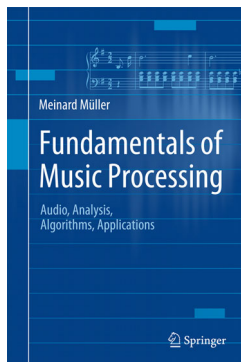


Lecture  
**Music Processing**

## Music Representations

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## 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](http://www.music-processing.de)

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Chapter	Music Processing Scenario
1	Music Representations
2	Fourier Analysis of Signals
3	Music Synchronization
4	Music Structure Analysis
5	Chord Recognition
6	Tempo and Beat Tracking
7	Content-Based Audio Retrieval
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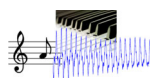
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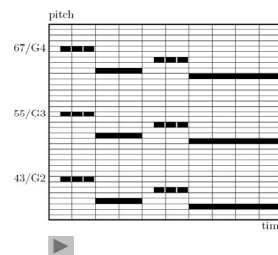
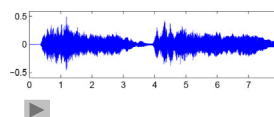
## Chapter 1: Music Representations

- 1.1 Sheet Music Representations
- 1.2 Symbolic Representations
- 1.3 Audio Representation
- 1.4 Further Notes



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

Allegro con brio (♩ = 108)

## Sheet Music Representation

### Piano keyboard and notes

## Sheet Music Representation

### Piano keyboard and notes

A4

A ≙ pitch spelling attribute  
4 ≙ octave number

## Sheet Music Representation

### Piano keyboard and notes

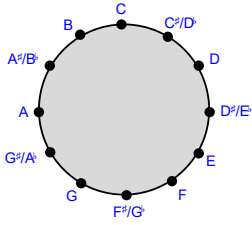
A3      A4

A ≙ pitch spelling attribute  
4 ≙ octave number

## Sheet Music Representation

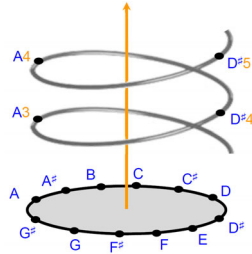
### Chromatic circle

Chroma  $\triangleq$  pitch spelling attribute



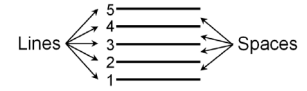
### Shepard's helix of pitch

Tone height  $\triangleq$  octave number

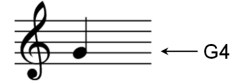


## Sheet Music Representation

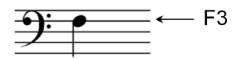
Staff



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



bar lines

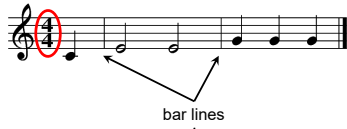


measure (bar)

## Sheet Music Representation

### Time signature

Four quarter notes per measure



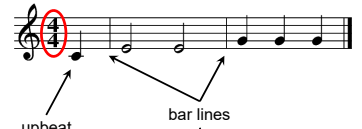
Six eighth notes per measure



## Sheet Music Representation

### Time signature

Four quarter notes per measure



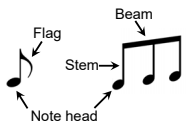
Six eighth notes per measure



## Sheet Music Representation

### Note durations

Parts of a note



Different durations of notes

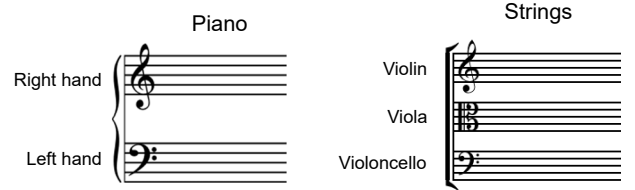


Different durations of rests



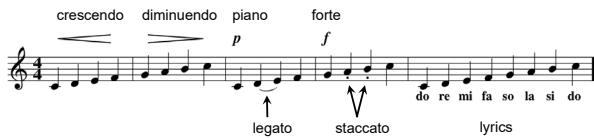
## Sheet Music Representation

### Staff systems



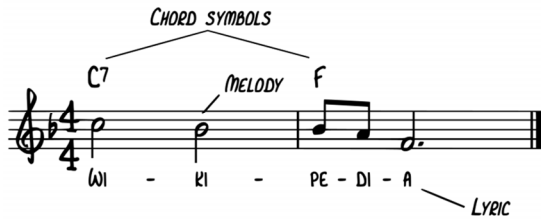
## Sheet Music Representation

### Dynamics and articulation



## Sheet Music Representation

## Sheet Music Representation



## 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 few 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

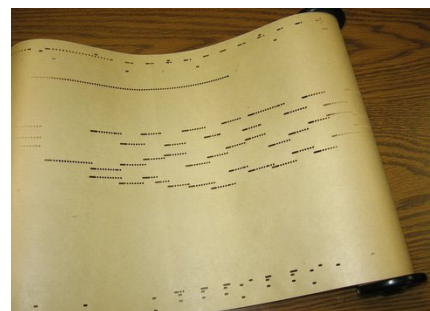
### MusicXML

```
<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



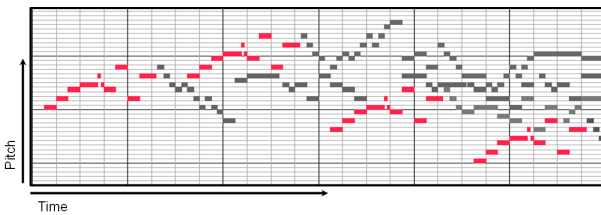
## Symbolic Representation

### 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

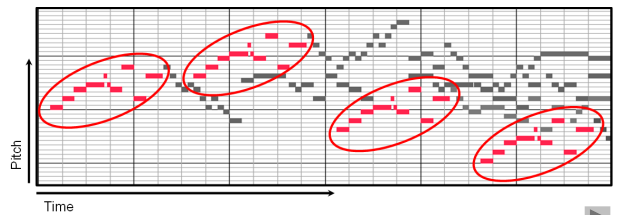
## Symbolic Representation

### Piano roll representation



## Symbolic Representation

### Piano roll representation



## Symbolic Representation

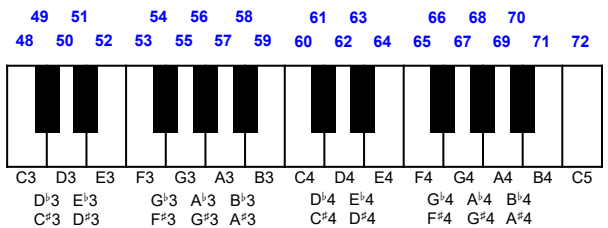
### MIDI representation

- 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)  $\triangleq$  piano keys



## Symbolic Representation

### MIDI representation

- MIDI note number (pitch)
  - $p = 21, \dots, 108 \triangleq$  piano keys
  - $p = 69 \triangleq$  concert pitch A4
- Key velocity  $\triangleq$  intensity
- MIDI channel  $\triangleq$  instrument
- Note-on / note-off events  $\triangleq$  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

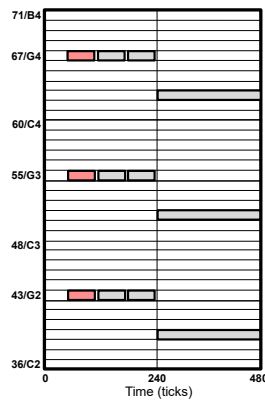
### MIDI representation



Time (Ticks)	Message	Channel	Note Number	Velocity
50	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



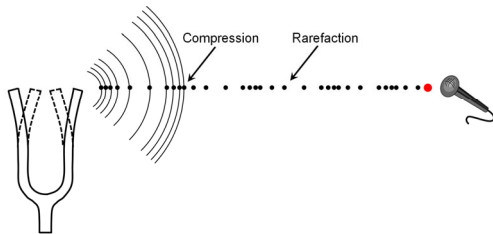
## Audio Representation

Various interpretations – Beethoven's Fifth

- Bernstein [▶](#)
- Karajan [▶](#)
- Scherbakov (piano) [▶](#)
- MIDI (piano) [▶](#)

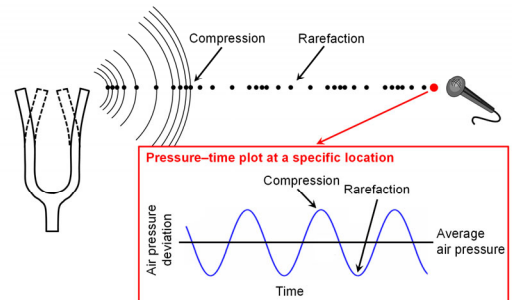
## Audio Representation

### Waveform



## Audio Representation

### Waveform



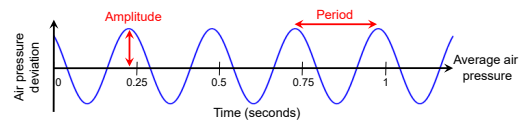
## Audio Representation

### 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):

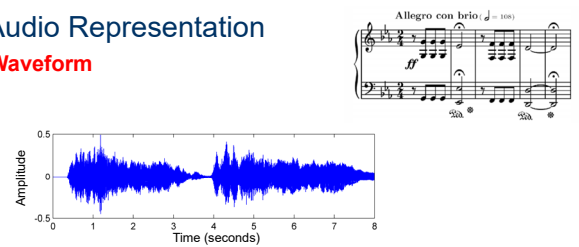
- Sinusoidal waveform
- Prototype of an acoustic realization of a musical note

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

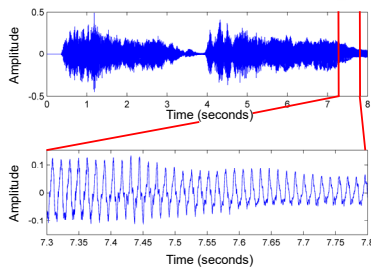
## Audio Representation

### Waveform



## Audio Representation

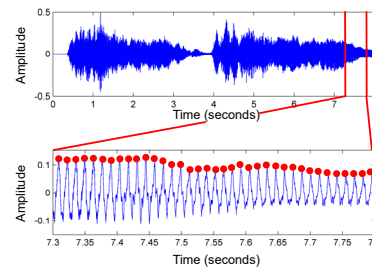
### Waveform



D2 (73.4 Hz)

## Audio Representation

### Waveform



D2 (73.4 Hz)

37 periods within 500 ms section





## Audio Representation

### 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

- intensity =  $\frac{\text{energy}}{\text{time} \cdot \text{area}} = \frac{\text{power}}{\text{area}} \left( \frac{\text{W}}{\text{m}^2} \right)$
- 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

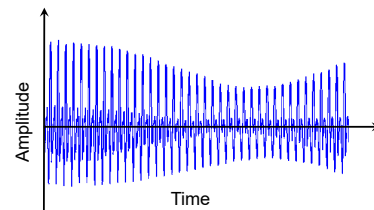
## Audio Representation

### 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	$10^{16}$

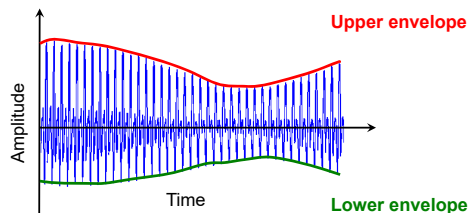
## Audio Representation

### Dynamics



## Audio Representation

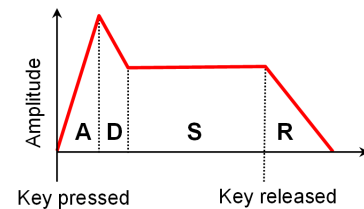
### Dynamics



## Audio Representation

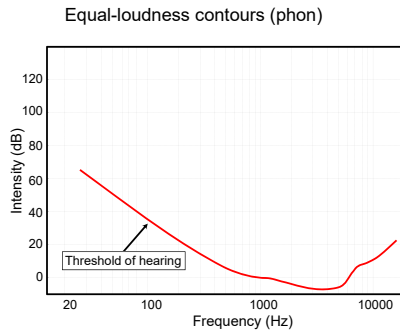
### Dynamics

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



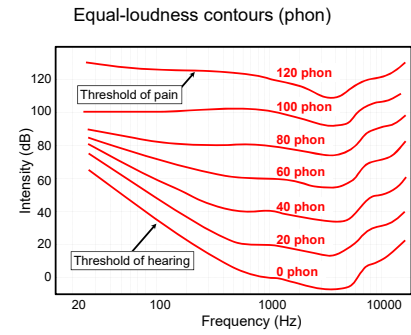
## Audio Representation

### Loudness



## Audio Representation

### Loudness



## Audio Representation

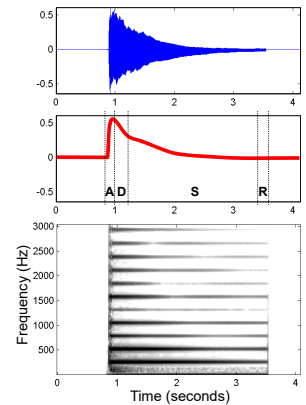
### Timbre

- 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

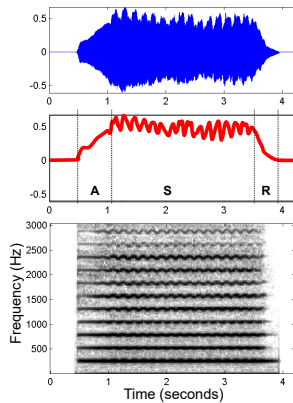
### Timbre

Violine playing note C4 (261.6 Hz)



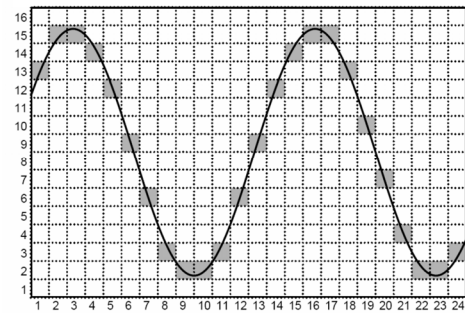
Vibrato:  
Frequency modulations

Tremolo:  
Amplitude modulations



## Audio Representation

### Digitization



## Audio Representation

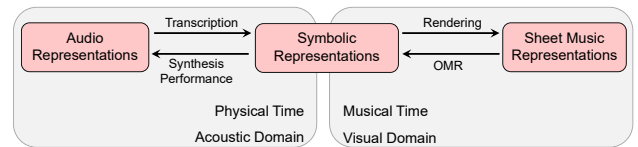
### Digitization

- Conversion 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

