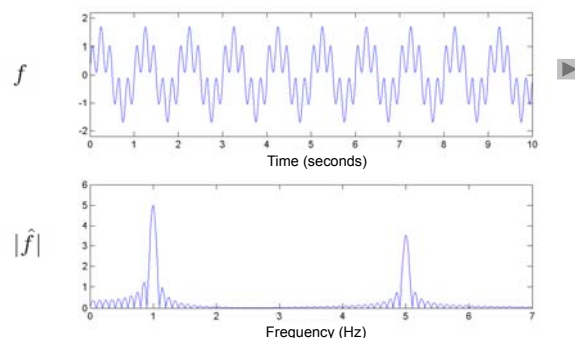Lecture
Music Processing

Audio Features

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Fourier Transform

Fourier Transform

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

Fourier representation $\quad f(t) = \int\limits_{\omega \in \mathbb{R}} c_\omega e^{2\pi i \omega t} d\omega \; , \; c_\omega = \hat{f}(\omega)$

Fourier transform $\qquad \hat{f}(\omega) = \int\limits_{t \in \mathbb{R}} f(t) e^{-2\pi i \omega t} dt$
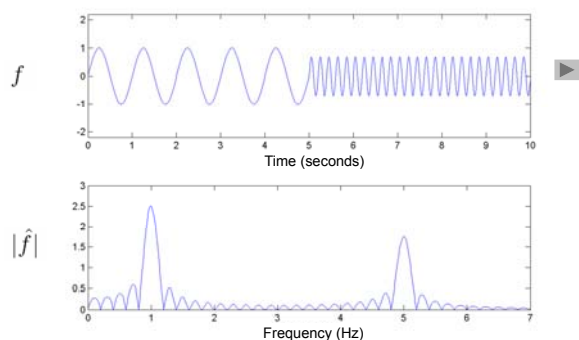

Fourier Transform

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Fourier transform $\qquad \hat{f}(\omega) = \int\limits_{t \in \mathbb{R}} f(t) e^{-2\pi i \omega t} dt$

- Tells which notes (frequencies) are played, but does not tell when the notes are played
- Frequency information is averaged over the entire time interval
- Time information is hidden in the phase
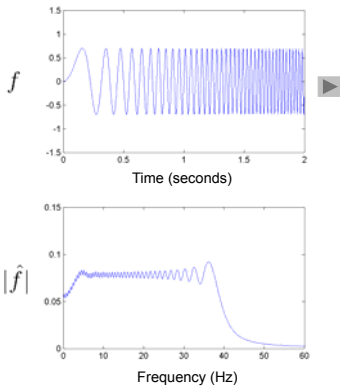

Fourier Transform
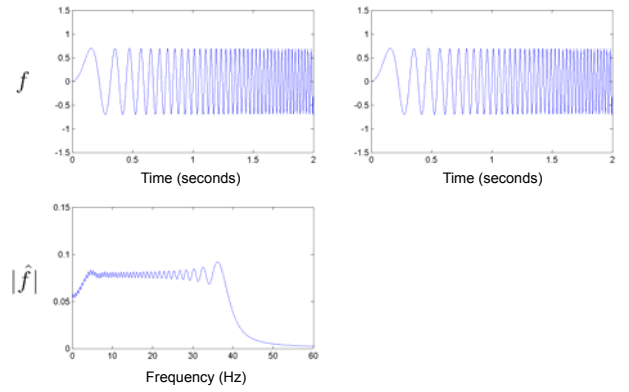

Short Time Fourier Transform

Idea (Dennis Gabor, 1946):

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

  $\rightarrow$ recovery of time information

- Short Time Fourier Transform (STFT)

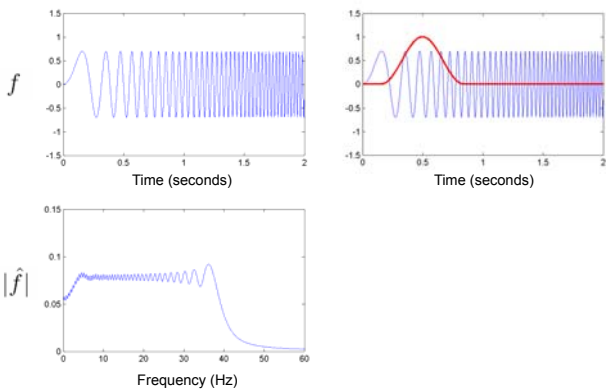- Section is determined by pointwise multiplication of the signal with a localizing window function
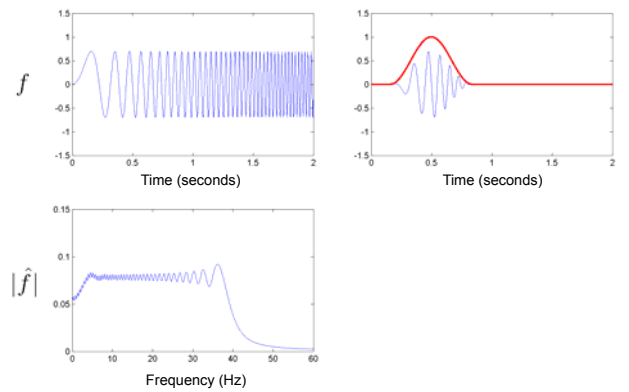
Short Time Fourier Transform
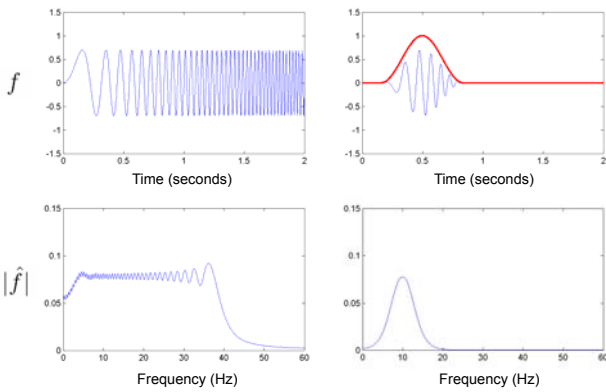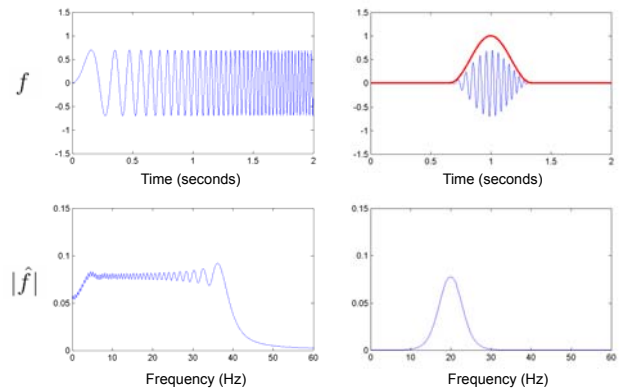

Short Time Fourier Transform

Short Time Fourier Transform
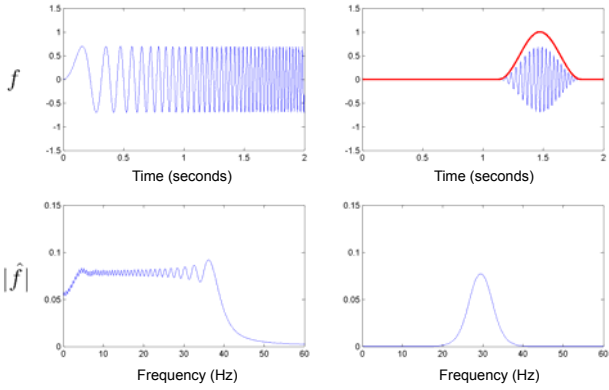

Short Time Fourier Transform

Short Time Fourier Transform

Short Time Fourier Transform

Short Time Fourier Transform

Short Time Fourier Transform

Definition

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

- Window function $\quad g : \mathbb{R} \to \mathbb{R} \quad (g \in L^2(\mathbb{R}), \|g\| = 1)$

- STFT $\quad \tilde{f}(\omega, t) := \int_{\mathbb{R}} f(u)\bar{g}(u-t)e^{-2\pi i \omega u} du = \langle f | g_{\omega,t} \rangle$

  with $\quad g_{\omega,t}(u) := e^{2\pi i \omega u} g(u-t), \quad u \in \mathbb{R}$

Short Time Fourier Transform

Intuition:

- $g_{\omega,t}$ is „musical note" of frequency ω, which oscillates within the translated window $u \to g(u-t)$
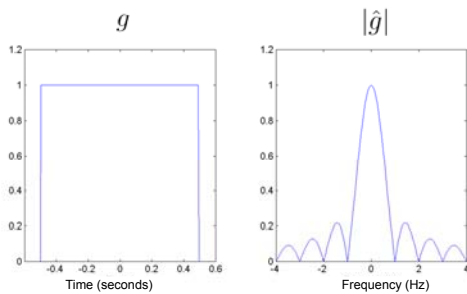

Short Time Fourier Transform

Intuition:

- $g_{\omega,t}$ is „musical note" of frequency ω, which oscillates within the translated window $u \to g(u-t)$

- Innere product $\langle f | g_{\omega,t} \rangle$ measures the correlation between the musical note $g_{\omega,t}$ and the signal f.
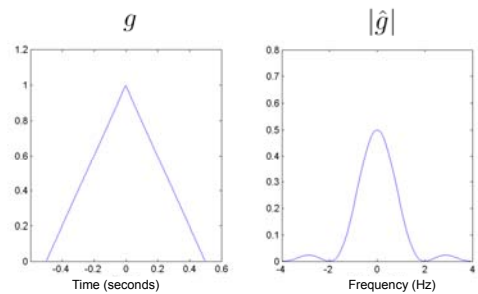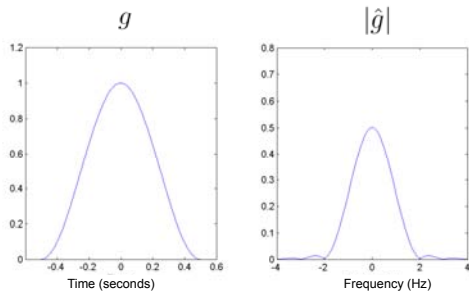
Window Function

Box window

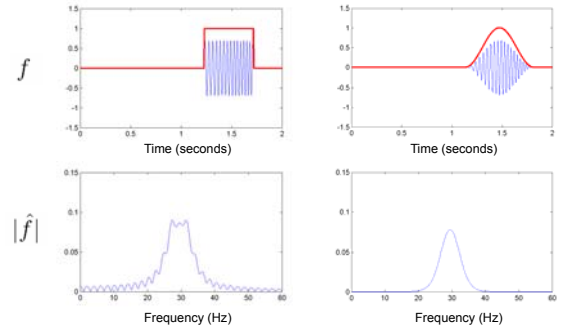

Window Function
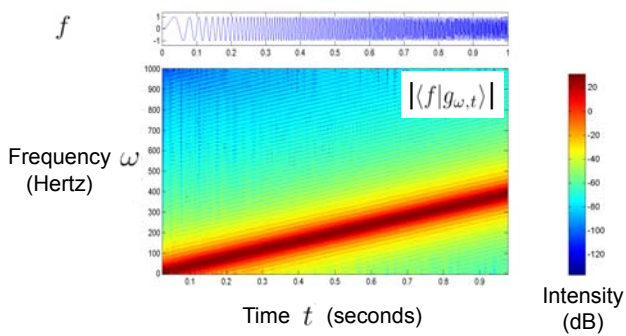
Triangle window

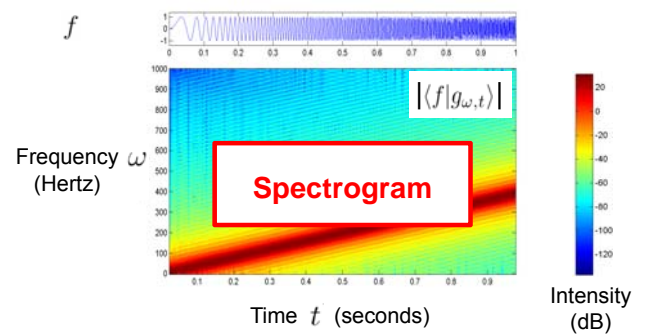## Window Function

Hann window

Window Function

Trade off between smoothing and „ringing"

Time-Frequency Representation

f

Frequency ω (Hertz)

$|\langle f | g_{\omega,t} \rangle|$

Time t (seconds)

Intensity (dB)

Time-Frequency Representation

f

Frequency ω (Hertz)

Spectrogram
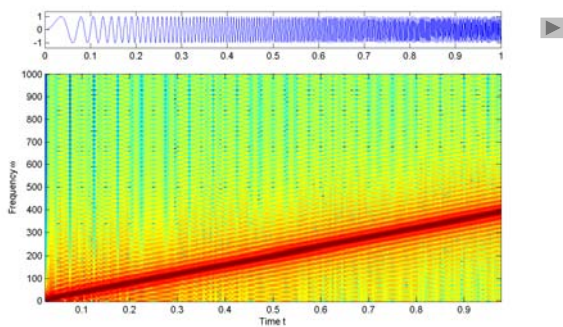
$|\langle f | g_{\omega,t} \rangle|$
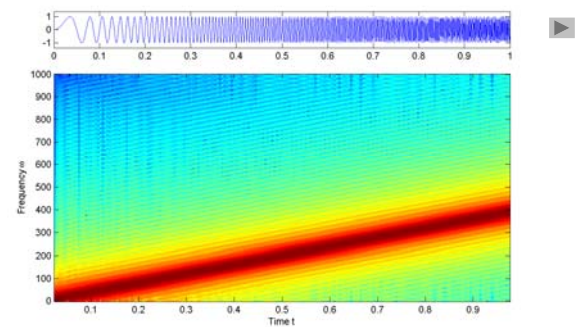
Time t (seconds)

Intensity (dB)

Time-Frequency Representation

Chirp signal and STFT with box window of length 0.05

Time-Frequency Representation

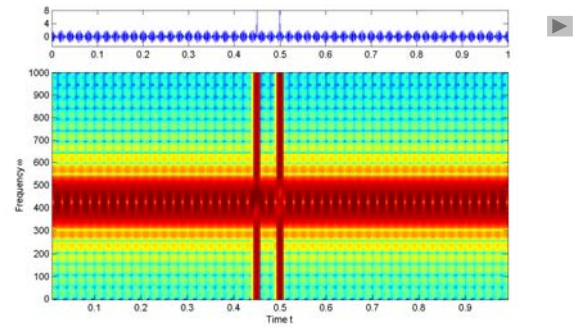Chirp signal and STFT with Hann window of length 0.05

Time-Frequency Localization

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

  Large window :   poor time resolution
                       good frequency resolution

  Small window :   good time resolution
                       poor frequency resolution

- Heisenberg Uncertainty Principle: there is no window function that localizes in time and frequency with arbitrary position.
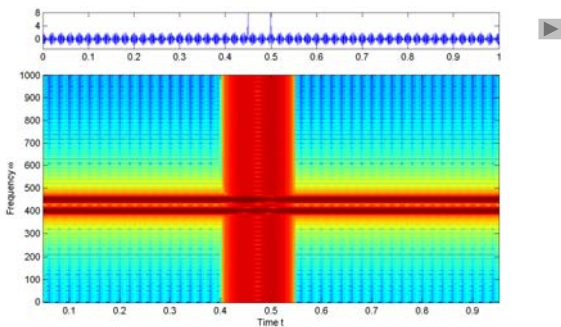
Short Time Fourier Transform

Signal and STFT with Hann window of length 0.02

Short Time Fourier Transform

Signal and STFT with Hann window of length 0.1

Heisenberg Uncertainty Principle

Window function $g \in L^2(\mathbb{R})$ with $\|g\| = 1$
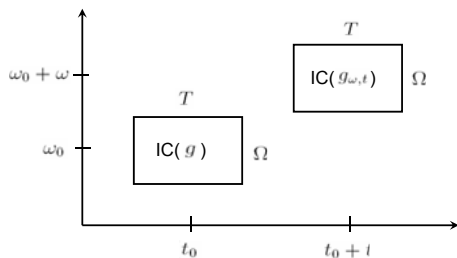
Center   Width

$$t_0 = t_0(g) := \int_{-\infty}^{\infty} t|g(t)|^2 dt \qquad T(g) := \left(\int_{-\infty}^{\infty} (t - t_0)^2 |g(t)|^2 dt\right)^{\frac{1}{2}}$$

$$\omega_0 = \omega_0(g) := \int_{-\infty}^{\infty} \omega|\hat{g}(\omega)|^2 d\omega \qquad \Omega(g) := \left(\int_{-\infty}^{\infty} (\omega - \omega_0)^2 |\hat{g}(\omega)|^2 d\omega\right)^{\frac{1}{2}}$$

$$\boxed{T(g) \cdot \Omega(g) \geq \frac{1}{4\pi}}$$

Information Cells

$$g_{\omega,t}(u) := e^{2\pi i \omega u} g(u - t) \qquad \text{"musical note"}$$

MATLAB

- MATLAB function SPECTROGRAM
- N = window length (in samples)
- M = overlap (usually $N/2$)
- Compute DFT_N for every windowed section
- Keep lower $N/2$ Fourier coefficients

$\rightarrow$ Sequence of spectral vectors
   (for each window a vector of dimension $N/2$)

Example

Let x be a discrete time signal $\quad x(n) = f(Tn)$

Sampling rate: $\quad 1/T = 22050 \text{ Hz}$
Window length: $\quad N = 4096$
Overlap: $\quad N/2 = 2048$
Hopsize: $\quad \text{window length} - \text{overlap}$

Let
$$\begin{aligned} v_0 &:= (x(0),\ x(1),\ \ldots\ ,\ x(4095)) \\ v_1 &:= (x(2048),\ \ldots\ ,\ x(6143)) \\ v_2 &:= (x(4096),\ \ldots\ ,\ x(8191)) \end{aligned}$$
$\vdots$

v_m corresponds to window $[m \cdot 2048 : m \cdot 2048 + 4095]$

Example

Time resolution:

$$\frac{\text{hopsize}}{\text{sampling rate}} = \frac{4096 - 2048}{22050} = 0.093 = 93\ ms$$

Frequency resolution:

$$v = v_0\ ,\quad \hat{v} := \text{DFT}_N(v)$$

$$\hat{v}(k) \approx \frac{1}{T} \cdot \hat{f}\left(\frac{k}{N} \cdot \frac{1}{T}\right)$$

$$\omega = \frac{k}{N} \cdot \frac{1}{T} = k \cdot \frac{22050}{4096} = k \cdot 5.38\ \text{Hz}$$

Pitch Features

Model assumption: Equal-tempered scale
- MIDI pitches: $\quad p \in [1 : 128]$
- Piano notes: $\quad p = 21\ (\text{A0})\ $ to $\ p = 108\ (\text{C8})$
- Concert pitch: $\quad p = 69\ (\text{A4})$
- Center frequency: $f_{\text{MIDI}}(p) = 2^{\frac{p-69}{12}} \cdot 440\ \text{Hz}$

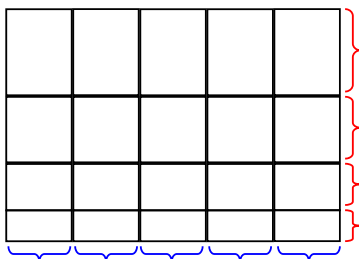$\rightarrow$ Logarithmic frequency distribution
Octave: doubling of frequency

Pitch Features

Idea: Binning of Fourier coefficients

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

Pitch Features

Time-frequency representation

Windowing in the time domain

Windowing in the frequency domain

Pitch Features

Details:
- Let $\hat{v}$ be a spectral vector obtained from a spectrogram w.r.t. a sampling rate $1/T$ and a window length N. The spectral coefficient $\hat{v}(k)$ corresponds to the frequency

$$f_{\text{coeff}}(k) := \frac{k}{N} \cdot \frac{1}{T}$$

- Let
$$S(p) := \{k : f_{\text{MIDI}}(p - 0.5) \leq f_{\text{coeff}}(k) < f_{\text{MIDI}}(p + 0.5)\}$$
be the set of coefficients assigned to a pitch $p \in [1 : 128]$
Then the pitch coefficient $P(p)$ is defined as

$$P(p) := \sum_{k \in S(p)} |\hat{v}(k)|^2$$

Pitch Features

Example: A4, *p* = 69
- Center frequency: $f(p = 69) = 2^{\frac{0}{12}} \cdot 440 = 440 \ Hz$
- Lower bound: $f(p = 68.5) = 2^{\frac{-0.5}{12}} \cdot 440 = 427.5 \ Hz$
- Upper bound: $f(p = 69.5) = 2^{\frac{0.5}{12}} \cdot 440 = 452.9 \ Hz$
- STFT with $N = 4096$, $1/T = 22050$

$$
\begin{aligned}
\vdots \\
f(k = 79) &= 425.3 \ Hz \\
f(k = 80) &= 430.7 \ Hz \\
f(k = 81) &= 436.0 \ Hz \\
f(k = 82) &= 441.4 \ Hz \\
f(k = 83) &= 446.8 \ Hz \\
f(k = 84) &= 452.2 \ Hz \\
f(k = 85) &= 457.6 \ Hz \\
\vdots
\end{aligned}
$$

Pitch Features

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\vdots
\end{aligned}
$$

$S(p = 69)$

$$P(p = 69) = \sum_{k=80}^{84} |\hat{v}(k)|^2$$

Pitch Features

Note	MIDI pitch	Center [Hz] frequency	Left [Hz] boundary	Right [Hz] boundary	Width [Hz]
A3	57	220.0	213.7	226.4	12.7
A#3	58	233.1	226.4	239.9	13.5
B3	59	246.9	239.9	254.2	14.3
C4	60	261.6	254.2	269.3	15.1
C#4	61	277.2	269.3	285.3	16.0
D4	62	293.7	285.3	302.3	17.0
D#4	63	311.1	302.3	320.2	18.0
E4	64	329.6	320.2	339.3	19.0
F4	65	349.2	339.3	359.5	20.2
F#4	66	370.0	359.5	380.8	21.4
G4	67	392.0	380.8	403.5	22.6
G#4	68	415.3	403.5	427.5	24.0
A4	69	440.0	427.5	452.9	25.4

Pitch Features

Note:
- $P \in \mathbb{R}^{128}$
- For some pitches, $S(p)$ may be empty. This particularly holds for low notes corresponding to narrow frequency bands.

→ Linear frequency sampling is problematic!

Solution:
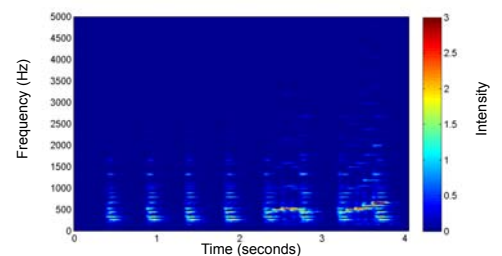Multi-resolution spectrograms or multirate filterbanks

Pitch Features

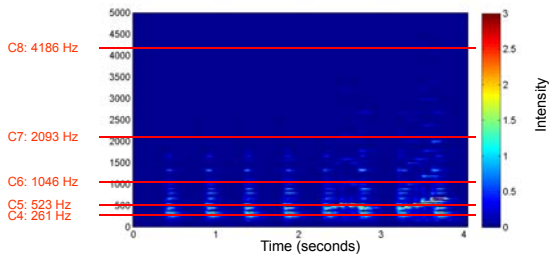Example: Friedrich Burgmüller, Op. 100, No. 2   ▶
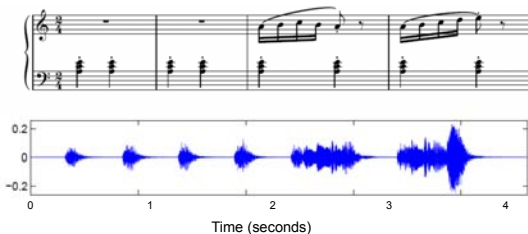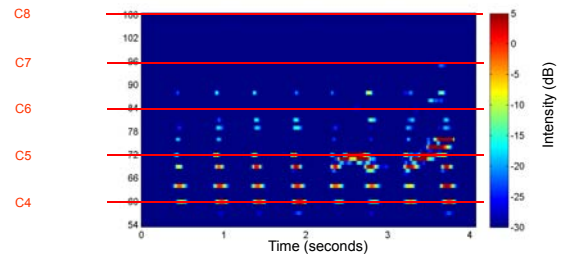

Pitch Features

Spectrogram

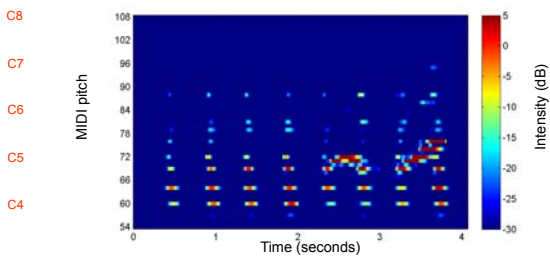## Pitch Features

Spectrogram

Pitch representation
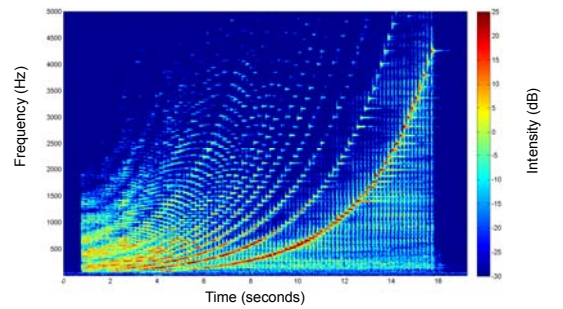
Pitch Features

Pitch representation

Pitch Features

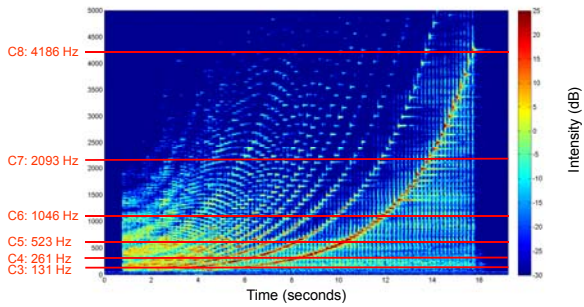Example: Chromatic scale

Spectrogram

Pitch Features
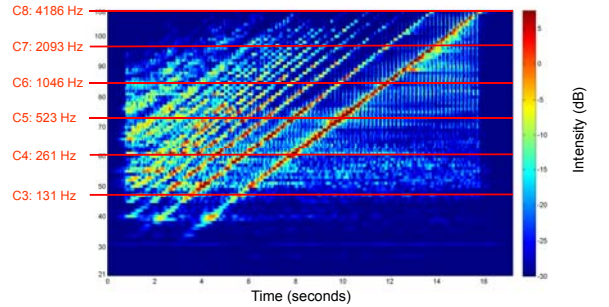
Example: Chromatic scale

Spectrogram
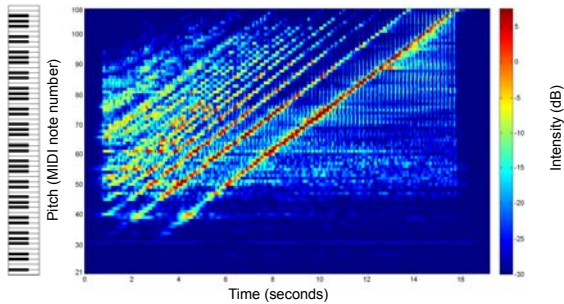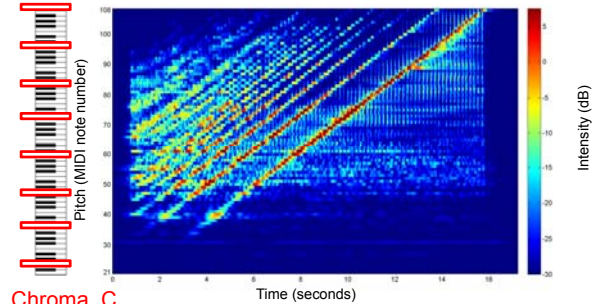
Pitch Features

Example: Chromatic scale

Log-frequency spectrogram

Pitch Features

Example: Chromatic scale

Log-frequency spectrogram
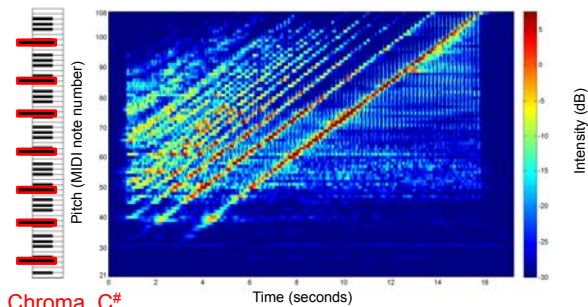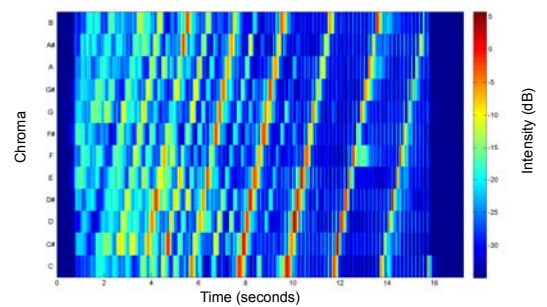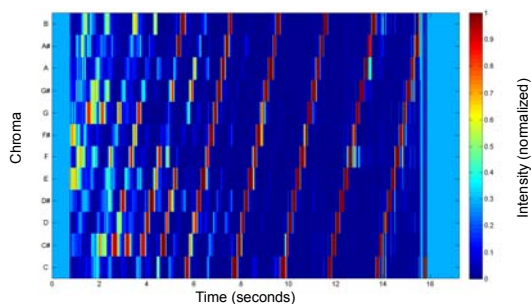

Pitch Features

Example: Chromatic scale

Log-frequency spectrogram

Chroma C

Pitch Features

Example: Chromatic scale

Log-frequency spectrogram

Chroma C#

Chroma Features

Example: Chromatic scale

Chroma representation

Chroma Features

Example: Chromatic scale

Chroma representation (normalized, Euclidean)

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.
- Seperation 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 $\;\hat{=}\;\{\dots,\,C0\,,\;C1\,,\;C2\,,\;C3\,,\;\dots\}$
- Computation: pitch features → chroma features
  Add up all pitches belonging to the same class
- Result: 12-dimensional chroma vector.

Chroma Features
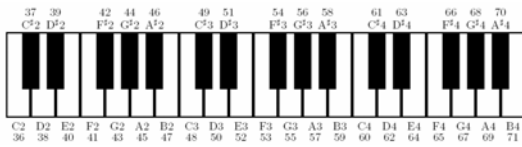
Chroma Features
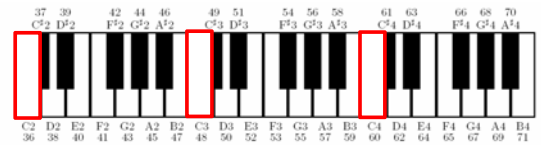
C2   C3   C4

Chroma C
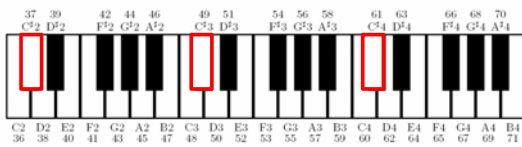
Chroma Features

C#2   C#3   C#4

Chroma C#
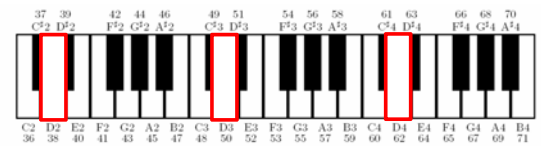
Chroma Features

D2   D3   D4

Chroma D

Chroma Features

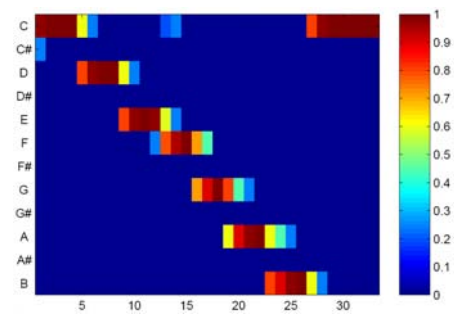Chromatic circle   Shepard's helix of pitch perception
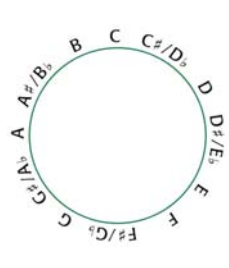
http://en.wikipedia.org/wiki/Pitch_class_space   Bartsch/Wakefield, IEEE Trans. Multimedia, 2005
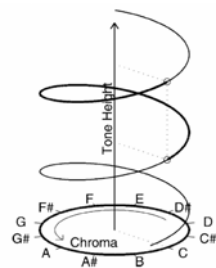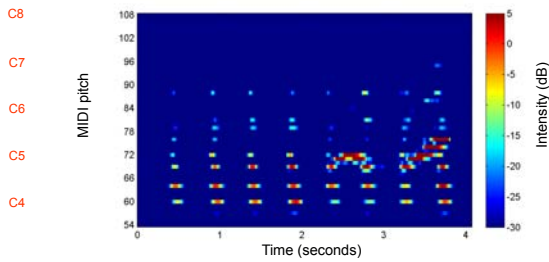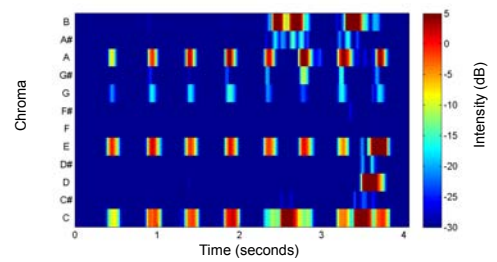
Chroma Features

Example: C-Major Scale

Chroma Features

Pitch representation

Chroma Features

Chroma representation

Chroma Features

Chroma representation (normalized)
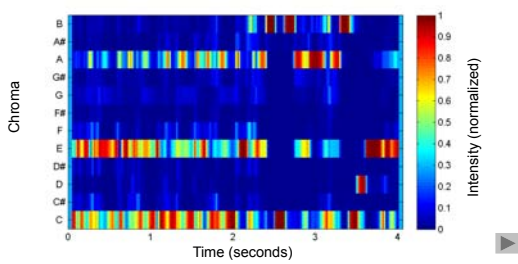
Chroma Features

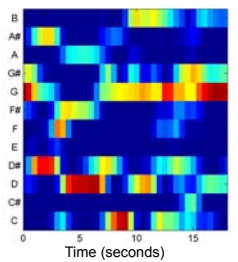Example: Beethoven's Fifth
Chroma representation (normalized, 10 Hz)
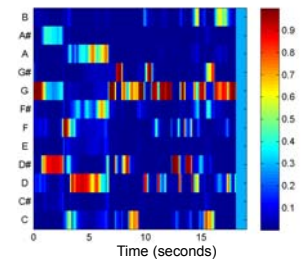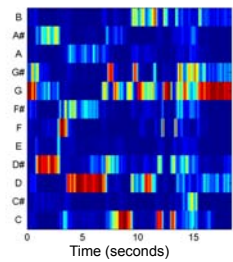
Chroma Features

Example: Beethoven's Fifth
Chroma representation (normalized, 2 Hz)
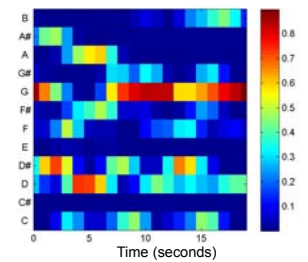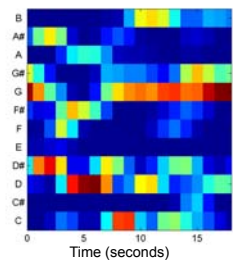Smoothing (2 seconds) + downsampling (factor 5)
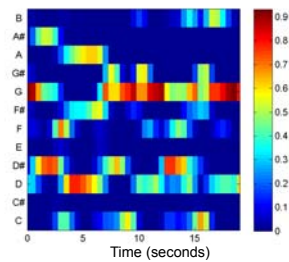
Chroma Features

Example: Beethoven's Fifth
Chroma representation (normalized, 1 Hz)
Smoothing (4 seconds) + downsampling (factor 10)

Chroma Features
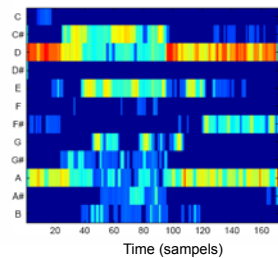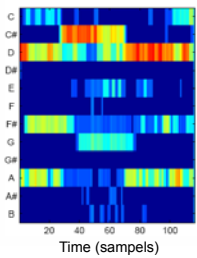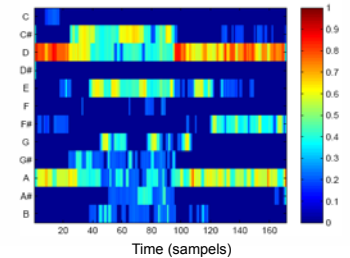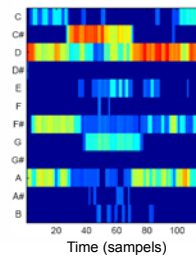
Example: Bach Toccata

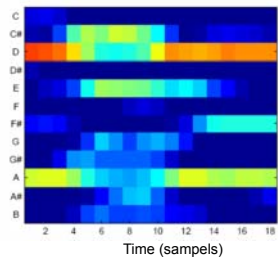Koopman ▶ ▶   Ruebsam ▶ ▶

Chroma Features

Example: Bach Toccata

Koopman ▶ ▶   Ruebsam ▶ ▶

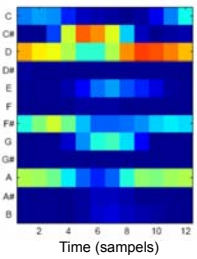Feature resolution: 10 Hz

Chroma Features

Example: Bach Toccata

Koopman ▶ ▶   Ruebsam ▶ ▶

Feature resolution: 1 Hz
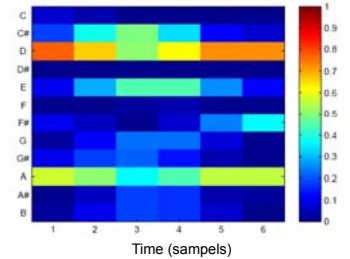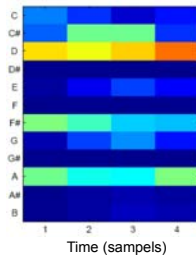
Chroma Features

Example: Bach Toccata

Koopman ▶ ▶   Ruebsam ▶ ▶


Feature resolution: 0.33 Hz

Chroma Features

- Sequence of chroma vectors correlates to the harmonic progression

- Normalization $v \to \frac{v}{\|v\|}$ makes features invariant to changes in dynamics

- Further quantization and smoothing: CENS features

- Taking logarithm before adding up pitch coefficients accounts for logarithmic sensation of intensity
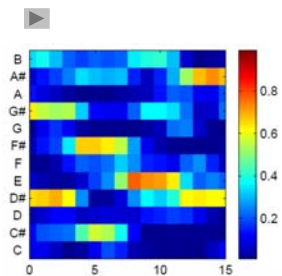
Chroma Features

Example: Zager & Evans "In The Year 2525"
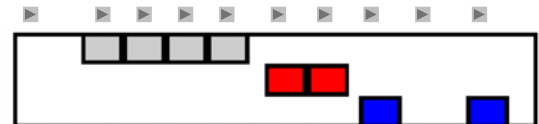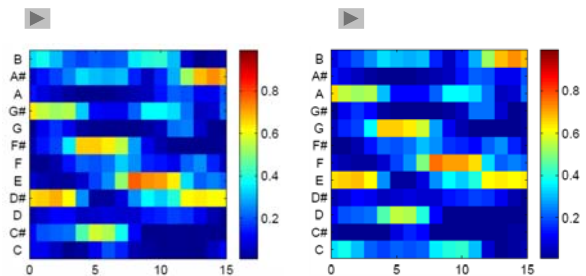

How to deal with transpositions?

Chroma Features

Example: Zager & Evans "In The Year 2525"

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

Chroma Features

Example: Zager & Evans "In The Year 2525"

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

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
- ISMIR 2011, Poster Session (PS2), Tuesday 13-15