Choral “Durch Dein Gefängnis” (*St. John’s Passion*) – **Local keys**



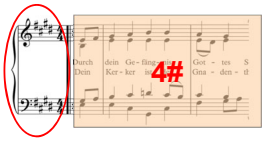
Series of fifths



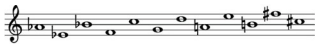


Harmony Analysis: Local Keys

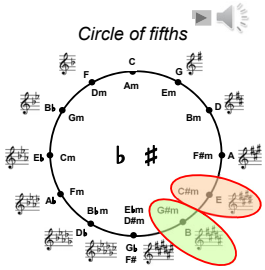
- Johann Sebastian Bach, Choral “Durch Dein Gefängnis” (*St. John’s Passion*) – **Local keys**



Series of fifths

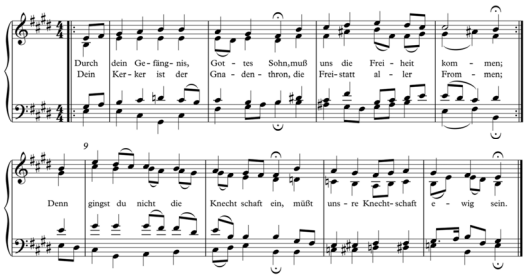


Circle of fifths



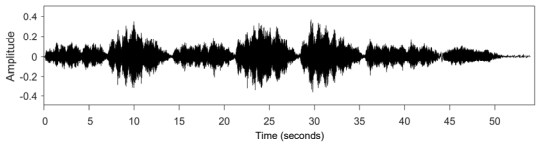
Visualization of Diatonic Scales

- Example: J.S. Bach, Choral “Durch Dein Gefängnis”
- **Score** – Piano reduction



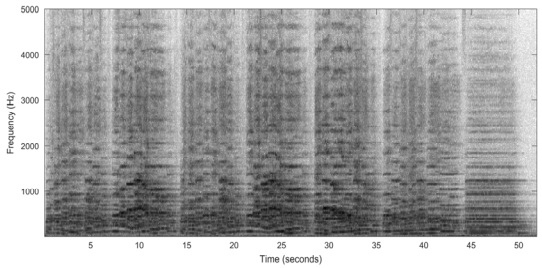
Visualization of Diatonic Scales

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



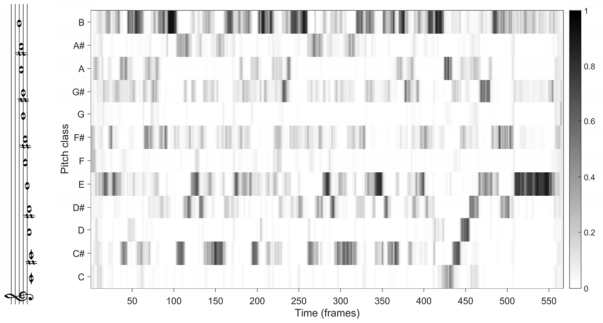
Visualization of Diatonic Scales

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



Visualization of Diatonic Scales

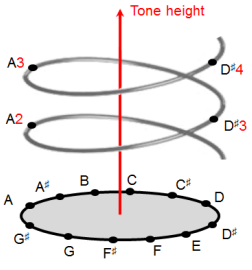
- Example: J.S. Bach, Choral “Durch Dein Gefängnis”
- **Audio** – Chroma features (Scholars Baroque Ensemble, Naxos 1994)



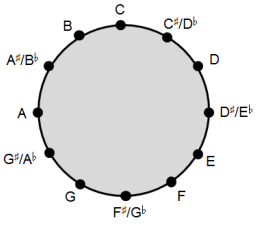
Chroma Features

- Human perception of pitch is periodic
- Two components: tone height (octave) and chroma (pitch class)

Shepard’s helix of pitch

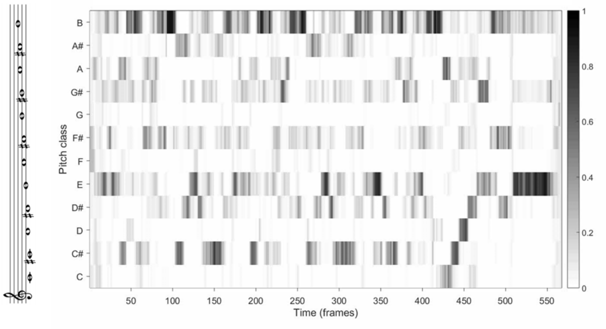


Chromatic circle



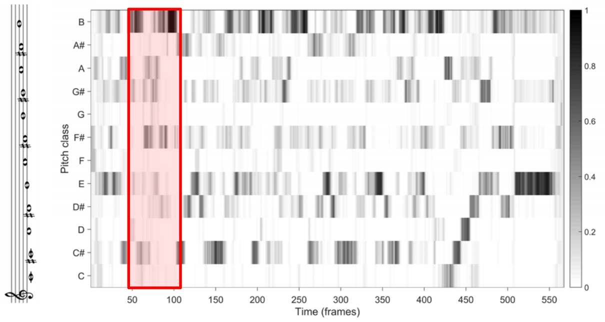
Visualization of Diatonic Scales

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



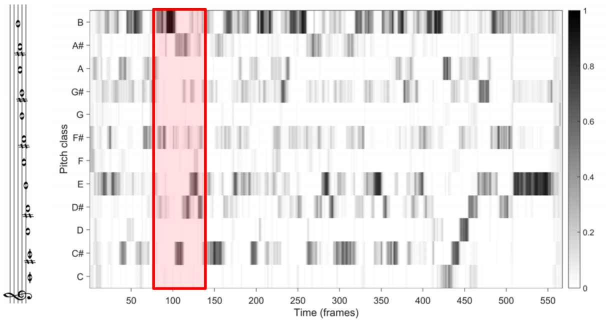
Visualization of Diatonic Scales

- Example: J.S. Bach, Choral "Durch Dein Gefängnis"
- Chroma features – smoothing



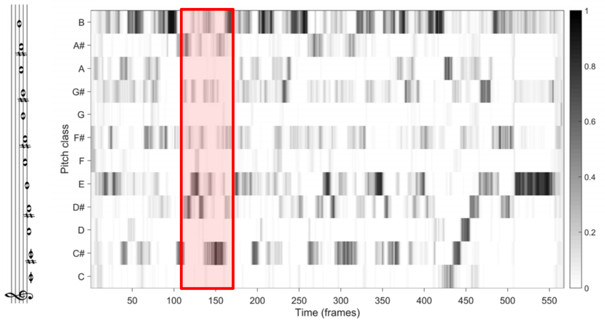
Visualization of Diatonic Scales

- Example: J.S. Bach, Choral "Durch Dein Gefängnis"
- Chroma features – smoothing



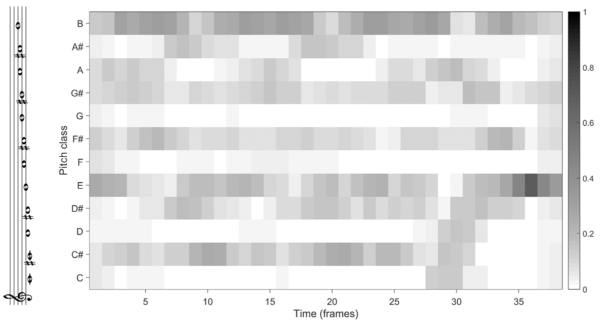
Visualization of Diatonic Scales

- Example: J.S. Bach, Choral "Durch Dein Gefängnis"
- Chroma features – smoothing



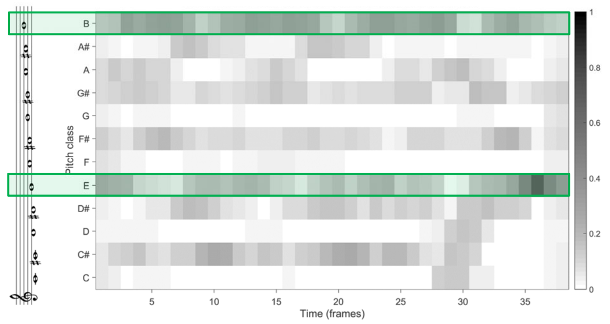
Visualization of Diatonic Scales

- Example: J.S. Bach, Choral "Durch Dein Gefängnis"
- Chroma features – smoothing



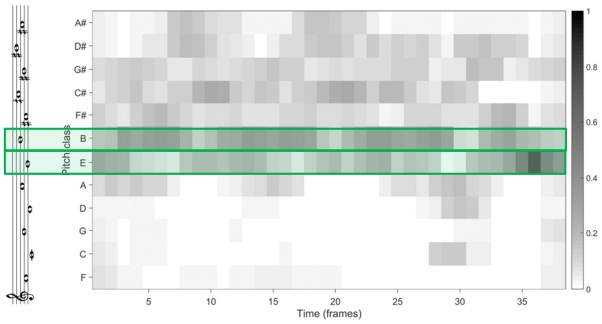
Visualization of Diatonic Scales

- Example: J.S. Bach, Choral "Durch Dein Gefängnis"
- Re-ordering to **perfect fifth** series



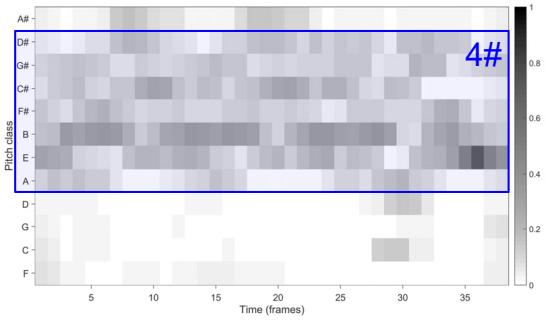
Visualization of Diatonic Scales

- Example: J.S. Bach, Choral “Durch Dein Gefängnis”
- Re-ordering to **perfect fifth** series



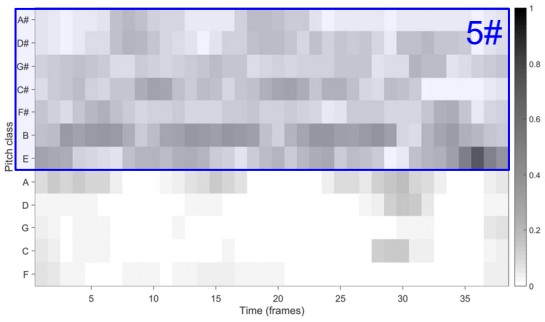
Visualization of Diatonic Scales

- Example: J.S. Bach, Choral “Durch Dein Gefängnis”
- Diatonic Scales (7 fifths)



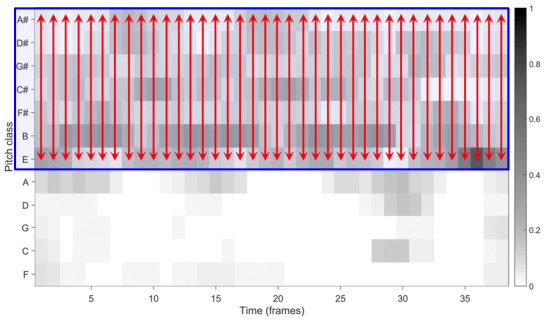
Visualization of Diatonic Scales

- Example: J.S. Bach, Choral “Durch Dein Gefängnis”
- Diatonic Scales (7 fifths)



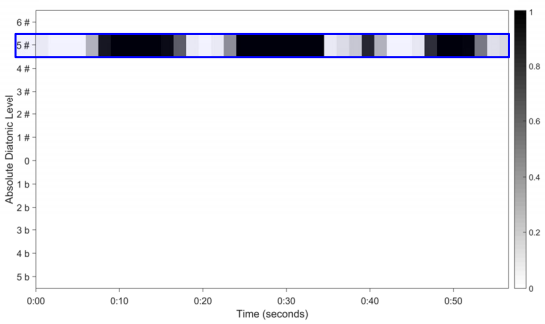
Visualization of Diatonic Scales

- Example: J.S. Bach, Choral “Durch Dein Gefängnis”
- Diatonic Scales – multiplication



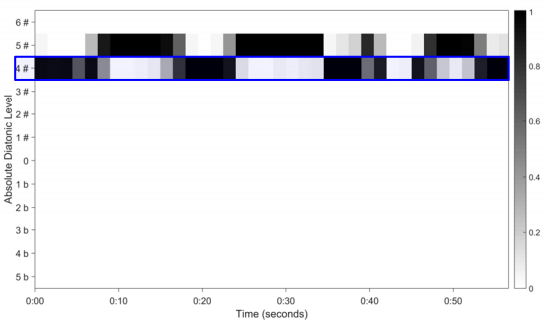
Visualization of Diatonic Scales

- Example: J.S. Bach, Choral “Durch Dein Gefängnis”
- Diatonic Scales – multiplication



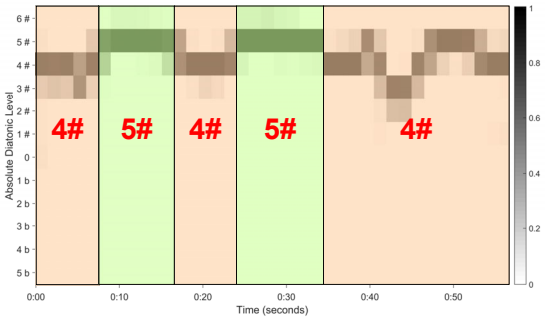
Visualization of Diatonic Scales

- Example: J.S. Bach, Choral “Durch Dein Gefängnis”
- Diatonic Scales – multiplication



Visualization of Diatonic Scales

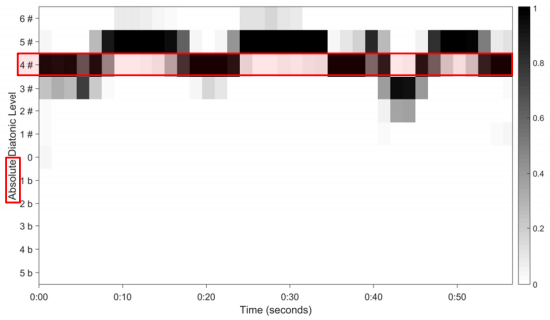
- Example: J.S. Bach, Choral “Durch Dein Gefängnis”
- Diatonic Scales – multiplication



Visualization of Diatonic Scales

- Example: J.S. Bach, Choral “Durch Dein Gefängnis”
- Diatonic Scales – shift to **global key**

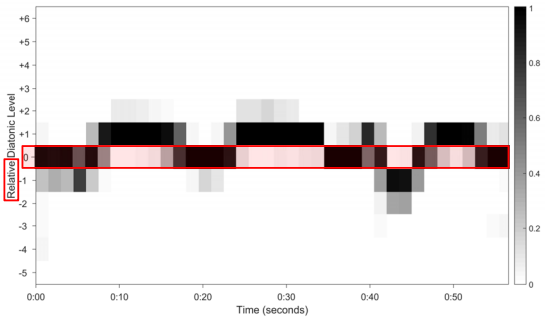
4 #
(E major)



Visualization of Diatonic Scales

- Example: J.S. Bach, Choral “Durch Dein Gefängnis”
- Diatonic Scales – shift to **global key**

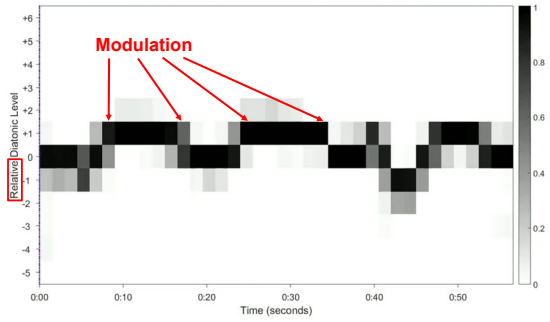
4 #
(E major)



Visualization of Diatonic Scales

- Example: J.S. Bach, Choral “Durch Dein Gefängnis”
- Diatonic Scales – relative

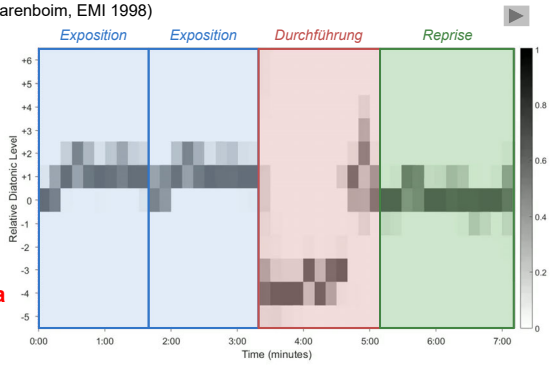
[1] C. Weiß, J. Habryka, “Chroma-Based Scale Matching for Audio Tonality Analysis”
Proc. Conference on Interdisciplinary Musicology, 2014.



Visualization of Diatonic Scales

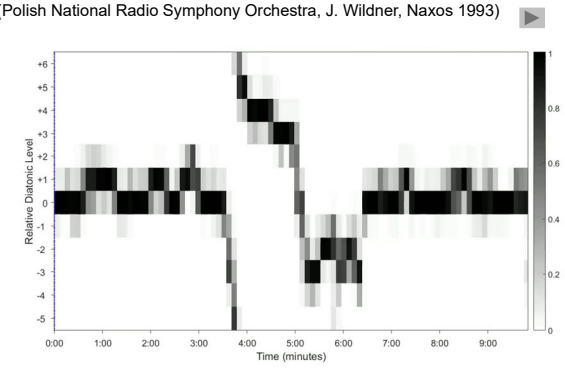
- L. v. Beethoven – Sonata No. 10 op. 14 Nr. 2, 1. Allegro — 0 ≙ 1
  (Barenboim, EMI 1998)

sonata form



Visualization of Diatonic Scales

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

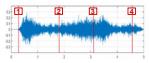


Cooperation: Musicology

- DFG-funded project: “Computer-Assisted Analysis of Harmonic Structures”
  - Harmony analysis and visualization
  - 1st phase: 2014–2018, 2nd phase: 2019–2023
- Partners:
  - Rainer Kleinertz, Musicology Univ. Saarland
  - Stephanie Klauk, Musicology Univ. Saarland
  - Meinard Müller, AudioLabs FAU
  - Christof Weiß, AudioLabs FAU
- Central work: Richard Wagner, *Der Ring des Nibelungen*
- *How is harmony organized at the large scale?*

Cross-Version Analysis

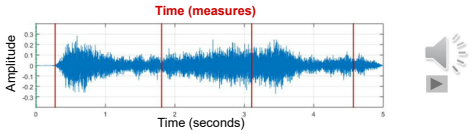
- 16 different performances (*versions*)
- Manual **measure annotations** for 3 versions



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

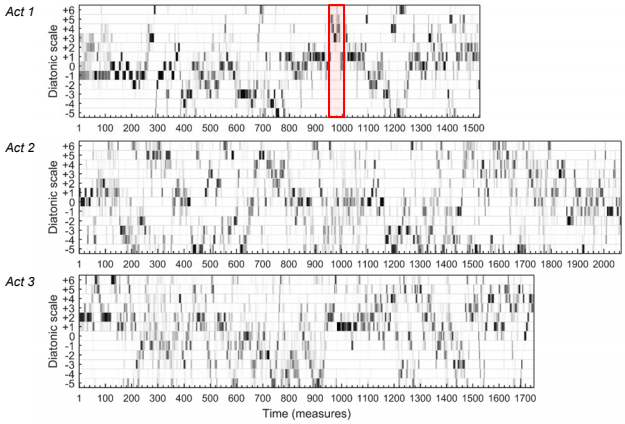
Cross-Version Analysis

- 16 different performances (*versions*)
- Manual **measure annotations** for 3 versions



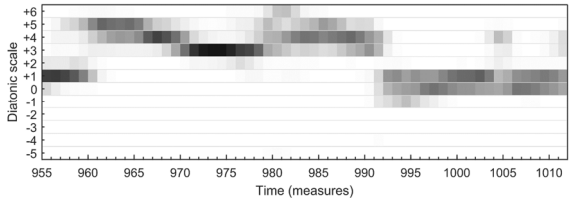
- Visualize cross-version consistency with gray scale

Die Walküre WWV 86 B



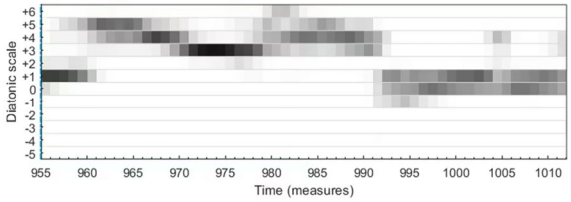
Die Walküre WWV 86 B

- Act 1, measures 955–1012
- Sieglinde’s narration

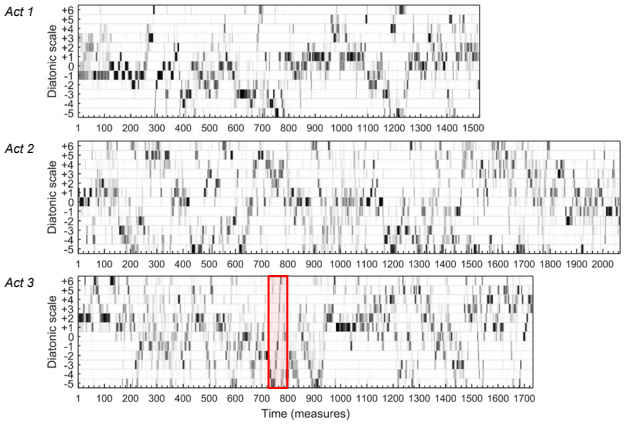


Die Walküre WWV 86 B

- Act 1, measures 955–1012
- Sieglinde’s narration

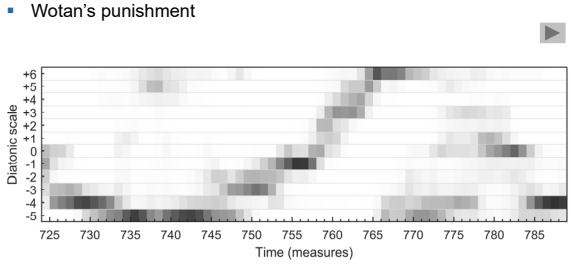


Die Walküre WWV 86 B



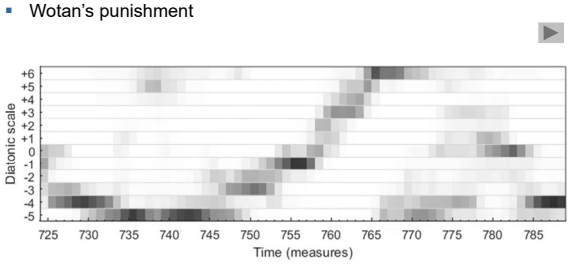
Die Walküre WWV 86 B

- Act 3, measures 724–789
- Wotan's punishment



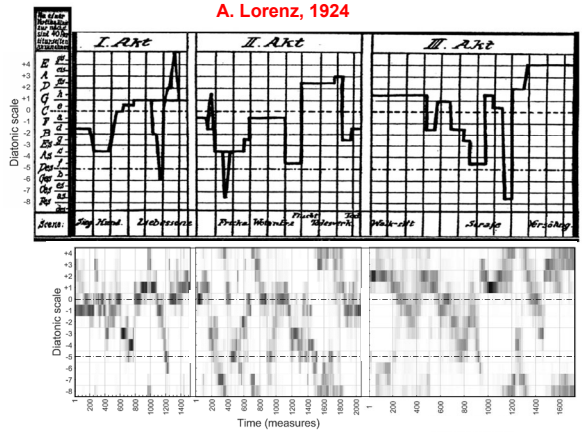
Die Walküre WWV 86 B

- Act 3, measures 724–789
- Wotan's punishment



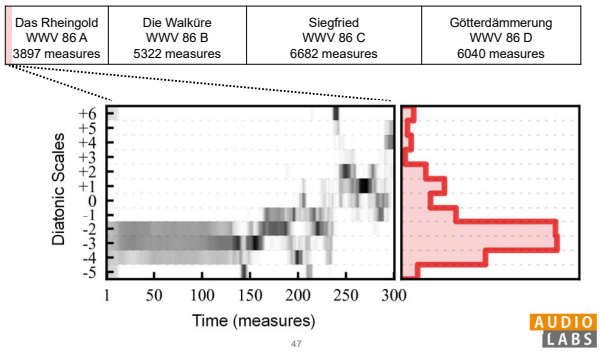
Die Walküre WWV 86 B

A. Lorenz, 1924



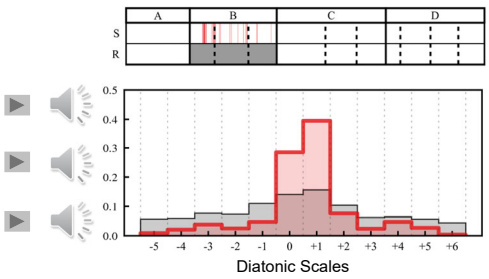
Exploring Tonal-Dramatic Relationships

- Histograms of Analysis over time



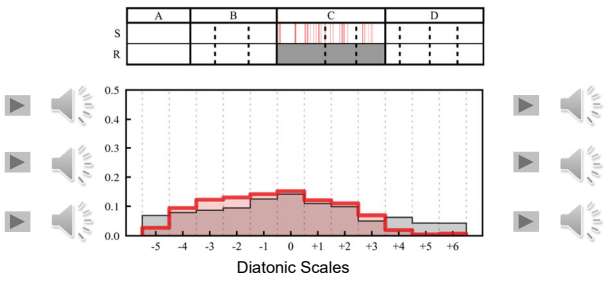
Exploring Tonal-Dramatic Relationships

Die Walküre – **Sword motif**



Exploring Tonal-Dramatic Relationships

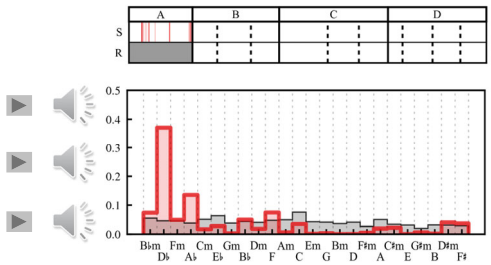
Siegfried – **Sword motif**



Diatonic Scales

Exploring Tonal-Dramatic Relationships

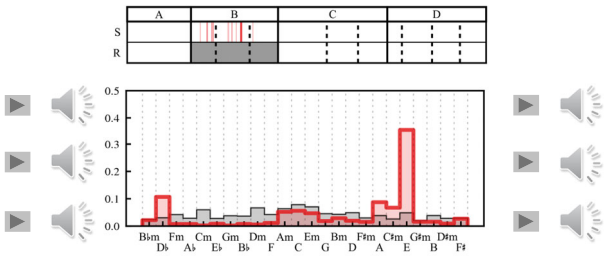
Das Rheingold – **Valhalla motif**



Chords

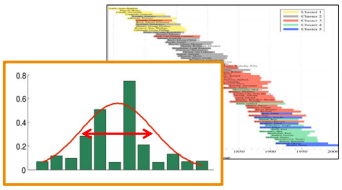
Exploring Tonal-Dramatic Relationships

Die Walküre – **Valhalla motif**



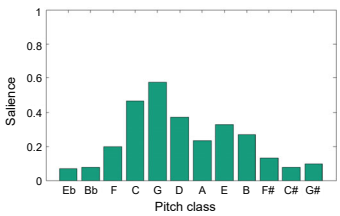
Chords

Corpus Analysis: Composer Styles



Tonal Complexity

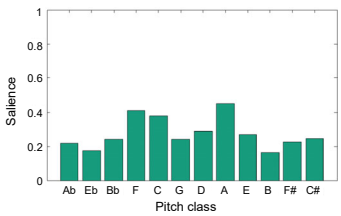
- Global chroma statistics (audio)
- **1783** – W. A. Mozart, „Linz“ symphony KV 425, 1. Adagio / Allegro



Circle of fifths →

Tonal Complexity

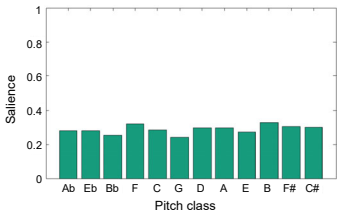
- Global chroma statistics (audio)
- **1883** – J. Brahms, Symphony No. 3, 1. Allegro con brio (F major)



Circle of fifths →

Tonal Complexity

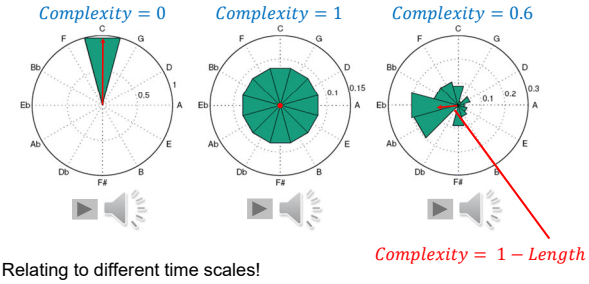
- Global chroma statistics (audio)
- **1940** – A. Webern, Variations for Orchestra op. 30



Circle of fifths →

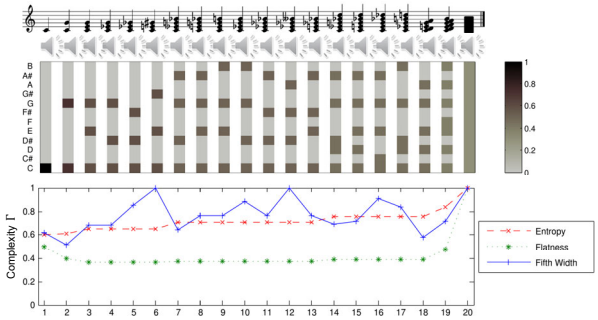
Tonal Complexity

- Realization of complexity measure Γ
- Distribution over *Circle of Fifths*

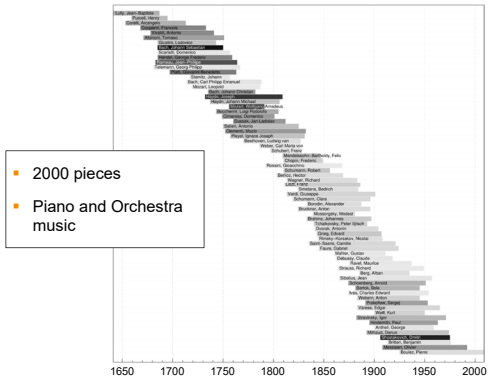


- Relating to different time scales!

Tonal Complexity – Chords

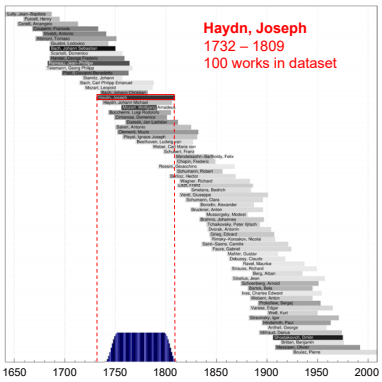


Analyzing Composer Styles

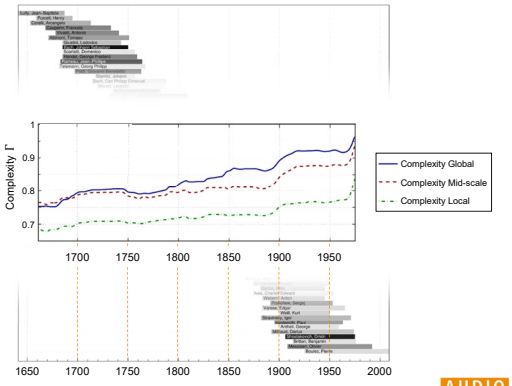


- 2000 pieces
- Piano and Orchestra music

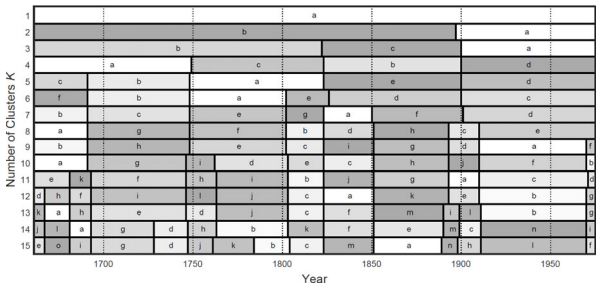
Analyzing Composer Styles



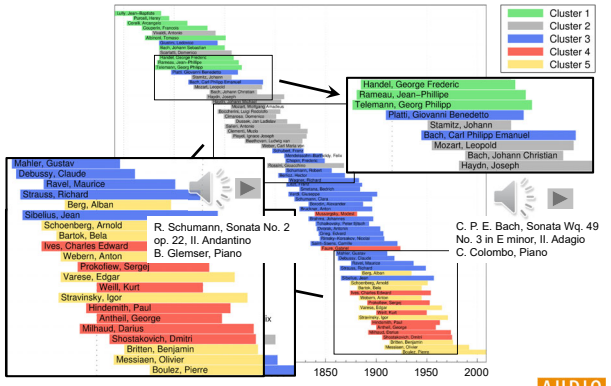
Analyzing Composer Styles



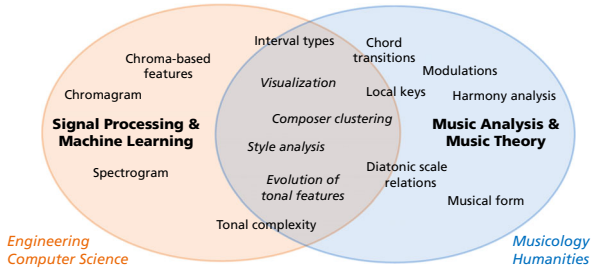
Clustering Composition Years



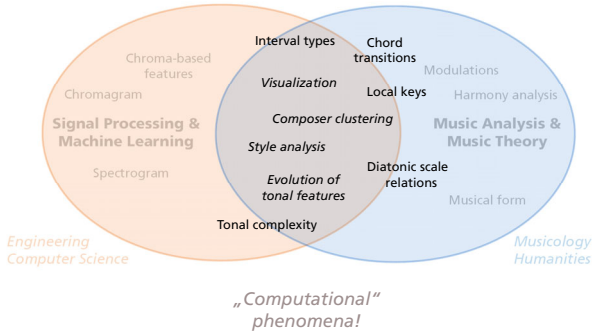
Clustering Composers



Conclusions



Conclusions



Lecture: Summer Term 2020

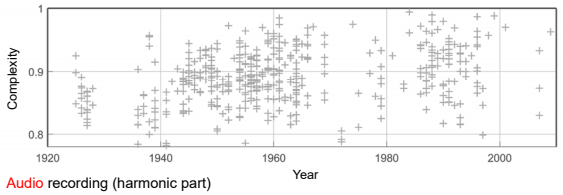
Digitale Musikanalyse: Wie gut können Computer hören?

Dr. Christof Weiß

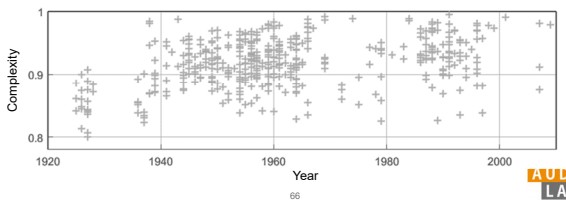
- BA Digital Humanities and Social Sciences
- Lecture + Exercises (5 SWS)
- Summer term 2020
- Time and place to be announced
- No musical prerequisites!

Tonal Complexity: Jazz Solos

- Symbolic transcription



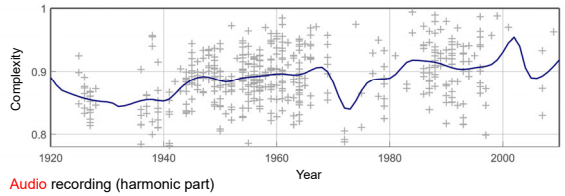
- Audio recording (harmonic part)



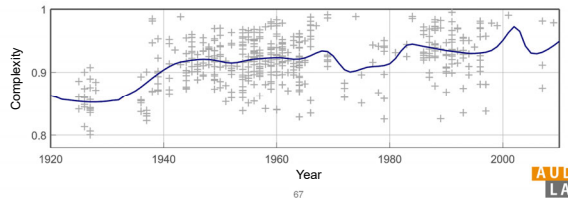
Tonal Complexity: Jazz Solos

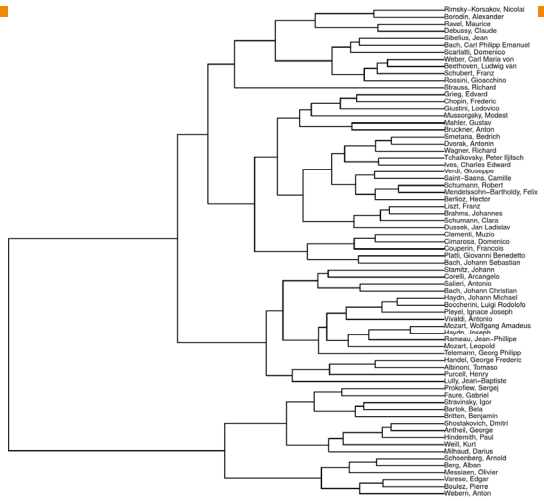
- Symbolic transcription

[7] Weiss / Balke / Abesser / Müller, *Computational Corpus Analysis: A Case Study on Jazz Solos*, Proc. Int. Conference on Music Information Retrieval 2018

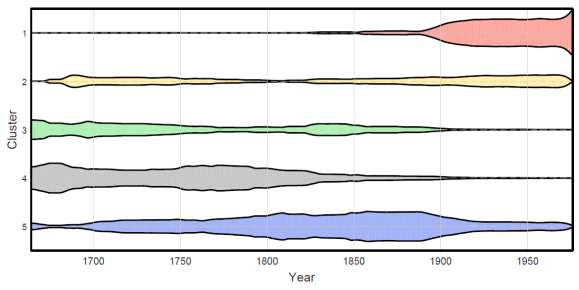


- Audio recording (harmonic part)

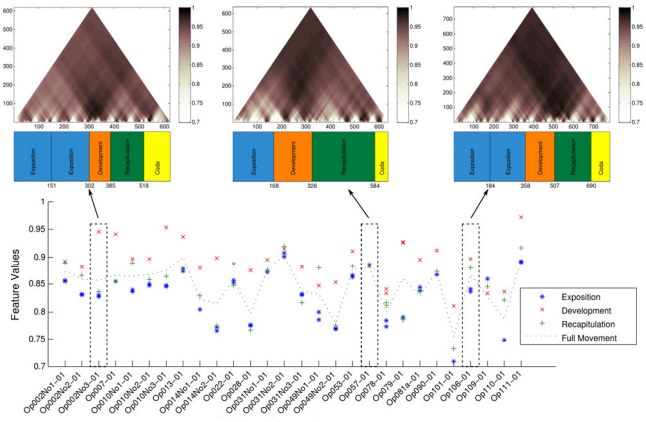




Clustering Individual Pieces

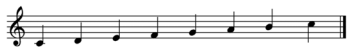


Tonal Complexity – Beethoven's Sonatas

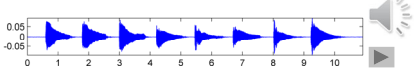


Signal Processing: Chroma Features

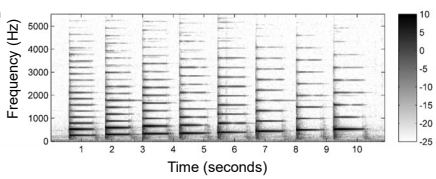
- Example: C major scale (piano)
  - Score



  - Audio – **Waveform**

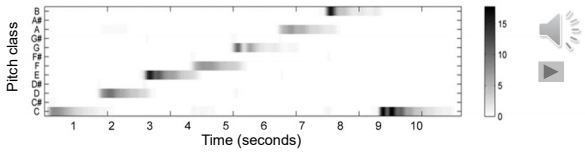


  - Audio - **Spectrogram**

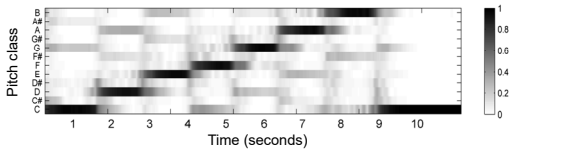


Signal Processing: Chroma Features

- Example: C major scale (piano)
  - Audio – **Chromagram**



  - Audio – **Chromagram (normalized)**



Music Genre Classification

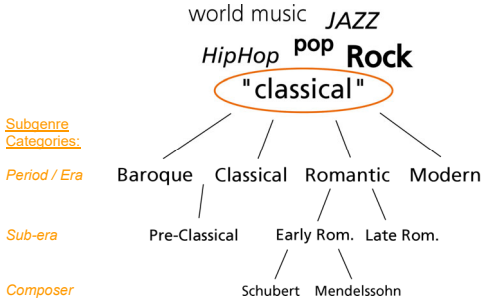
J. S. Bach, Brandenburg Concerto No. 2 in F major, I. Allegro, Cologne Chamber Orch.

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

R. Schumann, Sonata No. 2 op. 22, II. Andantino
B. Glemser, Piano

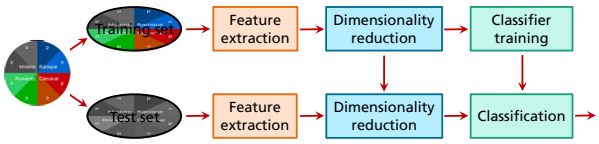
A. Webern, Variations for Orchestra op. 30
Ulster Orchestra

Music Genre Classification



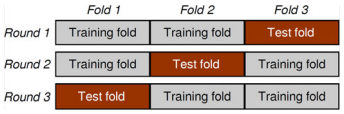
Music Genre Classification

- Typical approach: Supervised machine learning

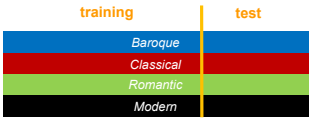


Music Genre Classification

- Experimental design: Evaluation with Cross Validation (CV)
- Separate data into different parts (*folds*)

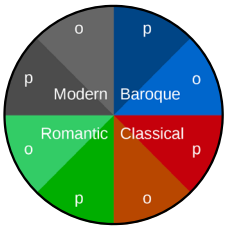


- Distribution of classes balanced for all folds

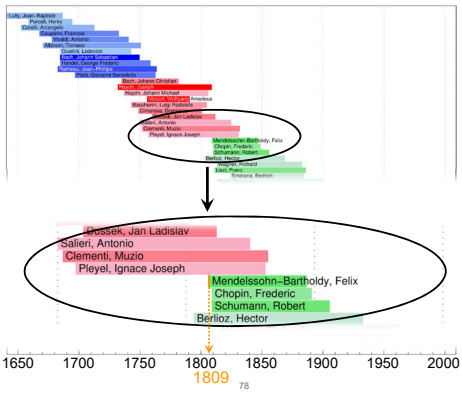


Classification Scenario

- Dataset: *CrossEraDB* (Historical Periods)
  - Balanced Piano (p) – Orchestra (o)
  - Each 200 pieces → 1600 in total



Classification Scenario

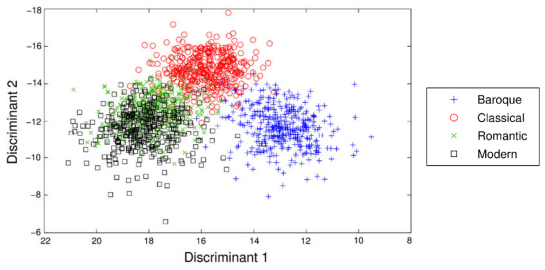


Classification Features

Standard	Dim.	Tonal	Dim.
MFCC	16	Interval cat.	6 x 4
OSC	14	Triad types	4 x 4
ZCR	1	Complexity	7 x 4
ASE	16	Chord progr.	11 x 5
SFM	16		
SCF	16		
SC	16		
LogLoud	12		
NormLoud	12		
Sum	119	Sum	123
Mean & Std	x 2	Mean & Std	x 2
Total	**238**	**Total**	**246**

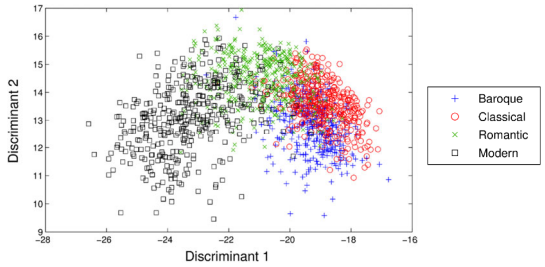
Dimensionality Reduction

- Reduce feature space to few dimensions (prevent **curse of dimensionality**)
- Maximize separation of classes with **Linear Discriminant Analysis (LDA)**
- Using **standard features** (MFCC, spectral envelope, …)



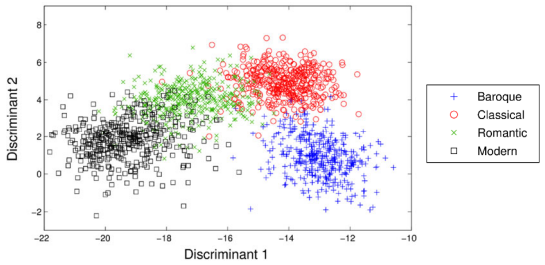
Dimensionality Reduction

- Reduce feature space to few dimensions
- Maximize separation of classes with **Linear Discriminant Analysis (LDA)**
- Using **tonal features** (interval, triad types, tonal complexity, … 4 time scales)



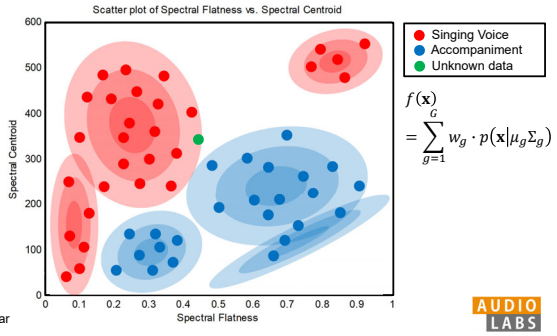
Dimensionality Reduction

- Reduce feature space to few dimensions
- Maximize separation of classes with **Linear Discriminant Analysis (LDA)**
- Using **tonal & standard features**



Classification methods

- Gaussian Mixture Models (GMM)

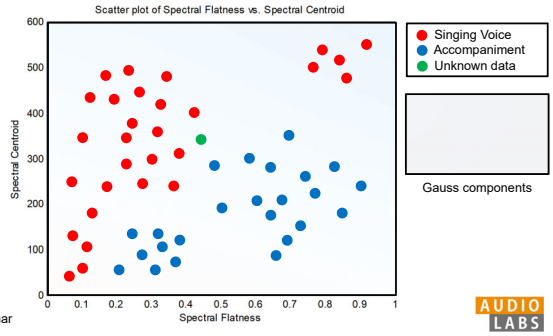


$$f(\mathbf{x}) = \sum_{g=1}^{G} w_g \cdot p(\mathbf{x}|\mu_g \Sigma_g)$$

Slides:
Christian Dittmar

Classification methods

- Gaussian Mixture Models (GMM)



Slides:
Christian Dittmar

Classification Results

- Gaussian Mixture Model (GMM) classifier, LDA reduction, 3-fold cross validation

	Full Dataset	Piano	Orchestra
Standard features	87 %	88 %	85 %
Tonal features	84 %	84 %	86 %
Combined	**92 %**	**86 %**	**80 %**

Weiss / Mauch / Dixon, *Timbre-Invariant Audio Features for Style Analysis of Classical Music*, ICMC / SMC 2014

AUDIO LABS

Classification Results

- Gaussian Mixture Model (GMM) classifier, LDA reduction, 3-fold cross validation

	Full Dataset	Piano	Orchestra
Standard features	87 %	88 %	85 %
Tonal features	84 %	84 %	86 %
Combined	**92 %**	**86 %**	**80 %**

Overfitting???

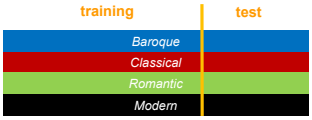
Weiss / Mauch / Dixon, *Timbre-Invariant Audio Features for Style Analysis of Classical Music*, ICMC / SMC 2014

AUDIO LABS

Classification Results

- GMM classifier, LDA reduction, 3-fold cross validation

	Full Dataset	Piano	Orchestra
Standard features	87 %	88 %	85 %
Tonal features	84 %	84 %	86 %
Combined	**92 %**	**86 %**	**80 %**



Flexer, *A Closer Look on Artist Filters for Musical Genre Classification*, ISMIR 2007

AUDIO LABS

Classification Results

- GMM classifier, LDA reduction, 3-fold cross validation
- **No composer filter**

	Full Dataset	Piano	Orchestra
Standard features	87 %	88 %	85 %
Tonal features	84 %	84 %	86 %
Combined	**92 %**	**86 %**	**80 %**

- **Using composer filter**

	Full Dataset	Piano	Orchestra
Standard features	54 %	36 %	70 %
Tonal features	73 %	70 %	78 %
Combined	**68 %**	**44 %**	**68 %**

Weiss / Müller, *Tonal Complexity Features for Style Classification of Classical Music*, ICASSP 2015

AUDIO LABS

Classification Results

- GMM classifier, LDA reduction, 3-fold cross validation
- **No composer filter**

	Full Dataset	Piano	Orchestra
Standard features	87 %	88 %	85 %
Tonal features	84 %	84 %	86 %
Combined	**92 %**	**86 %**	**80 %**

- **Using composer filter**

	Full Dataset	Piano	Orchestra
Standard features	54 %	36 %	70 %
Tonal features	73 %	70 %	78 %
Combined	**68 %**	**44 %**	**68 %**

Weiss / Müller, *Tonal Complexity Features for Style Classification of Classical Music*, ICASSP 2015

AUDIO LABS

Classification Results

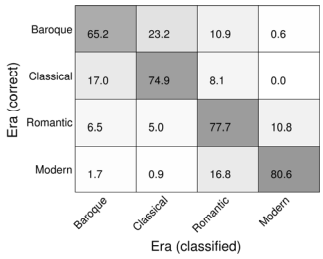
- What is actually learned?
- Pay attention to:
  - Overfitting
  - „Curse of dimensionality“ – use dimensionality reduction techniques
  - Artist / album effects
- Evaluation: „Figures of merit“:
  - Confusion matrix
  - Error examples: Consistently misclassified items
  - Listening tests
- Evaluation on unseen data (no cross validation)

Bob Sturm, *Classification Accuracy is not enough*, Journal of Intelligent Information Systems, 2013

AUDIO LABS

Classification Results – Confusion Matrix

- 80 tonal features, GMM with 1 Gaussian, LDA, composer filtering
- **Full** dataset
- Mean accuracy: **75 %**
- Inter-class standard deviation: **6.7 %**



Classification Results: Error Examples

- 80 tonal features, GMM with 1 Gaussian, LDA
- Look at **consistently** and **persistently** misclassified items

Class	*Composer*	*Piece*	*Classified*
Baroque	Bach, J. S.	Well-Tempered Piano 1, Prelude in E♭ minor BWV 853	Romantic
Baroque	Bach, J. S.	Well-Tempered Piano 1, Prelude in F major BWV 856	Romantic
Baroque	Bach, J. S.	Well-Tempered Piano 1, Prelude in A minor BWV 865	Romantic
Baroque	Bach, J. S.	Well-Tempered Piano 1, Prelude in B♭ major BWV 866	Romantic
Baroque	Bach, J. S.	Well-Tempered Piano 1, Prelude in B♭ minor BWV 867	Romantic
Baroque	Bach, J. S.	English Suite No. 3 in G minor BWV 808, Sarabande	Romantic
Baroque	Bach, J. S.	Brandenburg Conc. No. 1 in F major BWV 1046, Adagio	Romantic
Baroque	Bach, J. S.	Overture No. 2 in B minor BWV 1067, Badinerie	Romantic
Baroque	Bach, J. S.	Overture No. 3 in D major BWV 1068, Gigue	Romantic
Baroque	Couperin, F.	27 Ordres, Huitième ordre, IX. Rondeau passacaille	Romantic
Baroque	Corelli, A.	Concerto grosso op. 6 No. 2, III. Grave – Andante largo	Romantic
Baroque	Lully, J.-B.	Ballet de Xerces LWV 12, Gavotte en rondeau	Romantic
Baroque	Purcell, H.	Opera "Dido and Aeneas" Z. 626, Overture	Romantic
Baroque	Vivaldi, A.	"The Four Seasons," RV 293 "Autumn," Adagio molto	Romantic
Romantic	Schumann, R.	Kinderszenen op. 15, "Haschemann"	Baroque
Romantic	Grieg, E.	Holberg suite op. 40, Gavotte	Baroque
Romantic	Mendelssohn, F.	Symphony No. 4 in A major, IV. Saltarello, presto	Baroque
Modern	Shostakovich, D.	Preludes & Fugues op. 87 Fugue No. 1 in C major	Baroque
Modern	Shostakovich, D.	Preludes & Fugues op. 87 Fugue No. 5 in D major	Baroque