

# CS 583– Computational Audio -- Fall, 2021

Wayne Snyder  
Computer Science Department  
Boston University

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## Lecture 10

Chroma

Chord Recognition by template matching

Problems with Chord Recognition

Coding the algorithm



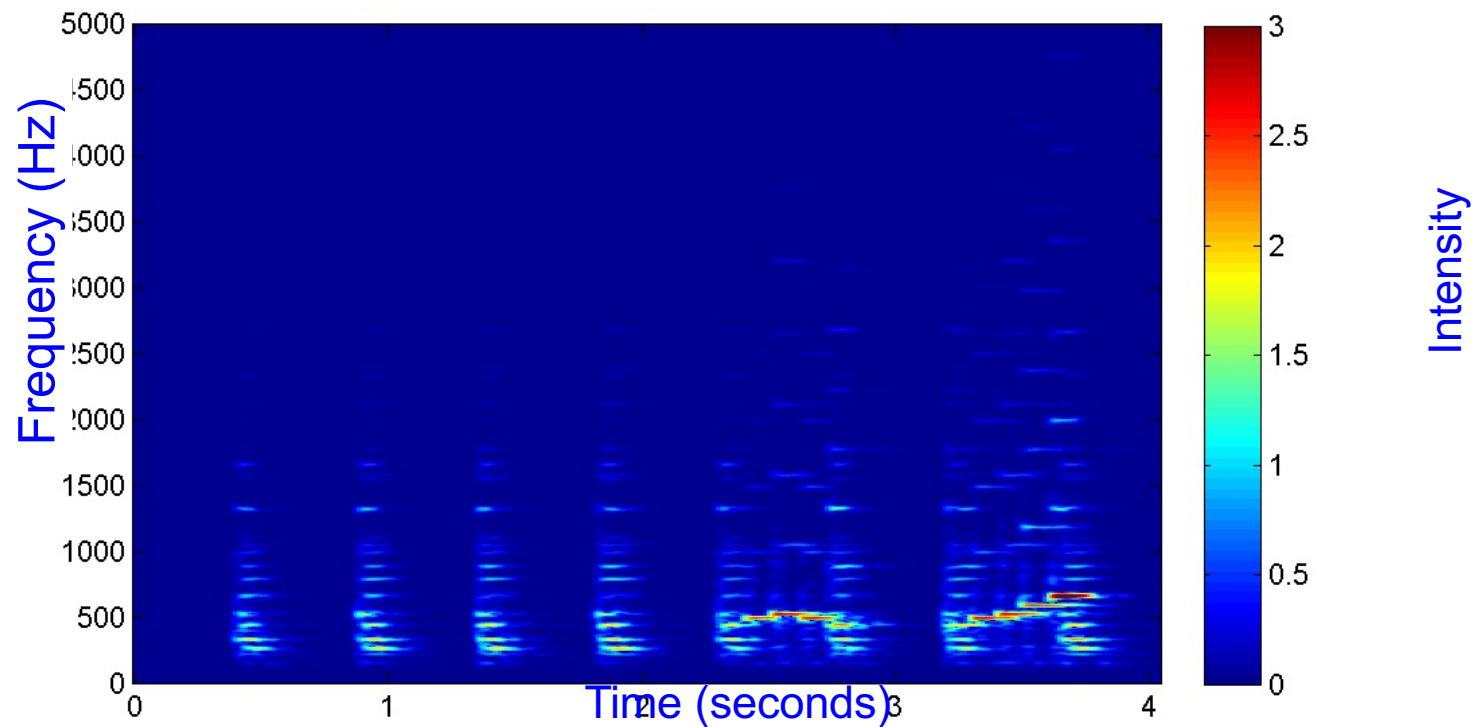
# A Spectrogram shows Pitch Features of a Musical Signal



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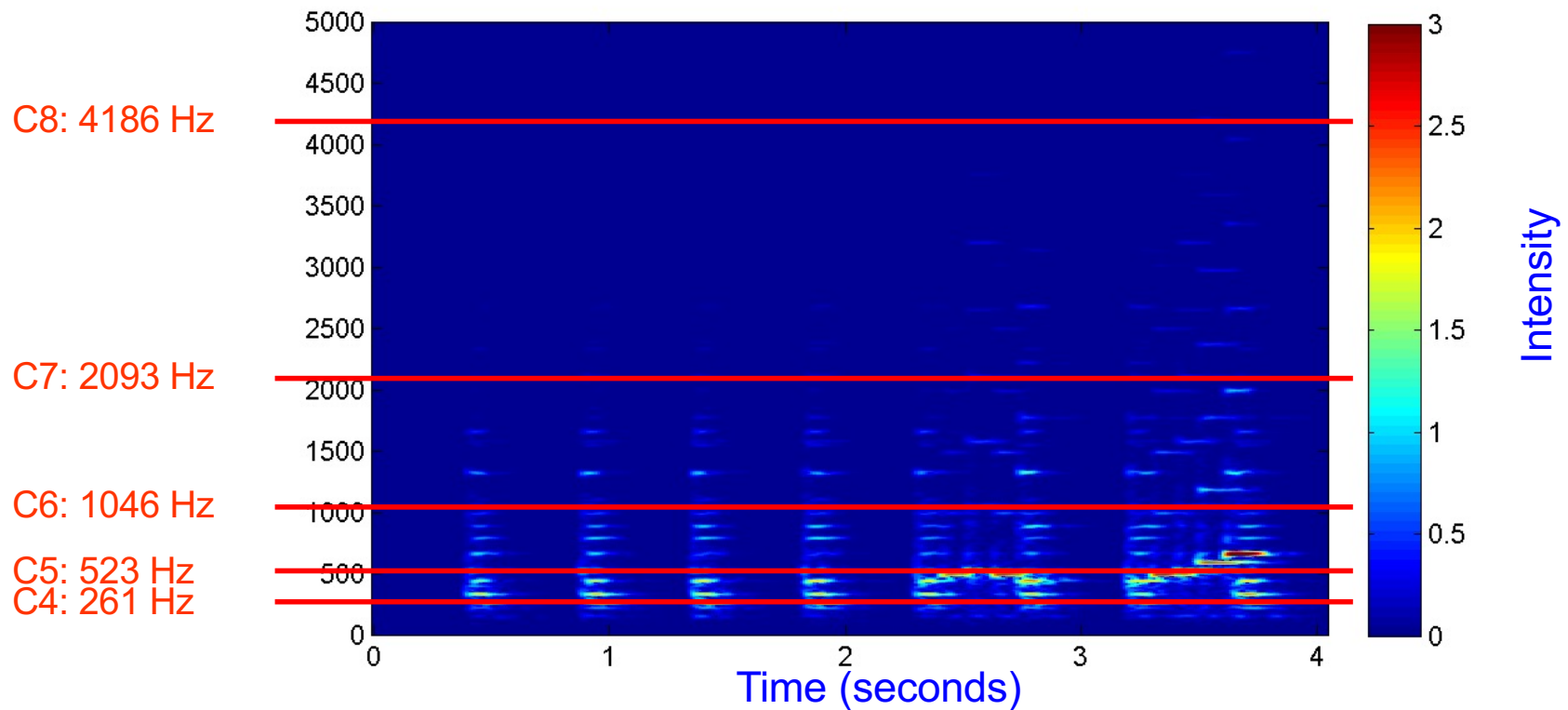
## Spectrogram



# Pitch Features



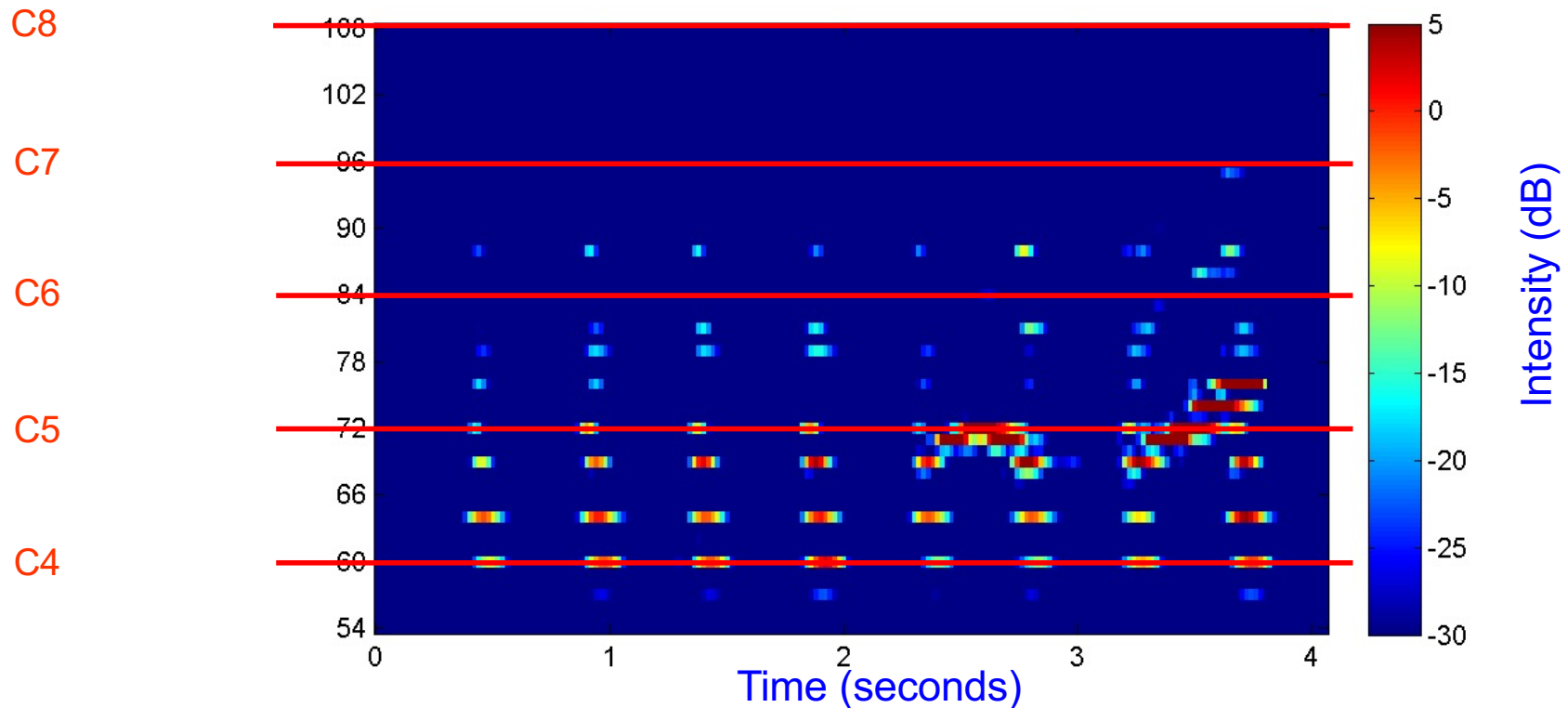
## Spectrogram



# Pitch Features



## Logarithmic Frequency Scale



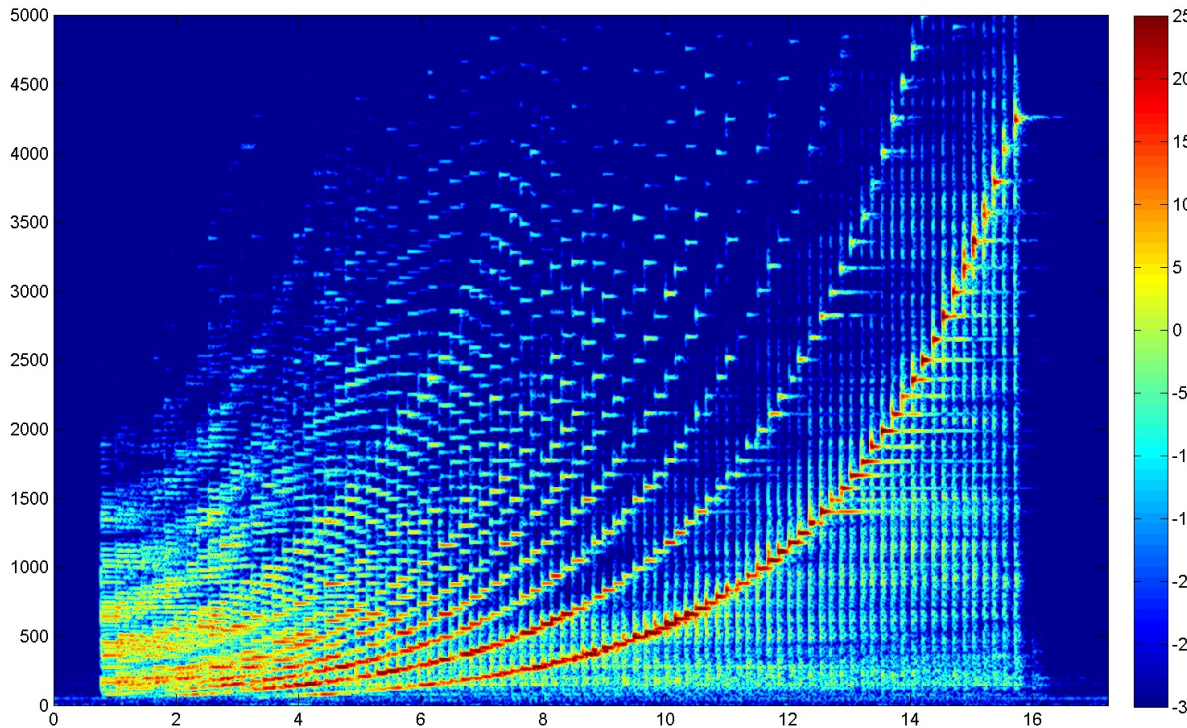
# Pitch Features

Example: Chromatic scale

Spectrogram

Position on the staff	Piano key	Name	MIDI	Frequency	Name	MIDI	Frequency
		(Black keys)					
	C6	84	1046.5				
	B5	83	987.77	Bb5	A#5	82	932.33
	A5	81	880.00	Ab5	G#5	80	830.61
	G5	79	783.99	Gb5	F#5	78	739.99
	F5	77	698.46				
	E5	76	659.26	Eb5	D#5	75	622.25
	D5	74	587.33	Db5	C#5	73	554.37
	C5	72	523.25				
	B4	71	493.88	Bb4	A#4	70	466.16
	A4	69	440.00	Ab4	G#4	68	415.30
	G4	67	392.00	Gb4	F#4	66	369.99
	F4	65	349.23				
	E4	64	329.63	Eb4	D#4	63	311.13
	D4	62	293.67	Db4	C#4	61	277.18
	C4	60	261.63				
	B3	59	246.94				
	A3	57	220.00	Bb3	A#3	58	233.08
	G3	55	196.00	Ab3	G#3	56	207.65
	F3	53	174.61	Gb3	F#3	54	185.00
	E3	52	164.81				
	D3	50	146.83	Eb3	D#3	51	155.56
	C3	48	130.81	Db3	C#3	49	138.59
	B2	47	123.47				
	A2	45	110.00	Bb2	A#2	46	116.54
	G2	43	97.999	Ab2	G#2	44	103.83
	F2	41	87.307	Gb2	F#2	42	92.499
	E2	40	82.407				
	D2	38	73.416	Eb2	D#2	39	77.782
	C2	36	65.406	Db2	C#2	37	69.296

Frequency (Hz)



Intensity (dB)

Time (seconds)

# Pitch Features

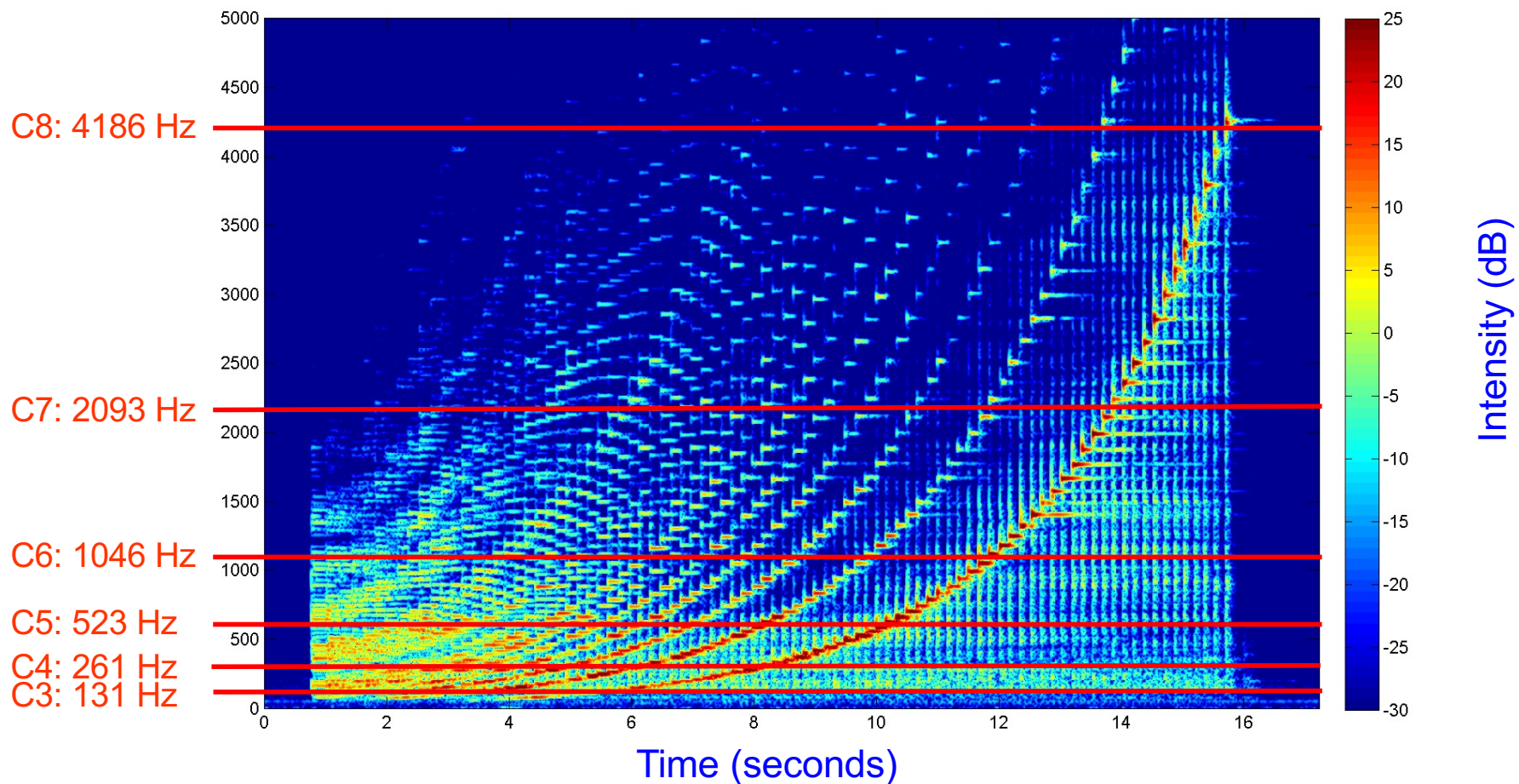


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Example: Chromatic scale



Spectrogram



# Pitch Features

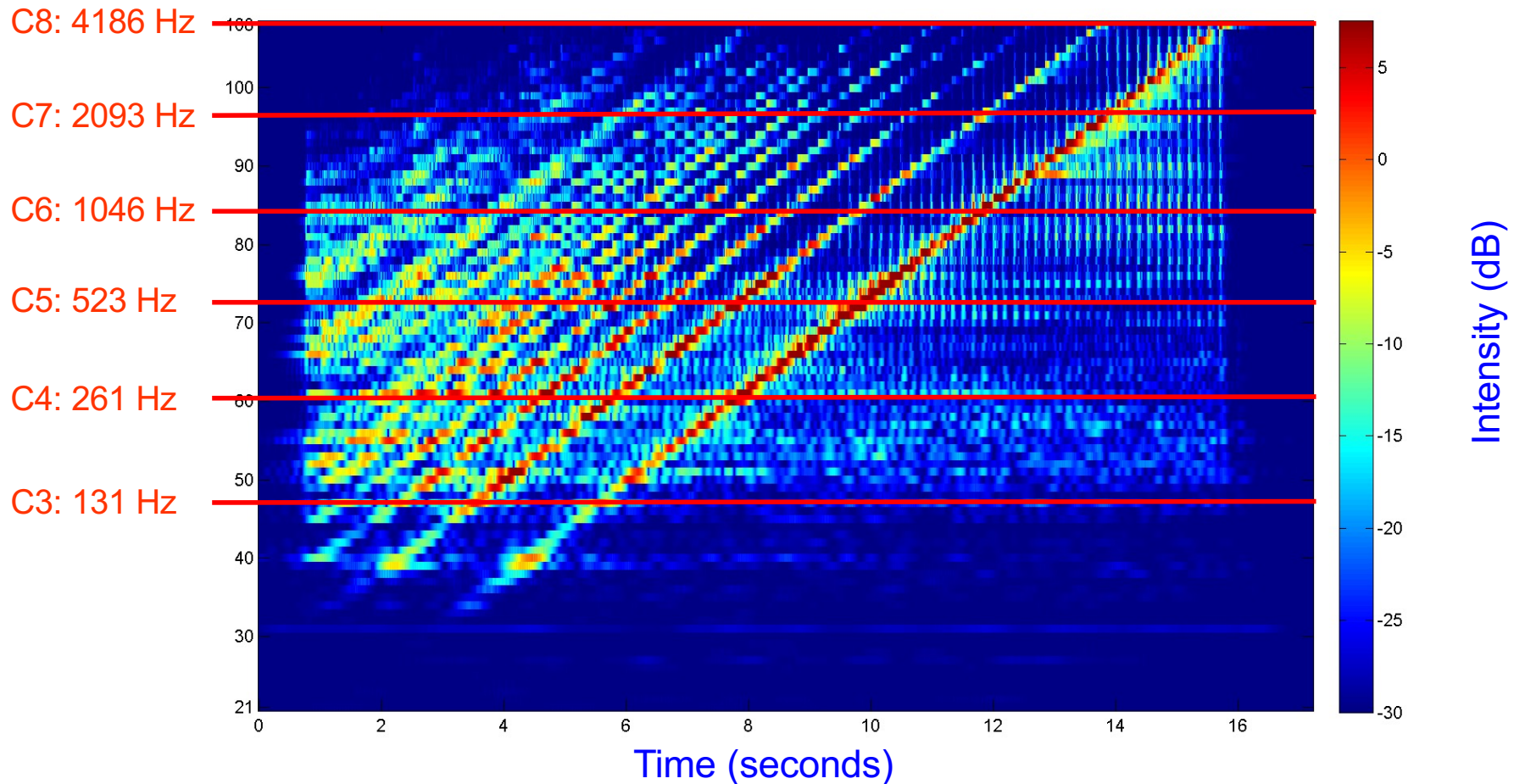


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Example: Chromatic scale



Log-frequency spectrogram



# Pitch Features

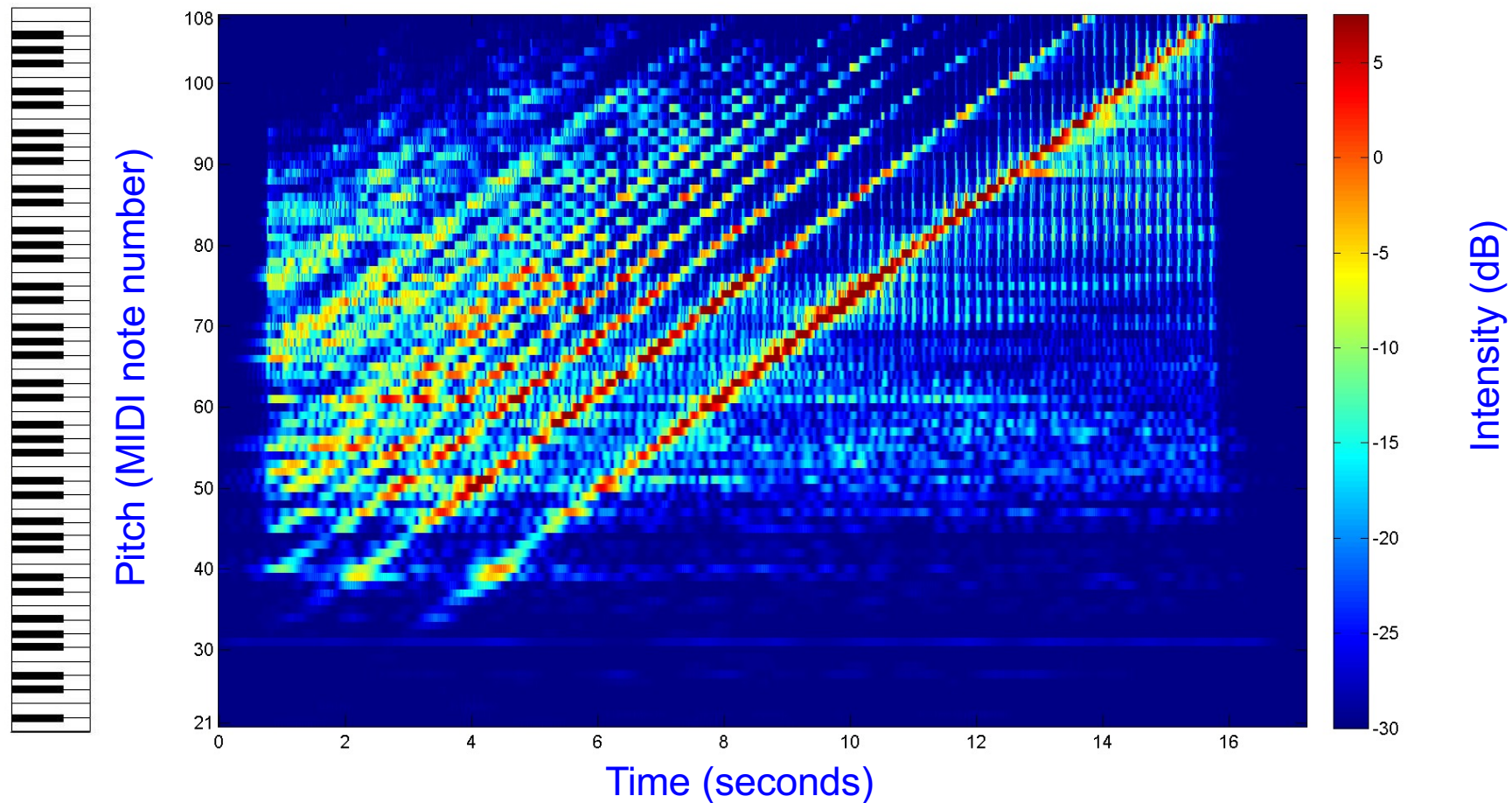


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Example: Chromatic scale



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**.

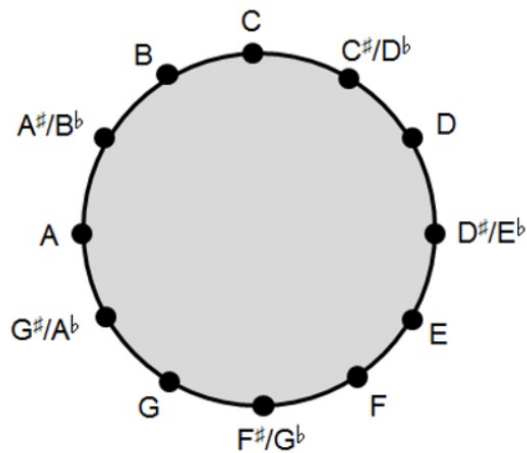
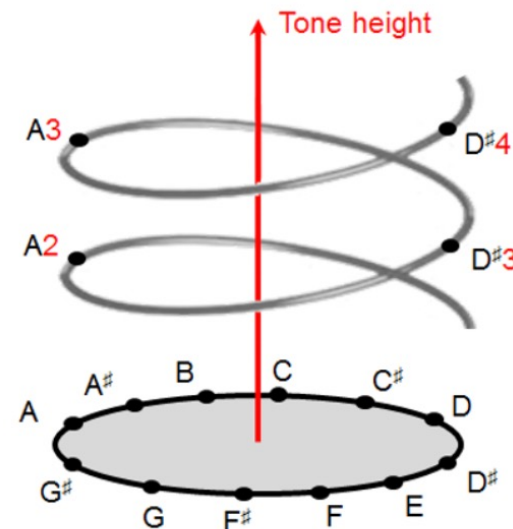


Figure 1.3 from [Müller, FMP, Springer 2015]



# Chroma Features



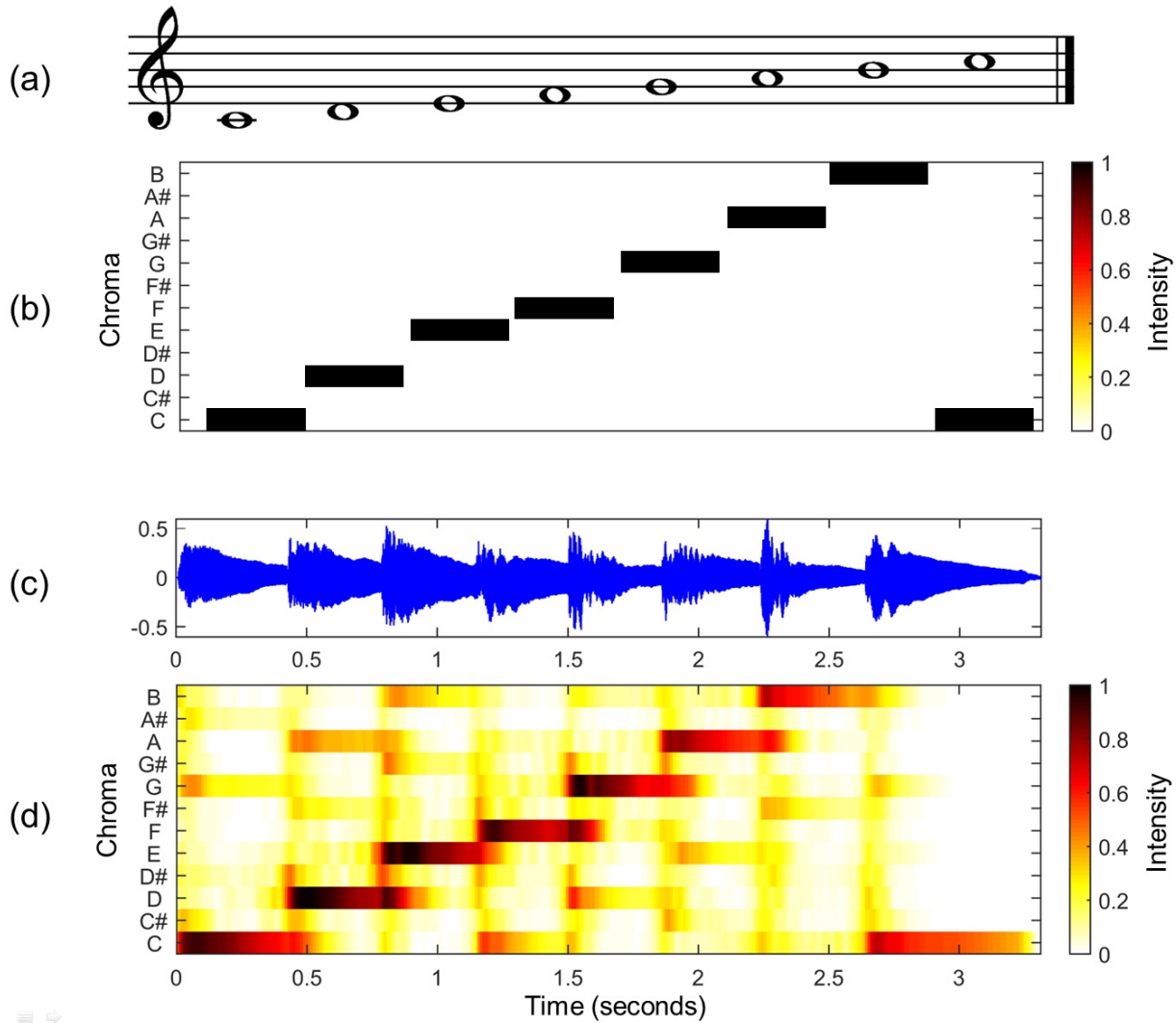
- Human perception of pitch is periodic in the sense that two pitches are perceived as similar in color if they differ by an octave.
- Separation of pitch into two components: **tone height** (octave number) and **chroma**.
- Chroma : 12 traditional pitch classes of the equal-tempered scale. For example:

Chroma C

- Computation: pitch features  $\rightarrow$  chroma features  
Add up all pitches belonging to the same class
- Result: 12-dimensional chroma vector.

$$\hat{=} \{ \dots , C_0 , C_1 , C_2 , C_3 , \dots \}$$

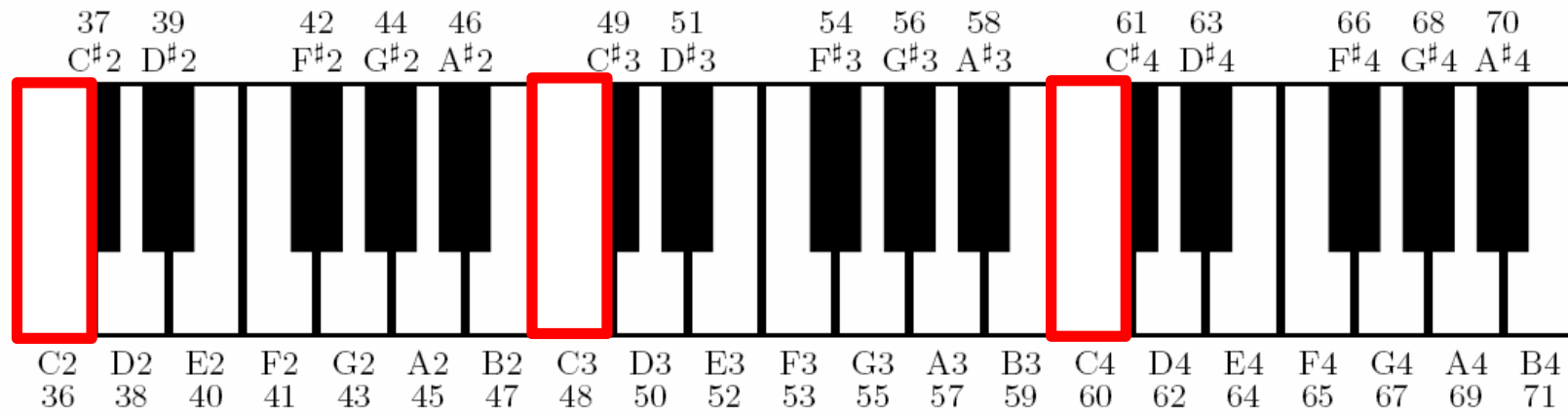
# Chroma Features



# Chroma Features



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C2

C3

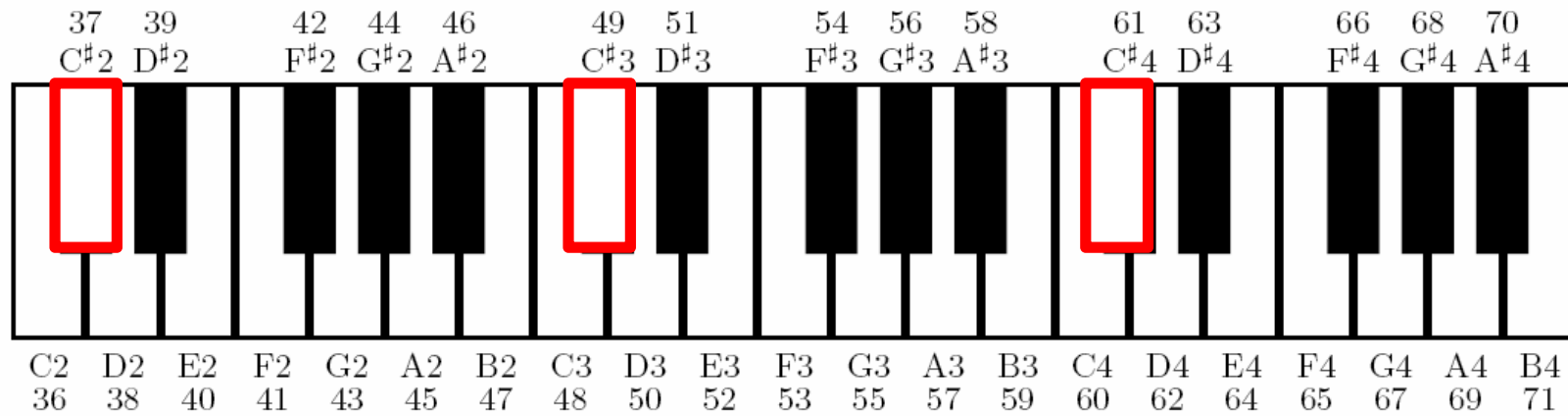
C4

Chroma C

# Chroma Features



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C#2

C#3

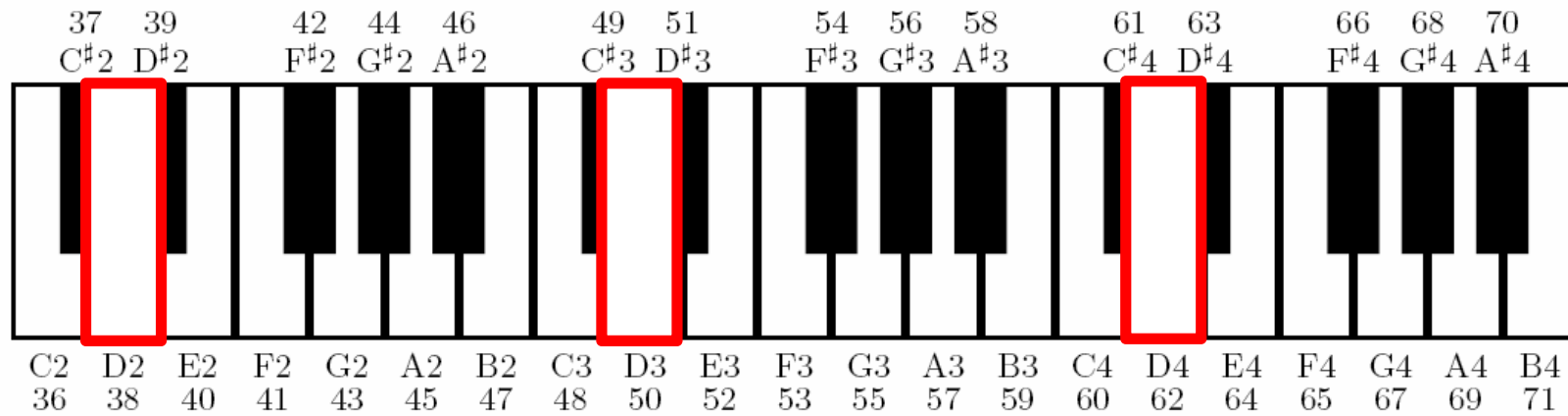
C#4

Chroma C#

# Chroma Features



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D2

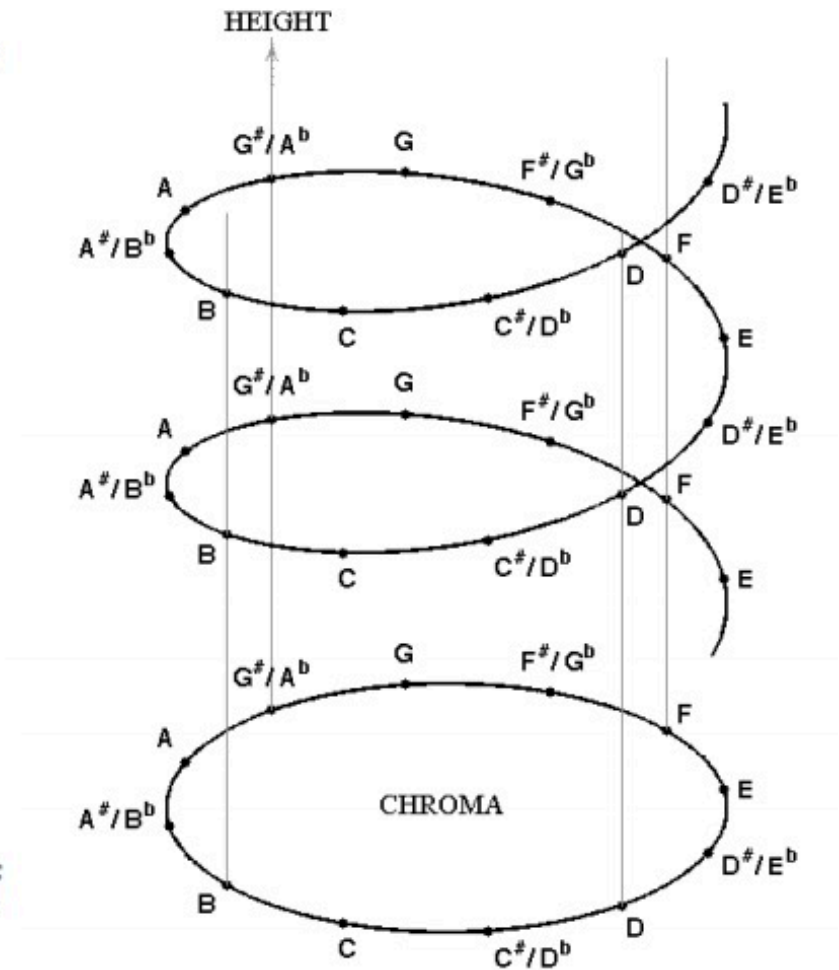
D3

D4

Chroma D

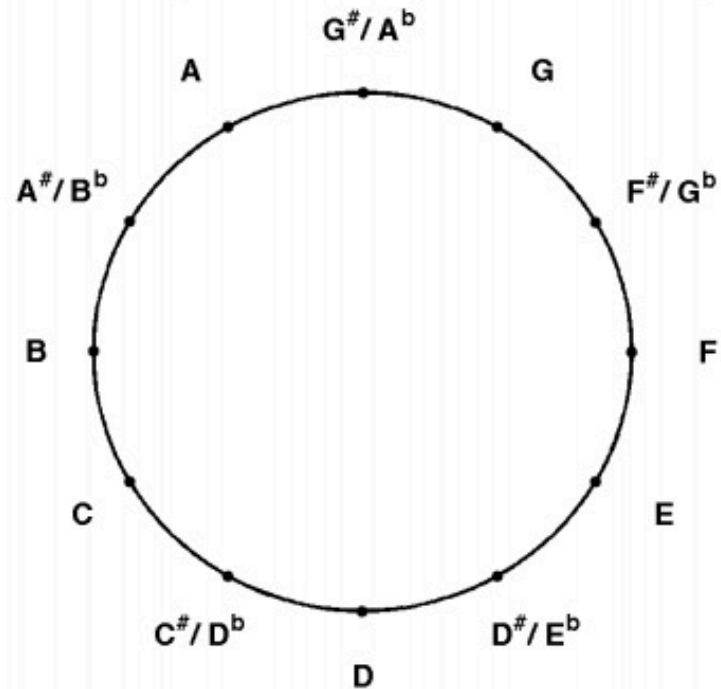
# Pitch perception

- 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

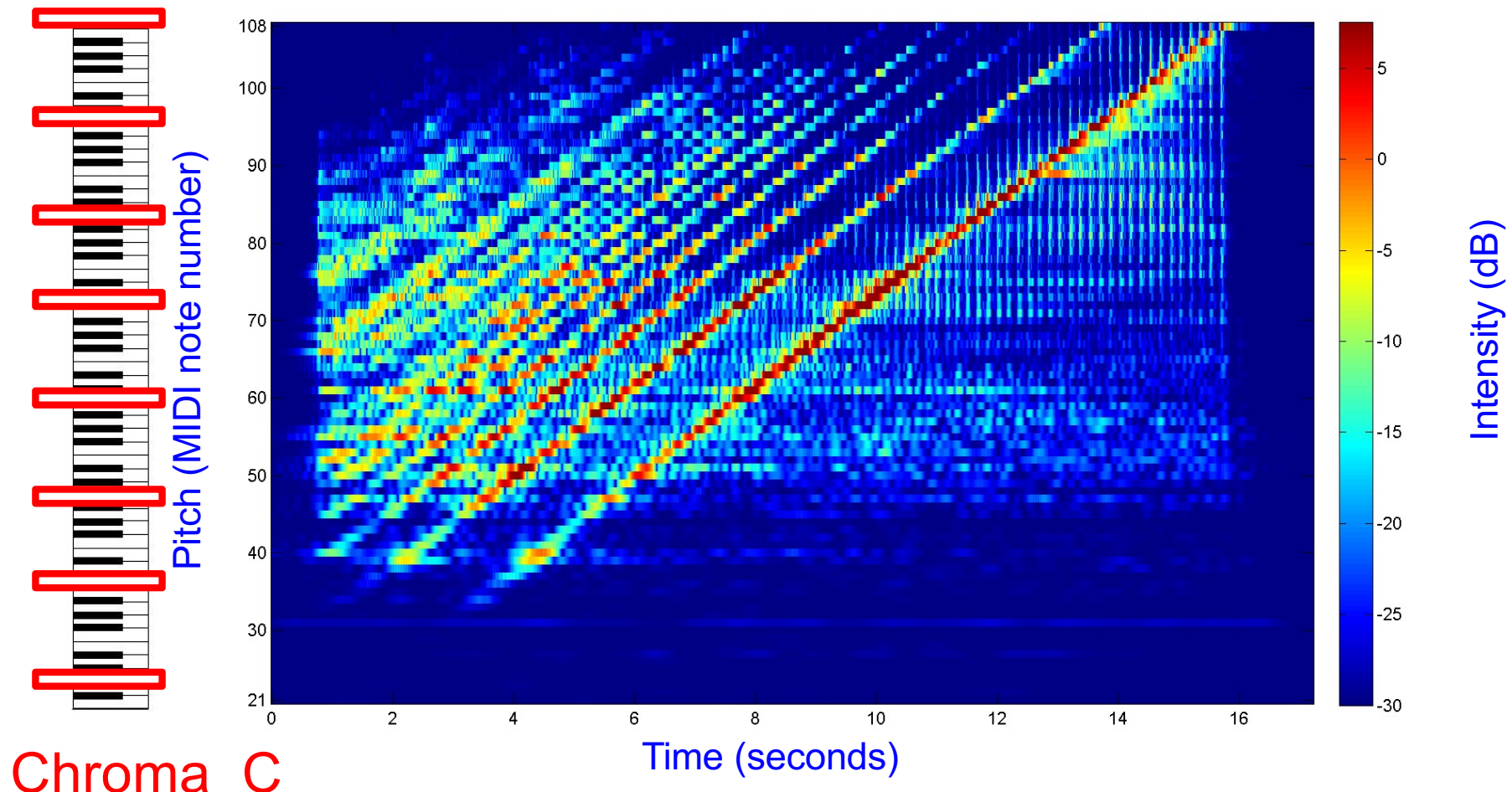


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Example: Chromatic scale



Log-frequency spectrogram



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

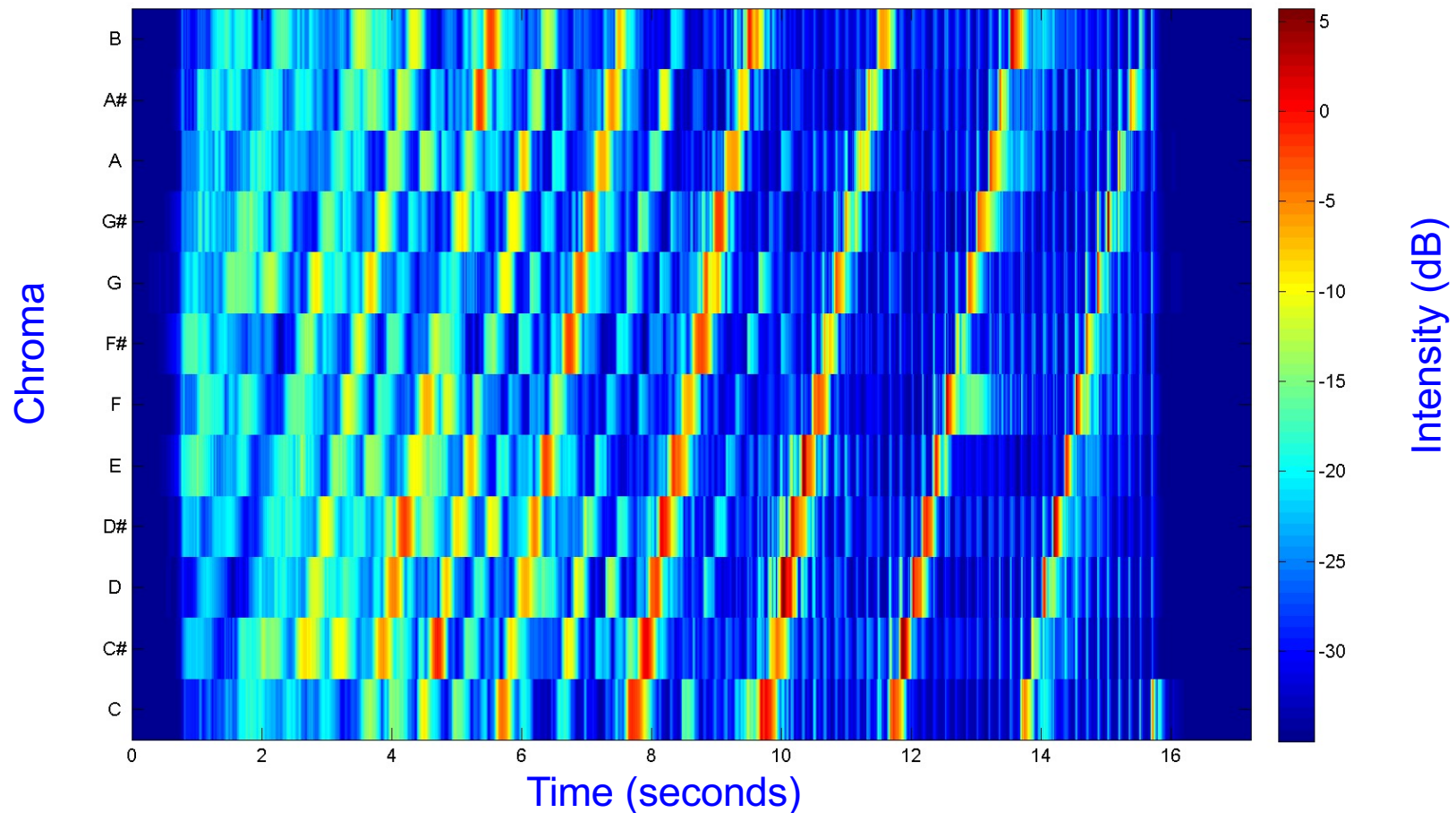


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Example: Chromatic scale



Chroma representation

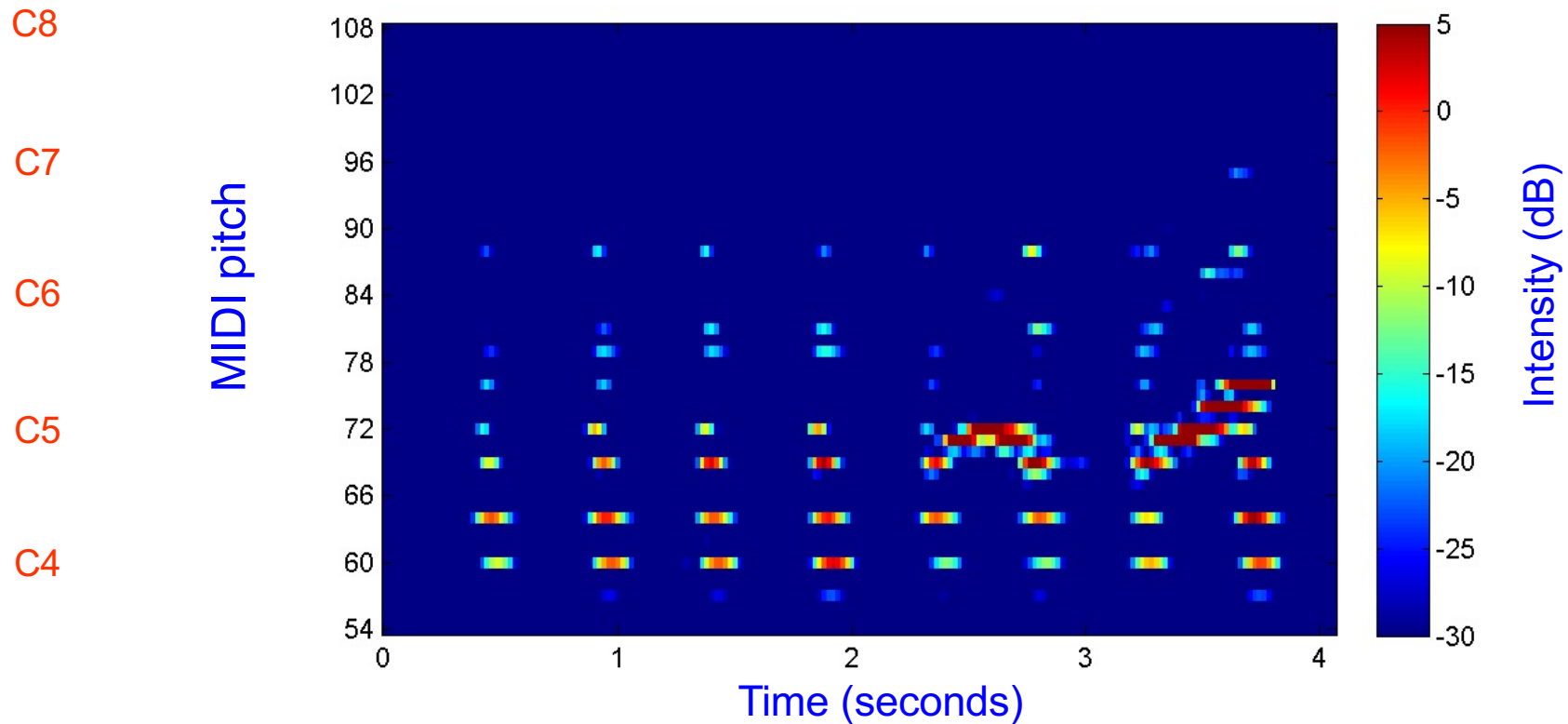




# Chroma Features



## Pitch representation





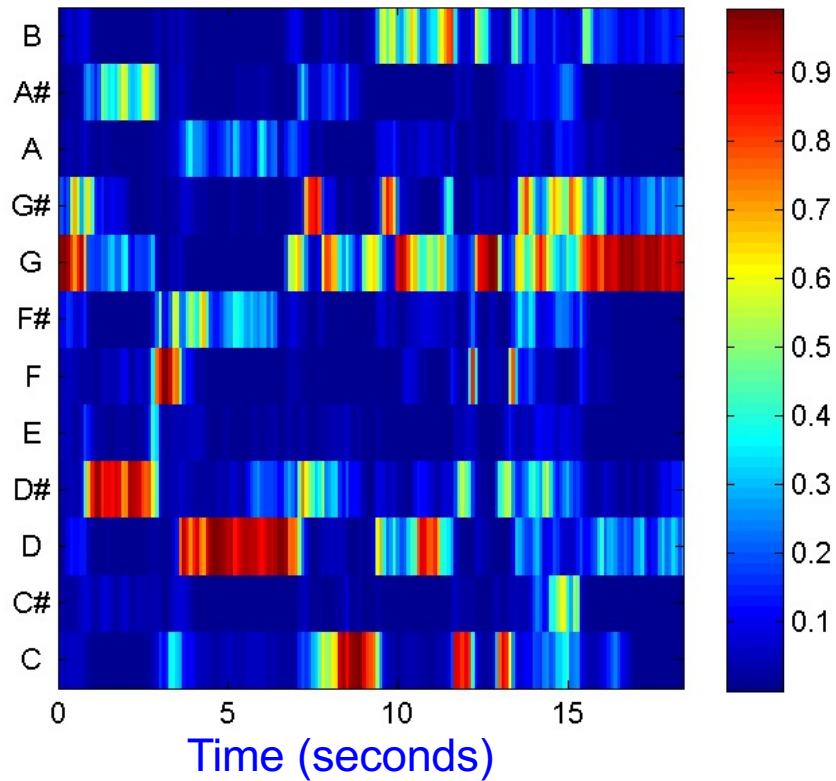
# Chroma Features

- 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

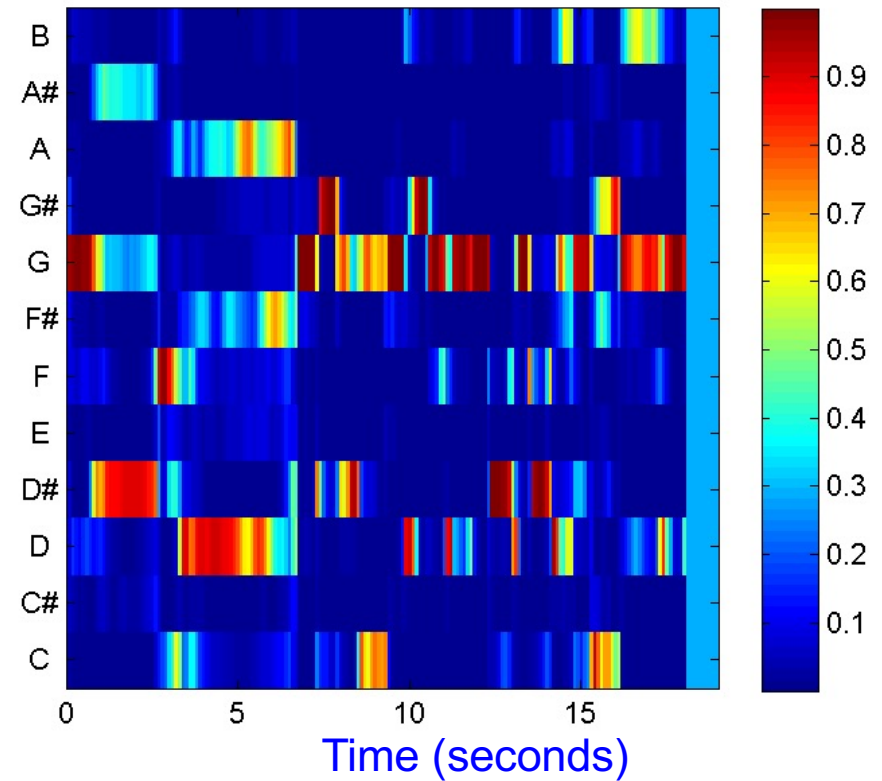
# Chroma Features

Example: Beethoven's Fifth  
Chroma representation

Karajan



Scherbakov



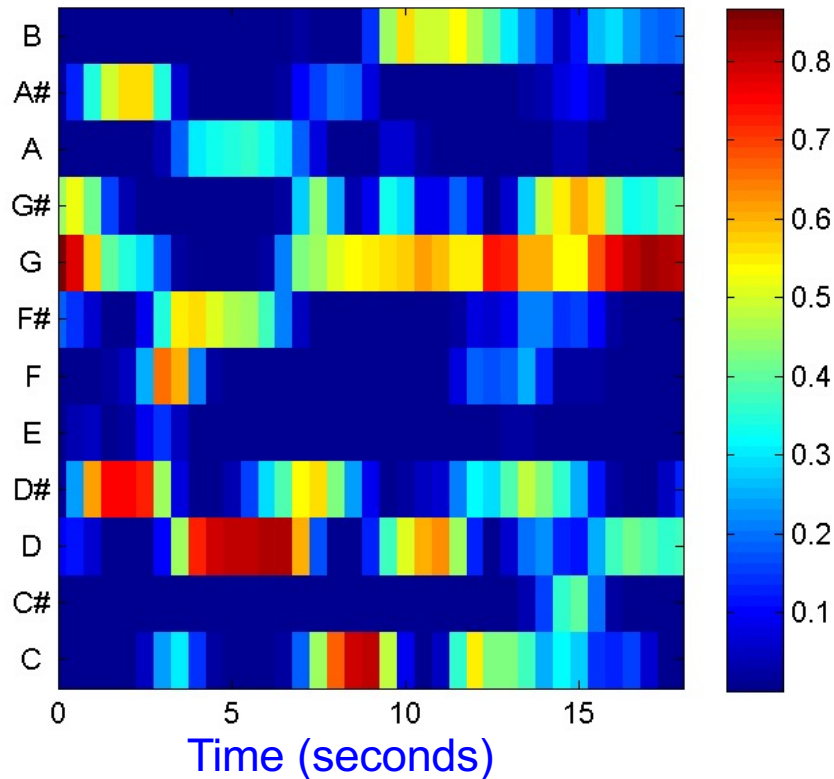
# Chroma Features: Effect of resolution

Example: Beethoven's Fifth

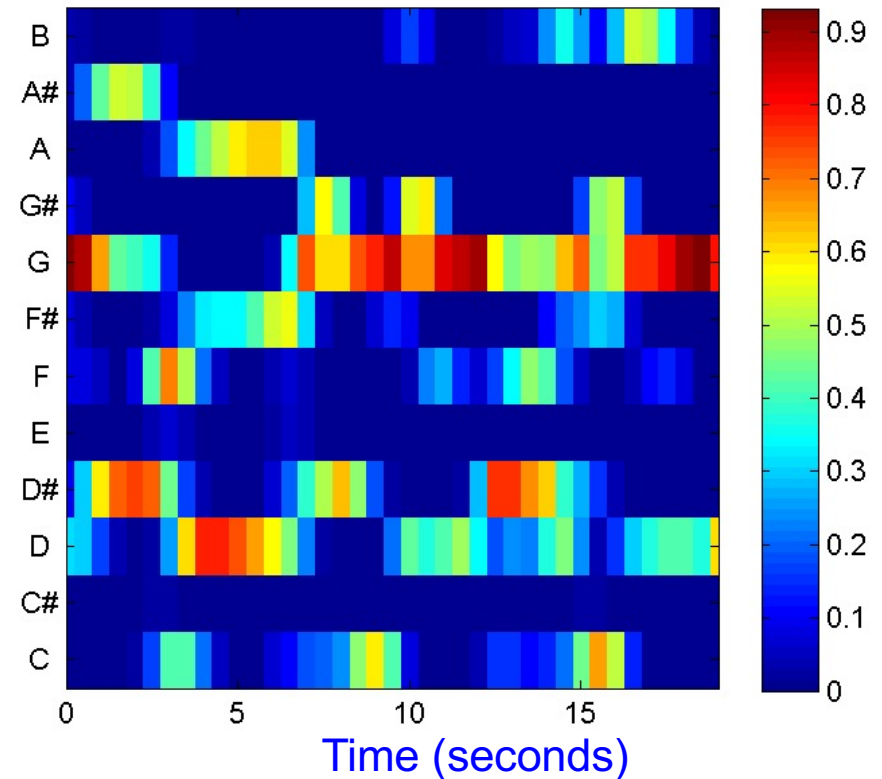
Chroma representation (normalized, 2 Hz)

Smoothing (2 seconds) + downsampling (factor 5)

Karajan



Scherbakov





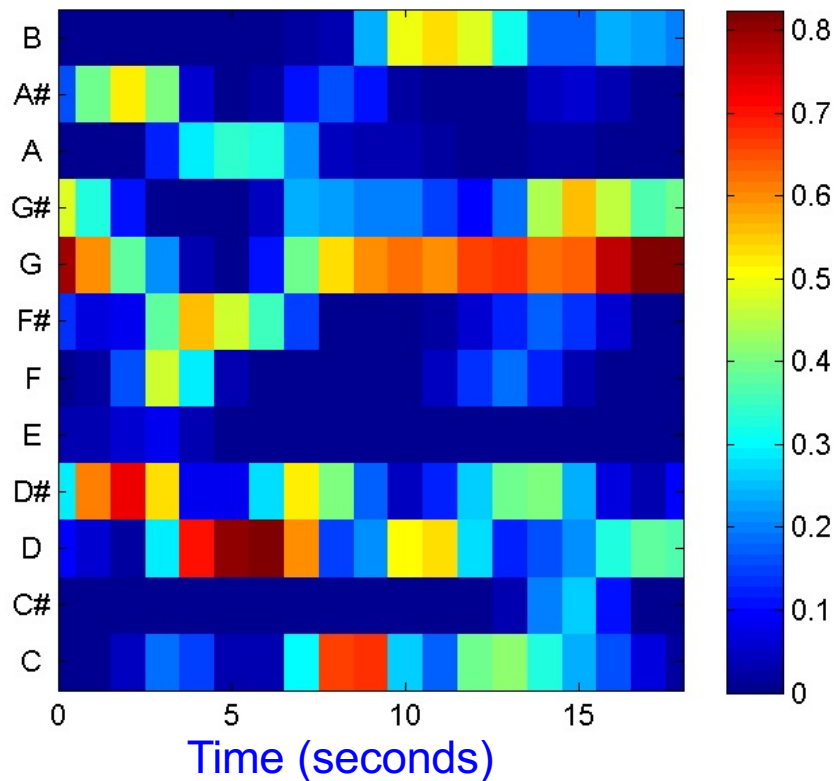
# Chroma Features: Effect of Resolution

Example: Beethoven's Fifth

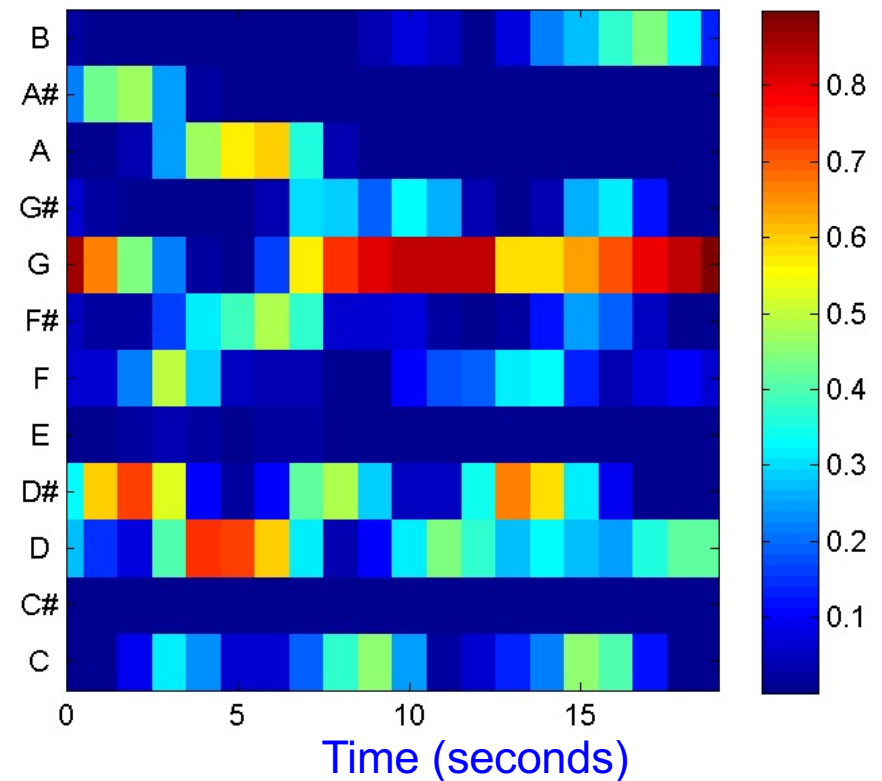
Chroma representation (normalized, 1 Hz)

Smoothing (4 seconds) + downsampling (factor 10)

Karajan



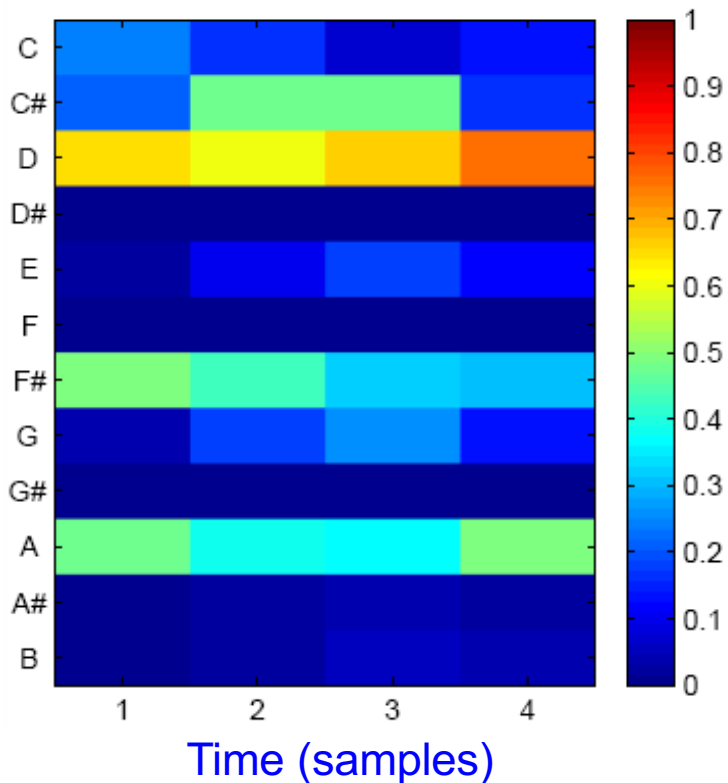
Scherbakov



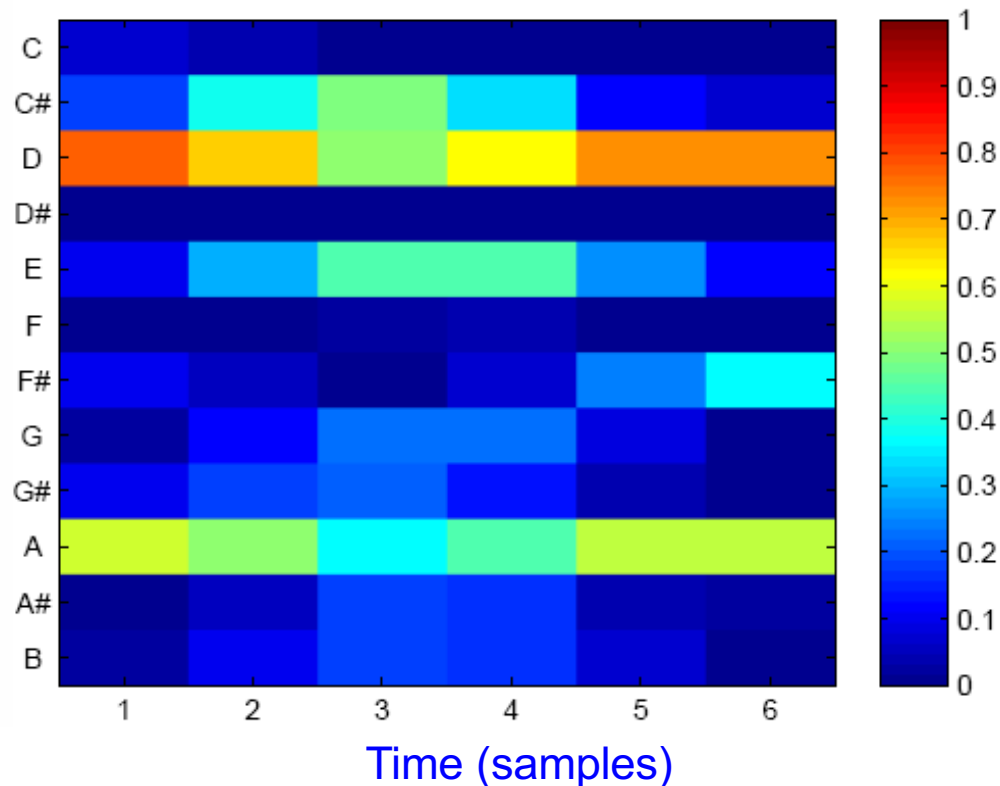
# Chroma Features: Time Scaling

Example: Bach Toccata

Koopman

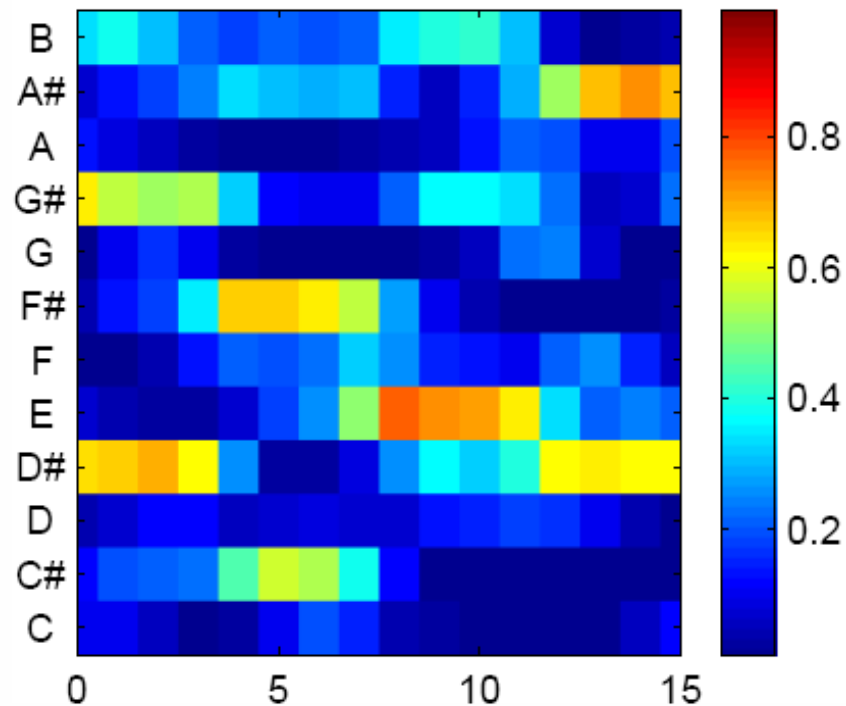


Ruebsam



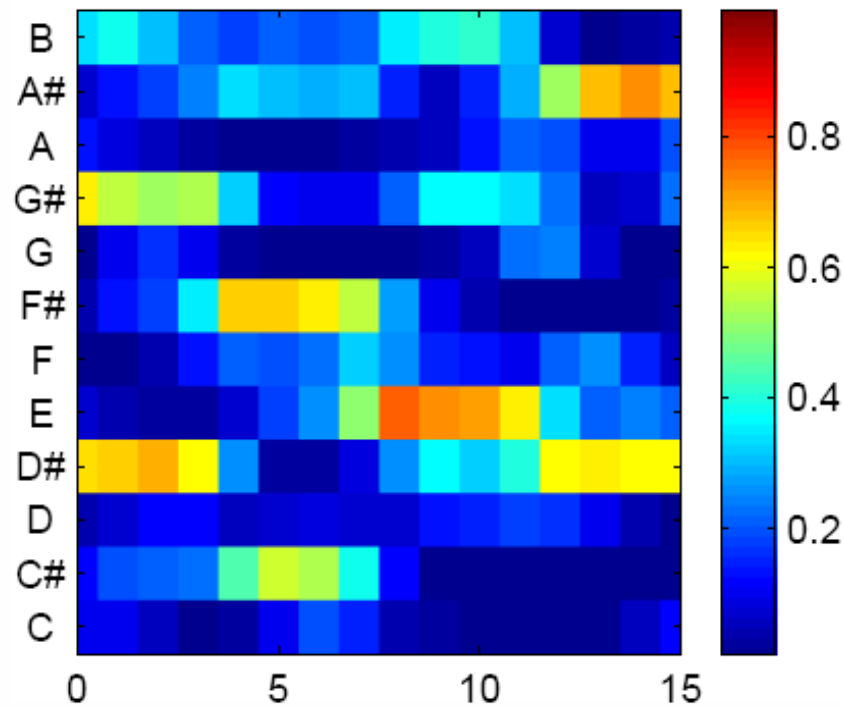
# Chroma Features: Effect of Transposition

Example: Zager & Evans “In The Year 2525”

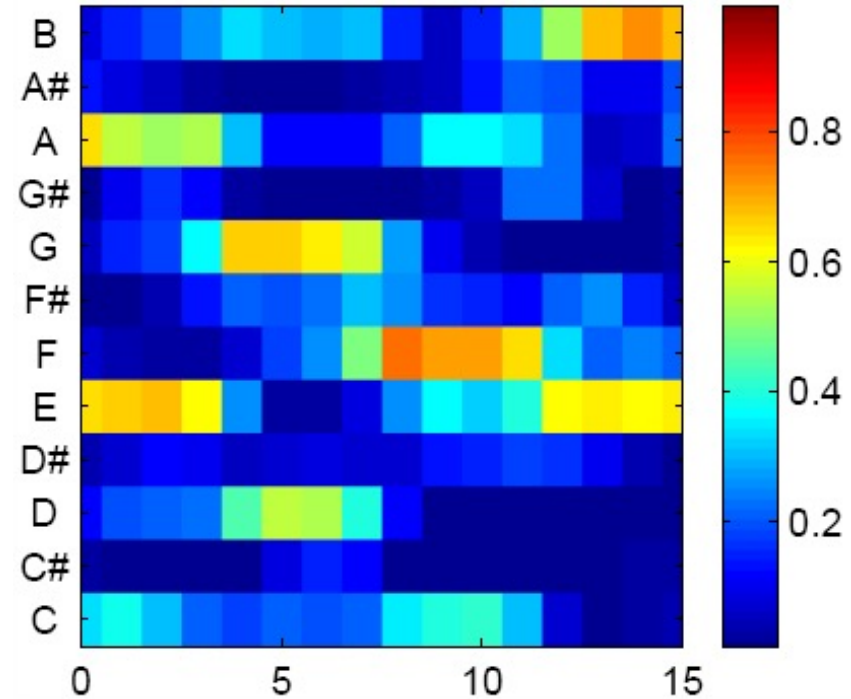


Original:  $(v^1, \dots, v^N)$

# Chroma Features: Effect of Transposition



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



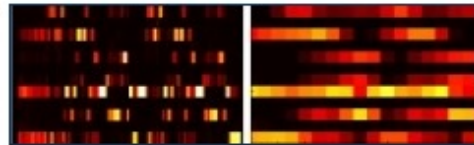
Shifted:  $(\sigma(v^1), \dots, \sigma(v^N))$

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



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

# Chord Recognition: What is a Chord?

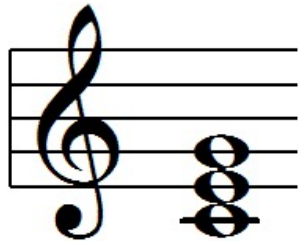
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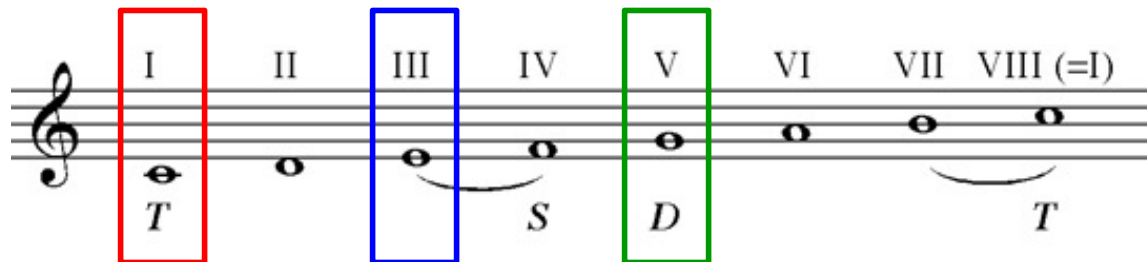
- Combination of three or more tones which sound simultaneously
- Chord classes
  - Triads including major, minor, diminished, augmented chords
  - Many other more complex chords such as seventh chords
- Here: focus on major and minor triads

# Musical Chords

## The C major chord



## Derived from the C major scale



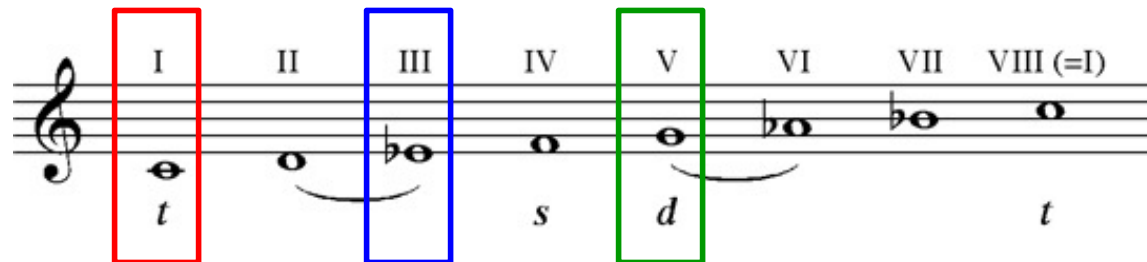
- C ---- the root
- E ---- the (major) third
- G ---- the fifth

# Musical Chords

## The C **minor** chord



## Derived from the C **minor** scale



**C** ---- the **root**

**E<sub>b</sub>** ---- 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	✓			✓				✓				



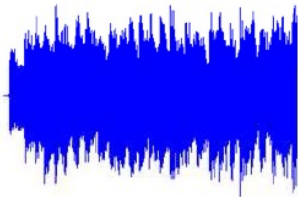
# Chord Recognition



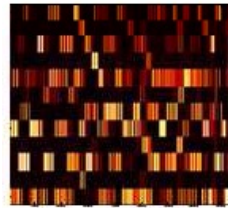
- Development of automatic methods for the harmonic analysis of audio data
- Applications in the field of music information retrieval:
  - music segmentation
  - cover song identification
  - audio matching
  - music structure analysis
  - ...

# Chord Recognition

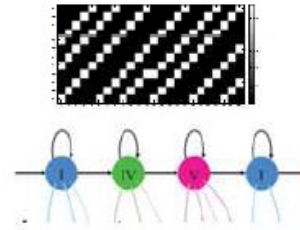
Signal



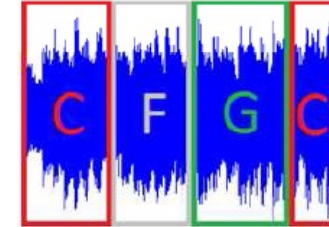
Feature  
Extraction



Classification



Result



Chroma features

- Type
- Resolution
- Compression
- Smoothing

Pattern matching

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

# Chord Recognition



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Given: Audio file



Output: Segmentation and chord labeling

Andantino Moderato

Johann Pachelbel  
George Winston

Piano

The image shows a musical score for the piece 'Pachelbel's Canon' by George Winston. It is in 4/4 time and marked 'Andantino Moderato'. The score is for piano and consists of two systems of music. The first system contains measures 1 through 6, and the second system contains measures 7 through 12. Fingerings are indicated by numbers 1-5 above or below notes. The word 'Piano' is written to the left of the first system. The word 'simile' appears in both staves of the first system. Below the notes, a series of chord labels are provided in blue text: C, G, A:min, E:min, F, C, F, G, C, G, A:min, E:min for the first system, and F, C, F, G, C, G, A:min, E:min, F, C, F, G for the second system.

C G A:min E:min F C F G C G A:min E:min

F C F G C G A:min E:min F C F G

# Binary Template: A Baseline Method for Chord Recognition



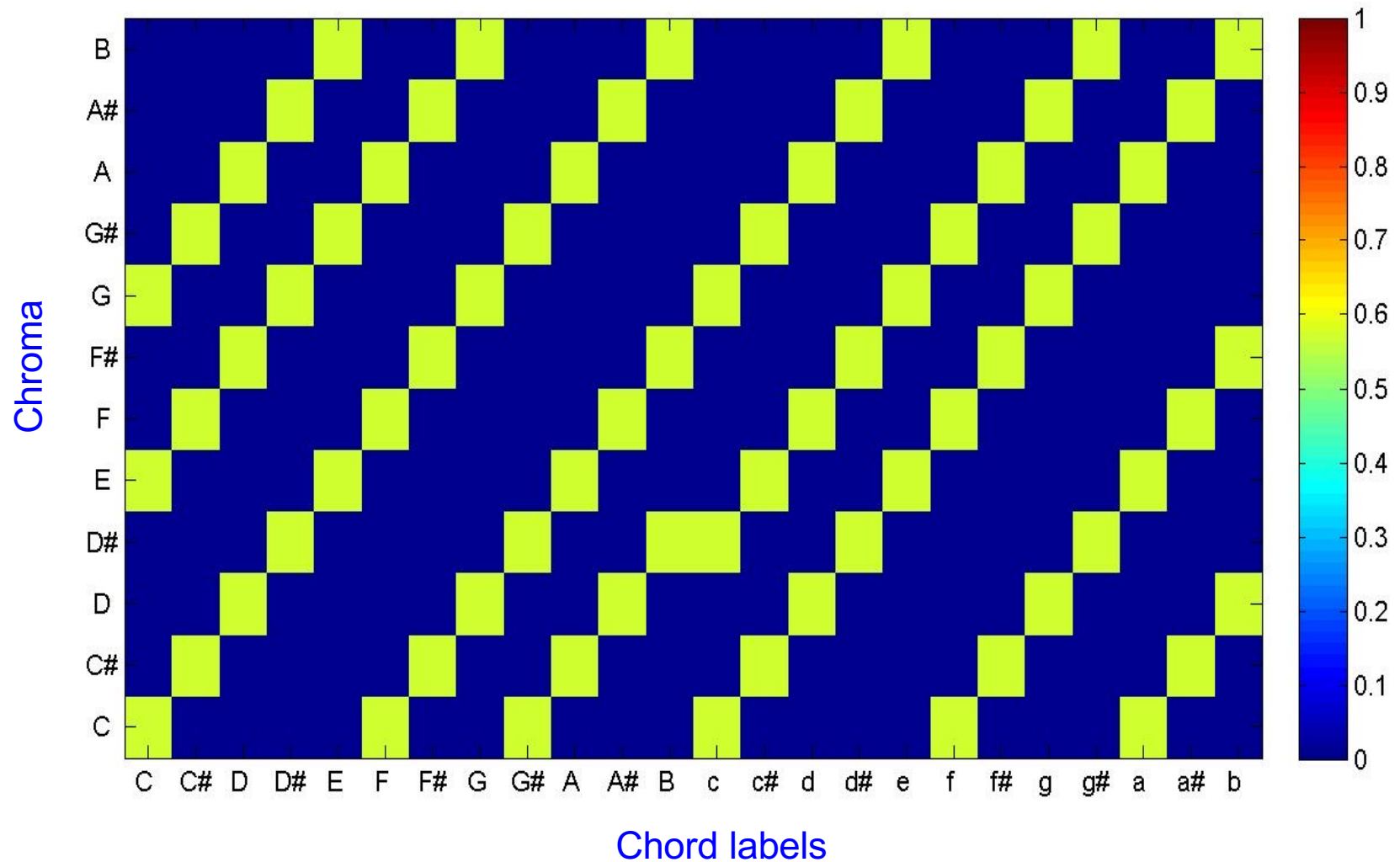
Chord templates 24 major/minor chords

Binary match on signal

	<b>C major</b>	<b>C# major</b>	<b>D major</b>	<b>D# major</b>	.....	<b>C minor</b>	<b>C# minor</b>	.....
<b>B</b>	0	0	0	0	.....	0	0	.....
<b>A#</b>	0	0	0	1	.....	0	0	.....
<b>A</b>	0	0	1	0	.....	0	0	.....
<b>G#</b>	0	1	0	0	.....	0	1	.....
<b>G</b>	1	0	0	1	.....	1	0	.....
<b>F#</b>	0	0	1	0	.....	0	0	.....
<b>F</b>	0	1	0	0	.....	0	0	.....
<b>E</b>	1	0	0	0	.....	0	1	.....
<b>D#</b>	0	0	0	1	.....	1	0	.....
<b>D</b>	0	0	1	0	.....	0	0	.....
<b>C#</b>	0	1	0	0	.....	0	1	.....
<b>C</b>	1	0	0	0	.....	1	0	.....

# Baseline Method for Chord Recognition

Chroma templates 24 major/minor chords



# Baseline Method for Chord Recognition

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24 chord templates  
(12 major, 12 minor)

Chroma feature  
extraction (frame-wise)

# Baseline Method for Chord Recognition



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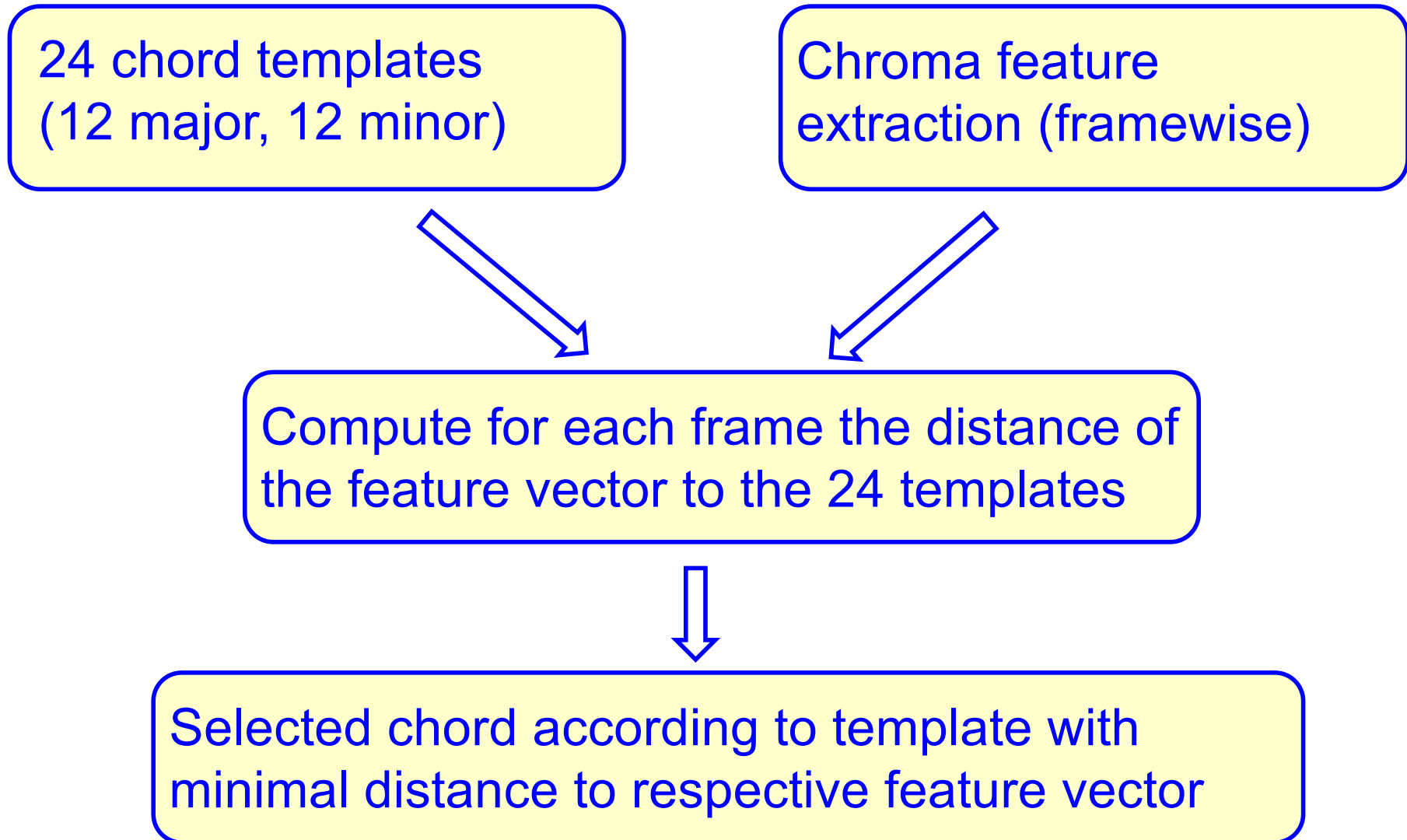
24 chord templates  
(12 major, 12 minor)

Chroma feature  
extraction (framewise)

Compute for each frame the distance of  
the feature vector to the 24 templates



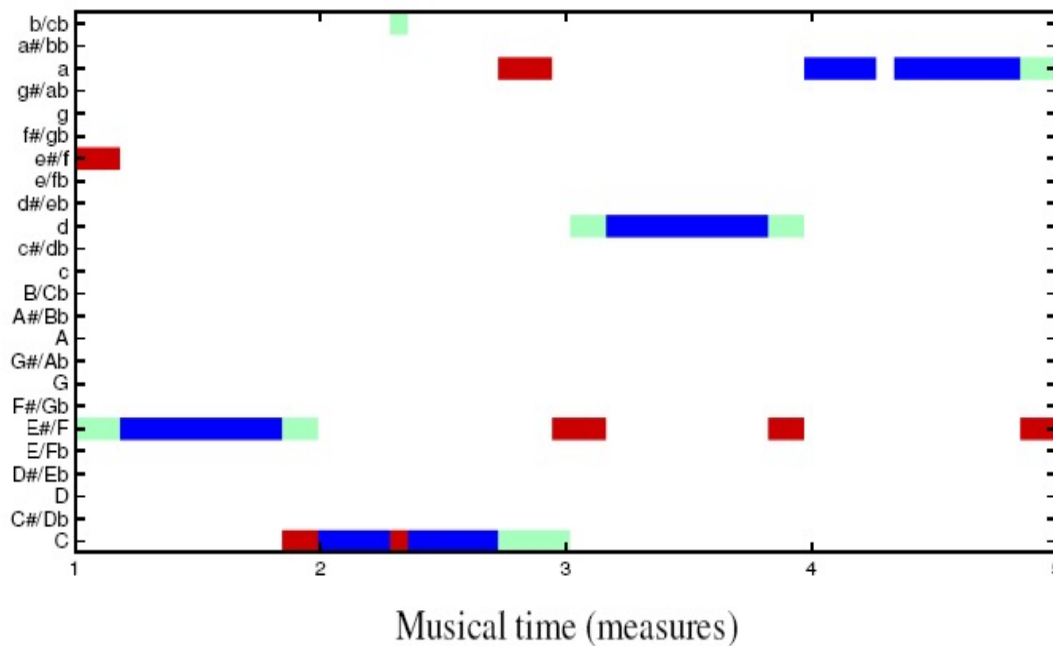
# Baseline Method for Chord Recognition



# Problems in Chord Recognition

Problem: Transitions between subsequent chord

Example: Chopin Mazurka Op. 68 No.3



- Correct
- False positive
- False negative

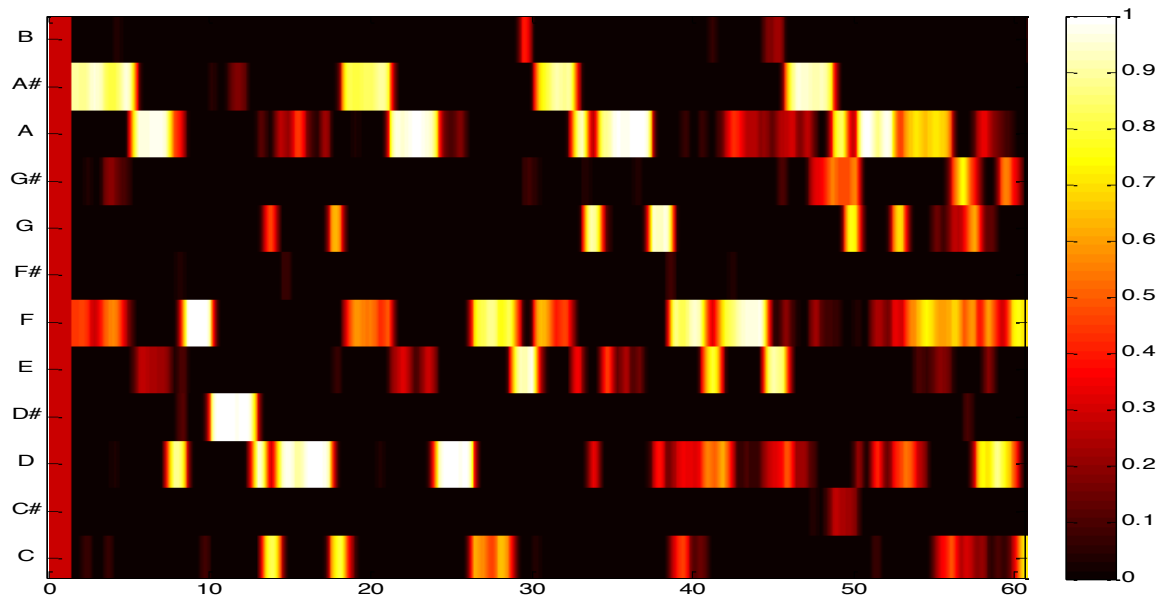
# Problems in Chord Recognition

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

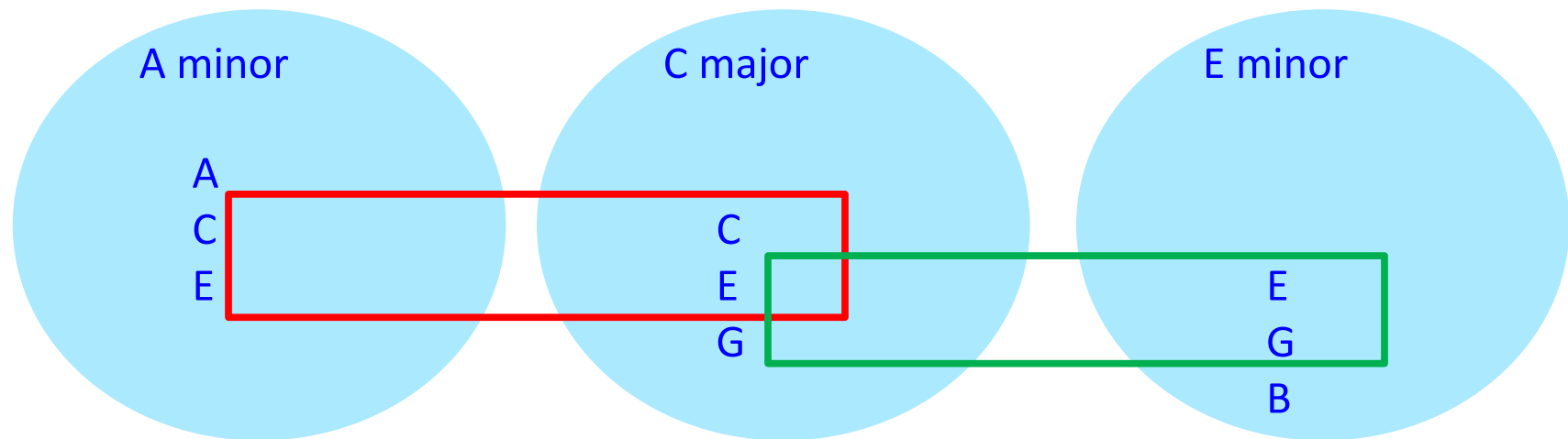


Problem: Broken chords

→ 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!



19

22