Università di Pisa

Intelligent Systems for Pattern Recognition

Spectrogram of musical instruments

Assignment 4 - Signal processing

Curriculum: Artificial Intelligence
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Musical instruments

Analyzing the spectrogram of different instruments

Main objective

The main task is to examine spectrograms of notes played with a variety of instruments and determine if we can identify which instrument produced each note by analyzing the spectrograms.

Approach

We will conduct visual analysis of spectral patterns, focusing on unique characteristics such as attack, decay, and harmonic content of each instrument to identify differences and similarities.

Tools

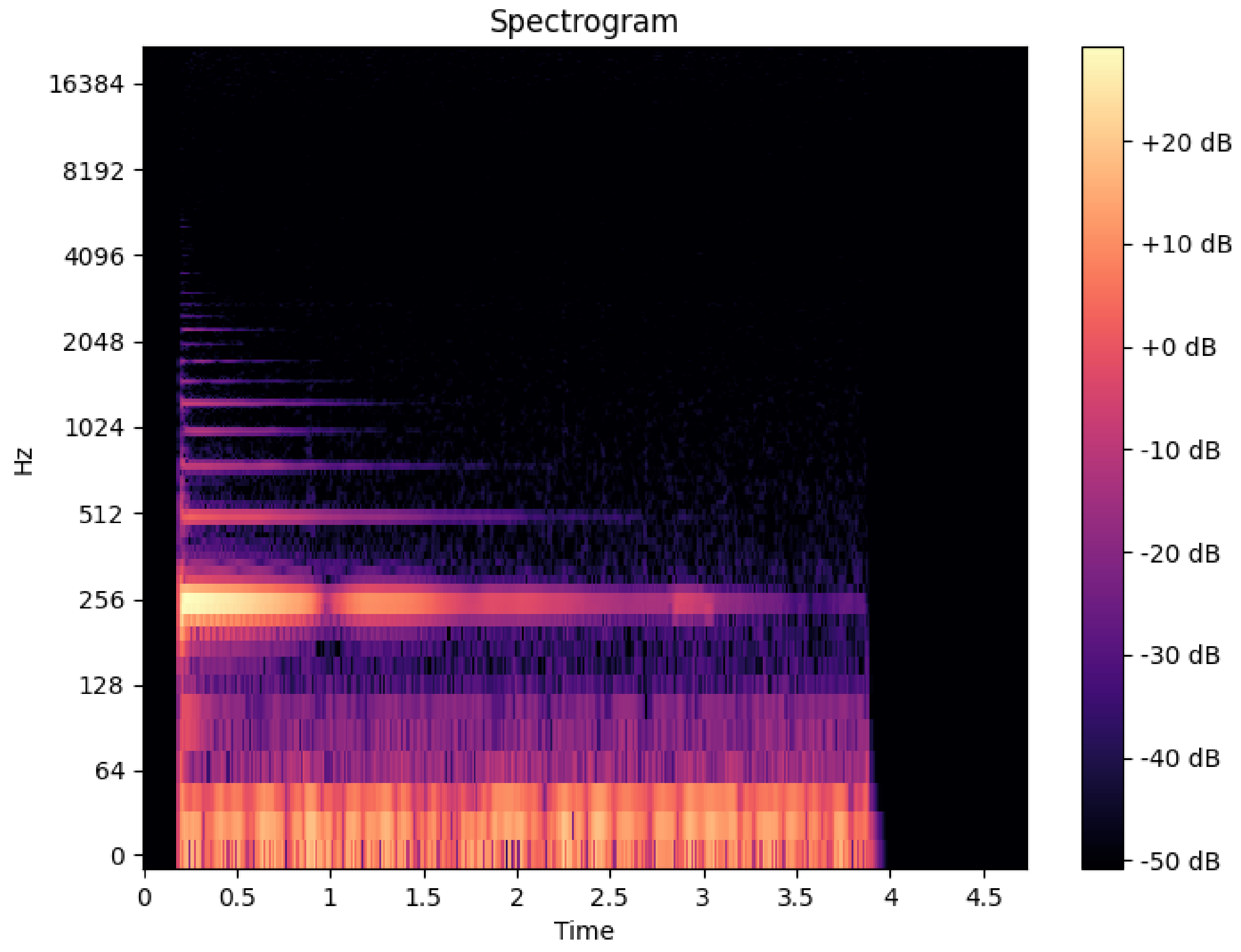
The plots are generated using the auxiliary library 'librosa' to analyze sound waves from musical instruments, and 'matplotlib' to visualize the plots.

Guitar

This is a plot of the spectrogram of a note played by a guitar, precisely a B3.

We can observe some aspects:

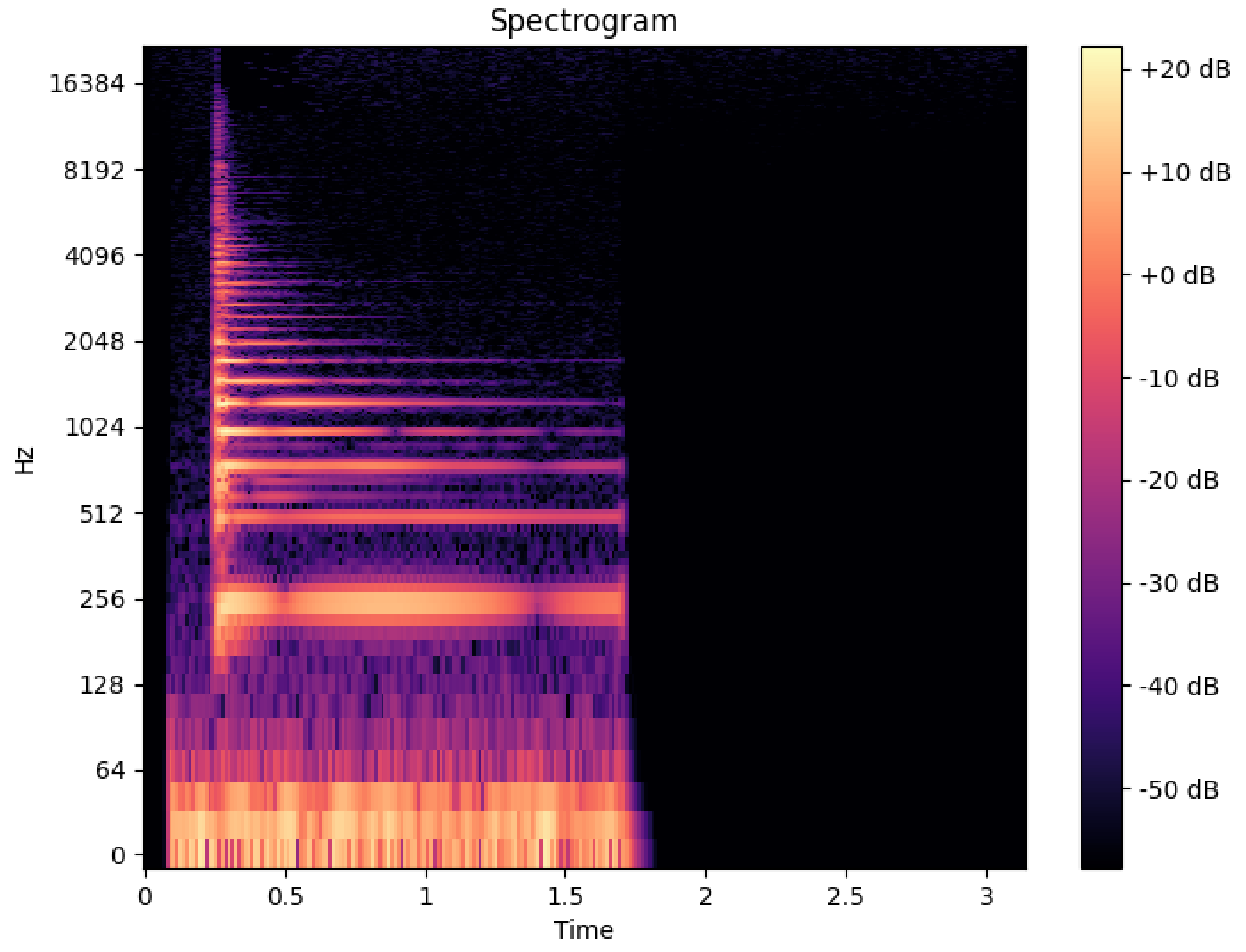
- **Pitch**: it initially spikes high within the first second and then gradually decays over time
- **Decay**: it occurs as the string is plucked, causing the vibration to diminish slowly, along with the decrease in decibels
- **Harmonics**: they are the parallel horizontal lines w.r.t to the fundamental frequency (approx. 250 Hz for a B3)
- **Fundamental frequency**: it persists throughout the entire recording, while the harmonics gradually diminish within the first couple of seconds



Mandolin

That is the spectrogram of a B3 played by a mandolin. Similar to the guitar, the mandolin is a string instrument, differing in length and materials. Visually, we can observe that the spectrogram behaves in basically the same manner.

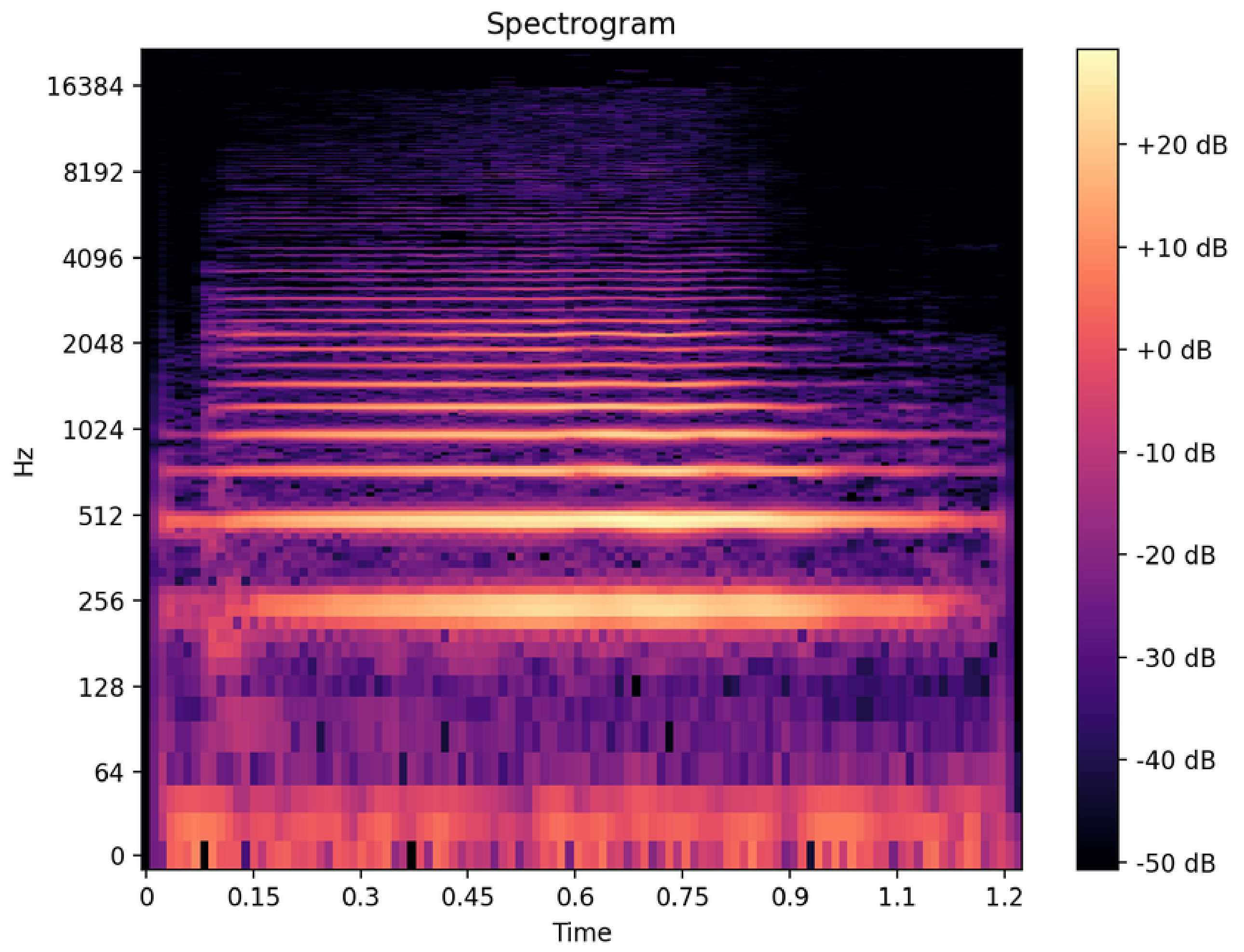
- **Pitch**: it behaves similarly to that of the guitar, spiking high and then decaying, but it ends after about 2 seconds. This could be related to the length of the string.
- **Decay**: it is almost immediate, especially for higher harmonics.
- **Harmonics**: they are more frequent w.r.t. the guitar ones. This is primarily attributed to the shape and construction materials of the instrument.
- **Fundamental frequency**: it is the same (approx. 250 Hz) and it's the most intense in the plot as we can expect.



Cello

Although the cello is a string instrument, it differs significantly from the guitar and the mandolin in terms of playing technique. While the guitar and mandolin can be played either with fingers or with a pick, the cello is played with a bow. A bow is a tensioned stick with horsehair coated in rosin affixed to it.

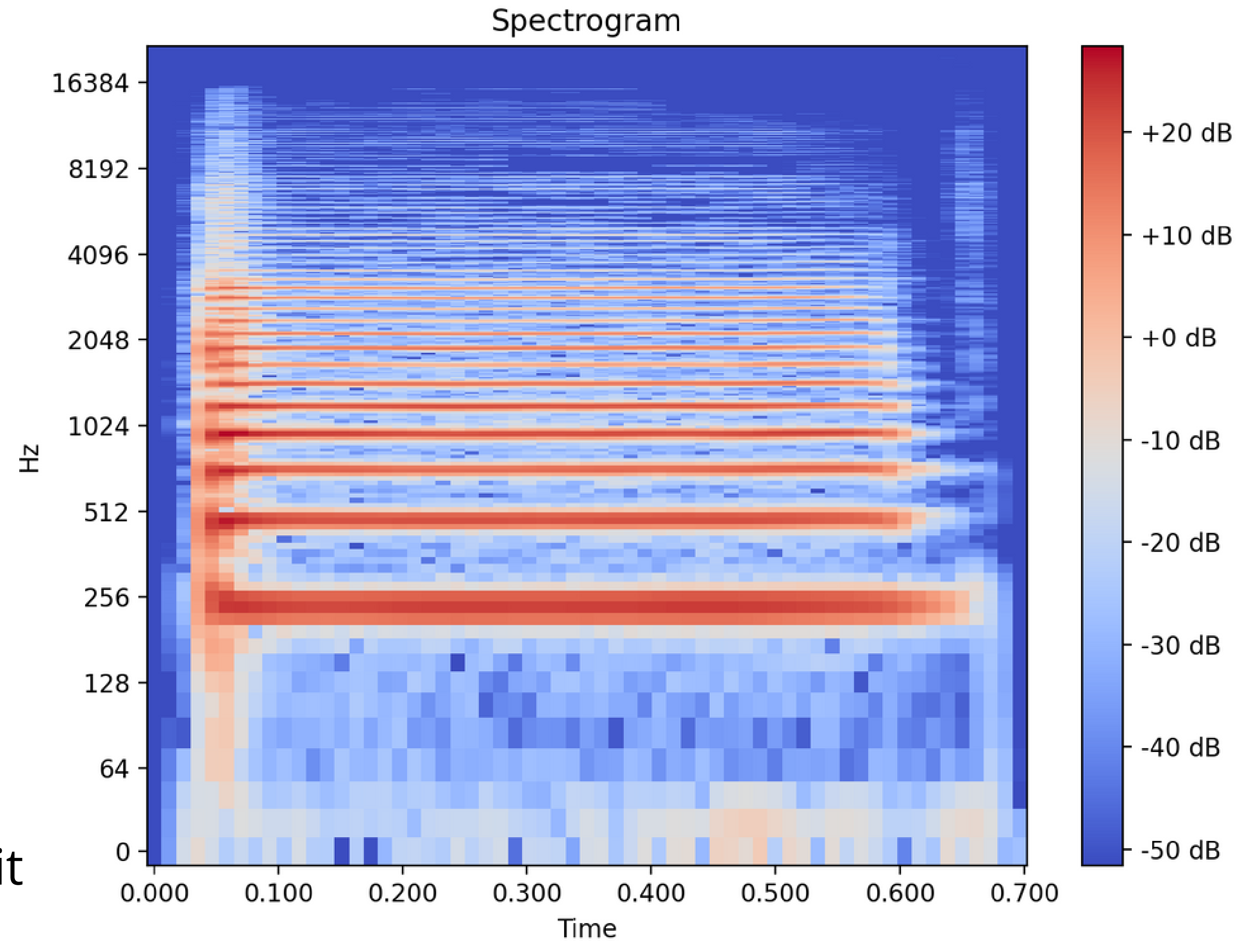
- **Pitch**: it is quite different from the previous examples. It ascends initially, reaches its peak with a rich sound in the middle section, and then descends towards the end.
- **Decay**: it is not solely attributed to the natural loss of string vibrations, but rather depends on how the player releases the bow to allow the note to conclude
- **Harmonics**: they are particularly pronounced on this instrument, and their visibility increases in the middle section as the player applies more friction with the bow.
- **Fundamental frequency**: it remains consistent (approximately 250 Hz for the B3 note), gaining intensity towards the middle and gradually diminishing towards the end



Saxophone

Now, let's examine the saxophone, a brass wind instrument that requires the player to control both the airflow and finger placement to select notes. The note is still a B3 for doing a comparison with the others.

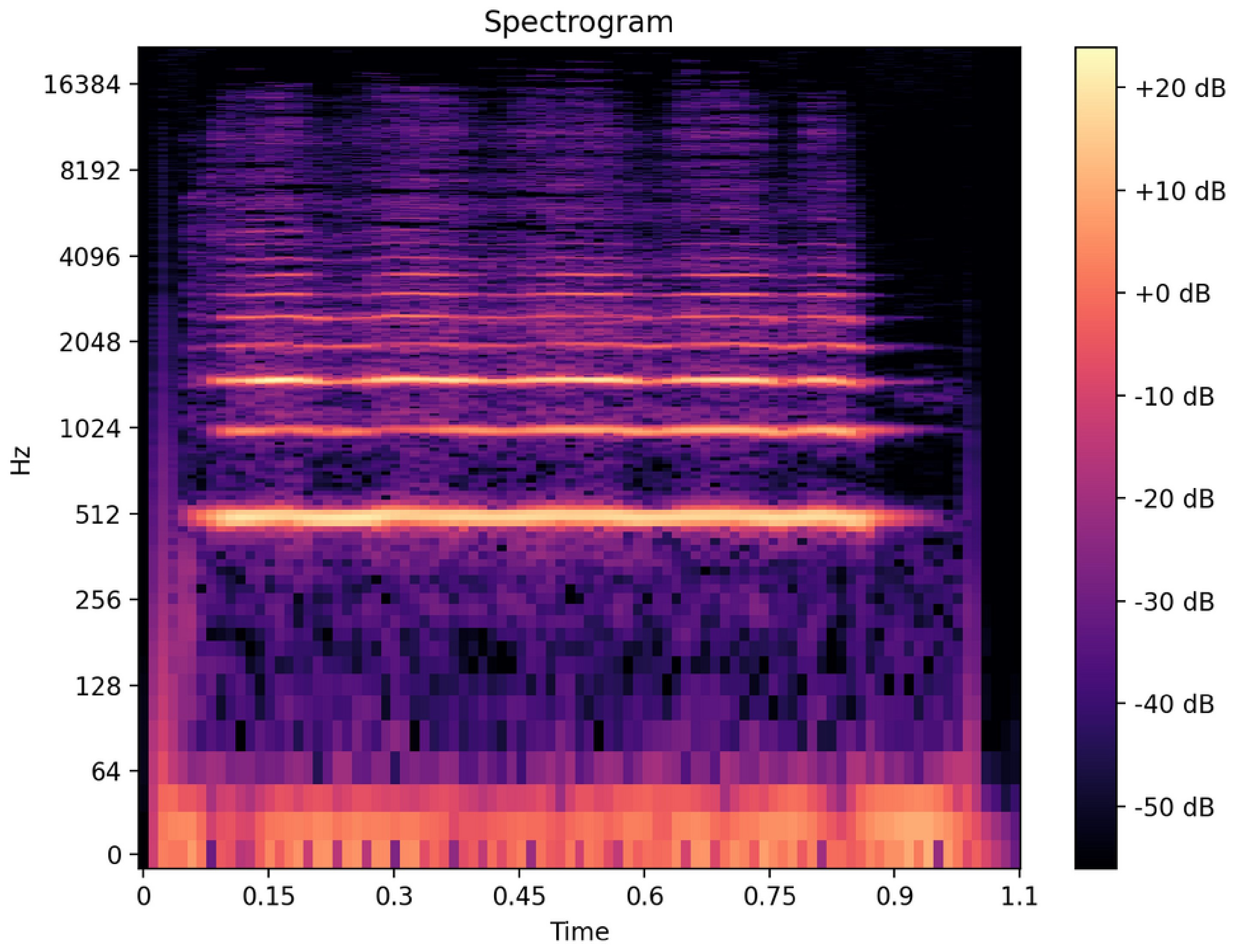
- **Pitch**: since the nature of the instrument is different, we see that the pitch begins with a strong onset and does not decay until the player stops blowing into the instrument.
- **Decay**: the decay is virtually nonexistent throughout the duration of the note. While there is a slight decay at the beginning and the end, it is overall minimal.
- **Harmonics**: these are present throughout the whole duration of the note, up to 16 kHz. The decay of the harmonics follows the decay of the fundamental frequency,
- **Fundamental frequency**: similar to the other instruments, we observe that the maximum intensity occurs around 250 Hz, and it remains constant throughout the duration of the note.



Flute

The flute, like the saxophone, is a wind instrument. While the playing technique and structure are similar, so are the waveforms. One noticeable difference is the presence of more vibrato in the flute, resulting in a wavering waveform in the spectrogram.

- **Pitch:** similar to the saxophone, it is evenly distributed and symmetric overall, and it is controlled by the player from start to finish.
- **Decay**: in contrast to the previous instruments, the decay here varies as it ascends and descends with the vibrato of the note, likely applied by the player.
- **Harmonics**: in the case of the flute, the harmonics are plentiful and extend up to 16 kHz, and they too are influenced by the vibrato of the note.
- **Fundamental frequency**: Being an octave higher than the previous note, this B4 note stands at approx. 512 Hz. It is subtly influenced by the vibrato, it remains relatively constant in the plot.



Code structure

Main functions with Librosa

For this task, I used the Short-Time Fourier Transform, which is a variation of the Fourier Transform, in order to capture the spectral representation of the signal in relation to time.

Then, I took the absolute value of the formula, and I plotted it. Before the plot, I converted it into decibels (dB) in order to align the representation of the signal towards the human perception of sound.

```python
def plot_spectrogram(path):

    # Load the audio file
    y, sr = librosa.load(path, sr=None)

    D = librosa.stft(y) # Short-Time Fourier Transform (STFT)

    # Plot the spectrogram
    plt.figure(figsize=(8, 6))
    librosa.display.specshow(librosa.amplitude_to_db(np.abs(D)), y_axis='log', x_axis='time', sr=sr)
    plt.colorbar(format='%+2.0f dB')
    plt.title('Spectrogram')

    plt.show()
```

Librosa offers various functions for analyzing audio signals, particularly those associated with music. In conjunction with Numpy and MatPlotLib I made and studied the plots and came up with the previous observations.

Conclusions

String Instruments

Overall, the spectrograms of string instruments like the guitar and the mandolin have some similarities. Both instruments produce a pronounced peak upon note initiation, which gradually decays over time as the string vibrations dissipate.

The spectrogram of the cello differs slightly due to its unique playing technique involving a bow. Despite also being a string instrument like the guitar and the mandolin, the cello's spectrogram appears more symmetric, and the shape of the curve is influenced by the intensity with which the player bows the strings.

Wind instruments

On the other hand, in the case of wind instruments, we observe that the spectrogram differs significantly from those of string instruments. Throughout most of the duration, the intensity remains relatively constant, although the flute exhibits some vibrato, likely resulting from the player's manipulation of the airflow.

Moreover, the spectrograms appear to contain a greater abundance of minor frequencies compared to those of string instruments, as evidenced by the richer coloration. This phenomenon is likely attributable to the propagation of additional minor frequencies and harmonics inherent to wind instruments.

Personal considerations

About the topic

Exploring how musical instruments work was fun, especially since I play the guitar. I've never looked so closely at how notes are shown on a sound graph before.

In my GitHub repository, I tried different types of graphs provided by Librosa to see various aspects of notes and different features.

It would definitely be interesting in the future to study these topics more, especially those related to music, to better understand how individual notes and even entire musical compositions work

Project related info

This is the link to my repo: https://github.com/danielebedini/ISPR_assignment1.

All the other experiments and plots that I made are stored in the 'utils.py' file. The library requirements are listed in a dedicated file, and you can find further information on how to execute the project in the README.md file.