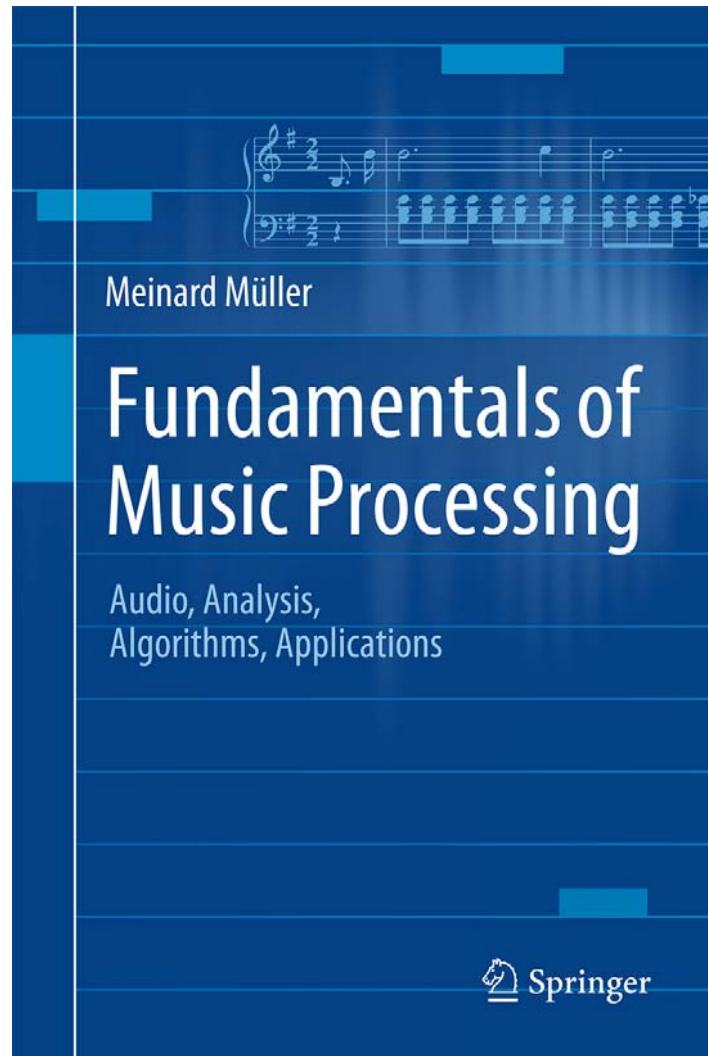


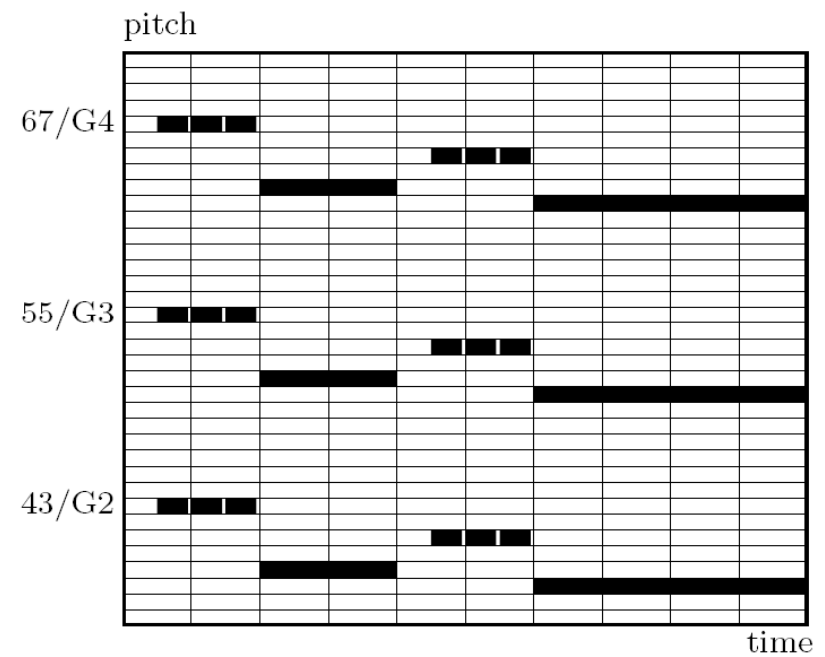
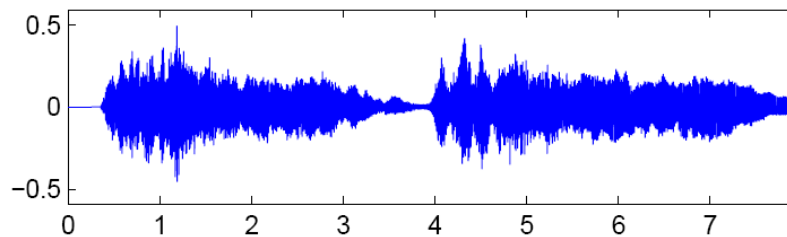
# Book: Fundamentals of Music Processing



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

Accompanying website:  
[www.music-processing.de](http://www.music-processing.de)

# Music Representations



# Music Representations

- Sheet music representation
  - visual description of a musical score
  - image format (printed or scanned)
- Symbolic representations
  - description based on entities with explicit musical meaning
  - given in digital format that can be parsed by a computer
- Audio representation
  - physical description
  - encoding of sound wave

# Sheet Music Representation

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

# Sheet Music Representation

Allegro con brio (♩ = 108)

*ff*

*Ped.* \* *Ped.* \*

# Sheet Music Representation

**Allegro con brio.  $\text{♩} = 108$ .**

Flauti.

Oboi.

Clarinetti in B.

Fagotti.

**Allegro con brio.  $\text{♩} = 108$ .**

Corni in Es.

Trombe in C.

Timpani in C.G.

**Allegro con brio.  $\text{♩} = 108$ .**

Violino I.

Violino II.

Viola.

Violoncello.

Basso.

This image displays a page of sheet music for a symphony orchestra. The music is in 2/4 time and marked 'Allegro con brio' with a tempo of 108 beats per minute. The score is divided into three systems. The first system includes staves for Flauti, Oboi, Clarinetti in B, and Fagotti. The second system includes staves for Corni in Es, Trombe in C, and Timpani in C.G. The third system includes staves for Violino I, Violino II, Viola, Violoncello, and Basso. The woodwind and string parts feature various dynamics such as *ff* (fortissimo) and *p* (piano). The woodwinds and strings play a rhythmic pattern of eighth and sixteenth notes, while the brass instruments play a more melodic line. The timpani provide a steady rhythmic accompaniment.

# Sheet Music Representation

*CHORD SYMBOLS*

*C7* *F*

*MELODY*

*Wl - Kl - PE - DI - A*

*LYRIC*

A hand-drawn musical score 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 measures. The first measure contains a whole note on G4, with the chord symbol 'C7' written above it. The second measure contains a whole note on F4, with the chord symbol 'F' written above it. The third measure contains a half note on E4 and a half note on D4, with the chord symbol 'F' written above it. The fourth measure contains a whole note on C4. Below the staff, the lyrics 'Wl - Kl - PE - DI - A' are written, with hyphens indicating the syllables are spread across the measures. Handwritten labels with leader lines identify the 'CHORD SYMBOLS' (C7 and F), the 'MELODY' (the notes on the staff), and the 'LYRIC' (the text below the staff).

# Sheet Music Representation





# Symbolic Representation

- Symbolic description of music
    - based on entities that have an explicit musical meaning
    - given in some digital format
    - can be parsed by a computer
  - Note:
    - Scanned sheet music based on pixels
    - Digital audio file based on samples
- are **not** regarded as being symbolic music formats

# Symbolic Representation

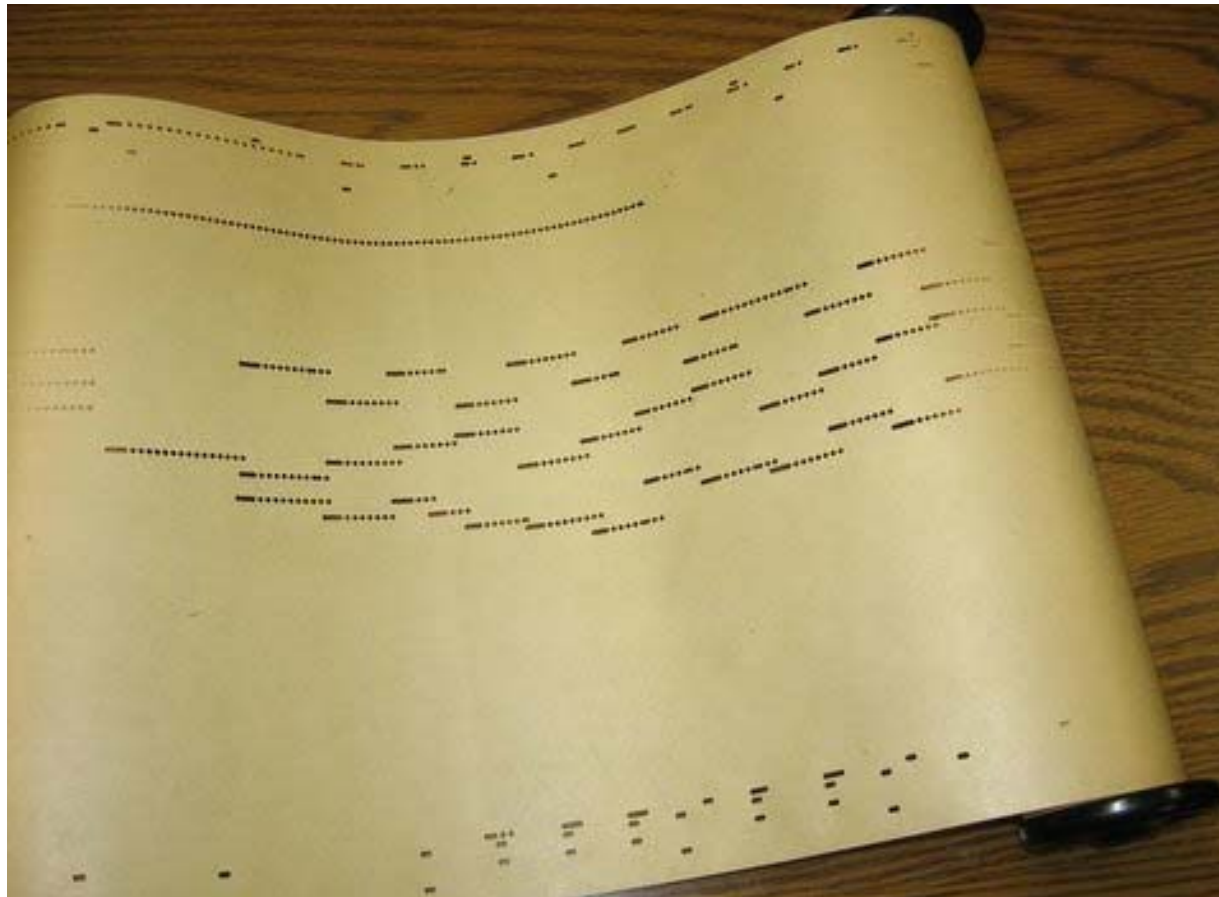
## MusicXML

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



# Symbolic Representation

## Piano roll representation



# Symbolic Representation

## Piano roll representation



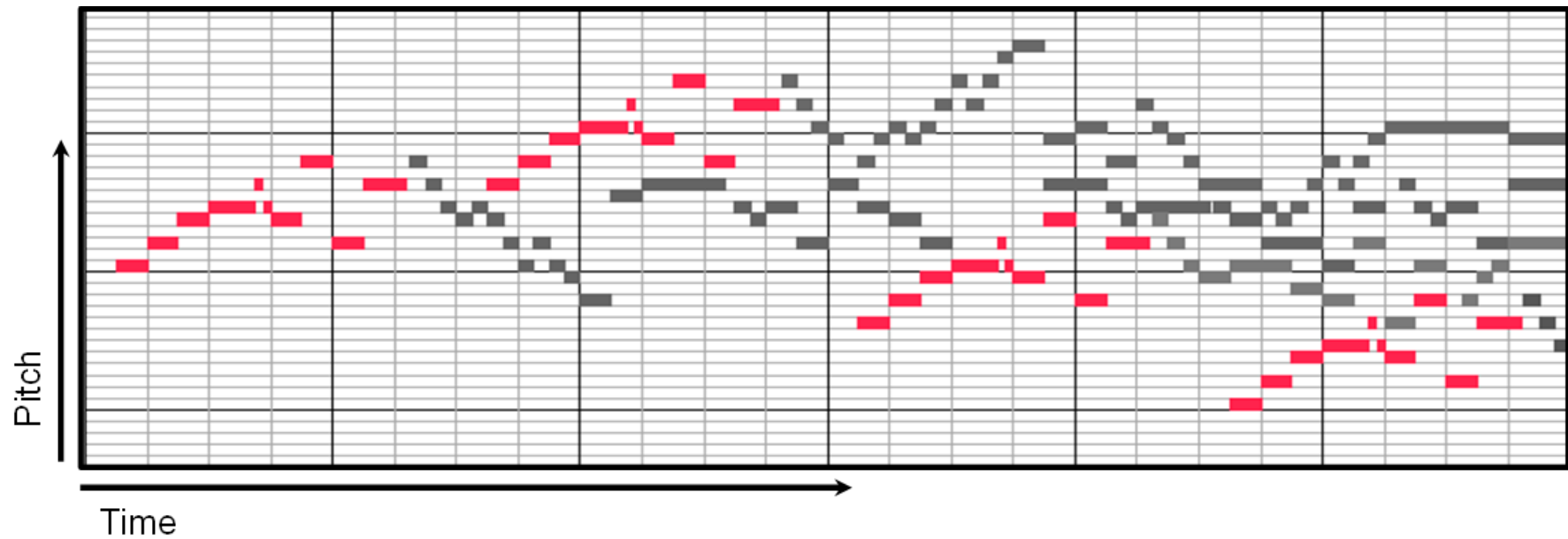
# Symbolic Representation

## Piano roll representation

- Piano roll: music storage medium used to operate a player piano
- Perforated paper rolls
- Holes in the paper encode the note parameters onset, duration, and pitch
- First pianola: 1895

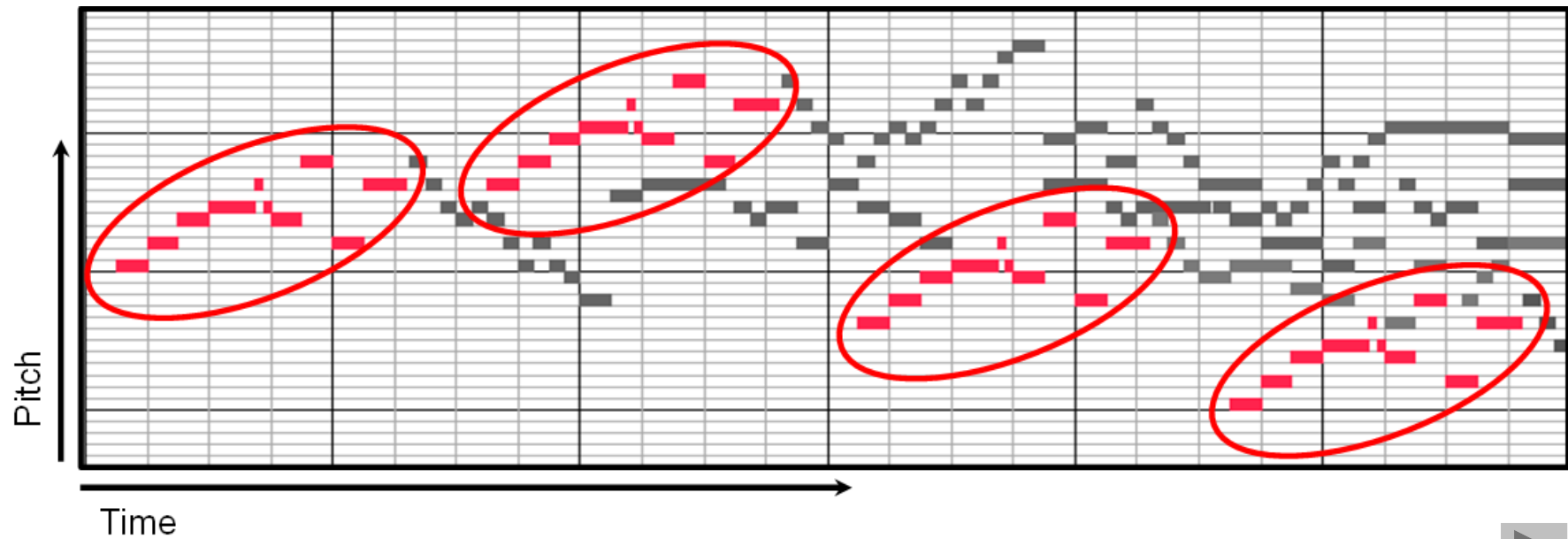
# Symbolic Representation

## Piano roll representation



# Symbolic Representation

## Piano roll representation



# Symbolic Representation

## **MIDI representation**

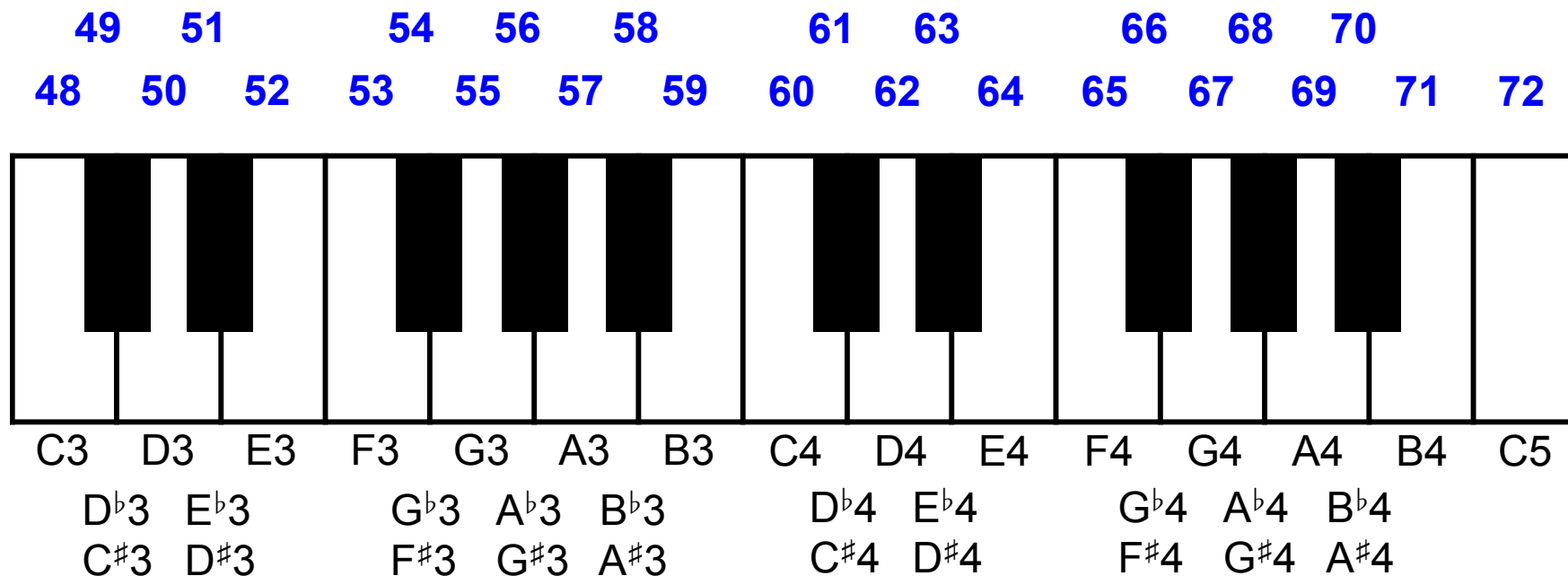
- Musical Instrument Digital Interface (MIDI)
- Standard protocol for controlling and synchronizing digital instruments
- Standard MIDI File (SMF) is used for collecting and storing MIDI messages
- SMF file is often called MIDI file



# Symbolic Representation

## MIDI representation

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



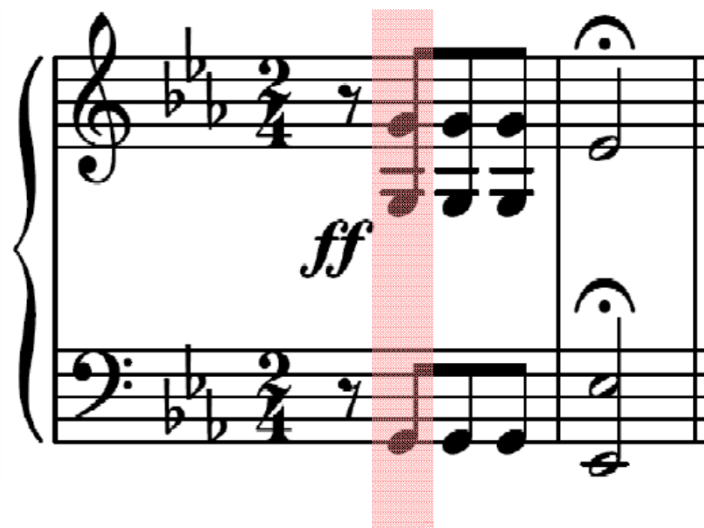
# Symbolic Representation

## MIDI representation

- MIDI note number (pitch)  
 $p = 21, \dots, 108 \triangleq$  piano keys  
 $p = 69 \triangleq$  concert pitch A4
- Key velocity  $\triangleq$  intensity
- MIDI channel  $\triangleq$  instrument
- Note-on / note-off events  $\triangleq$  onset time & duration
- Tempo measured in clock pulses or ticks  
(each MIDI event has a timestamp)
- Absolute tempo specified by
  - ticks per quarter note (musical time)
  - micro-seconds per tick (physical time)

# Symbolic Representation

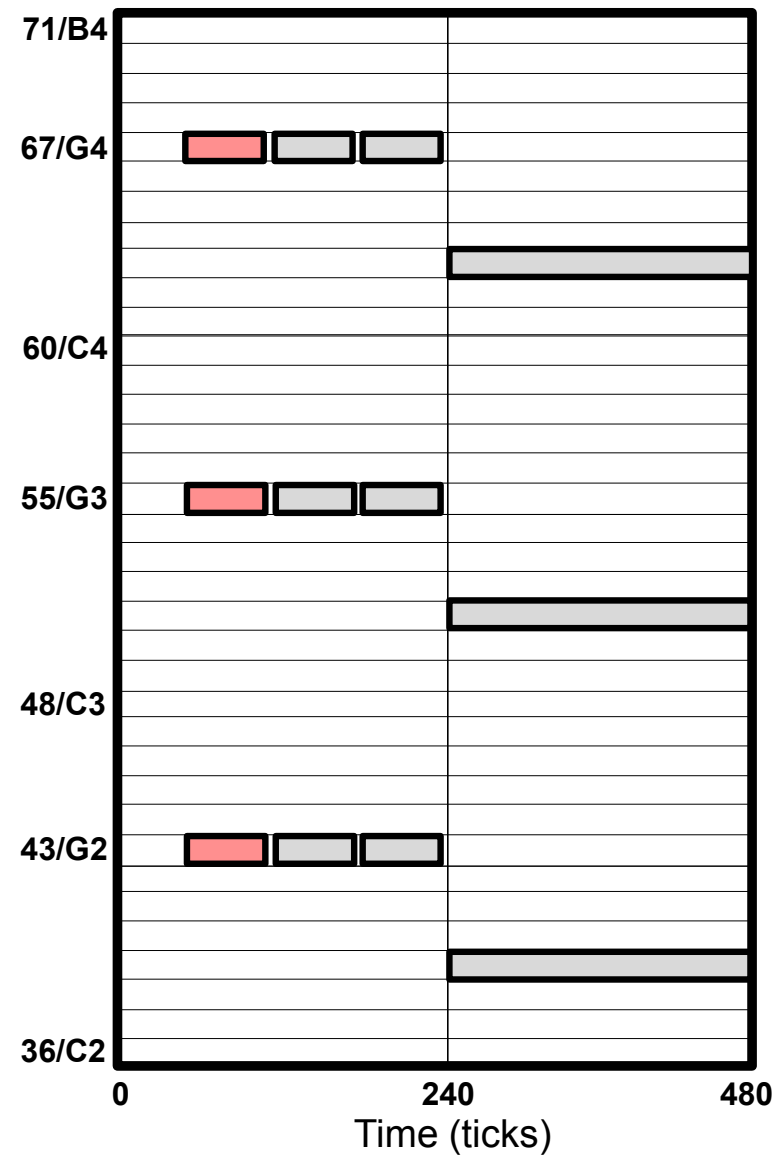
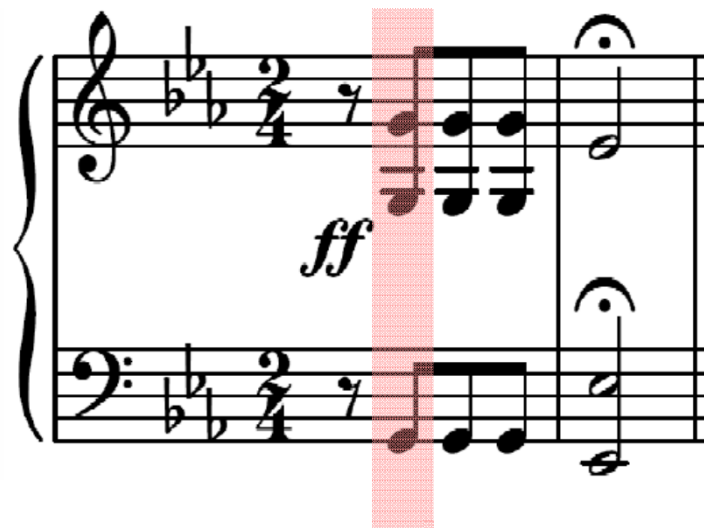
## MIDI representation



Time (Ticks)	Message	Channel	Note Number	Velocity
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

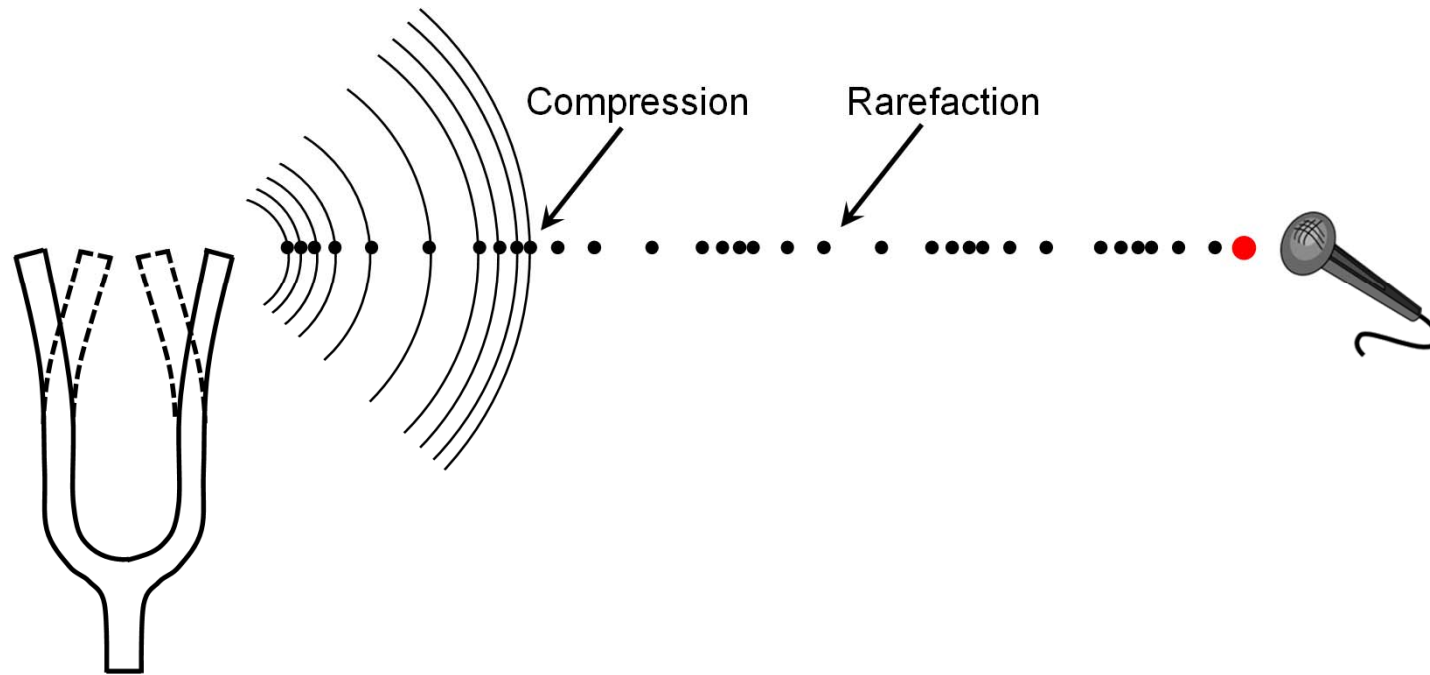
# Symbolic Representation

## MIDI representation



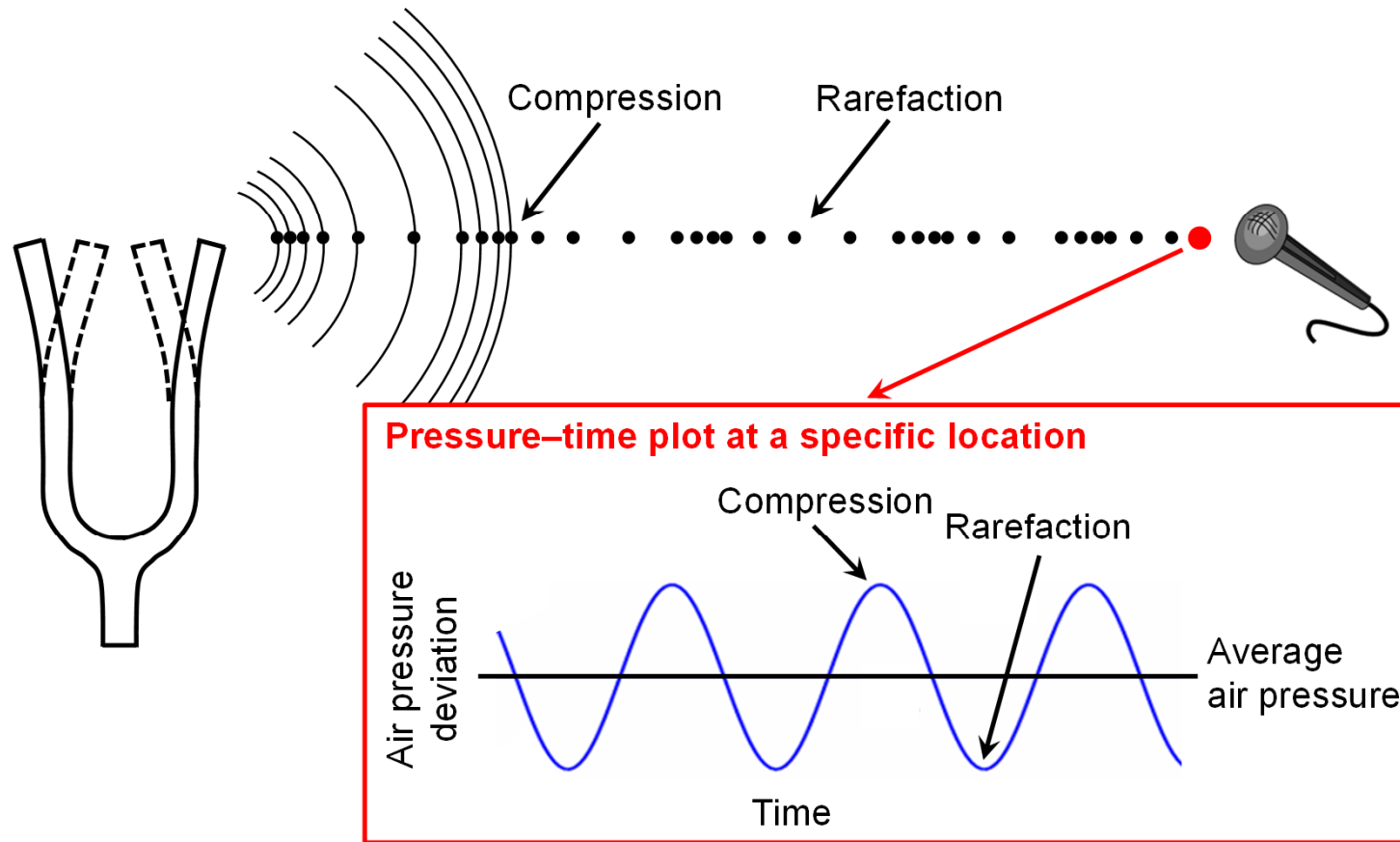
# Audio Representation

## Waveform



# Audio Representation

## Waveform



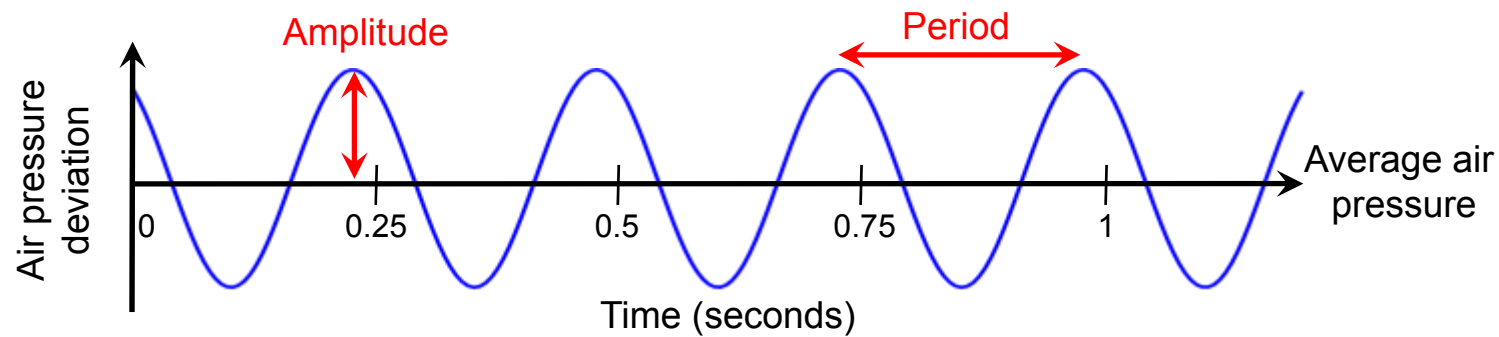
# Audio Representation

## 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):

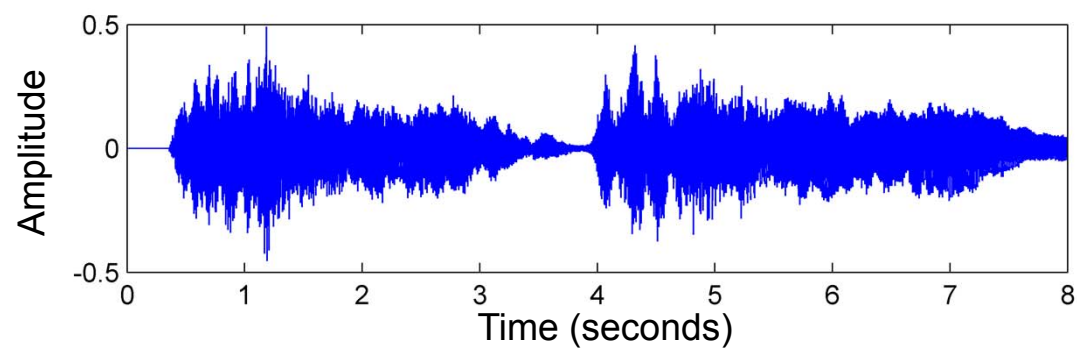
- Sinusoidal waveform
- Prototype of an acoustic realization of a musical note

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

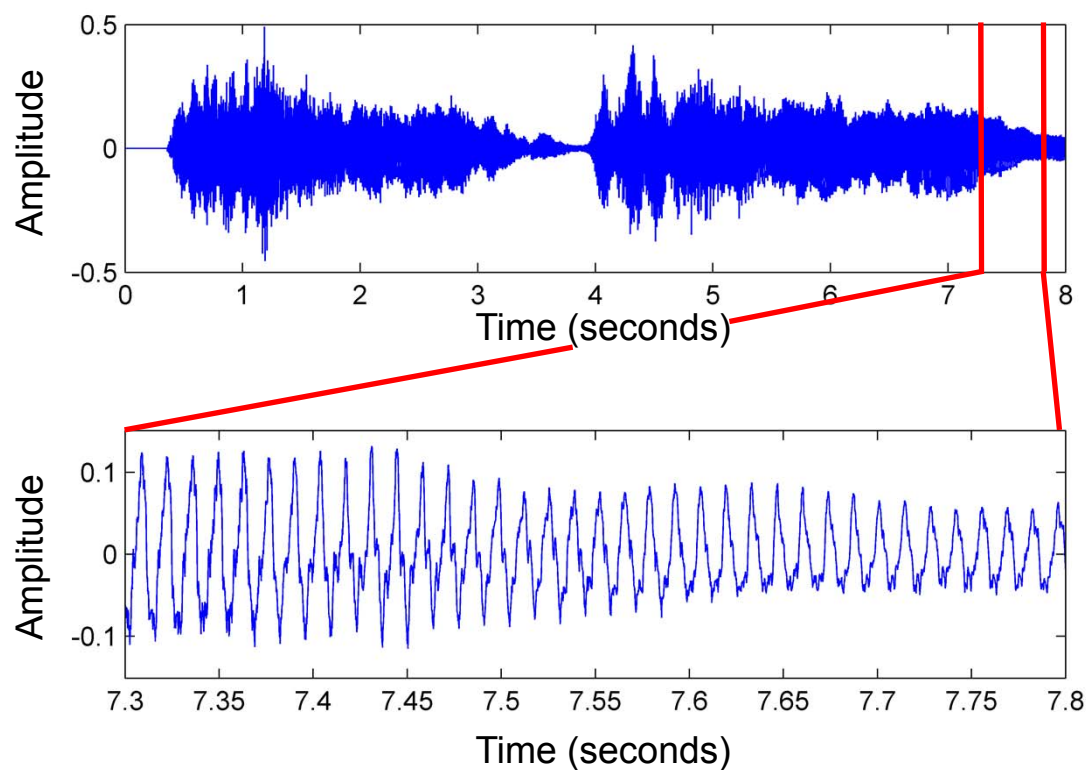


# Audio Representation

## Waveform

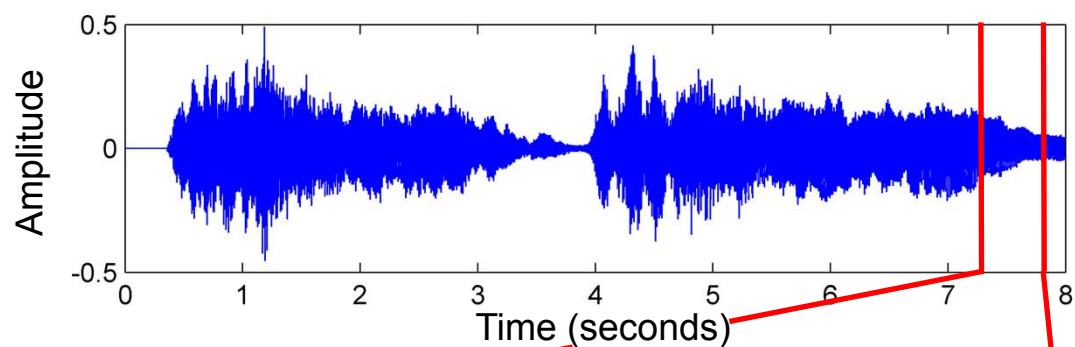


D2 (73.4 Hz)

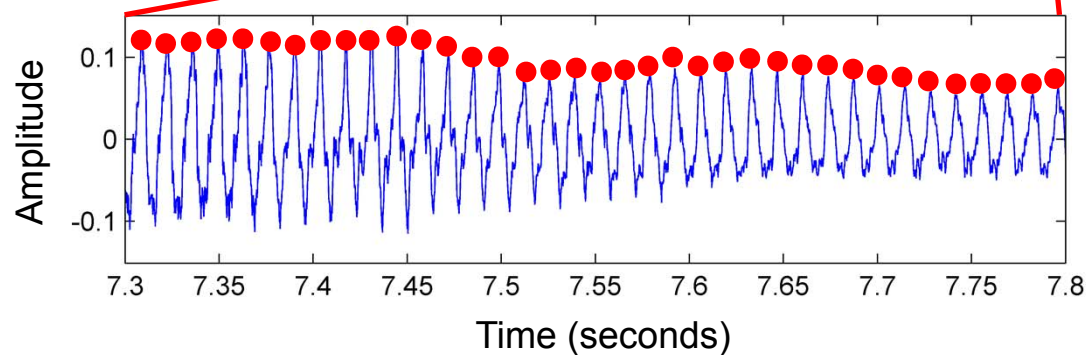


# Audio Representation

## 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

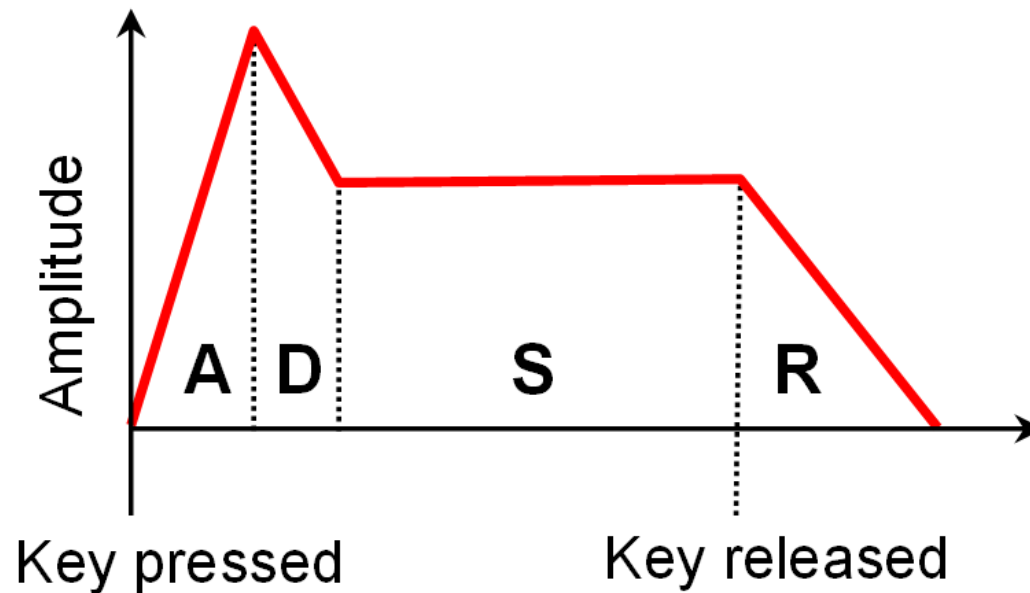
## Dynamics

- 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

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





# Audio Representation

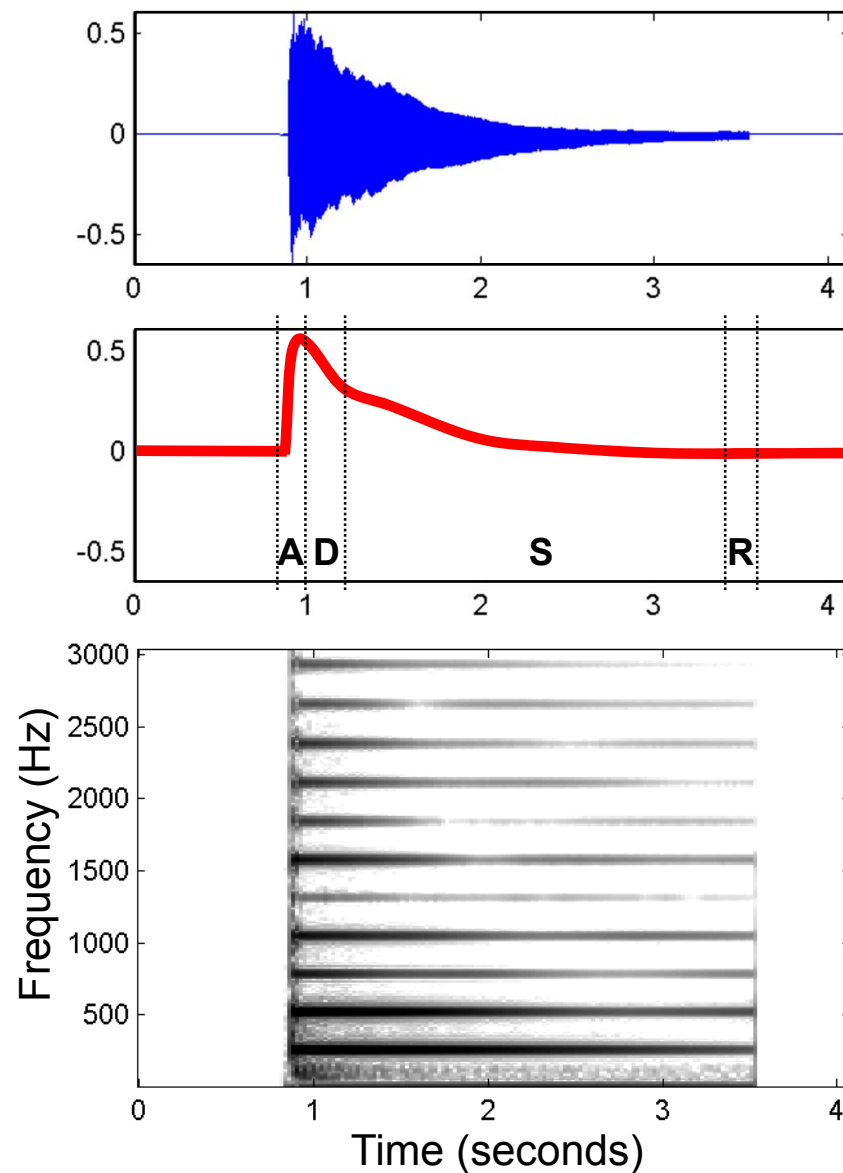
## Timbre

- 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

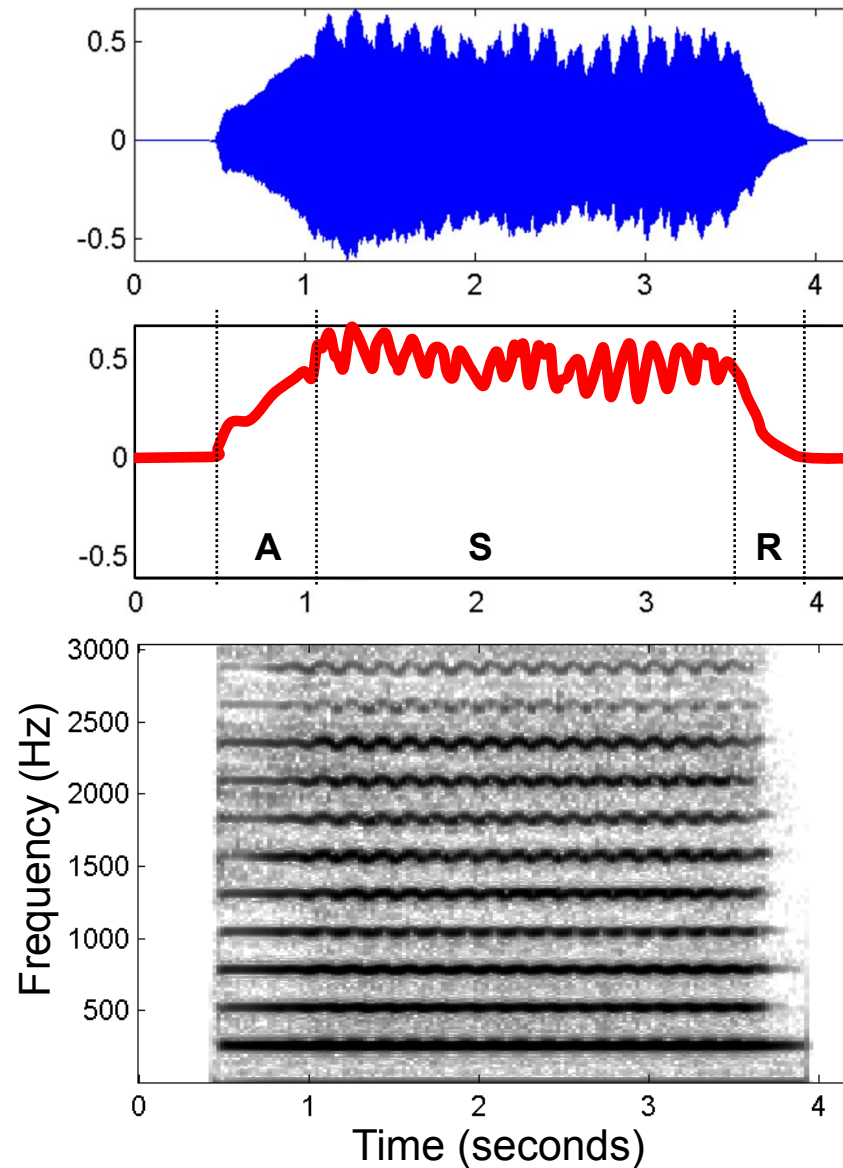
## Timbre

Violine playing  
note C4 (261.6 Hz)



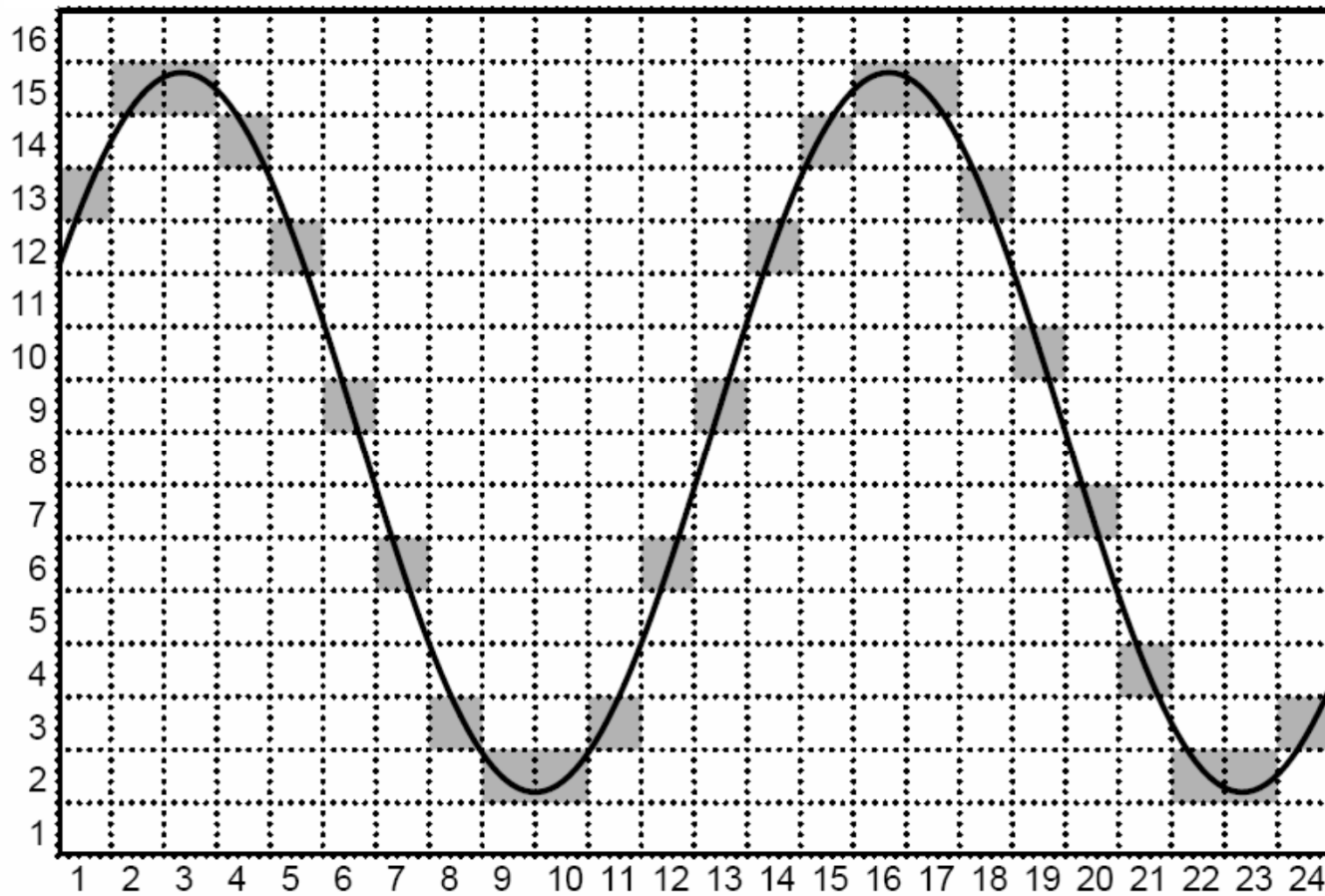
Vibrato:  
Frequency modulations

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