

Hochschule für Musik Karlsruhe

Blockvorlesung

Advanced Audio-Based Music Processing

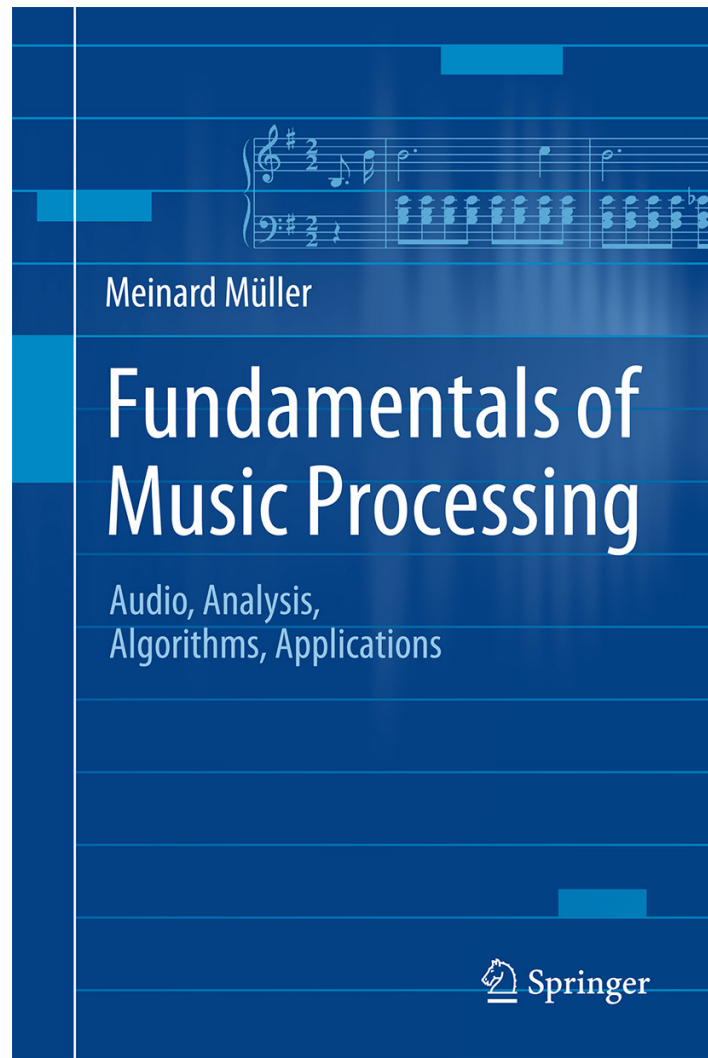
1. Music Representations

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

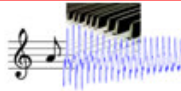

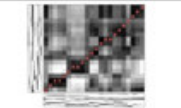

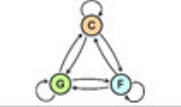
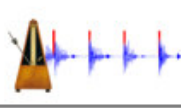
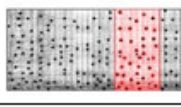
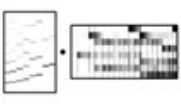
Book: Fundamentals of Music Processing



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

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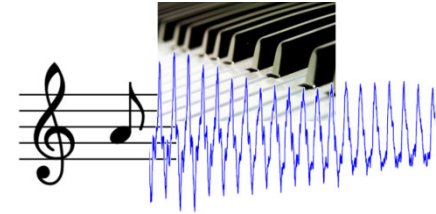
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Chapter 1: Music Representations

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

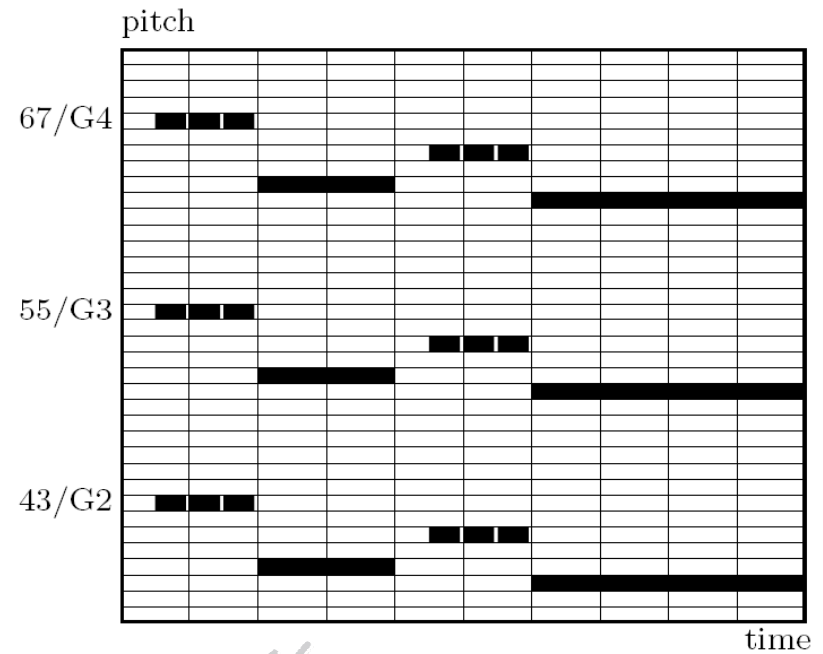
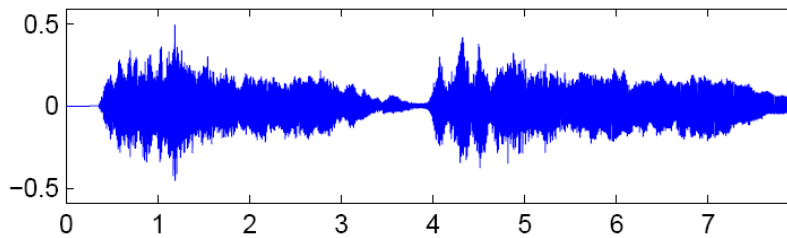


Musical information can be represented in many different ways. In Chapter 1, we consider three widely used music representations: sheet music, symbolic, and audio representations. This first chapter also introduces basic terminology that is used throughout the book. In particular, we discuss musical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

Music Representations

Allegro con brio ($\text{♩} = 108$)

The image shows a musical score for piano in 2/4 time, marked *ff* (fortissimo). The tempo is *Allegro con brio* with a quarter note equal to 108 beats per minute. The score consists of two staves: a treble clef staff and a bass clef staff. The treble staff features a melody with eighth-note patterns and accents. The bass staff features a rhythmic accompaniment with eighth-note patterns and accents. The piece is marked with *ff* and includes accents (*acc.*) with asterisks.



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

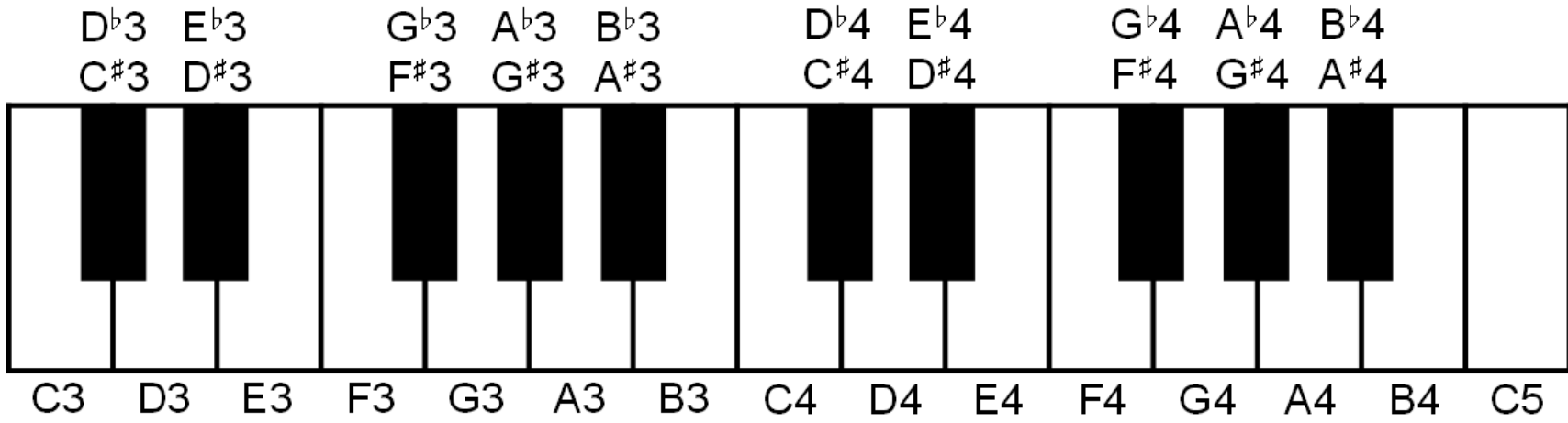
Allegro con brio (♩ = 108)

The image shows a musical score for piano in 2/4 time, featuring a forte (ff) dynamic and a crescendo (Ced.) with a star symbol. The score is written on two staves, treble and bass clef, with a key signature of two flats (B-flat and E-flat). The tempo is marked "Allegro con brio" with a quarter note equal to 108 beats per minute. The music consists of a series of chords and melodic lines. The first staff (treble clef) starts with a forte (ff) dynamic and features a series of chords. The second staff (bass clef) starts with a forte (ff) dynamic and features a series of chords. The score is divided into four measures. The first measure contains a series of chords in both staves. The second measure contains a series of chords in both staves. The third measure contains a series of chords in both staves. The fourth measure contains a series of chords in both staves. The score is marked with a forte (ff) dynamic and a crescendo (Ced.) with a star symbol.



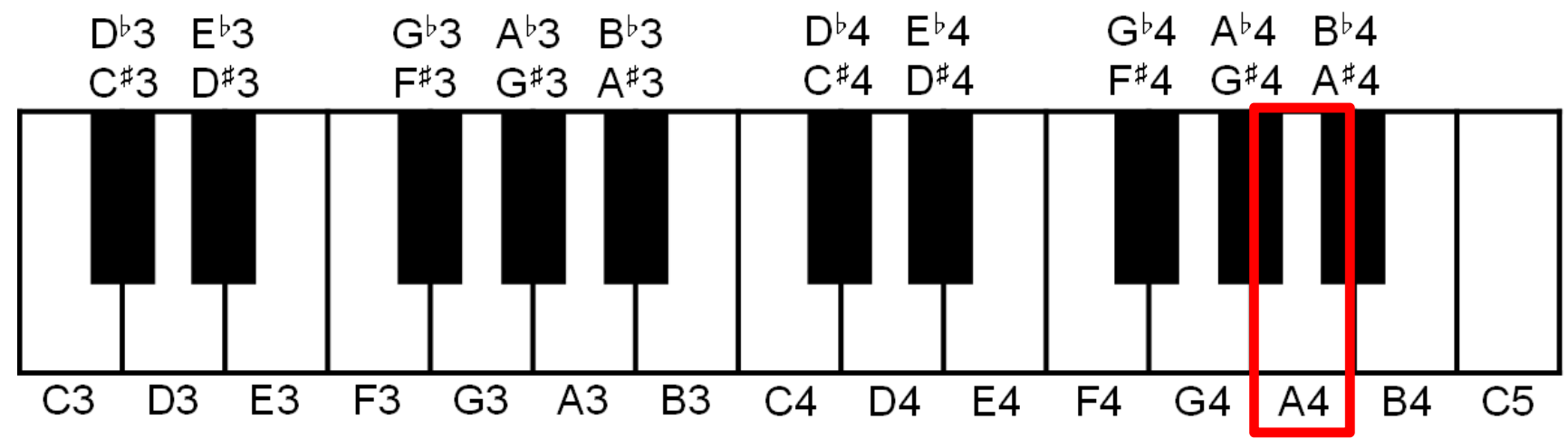
Sheet Music Representation

Piano keyboard and notes



Sheet Music Representation

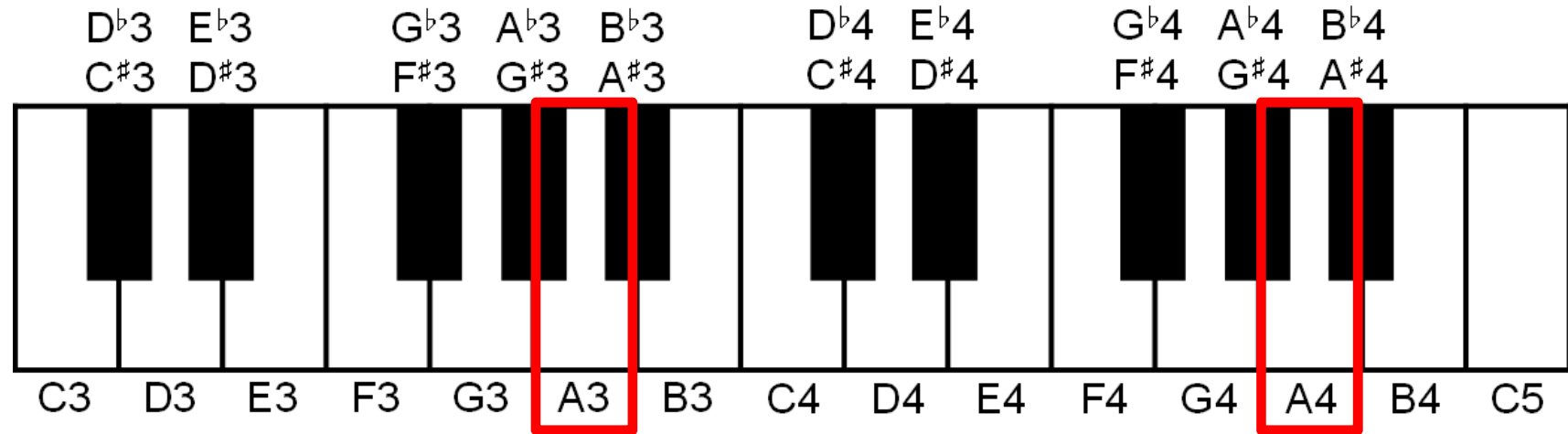
Piano keyboard and notes



A \triangleq pitch class
4 \triangleq octave number

Sheet Music Representation

Piano keyboard and notes

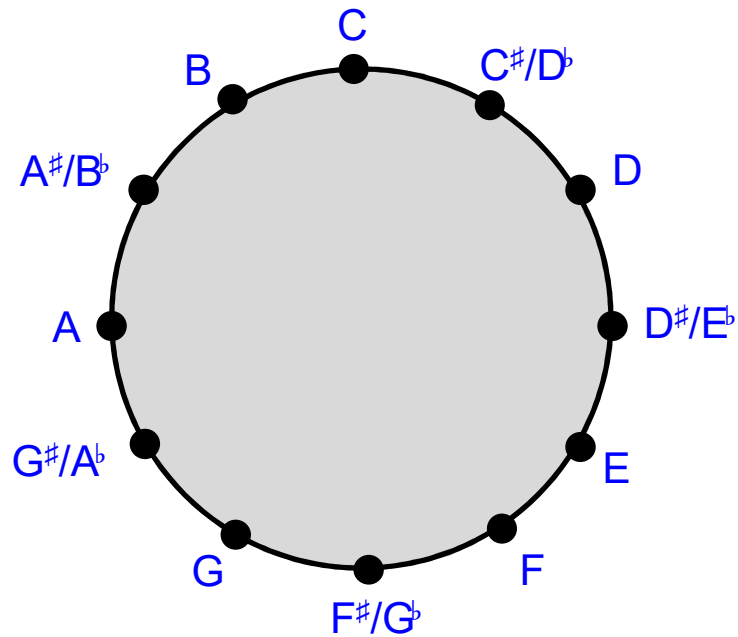


A \triangleq pitch class
4 \triangleq octave number

Sheet Music Representation

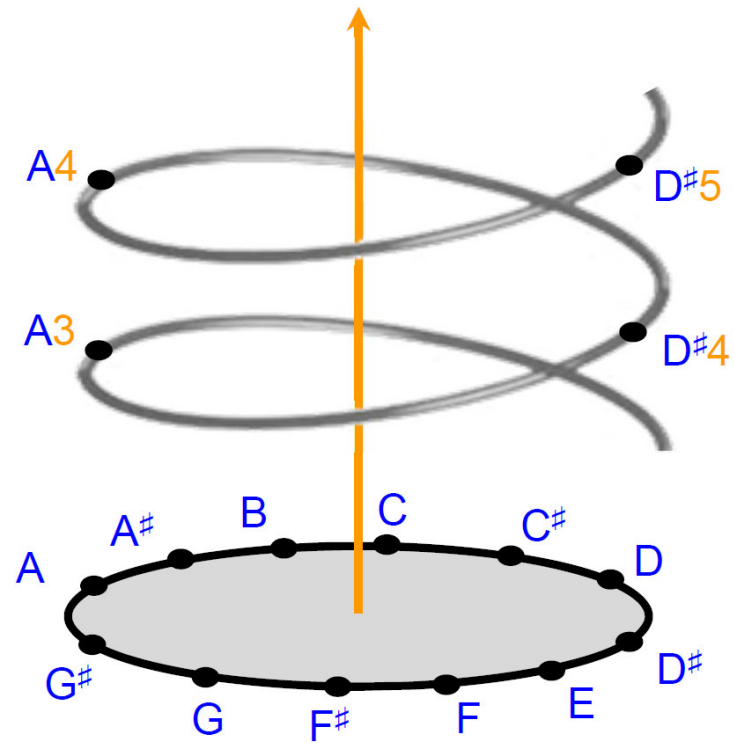
Chromatic circle

Chroma \triangleq pitch spelling attribute



Shepard's helix of pitch

Tone height \triangleq octave number



Sheet Music Representation

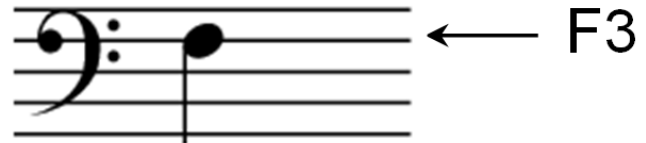
Staff



Staff with G-clef



Staff with F-clef



Sheet Music Representation

Musical score of a C-major scale



A musical score for a C-major scale on a treble clef staff. The staff contains eight notes: C4, D4, E4, F4, G4, A4, B4, and C5. Each note is represented by a black dot with a vertical stem and a short horizontal line. The notes are arranged in ascending order from left to right. The final note, C5, is positioned on the first line of the staff. The staff ends with a double bar line.

C4 D4 E4 F4 G4 A4 B4 C5

Sheet Music Representation

Musical score of a C-major scale



A musical score for a C-major scale on a single treble clef staff. The notes are C4, D4, E4, F4, G4, A4, B4, and C5, each represented by a quarter note. The notes are positioned on the staff as follows: C4 on the first line, D4 on the first space, E4 on the second line, F4 on the second space, G4 on the third line, A4 on the third space, B4 on the fourth line, and C5 on the fourth space. The notes are connected by a single horizontal line.

C4 D4 E4 F4 G4 A4 B4 C5

Musical score of a C-minor scale



A musical score for a C-minor scale on a single treble clef staff. The notes are C4, D4, E^b4, F4, G4, A^b4, B^b4, and C5, each represented by a quarter note. The notes are positioned on the staff as follows: C4 on the first line, D4 on the first space, E^b4 on the second line, F4 on the second space, G4 on the third line, A^b4 on the third space, B^b4 on the fourth line, and C5 on the fourth space. The notes are connected by a single horizontal line. The key signature, consisting of three flats (B^b, E^b, and A^b), is circled in red.

C4 D4 E^b4 F4 G4 A^b4 B^b4 C5

Key signature
consisting of
three flats

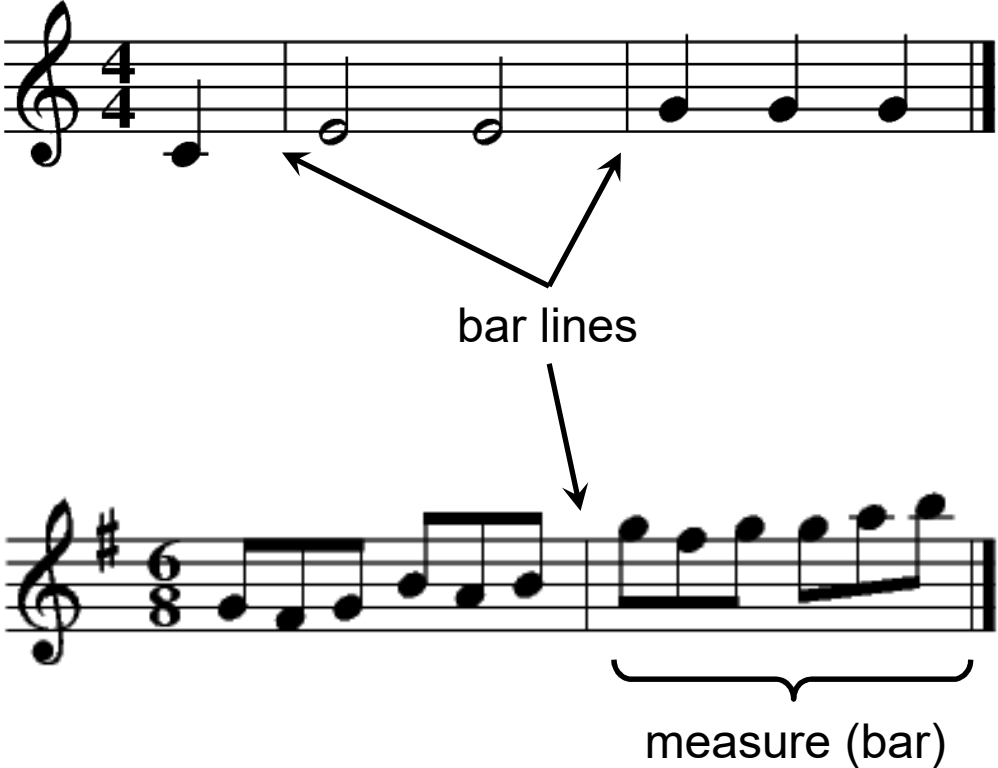
Sheet Music Representation

Time signature



Sheet Music Representation

Time signature



Sheet Music Representation

Time signature

Four quarter notes
per measure



bar lines

Six eighth notes
per measure

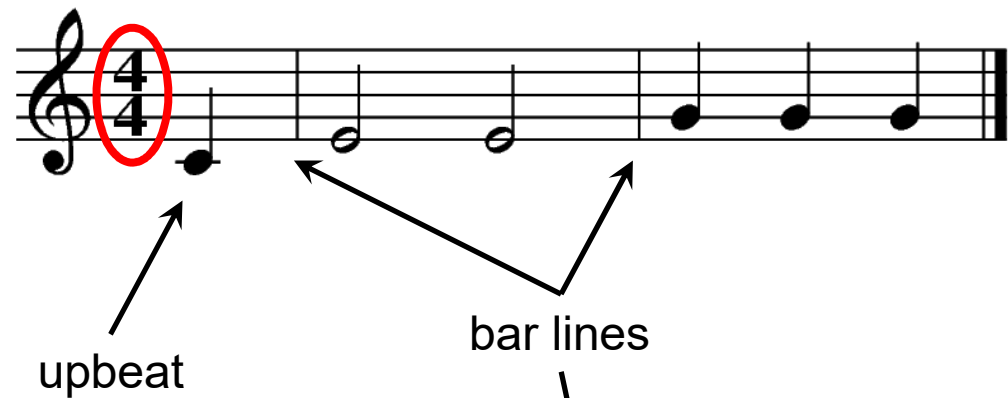


measure (bar)

Sheet Music Representation

Time signature

Four quarter notes
per measure



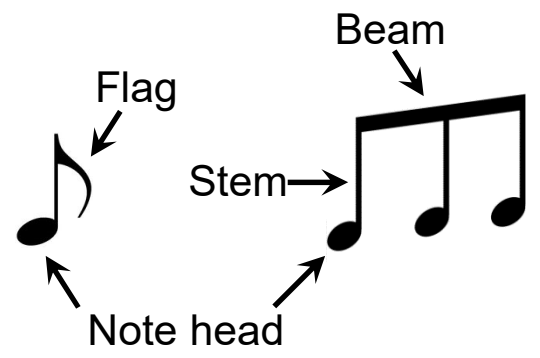
Six eighth notes
per measure



Sheet Music Representation

Note durations

Parts of a note



Different durations of notes

A musical staff in treble clef showing five different note durations. From left to right: a whole note (one bar), a half note (two bars), a quarter note (four bars), an eighth note (eight bars), and a sixteenth note (sixteen bars). Each note is labeled below the staff: 'Whole note', 'Half note', 'Quarter note', 'Eighth note', and 'Sixteenth note'.

Different durations of rests

A musical staff in treble clef showing five different durations of rests. From left to right: a whole rest (one bar), a half rest (two bars), a quarter rest (four bars), an eighth rest (eight bars), and a sixteenth rest (sixteen bars). Each rest is labeled below the staff: 'Whole rest', 'Half rest', 'Quarter rest', 'Eighth rest', and 'Sixteenth rest'.

Sheet Music Representation

Staff systems

Piano



Strings



Sheet Music Representation

Dynamics and articulation

The image displays a single staff of music in 4/4 time, starting with a treble clef. The melody consists of a sequence of quarter notes: C4, D4, E4, F4, G4, A4, B4, C5, B4, A4, G4, F4, E4, D4, C4. Above the staff, four dynamic markings are indicated with wedge-shaped symbols: 'crescendo' (wedge opening to the right), 'diminuendo' (wedge opening to the left), 'piano' (written as *p*), and 'forte' (written as *f*). Below the staff, two articulation markings are shown: 'legato' (indicated by a slur under the notes G4, A4, B4) and 'staccato' (indicated by two upward-pointing arrows under the notes C5 and B4). The lyrics 'do re mi fa so la si do' are written below the notes, with 'do' under C4, 're' under D4, 'mi' under E4, 'fa' under F4, 'so' under G4, 'la' under A4, 'si' under B4, and 'do' under C5. The word 'lyrics' is centered below the entire line of text.

Sheet Music Representation

Allegro con brio. $\text{♩} = 108.$

Flauti.

Oboi.

Clarineti in B.

Fagotti.

Corni in Es.

Trombe in C.

Timpani in C.G.

Violino I.

Violino II.

Viola.

Violoncello.

Basso.

The image displays a page of sheet music for a symphony, featuring 12 staves for various instruments. The music is in 2/4 time, marked 'Allegro con brio' with a tempo of 108 beats per minute. The instruments listed are Flauti, Oboi, Clarineti in B., Fagotti, Corni in Es., Trombe in C., Timpani in C.G., Violino I., Violino II., Viola, Violoncello, and Basso. The music is written in a key signature of two flats (B-flat and E-flat). Dynamics include 'ff' (fortissimo) and 'p' (piano). The score is divided into three systems, each starting with the tempo and time signature. The first system includes Flauti, Oboi, Clarineti in B., and Fagotti. The second system includes Corni in Es., Trombe in C., and Timpani in C.G. The third system includes Violino I., Violino II., Viola, Violoncello, and Basso. The music is written in a key signature of two flats (B-flat and E-flat). Dynamics include 'ff' (fortissimo) and 'p' (piano). The score is divided into three systems, each starting with the tempo and time signature. The first system includes Flauti, Oboi, Clarineti in B., and Fagotti. The second system includes Corni in Es., Trombe in C., and Timpani in C.G. The third system includes Violino I., Violino II., Viola, Violoncello, and Basso.



Sheet Music Representation

A hand-drawn musical notation on a single staff in 4/4 time, featuring a treble clef and a key signature of one flat (Bb). The lyrics are "WIKIPEDIA". The notation includes a whole note for "WI", a half note for "KI", and a quarter note followed by a dotted quarter note for "PE - DI - A". Handwritten annotations include "CHORD SYMBOLS" with lines pointing to "C7" above the first measure and "F" above the third measure. "MELODY" is written above the staff with a line pointing to the notes. "LYRIC" is written below the staff with a line pointing to the word "A".

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

Sheet Music Representation



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

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

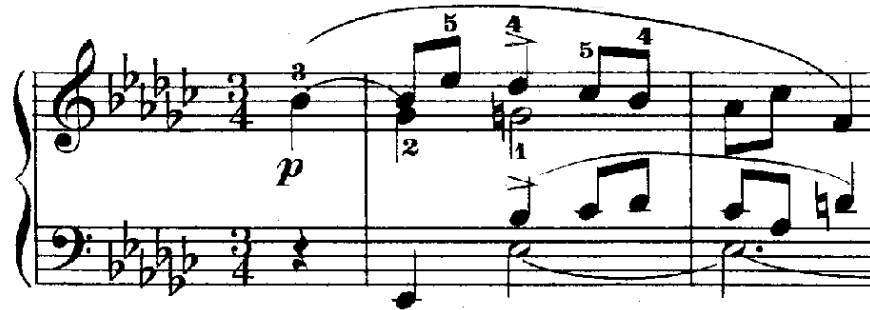
```
<note>  
  <pitch>  
    <step>E</step>  
    <alter>-1</alter>  
    <octave>4</octave>  
  </pitch>  
  <duration>2</duration>  
  <type>half</type>  
</note>
```



Symbolic Representation

Optical Music Recognition

Original score



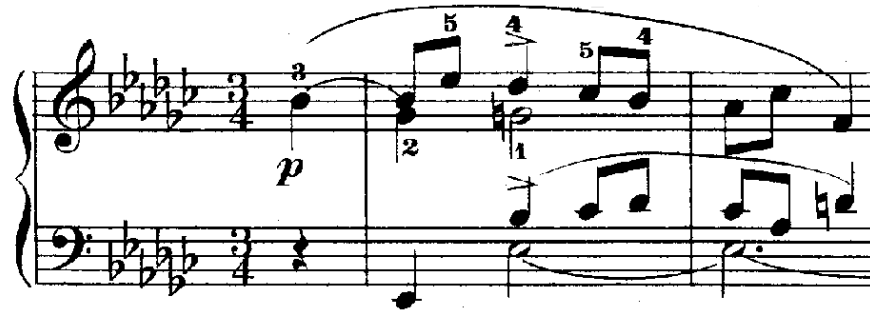
OMR score



Symbolic Representation

Optical Music Recognition

Original score



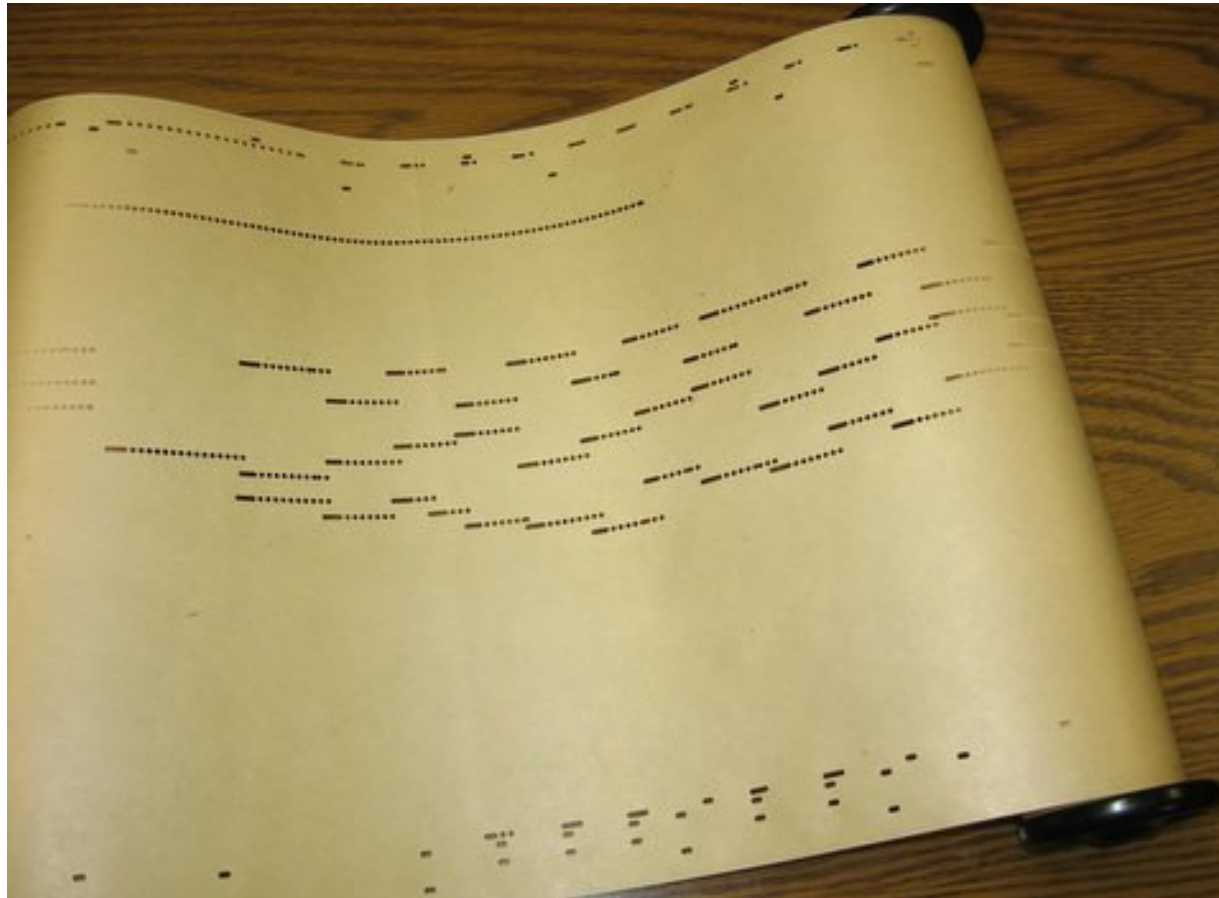
OMR score



OMR errors

Symbolic Representation

Piano roll representation



Symbolic Representation

Piano roll representation



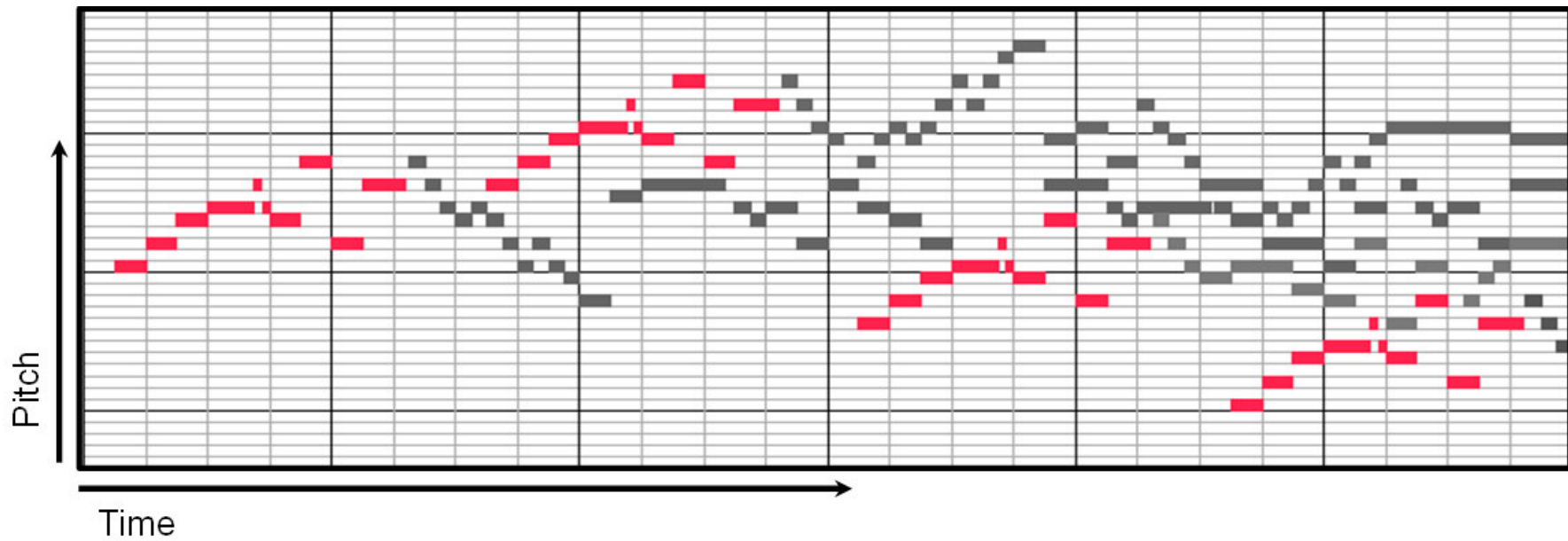
Symbolic Representation

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

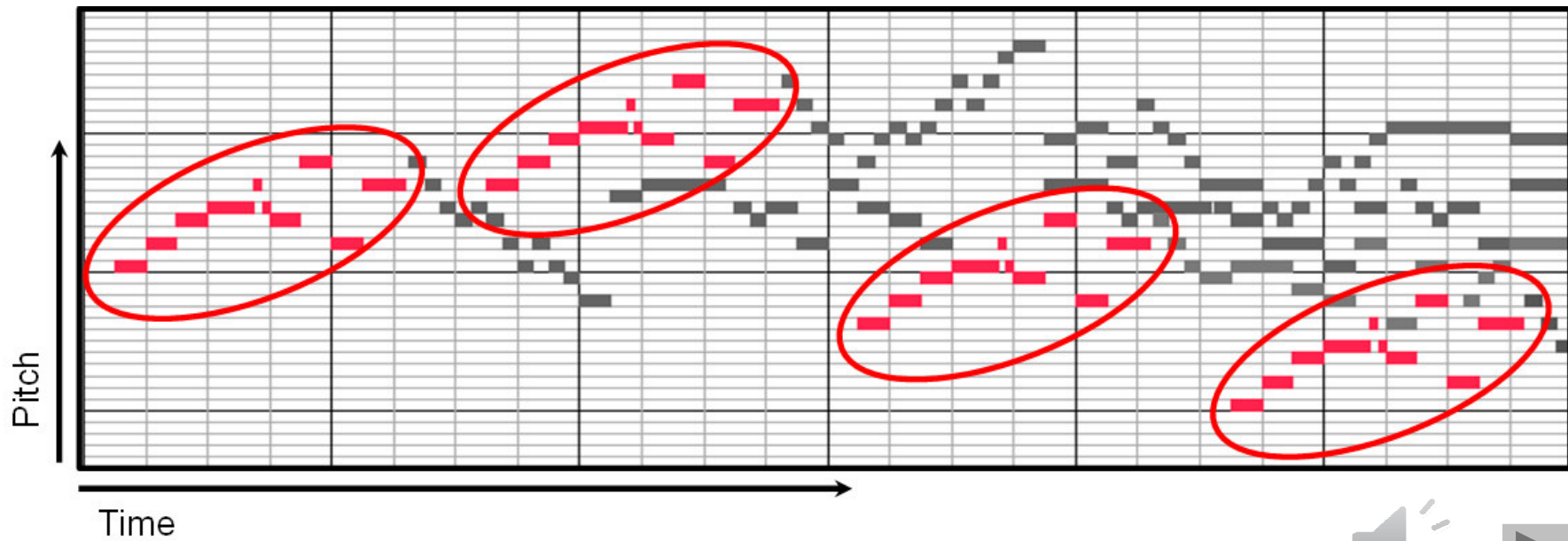
Symbolic Representation

Piano roll representation



Symbolic Representation

Piano roll representation



Symbolic Representation

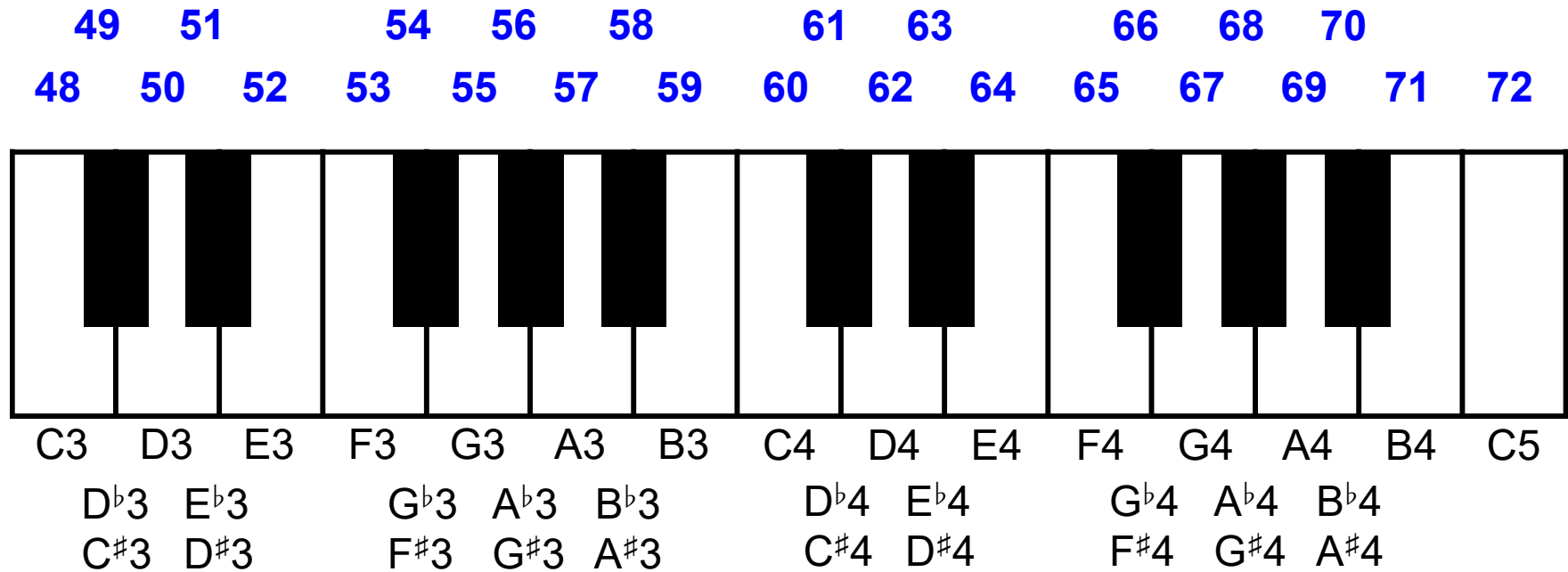
MIDI representation

- 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) \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

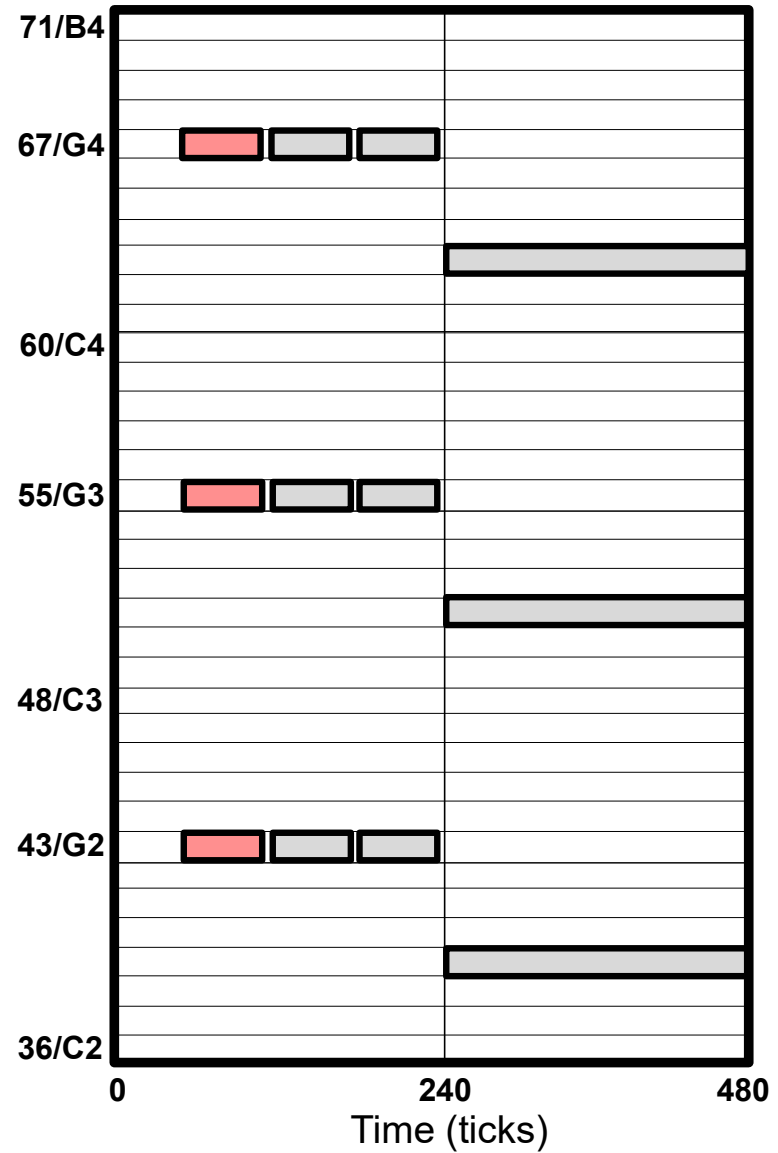
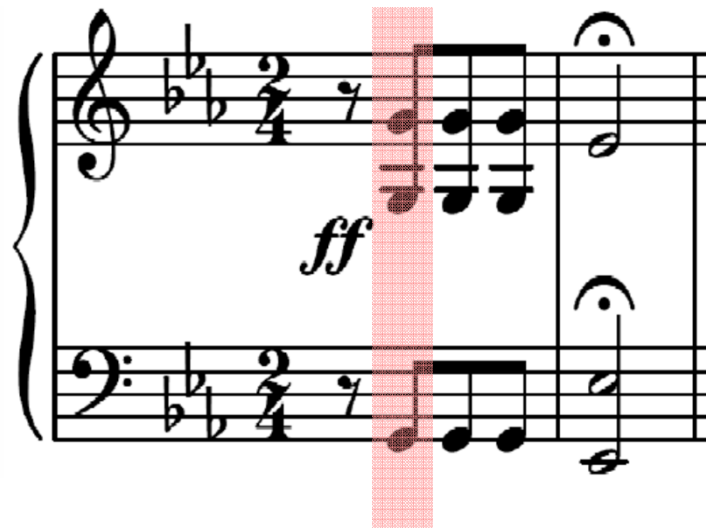
MIDI representation



Time (Ticks)	Message	Channel	Note Number	Velocity
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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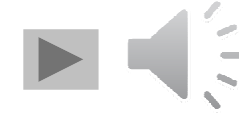
Audio Representation

Various interpretations – Beethoven's Fifth

Bernstein



Karajan



Scherbakov (piano)

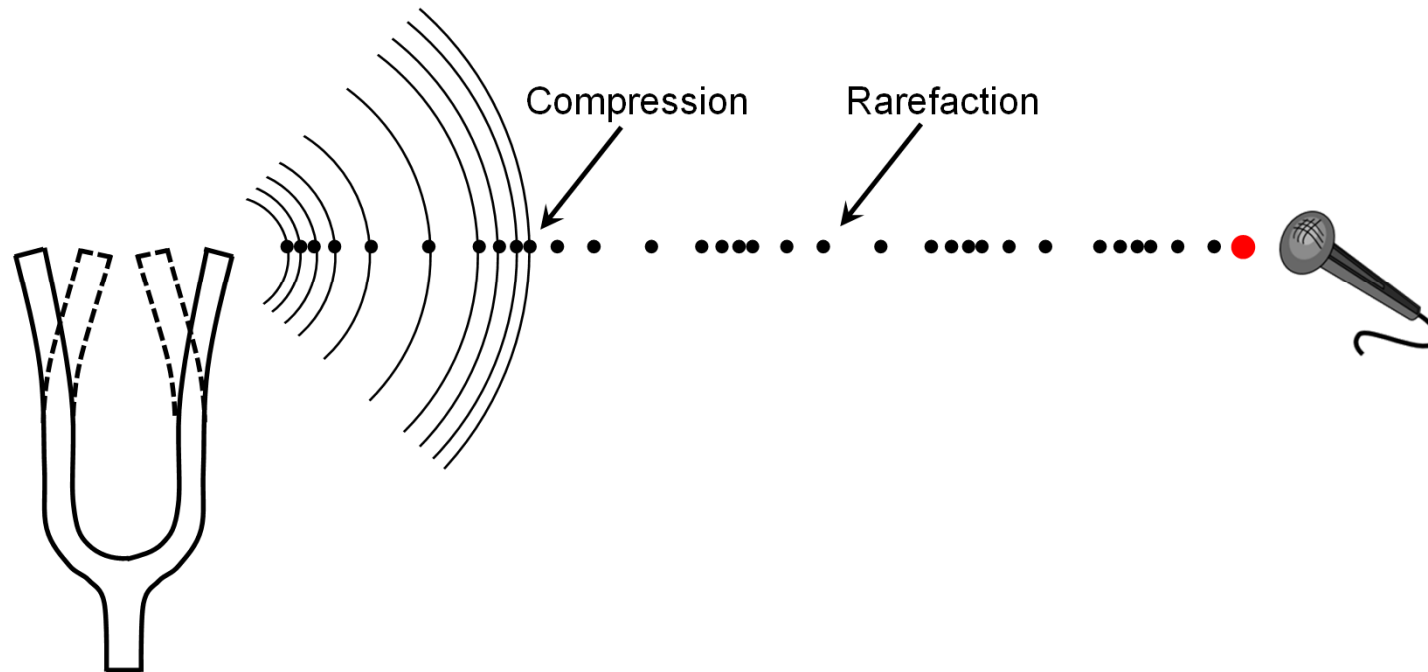


MIDI (piano)



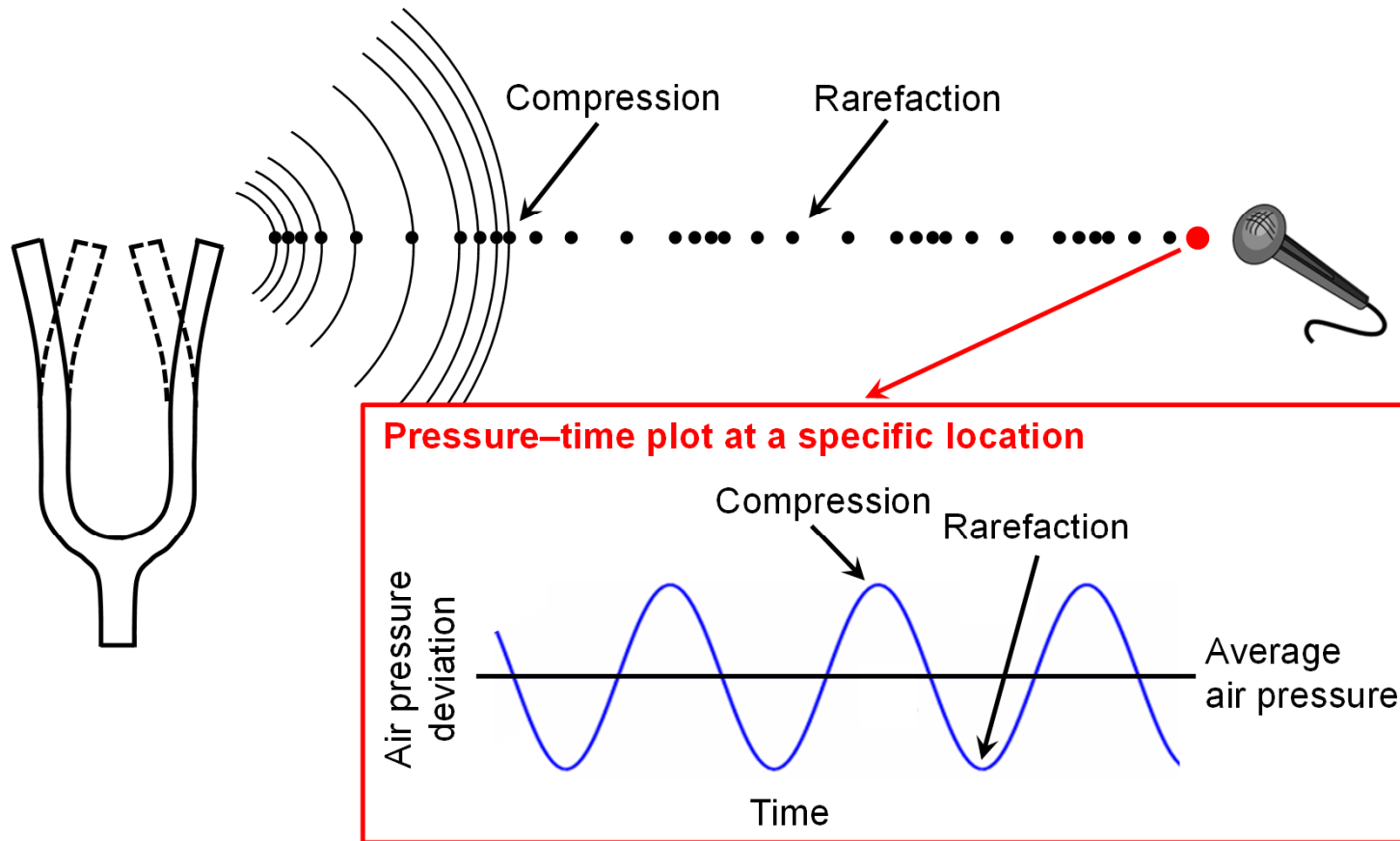
Audio Representation

Waveform



Audio Representation

Waveform



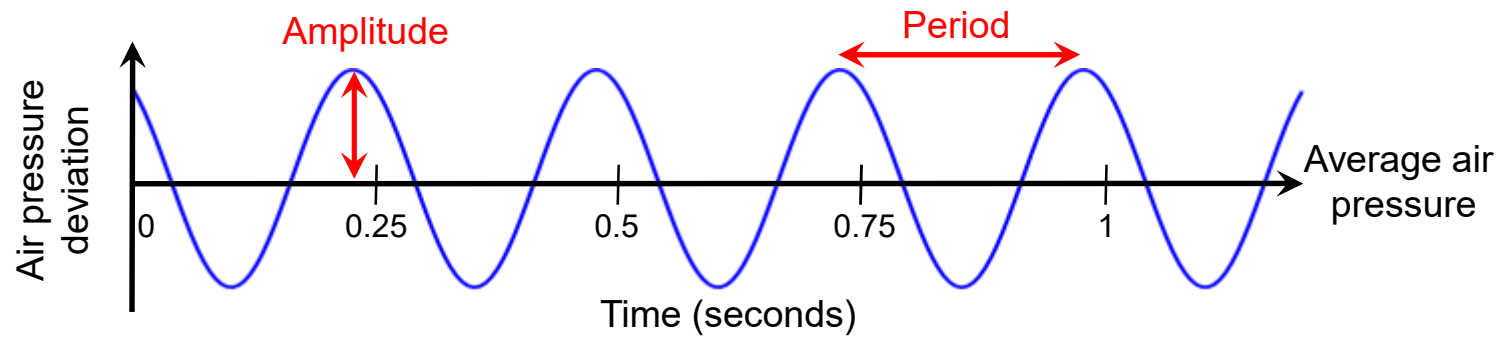
Audio Representation

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):

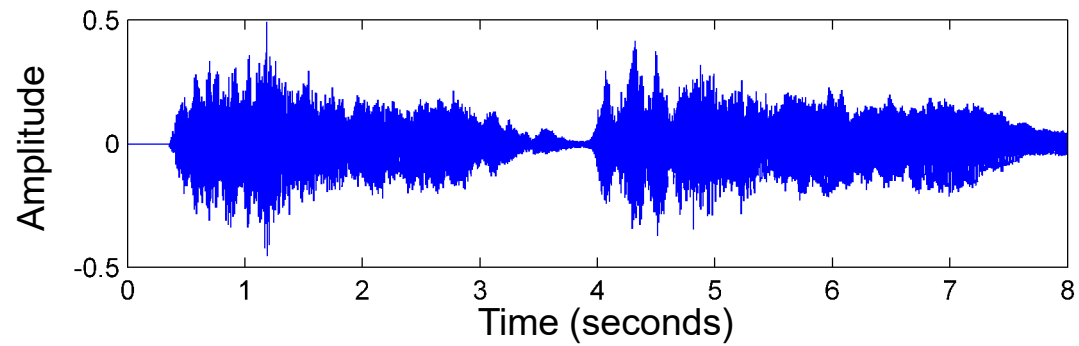
- Sinusoidal waveform
- Prototype of an acoustic realization of a musical note

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

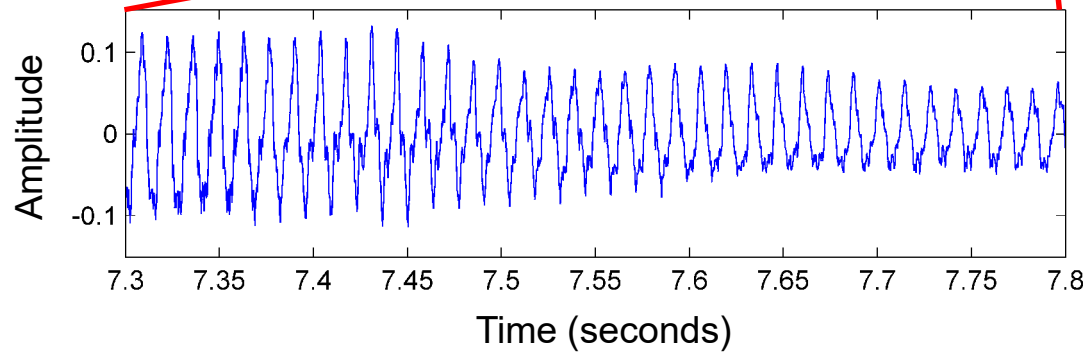
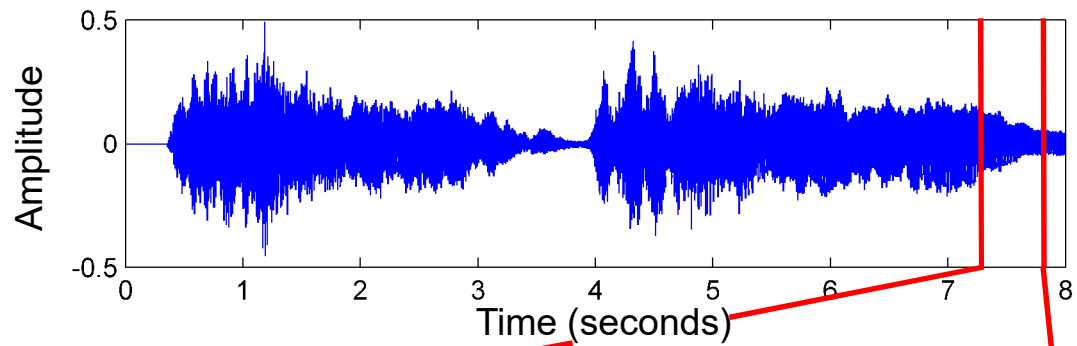
Audio Representation

Waveform



Audio Representation

Waveform

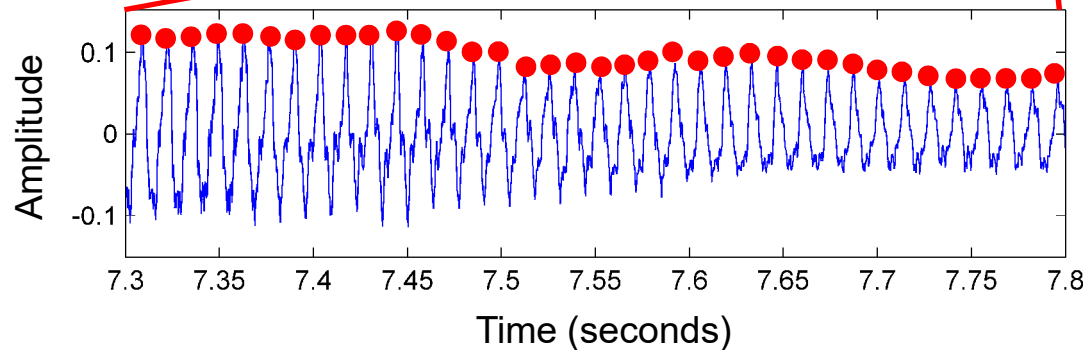
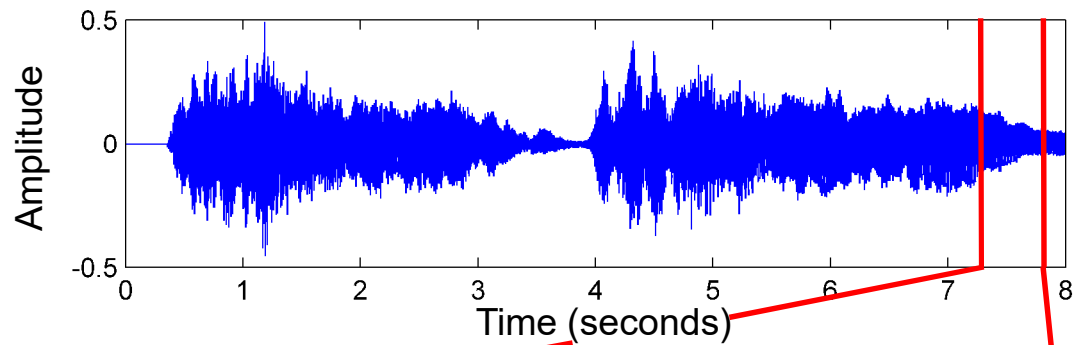


D2 (73.4 Hz)



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 \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 (\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

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

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



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

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

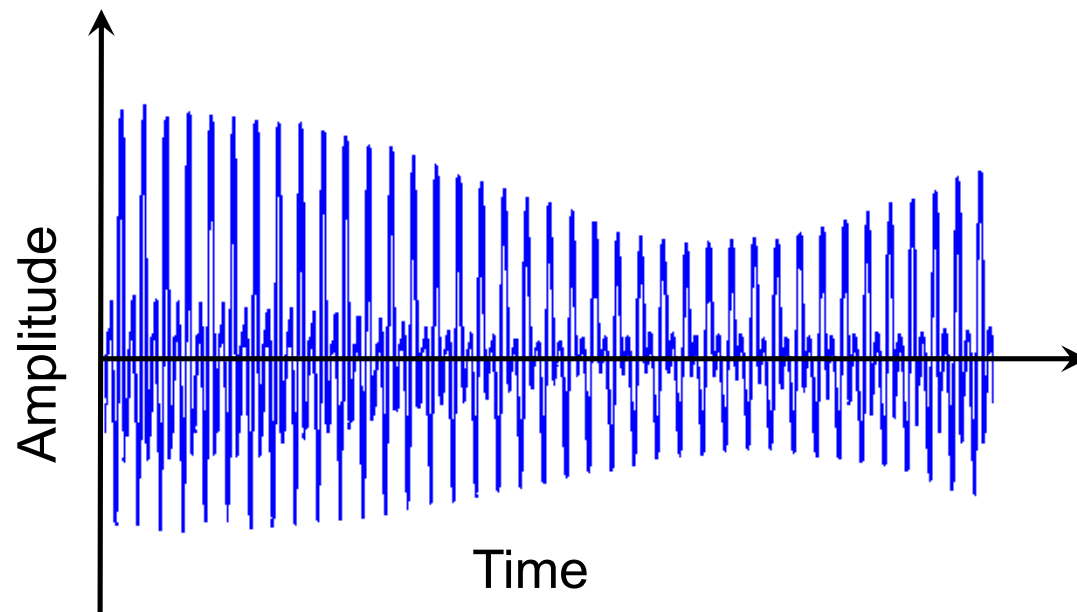
Audio Representation

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}

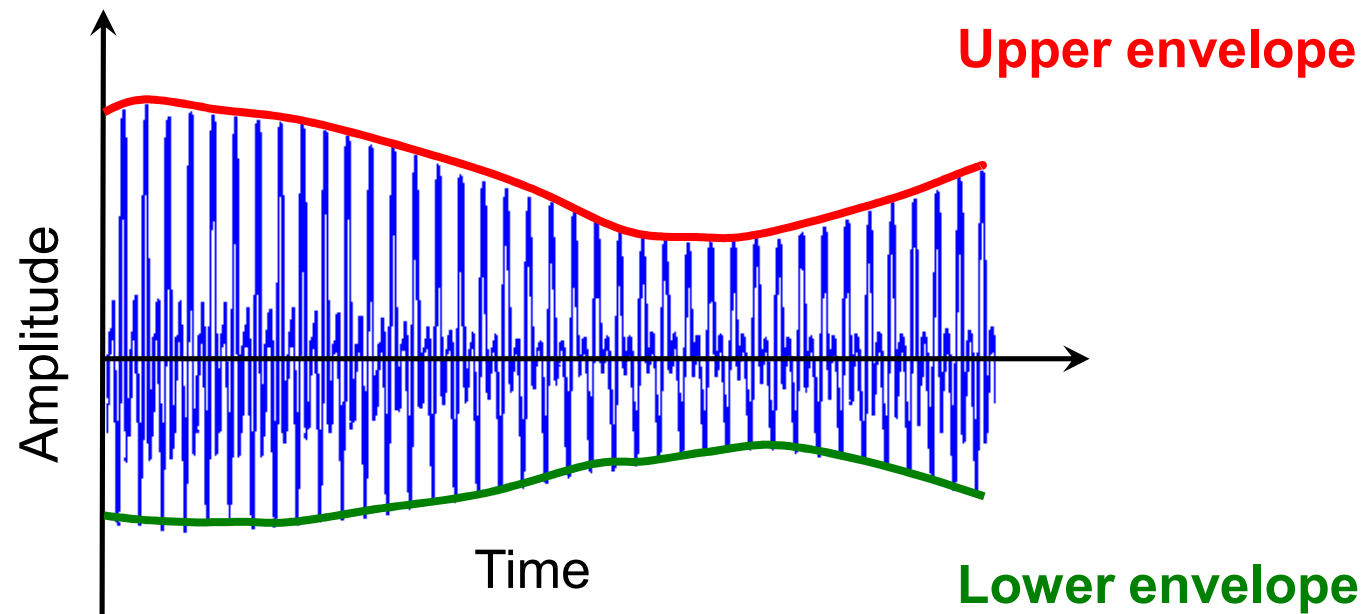
Audio Representation

Dynamics



Audio Representation

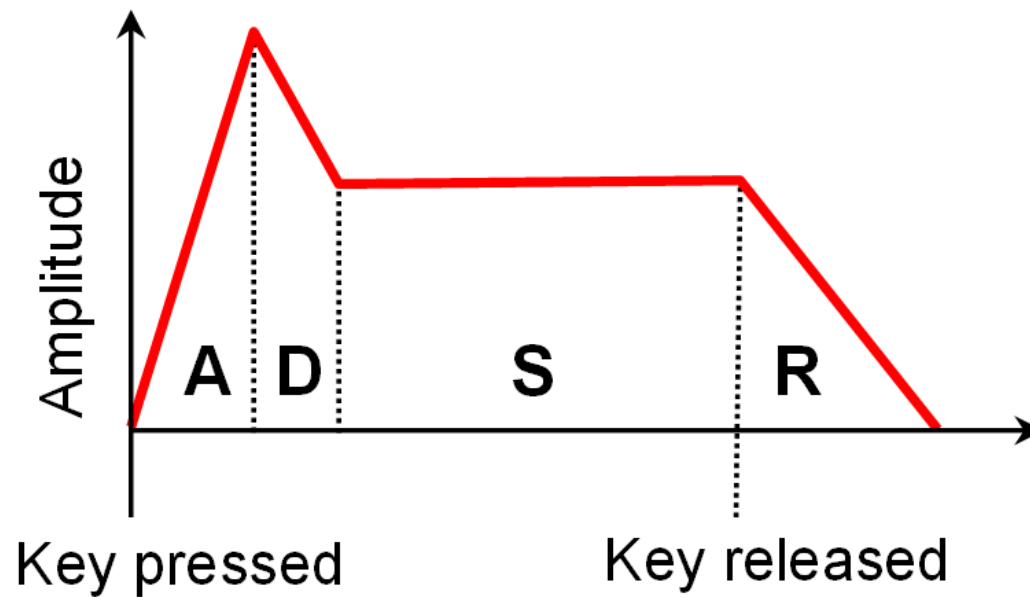
Dynamics



Audio Representation

Dynamics

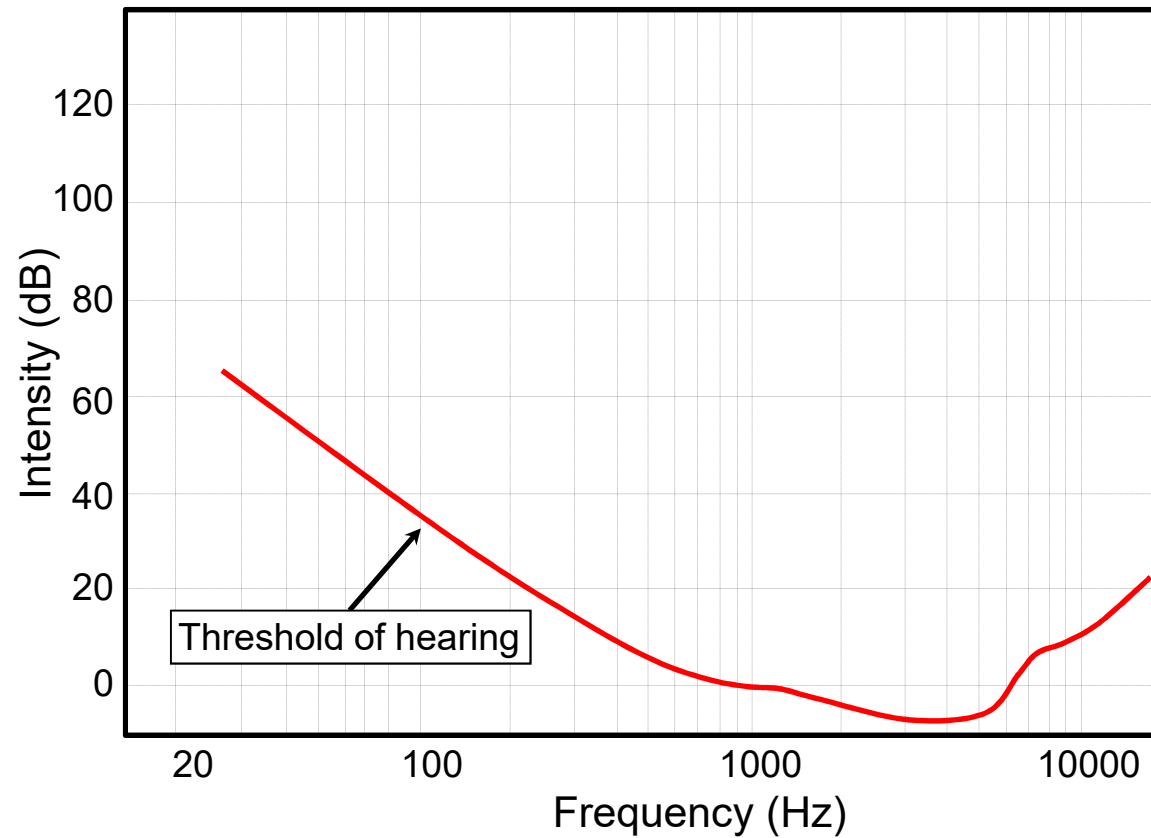
ADSR model: attack (A), decay (D), sustain (S), and release (R) phase



Audio Representation

Loudness

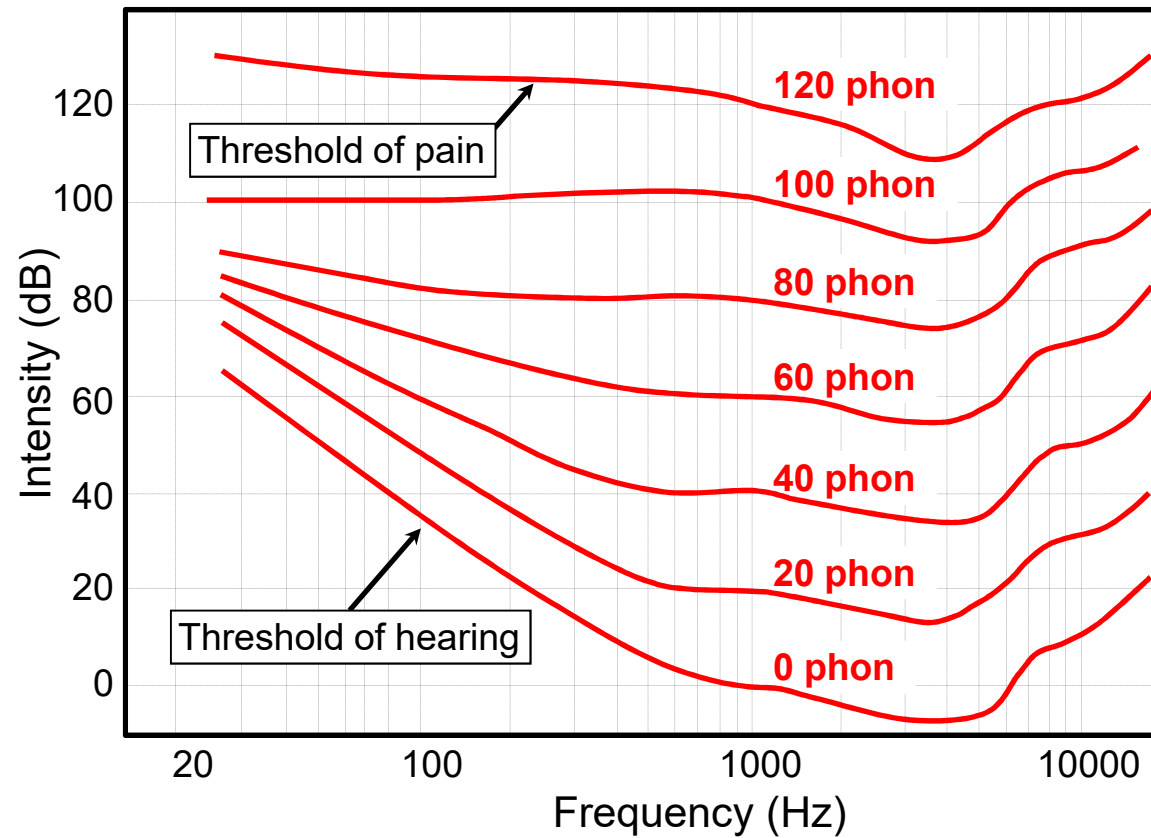
Equal-loudness contours (phon)



Audio Representation

Loudness

Equal-loudness contours (phon)



Audio Representation

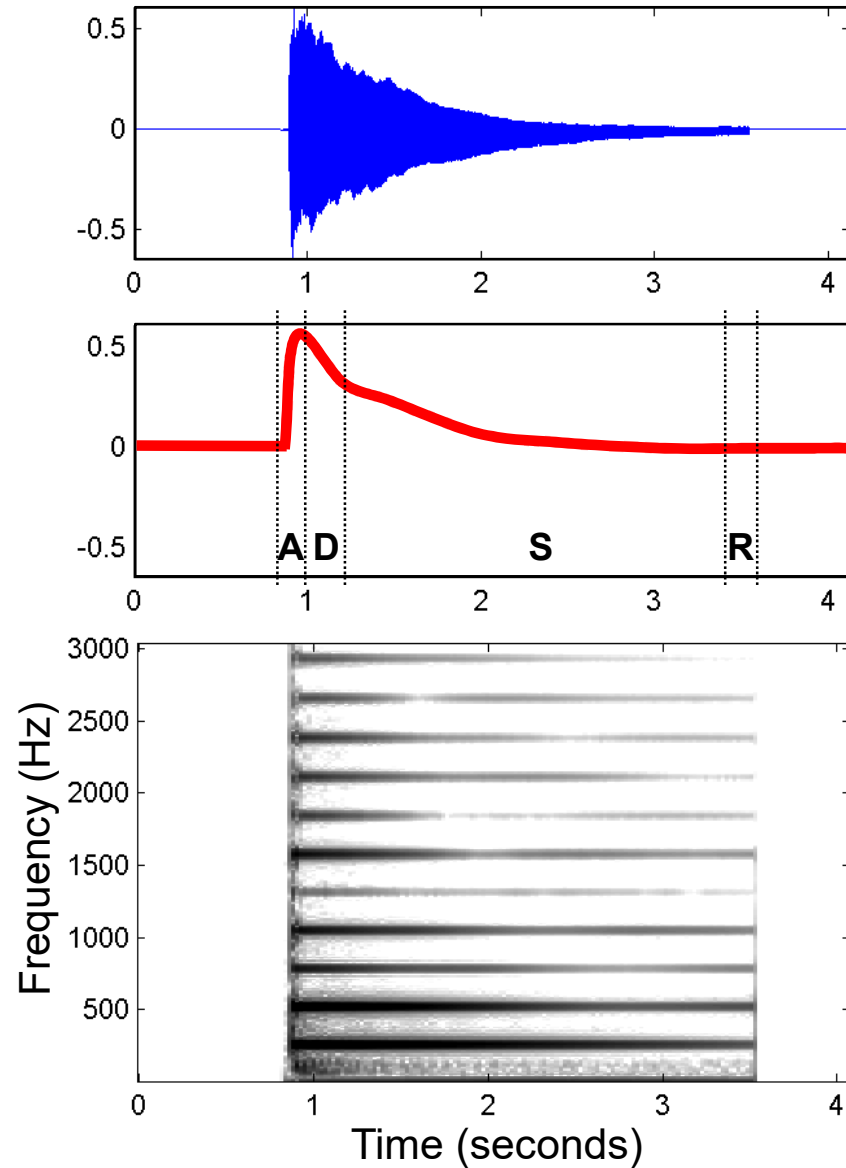
Timbre

- 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

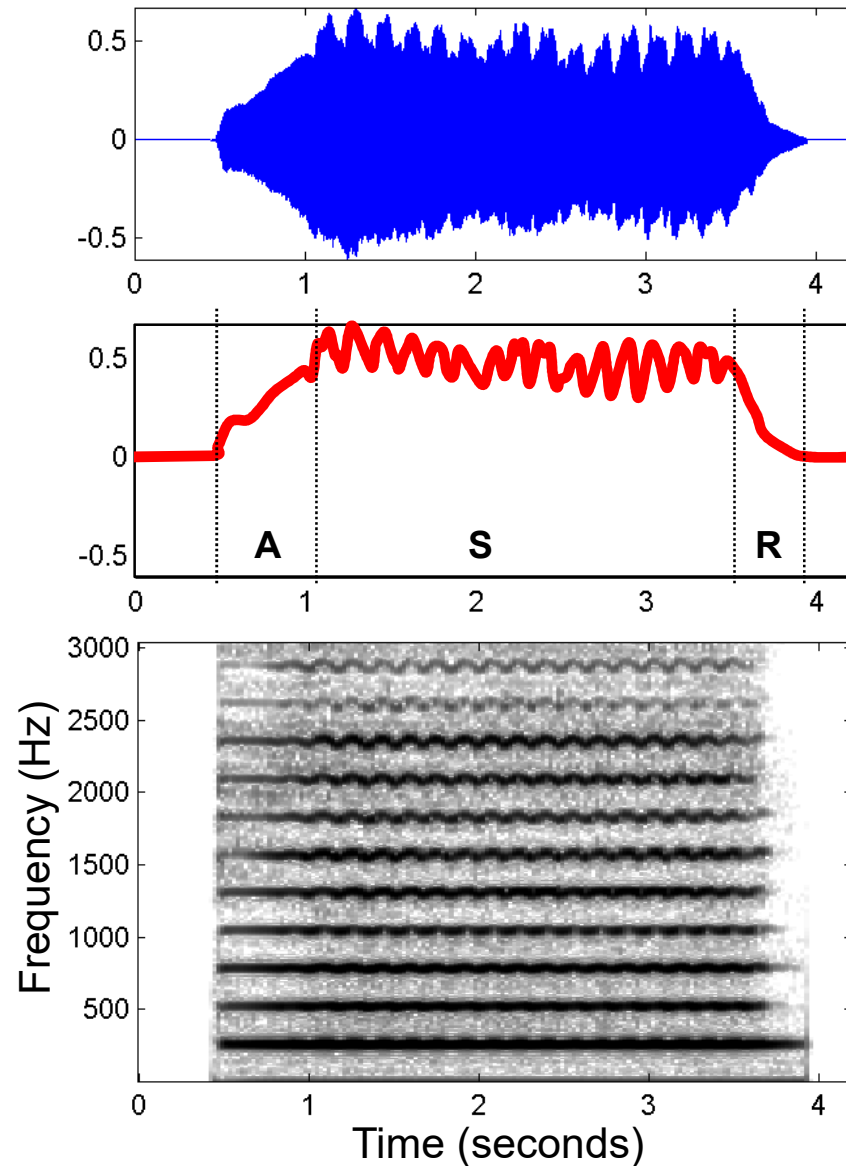
Timbre

Violin playing
note C4 (261.6 Hz)



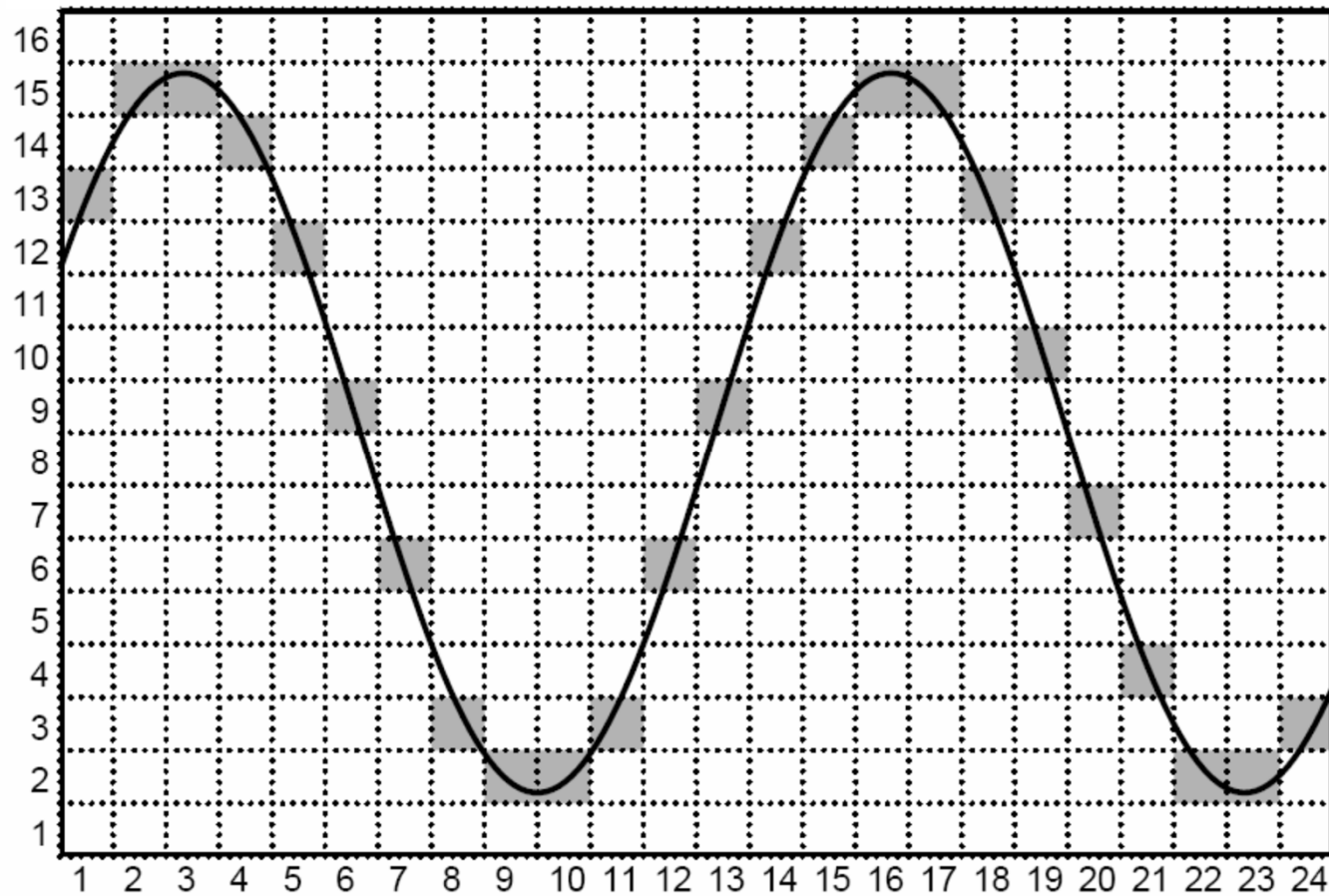
Vibrato:
Frequency modulations

Tremolo:
Amplitude modulations



Audio Representation

Digitization



Audio Representation

Digitization

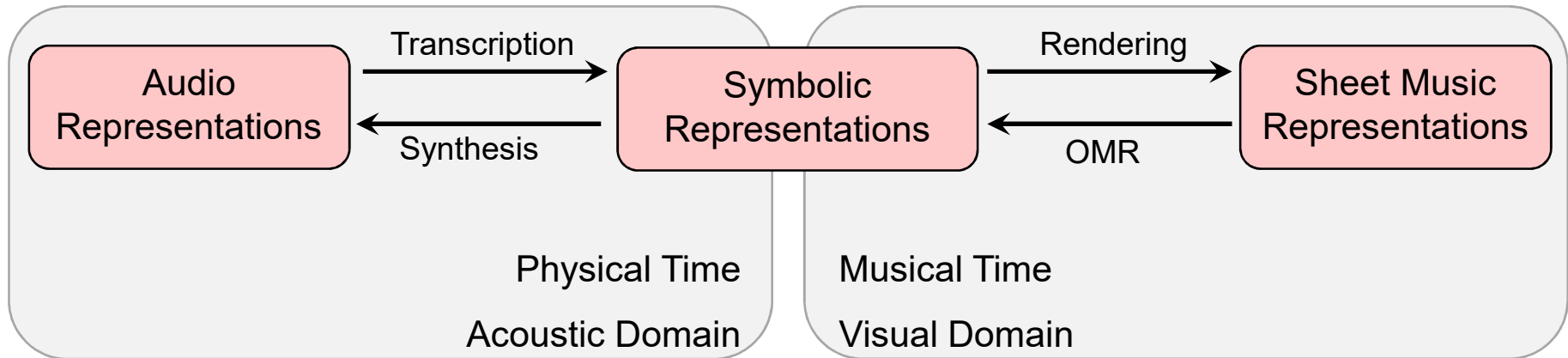
- Conversion of continuous-time (analog) signal into a discrete signal
- Sampling (discretization of time axis)
- Quantization (discretization of amplitudes)

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

Computational tasks

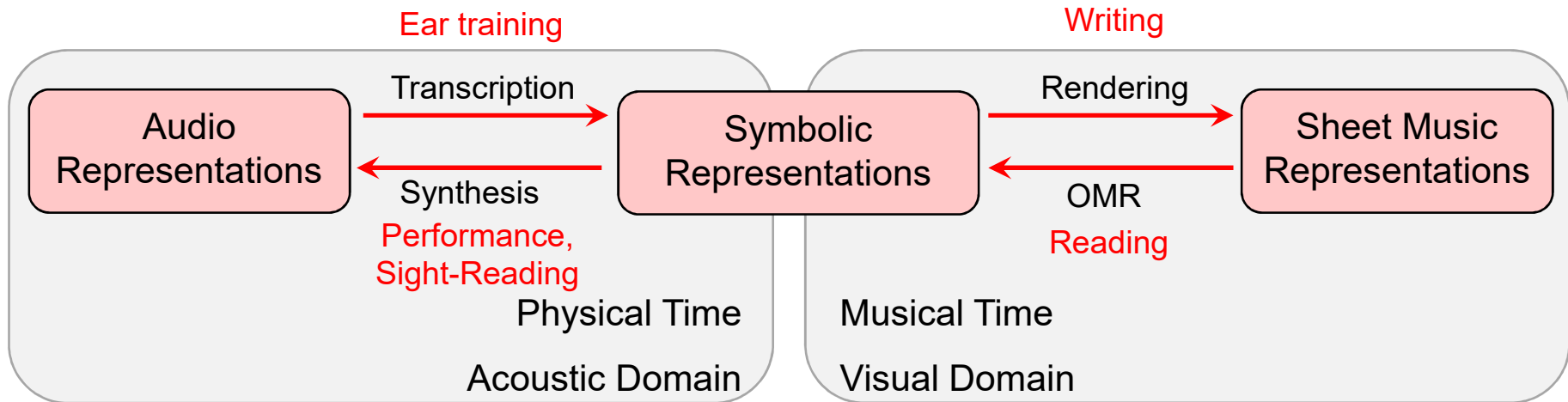


OMR = optical music recognition

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