CS 583– Computational Audio -- Fall, 2021

Wayne Snyder
Computer Science Department
Boston University

Lecture 10

Chroma

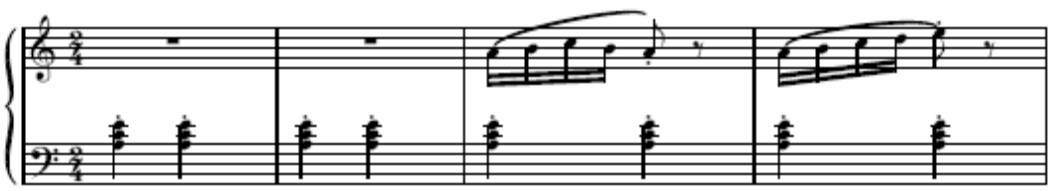
Chord Recognition by template matching

Problems with Chord Recognition

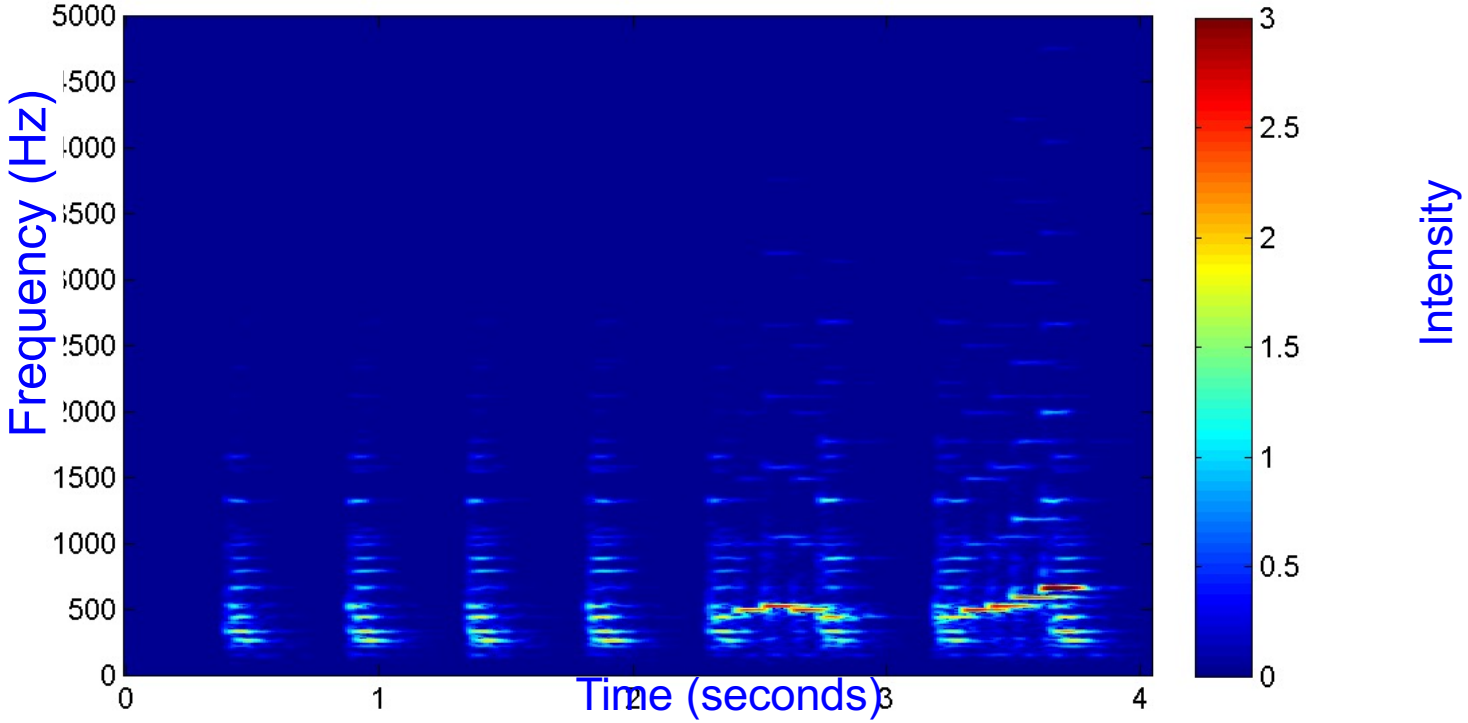
Coding the algorithm

Computer Science

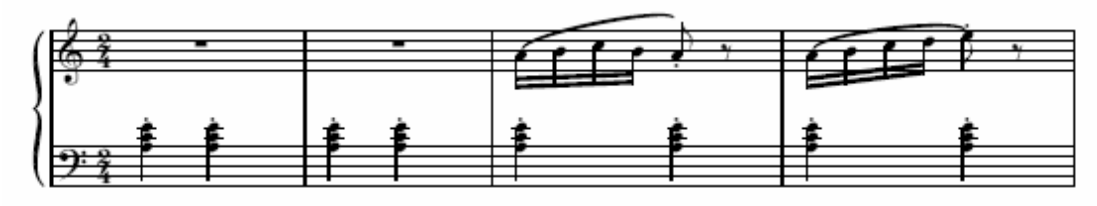
A Spectrogram shows Pitch Features of a Musical Signal



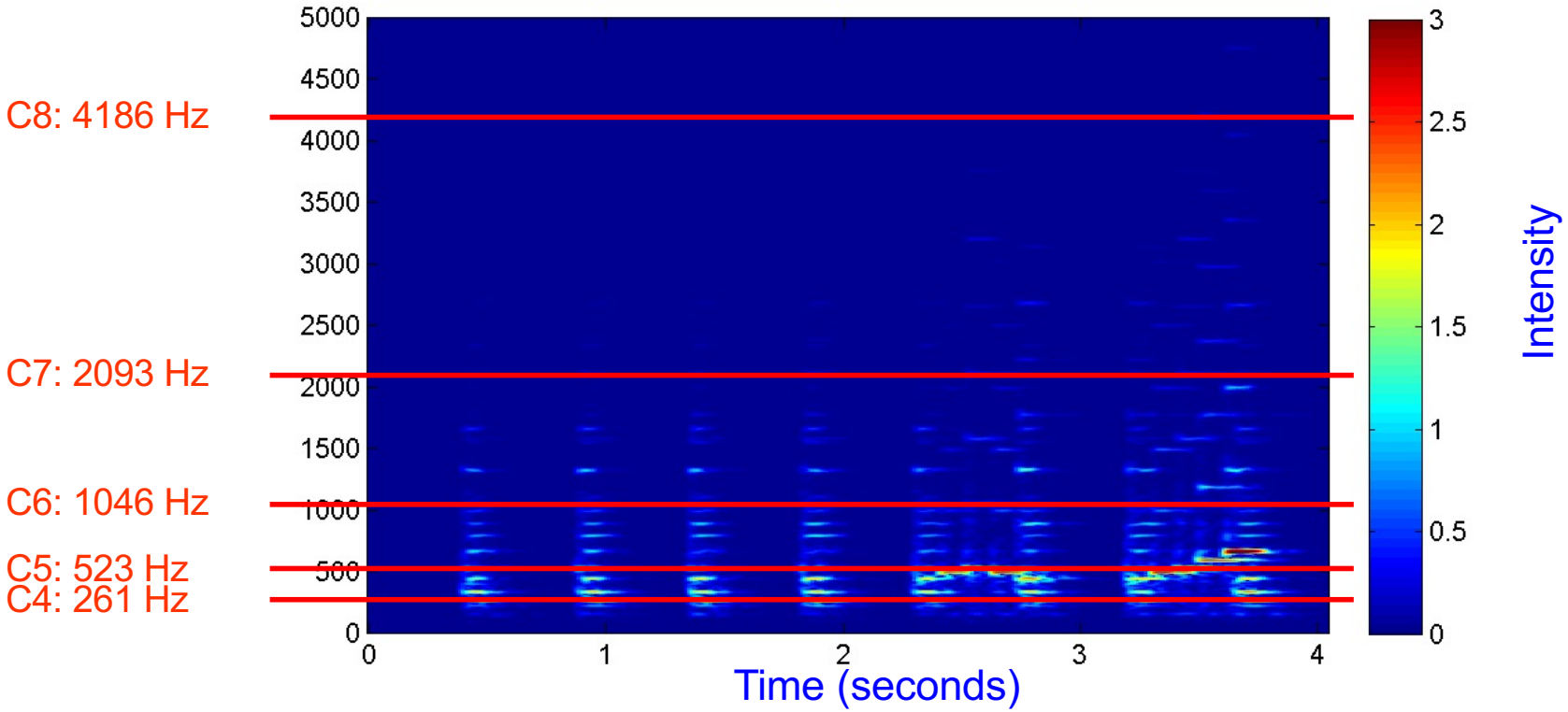
Spectrogram



Pitch Features

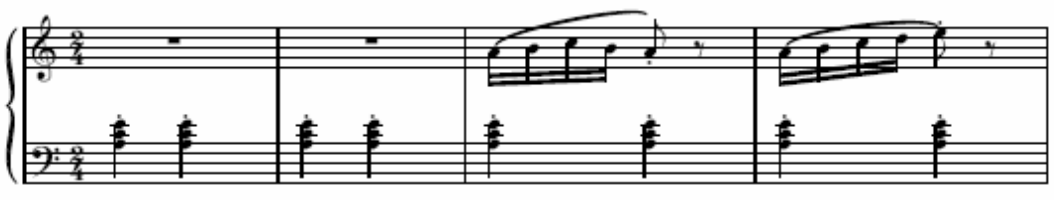


Spectrogram

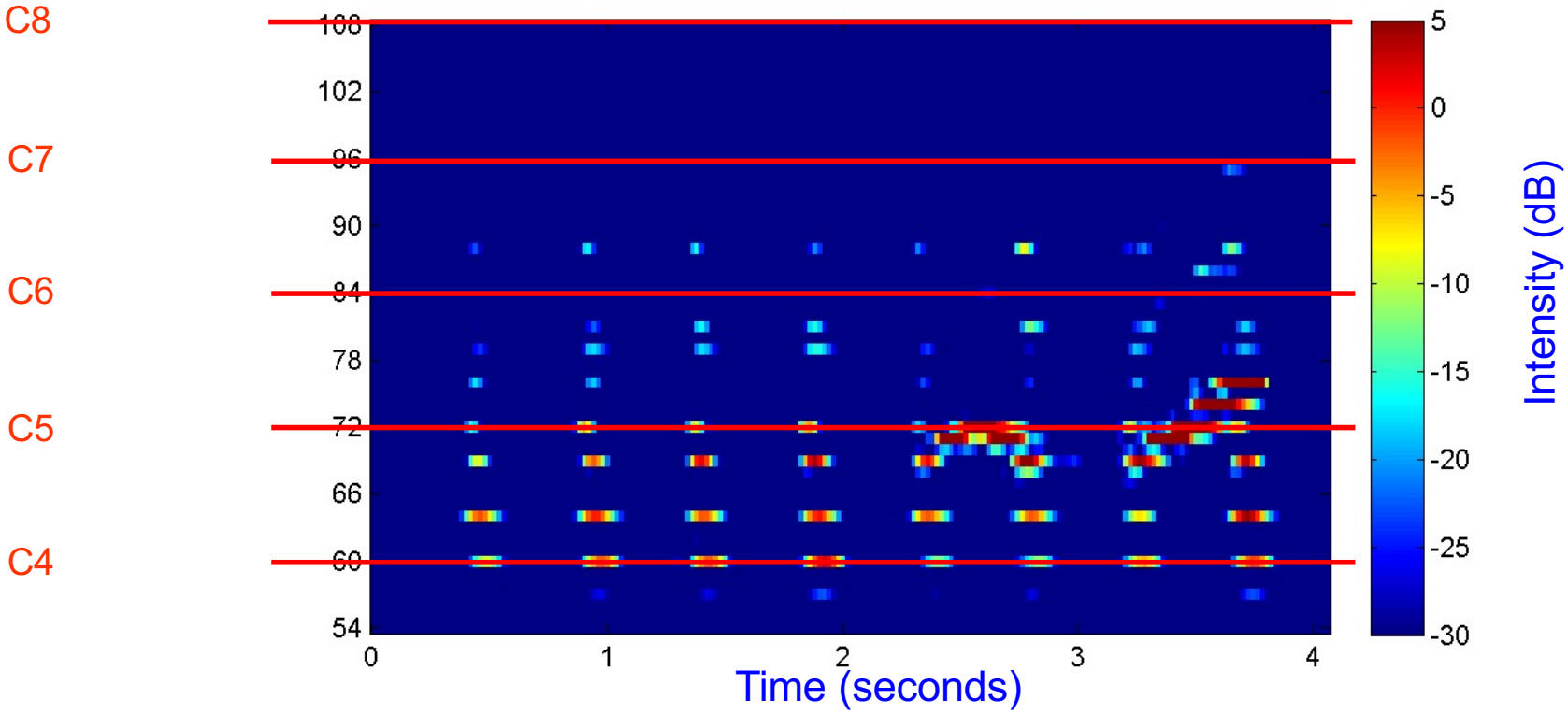


Pitch Features

Computer Science



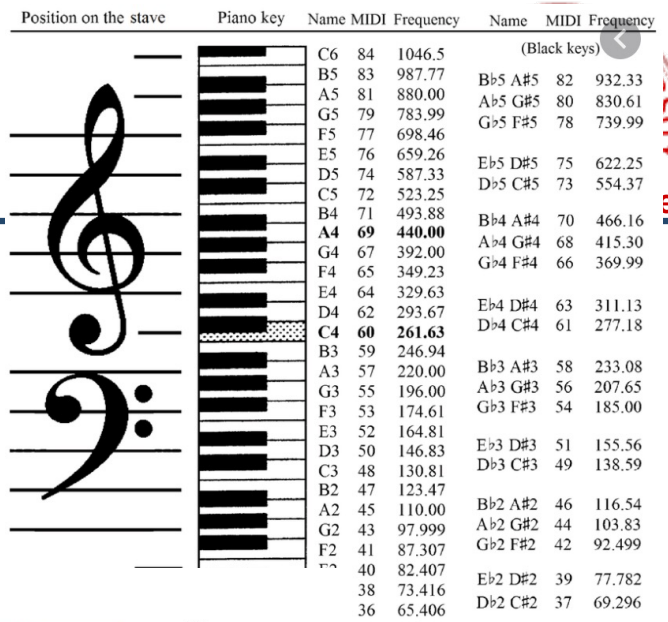
Logarithmic Frequency Scale

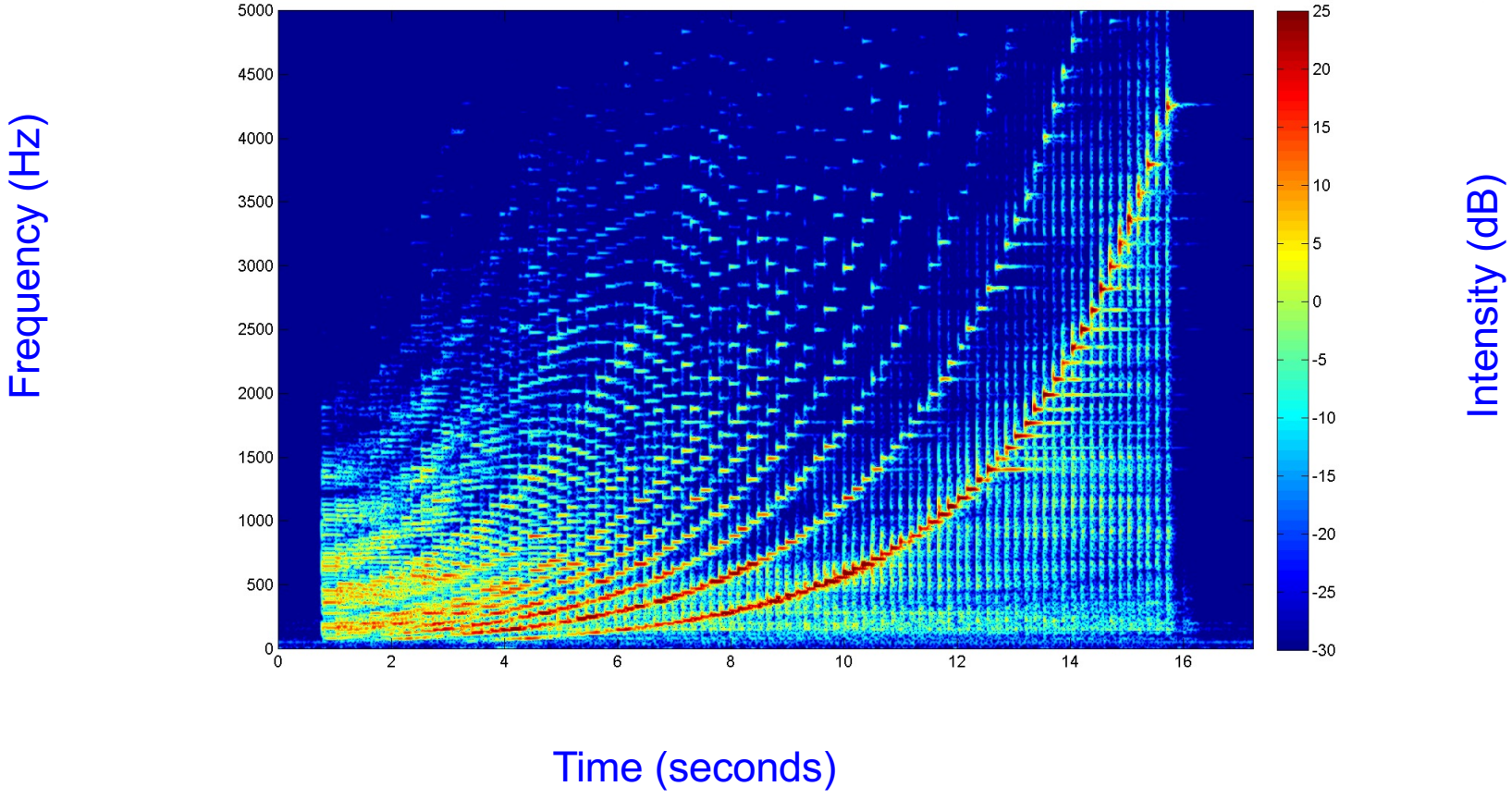


Pitch Features

Example: Chromatic scale

Spectrogram



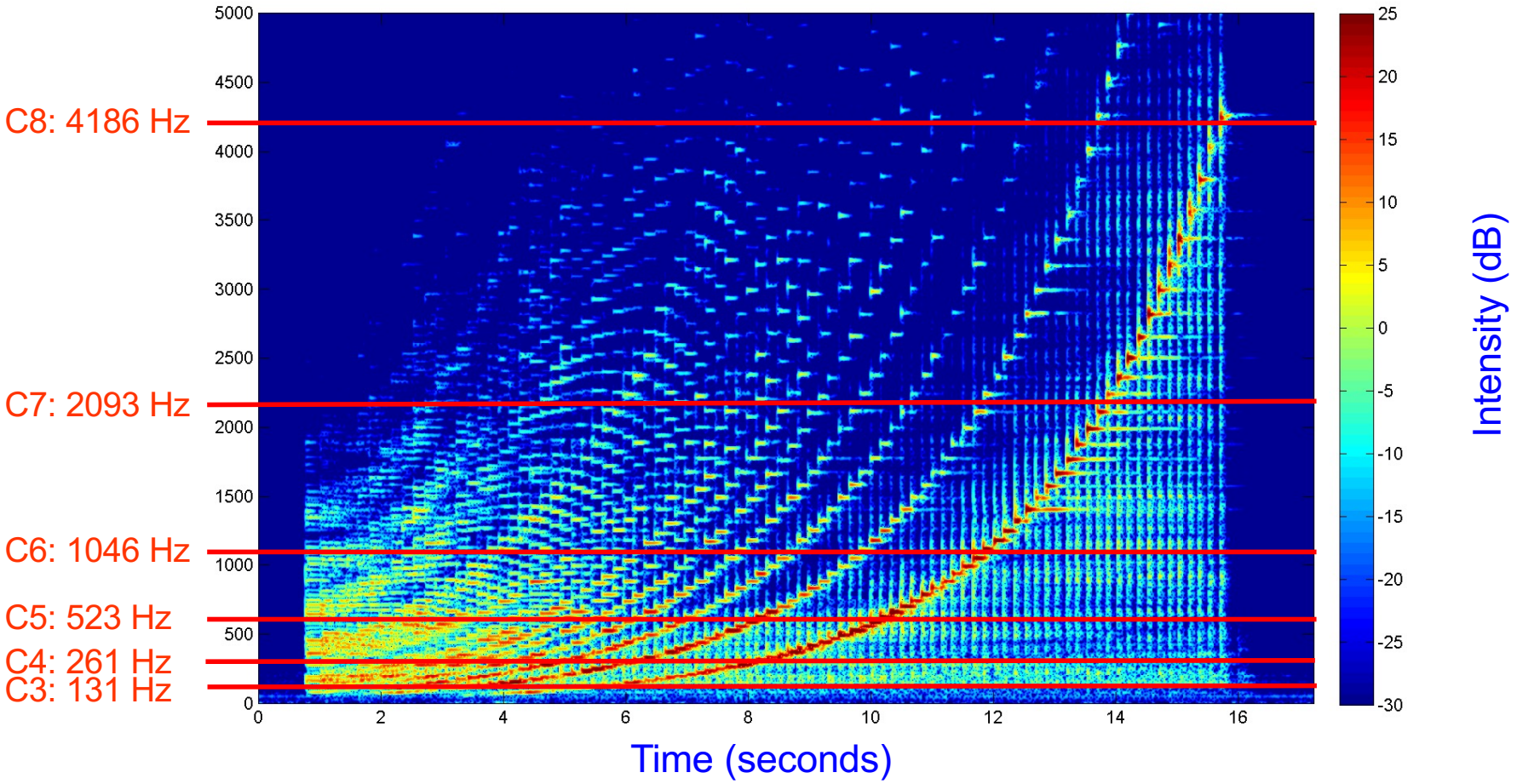


Pitch Features

Computer Science

Example: Chromatic scale

Spectrogram

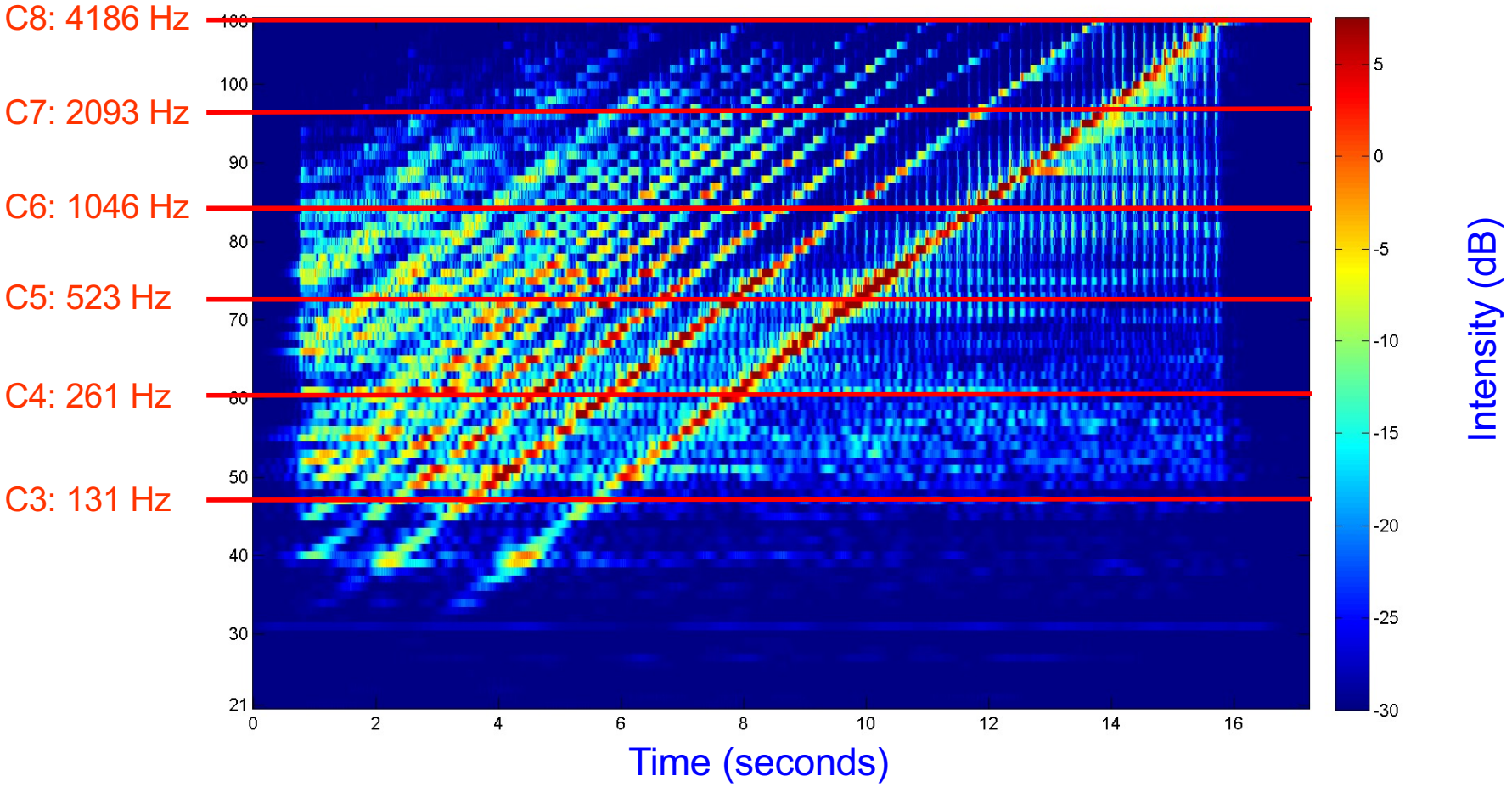


Pitch Features

Computer Science

Example: Chromatic scale

Log-frequency spectrogram

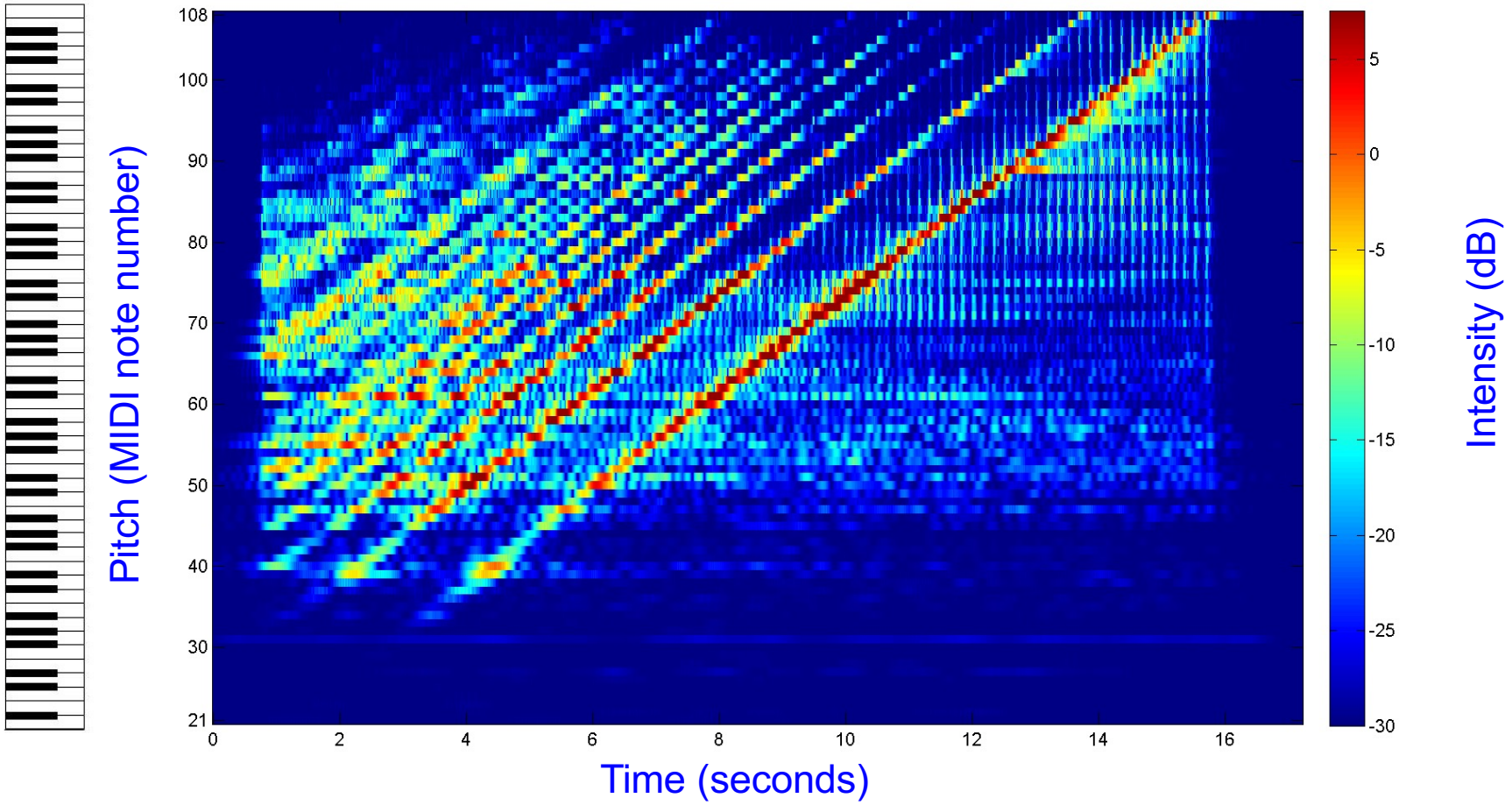


Pitch Features

Computer Science

Example: Chromatic scale

Log-frequency spectrogram



Chroma Features

- Human perception of pitch is periodic in the sense that two pitches are perceived as similar in color if they differ by an octave.
- Separation of pitch into two components: tone height (octave number) and chroma.

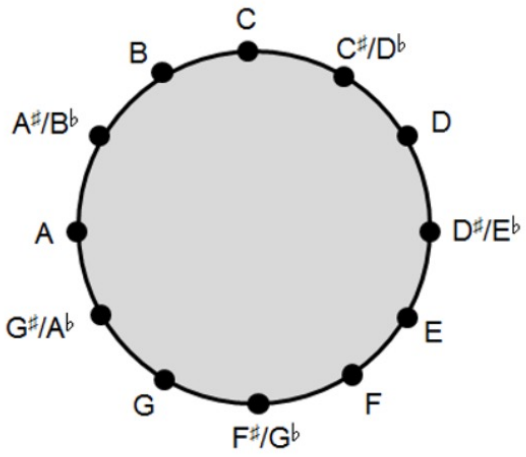
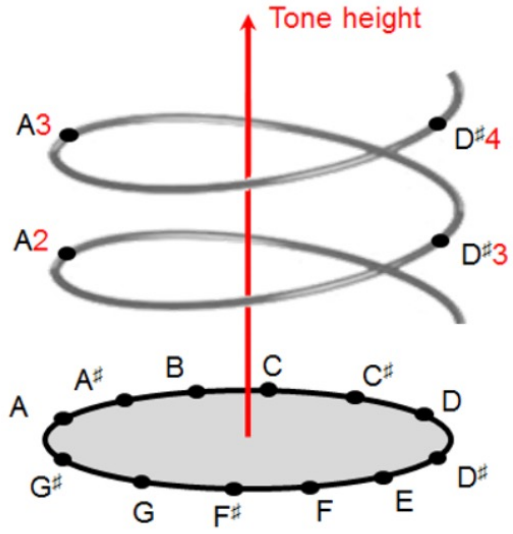


Figure 1.3 from [Müller, FMP, Springer 2015]



Chroma Features

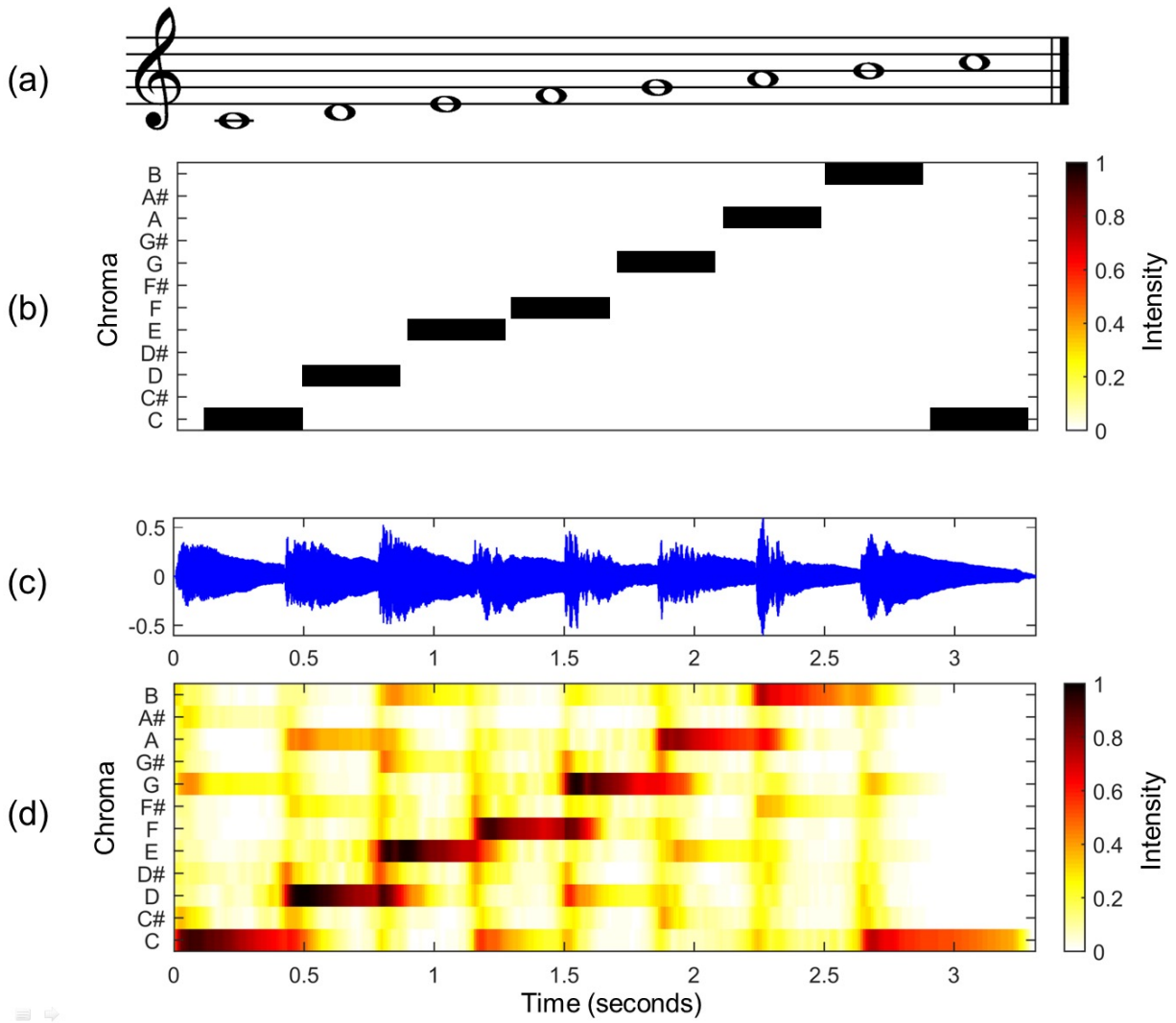
- Human perception of pitch is periodic in the sense that two pitches are perceived as similar in color if they differ by an octave.
- Separation of pitch into two components:
  tone height (octave number) and chroma.
- Chroma : 12 traditional pitch classes of the equal-tempered scale.
  For example:

  Chroma C
- Computation: pitch features → chroma features

  Add up all pitches belonging to the same class
- Result: 12-dimensional chroma vector.

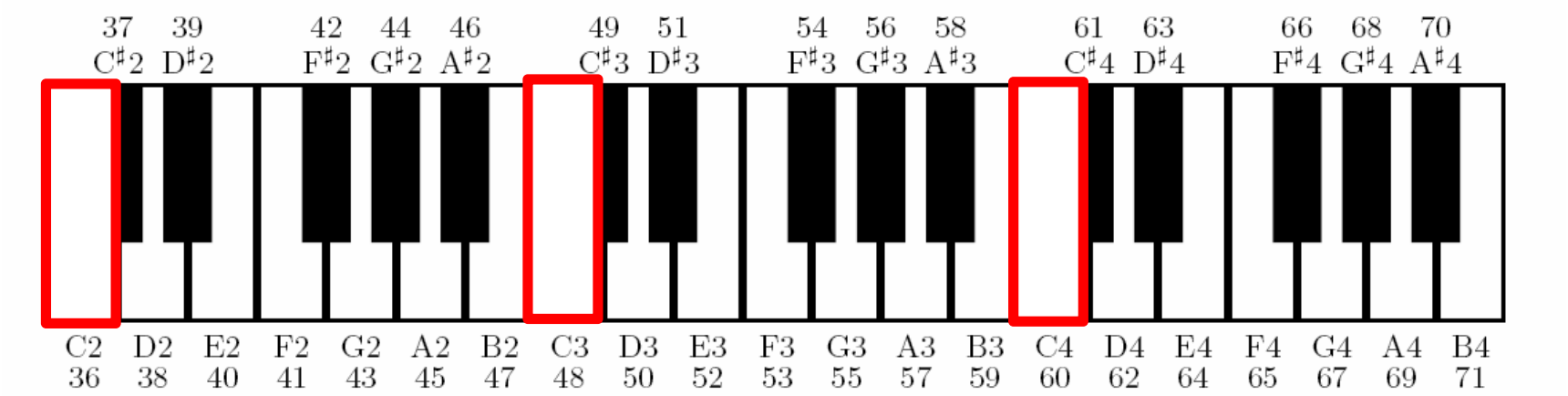
$$\widehat{=} \{\ldots\ ,\ \mathrm{C0}\ ,\ \mathrm{C1}\ ,\ \mathrm{C2}\ ,\ \mathrm{C3}\ ,\ \ldots\}$$

Chroma Features



Chroma Features

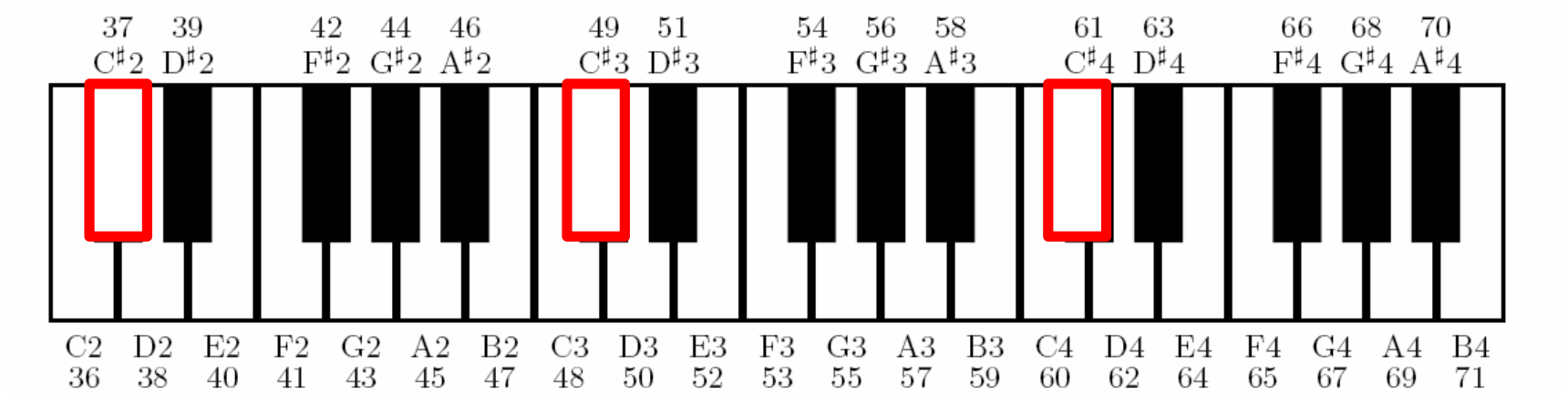
Computer Science



C2 C3 C4

Chroma C

Chroma Features

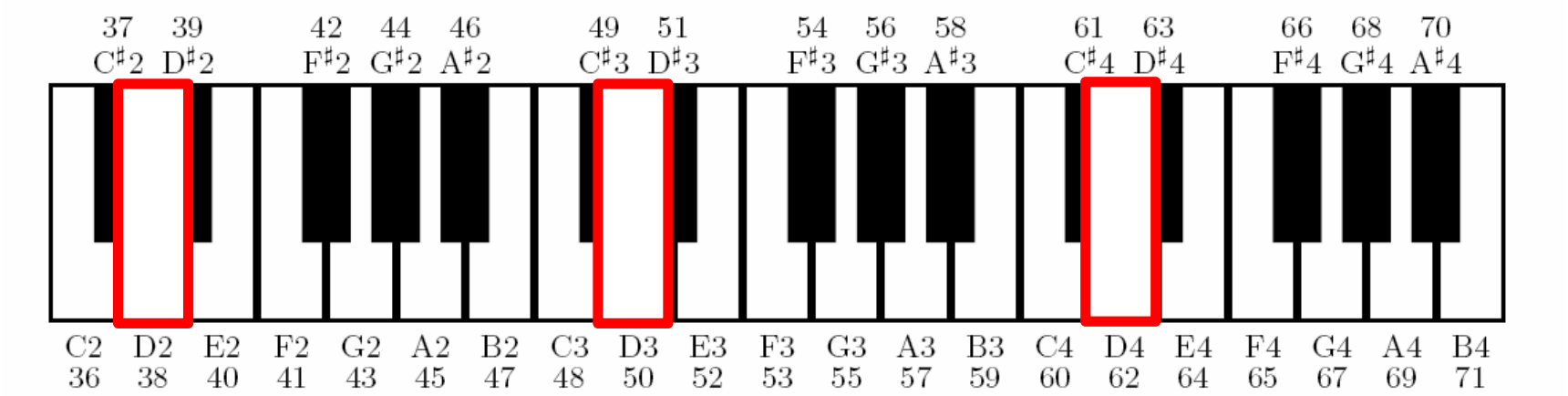


C♯2 C♯3 C♯4

Chroma C♯

Chroma Features

Computer Science

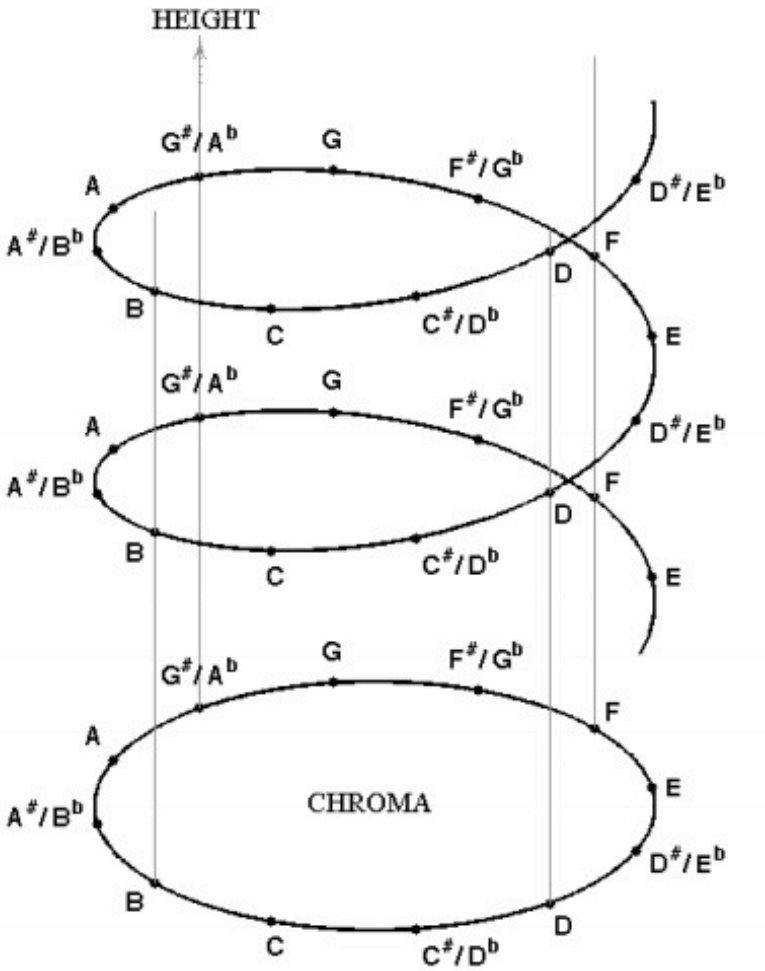


D2 D3 D4

Chroma D

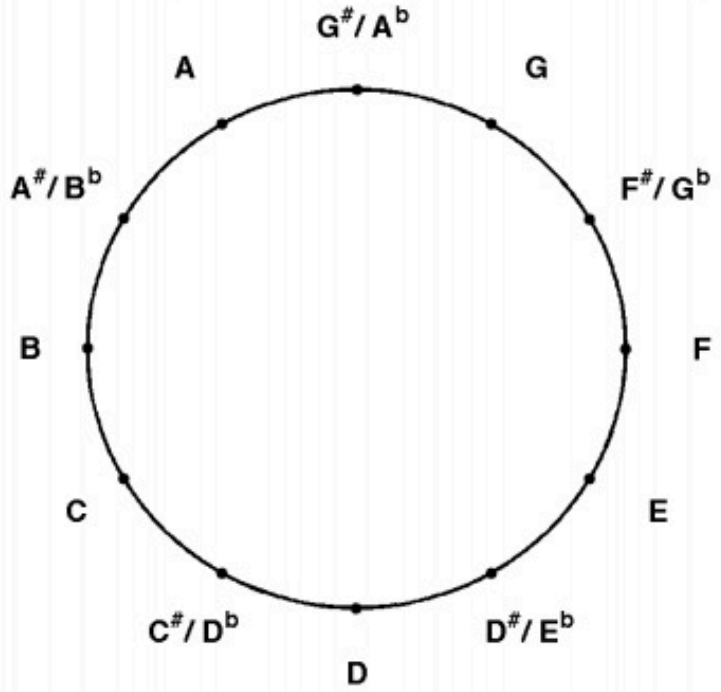
Pitch perception

- The pitch helix is a representation of pitch relationships that places tones in the surface of a cylinder (Shepard, 2001)
- Models the special relationship that exists between octave intervals.
- The model is a function of 2-dimensions:
- Height: naturally organizes pitches from low to high
- Chroma: represents the inherent circularity of pitch organization



Chroma

- Chroma describes the angle of pitch rotation as it traverses the helix
- Two octave-related pitches will share the same angle in the chroma circle: a relation that is not captured by a linear pitch scale (or even Mel).



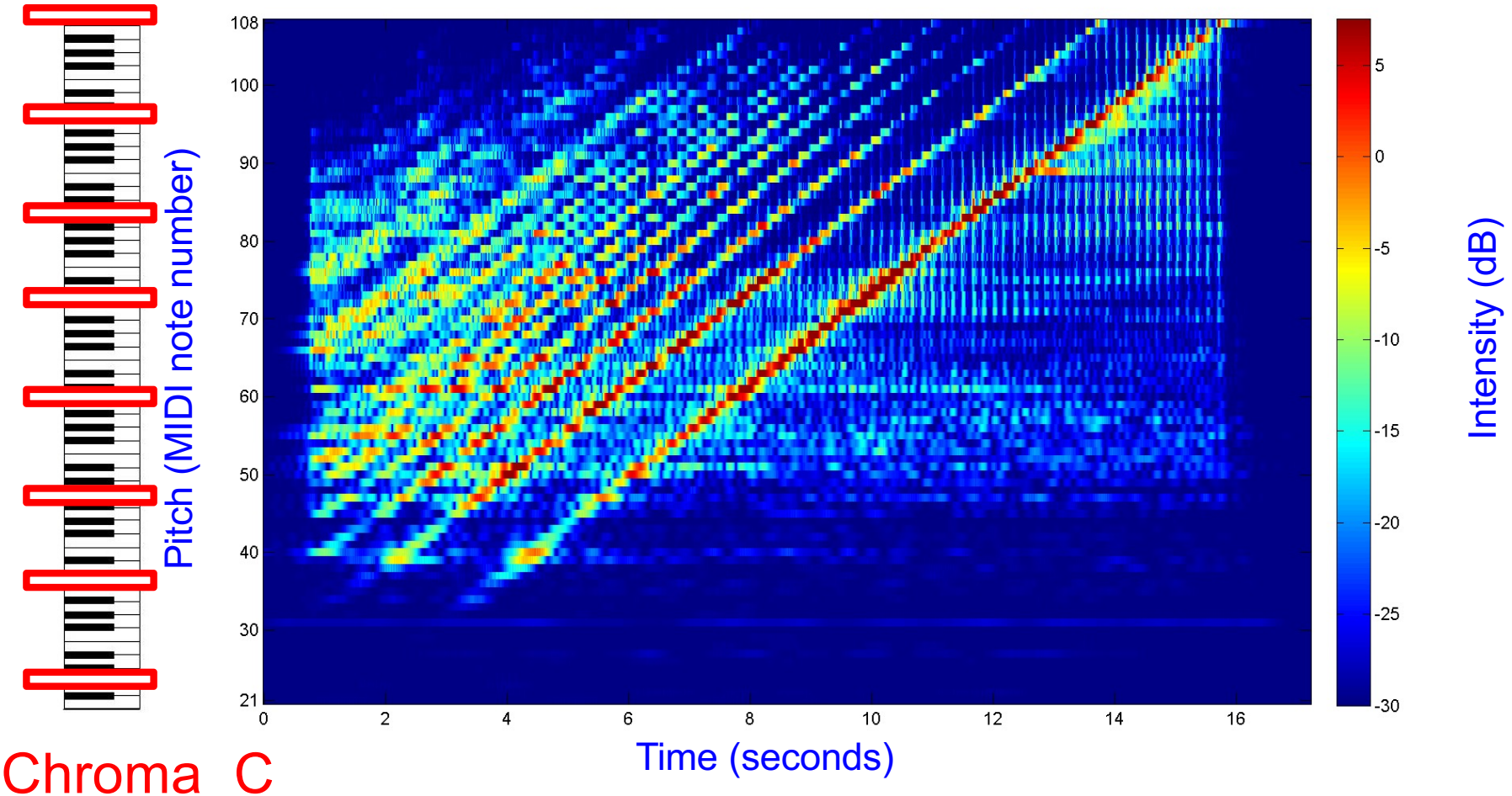
- For the analysis of western tonal music we quantize this angle into 12 positions or pitch classes.

Pitch Features: Chroma

Computer Science

Example: Chromatic scale

Log-frequency spectrogram

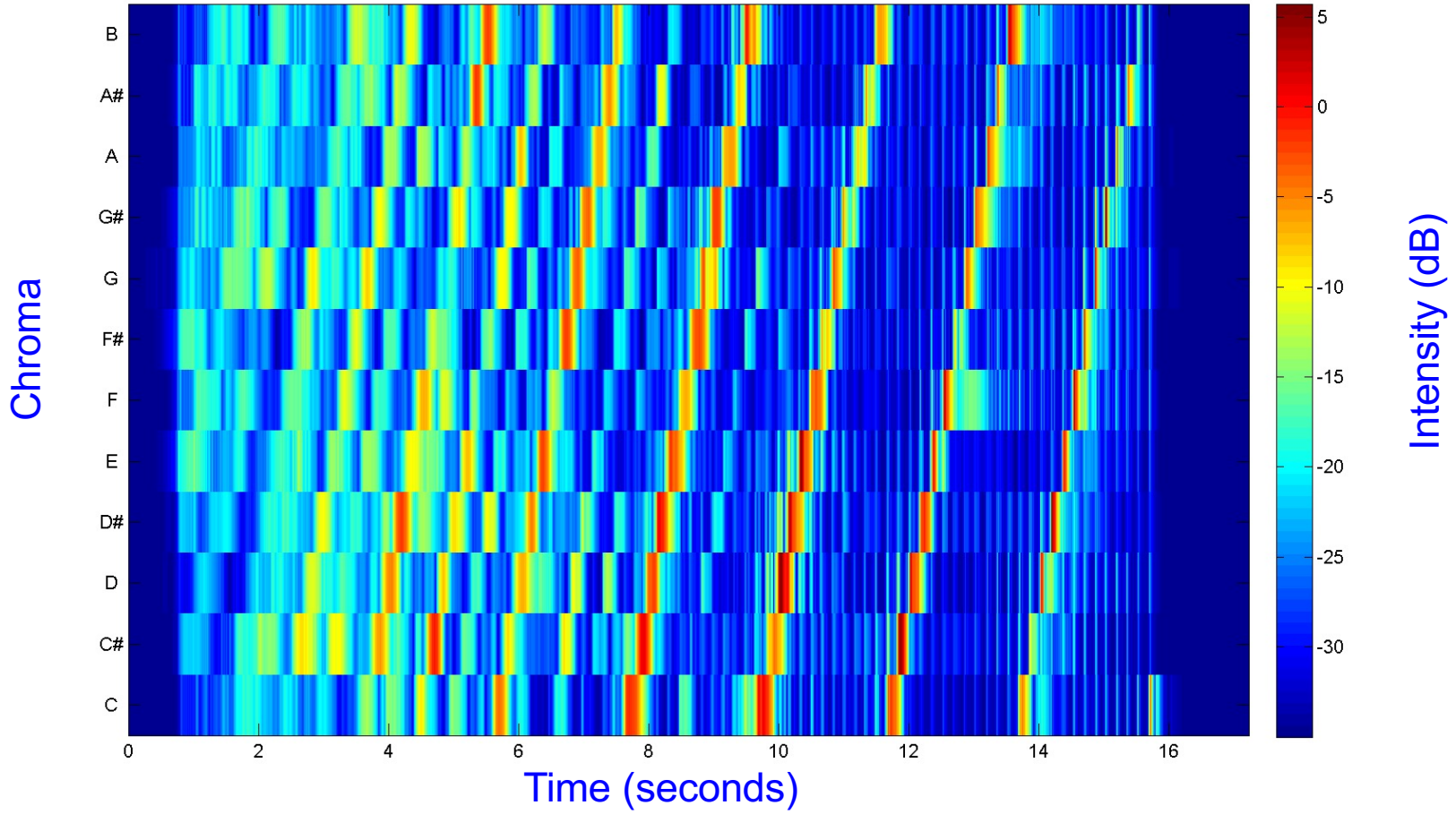


Chroma Features: Collapse spectrogram into 12 Chroma Bins (just all up all chroma)

Computer Science

Example: Chromatic scale

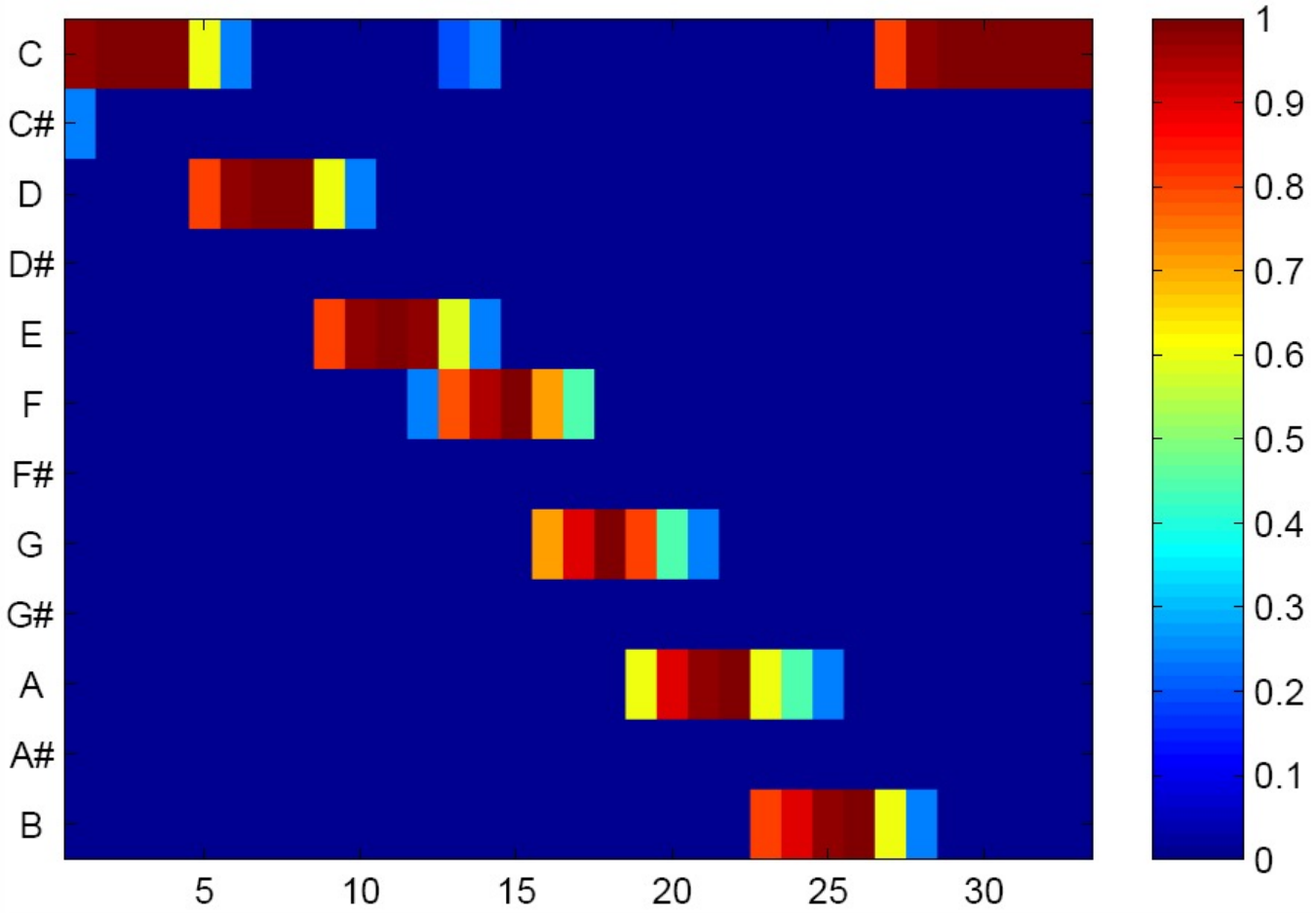
Chroma representation



Chroma Features

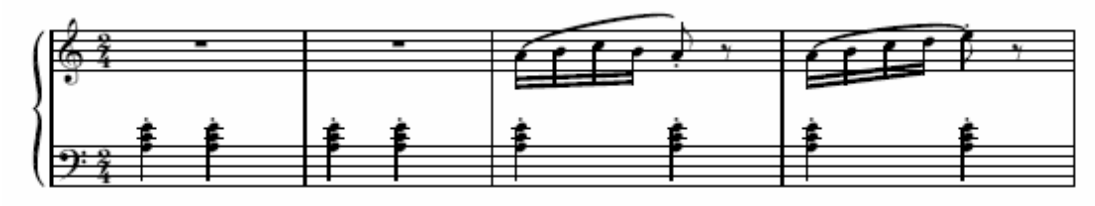
Computer Science

Example: C-Major Scale

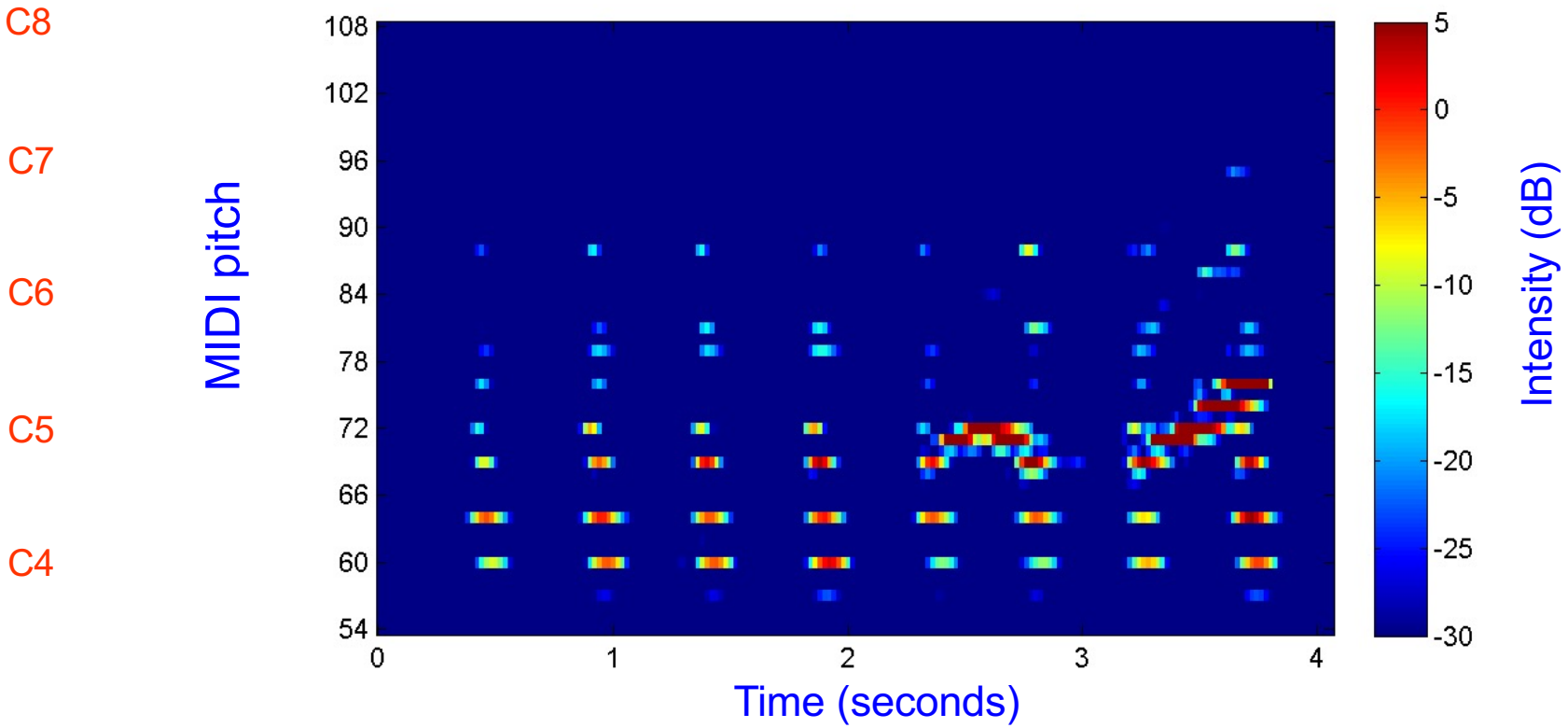


Chroma Features

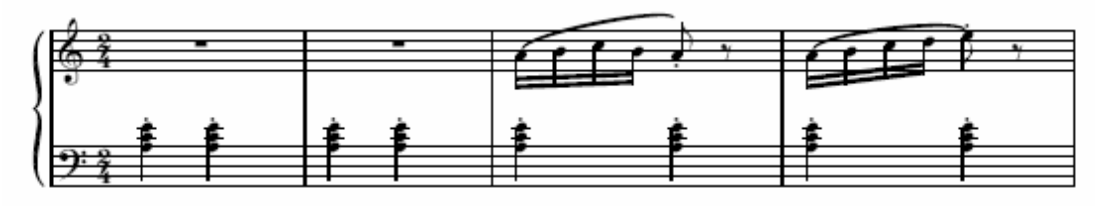
Computer Science



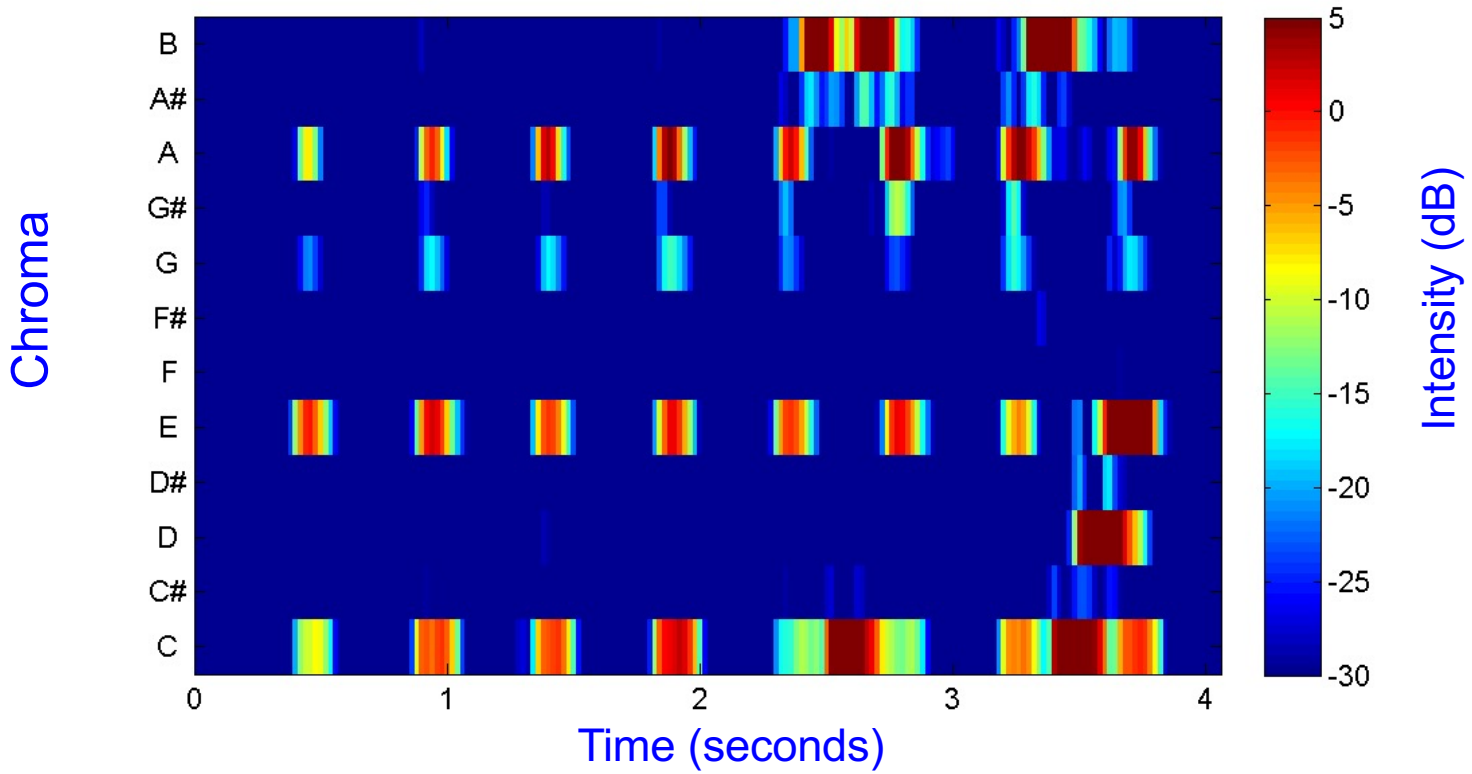
Pitch representation



Chroma Features



Chroma representation



Chroma Features

- Sequence of chroma vectors correlates to the harmonic progression
- Normalization $v \rightarrow \frac{v}{\|v\|}$ makes features invariant to changes in dynamics
- Further quantization and smoothing
- Taking logarithm before adding up pitch coefficients accounts for logarithmic sensation of intensity

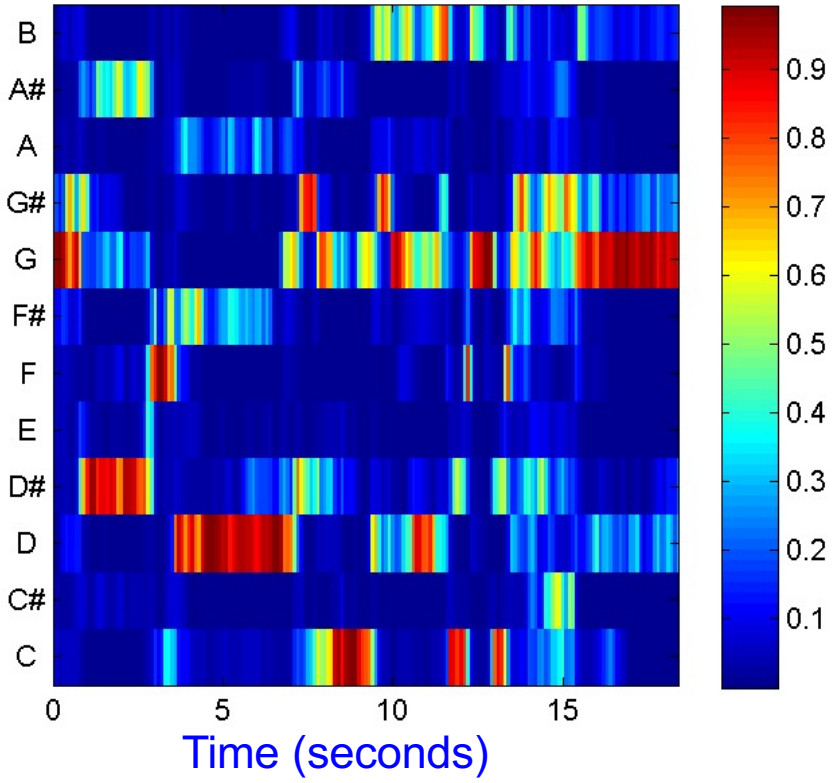
Chroma Features

Computer Science

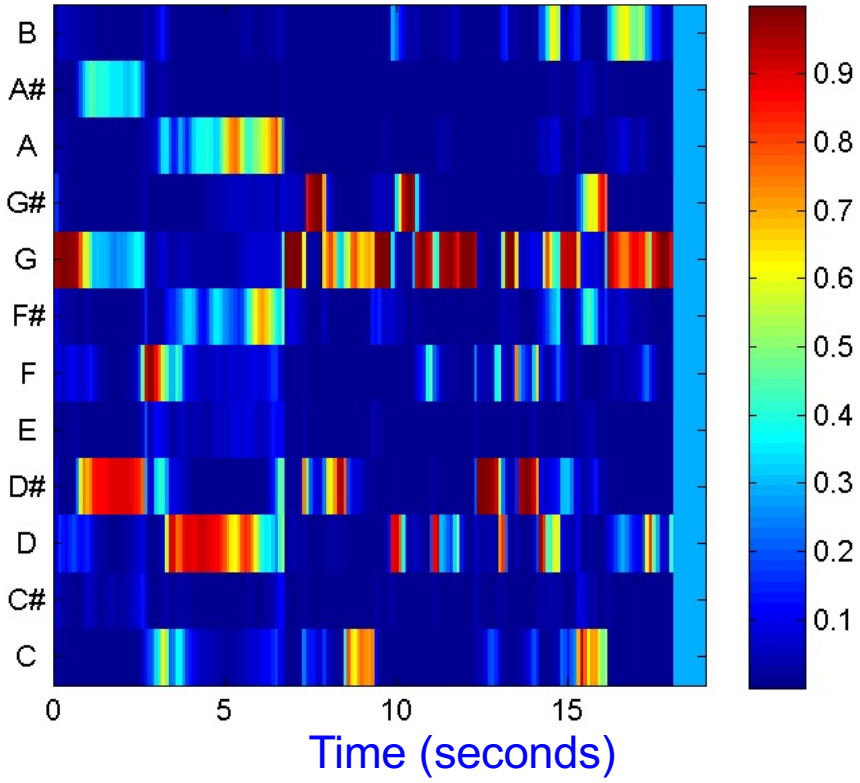
Example: Beethoven's Fifth

Chroma representation

Karajan



Scherbakov



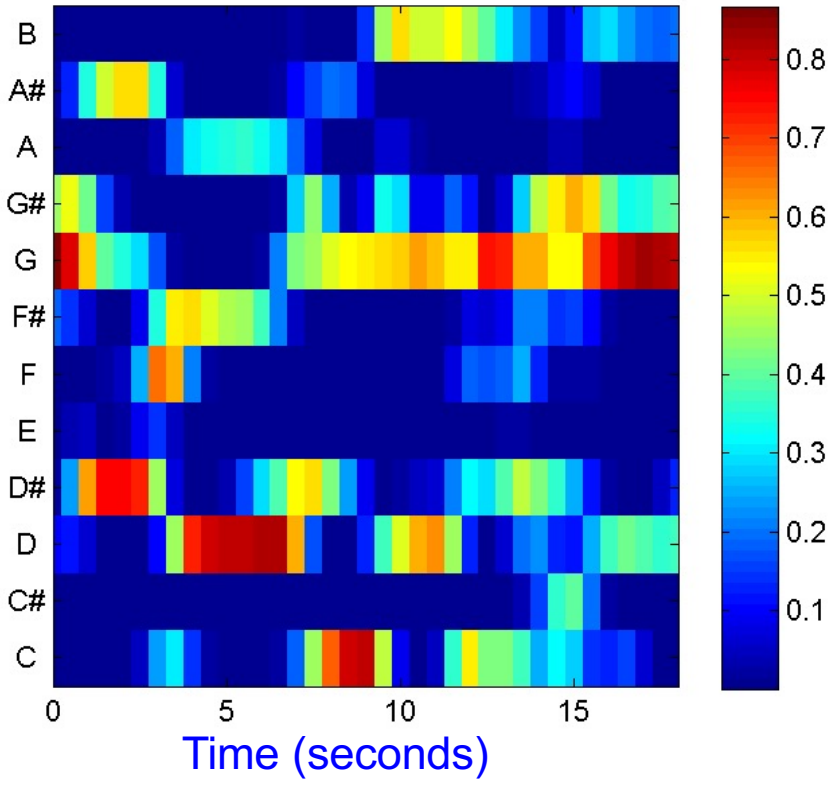
Chroma Features: Effect of resolution

Example: Beethoven's Fifth

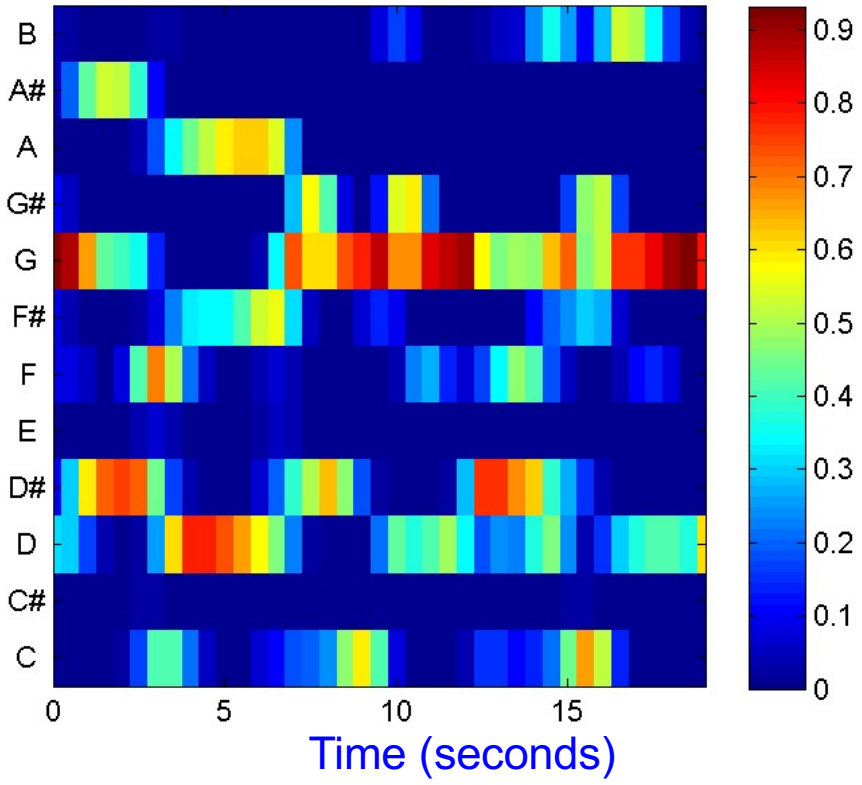
Chroma representation (normalized, 2 Hz)

Smoothing (2 seconds) + downsampling (factor 5)

Karajan



Scherbakov



Chroma Features: Effect of Resolution

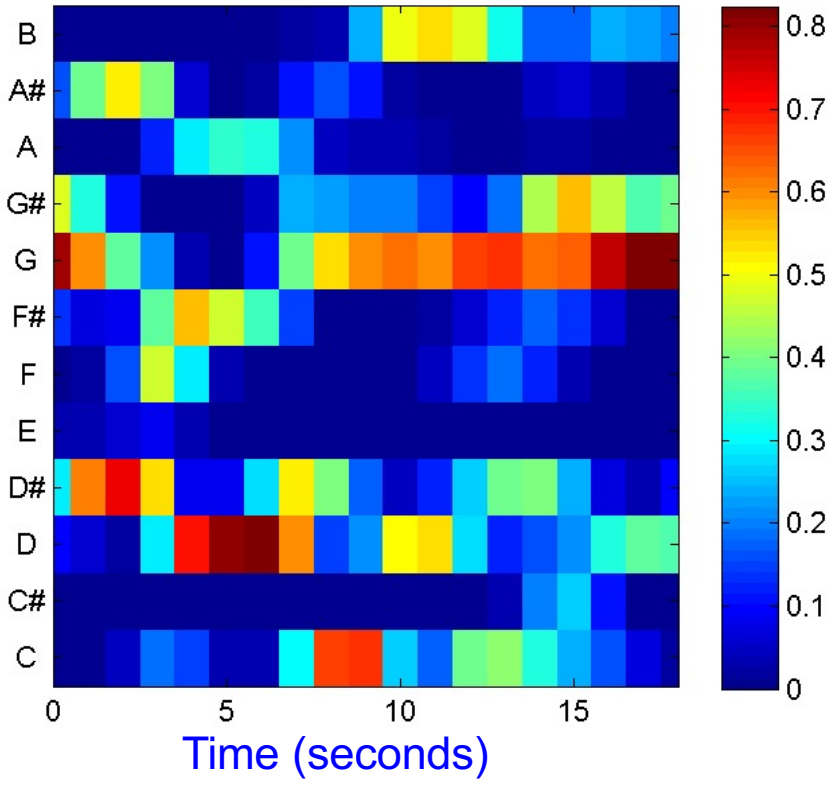
Computer Science

Example: Beethoven's Fifth

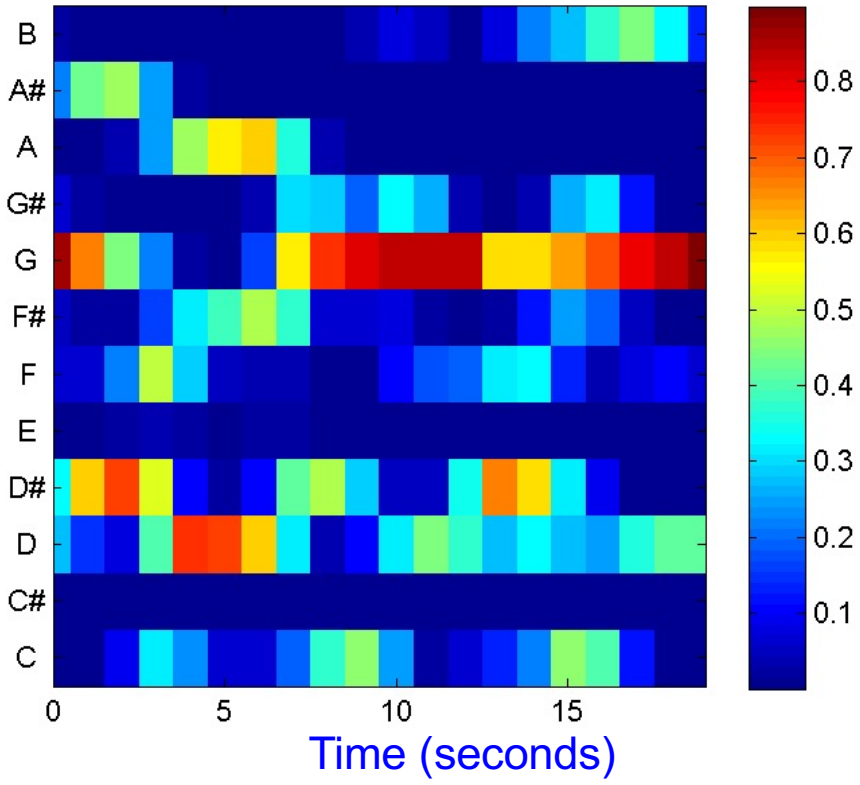
Chroma representation (normalized, 1 Hz)

Smoothing (4 seconds) + downsampling (factor 10)

Karajan



Scherbakov

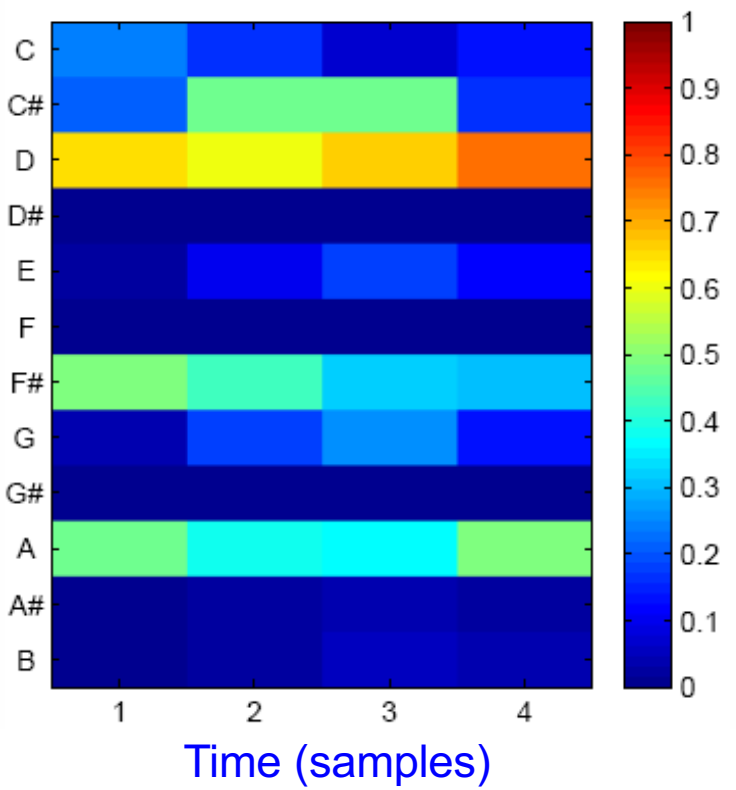


Chroma Features: Time Scaling

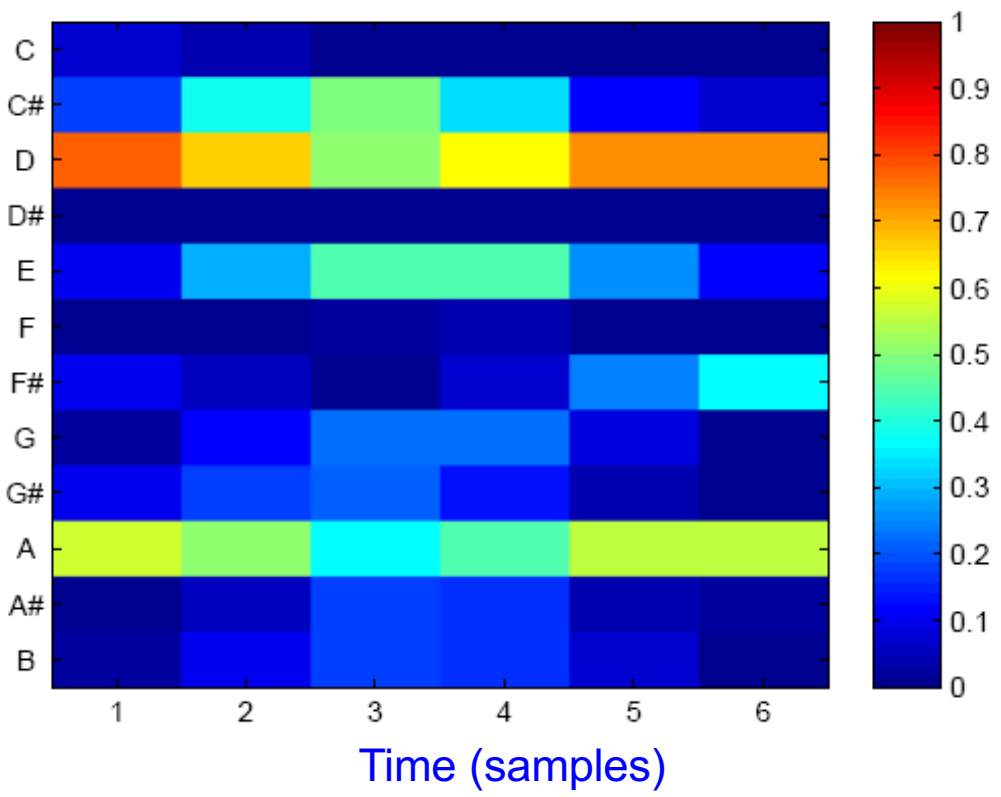
Computer Science

Example: Bach Toccata

Koopman



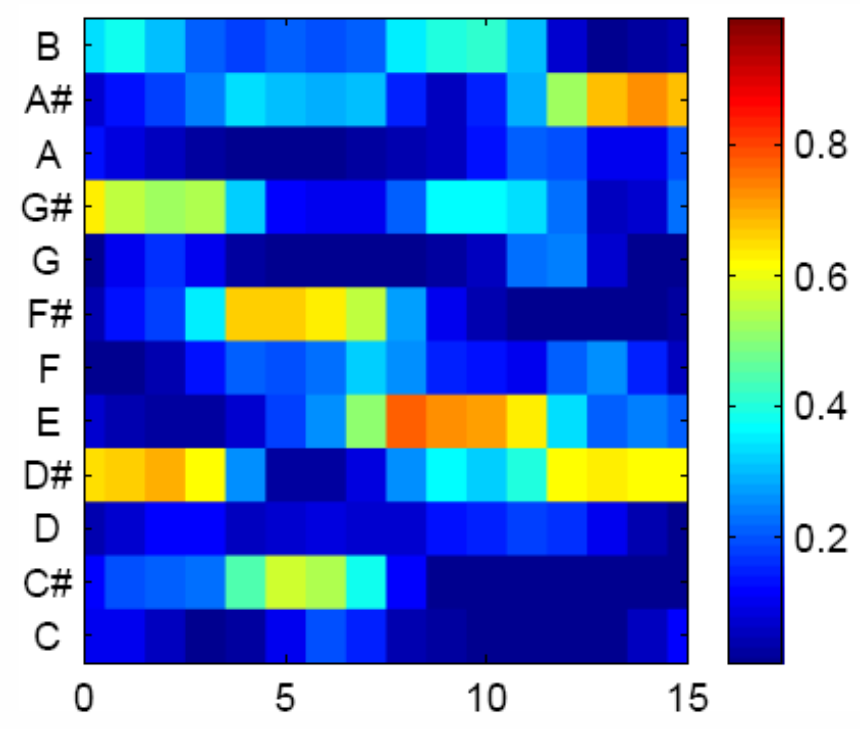
Ruebsam



Chroma Features: Effect of Transposition

Computer Science

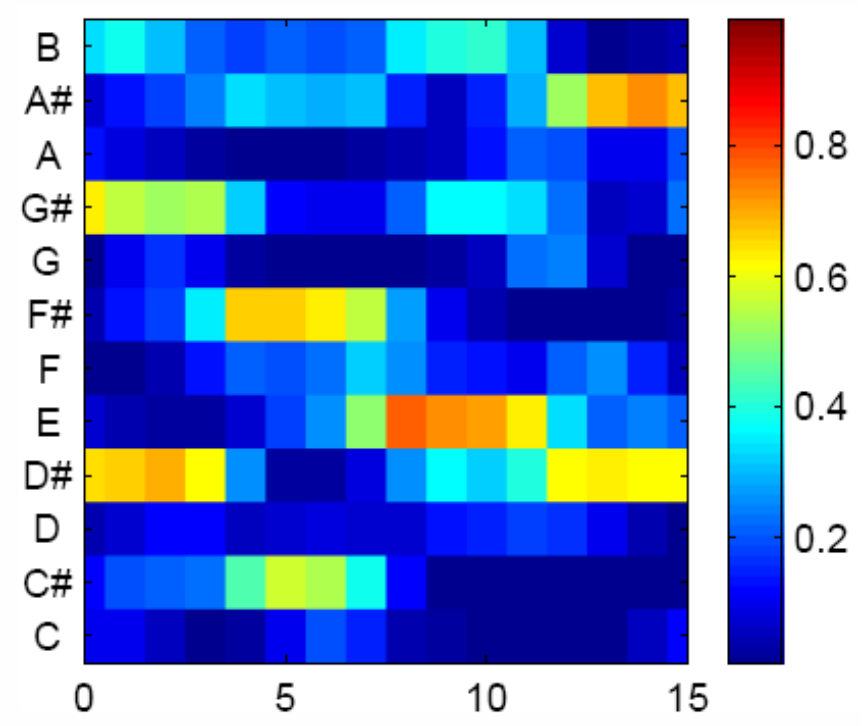
Example: Zager & Evans “In The Year 2525”

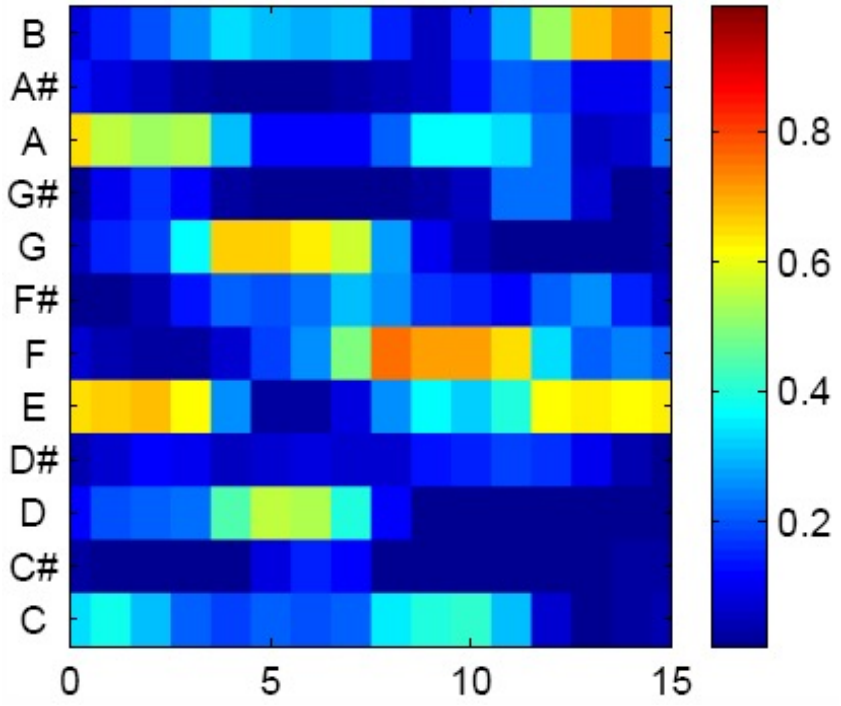


Original: $(v^1, \ldots, v^N)$

Chroma Features: Effect of Transposition

BOSTON UNIVERSITY
Computer Science





Original: $(v^1, \ldots, v^N)$

Shifted: $(\sigma(v^1), \ldots, \sigma(v^N))$

Solution: Must either transpose one of the signals, or rotate the chroma through all 12 positions!

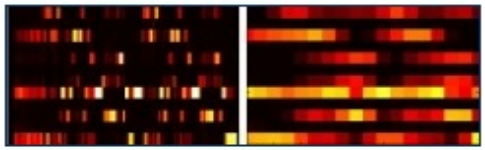
Audio Features

- There are many ways to implement chroma features
- Properties may differ significantly
- Appropriateness depends on respective application

Chroma Toolbox: Pitch, Chroma, CENS, CRP

max planck institut informatik

UNIVERSITÄT DES SAARLANDES



universitätbonn

- http://www.mpi-inf.mpg.de/resources/MIR/chromatoolbox/
- MATLAB implementations for various chroma variants

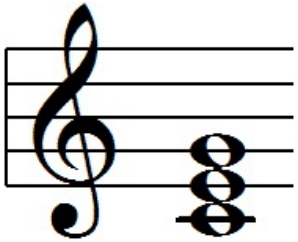
Chord Recognition: What is a Chord?

- Combination of three or more tones which sound simultaneously
- Chord classes
  - Triads including major, minor, diminished, augmented chords
  - Many other more complex chords such as seventh chords
- Here: focus on major and minor triads

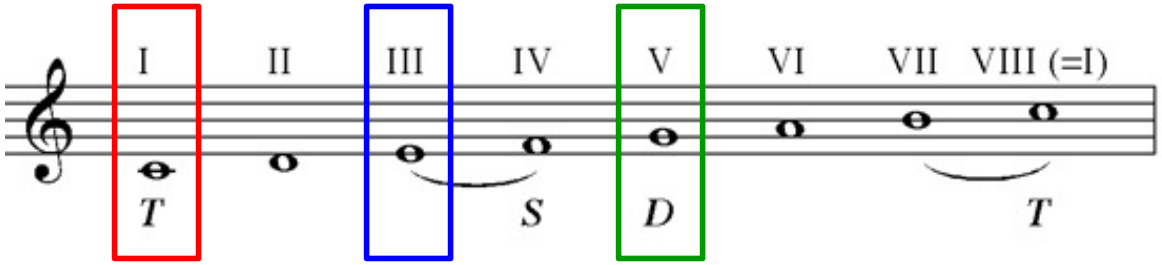
Musical Chords

Computer Science

The C **major** chord



Derived from the C **major** scale



C ---- the root

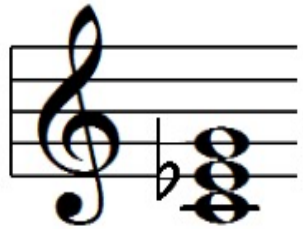
E ---- the (**major**) third

G ---- the fifth

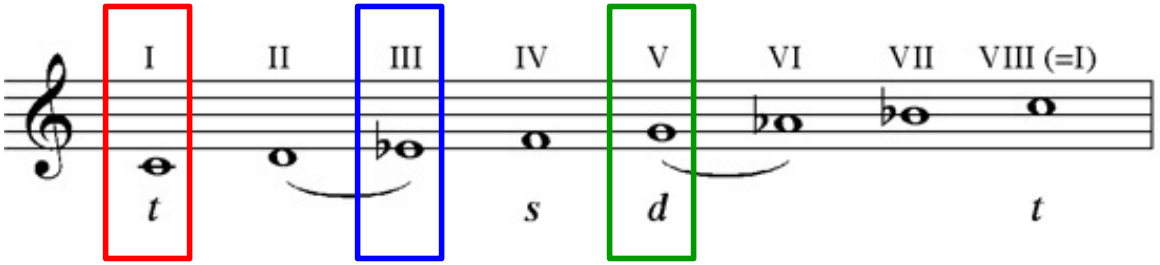
Musical Chords

Computer Science

The C **minor** chord



Derived from the C **minor** scale



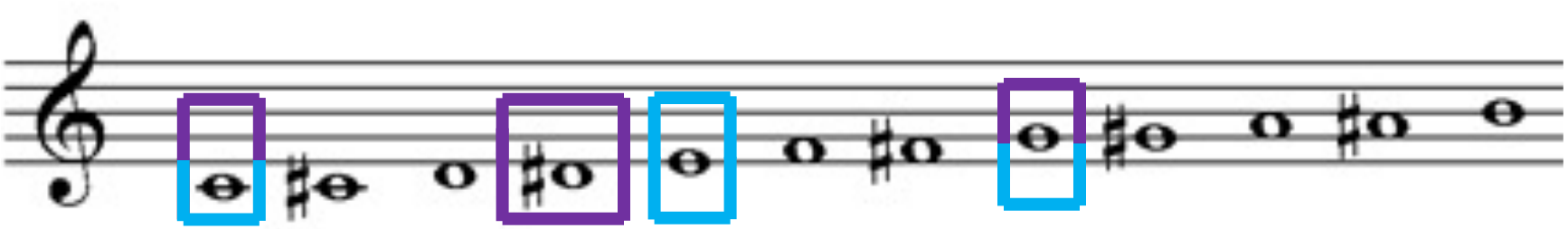
C ---- the root

Eb ---- the (**minor**) third

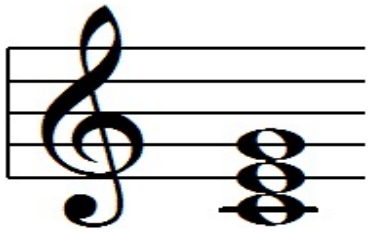
G ---- the fifth

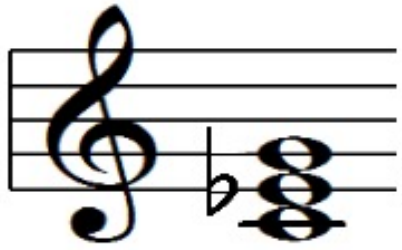
Musical Chords

Structure of the 24 major/minor chords



	0	1	2	3	4	5	6	7	8	9	10	11
	C	C#	D	D#	E	F	F#	G	G#	A	A#	B
C major	✓				✓			✓				
C minor	✓			✓				✓				





Chord Recognition

- Development of automatic methods for the
  harmonic analysis of audio data

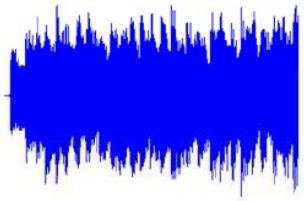
- Applications in the field of music information retrieval:

  - music segmentation
  - cover song identification
  - audio matching
  - music structure analysis
  - …

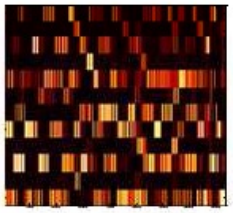
Chord Recognition

Computer Science

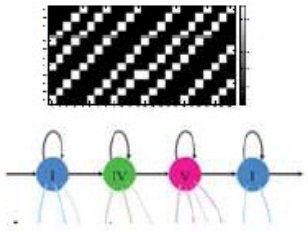
Signal



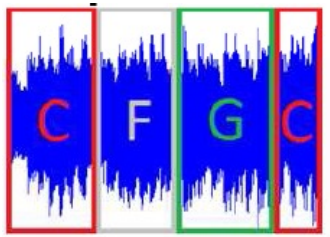
Feature Extraction



Classification



Result



Chroma features

- Type
- Resolution
- Compression
- Smoothing

Pattern matching

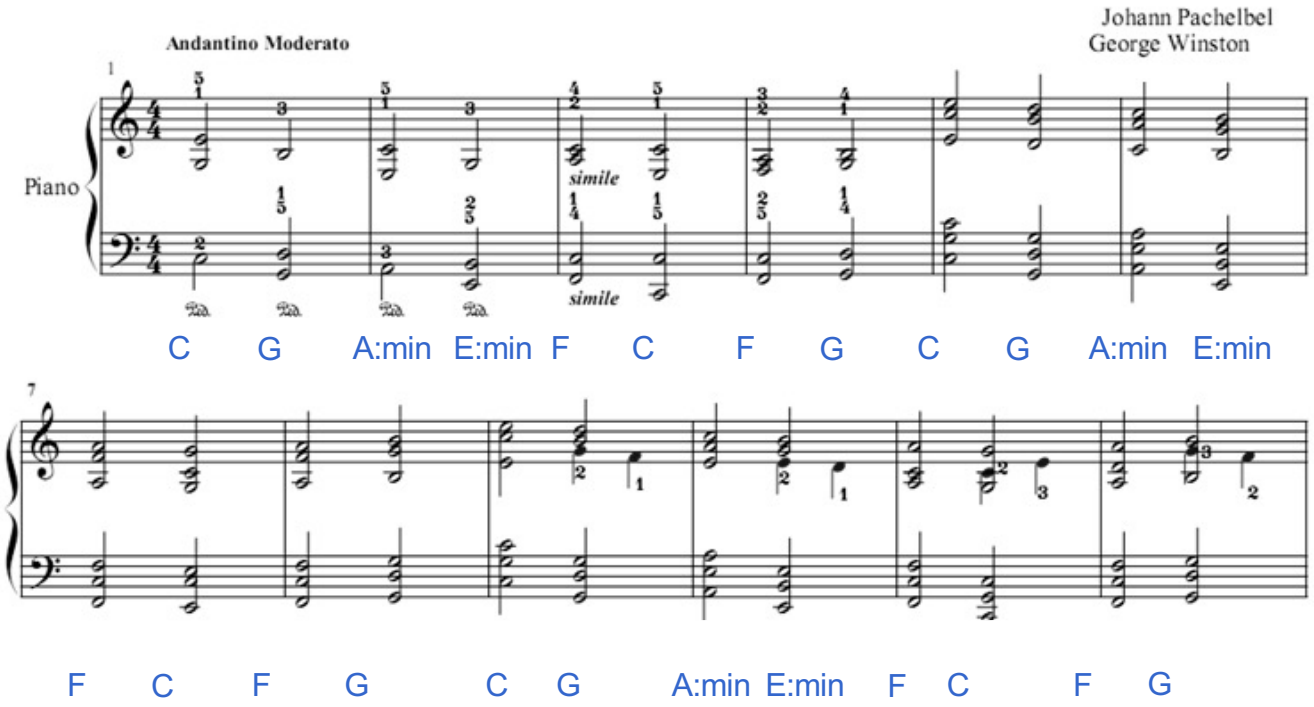
- Binary Template
- Gaussian
- Hidden Markov Models
- Graphical Models

Chord Recognition

Computer Science

Given: Audio file

Output: Segmentation and chord labeling



Binary Template: A Baseline Method for Chord Recognition

Chord templates 24 major/minor chords

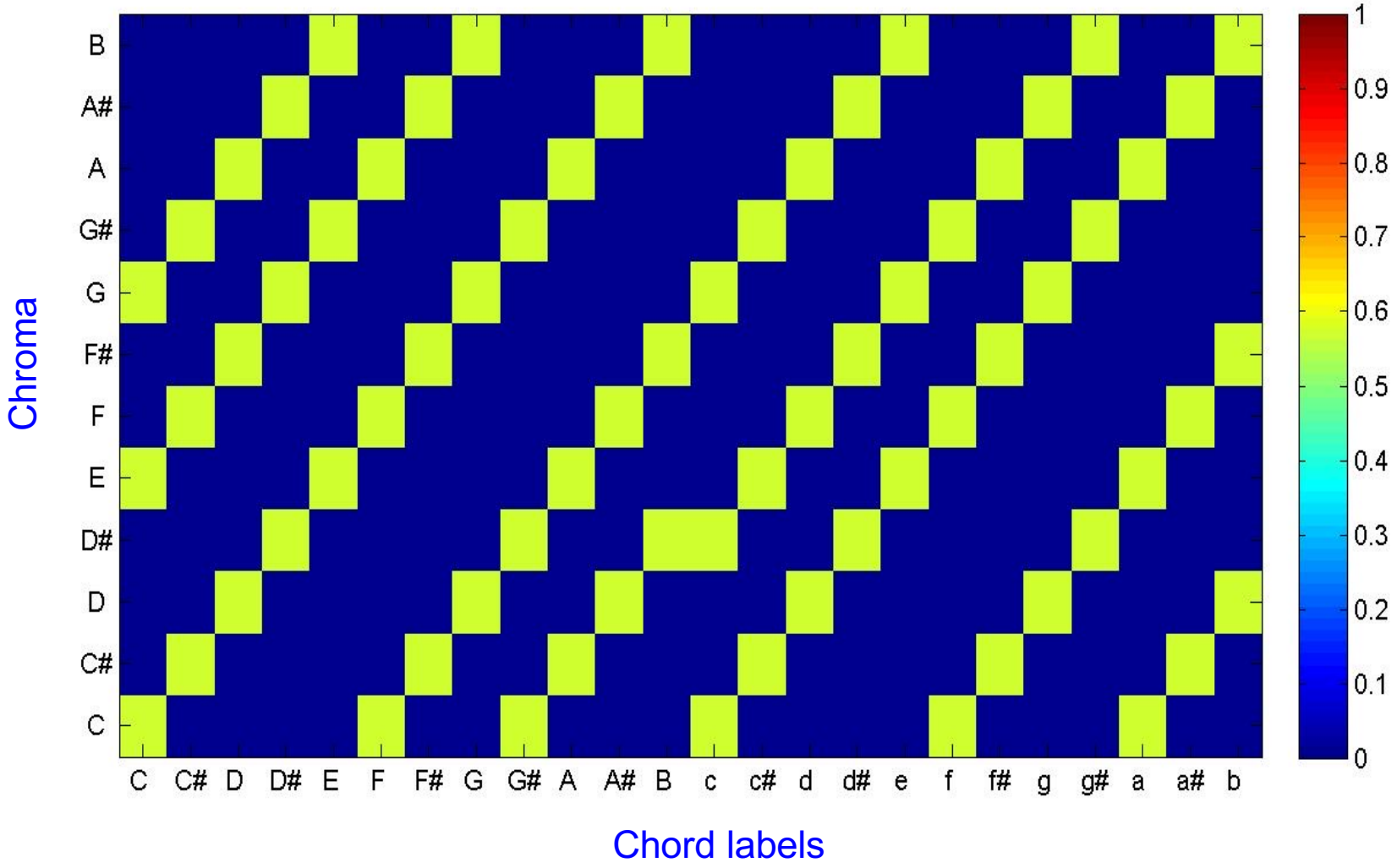
Binary match on signal

	C major	C# major	D major	D# major	……	C minor	C# minor	……
B	0	0	0	0	……	0	0	……
A#	0	0	0	1	……	0	0	……
A	0	0	1	0	……	0	0	……
G#	0	1	0	0	……	0	1	……
G	1	0	0	1	……	1	0	……
F#	0	0	1	0	……	0	0	……
F	0	1	0	0	……	0	0	……
E	1	0	0	0	……	0	1	……
D#	0	0	0	1	……	1	0	……
D	0	0	1	0	……	0	0	……
C#	0	1	0	0	……	0	1	……
C	1	0	0	0	……	1	0	……

Baseline Method for Chord Recognition

Computer Science

Chroma templates 24 major/minor chords



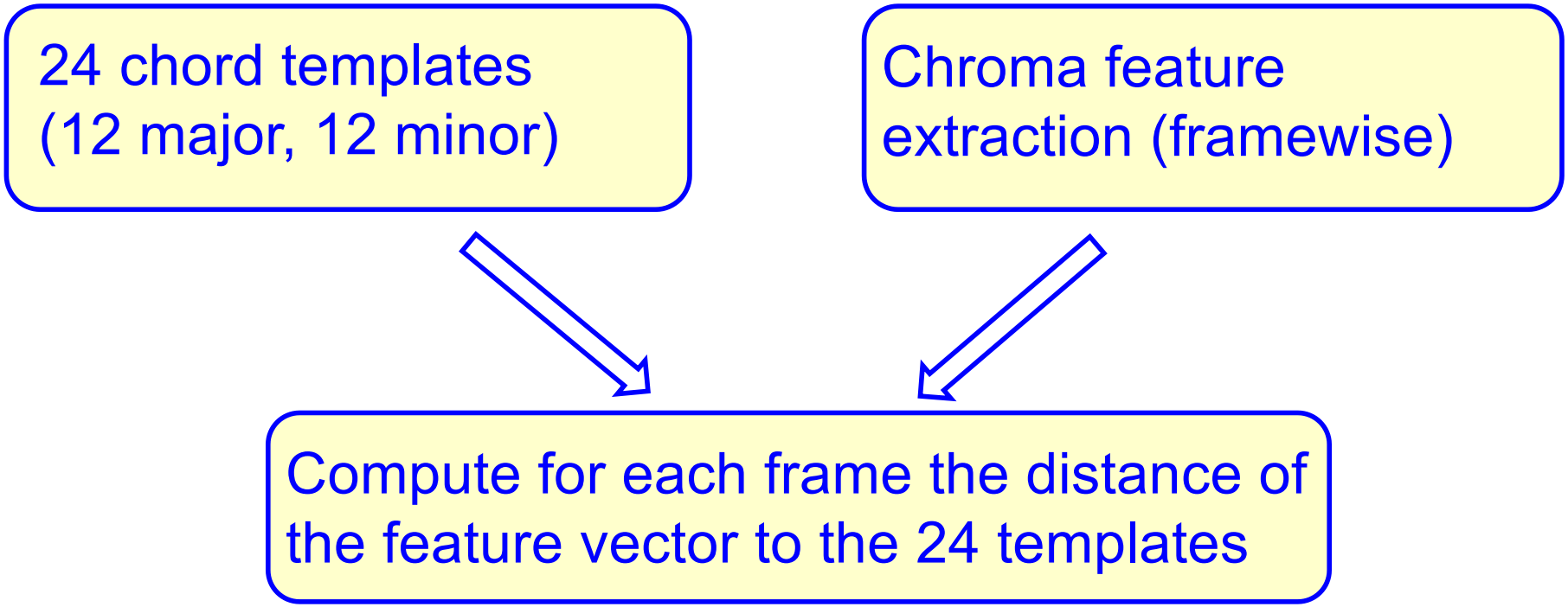
Baseline Method for Chord Recognition

Computer Science

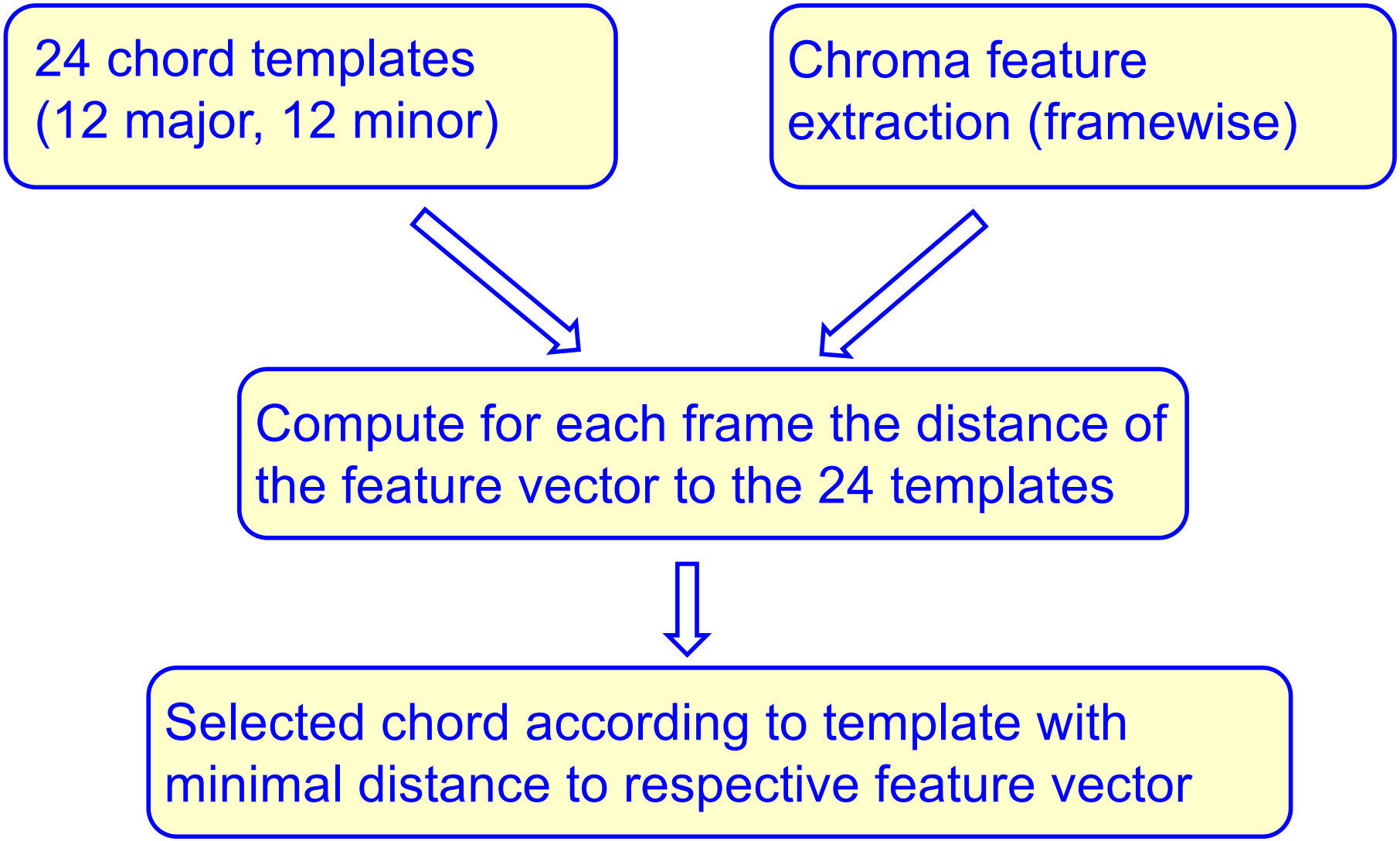
24 chord templates
(12 major, 12 minor)

Chroma feature
extraction (framewise)

Baseline Method for Chord Recognition



Baseline Method for Chord Recognition

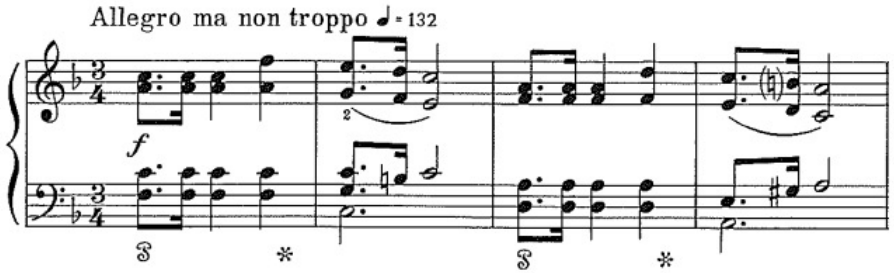


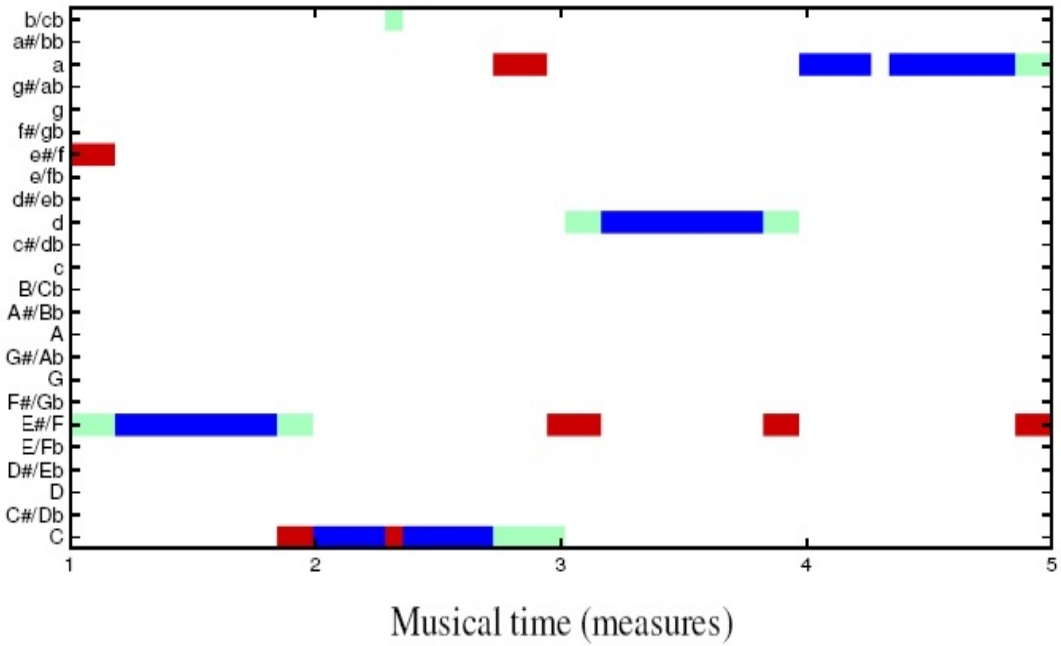
Problems in Chord Recognition

Computer Science

Problem: Transitions between subsequent chord

Example: Chopin Mazurka Op. 68 No.3





Correct

False positive

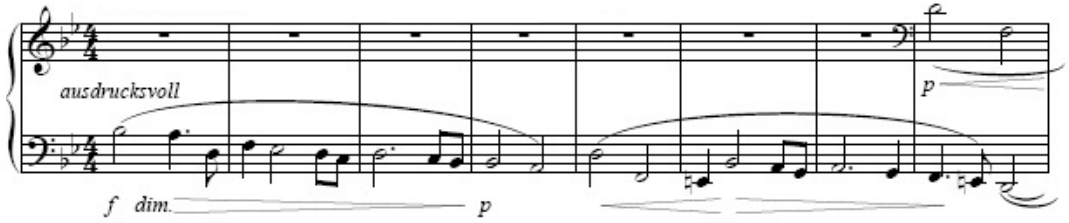
False negative

Problems in Chord Recognition

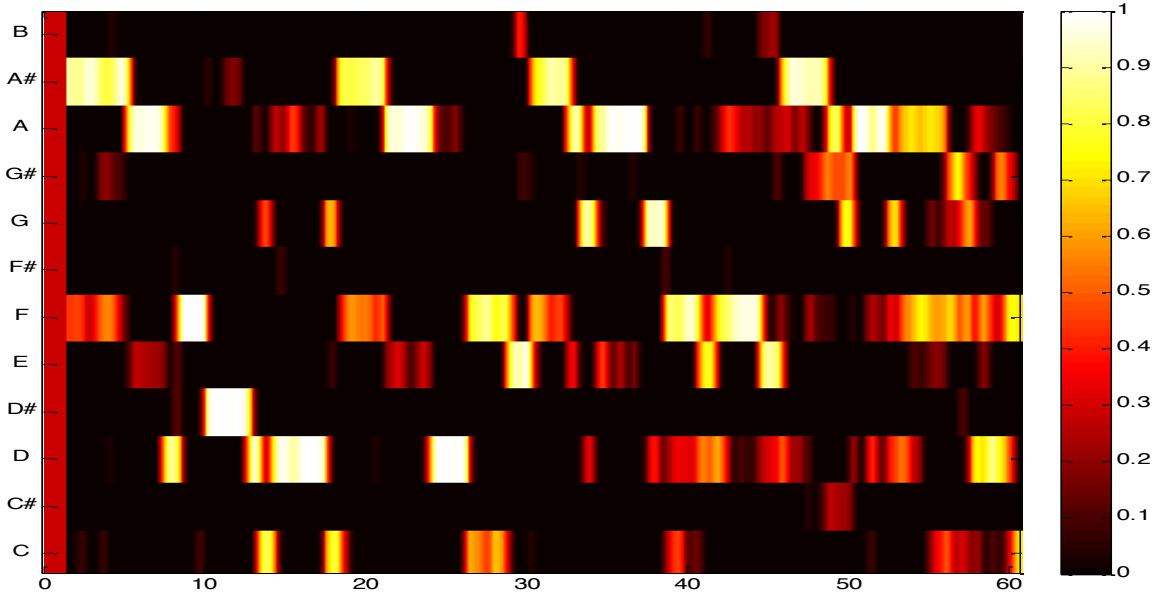
Computer Science

Problem: Monphonic musical passages

Example: Excerpt of Wagner's Meistersinger



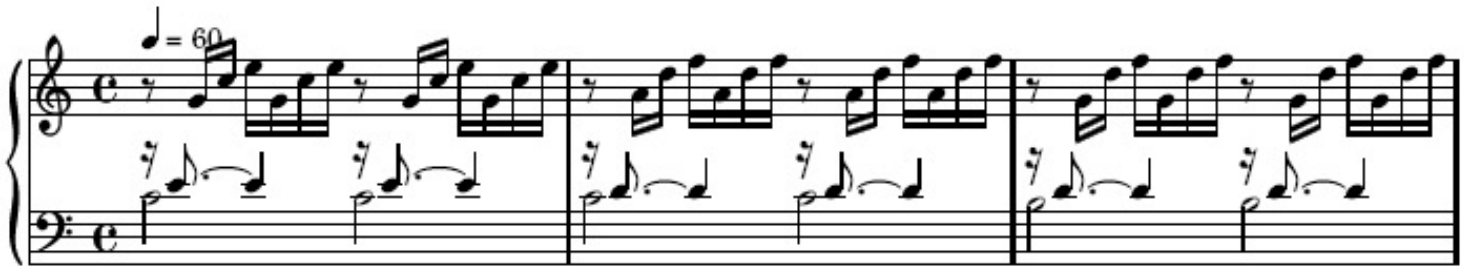
Chromagram



Problems in Chord Recognition

Problem: Frame-wise chord analysis may not be meaningful

Example: Bach: Prelude C major, BWV 846

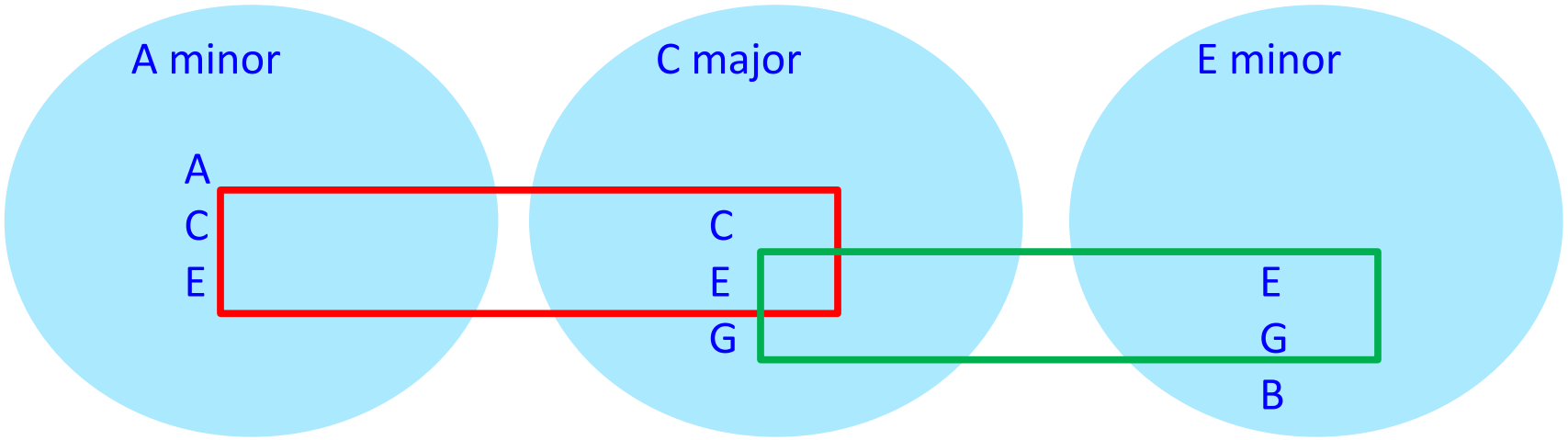


Problem: Broken chords

→ Measure-wise chord analysis necessary

Problems in Chord Recognition

Problem: Ambiguity of chords



Problems in Chord Recognition

Problem: Only very simple music uses only the 24 major and minor triads!
Advanced chord recognition is difficult!

Example: WTC, Prelude C major, mm.19-25: Diminished Seventh Chord!