Hochschule für Musik Karlsruhe

Blockvorlesung

Advanced Audio-Based Music Processing
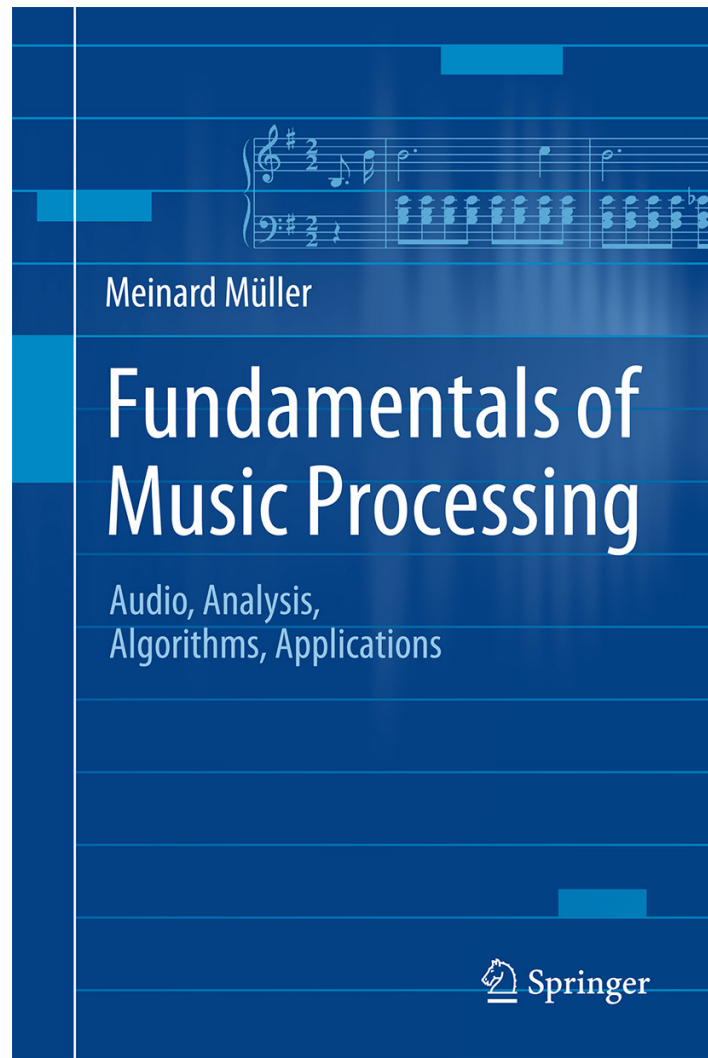
1. Music Representations

Christof Weiß, Frank Zalkow, Meinard Müller

International Audio Laboratories Erlangen

christof.weiss@audiolabs-erlangen.de
frank.zalkow@audiolabs-erlangen.de
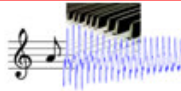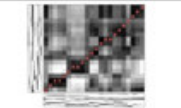meinard.mueller@audiolabs-erlangen.de

FAU FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

University of Music Hochschule für Musik Karlsruhe
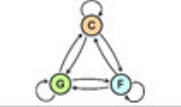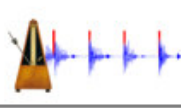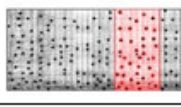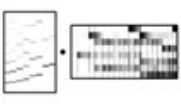
Fraunhofer IIS

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

Book: Fundamentals of Music Processing

Chapter		Music Processing Scenario
1		Music Represenations
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
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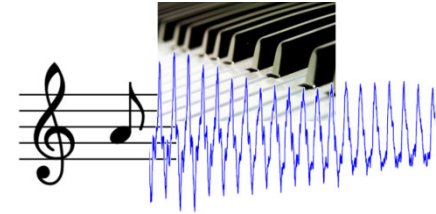ISBN: 978-3-319-21944-8
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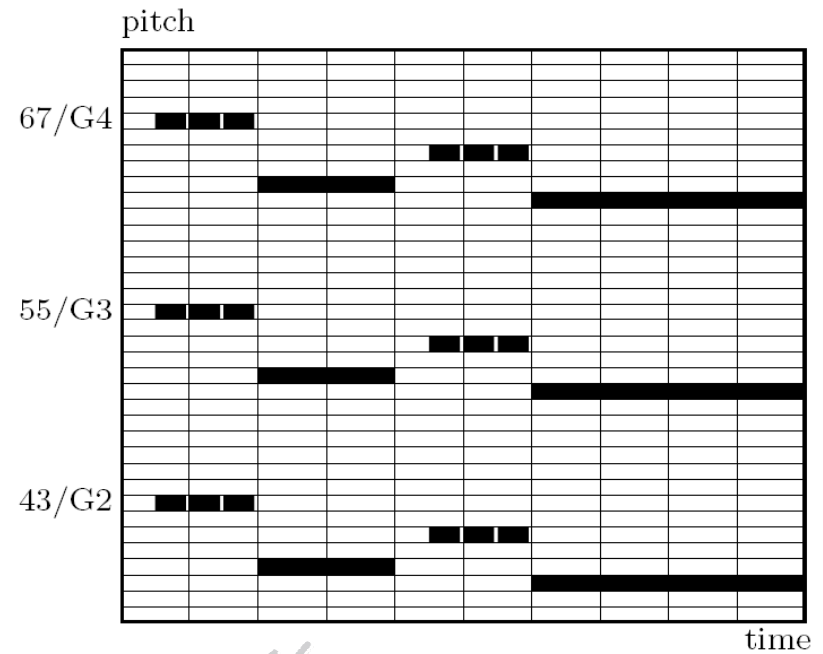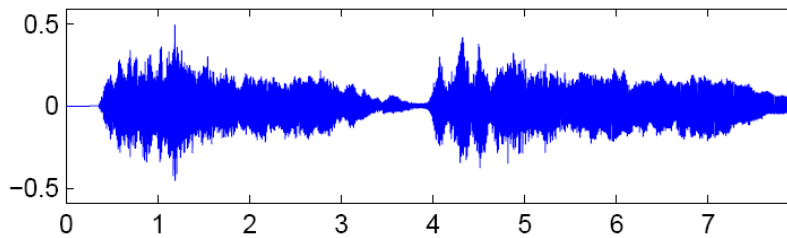
Chapter 1: Music Representations

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

Music Representations

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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
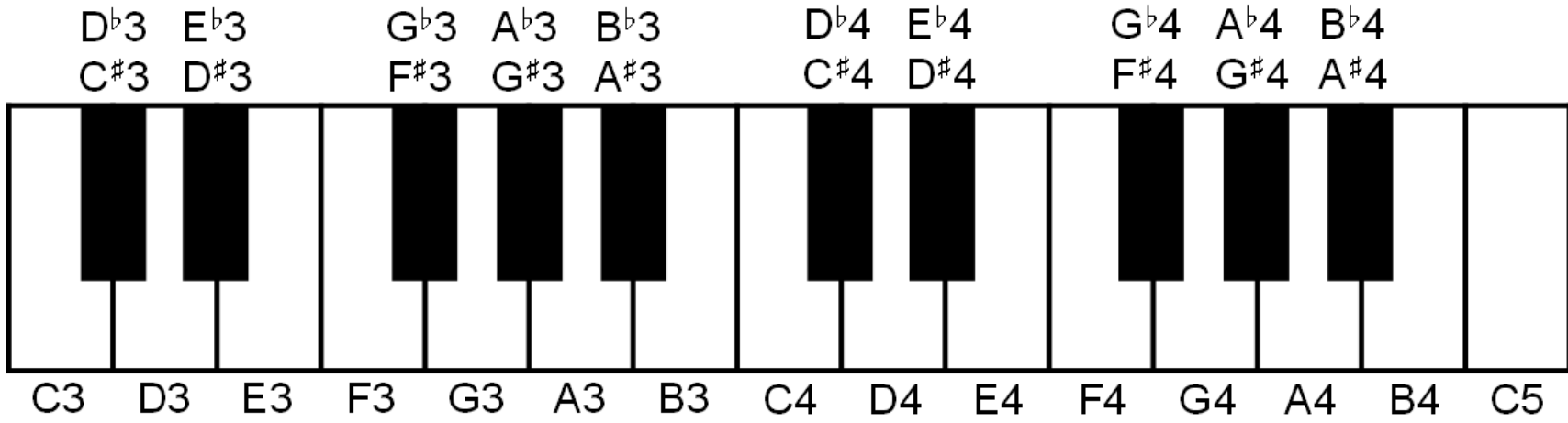
Sheet Music Representation

Sheet Music Representation
Piano keyboard and notes

Sheet Music Representation
Piano keyboard and notes
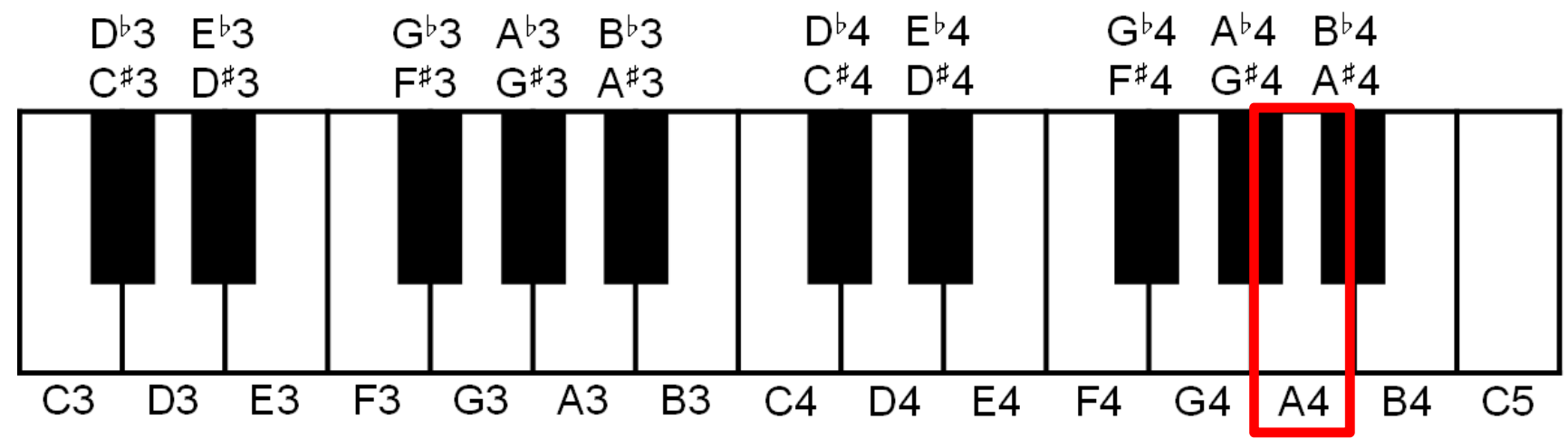
A ≜ pitch class
4 ≜ octave number

Sheet Music Representation
Piano keyboard and notes
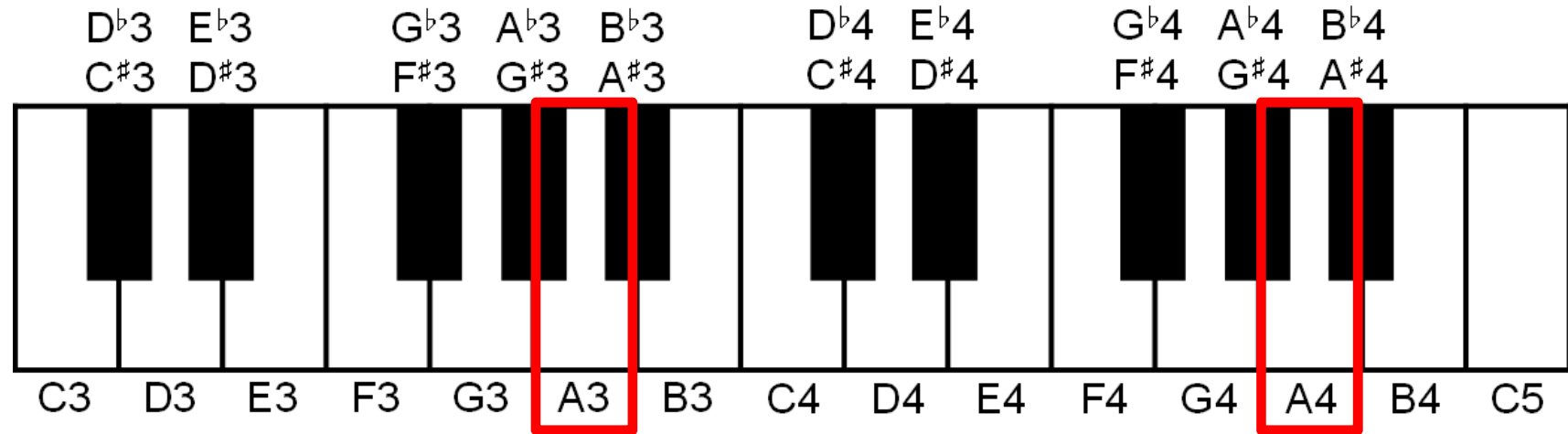
A ≜ pitch class

4 ≜ octave number

Sheet Music Representation

Chromatic circle

Chroma ≜ pitch spelling attribute
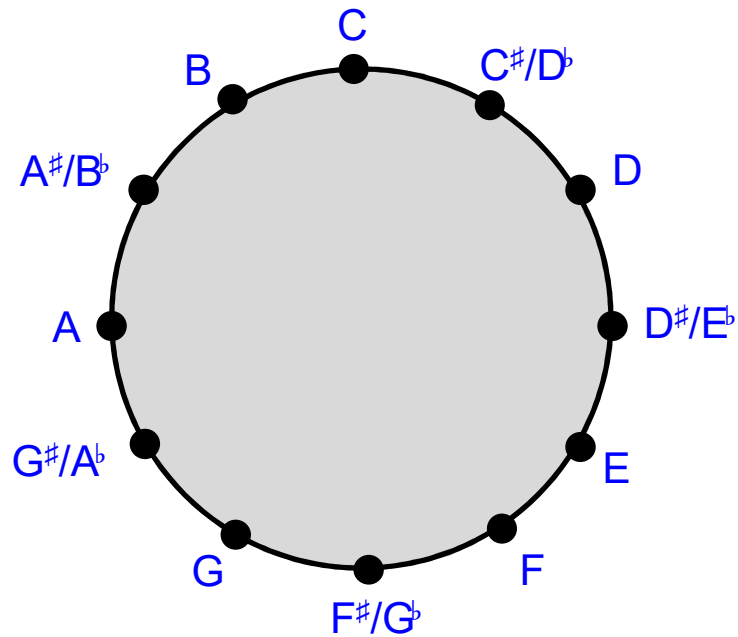
Shepard's helix of pitch

Tone height ≜ octave number

Sheet Music Representation

Staff

Lines ⟷ 5 / 4 / 3 / 2 / 1 ⟷ Spaces

Staff with G-clef

← G4

Staff with F-clef

← F3

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
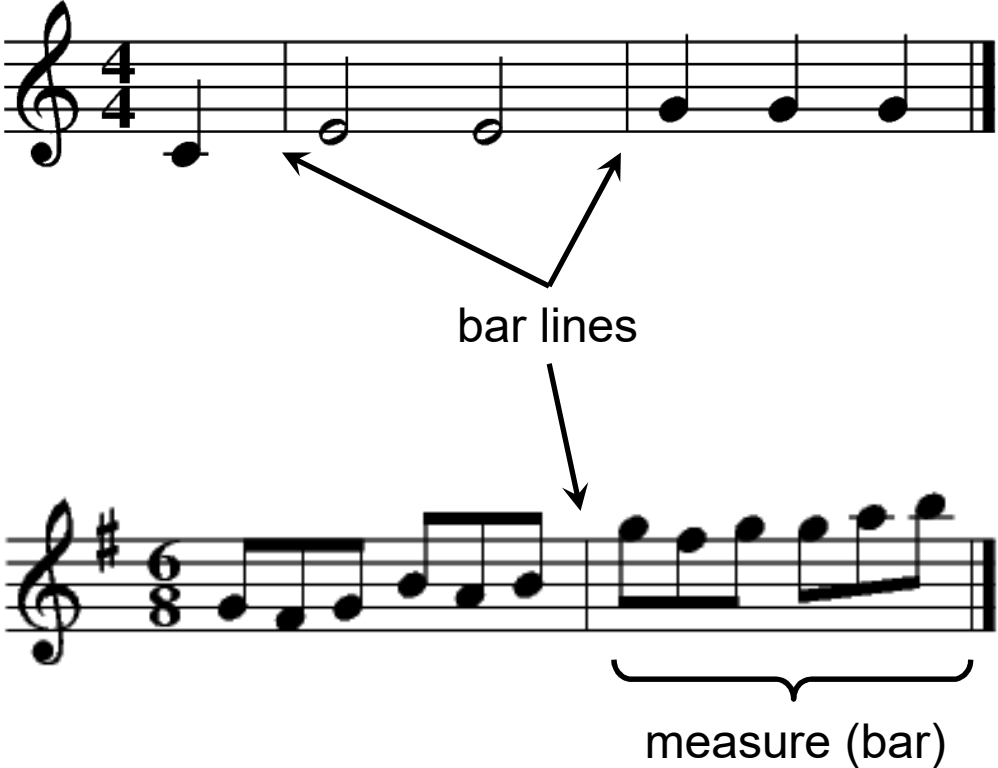
Sheet Music Representation
Time signature

Four quarter notes per measure
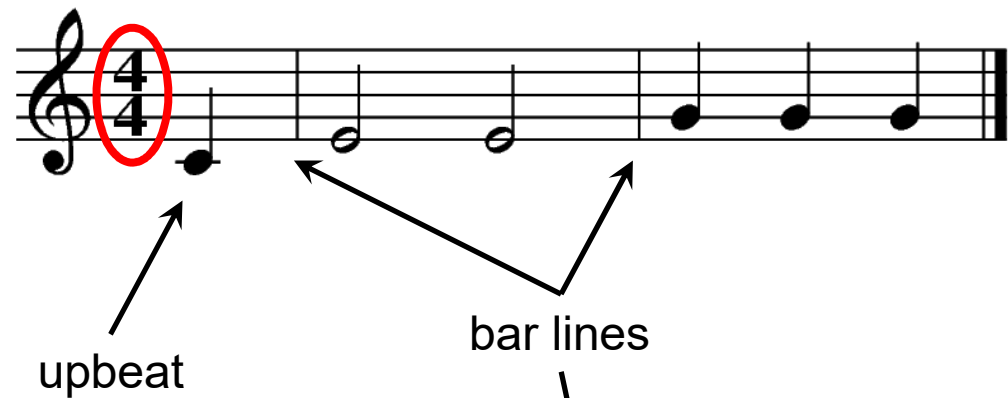
Six eighth notes per measure

upbeat

bar lines

measure (bar)

Sheet Music Representation
Note durations

Parts of a note
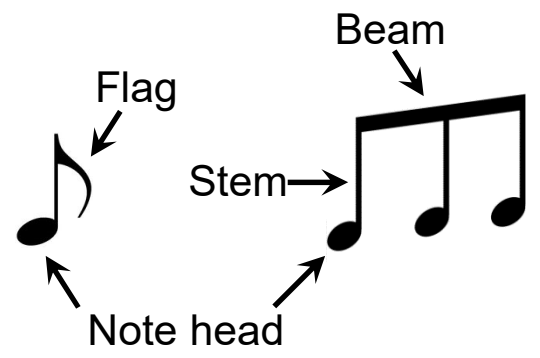
Flag

Beam

Stem →

Note head

Different durations of notes

Whole note	Half note	Quarter note	Eighth note	Sixteenth note

Different durations of rests

Whole rest	Half rest	Quarter rest	Eighth rest	Sixteenth rest

Sheet Music Representation
Staff systems

Piano

Strings

Right hand

Left hand

Violin

Viola

Violoncello

Sheet Music Representation
Dynamics and articulation

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 fews staves

- Lead sheet: specifies only melody, lyrics and harmonies (chord symbols); used for popular music to capture essential elements of a song

Sheet Music Representation

Music Representations

- Sheet music representation

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- **Symbolic representations**

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- Audio representation

  - physical description

  - encoding of sound wave

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
Optical Music Recognition
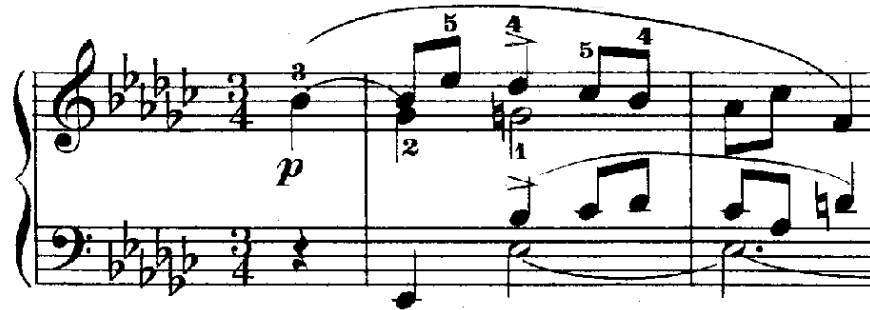
Original score

OMR score

Symbolic Representation
Optical Music Recognition

Original score
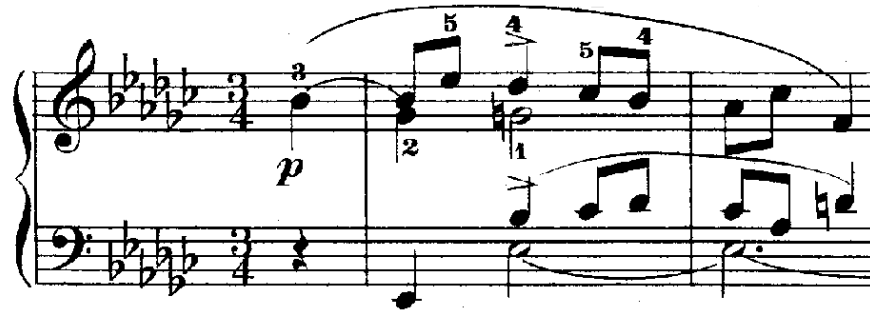
OMR score

OMR errors

Symbolic Representation
Piano roll representation
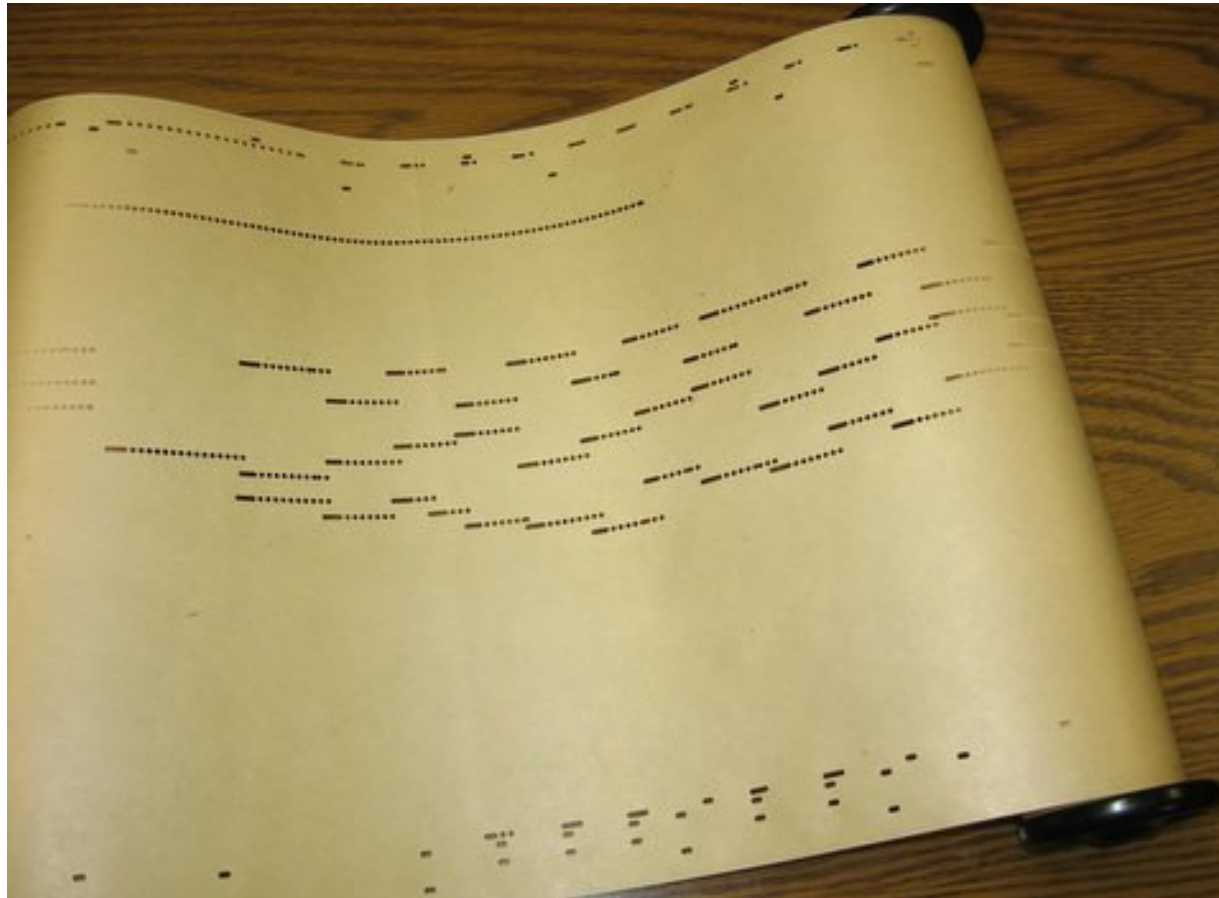
Symbolic Representation
Piano roll representation

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
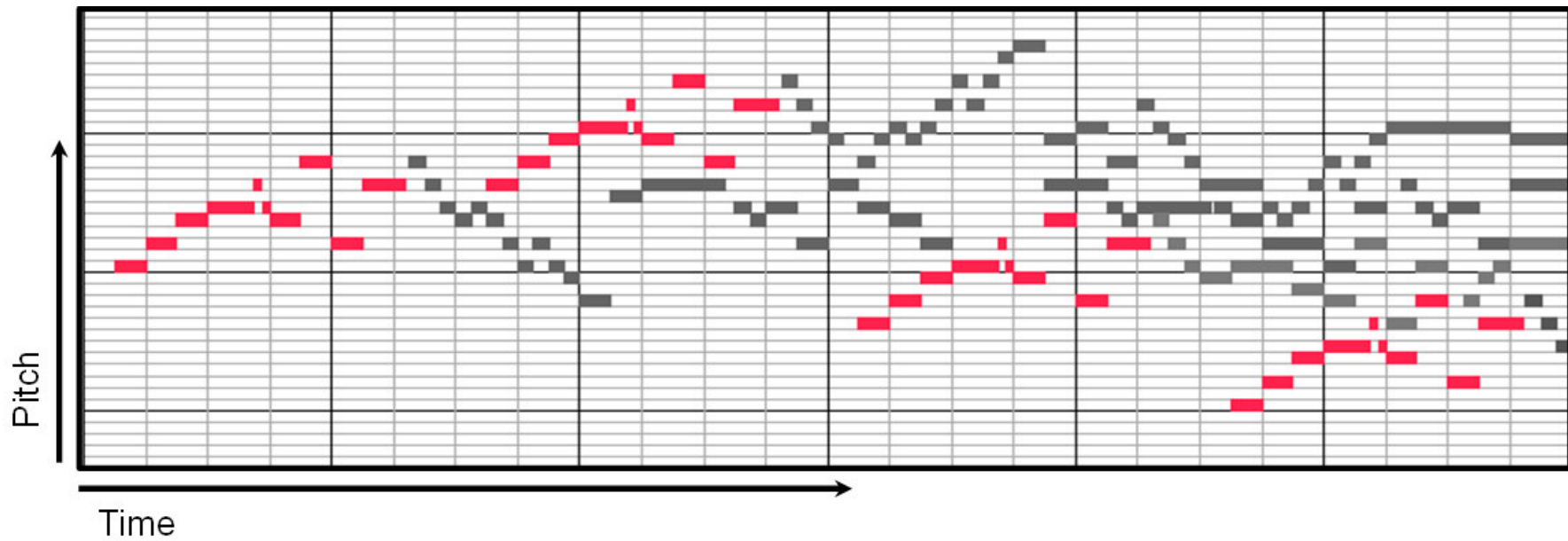
Symbolic Representation
Piano roll representation
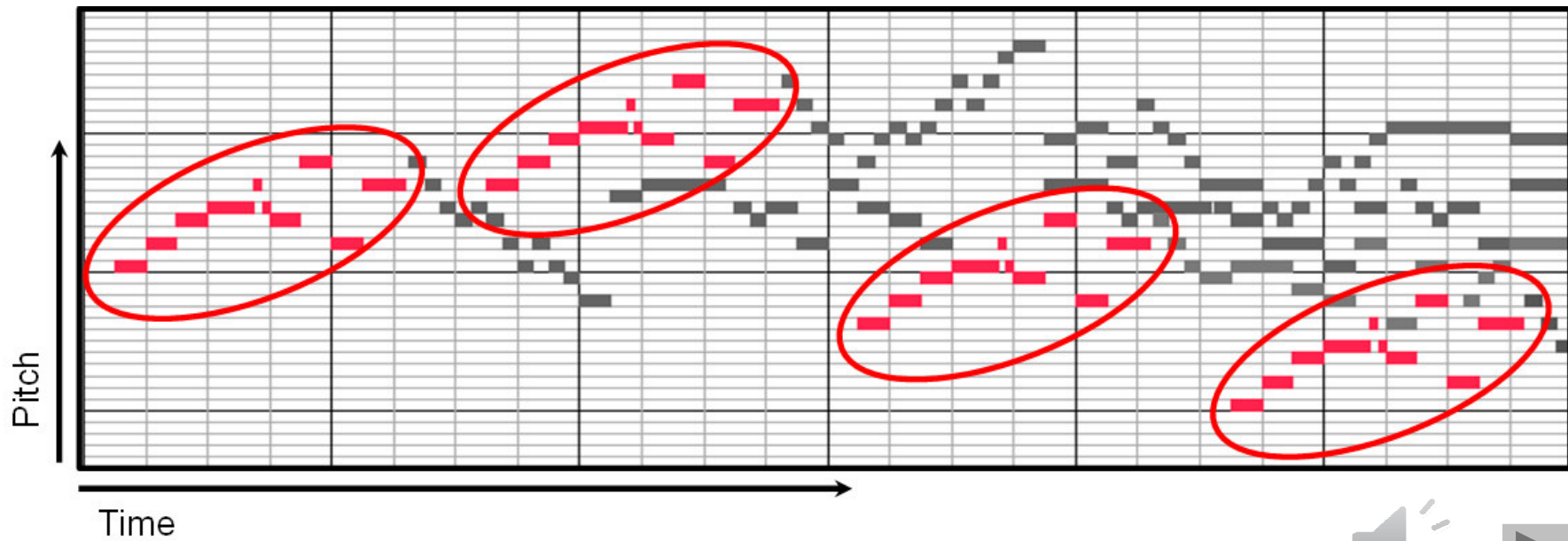
Symbolic Representation
MIDI representation

- 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
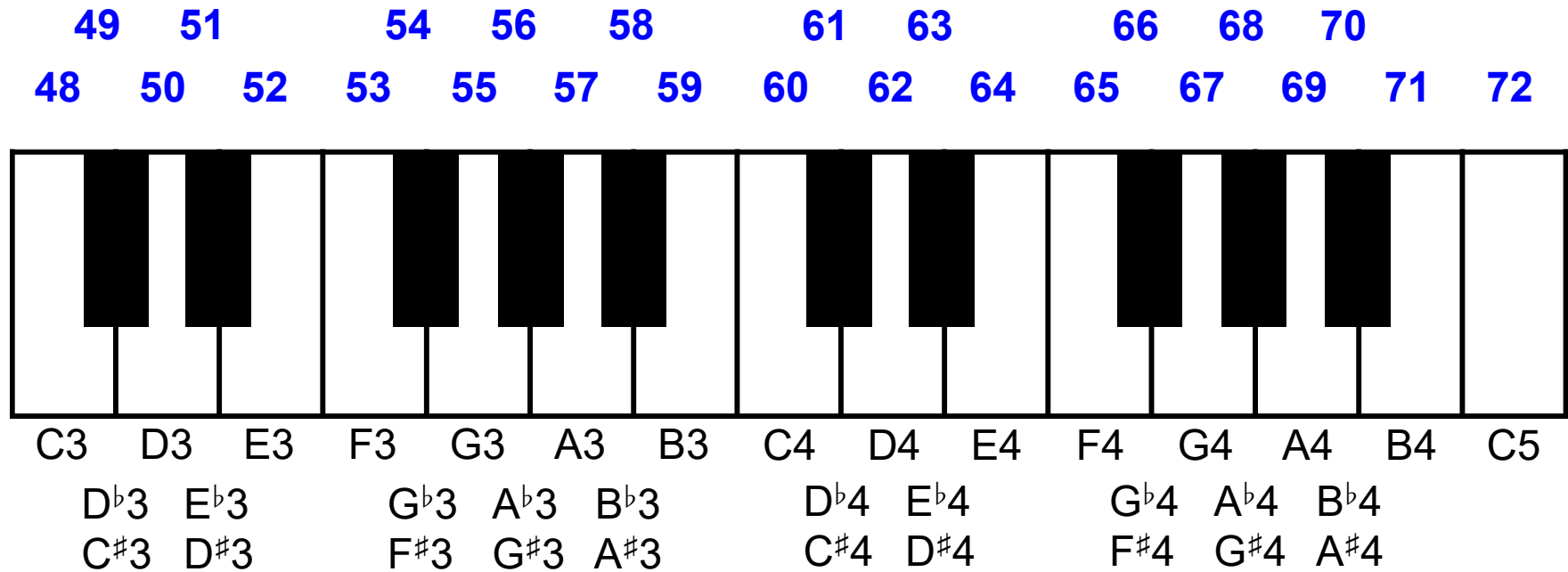
Symbolic Representation
MIDI representation

- 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
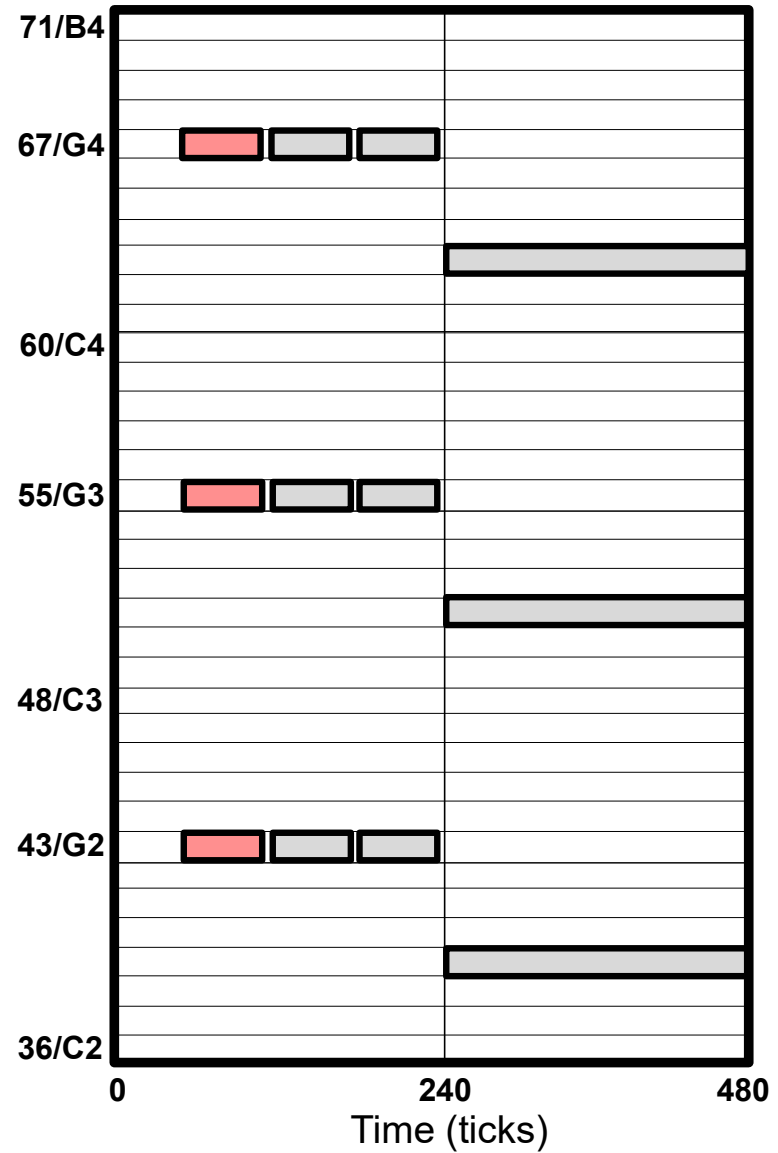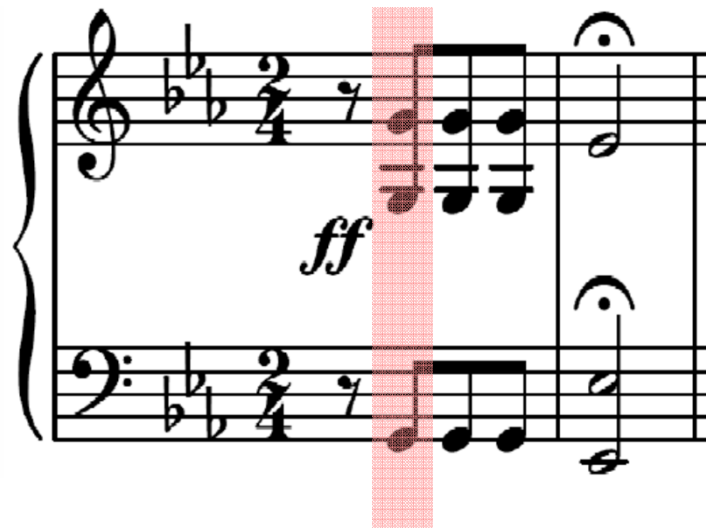
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  - encoding of sound wave

Audio Representation

Various interpretations – Beethoven's Fifth
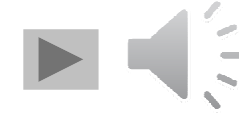
Bernstein	▶ 🔊
Karajan	▶ 🔊
Scherbakov (piano)	▶ 🔊
MIDI (piano)	▶ 🔊

Audio Representation
Waveform

Compression

Rarefaction

Audio Representation
Waveform

Compression   Rarefaction

Pressure–time plot at a specific location

Compression   Rarefaction

Air pressure deviation

Average air pressure
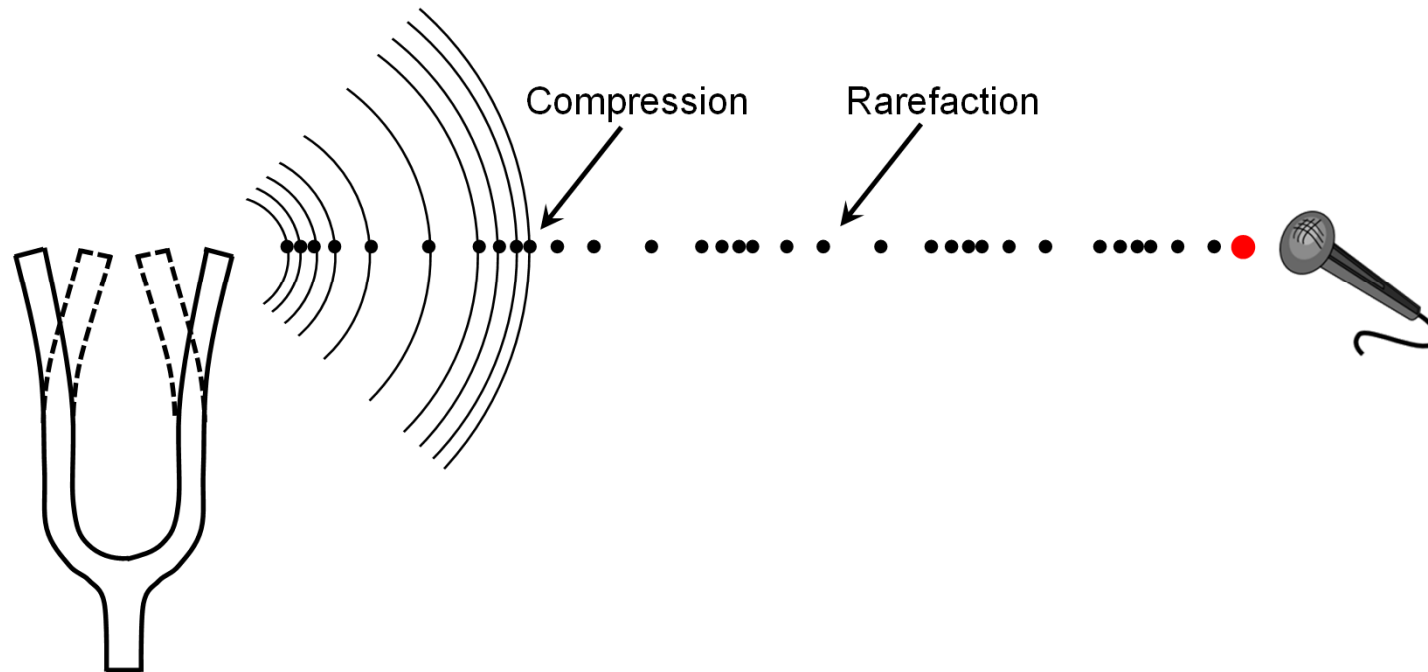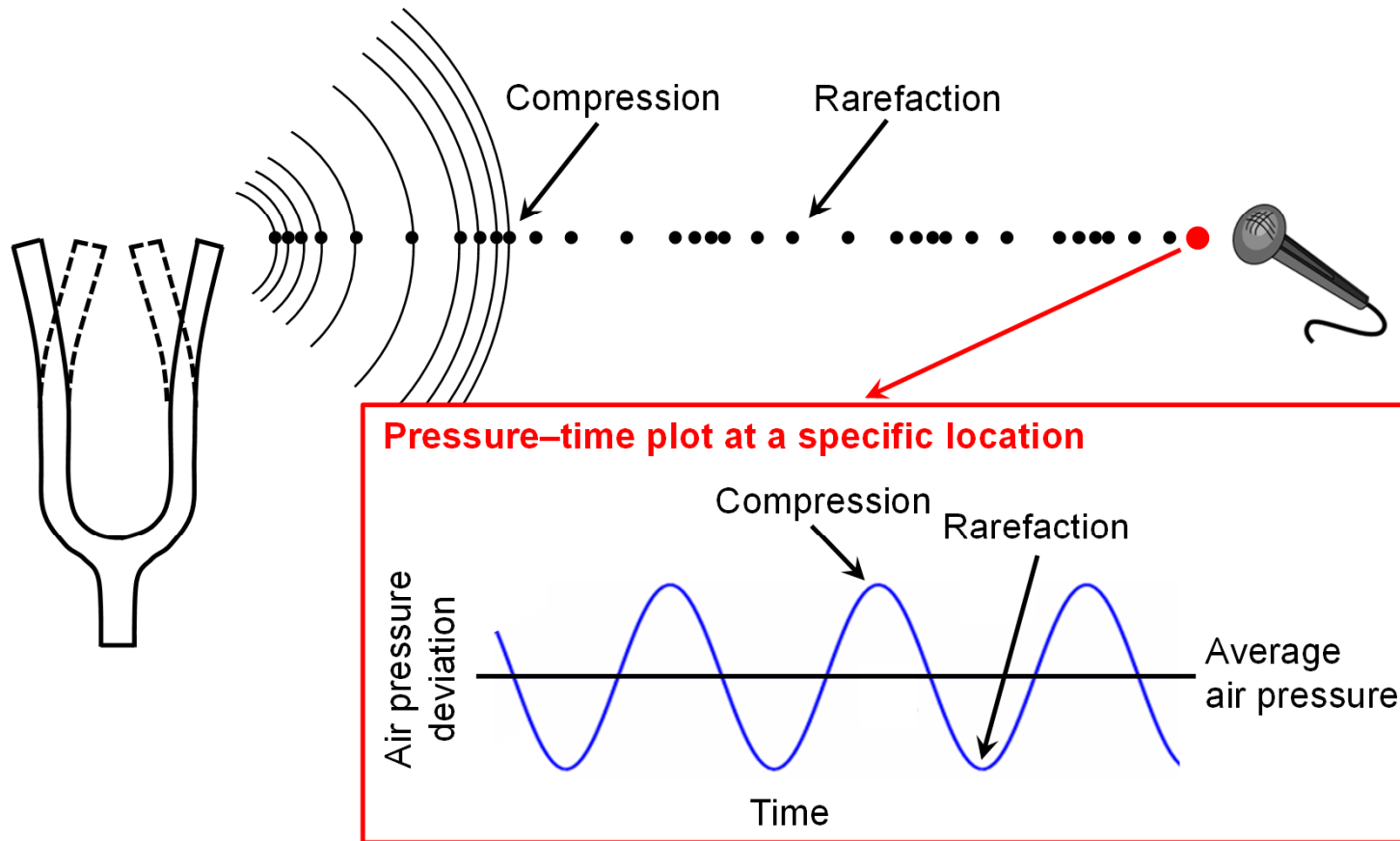
Time

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
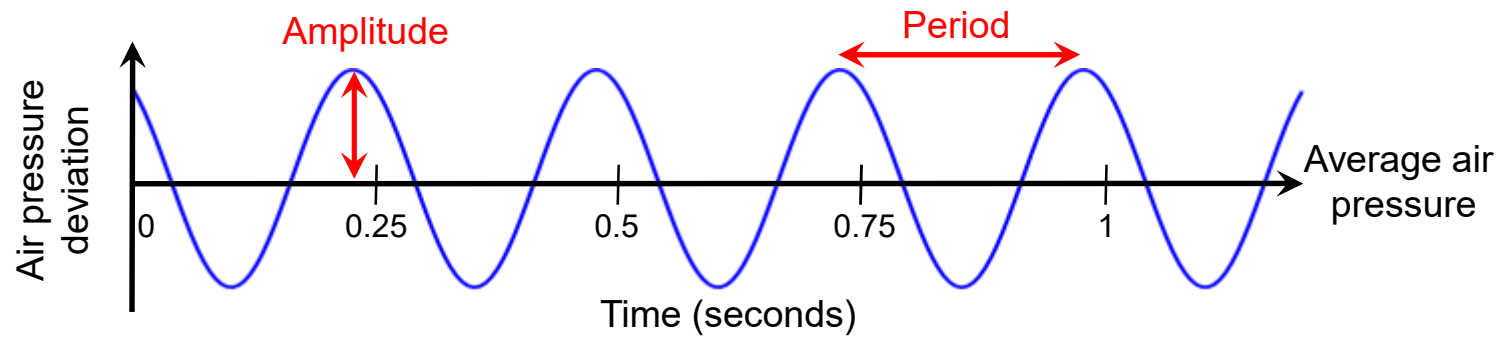
Audio Representation
Waveform

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 $= \dfrac{1}{p}$ (measured in Hz)

- Amplitude a : air pressure at high pressure points

Audio Representation
Waveform
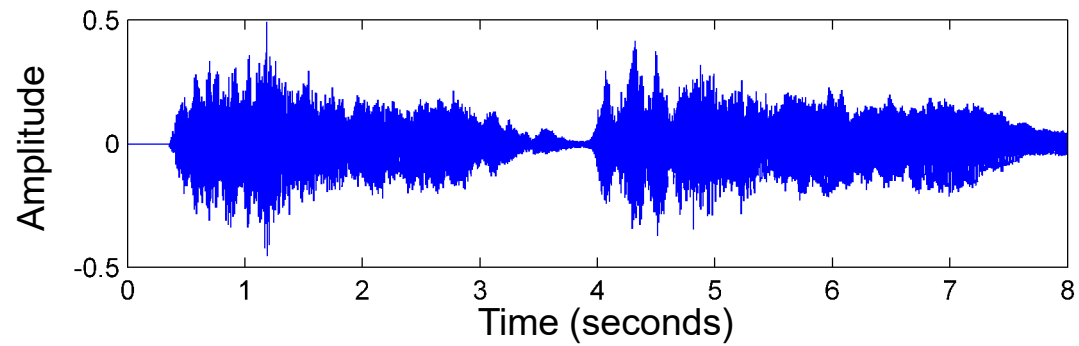
Audio Representation
Waveform
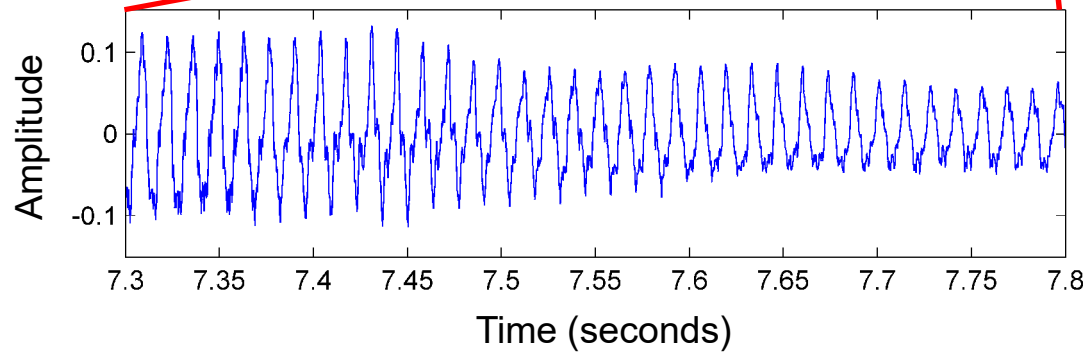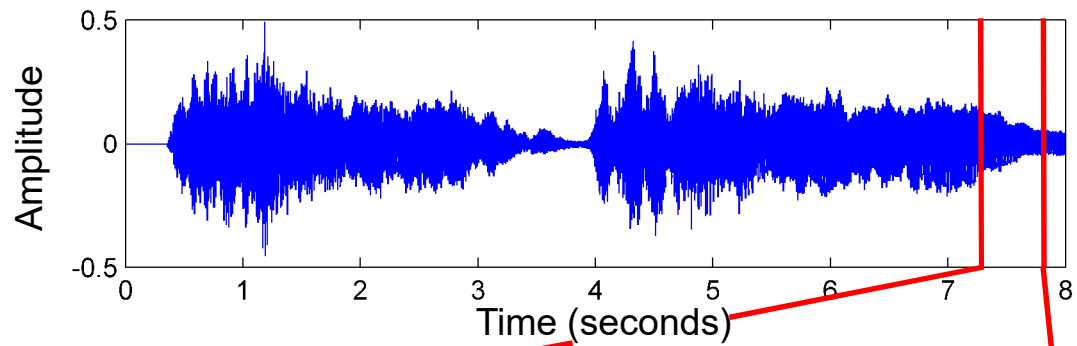
D2 (73.4 Hz)

Audio Representation
Waveform
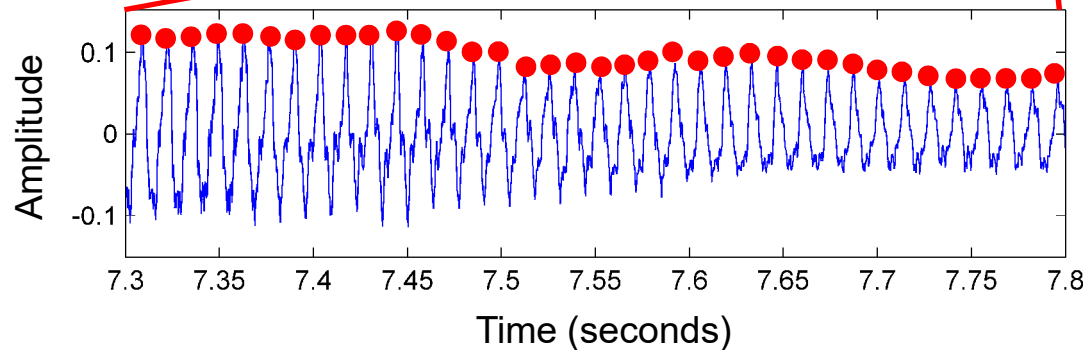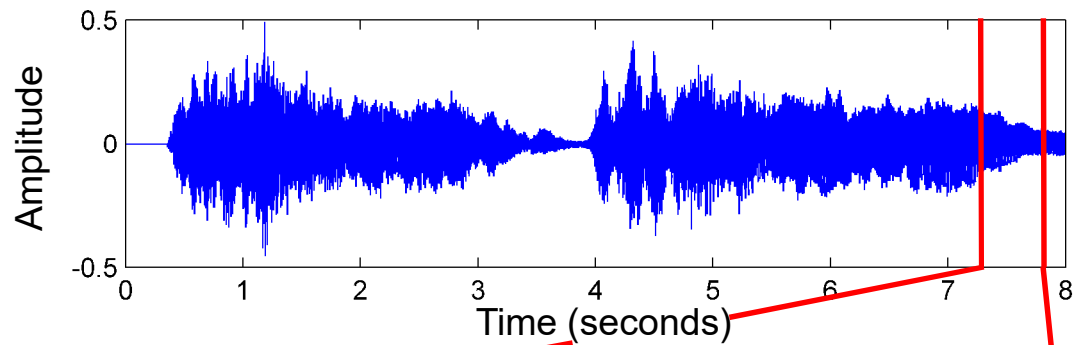
D2 (73.4 Hz)

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
  ($\triangleq$ fundamental frequency)

- Example: A4 (also called concert pitch) $\triangleq$ 440 Hz

- Slight changes in frequency have no effect on
  perceived pitch (pitch $\triangleq$ entire range of frequencies)

- Pitch perception: logarithmic in frequency
  Example: octave $\triangleq$ 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)

- Reference or standard pitch: $p = 69$ (A4) $\triangleq$ 440 Hz

- Center frequency of a note with MIDI pitch p

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

Audio Representation
Pitch

- **Semitone:** difference between two subsequent scale steps

- Ratio of frequencies one semitone apart is constant:

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

- **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

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

Mix

octave   fifth   major third

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

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

- Decibel (dB): logarithmic unit to measure intensity relative to a reference level

- Reference level: threshold of hearing (THO) $\quad I_{\text{TOH}} := 10^{-12} \, \text{W}/\text{m}^2$

- Intensity I measured in dB: $\qquad \text{dB}(I) := 10 \cdot \log_{10}\left(\dfrac{I}{I_{\text{TOH}}}\right)$

- Examples:

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

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

Audio Representation
Dynamics

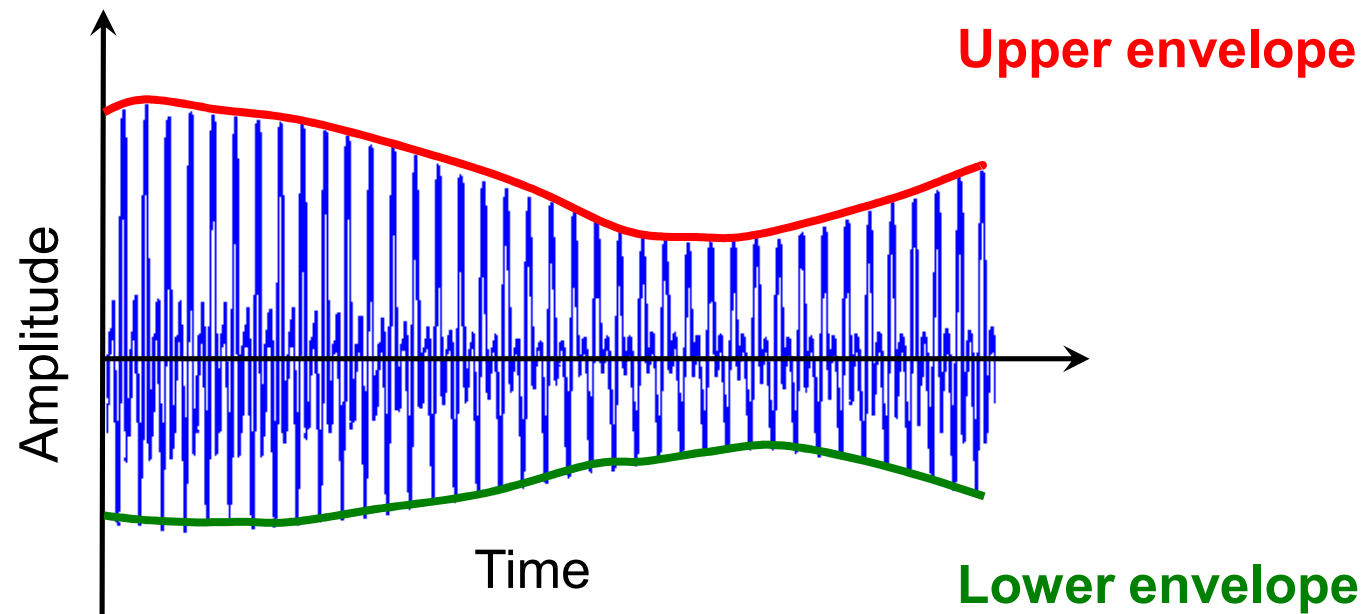| Source	Intensity	Intensity level	× TOH
Threshold of hearing (TOH)	10^{-12}	**0 dB**	1
Whisper	10^{-10}	**20 dB**	10^2
Pianissimo	10^{-8}	**40 dB**	10^4
Normal conversation	10^{-6}	**60 dB**	10^6
Fortissimo	10^{-2}	**100 dB**	10^{10}
Threshold of pain	10	**130 dB**	10^{13}
Jet take-off	10^2	**140 dB**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

Audio Representation
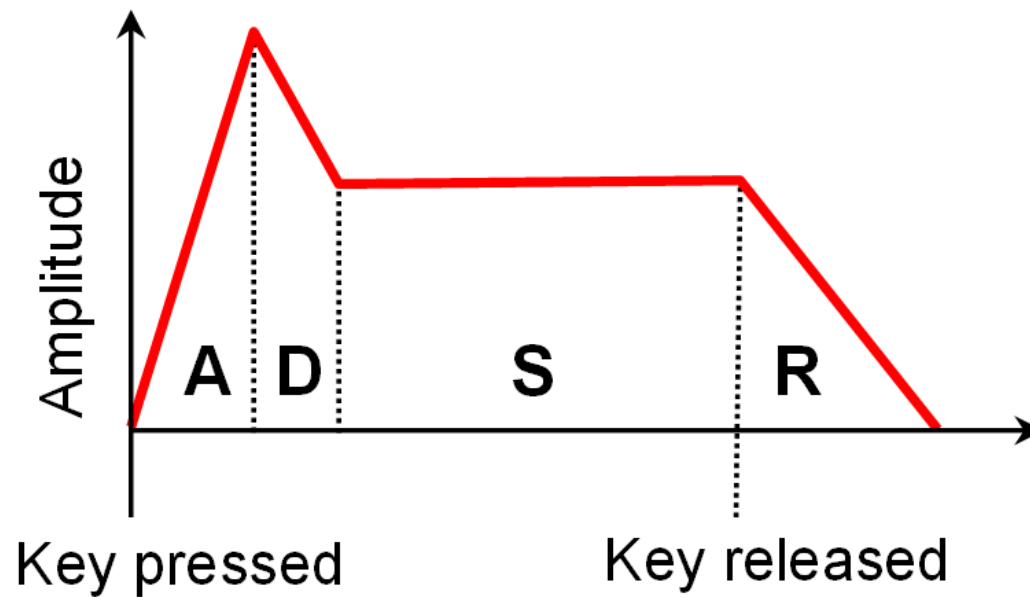## Dynamics
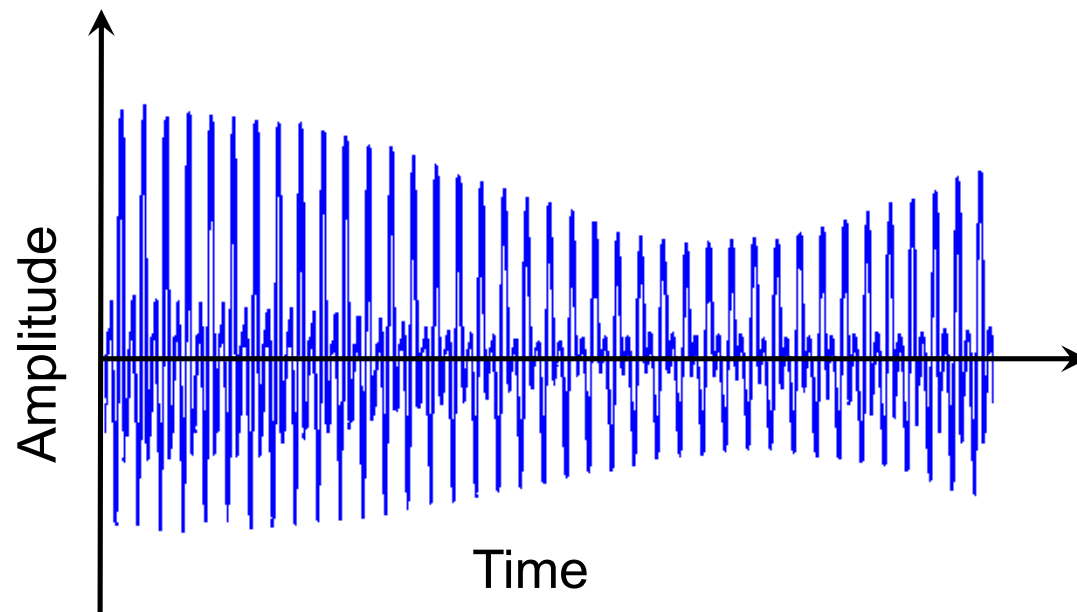
Audio Representation
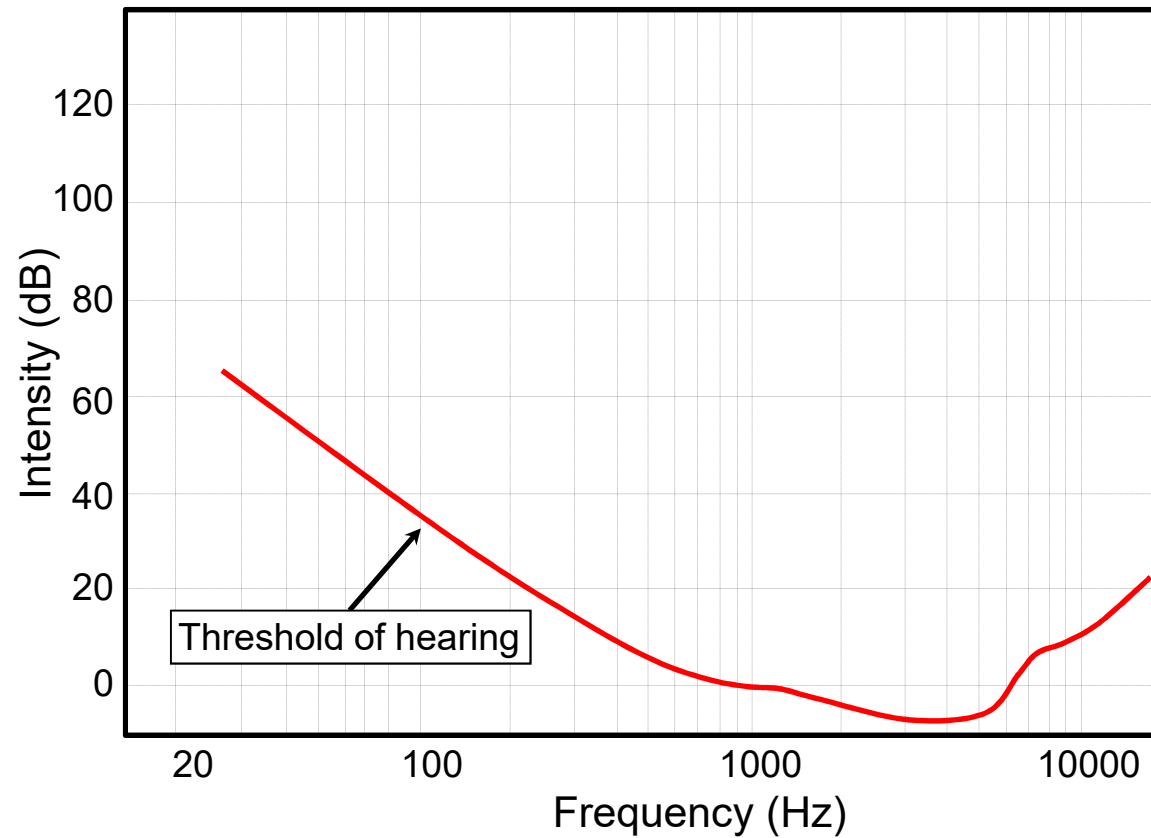## Dynamics

Audio Representation
Dynamics

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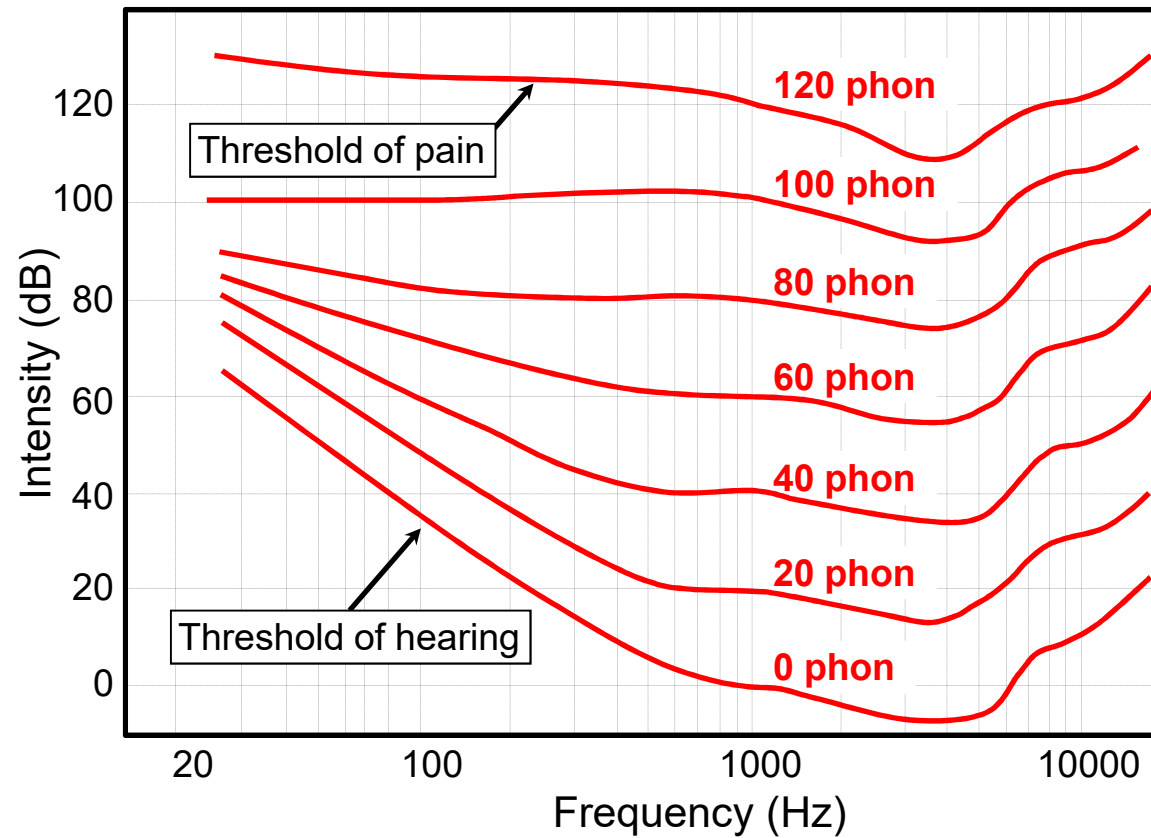
Audio Representation
Loudness

Equal-loudness contours (phon)

Audio Representation
Loudness

Equal-loudness contours (phon)
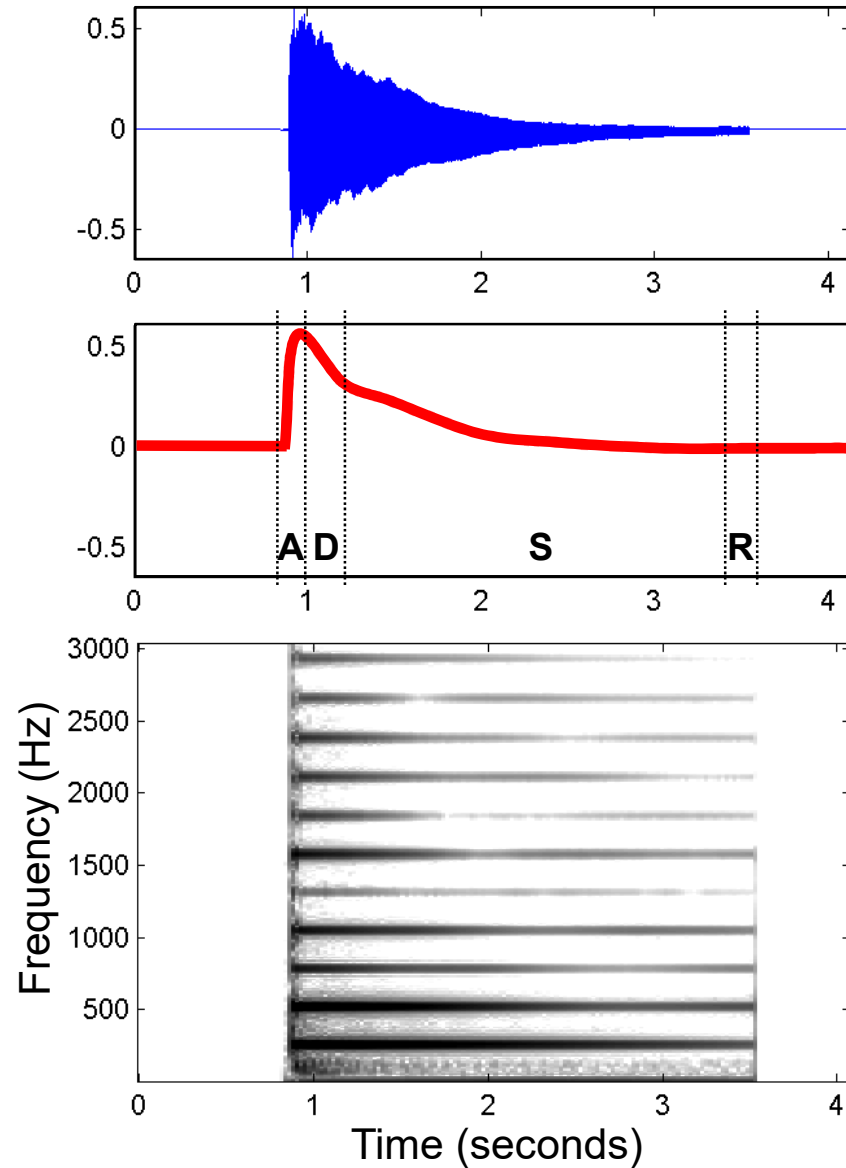
Audio Representation
Timbre

- 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

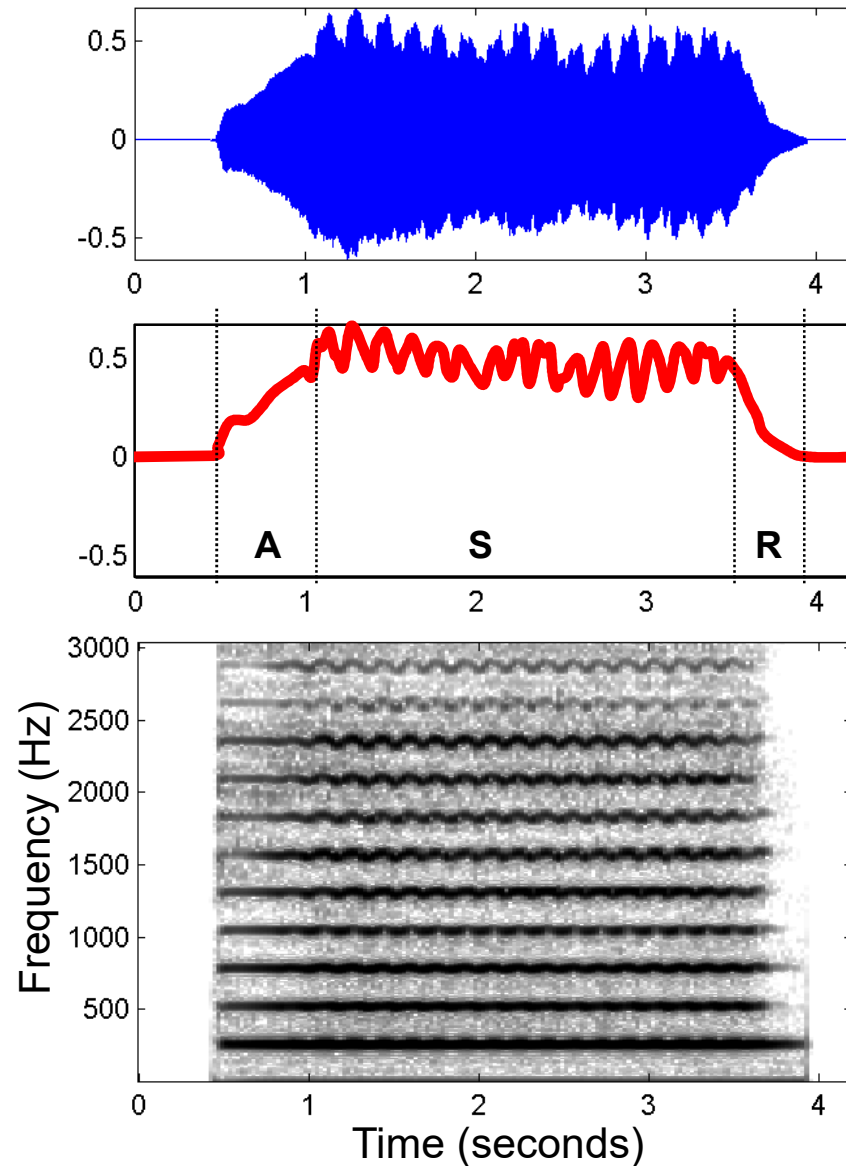Piano playing

note C4 (261.6 Hz)

▶ 🔊

Audio Representation
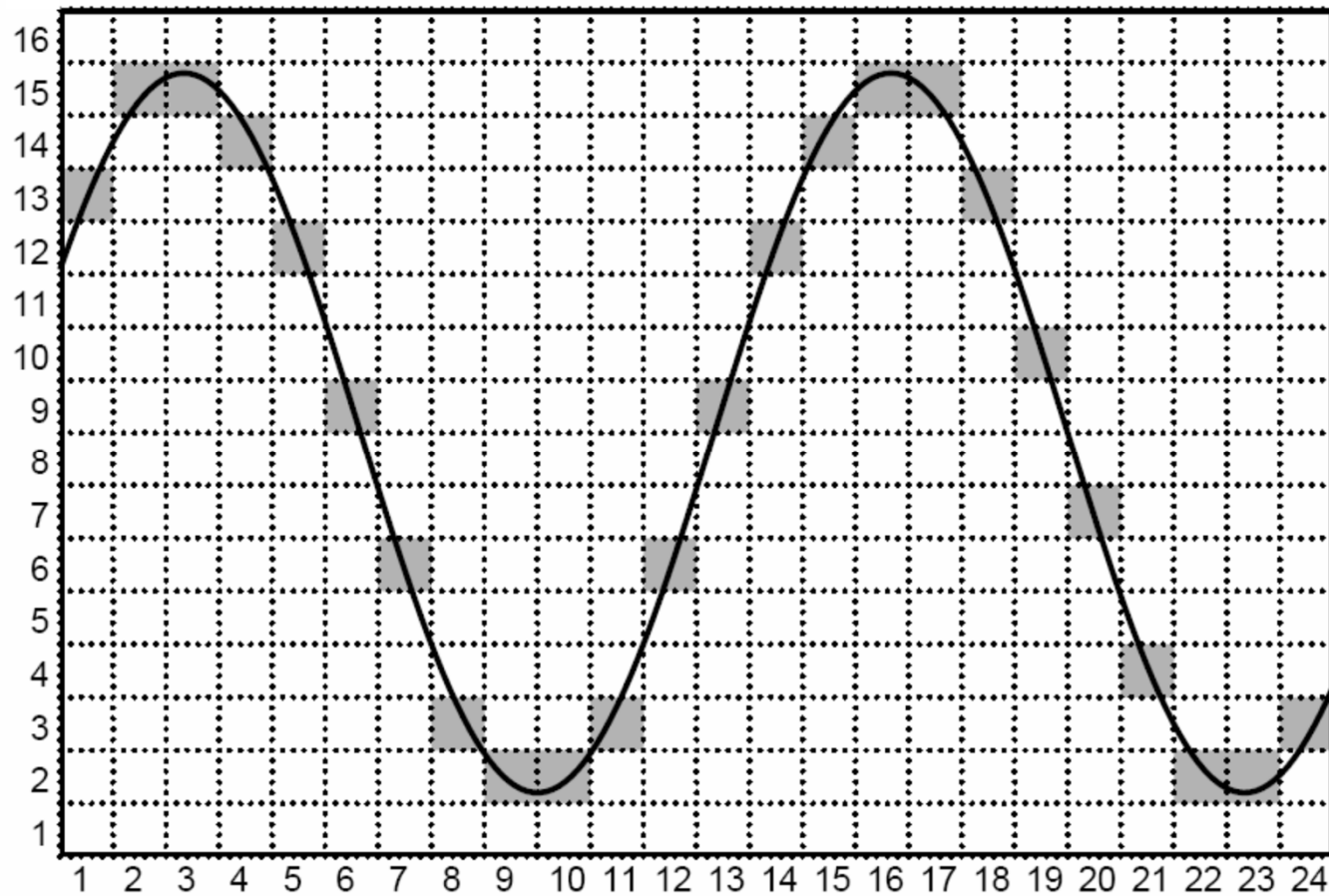## Timbre

Violin playing
note C4 (261.6 Hz)

▶ 🔊

Vibrato:
Frequency modulations

Tremolo:
Amplitude modulations

Digitization
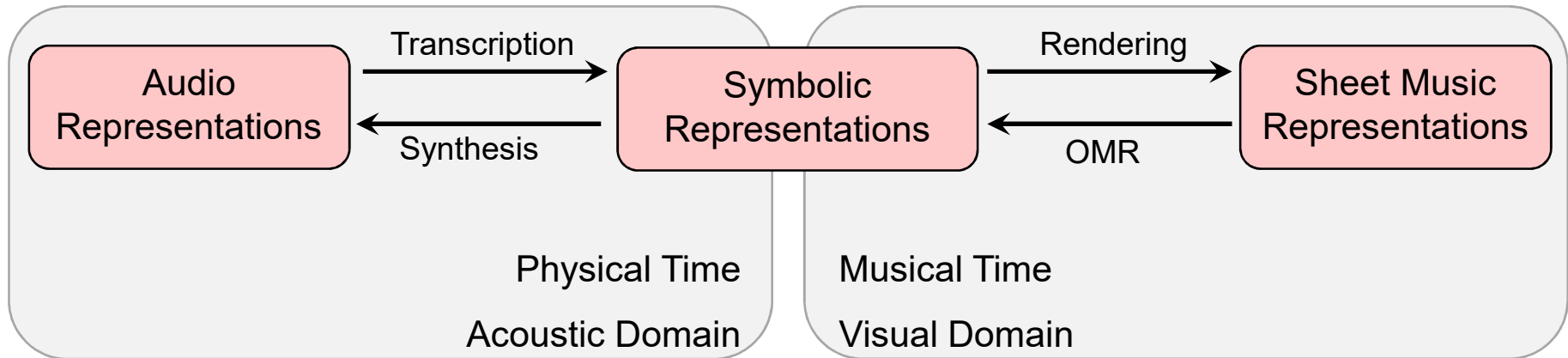
Audio Representation
Digitization

- 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
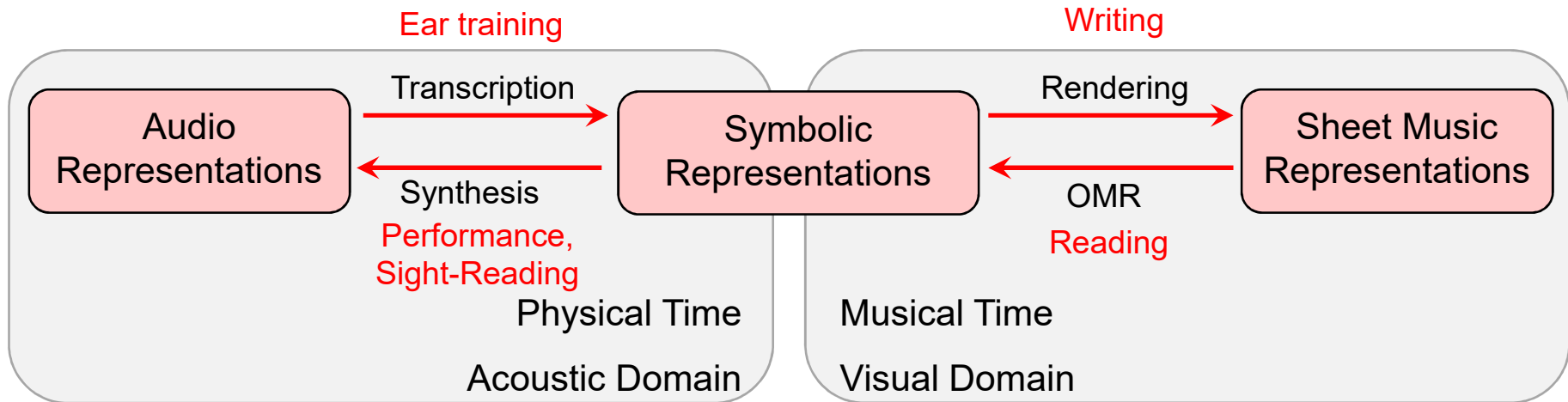## Computational tasks

OMR = optical music recognition

Process of transforming sheet music into a symbolic representation

Music Representations
Human skills

OMR = optical music recognition

Process of transforming sheet music into a symbolic representation