

Lecture

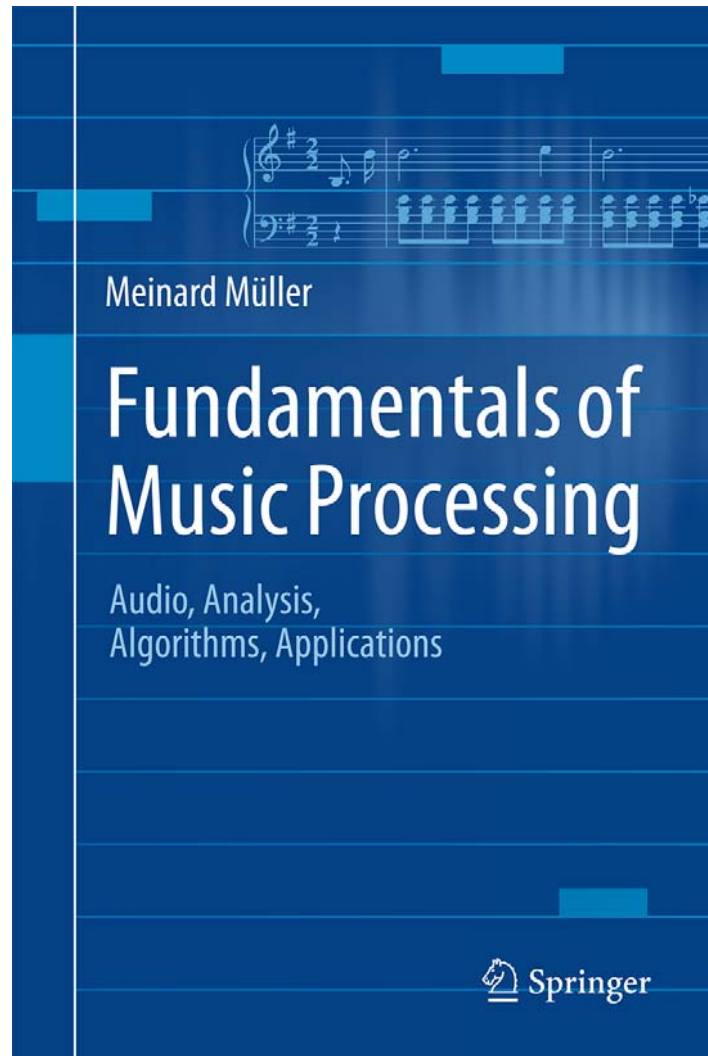
Music Processing

Music Representations

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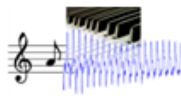

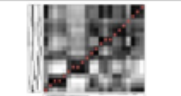


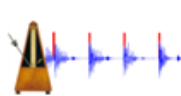
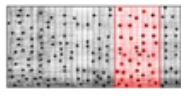
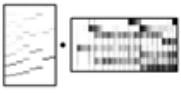
Book: Fundamentals of Music Processing



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

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

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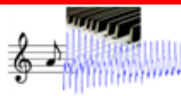

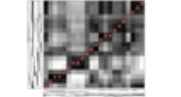


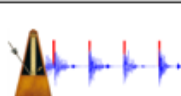
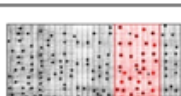
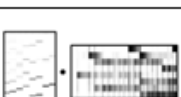
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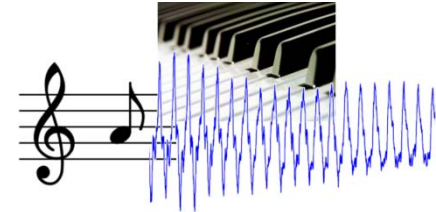
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Chapter 1: Music Representations

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

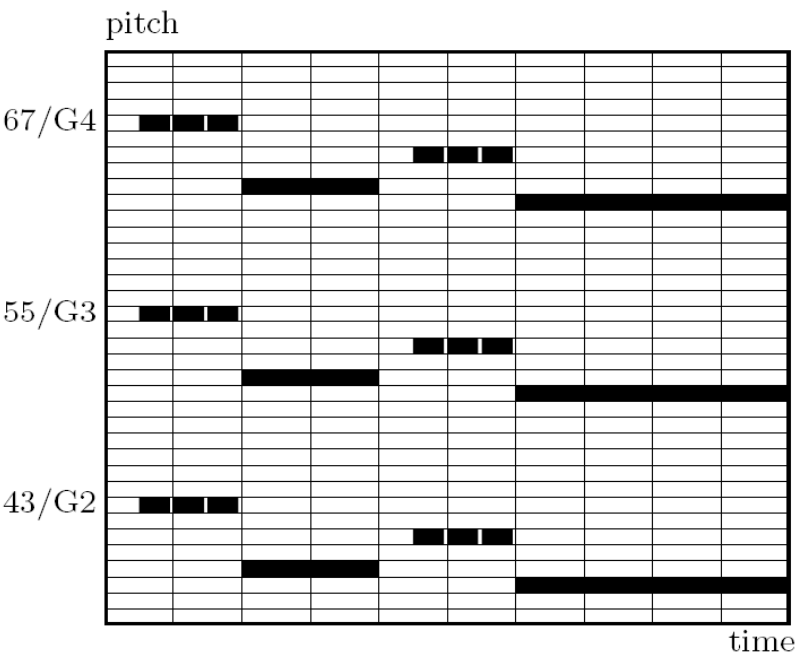
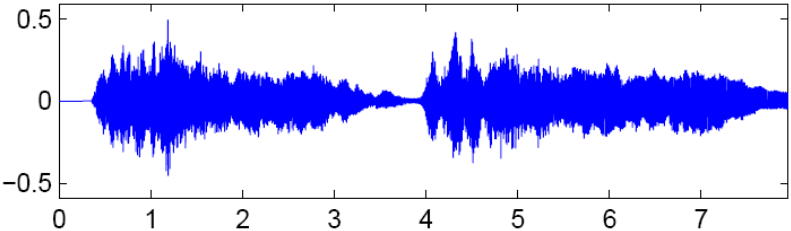


Musical information can be represented in many different ways. In Chapter 1, we consider three widely used music representations: sheet music, symbolic, and audio representations. This first chapter also introduces basic terminology that is used throughout the book. In particular, we discuss musical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

Music Representations

Allegro con brio ($\text{♩} = 108$)

The musical score is for a piano piece in 2/4 time, marked *ff* (fortissimo). It features a melody in the right hand and a bass line in the left hand. The tempo is *Allegro con brio* with a quarter note equal to 108 beats per minute. The score includes two *Rit.* (ritardando) markings with asterisks, indicating a gradual deceleration at the end of the first and second phrases.



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

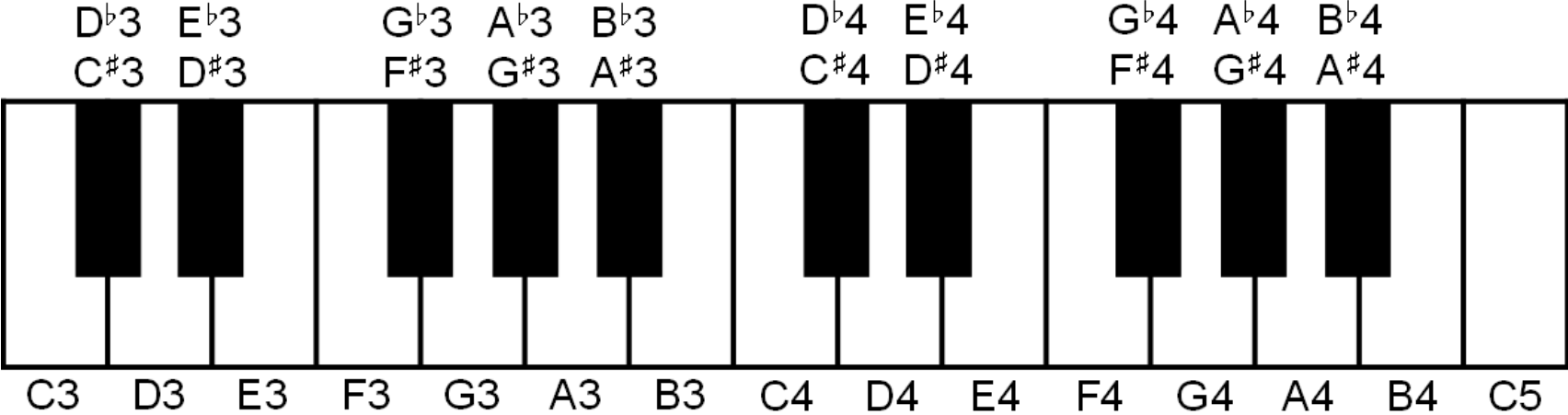
Sheet Music Representation

Allegro con brio (♩ = 108)

The image shows a musical score for piano in 2/4 time, featuring a forte (*ff*) dynamic and a 'Ped.' marking with a flower symbol. The score is written in a grand staff with a treble and bass clef. The key signature has 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 two staves. The first staff (treble clef) starts with a forte (*ff*) dynamic and features a series of chords and a melodic line. The second staff (bass clef) features a melodic line with a 'Ped.' marking and a flower symbol. The score is divided into four measures by vertical bar lines.

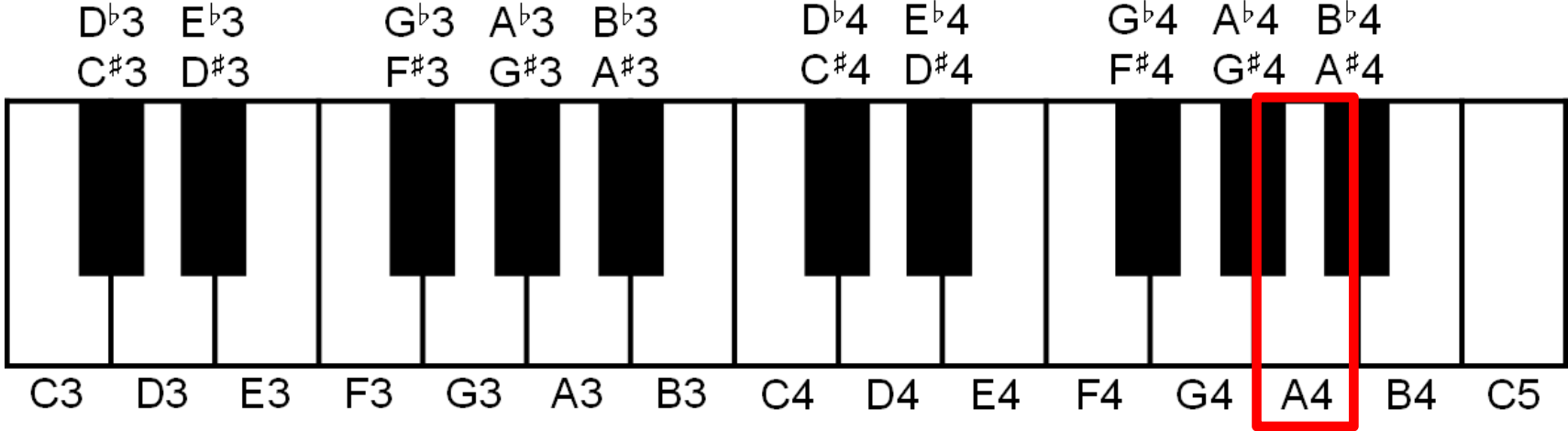
Sheet Music Representation

Piano keyboard and notes



Sheet Music Representation

Piano keyboard and notes

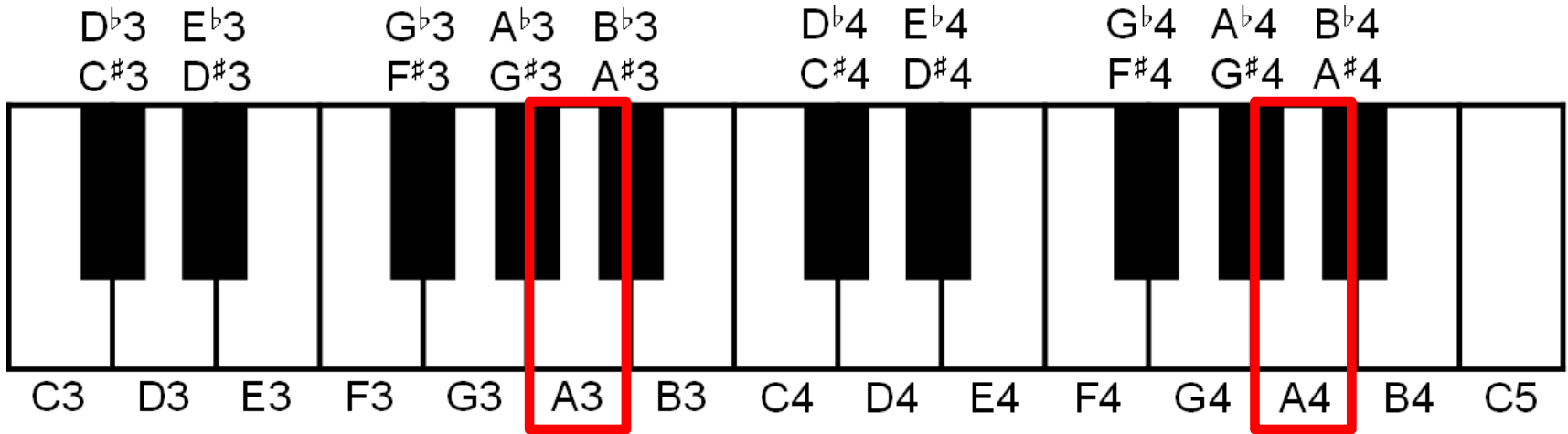


A4

A \triangleq pitch spelling attribute
4 \triangleq octave number

Sheet Music Representation

Piano keyboard and notes

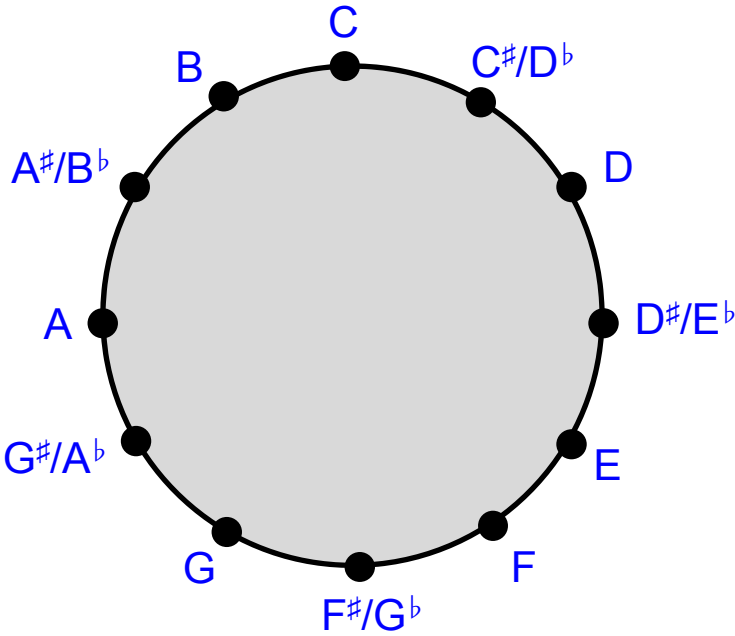


A \triangleq pitch spelling attribute
4 \triangleq octave number

Sheet Music Representation

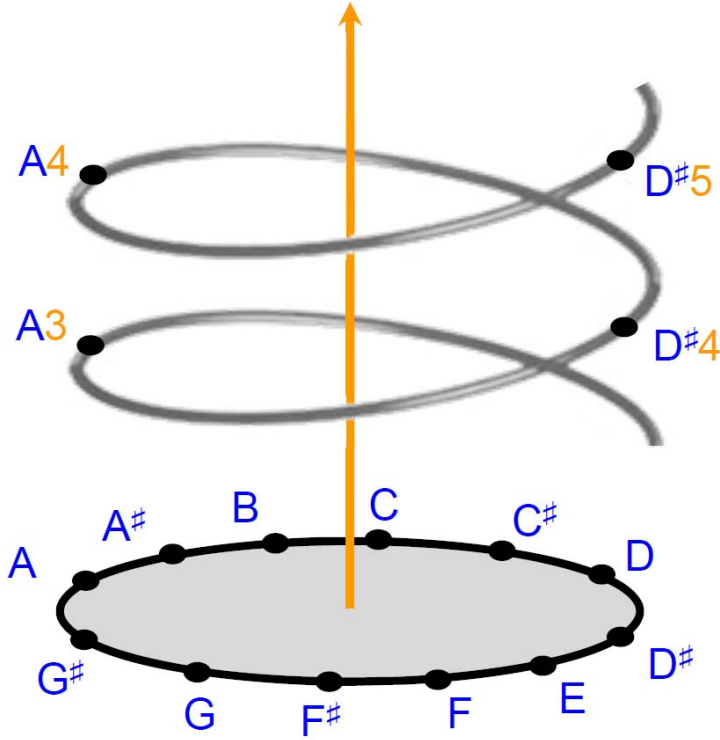
Chromatic circle

Chroma \triangleq pitch spelling attribute



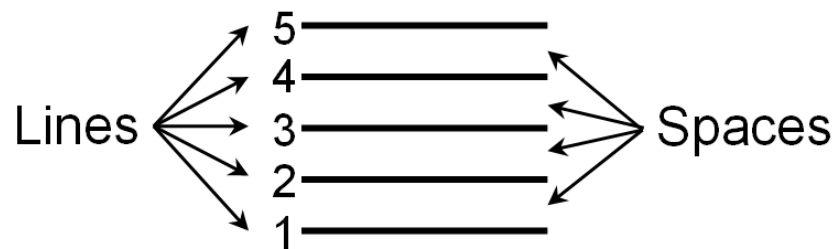
Shepard's helix of pitch

Tone height \triangleq octave number



Sheet Music Representation

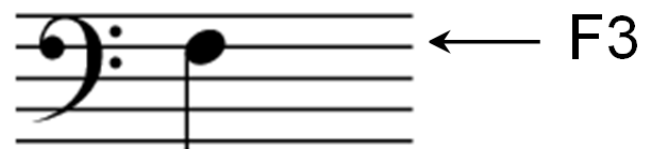
Staff



Staff with G-clef



Staff with F-clef



Sheet Music Representation

Musical score of a C-major scale



Sheet Music Representation

Musical score of a C-major scale



A musical staff in treble clef showing the C-major scale. The notes are C4, D4, E4, F4, G4, A4, B4, and C5, all marked with natural signs. The notes are placed on the following lines of the staff: C4 on the first line, D4 on the second line, E4 on the third line, F4 on the fourth line, G4 on the fifth line, A4 on the first space, B4 on the second space, and C5 on the third space.

Musical score of a C-minor scale



A musical staff in treble clef showing the C-minor scale. The notes are C4, D4, E^b4, F4, G4, A^b4, B^b4, and C5. The notes are placed on the following lines of the staff: C4 on the first line, D4 on the second line, E^b4 on the third line, F4 on the fourth line, G4 on the fifth line, A^b4 on the first space, B^b4 on the second space, and C5 on the third space. The key signature consists of three flats (B^b, E^b, and A^b), which are circled in red.

Key signature consisting of three flats

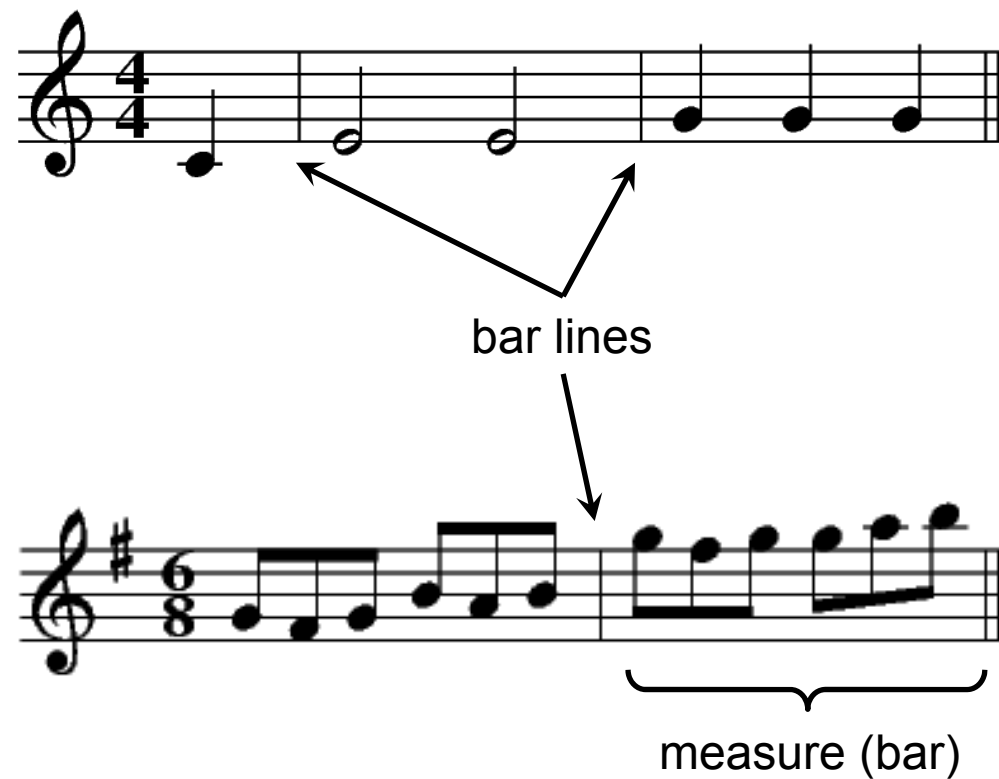
Sheet Music Representation

Time signature



Sheet Music Representation

Time signature



Sheet Music Representation

Time signature

Four quarter notes
per measure



bar lines

Six eighth notes
per measure

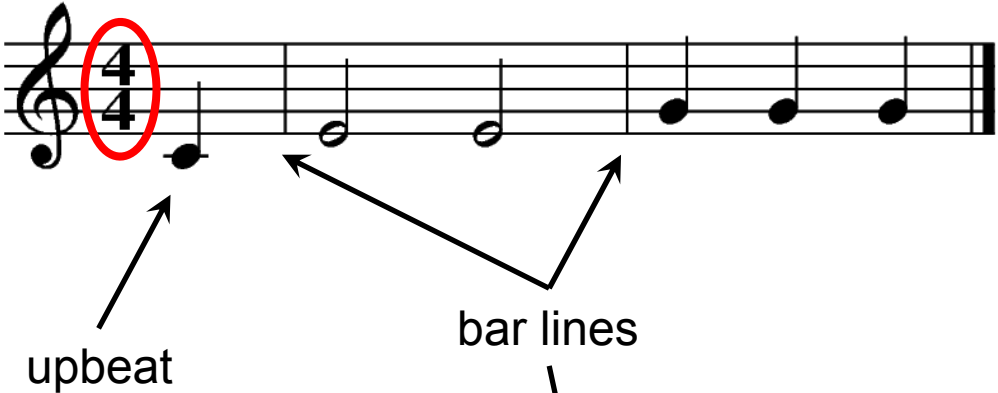


measure (bar)

Sheet Music Representation

Time signature

Four quarter notes
per measure



upbeat

bar lines

Detailed description: A musical staff in treble clef with a 4/4 time signature. The time signature is circled in red. The staff contains four measures. The first measure starts with an upbeat (a quarter note) followed by three quarter notes. The subsequent three measures each contain four quarter notes. Vertical bar lines separate the measures. An arrow points from the text 'upbeat' to the first note. Two arrows point from the text 'bar lines' to the first and second bar lines.

Six eighth notes
per measure



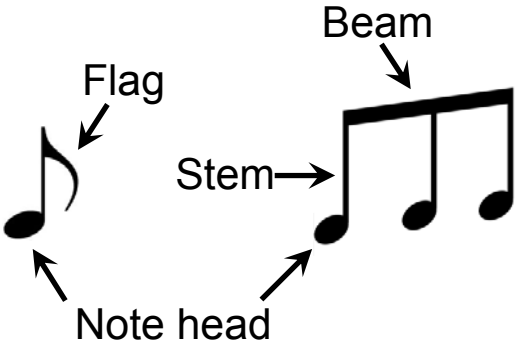
measure (bar)

Detailed description: A musical staff in treble clef with a 6/8 time signature. The time signature is circled in red. The staff contains three measures. The first measure has six eighth notes. The second measure has a dotted quarter note followed by an eighth note. The third measure has a dotted quarter note followed by an eighth note. A bracket under the third measure is labeled 'measure (bar)'. An arrow points from the text 'bar lines' (located above the first staff) to the first bar line of this staff.

Sheet Music Representation

Note durations

Parts of a note



Different durations of notes

A musical staff in treble clef showing five notes of different durations: 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).

Whole note Half note Quarter note Eighth note Sixteenth note

Different durations of rests

A musical staff in treble clef showing five rests of different durations: 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).

Whole rest Half rest Quarter rest Eighth rest Sixteenth rest

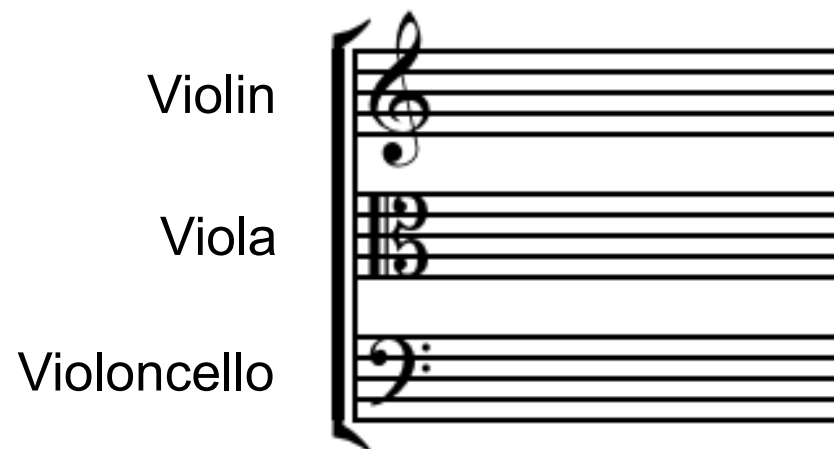
Sheet Music Representation

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 notation is divided into four measures. The first measure contains four quarter notes (C4, D4, E4, F4) with a 'crescendo' hairpin above it. The second measure contains four quarter notes (G4, A4, B4, C5) with a 'diminuendo' hairpin above it. The third measure contains four quarter notes (B4, A4, G4, F4) with a slur underneath and an upward-pointing arrow labeled 'legato' below it; the dynamic marking 'piano' (*p*) is placed above this measure. The fourth measure contains four quarter notes (E4, D4, C4, B3) with a 'forte' (*f*) dynamic marking above it and two downward-pointing arrows labeled 'staccato' below it. The final two notes of the fourth measure, C4 and B3, have the lyrics 'do re mi fa so la si do' written below them, with the word 'lyrics' centered under the entire phrase.

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 tempo is marked 'Allegro con brio' with a metronome marking of 108 beats per minute. The music is in 2/4 time and B-flat major. The staves are arranged in three groups: woodwinds (Flauti, Oboi, Clarineti in B, Fagotti), brass and percussion (Corni in Es, Trombe in C, Timpani in C.G.), and strings (Violino I, Violino II, Viola, Violoncello, Basso). Dynamics include fortissimo (ff) and piano (p). The woodwinds and strings have active parts, while the brass and percussion are mostly silent in this section.

Sheet Music Representation

A hand-drawn musical notation on a five-line staff. The staff begins with a treble clef, a key signature of one flat (Bb), and a 4/4 time signature. The melody consists of four notes: a half note G4 (labeled 'W'), a half note Bb4 (labeled 'KI'), a quarter note D5 (labeled 'PE'), and a quarter note A4 (labeled 'DI - A'). Above the staff, the text 'CHORD SYMBOLS' is written, with lines pointing to 'C7' above the first note and 'F' above the third note. The word 'MELODY' is written above the staff with a line pointing to the first two notes. Below the staff, the lyrics 'WIKIPEDIA' are written, with hyphens under 'KI' and 'DI - A'. The word 'LYRIC' is written below the staff with a line pointing to the 'A'.

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

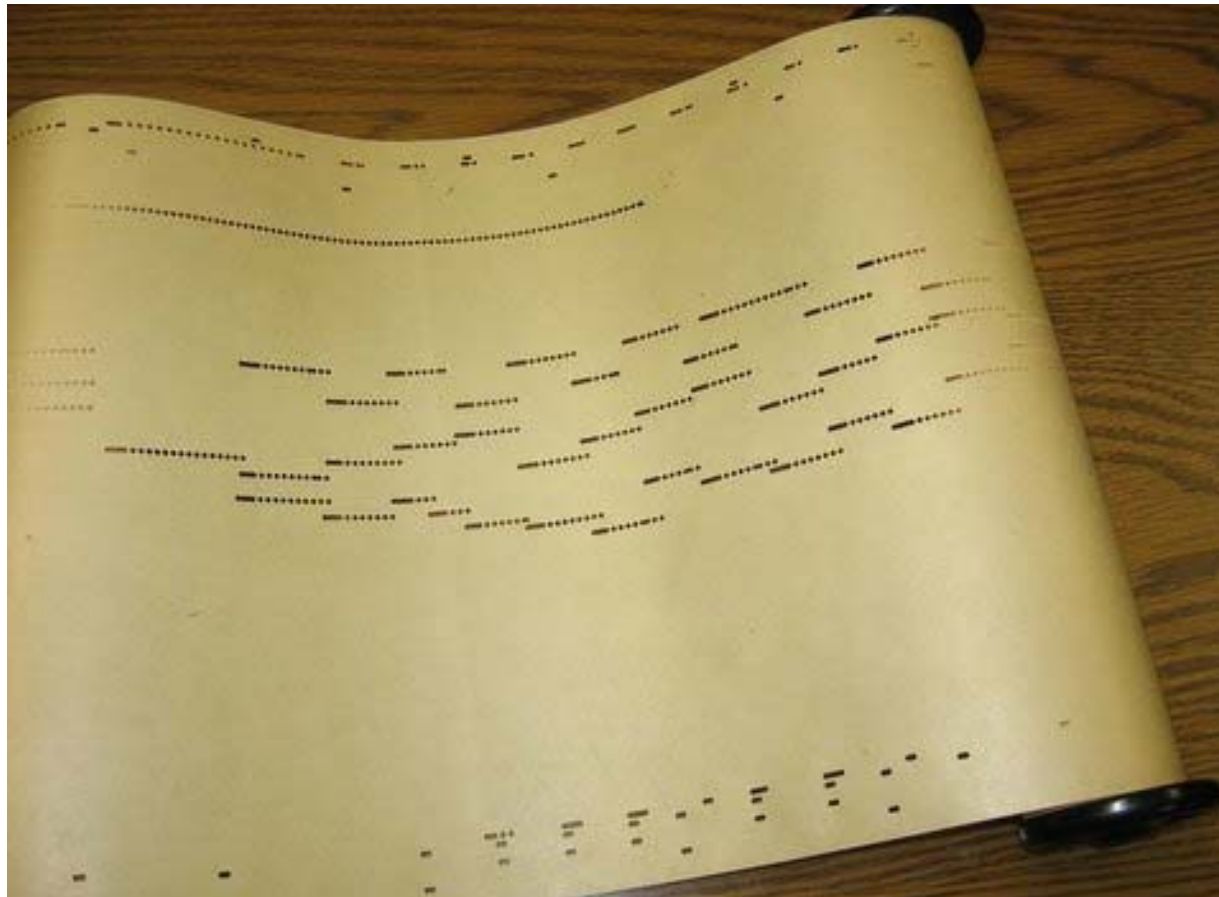
MusicXML

```
<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



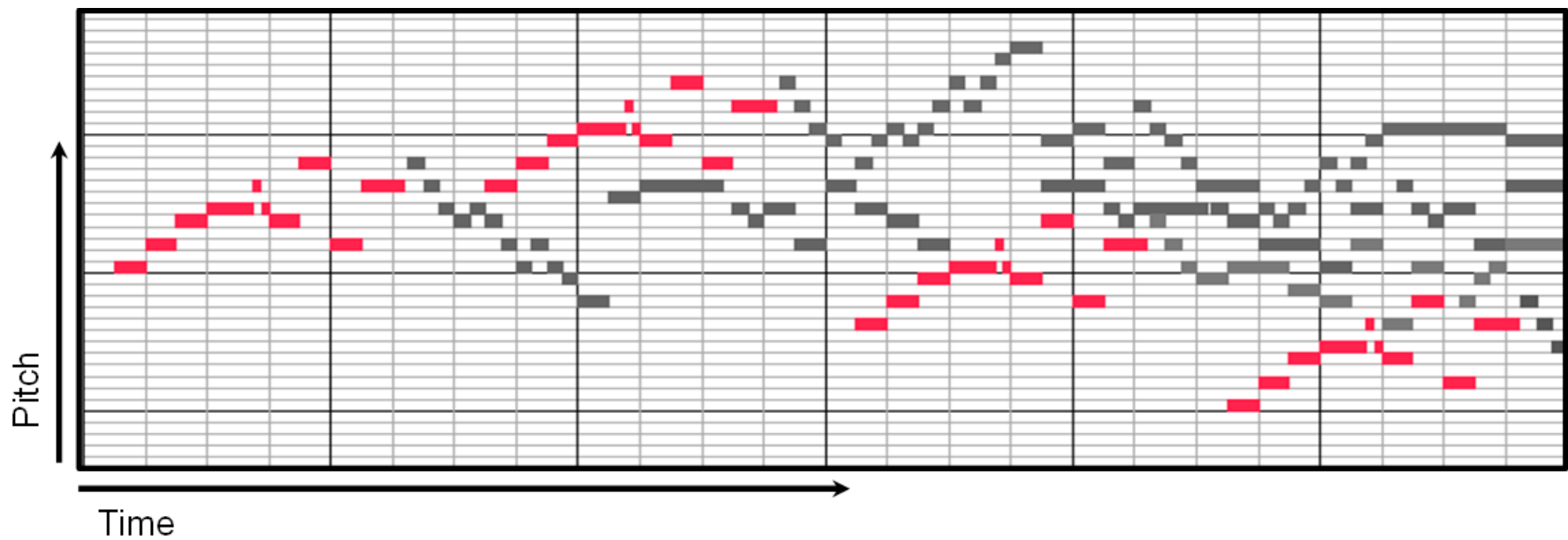
Symbolic Representation

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

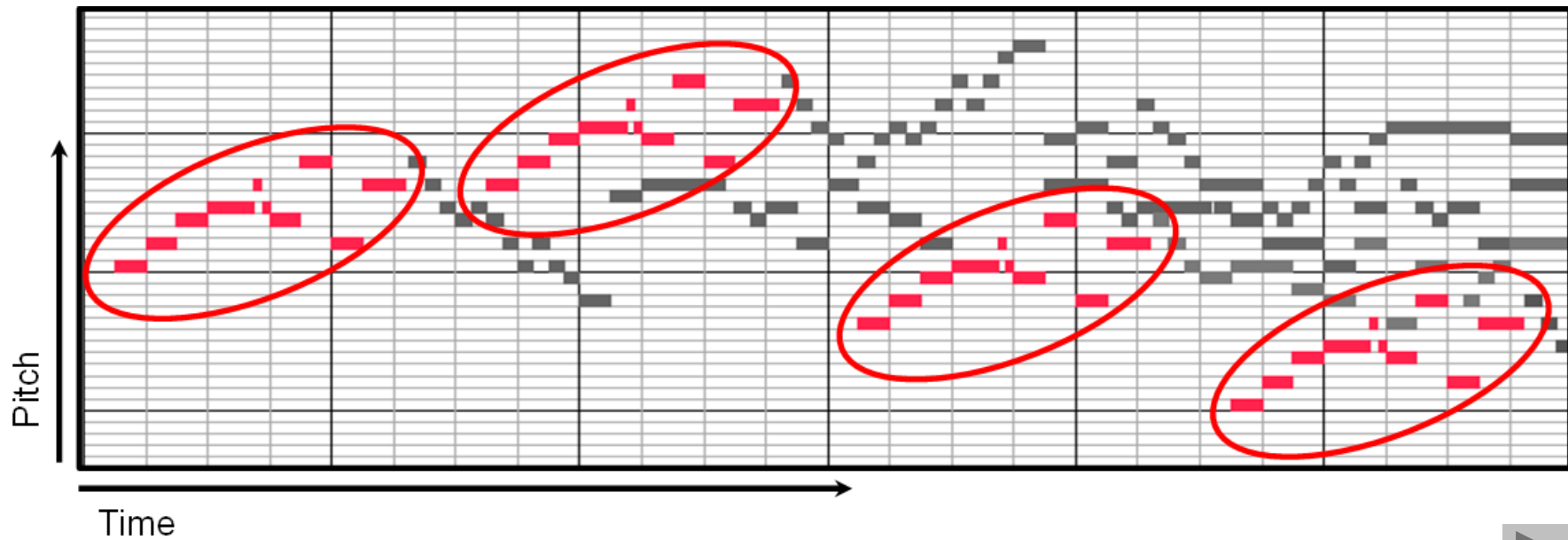
Symbolic Representation

Piano roll representation



Symbolic Representation

Piano roll representation



Symbolic Representation

MIDI representation

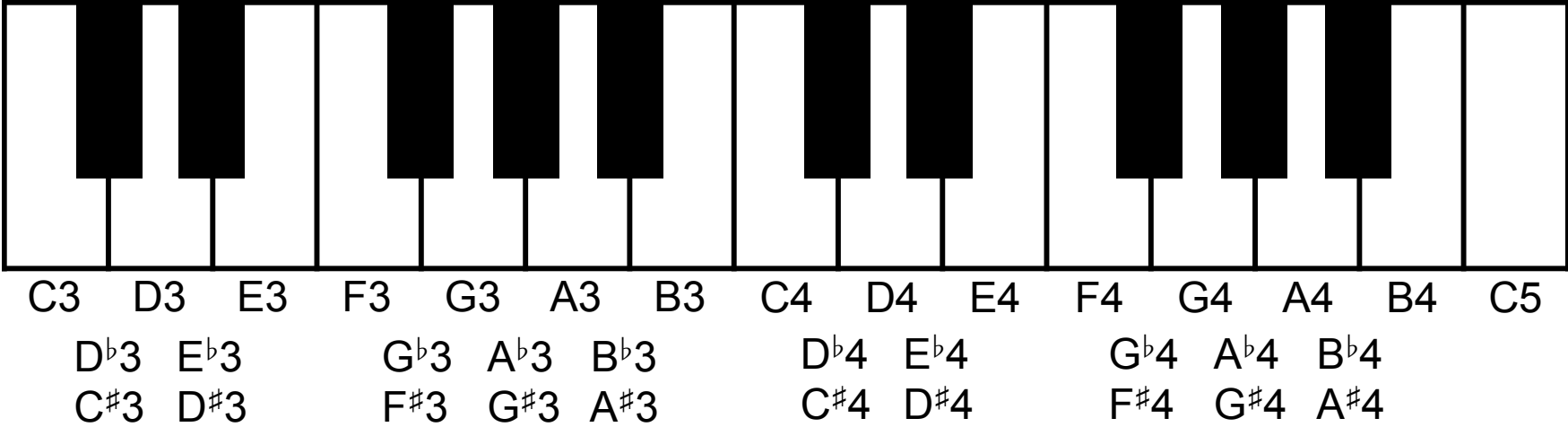
- Musical Instrument Digital Interface (MIDI)
- Standard protocol for controlling and synchronizing digital instruments
- Standard MIDI File (SMF) is used for collecting and storing MIDI messages
- SMF file is often called MIDI file

Symbolic Representation

MIDI representation

MIDI note numbers (MNN) \triangleq piano keys

49 51 54 56 58 61 63 66 68 70
48 50 52 53 55 57 59 60 62 64 65 67 69 71 72



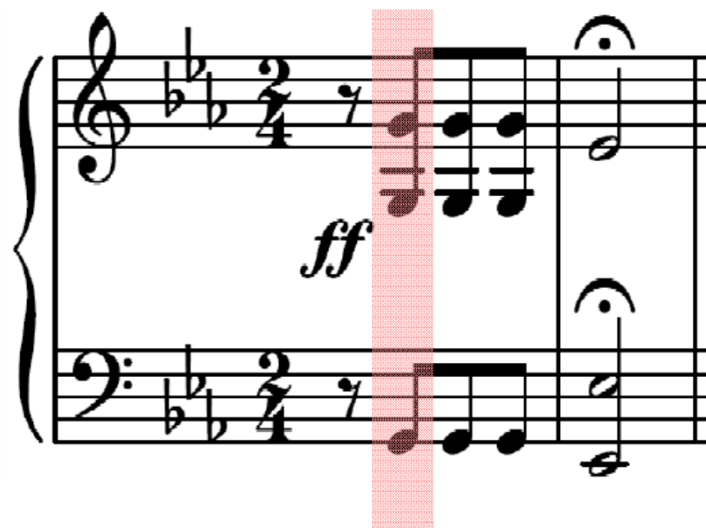
Symbolic Representation

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

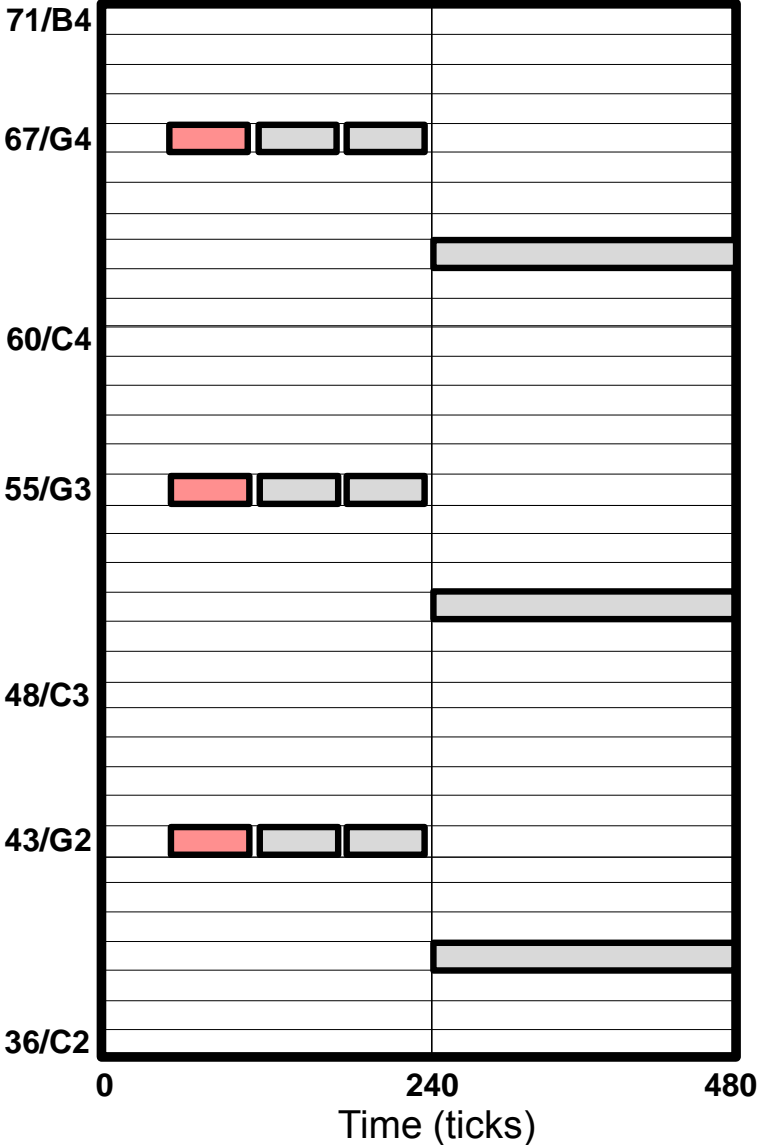
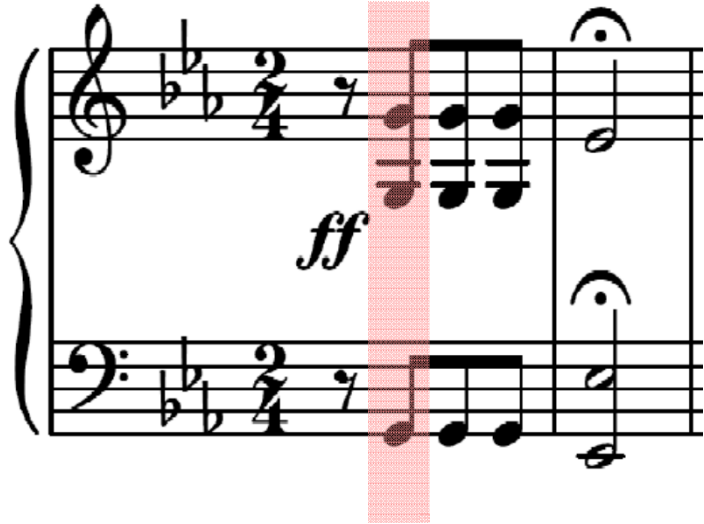
MIDI representation



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



Audio Representation

Various interpretations – Beethoven's Fifth

Bernstein



Karajan



Scherbakov (piano)

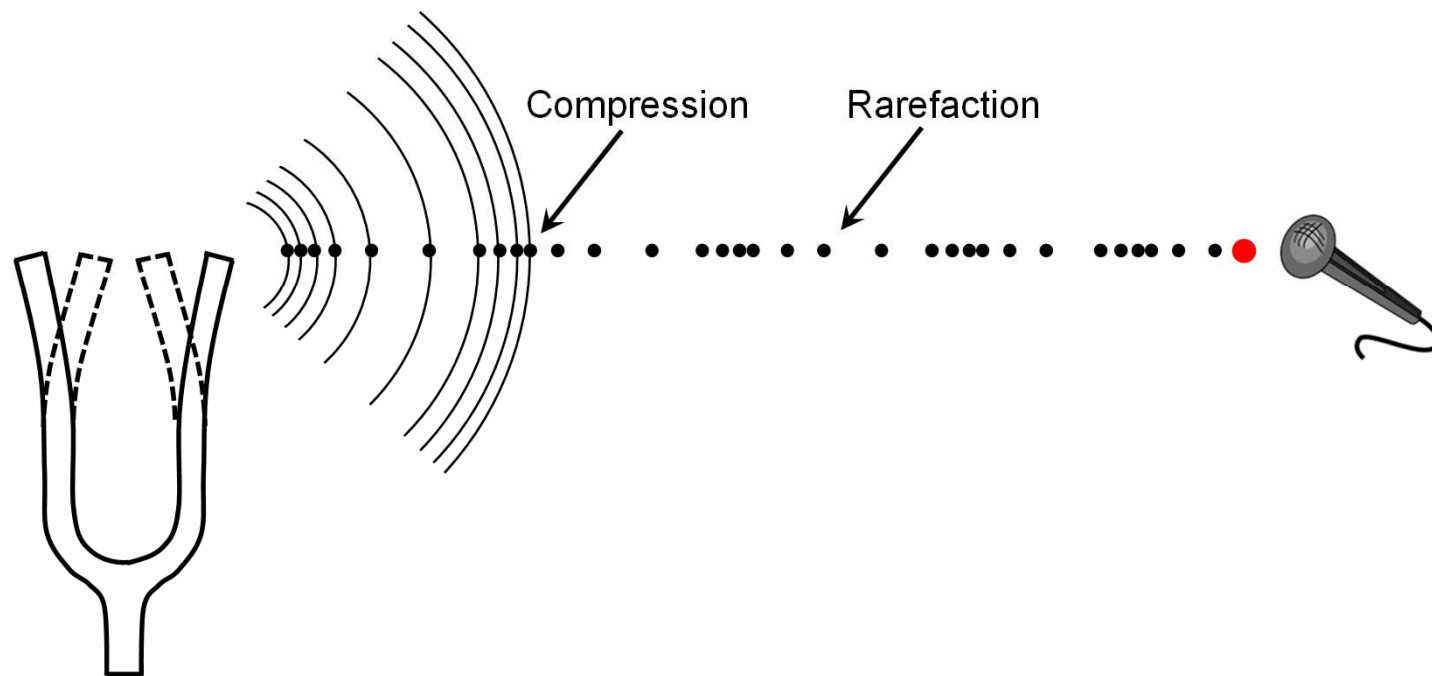


MIDI (piano)



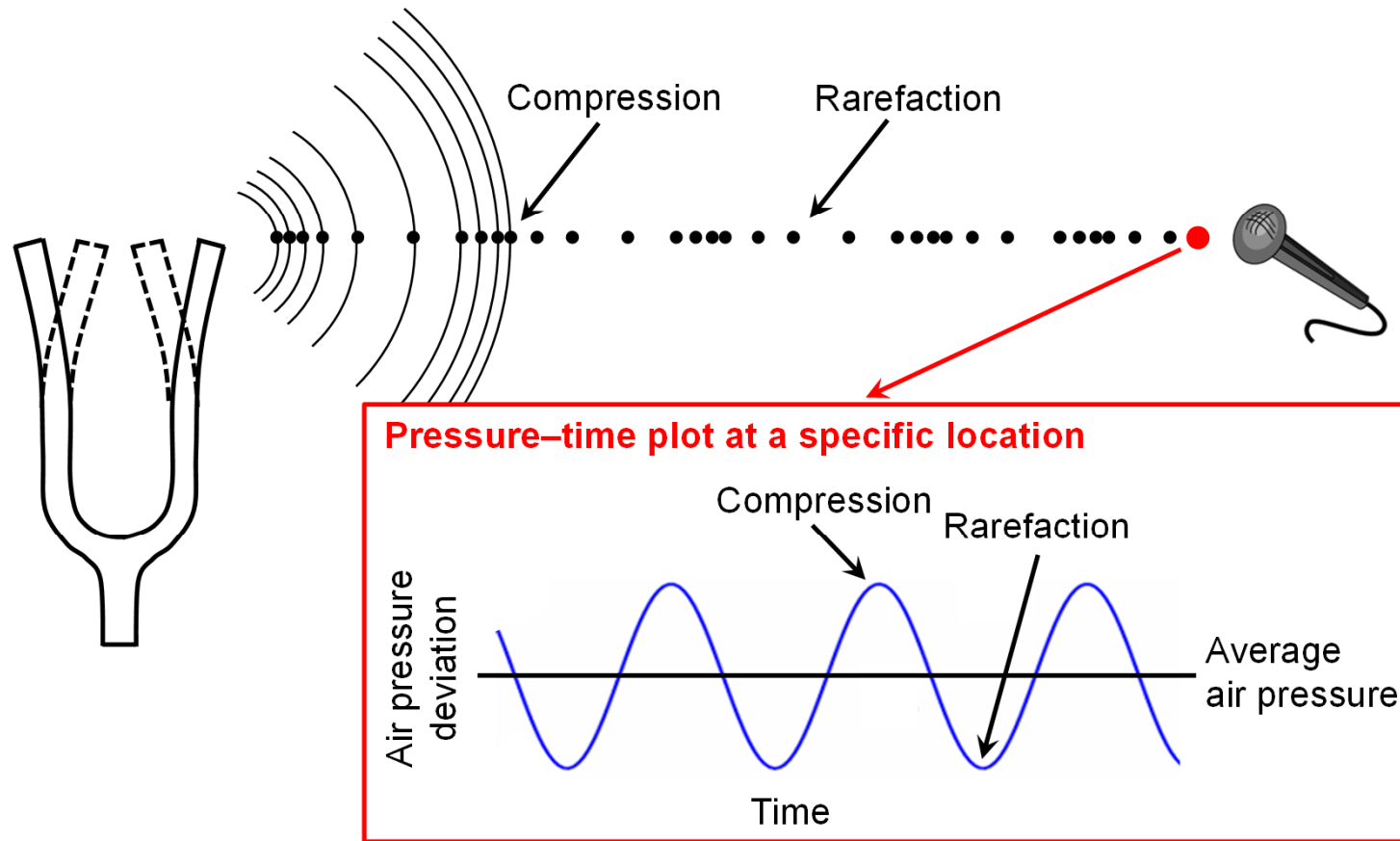
Audio Representation

Waveform



Audio Representation

Waveform



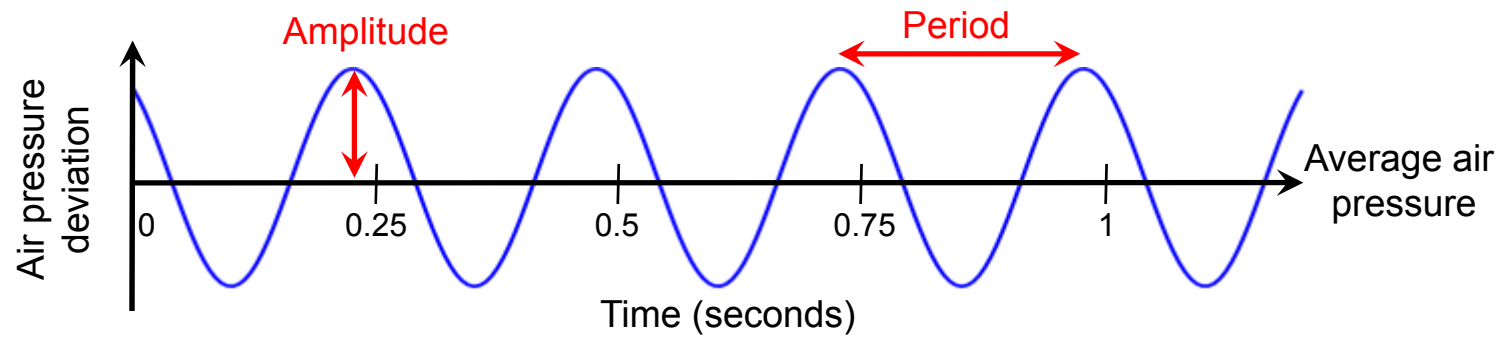
Audio Representation

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):

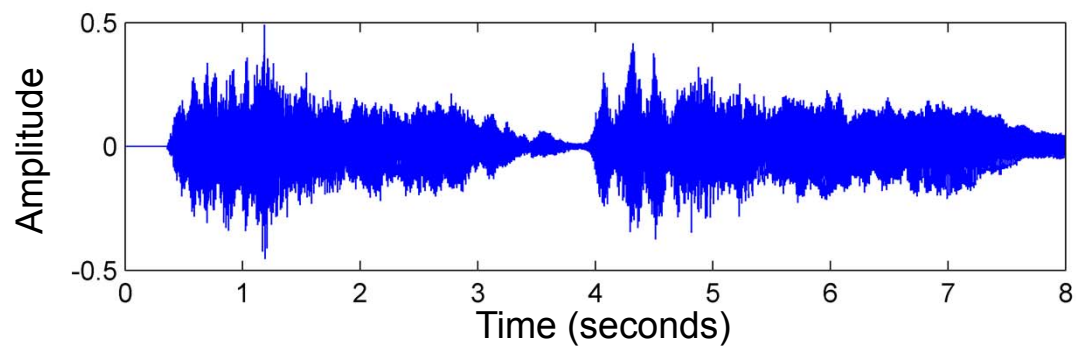
- Sinusoidal waveform
- Prototype of an acoustic realization of a musical note

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

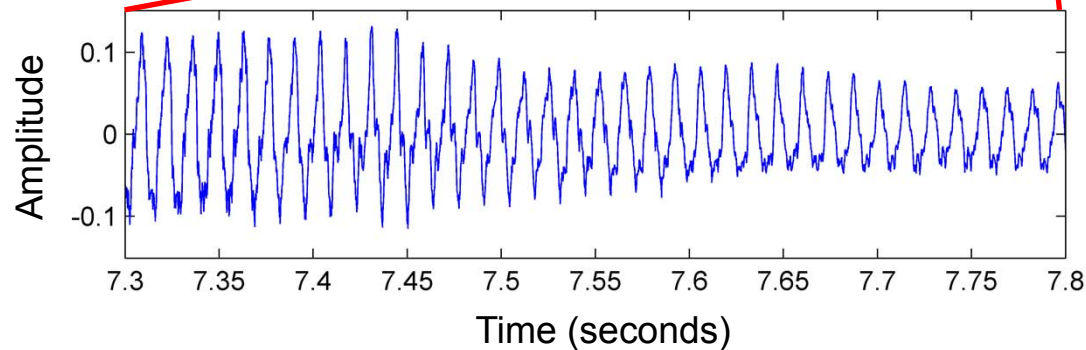
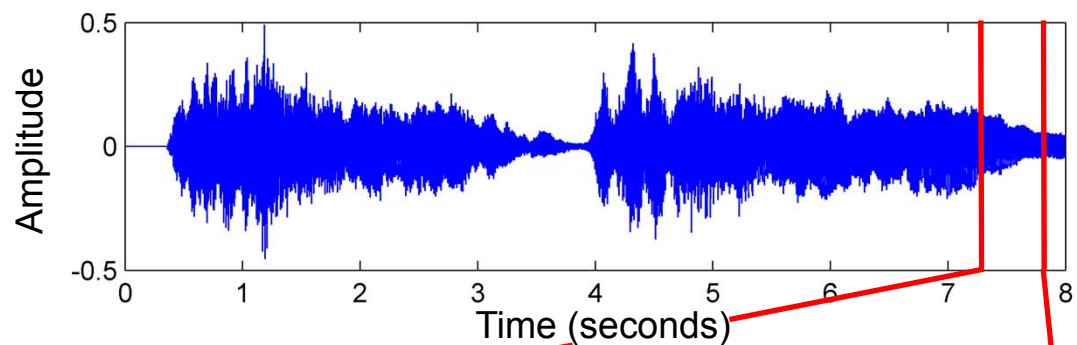
Audio Representation

Waveform



Audio Representation

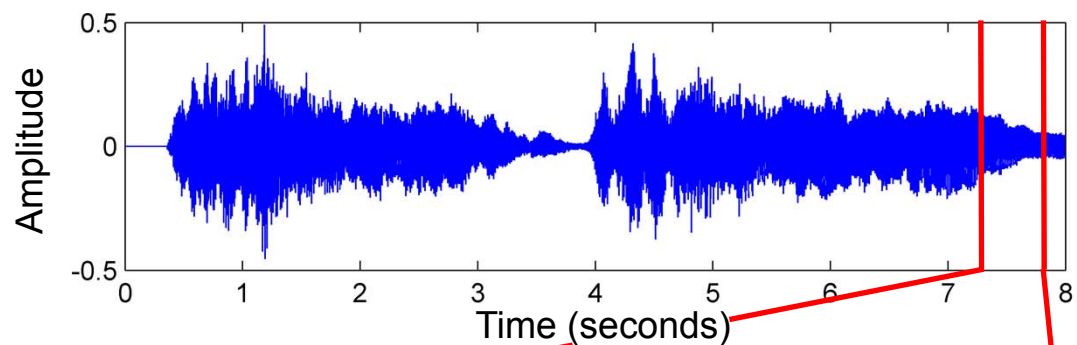
Waveform



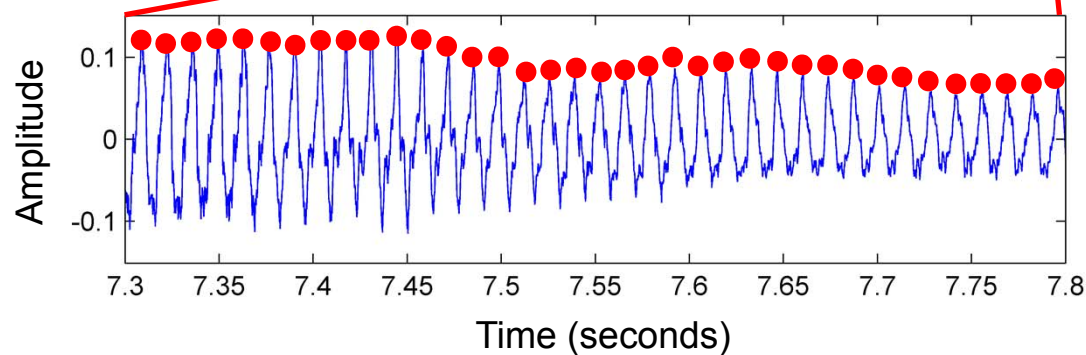
D2 (73.4 Hz)

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)
- Referenz 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



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

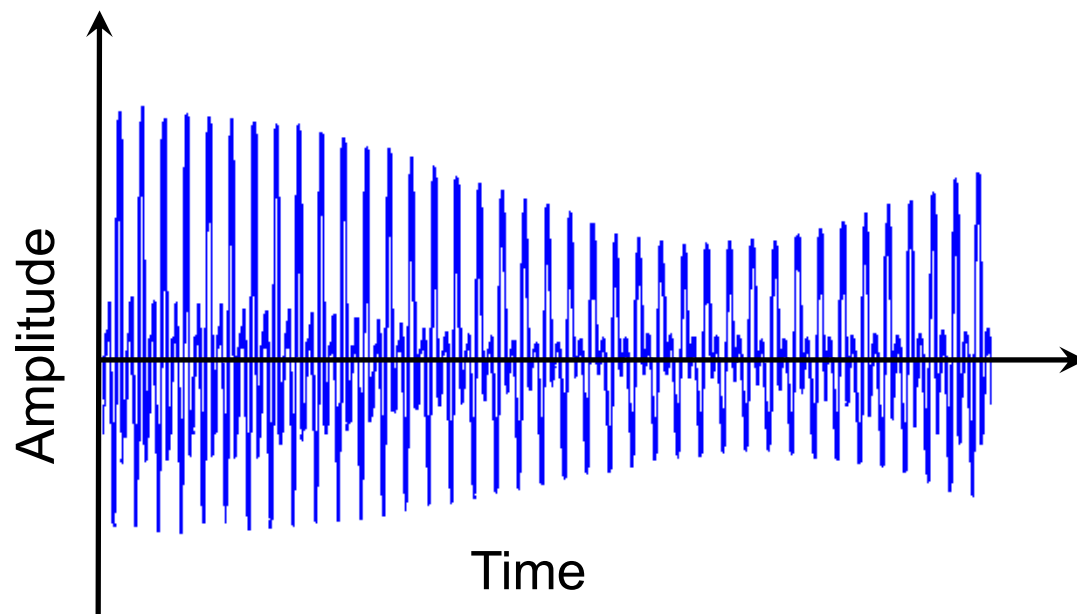
Audio Representation

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}

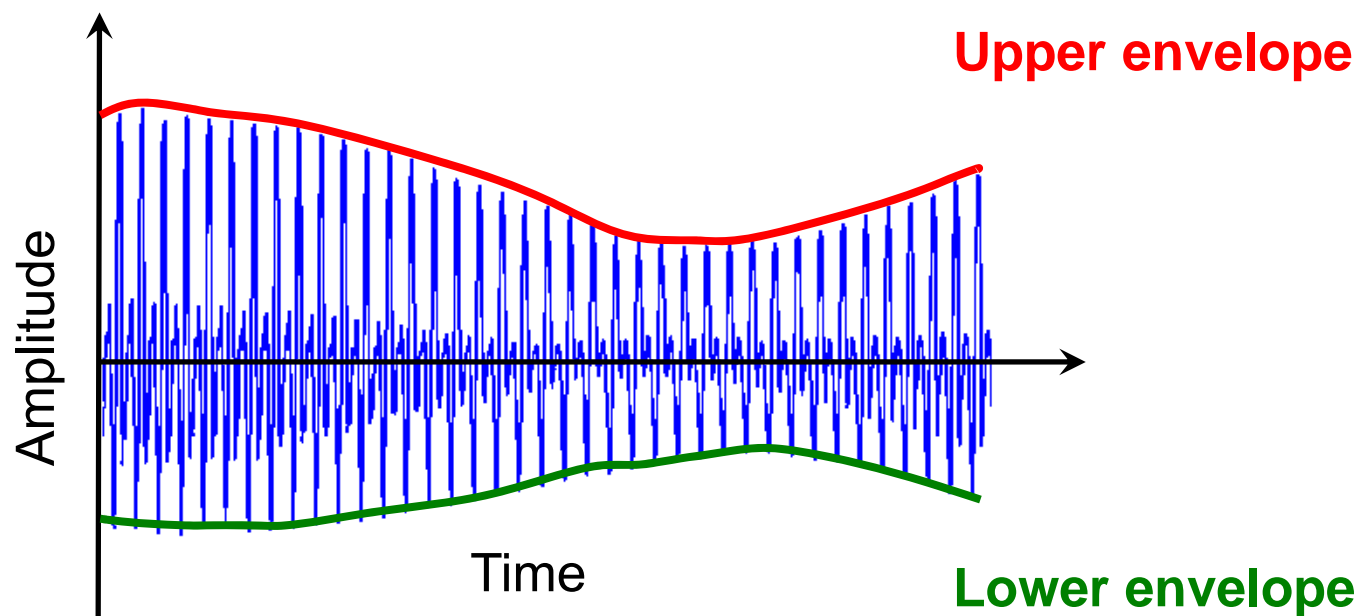
Audio Representation

Dynamics



Audio Representation

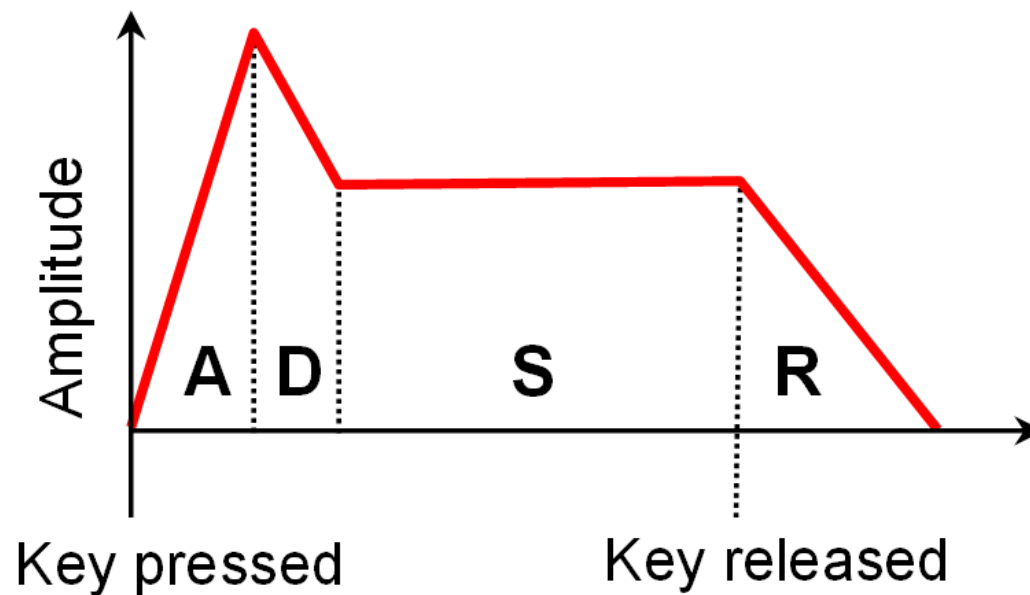
Dynamics



Audio Representation

Dynamics

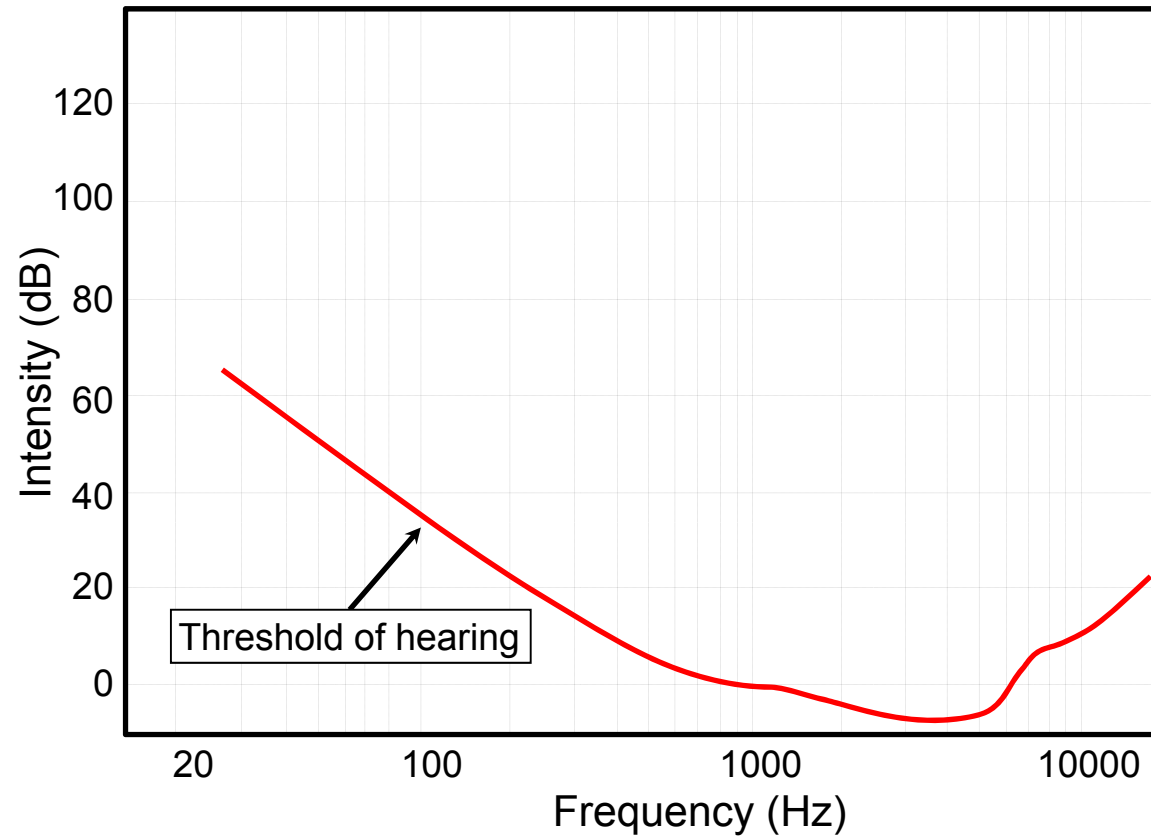
ADSR model: attack (A), decay (D), sustain (S), and release (R) phase



Audio Representation

Loudness

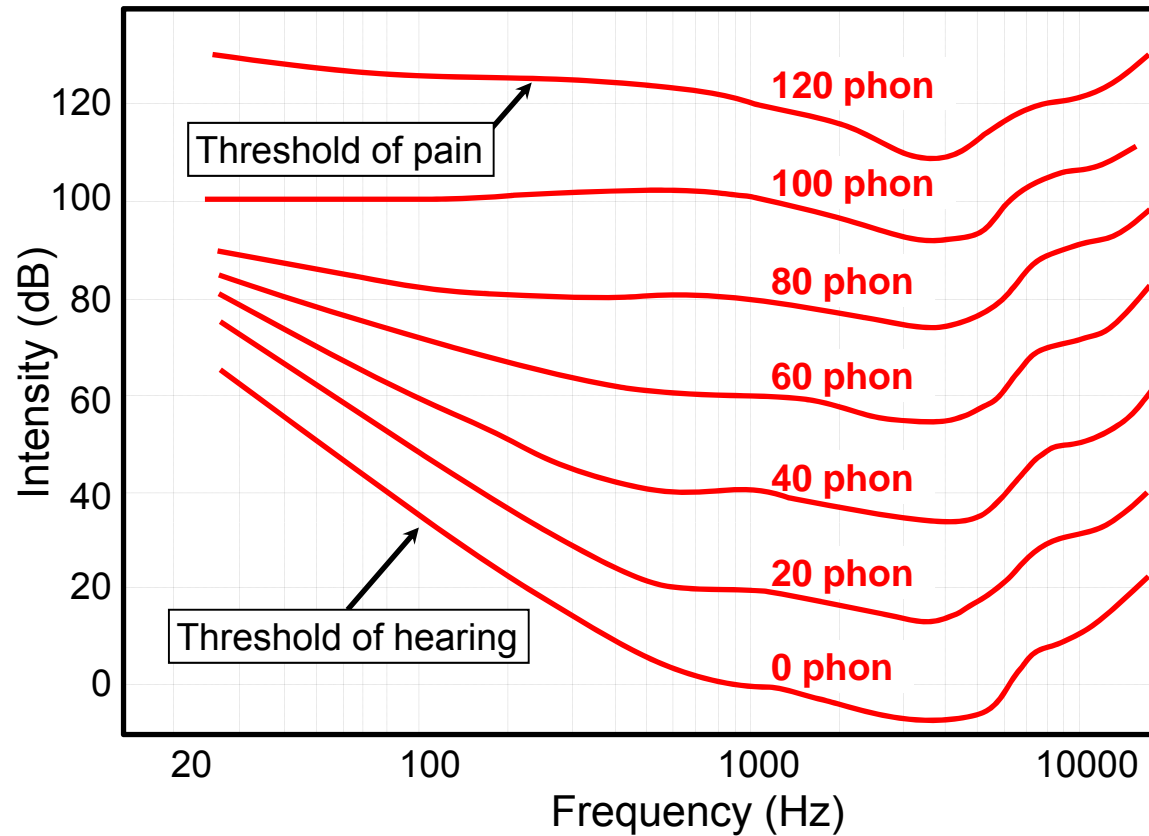
Equal-loudness contours (phon)



Audio Representation

Loudness

Equal-loudness contours (phon)



Audio Representation

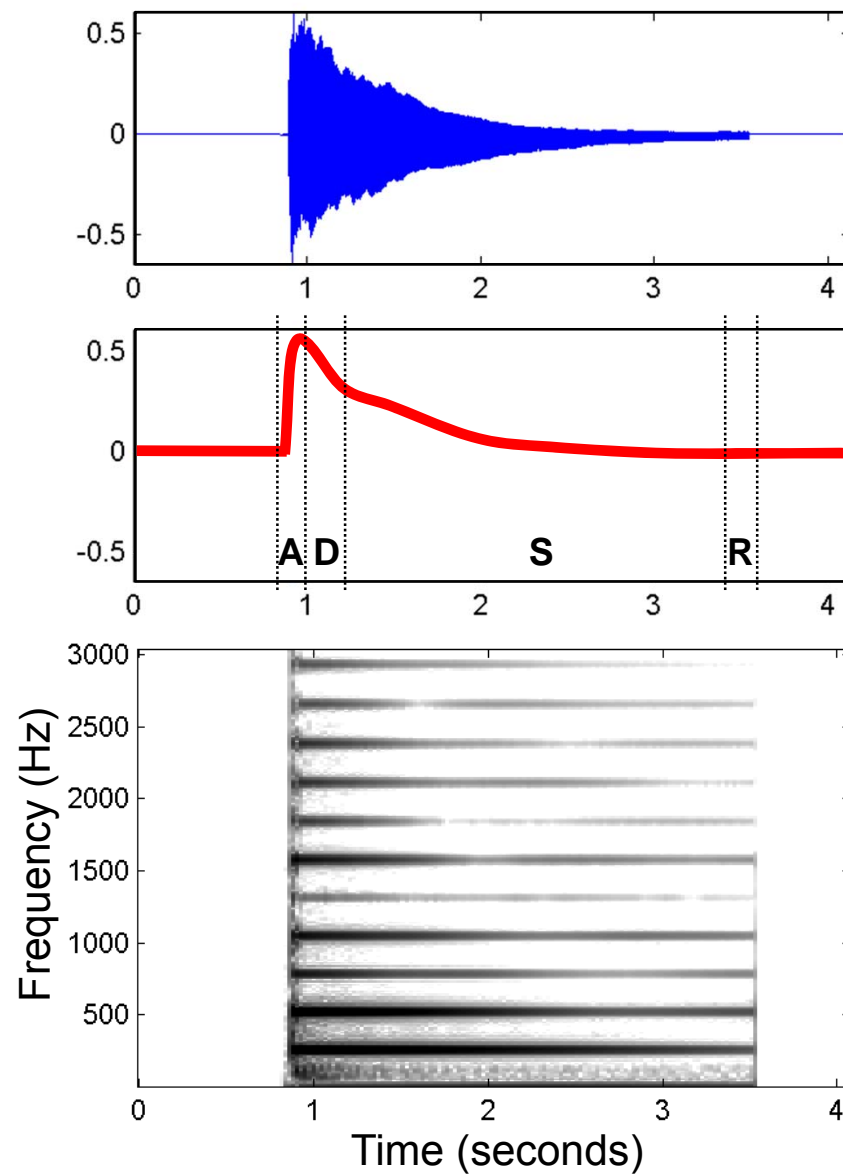
Timbre

- 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

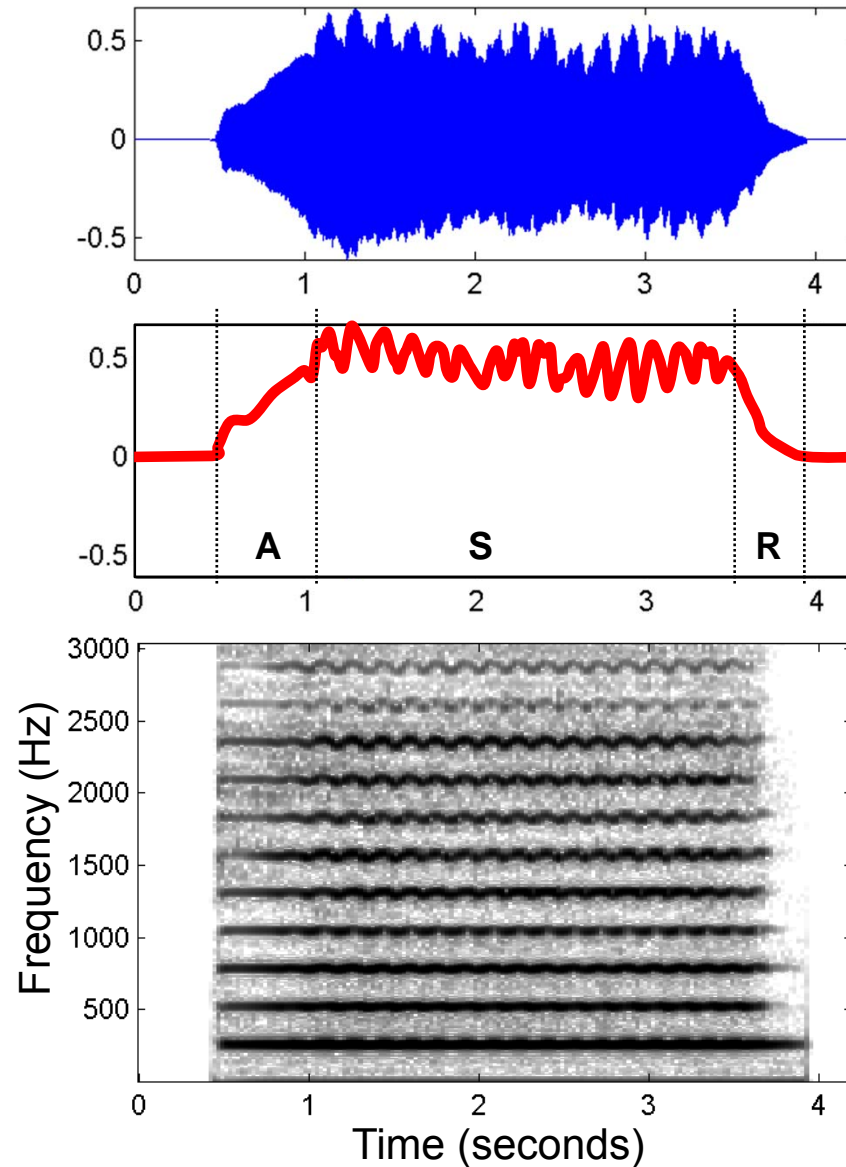
Timbre

Violine playing
note C4 (261.6 Hz)



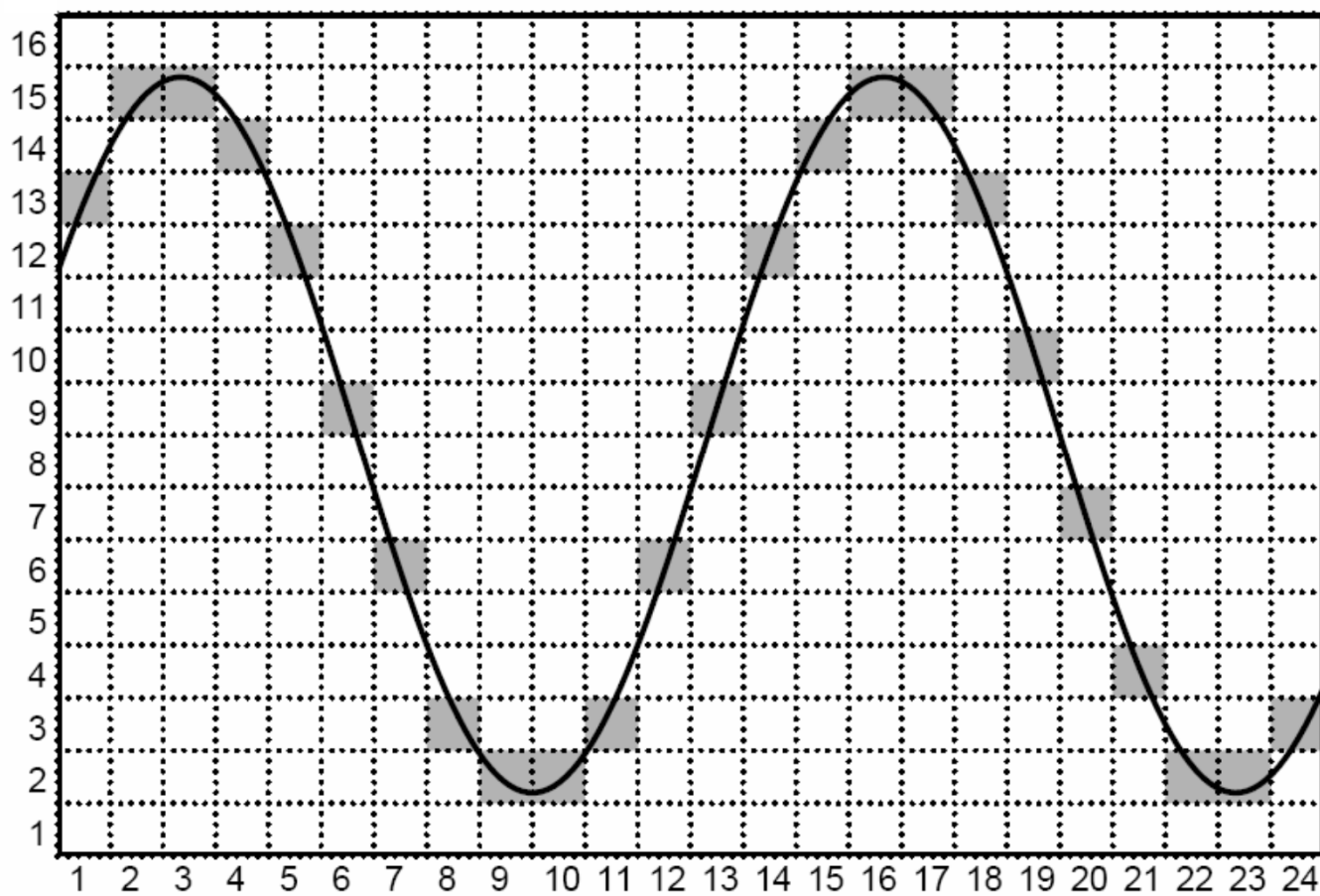
Vibrato:
Frequency modulations

Tremolo:
Amplitude modulations



Audio Representation

Digitization



Audio Representation

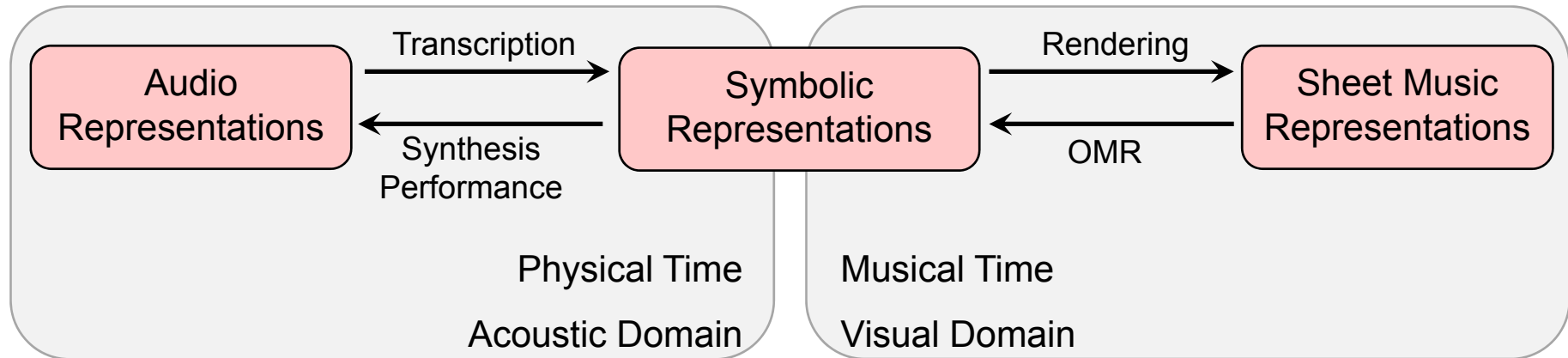
Digitization

- 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



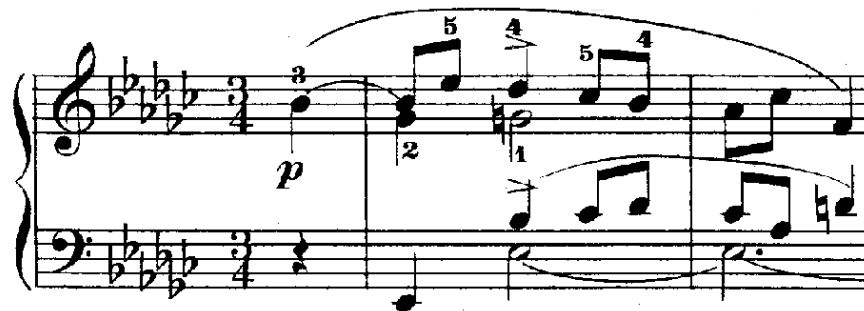
OMR = optical music recognition

Process of transforming sheet music into a symbolic representation

Music Representations

OMR

Original score



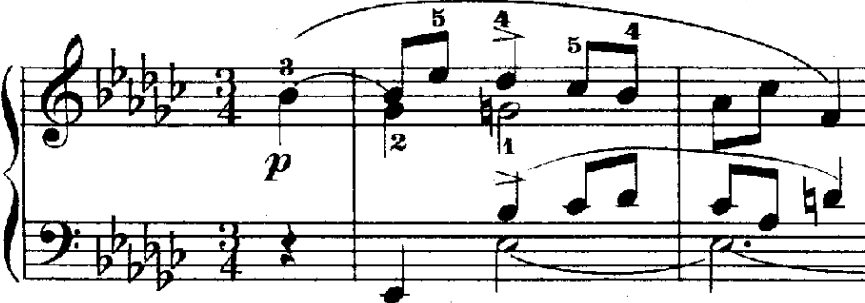
OMR score



Music Representations

OMR

Original score



OMR score



OMR errors