

Introduction to Audio Content Analysis

Module 7.5: Musical Key Recognition

alexander lerch

introduction

overview

corresponding textbook section

Section 7.5

■ lecture content

- definition of musical key
- pitch chroma feature
- standard approach for key recognition

■ learning objectives

- explain the defining properties of a musical key
- implement a simple pitch chroma feature extractor
- describe and discuss a simple automatic key recognition system



introduction

overview

corresponding textbook section

Section 7.5

■ lecture content

- definition of musical key
- pitch chroma feature
- standard approach for key recognition

■ learning objectives

- explain the defining properties of a musical key
- implement a simple pitch chroma feature extractor
- describe and discuss a simple automatic key recognition system



key

tonic & mode

- **tonic:** first scale degree
 - most “important” pitch class
- **mode:** set of diatonic pitch relationships
 - Major: 2, 2, 1, 2, 2, 2, 1
 - Minor: 2, 1, 2, 2, 1, 2, 2

The image displays eight musical staves, each representing a different scale or mode. Each staff is divided into two parts by a double bar line. The scales are labeled as follows:

- Major (first part) and (Aeolic) Minor (second part)
- (Harmonic) Minor (first part) and Dorian (second part)
- Phrygian (first part) and Lydian (second part)
- Mixolydian (first part) and Lokrian (second part)
- Chromatic (first part) and Wholetone (second part)

key

key & key signature 1/2

- **key:**
defined by *tonic* (root note) and *mode*
 - defines a set of pitch classes constructing both pitch and harmonic content
- **modulation** (local key changes):
common in various styles, uncommon in others
- **key signature:**
indicates current key with accidentals (score notation)

key

key & key signature 1/2

- **key:**
defined by *tonic* (root note) and *mode*
 - defines a set of pitch classes constructing both pitch and harmonic content
- **modulation** (local key changes):
common in various styles, uncommon in others
- **key signature:**
indicates current key with accidentals (score notation)

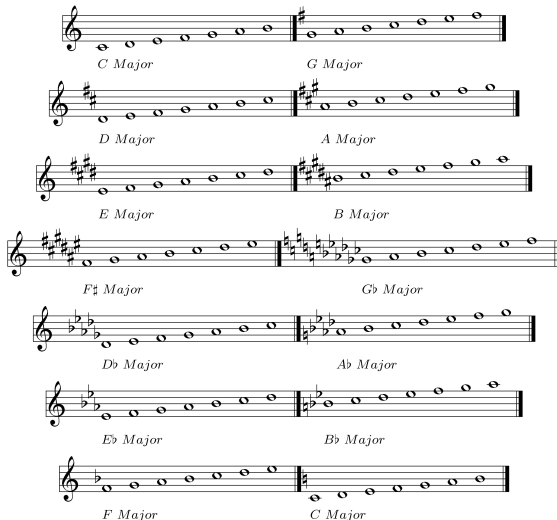
key

key & key signature 1/2

- **key:**
defined by *tonic* (root note) and *mode*
 - defines a set of pitch classes constructing both pitch and harmonic content
- **modulation** (local key changes):
common in various styles, uncommon in others
- **key signature:**
indicates current key with accidentals (score notation)

key

key & key signature 2/2



C Major *G Major*

D Major *A Major*

E Major *B Major*

F# Major *Gb Major*

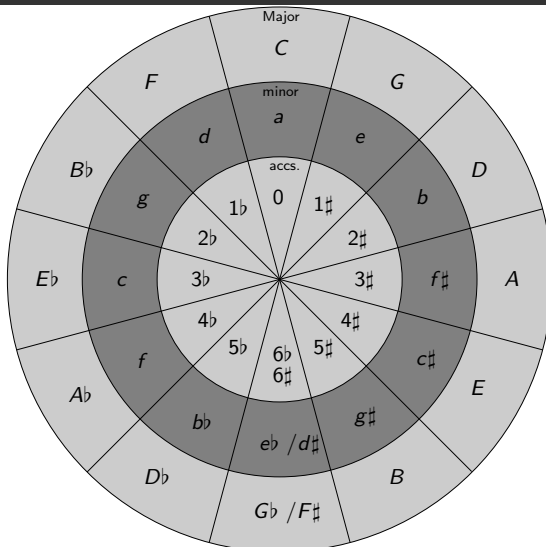
Db Major *Ab Major*

Eb Major *Bb Major*

F Major *C Major*

musical pitch

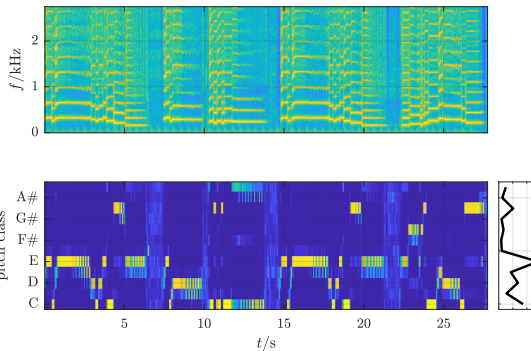
key: circle of fifths



pitch chroma

introduction

- pitch class distribution
- 12-dimensional vector
- **no** octave information
 - robust representation
 - no differentiation between unison and octave



pitch chroma

computation 1/2

- 1 divide spectral representation into **semi-tone bands**
- 2 compute **mean per band**

$$\mu(j, n) = \frac{1}{k_u(j) - k_l(j) + 1} \sum_{k=k_l(j)}^{k_u(j)} |X(k, n)|$$

- 3 sum/mean every 12th band

$$\nu(j \% 12, n) = \sum_{o=o_l}^{o_u} \mu(j, n),$$

$$\nu(n) = [\nu(0, n), \nu(1, n), \nu(2, n), \dots, \nu(10, n), \nu(11, n)]^T$$

pitch chroma

computation 1/2

- 1 divide spectral representation into **semi-tone bands**
- 2 compute **mean per band**

$$\mu(j, n) = \frac{1}{k_u(j) - k_l(j) + 1} \sum_{k=k_l(j)}^{k_u(j)} |X(k, n)|$$

- 3 sum/mean every 12th band

$$\nu(j \% 12, n) = \sum_{o=o_l}^{o_u} \mu(j, n),$$

$$\nu(n) = [\nu(0, n), \nu(1, n), \nu(2, n), \dots, \nu(10, n), \nu(11, n)]^T$$

pitch chroma

computation 1/2

- 1 divide spectral representation into **semi-tone bands**
- 2 compute **mean per band**

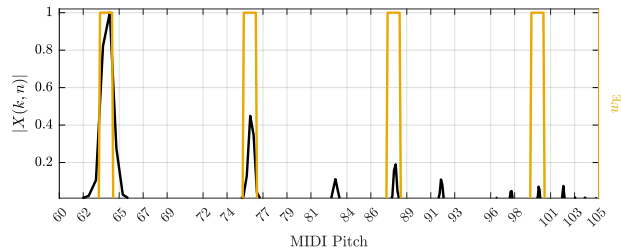
$$\mu(j, n) = \frac{1}{k_u(j) - k_l(j) + 1} \sum_{k=k_l(j)}^{k_u(j)} |X(k, n)|$$

- 3 sum/mean every 12th band

$$\begin{aligned} \nu(j \% 12, n) &= \sum_{o=o_l}^{o_u} \mu(j, n), \\ \nu(n) &= [\nu(0, n), \nu(1, n), \nu(2, n), \dots, \nu(10, n), \nu(11, n)]^T \end{aligned}$$

pitch chroma

computation 2/2



pitch chroma

computation: simple variants

■ STFT:

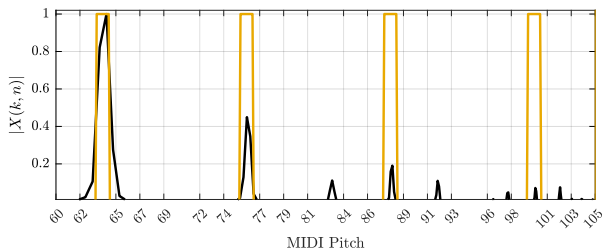
- *weighted* mean of bins (window function)
- *tonalness preprocessing* (local maxima etc)

■ sum of **filterbank** output energies

■ CQT:

- sum of bins/peaks

■ beat-synchronous chroma



matlab source: [plotPitchChromaGrouping.m](https://github.com/ericniebler/pitch-chroma-grouping)

pitch chroma

computation: simple variants

■ STFT:

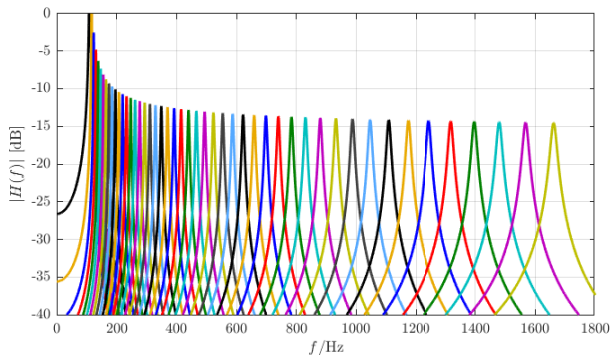
- *weighted* mean of bins (window function)
- *tonalness preprocessing* (local maxima etc)

■ sum of **filterbank** output energies

■ CQT:

- sum of bins/peaks

■ beat-synchronous chroma



matlab source: [plotResonanceFilterBank.m](#)

pitch chroma

computation: simple variants

■ STFT:

- *weighted* mean of bins
(window function)
- *tonalness preprocessing*
(local maxima etc)

■ sum of **filterbank** output energies

■ CQT:

- sum of bins/peaks

■ beat-synchronous chroma

pitch chroma

computation: simple variants

■ STFT:

- *weighted* mean of bins (window function)
- *tonalness preprocessing* (local maxima etc)

■ sum of **filterbank** output energies

■ CQT:

- sum of bins/peaks

■ beat-synchronous chroma

pitch chroma normalization

■ pitch chroma as *distribution*:

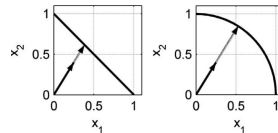
$$\sum_{k=0}^{11} \nu(k, n) = 1$$

■ pitch chroma as *vector*:

$$\sqrt{\sum_{k=0}^{11} \nu(k, n)^2} = 1$$

■ other options:

- e.g., short-term energy normalization (CENS)



pitch chroma normalization

- pitch chroma as *distribution*:

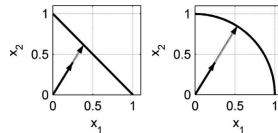
$$\sum_{k=0}^{11} \nu(k, n) = 1$$

- pitch chroma as *vector*:

$$\sqrt{\sum_{k=0}^{11} \nu(k, n)^2} = 1$$

- other options:

- e.g., short-term energy normalization (CENS)



pitch chroma normalization

- pitch chroma as *distribution*:

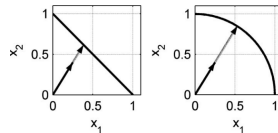
$$\sum_{k=0}^{11} \nu(k, n) = 1$$

- pitch chroma as *vector*:

$$\sqrt{\sum_{k=0}^{11} \nu(k, n)^2} = 1$$

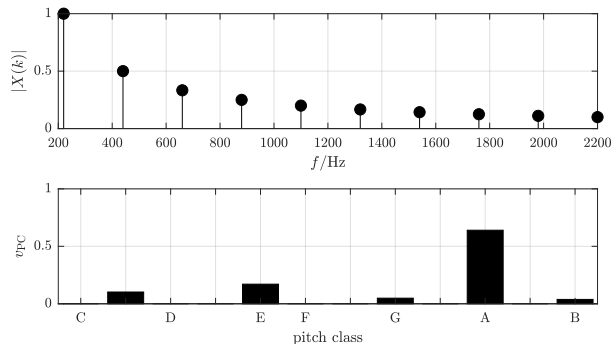
- other options:

- e.g., short-term energy normalization (CENS)



pitch chroma

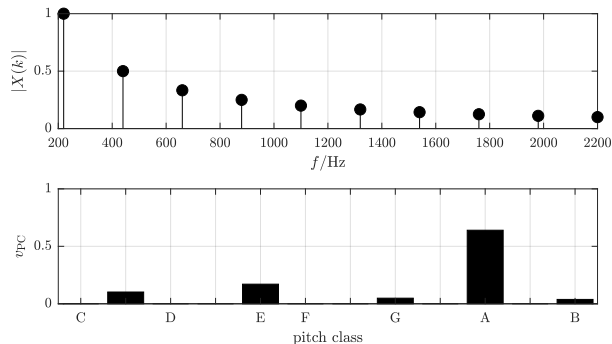
problem 1: amplitude distortion



- every pitch contains not only fundamental but higher harmonics
 - ⇒ de-emphasize higher frequencies
 - ⇒ build amplitude model
 - ⇒ use multi-pitch detection system

pitch chroma

problem 1: amplitude distortion



- every pitch contains not only fundamental but higher harmonics
 - ⇒ de-emphasize higher frequencies
 - ⇒ build amplitude model
 - ⇒ use multi-pitch detection system

pitch chroma

problem 2: frequency distortion

- higher harmonics are not “in-tune”

Harmonic	$ \Delta C(f, f_T) $
$f = f_0$	0
$f = 2 \cdot f_0$	0
$f = 3 \cdot f_0$	1.955
$f = 4 \cdot f_0$	0
$f = 5 \cdot f_0$	13.6863
$f = 6 \cdot f_0$	1.955
$f = 7 \cdot f_0$	31.1741
$\mu_{ \Delta C }$	6.9672

key detection

introduction

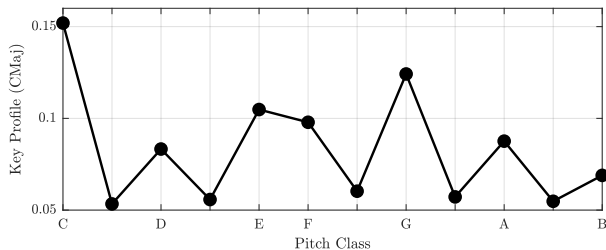
assumption:

- *pitch class distribution* is prototypical for key
 - tonic/root note is tonal center
 - tonal and harmonic relations define importance and occurrence of individual pitch classes
 - different root notes result in simple shift of distribution

key detection

processing steps of simple key detection

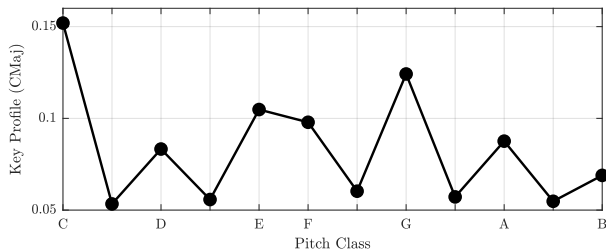
- 1 define reference distribution for specific keys
- 2 extract average pitch chroma from audio
- 3 compute distance between template and extracted chroma



key detection

processing steps of simple key detection

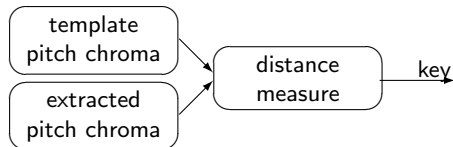
- 1 define reference distribution for specific keys
- 2 extract average pitch chroma from audio
- 3 compute distance between template and extracted chroma



key detection

processing steps of simple key detection

- 1 define reference distribution for specific keys
- 2 extract average pitch chroma from audio
- 3 compute distance between template and extracted chroma



key detection

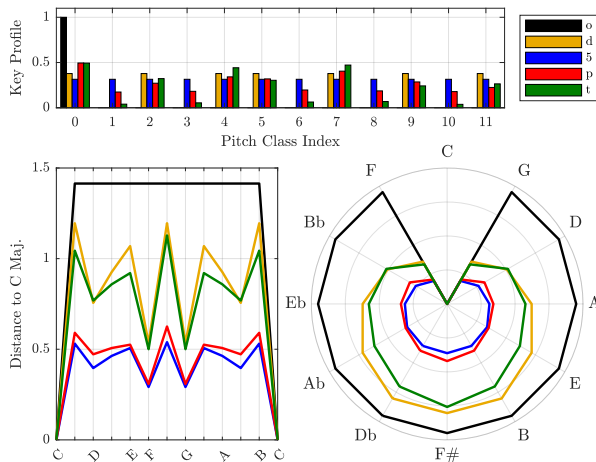
key template distance animation



key detection

key templates

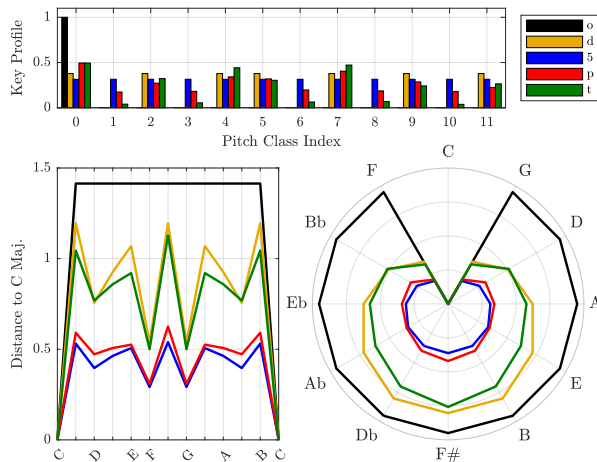
- *Orthogonal ν_o* : root note is most salient component, other components negligible
 - same distance to all keys
 - no major/minor distinction
- *Diatonic ν_d* : all key-inherent pitches weighted equally
 - linear increasing key dist
- *Probe tone Ratings ν_p* : derived from perceptual tonal similarity
- *Extracted Key Profiles ν_k* : derived from real-world data



key detection

key templates

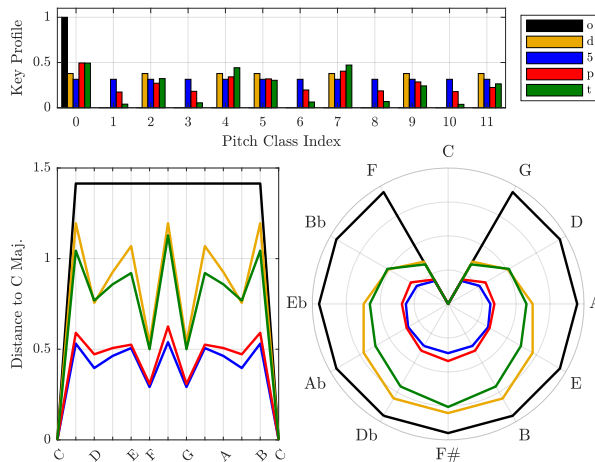
- *Orthogonal* ν_o : root note is most salient component, other components negligible
 - same distance to all keys
 - no major/minor distinction
- *Diatonic* ν_d : all key-inherent pitches weighted equally
 - linear increasing key dist
- *Probe tone Ratings* ν_p : derived from perceptual tonal similarity
- *Extracted Key Profiles* ν_k : derived from real-world data



key detection

key templates

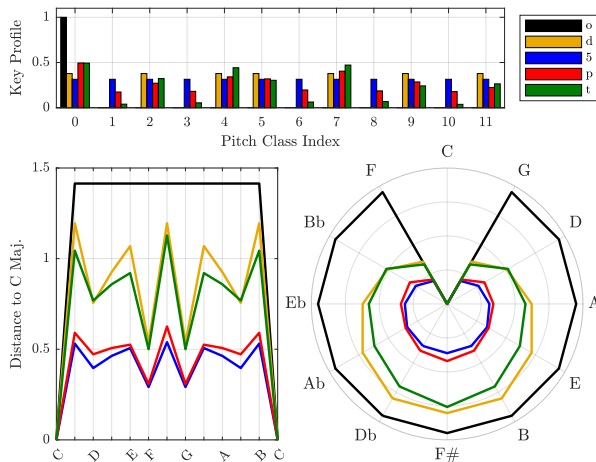
- *Orthogonal* ν_o : root note is most salient component, other components negligible
 - same distance to all keys
 - no major/minor distinction
- *Diatonic* ν_d : all key-inherent pitches weighted equally
 - linear increasing key dist
- *Probe tone Ratings* ν_p : derived from perceptual tonal similarity
- *Extracted Key Profiles* ν_t : derived from real-world data



key detection

key templates

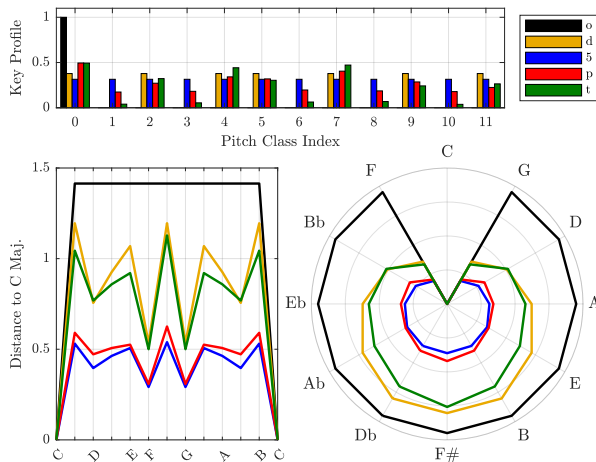
- *Orthogonal* ν_o : root note is most salient component, other components negligible
 - same distance to all keys
 - no major/minor distinction
- *Diatonic* ν_d : all key-inherent pitches weighted equally
 - linear increasing key dist
- *Probe tone Ratings* ν_p : derived from perceptual tonal similarity
- *Extracted Key Profiles* ν_t : derived from real-world data



key detection

key templates

- *Orthogonal* ν_o : root note is most salient component, other components negligible
 - same distance to all keys
 - no major/minor distinction
- *Diatonic* ν_d : all key-inherent pitches weighted equally
 - linear increasing key dist
- *Probe tone Ratings* ν_p : derived from perceptual tonal similarity
- *Extracted Key Profiles* ν_t : derived from real-world data



key detection

variants

- **tonalness weight:**
estimate the tonality/noisiness and weight instantaneous pitch chroma
- **multiple estimations:**
split piece into regions and estimate key through majority
- **real-time key detection:**
estimate in sliding window

key detection

variants

- **tonalness weight:**
estimate the tonality/noisiness and weight instantaneous pitch chroma
- **multiple estimations:**
split piece into regions and estimate key through majority
- **real-time key detection:**
estimate in sliding window

key detection

variants

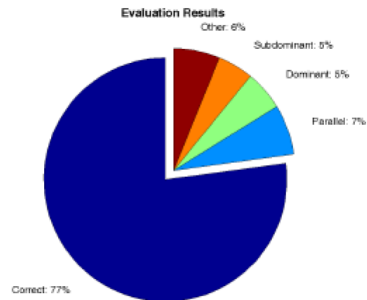
- **tonalness weight:**
estimate the tonality/noisiness and weight instantaneous pitch chroma
- **multiple estimations:**
split piece into regions and estimate key through majority
- **real-time key detection:**
estimate in sliding window

key detection

results & typical errors

■ typical errors: related keys

- Dominant
- Subdominant
- Relative
- Major/Minor



graph from¹

¹A. Lerch, "Ein Ansatz zur automatischen Erkennung der Tonart in Musikdateien," in *Proceedings of the VDT International Audio Convention* (23. Tonmeistertagung), Leipzig, Nov. 2004.

summary

lecture content

■ musical key

- set of pitch classes constructing pitched content
- defined by *tonic* (important center) and *mode* (scale)

■ pitch chroma

- reduced 12-dimensional octave-independent pitch representation
- relatively robust against timbre variation

■ automatic key recognition

- standard approach is template-based
- extracted average pitch chroma is compared with predefined template
- inverse distance measure indicates key likelihoods

