Lecture

Music Processing

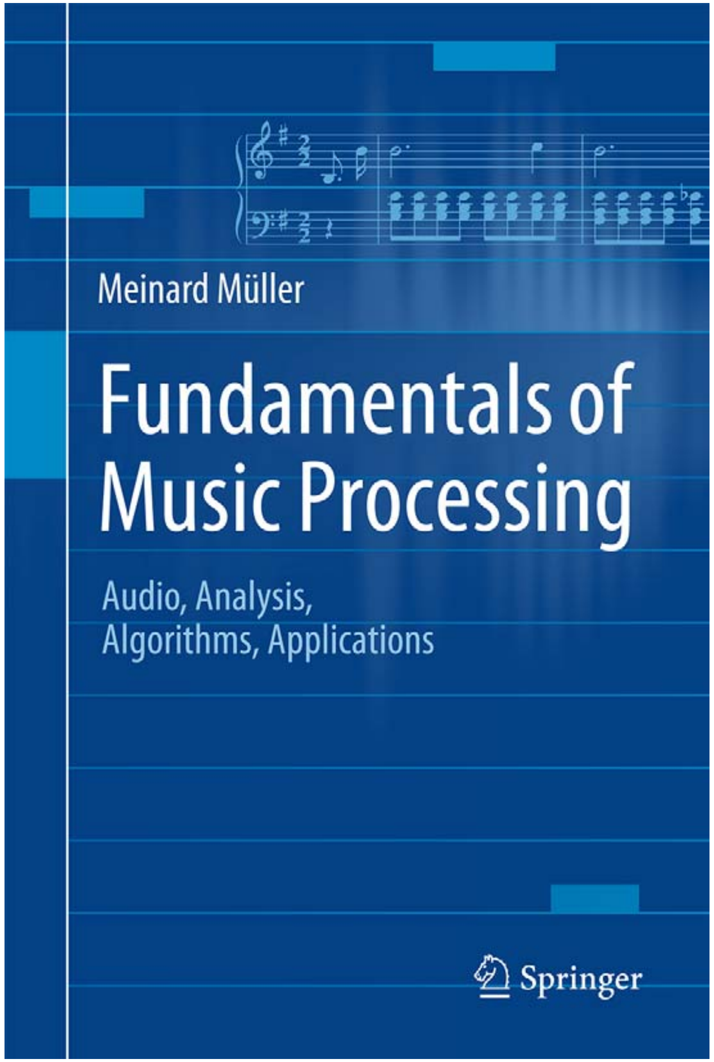
Music Representations

Meinard Müller

International Audio Laboratories Erlangen

meinard.mueller@audiolabs-erlangen.de

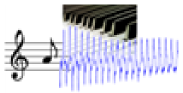
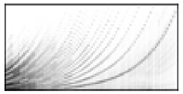
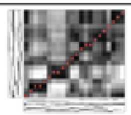
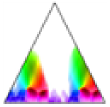
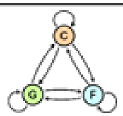
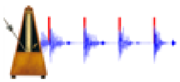
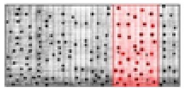
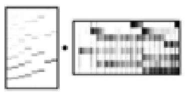
Book: Fundamentals of Music Processing



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

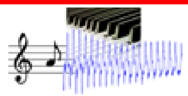
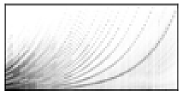
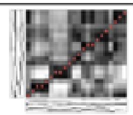
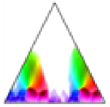
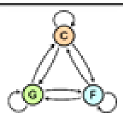
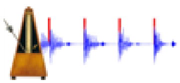
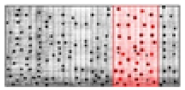
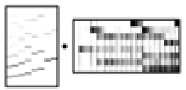
Book: Fundamentals of Music Processing

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
8		Musically Informed Audio Decomposition

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

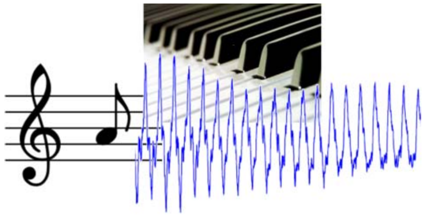
Book: Fundamentals of Music Processing

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
8		Musically Informed Audio Decomposition

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

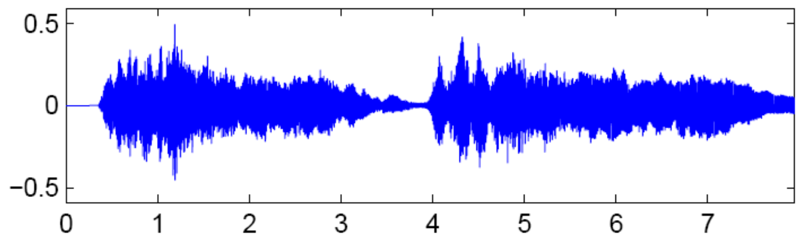
Accompanying website:
www.music-processing.de

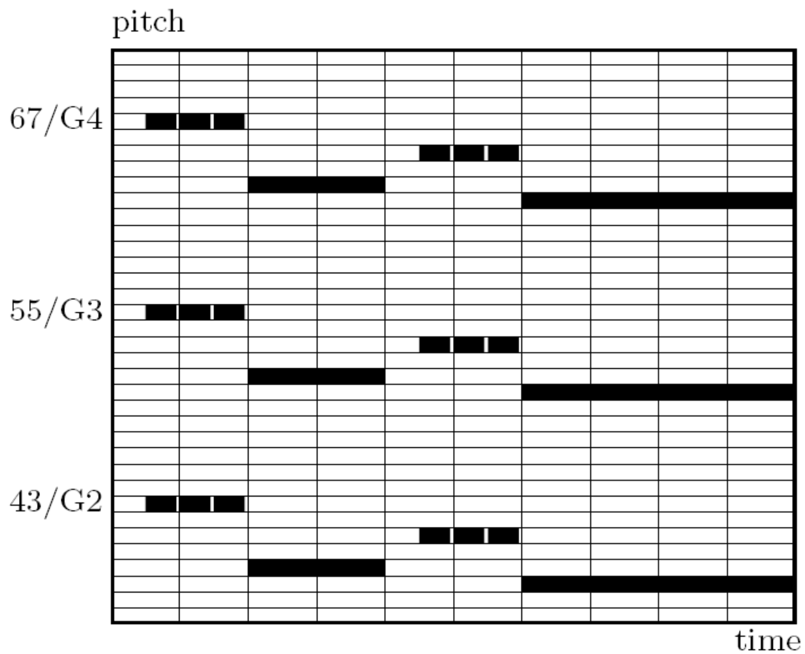
Chapter 1: Music Representations



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



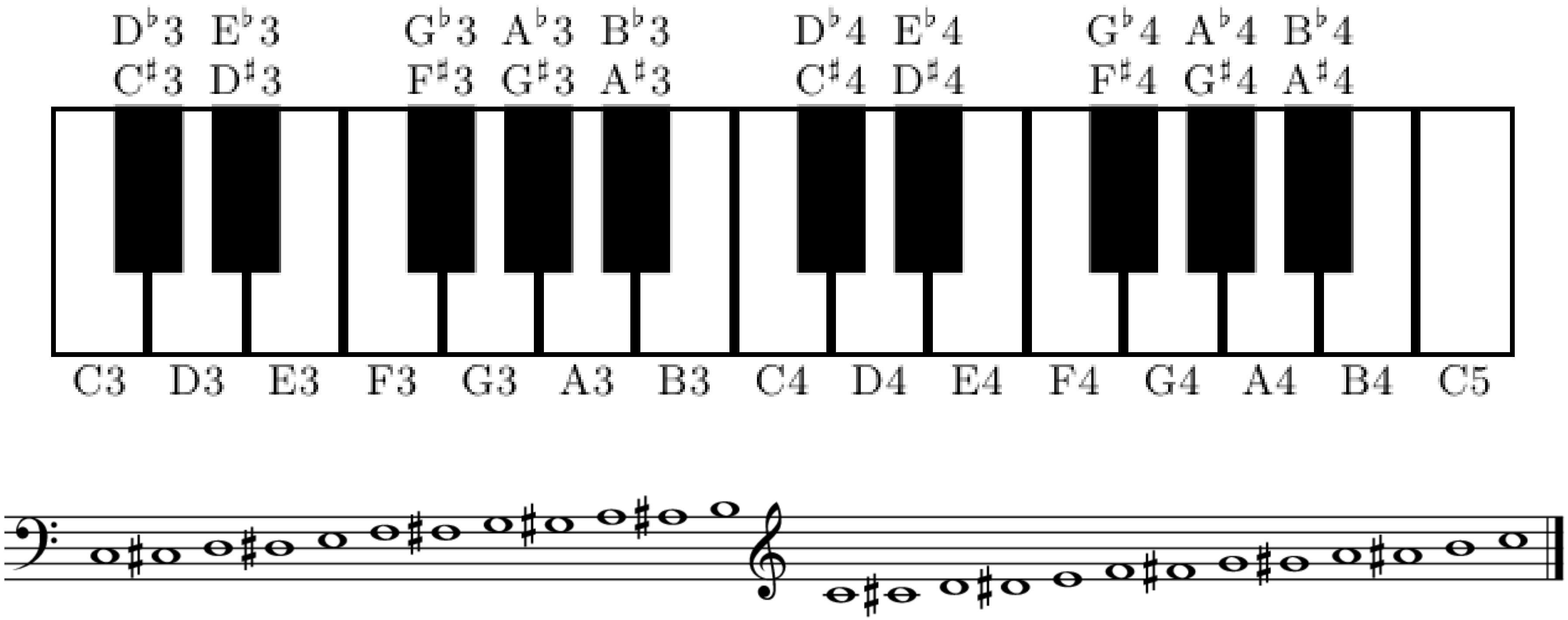


Music Representations

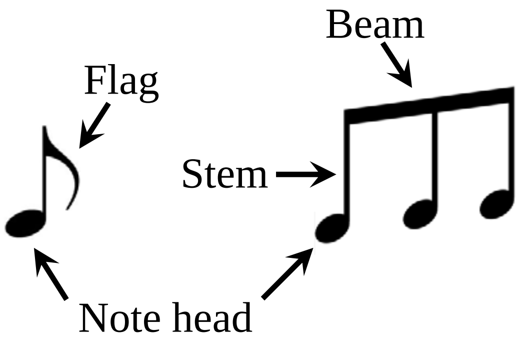
- Score representation: symbolic description
- MIDI representation: hybrid description (models note events explicitely but may also encode performance subtleties)
- Audio representation: physical description (encodes a sound wave)

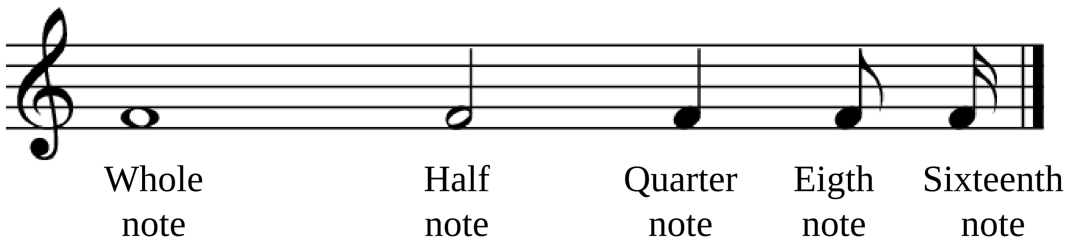
Score Representation

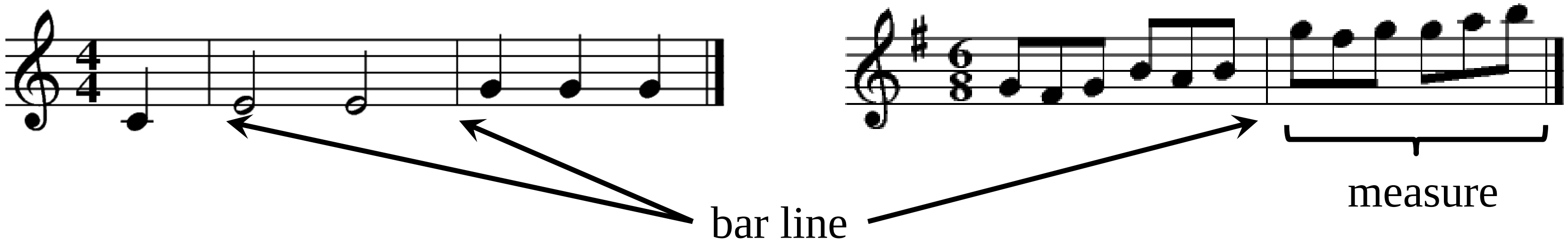
Score Representation



Score Representation



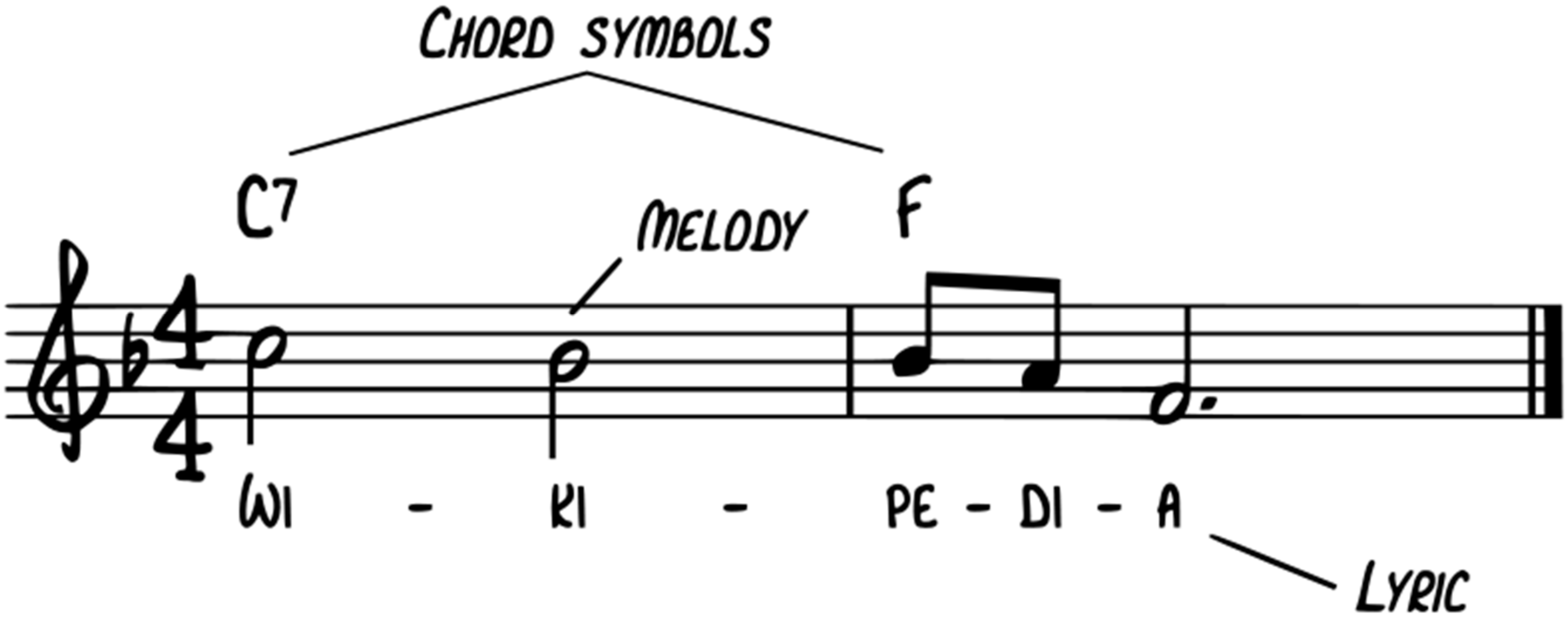




Score Representation

Score Representation

Score Representation



Score Representation

Score 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

Score Representation

- Scanned image

- Various symbolic data formats
  - Lilypond
  - MusicXML

- Optical Music Recognition (OMR)

- Music notation software
  - Finale
  - Sibelius

Score Representation

MusicXML

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

Score Representation

Musical score / sheet music:

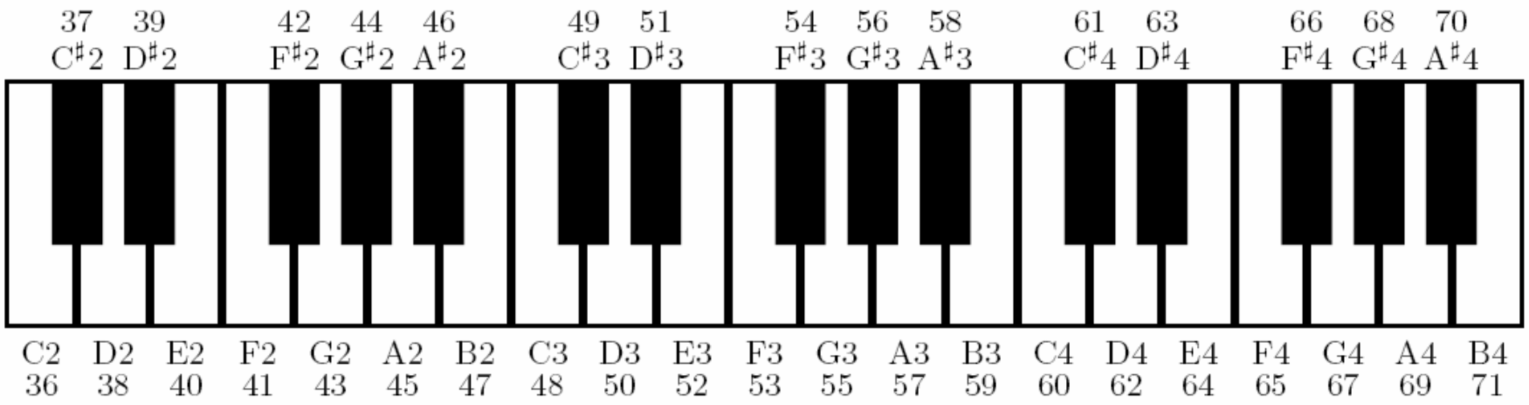
- Graphical / textual encoding of musical parameters (note onsets, pitches, durations, tempo, measure, dynamics, instrumentation)
- Guide for performing music
- Leaves freedom for various interpretations

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

MIDI Representation

MIDI note numbers (MNN) $\triangleq$ piano keys



MIDI Representation

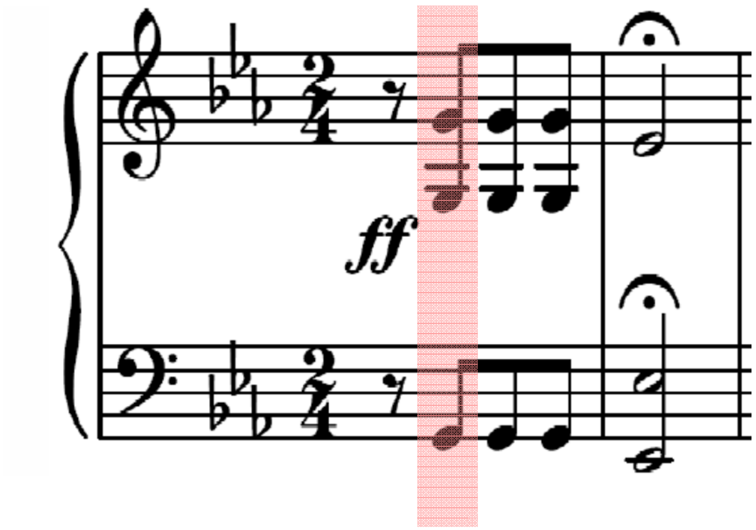
MIDI parameters:

- MIDI note number (pitch) $[0:127]$

  p = 21, …, 108 $\triangleq$ „piano keys“

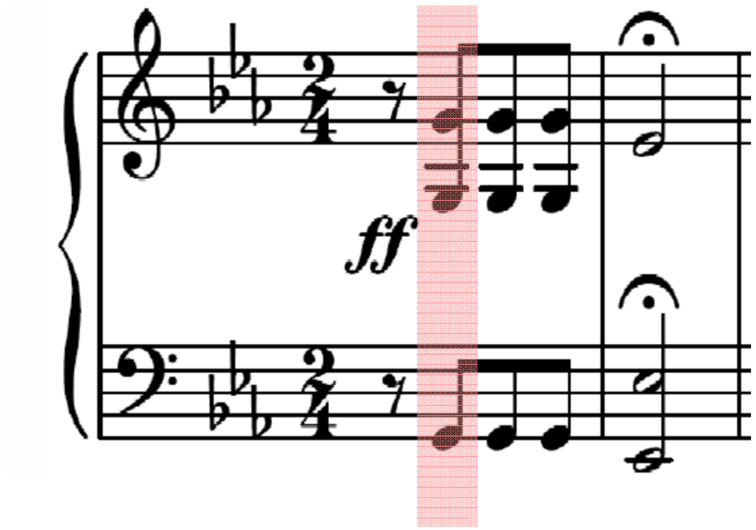
  p = 69 $\triangleq$ concert pitch A $(440Hz)$
- Key velocity $[0:127]$ $\triangleq$ intensity
- MIDI channel $[0:15]$ $\triangleq$ instrument
- Note-on / note-off events $\triangleq$ onset time & duration
- Tempo measured in clock pulses or ticks
  (each MIDI event has a timestamp)
- Absolute tempo specified by
  - ticks per quarter note (musical time)
  - micro-seconds per tick (physical time)

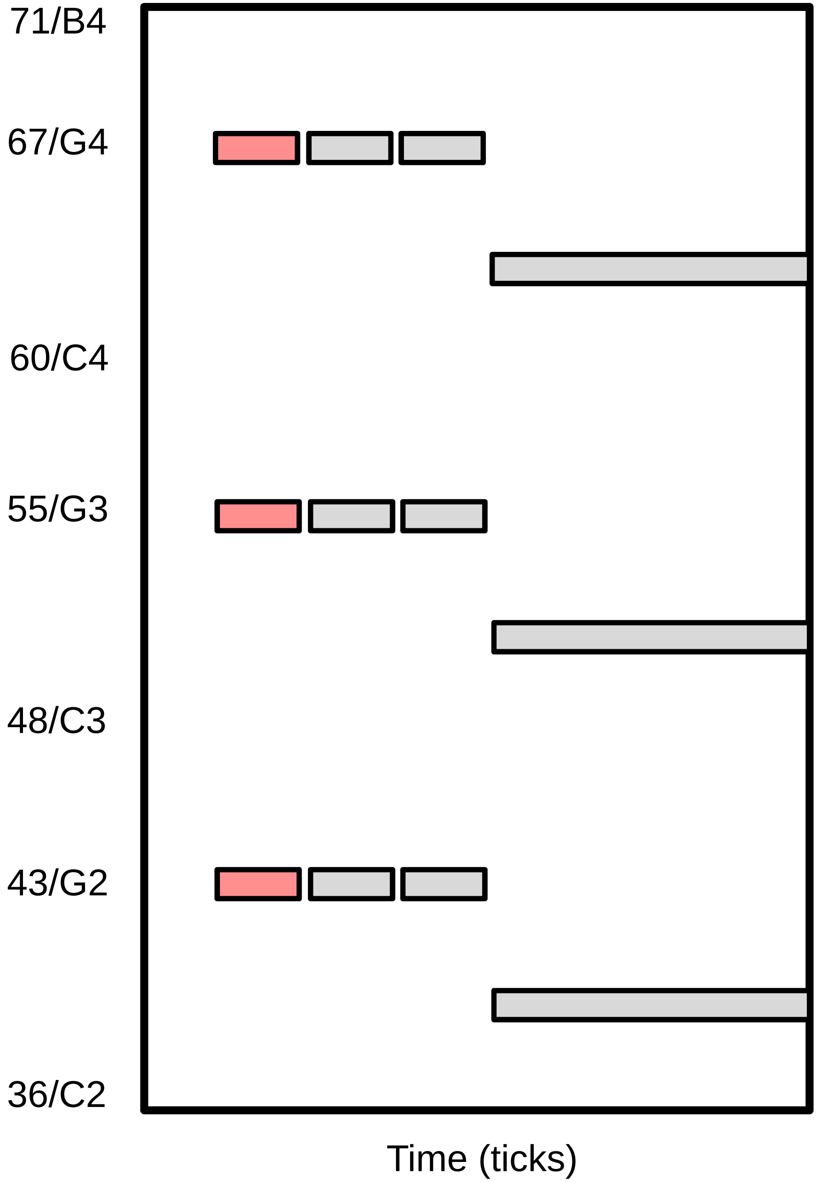
MIDI Representation



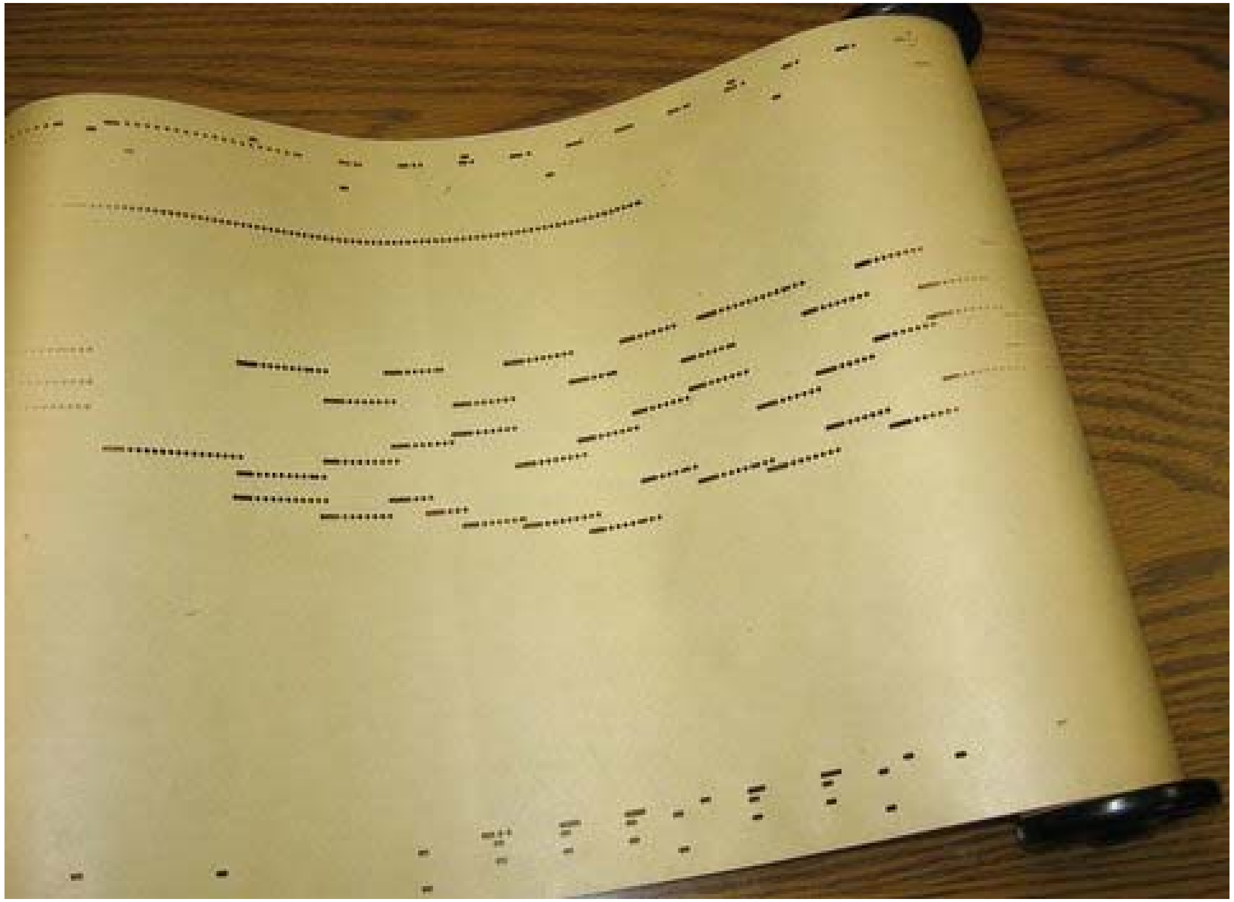
Time (Ticks)	Message	Channel	Note Number	Velocity
60	NOTE ON	1	67	100
0	NOTE ON	1	55	100
0	NOTE ON	2	43	100
55	NOTE OFF	1	67	0
0	NOTE OFF	1	55	0
0	NOTE OFF	2	43	0
5	NOTE ON	1	67	100
0	NOTE ON	1	55	100
0	NOTE ON	2	43	100
55	NOTE OFF	1	67	0
0	NOTE OFF	1	55	0
0	NOTE OFF	2	43	0
5	NOTE ON	1	67	100
0	NOTE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

MIDI Representation





MIDI Representation



MIDI Representation

MIDI 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

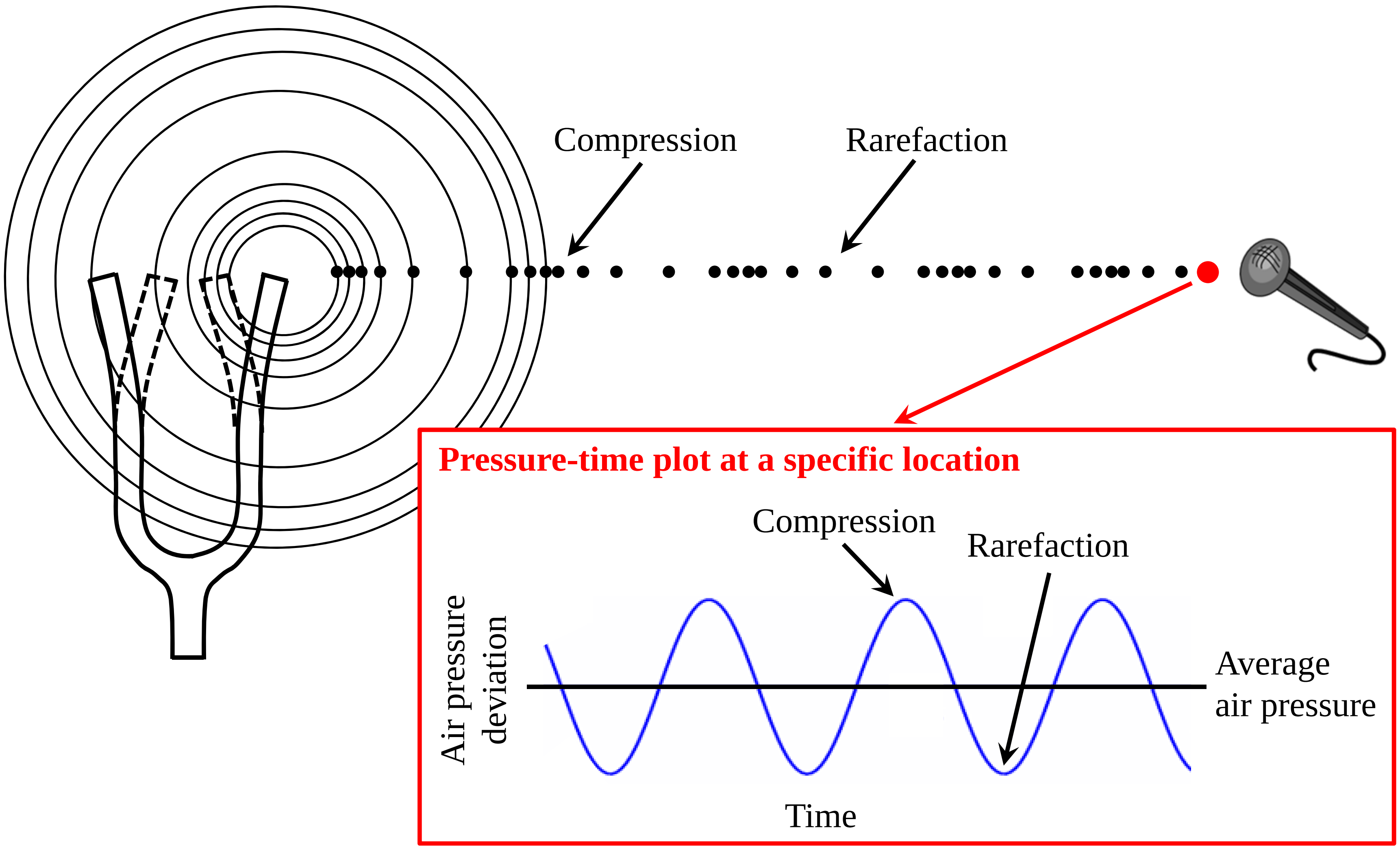
Audio Representation

Various interpretations – Beethoven's Fifth

Bernstein
Karajan
Scherbakov (piano)
MIDI (piano)

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

Pure tone (harmonic sound):

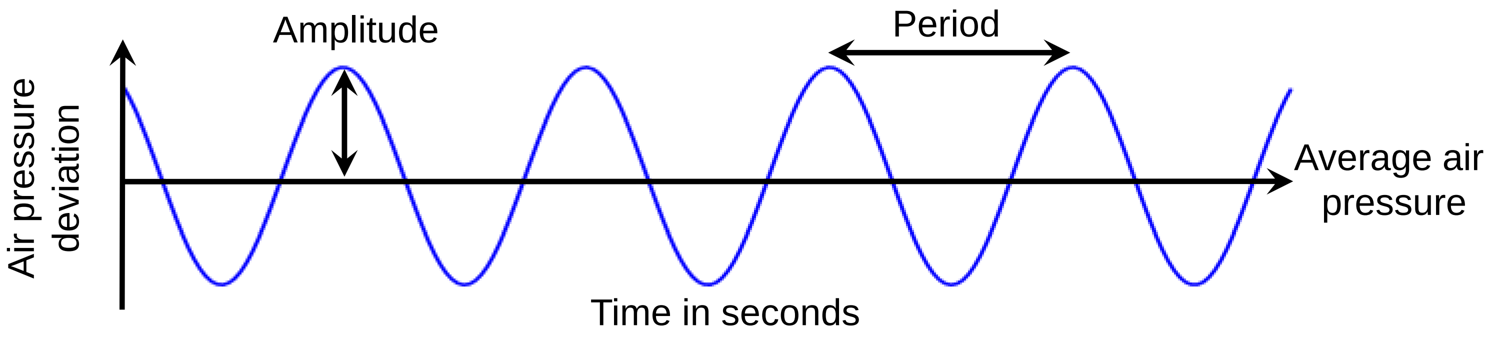
- Sinusoidal waveform
- Prototype of an acoustic realization of a musical note

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

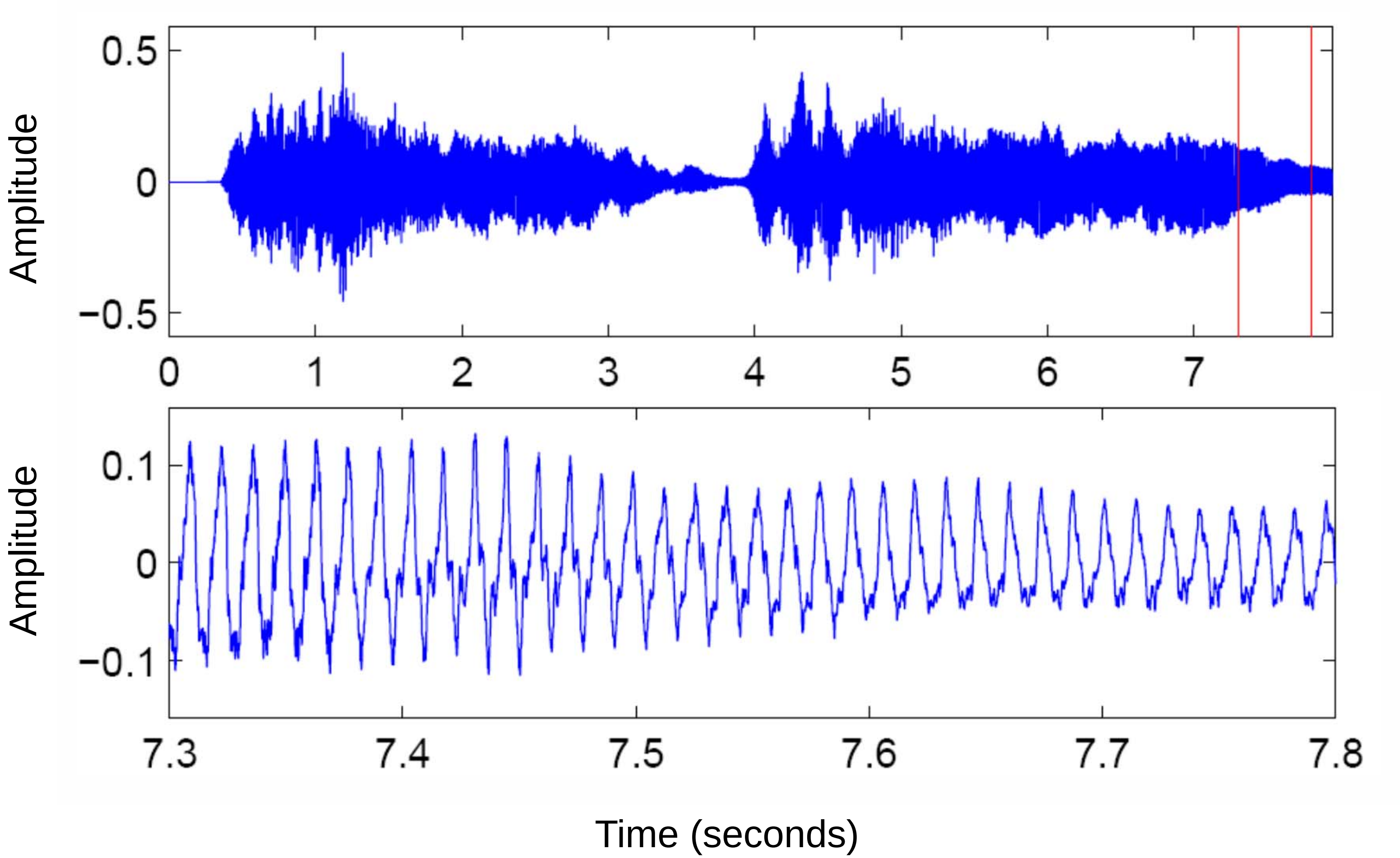
Audio Representation

Waveform



Audio Representation

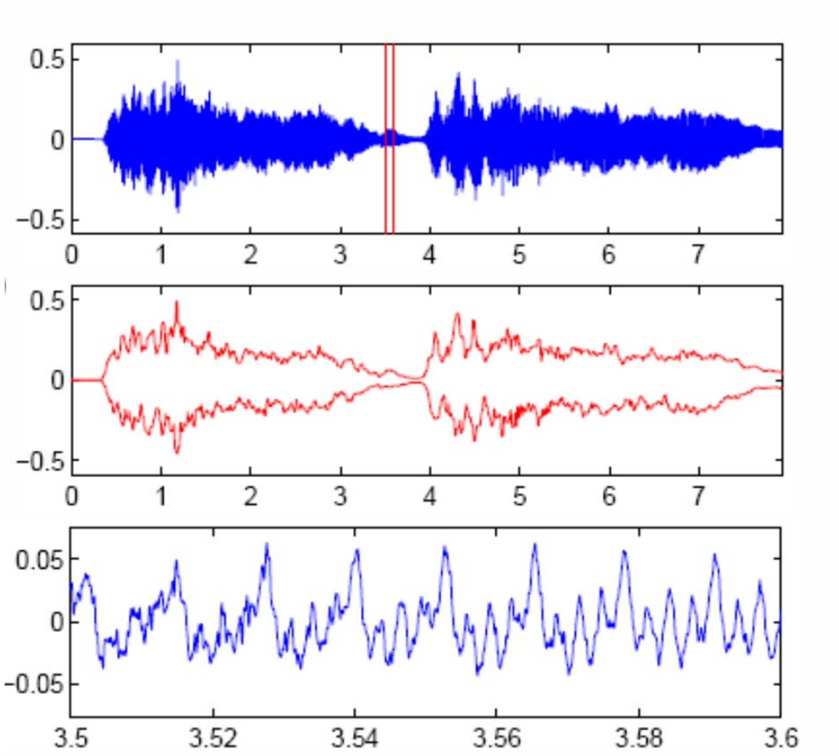
Waveform



Audio Representation

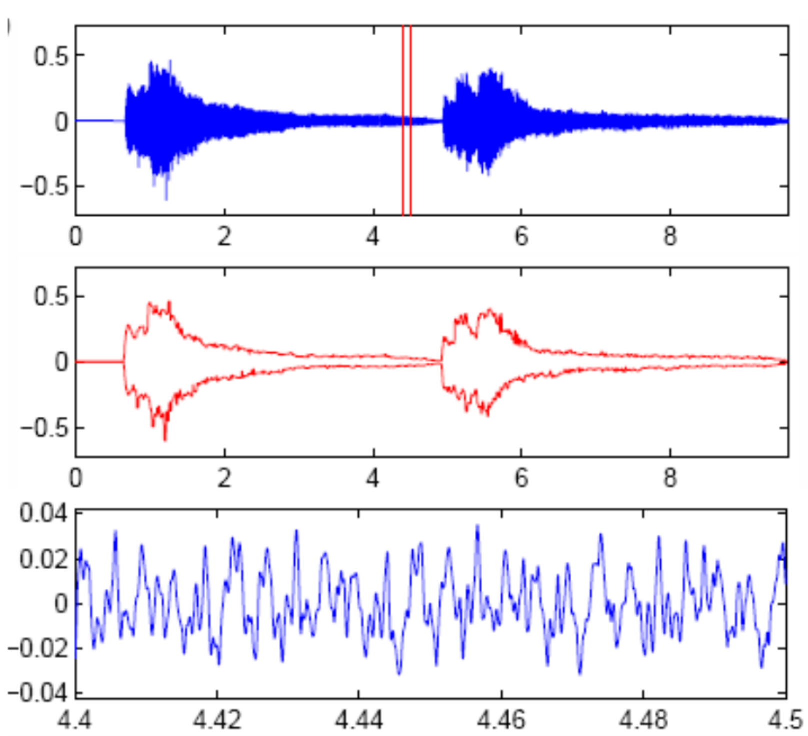
Waveform

Bernstein (orchestra)



Time (seconds)

Glen Gould (piano)



Time (seconds)

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 $\triangleq$ fundamental frequency (e.g. 440 Hz)
  2. Harmonic $\triangleq$ first overtone (e.g. 880 Hz)
  3. Harmonic $\triangleq$ second overtone (e.g. 1320 Hz)

Audio Representation

Pitch

- Property that correlates to the perceived frequency (≙ fundamental frequency)
- Example: middle A or 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 devided up into 12 logarithmically equal parts
- Notes correspond to piano keys $p = 21\ \text{(A0)}\ \ \text{to}\ \ p = 108\ \text{(C8)}$
- Referenz: standard pitch $p = 69\ \text{(A4)} \triangleq 440\ \text{Hz}$
- Frequency of a note with MIDI pitch p

$$f_{\text{MIDI}}(p) = 2^{\frac{p-69}{12}} \cdot 440$$

Audio Representation

Harmonics

Mix

Harmonics: Frequency = integer multiples of fundamental frequency

Deviation in cents: +2 -14 +2 -31 +4 -14 -49 +2 +41 -31 -12

MIDI: Frequency = fundamental frequency of MIDI pitch

Stereo file: Harmonics vs. MIDI

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

- $$intensity = \frac{energy}{time \cdot area} = \frac{power}{area} \qquad \left(\frac{W}{m^2}\right)$$
- Decibel (dB): logarithmic unit to measure intensity relative to a reference level
- Reference level: threshold of hearing (THO) $P_0 = 1 \cdot 10^{-12} \frac{W}{m^2}$
- Intensity P_1 measured in dB: $dB(P_1) = 10 \cdot \log_{10}\left(\frac{P_1}{P_0}\right)$
- Examples:

$$P_1 = 10 \cdot P_0 \rightarrow P_1 \text{ has a sound level of } 10\, dB$$

$$P_2 = 100 \cdot P_0 \rightarrow P_2 \text{ has a sound level of } 20\, dB$$

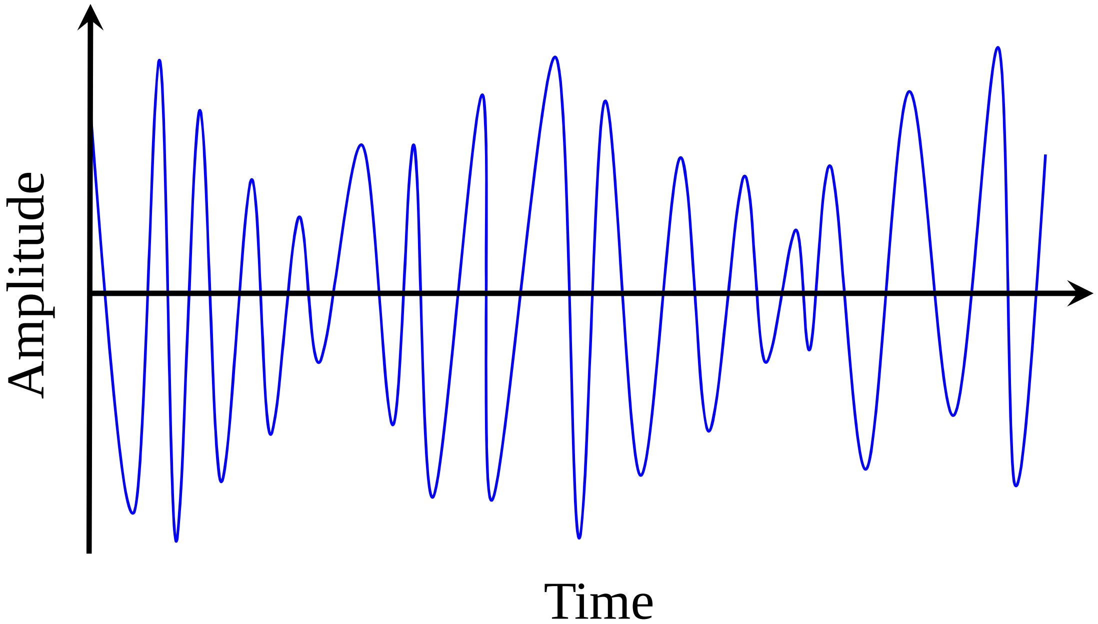
Audio Representation

Dynamics

Source	Intensity	Intensity level	× TOH
Threshold of hearing (TOH)	10^{-12}	**0 dB**	0
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}

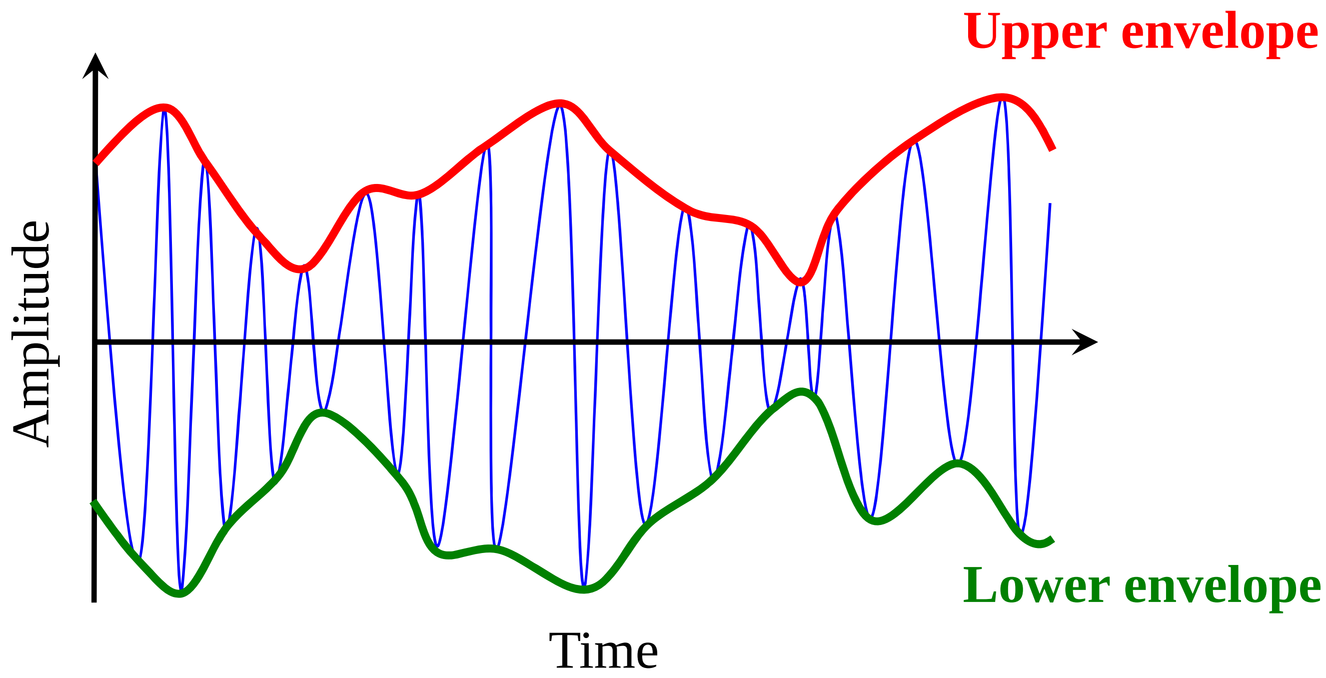
Audio Representation

Dynamics



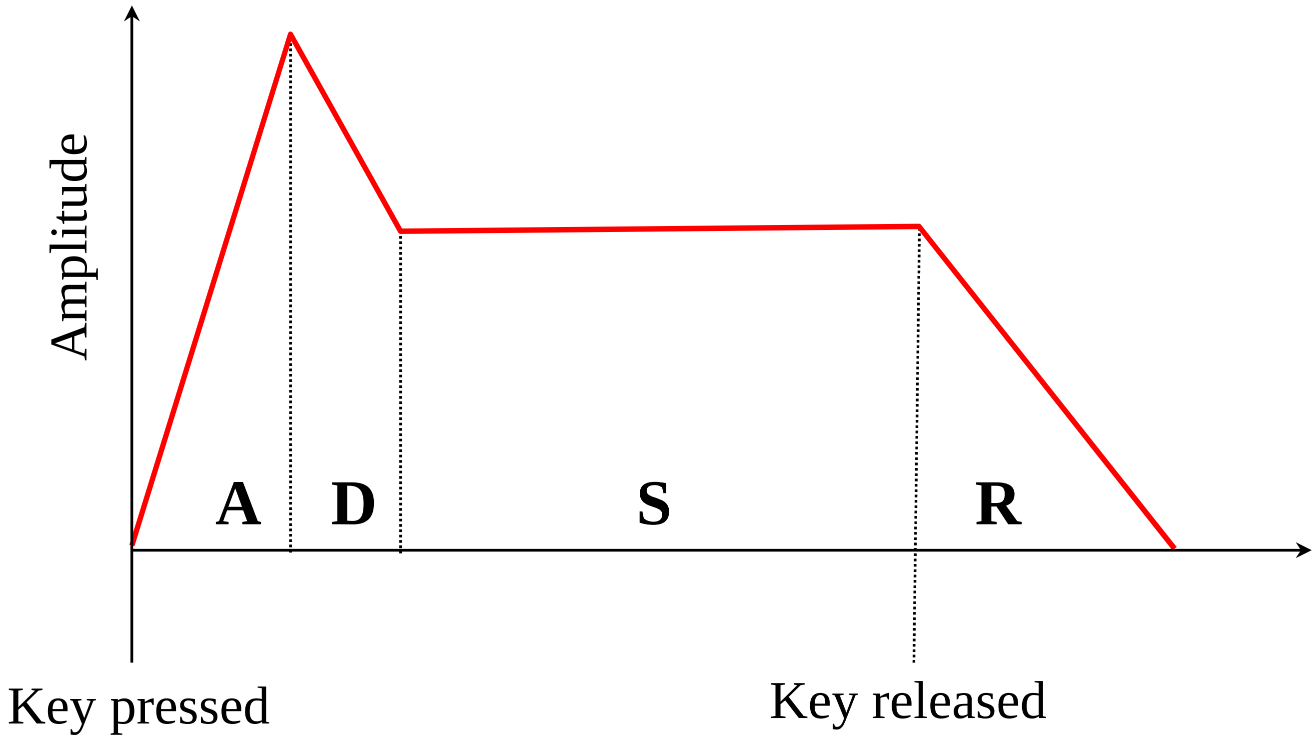
Audio Representation

Dynamics



Audio Representation

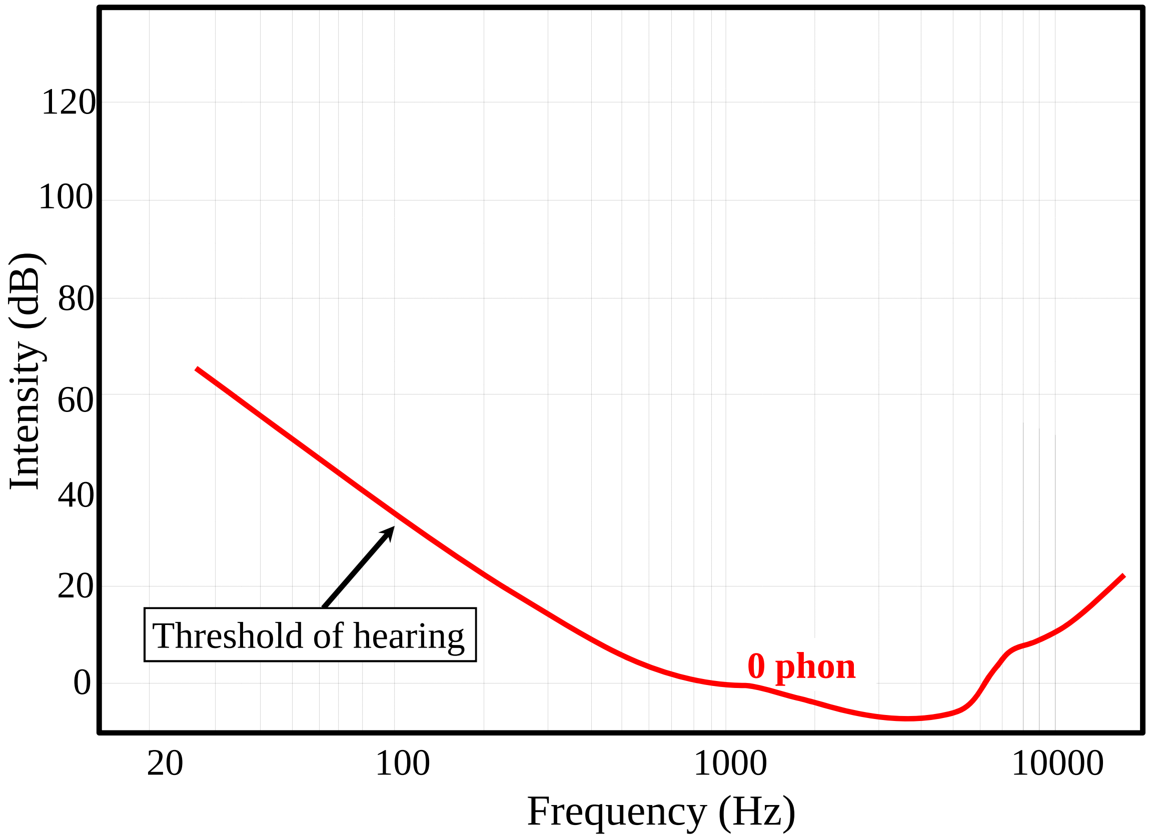
Dynamics



Audio Representation

Loudness

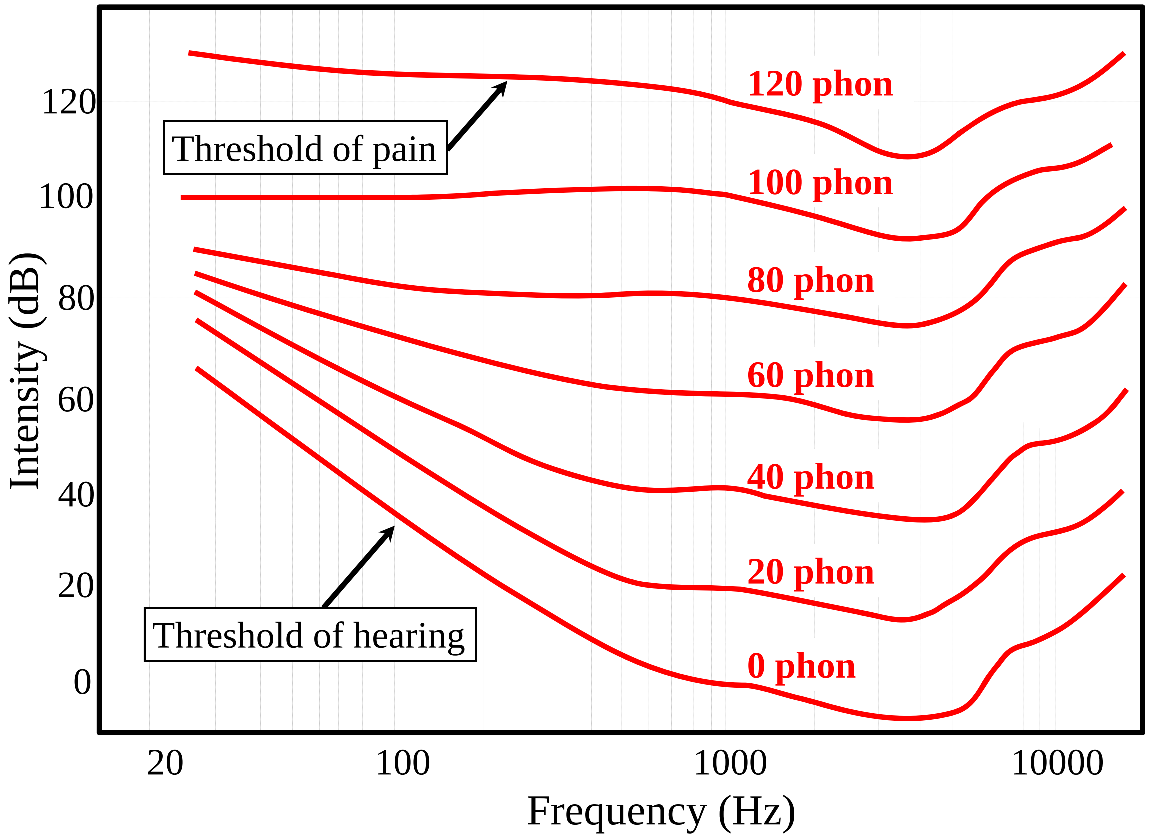
Equal-loudness contours (phon)



Audio Representation

Loudness

Equal-loudness contours (phon)



Audio Representation

Timbre

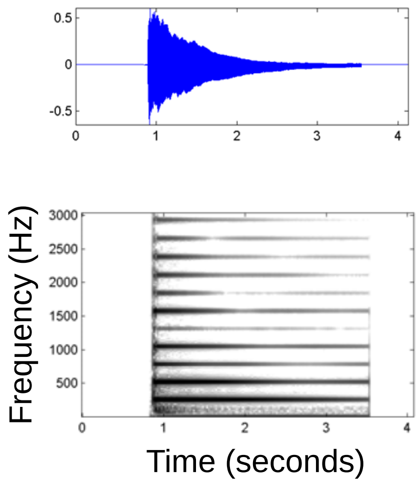
- Quality of musical sound that distinguishes different types of sound production such as voices or instruments
- Tone quality
- Tone color
- Depends on energy distribution in harmonics

Audio Representation

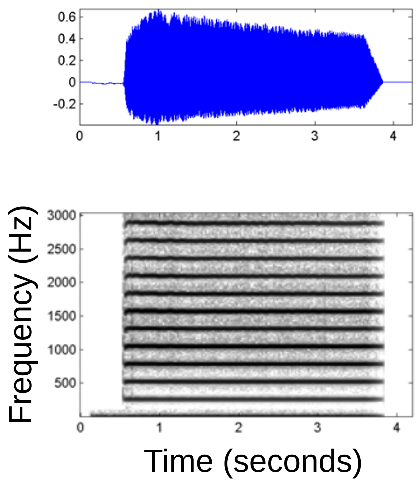
Timbre

All instruments play the same note C4 (261.6 Hz)

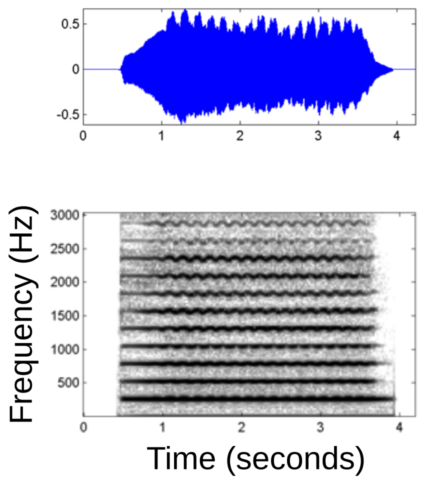
Piano



Trumpet

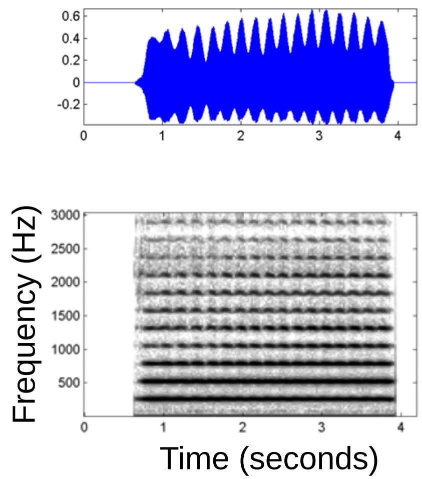


Violine



Vibrato: Frequency modulation

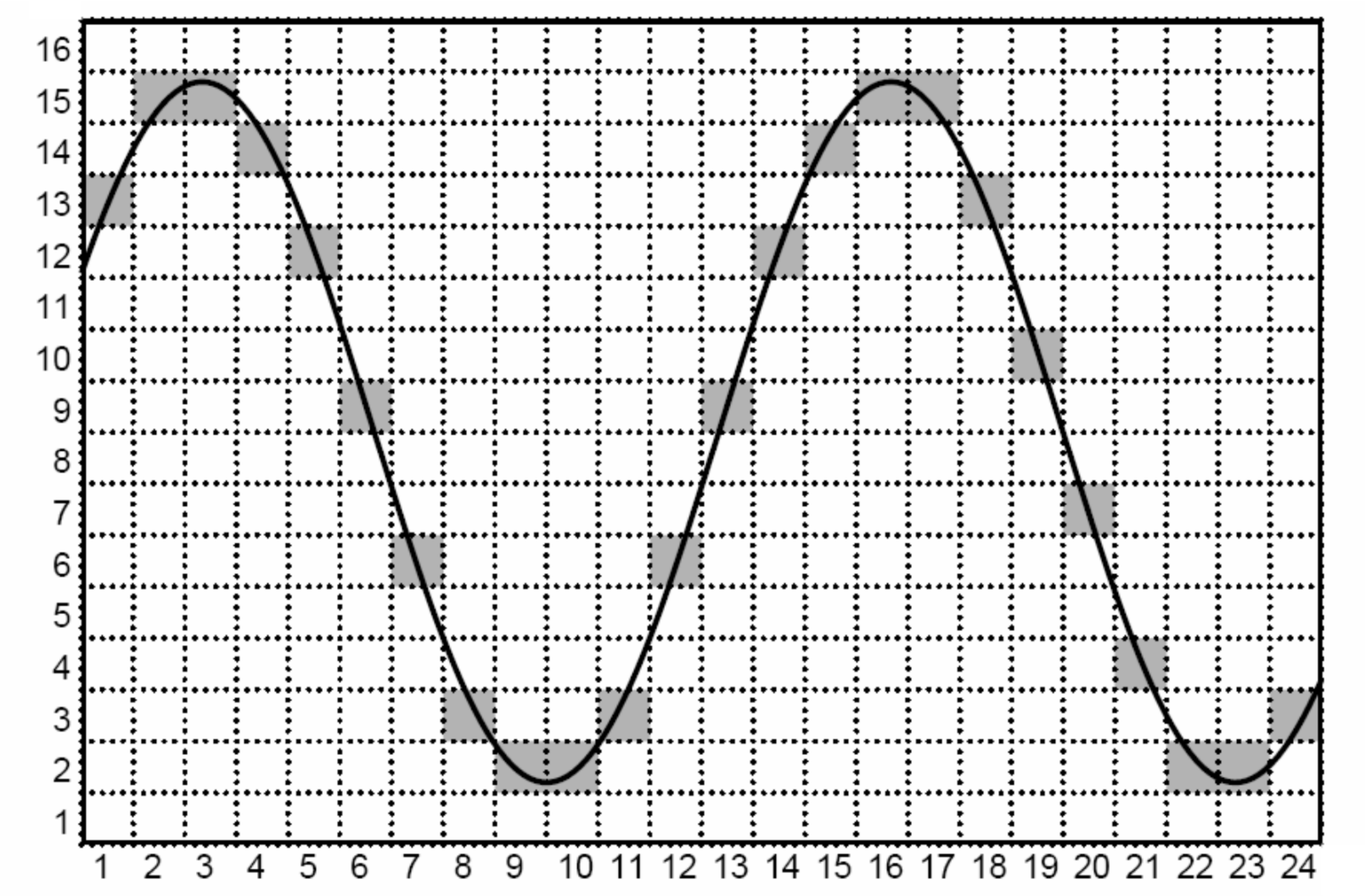
Flute



Tremolo: Amplitude modulation

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