INTERNATIONAL AUDIO LABORATORIES ERLANGEN

AUDIO LABS

Lecture

Music Processing

Music Representations

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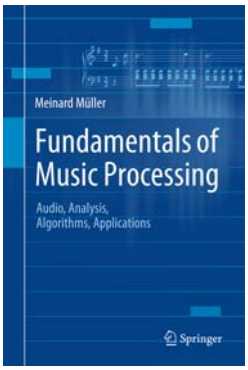
Fraunhofer IIS

Book: Fundamentals of Music Processing



Meinard Müller
Fundamentals of Music Processing
Audio, Analysis, Algorithms, Applications
483 p., 249 illus., hardcover
ISBN: 978-3-319-21944-8
Springer, 2015

Accompanying website:
www.music-processing.de

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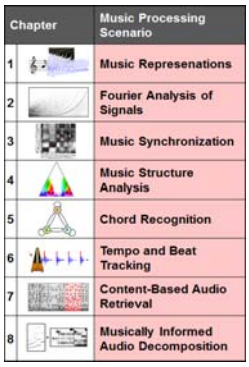

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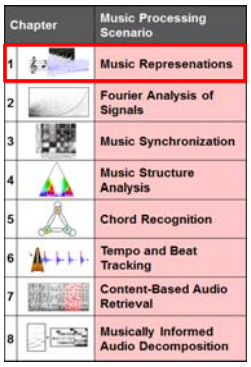

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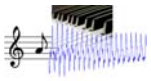
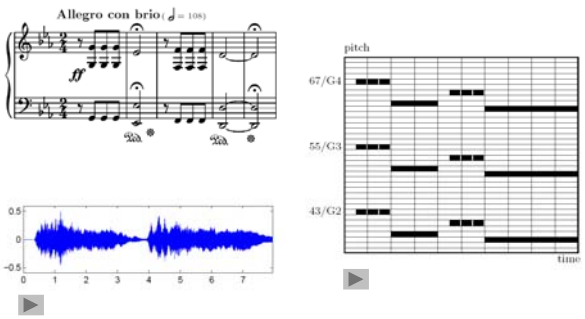
Chapter 1: Music Representations



Musical information can be represented in many different ways. In Chapter 1, we consider three widely used music representations: sheet music, symbolic, and audio representations. This first chapter also introduces basic terminology that is used throughout the book. In particular, we discuss musical and acoustic properties of audio signals including aspects such as frequency, pitch, dynamics, and timbre.

Music Representations



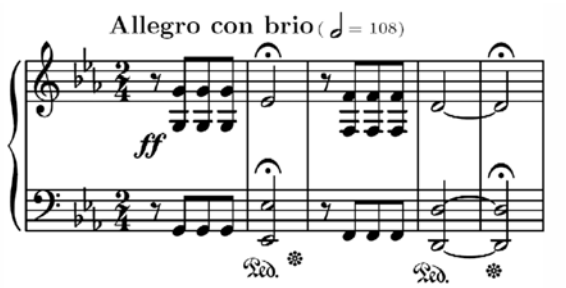
Music Representations

- Sheet music representation
  - visual description of a musical score
  - image format (printed or scanned)
- Symbolic representations
  - description based on entities with explicit musical meaning
  - given in digital format that can be parsed by a computer
- Audio representation
  - physical description
  - encoding of sound wave

Sheet Music Representation

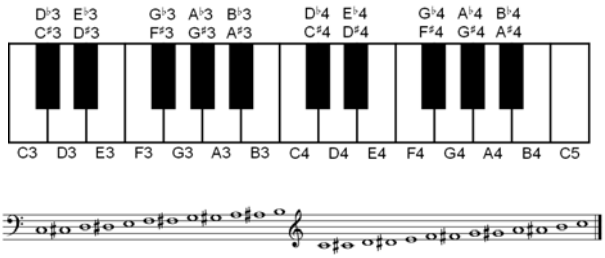
- Graphical-textual encoding of musical parameters
  - notes (onsets, pitches, durations)
  - tempo, measure, dynamics
  - instrumentation
  - …
- Guide for performing music
- Leaves freedom for various interpretations

Sheet Music Representation



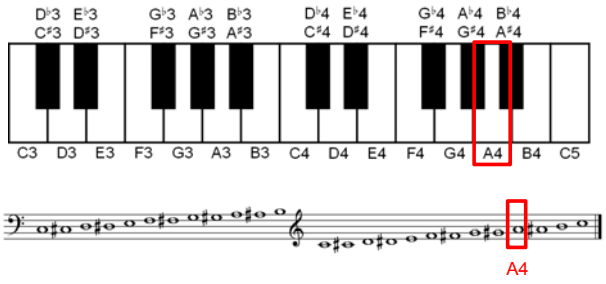
Sheet Music Representation

Piano keyboard and notes



Sheet Music Representation

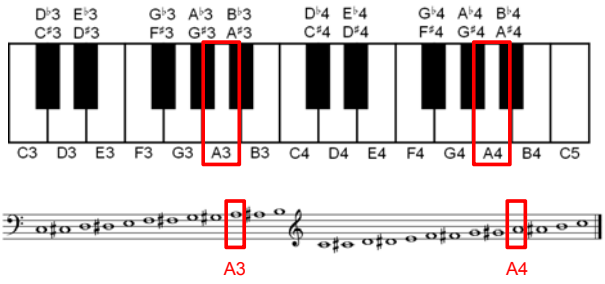
Piano keyboard and notes



A ≙ pitch spelling attribute
4 ≙ octave number

Sheet Music Representation

Piano keyboard and notes

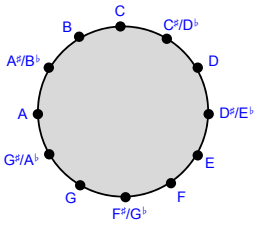


A ≙ pitch spelling attribute
4 ≙ octave number

Sheet Music Representation

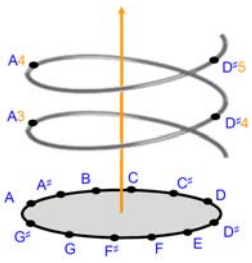
Chromatic circle

Chroma ≙ pitch spelling attribute



Shepard's helix of pitch

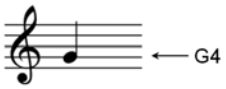
Tone height ≙ octave number



Sheet Music Representation

Staff

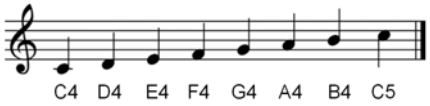
Staff with G-clef



Staff with F-clef

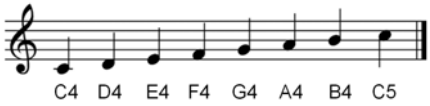
Sheet Music Representation

Musical score of a C-major scale

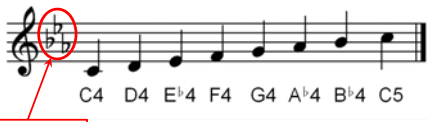


Sheet Music Representation

Musical score of a C-major scale



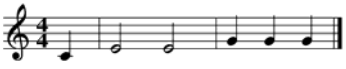
Musical score of a C-minor scale

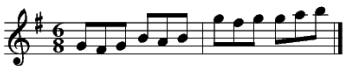


Key signature consisting of three flats

Sheet Music Representation

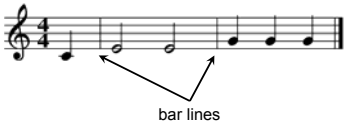
Time signature

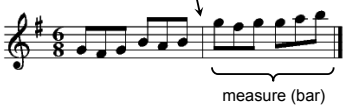




Sheet Music Representation

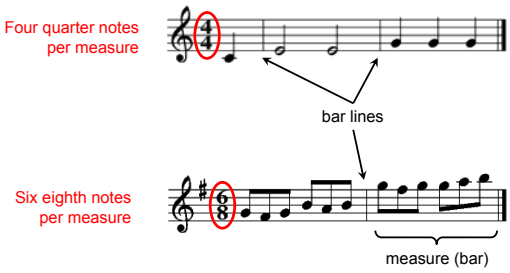
Time signature





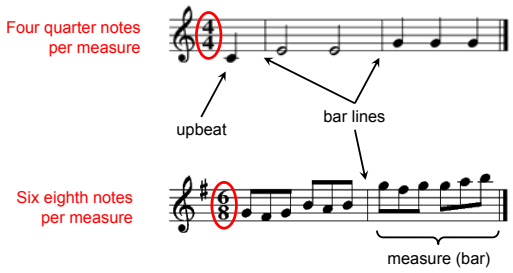
Sheet Music Representation

Time signature



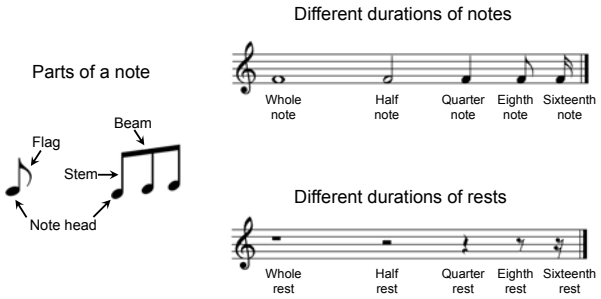
Sheet Music Representation

Time signature



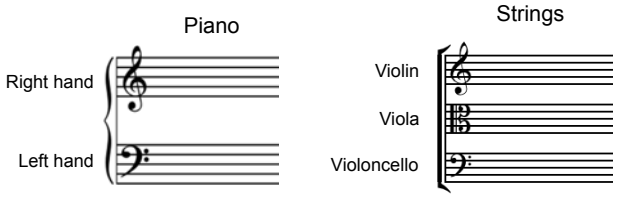
Sheet Music Representation

Note durations



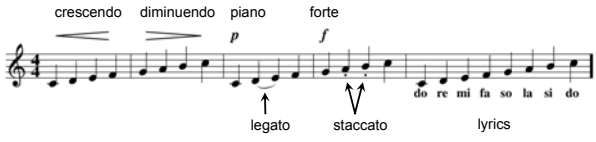
Sheet Music Representation

Staff systems

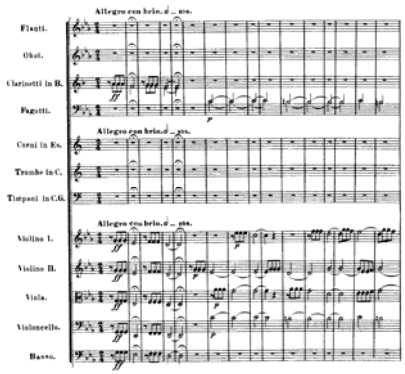


Sheet Music Representation

Dynamics and articulation



Sheet Music Representation



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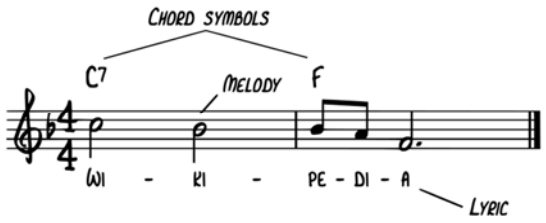
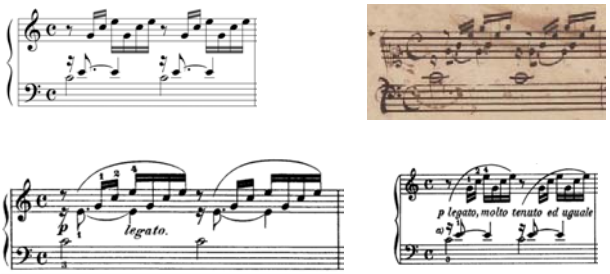


Sheet Music Representation



Sheet Music Representation

Types of score

- Full score: shows music for all instruments and voices; used by conductors
- Piano (reduction) score: transcription for piano
  Example: Liszt transcription of Beethoven symphonies
- Short score: reduction of a work for many instruments to just a fews staves
- Lead sheet: specifies only melody, lyrics and harmonies (chord symbols); used for popular music to capture essential elements of a song

Symbolic Representation

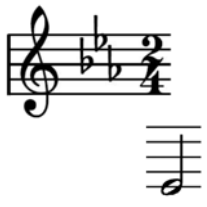
- Symbolic description of music
  - based on entities that have an explicit musical meaning
  - given in some digital format
  - can be parsed by a computer
- Note:
  - Scanned sheet music based on pixels
  - Digital audio file based on samples

  are not regarded as being symbolic music formats

Symbolic Representation

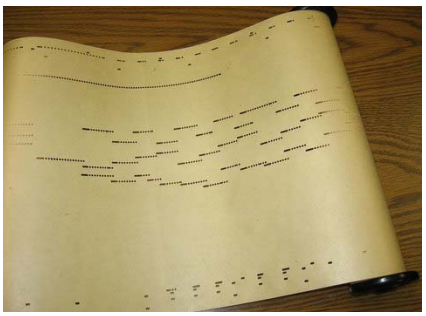
MusicXML

```
<note>
  <pitch>
    <step>E</step>
    <alter>-1</alter>
    <octave>4</octave>
  </pitch>
  <duration>2</duration>
  <type>half</type>
</note>
```



Symbolic Representation

Piano roll representation



Symbolic Representation

Piano roll representation

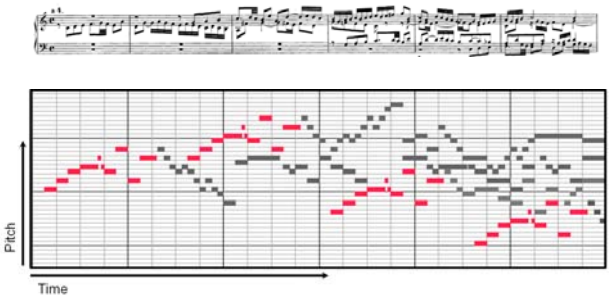
Symbolic Representation

Piano roll representation

- Piano roll: music storage medium used to operate a player piano
- Perforated paper rolls
- Holes in the paper encode the note parameters onset, duration, and pitch
- First pianola: 1895

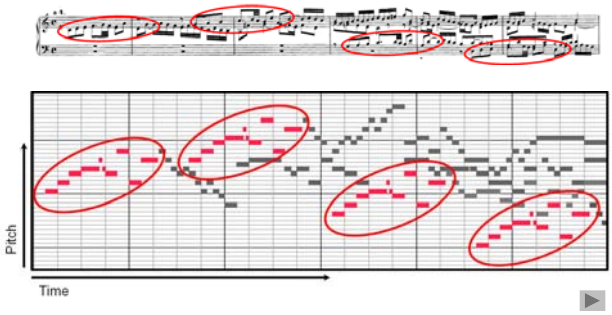
Symbolic Representation

Piano roll representation



Symbolic Representation

Piano roll representation



Symbolic Representation

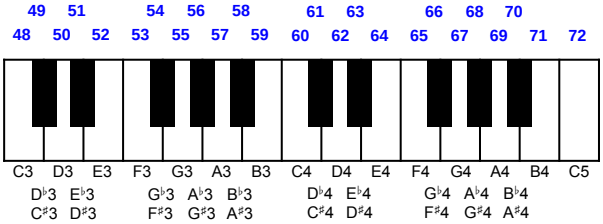
MIDI representation

- Musical Instrument Digital Interface (MIDI)
- Standard protocol for controlling and synchronizing digital instruments
- Standard MIDI File (SMF) is used for collecting and storing MIDI messages
- SMF file is often called MIDI file

Symbolic Representation

MIDI representation

MIDI note numbers (MNN) ≙ piano keys



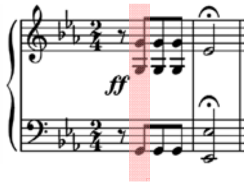
Symbolic Representation

MIDI representation

- MIDI note number (pitch)
  p = 21, …, 108 ≙ piano keys
  p = 69 ≙ concert pitch A4
- Key velocity ≙ intensity
- MIDI channel ≙ instrument
- Note-on / note-off events ≙ onset time & duration
- Tempo measured in clock pulses or ticks
  (each MIDI event has a timestamp)
- Absolute tempo specified by
  - ticks per quarter note (musical time)
  - micro-seconds per tick (physical time)

Symbolic Representation

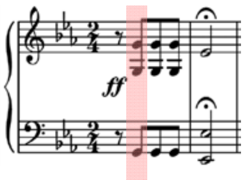
MIDI representation

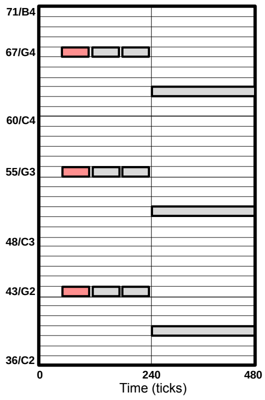


Time (Ticks)	Message	Channel	Note Number	Velocity
60	NOTE ON	1	67	100
0	NOTE ON	1	55	100
0	NOTE ON	2	43	100
55	NOTE OFF	1	67	0
0	NOTE OFF	1	55	0
0	NOTE OFF	2	43	0
5	NOTE ON	1	67	100
0	NOTE ON	1	55	100
0	NOTE ON	2	43	100
55	NOTE OFF	1	67	0
0	NOTE OFF	1	55	0
0	NOTE OFF	2	43	0
5	NOTE ON	1	67	100
0	NOTE ON	1	55	100
0	NOTE ON	2	43	100
55	NOTE OFF	1	67	0
0	NOTE OFF	1	55	0
0	NOTE OFF	2	43	0
5	NOTE ON	1	63	100
0	NOTE ON	2	51	100
0	NOTE ON	2	39	100
240	NOTE OFF	1	63	0
0	NOTE OFF	2	51	0
0	NOTE OFF	2	39	0

Symbolic Representation

MIDI representation





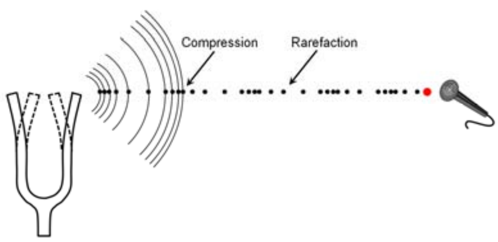
Audio Representation

Various interpretations – Beethoven's Fifth

- Bernstein
- Karajan
- Scherbakov (piano)
- MIDI (piano)

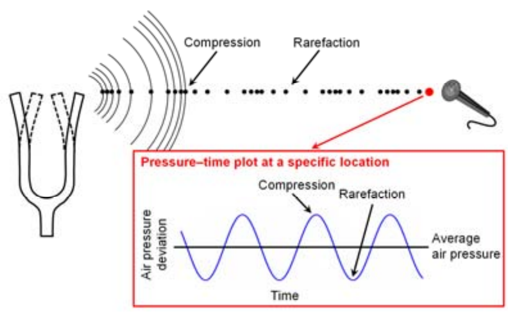
Audio Representation

Waveform



Audio Representation

Waveform



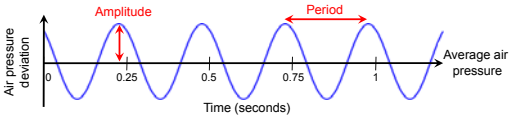
Audio Representation

Waveform

- Audio signal encodes change of air pressure at a certain location generated by a vibrating object (e.g. string, vocal cords, membrane)
- Waveform (pressure-time plot) is graphical representation of audio signal
- Parameters: amplitude, frequency / period

Audio Representation

Waveform



Audio Representation

Waveform

Pure tone (harmonic sound):

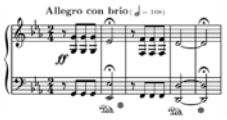
- Sinusoidal waveform
- Prototype of an acoustic realization of a musical note

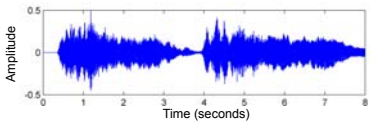
Parameters:

- Period p : time between to successive high pressure points
- Frequency $f = \frac{1}{p}$ (measured in Hz)
- Amplitude a : air pressure at high pressure points

Audio Representation

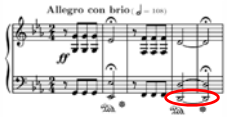
Waveform

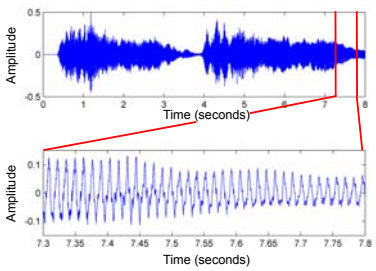




Audio Representation

Waveform

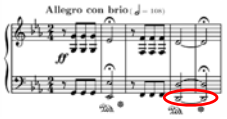


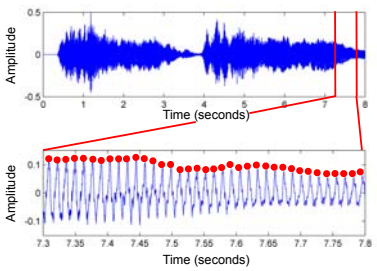


D2 (73.4 Hz)

Audio Representation

Waveform





D2 (73.4 Hz)

37 periods within 500 ms section

Audio Representation

Sound

- Sound: superposition of sinusoidals
- When realizing musical notes on an instrument one obtains a complex superposition of pure tones (and other noise-like components)
- Harmonics: integer multiples of fundamental frequency
  1. Harmonic ≙ fundamental frequency (e.g. 440 Hz)
  2. Harmonic ≙ first overtone (e.g. 880 Hz)
  3. Harmonic ≙ second overtone (e.g. 1320 Hz)

Audio Representation

Pitch

- Property that correlates to the perceived frequency (≙ fundamental frequency)
- Example: A4 (also called concert pitch) ≙ 440 Hz
- Slight changes in frequency have no effect on perceived pitch (pitch ≙ entire range of frequencies)
- Pitch perception: logarithmic in frequency
  Example: octave ≙ doubling of frequency

Audio Representation

Pitch

Equal-tempered scale: A system of tuning in which every pair of adjacent notes has an identical frequency ratio

Western music: 12-tone equal-tempered scale

- Each octave is divided up into 12 logarithmically equal parts
- Notes correspond to piano keys: p = 21 (A0) to p = 108 (C8)
- Referenz or standard pitch: p = 69 (A4) ≙ 440 Hz
- Center frequency of a note with MIDI pitch p

$$F_{\text{pitch}}(p) = 2^{(p-69)/12} \cdot 440 \quad \text{(Hz)}$$

Audio Representation

Pitch

- **Semitone:** difference between two subsequent scale steps
- Ratio of frequencies one semitone apart is constant:

$$F_{\text{pitch}}(p+1)/F_{\text{pitch}}(p) = 2^{1/12} \approx 1.059463$$

- **Cent:** 1200 cents per octave (by definition)
  100 cents per semitone (equivalent definition)
- Ratio of frequencies one cent apart is constant:

$$2^{1/1200} \approx 1.0005777895$$

Audio Representation

Pitch

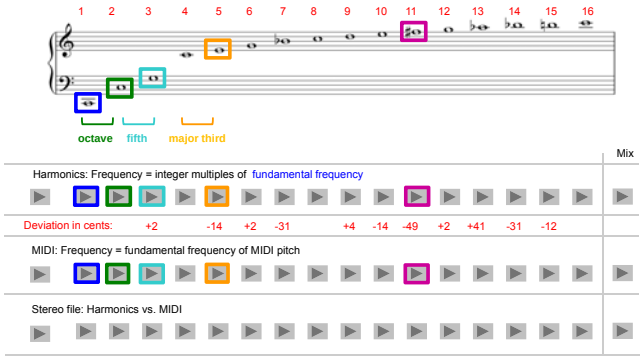
- Difference in cents between two frequencies ω_1 and ω_2:

$$\log_2\left(\frac{\omega_1}{\omega_2}\right) \cdot 1200$$

- Just noticeable difference = threshold of what is perceptible
  - varies from person to person
  - depends on other aspects such as the timbre
  - 25 cents recognizable by most people
  - 10 cents recognizable only by trained listeners

Audio Representation

Harmonics



Audio Representation
Dynamics

- Intensity of a sound
- Energy of the sound per time and area
- Loudness: subjective (psychoacoustic) perception of intensity (depends on frequency, timbre, duration)

Audio Representation
Dynamics

- $\text{intensity} = \frac{\text{energy}}{\text{time} \cdot \text{area}} = \frac{\text{power}}{\text{area}} \quad \left(\frac{\text{W}}{\text{m}^2}\right)$
- Decibel (dB): logarithmic unit to measure intensity relative to a reference level
- Reference level: threshold of hearing (THO) $I_{\text{TOH}} := 10^{-12}\ \text{W/m}^2$
- Intensity I measured in dB: $\text{dB}(I) := 10 \cdot \log_{10}\left(\frac{I}{I_{\text{TOH}}}\right)$
- Examples:

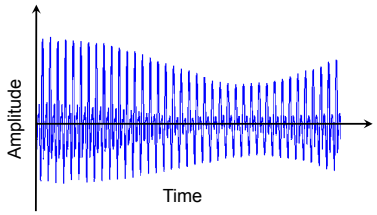
$I = 10 \cdot I_{\text{TOH}} \rightarrow I$ has a sound level of 10 dB

$I = 100 \cdot I_{\text{TOH}} \rightarrow I$ has a sound level of 20 dB

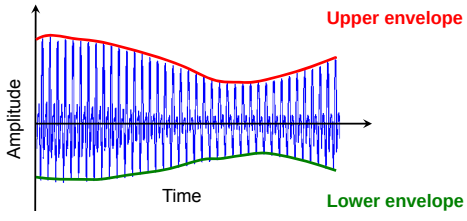
Audio Representation
Dynamics

Source	Intensity	Intensity level	× TOH
Threshold of hearing (TOH)	10^{-12}	0 dB	1
Whisper	10^{-10}	20 dB	10^{2}
Pianissimo	10^{-8}	40 dB	10^{4}
Normal conversation	10^{-6}	60 dB	10^{6}
Fortissimo	10^{-2}	100 dB	10^{10}
Threshold of pain	10	130 dB	10^{13}
Jet take-off	10^{2}	140 dB	10^{14}
Instant perforation of eardrum	10^{4}	160 dB	10^{16}

Audio Representation
Dynamics

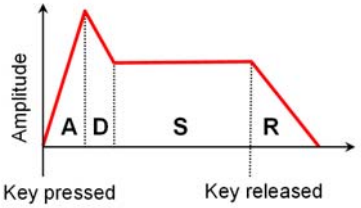


Audio Representation
Dynamics



Audio Representation
Dynamics

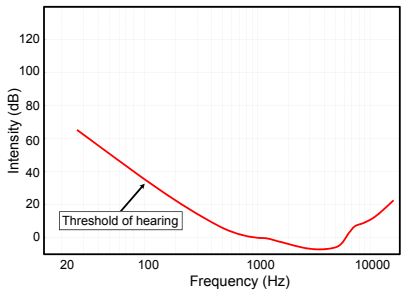
ADSR model: attack (A), decay (D), sustain (S), and release (R) phase



Audio Representation

Loudness

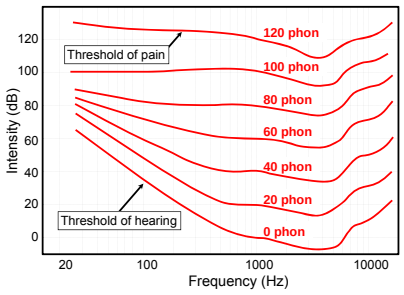
Equal-loudness contours (phon)



Audio Representation

Loudness

Equal-loudness contours (phon)



Audio Representation

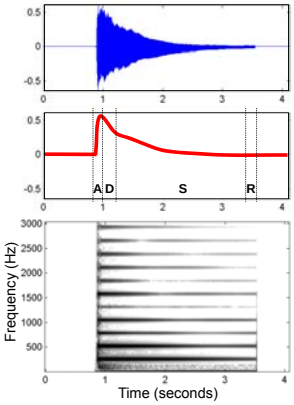
Timbre

- Quality of musical sound that distinguishes different types of sound production such as voices or instruments
- Tone quality
- Tone color
- Depends on energy distribution in harmonics

Audio Representation

Timbre

Piano playing
note C4 (261.6 Hz)



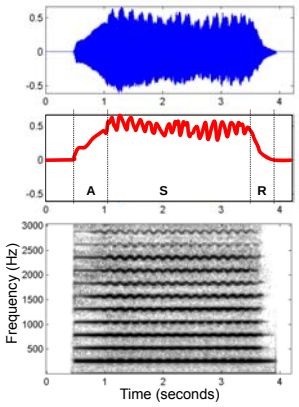
Audio Representation

Timbre

Violine playing
note C4 (261.6 Hz)

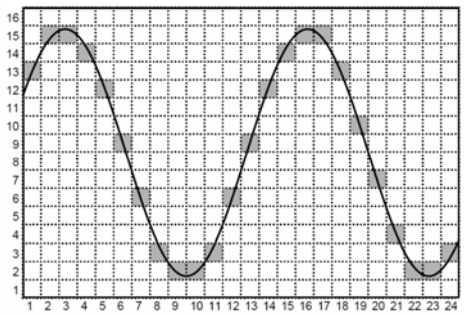
Vibrato:
Frequency modulations

Tremolo:
Amplitude modulations



Audio Representation

Digitization



Audio Representation

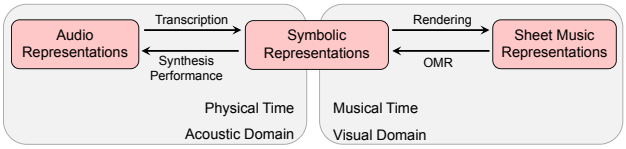
Digitization

- Convertion of continuous-time (analog) signal into a discrete signal
- Sampling (discretization of time axis)
- Quantization (discretization of amplitudes)

Examples:

- Audio CD: 44100 Hz sampling rate
  16 bits (65536 values) used for quantization
- Telephone: 8000 Hz sampling rate
  8 bits (256 values) used for quantization

Music Representations

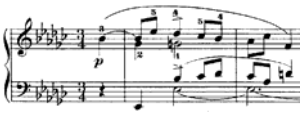


OMR = optical music recognition
Process of transforming sheet music into a symbolic representation

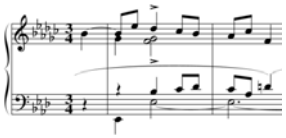
Music Representations

OMR

Original score



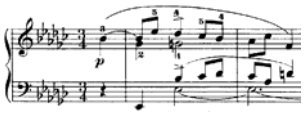
OMR score



Music Representations

OMR

Original score



OMR score