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Download Chapter notebook (ipynb)

Mandatory Lesson Feedback Survey

- How is timeseries data visualised?
- Why do we need to tidy up/filter the data?
- How to study correlation among timeseries data points?

- Learning ways to display multiple time series.
- Understanding why filtering is needed.
- Explaining fourier spectrum of time series.
- Knowledge of correlation matrix of time series.

Prerequisites

- Dataframes 1 and 2
- Image Handling
- Basics of Numpy Arrays

```
1 from pandas import read_csv
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords):  
  ModuleNotFoundError: No module named 'pandas'  
2  
3 Detailed traceback:  
4   File "<string>", line 1, in <module>  
5   File "/home/runner/.local/share/renv/cache/v5/R-4.2/x86_64-pc-linux-  
    gnu/reticulate/1.24/ffdf27627a3c1537478073c43b6e7980/reticulate/  
    python/rpytools/loader.py", line 39, in _import_hook  
6     module = _import(
```

```
1 from numpy import arange, zeros, linspace, sin, pi, c_, mean, var,  
  array  
2 from numpy import correlate, corrcoef, fill_diagonal, amin, amax,  
  asarray  
3 from numpy import around  
4 from numpy.ma import masked_less, masked_greater  
5  
6 from matplotlib.pyplot import subplots, yticks, legend, axis, figure,  
  show
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords):  
  ModuleNotFoundError: No module named 'matplotlib'  
2
```

```
3 Detailed traceback:
4   File "<string>", line 1, in <module>
5   File "/home/runner/.local/share/renv/cache/v5/R-4.2/x86_64-pc-linux-
      gnu/reticulate/1.24/ffdf27627a3c1537478073c43b6e7980/reticulate/
      python/rpytools/loader.py", line 39, in _import_hook
6     module = _import(
```

Python Function

Please execute the following function definition before proceeding. The function code takes data and creates a plot of all columns as time series, one above the other. When you execute the function code nothing happens. Similar to the import, running a function code will only activate it and make it available for later use.

```
1 def plot_series(data, sr):
2     '''
3     Time series plot of multiple time series
4     Data are normalised to mean=0 and var=1
5
6     data: nxm numpy array. Rows are time points, columns are recordings
7     sr: sampling rate, same time units as period
8     '''
9
10    samples = data.shape[0]
11    sensors = data.shape[1]
12
13    period = samples // sr
14
15    time = linspace(0, period, period*sr)
16
17    offset = 5 # for mean=0 and var=1 normalised data
18
19    # Calculate means and standard deviations of all columns
20    means = data.mean(axis=0)
21    stds = data.std(axis=0)
22
23    # Plot each series with an offset
24    fig, ax = subplots(figsize=(7, 8))
25
26    ax.plot(time, (data - means)/stds + offset*arange(sensors-1,-1,-1))
27    ;
28    ax.plot(time, zeros((samples, sensors)) + offset*arange(sensors
29    -1,-1,-1), '--',color='gray');
30
31    yticks([]);
32
33    names = [str(x) for x in range(sensors)]
```

```
33     legend(names)
34
35     ax.set(xlabel='Time')
36
37     axis('tight');
38
39     return fig, ax
```

Example: Normal and Pathological EEG

As an example, let us import two sets of time series data and convert them to numpy arrays, here called *data_back* and *data_epil*. They represent human electroencephalogram (EEG) as recorded during normal *background* activity and during an epileptic seizure called *absence* seizure.

```
1 df_back = read_csv("data/EEG_background.txt", delim_whitespace=True)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'read_csv' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 df_epil = read_csv("data/EEG_absence.txt", delim_whitespace=True)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'read_csv' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 sr = 256      # 1 / seconds
2 period = 6    # seconds
3 channels = 10
4
5 d1 = df_back.to_numpy()
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'df_back' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 d2 = df_epil.to_numpy()
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'df_epil' is not defined
2
```

```
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 data_back = d1[:period*sr:, :channels]
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'd1' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 data_epil = d2[:period*sr:, :channels]
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'd2' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

The `read_csv` function is used with the keyword argument `delim_whitespace`. When set to `True`, this allows to import data that are space-separated (rather than comma-separated). If you check the data .txt files, you will see that the numbers (which represent voltages) are indeed separated by space, not comma.

Next, three constants are assigned: The sampling rate, `sr`, which is given in number of samples recorded per seconds; the duration of the recording, `period`, which is given in seconds; and the number of columns, referred to as `channels`, to be extracted from the recording. We use the first 10 columns in this lesson.

The data are then converted from a data frame to Numpy arrays.

To see the names of the channels (or recording sensors) we can use `head`.

```
1 df_back.head()
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'df_back' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

The row indices and column names for the seizure data look the same. The names of the recording channels are from the commonly used 10-20 system to record voltages of brain activity from the scalp in humans. E.g. 'F' stands for the frontal lobe.

We can now use the plot function from above to plot the data. Note from the definition (first line) that two input arguments are required: the data set and the sampling rate.

```
1 plot_series(data_back, sr)
2 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'data_back' is not defined
3
4 Detailed traceback:
5   File "<string>", line 1, in <module>
6 show()
7 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'show' is not defined
8
9 Detailed traceback:
10  File "<string>", line 1, in <module>
```

```
1 plot_series(data_epil, sr);
2 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'data_epil' is not defined
3
4 Detailed traceback:
5   File "<string>", line 1, in <module>
6 show()
7 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'show' is not defined
8
9 Detailed traceback:
10  File "<string>", line 1, in <module>
```

Observations

1. Background:

- There are irregular oscillations of all recorded brain potentials.
- Oscillations recorded at different locations above the brain differ.
- Oscillations are not stable but modulated over time.
- There are different frequency components in each trace.

2. Epileptic Seizure:

- There are regular oscillations.
- Oscillations recorded at different locations are not identical but similar or at least related in shape.
- Despite some modulation, oscillations are fairly stable over time.
- There are repetitive motifs composed of two major components throughout the recording, a sharp *spike* and a slow *wave*.

Task

Quantify features of these time series data to get an overview. As a univariate feature we can use the frequency content. This takes into account the fact that the rows (or samples) are not independent of each other but are organised along the time axis. In consequence, there are correlations between data points along the rows of each column and the **Fourier spectrum** can be used to identify these.

The Fourier spectrum assumes that the data are stationary and can be thought of as a superposition of regular sine waves with different frequencies. Its output will show which of the frequencies are present in the data and also their respective amplitudes.

As a bivariate feature we can use the cross-correlation matrix.

Work Through Example

Check the Numpy array containing the background and seizure data.

```
1 print(data_back.shape, data_epil.shape)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'data_back' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

There are 1536 rows and 10 columns.

Display data with offset

Take a look at the code of the function `plot_series` that creates the time series plot. It requires the input of a data file where the row index is interpreted as time. In addition, the sampling rate `sr` is required to be able to extract the time scale. The sampling rate specifies the number of samples recorded per unit time.

The sensors or recording channels are assumed to be in the columns.

```
1 def plot_series(data, sr):
2     '''
3     Time series plot of multiple time series
4     Data are normalised to mean=0 and var=1
5
6     data: nxm numpy array. Rows are time points, columns are channels
7     sr: sampling rate, same time units as period
8     '''
9
```

```
10     samples = data.shape[0]
11     sensors = data.shape[1]
12
13     period = samples // sr
14
15     time = linspace(0, period, period*sr)
16
17     offset = 5 # for mean=0 and var=1 normalised data
18
19     # Calculate means and standard deviations of all columns
20     means = data.mean(axis=0)
21     stds = data.std(axis=0)
22
23     # Plot each series with an offset
24     fig, ax = subplots(figsize=(7, 8))
25
26     ax.plot(time, (data - means)/stds + offset*arange(sensors-1,-1,-1))
27         ;
28     ax.plot(time, zeros((samples, sensors)) + offset*arange(sensors
29         -1,-1,-1), '--',color='gray');
30
31     yticks([]);
32
33     names = [str(x) for x in range(sensors)]
34     legend(names)
35
36     ax.set(xlabel='Time')
37
38     axis('tight');
39
40     return fig, ax
```

The declaration syntax **def** is followed by the function name and, in parenthesis, the input arguments. It is completed with a colon.

Following the declaration is the documentation of the function.

Next comes the function code, all indented.

The function closes with the optional output syntax **return** and any number of returned variables, anything that might be used as a product of running the function.

In our example, the figure environment and the coordinate system are ‘returned’, and can in principle be used to further modify the plot.

Here is how to call the function and then add a title and the sensor names to the display.

```
1 (fig, ax) = plot_series(data_epil, sr)
2 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
   name 'data_epil' is not defined
```

```
3
4 Detailed traceback:
5   File "<string>", line 1, in <module>
6   names = df_back.columns[:channels]
7   Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
8     name 'df_back' is not defined
9
10 Detailed traceback:
11   File "<string>", line 1, in <module>
12   fig.suptitle('Recording of Absence Seizure', fontsize=16);
13   Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
14     name 'fig' is not defined
15
16 Detailed traceback:
17   File "<string>", line 1, in <module>
18   legend(names);
19   Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
20     name 'legend' is not defined
21
22 Detailed traceback:
23   File "<string>", line 1, in <module>
24   show()
25   Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
26     name 'show' is not defined
27
28 Detailed traceback:
29   File "<string>", line 1, in <module>
```

A function usually (but not necessarily) takes in one or several variables or values, processes them, and produces a specific result. The variable(s) given to a function and those produced by it are referred to as input arguments, and outputs respectively.

There are different ways to create functions in Python. In this course, we will be using `def` to implement our own functions. This is the easiest, and by far the most common method for declaring functions. The structure of a typical function defined using `def` can be seen in the `plot_series` example:

There are several points to remember in relation to functions:

- The name of a function follows same principles as that of any other variable. It must be in lower-case characters.
- The input arguments of a function, e.g. *data* and *sr* in the example, are essentially variables whose scope is the function. That is, they are only accessible within the function itself, and not from outside the function.
- Variables defined inside of a function, should not use the same name as variables defined outside. Otherwise they may override each other.

It is important for a function to only perform one specific task. As such it can be used independent of

the current context. Try to avoid incorporating separable tasks into a single function.

Once you start creating functions for different purposes you can start to build your own library of ready-to-use functions to address different needs. This is the primary principle of a popular programming paradigm known as functional programming.

Filtering

Data sets with complex waveforms contain many different components which may or may not be relevant for a specific question.

Data filtering is applied to take out specific components. Component in this context refers to ‘frequency’, i.e. the number of cycles per unit of time. Thus a small number refers to low frequencies with long periods (cycles) and a large number to high frequencies with short periods.

Let us see a simple example how both low- and high-frequency components can be filtered (suppressed) in the example time series.

Here is a simple function which takes two additional input arguments, the low and the high cut-off.

```
1 def data_filter(data, sr, low, high):
2     """
3     Filtering of multiple time series.
4
5     data: nxm numpy array. Rows are time points, columns are recordings
6     sr: sampling rate, same time units as period
7
8     low: Low cut-off frequency (high-pass filter)
9     high: High cut-off frequency (low-pass filter)
10
11     return: filtered data
12     """
13
14     from scipy.signal import butter, sosfilt
15
16     order = 5
17
18     filter_settings = [low, high, order]
19
20     sos = butter(order, (low, high), btype='bandpass', fs=sr, output='
    sos')
21
22     data_filtered = zeros((data.shape[0], data.shape[1]))
23
24     for index, column in enumerate(data.transpose()):
25         forward = sosfilt(sos, column)
26         backwards = sosfilt(sos, forward[-1::-1])
27         data_filtered[:, index] = backwards[-1::-1]
```

```
28
29     return data_filtered
```

```
1 data_back_filt = data_filter(data_back, sr, 8, 13)
2 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'data_back' is not defined
3
4 Detailed traceback:
5   File "<string>", line 1, in <module>
6   (fig, ax) = plot_series(data_back_filt, sr)
7 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'data_back_filt' is not defined
8
9 Detailed traceback:
10  File "<string>", line 1, in <module>
11  fig.suptitle('Filtered Recording of Background EEG', fontsize=16);
12 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'fig' is not defined
13
14 Detailed traceback:
15  File "<string>", line 1, in <module>
16  legend(names);
17 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'legend' is not defined
18
19 Detailed traceback:
20  File "<string>", line 1, in <module>
21  show()
22 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'show' is not defined
23
24 Detailed traceback:
25  File "<string>", line 1, in <module>
```

The frequency range from 8 to 13 Hz is referred to as alpha band in the electroencephalogram. It is thought that this represents a kind of idling rhythm of the brain, i.e. an activity where the brain is not actively processing sensory input.

DIY1: Band-pass filtered data

Create figures of the delta (1-4 Hz) band for both the background and the seizure EEG. Note the differences.

```
1 data_back_filt = data_filter(data_back, sr, 1, 4)
2 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'data_back' is not defined
3
4 Detailed traceback:
```

```
5 File "<string>", line 1, in <module>
6 (fig, ax) = plot_series(data_back_filt, sr)
7 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'data_back_filt' is not defined
8
9 Detailed traceback:
10 File "<string>", line 1, in <module>
11 fig.suptitle('Delta Band of Background EEG', fontsize=16);
12 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'fig' is not defined
13
14 Detailed traceback:
15 File "<string>", line 1, in <module>
16 legend(names);
17 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'legend' is not defined
18
19 Detailed traceback:
20 File "<string>", line 1, in <module>
21 show()
22 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'show' is not defined
23
24 Detailed traceback:
25 File "<string>", line 1, in <module>
```

```
1 data_epil_filt = data_filter(data_epil, sr, 1, 4)
2 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'data_epil' is not defined
3
4 Detailed traceback:
5 File "<string>", line 1, in <module>
6 (fig, ax) = plot_series(data_epil_filt, sr)
7 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'data_epil_filt' is not defined
8
9 Detailed traceback:
10 File "<string>", line 1, in <module>
11 fig.suptitle('Delta Band of Seizure EEG', fontsize=16);
12 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'fig' is not defined
13
14 Detailed traceback:
15 File "<string>", line 1, in <module>
16 legend(names);
17 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'legend' is not defined
18
19 Detailed traceback:
20 File "<string>", line 1, in <module>
21 show()
```

```
22 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
    name 'show' is not defined
23
24 Detailed traceback:
25   File "<string>", line 1, in <module>
```

Fourier Spectrum

The Fourier spectrum decomposes the time series into a sum of sine waves. The spectrum gives the coefficients of each of the sine wave components. The coefficients are directly related to the amplitudes needed to optimally fit the sum of all sine waves to recreate the original data.

However, the assumption behind the Fourier transform is that the data are provided as in infinitely long stationary time series. These assumptions are not fulfilled as the data are finite and stationarity of a biological system can typically not be guaranteed. Thus, interpretation needs to be cautious.

Fourier Transform of EEG data We import the Fourier transform function `fft` from `scipy.fftpack` and can use it to transform all columns at the same time.

```
1 from scipy.fftpack import fft
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords):
  ModuleNotFoundError: No module named 'scipy'
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
5   File "/home/runner/.local/share/renv/cache/v5/R-4.2/x86_64-pc-linux-
      gnu/reticulate/1.24/ffdf27627a3c1537478073c43b6e7980/reticulate/
      python/rpytools/loader.py", line 39, in _import_hook
6     module = _import(
```

```
1 data_back_fft = fft(data_back, axis=0)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'fft' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

To plot the results, a couple of steps are required.

First, we obtain a Fourier spectrum for every data column, so we need to define how many plots we want to have. If we take only columns, we can display them all in one go.

Second, the Fourier transform results in twice the number of complex coefficients (positive and negative) of which we only need the first half.

Third, the Fourier transform outputs complex numbers. To display the 'amplitude' of a frequency (the coefficient corresponding to the amplitude of the sine wave with that frequency) we take the absolute value of the complex numbers.

```
1 no_win = 2
2
3 rows = data_back.shape[0]
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'data_back' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 freqs = (sr/2)*linspace(0, 1, int(rows/2))
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'rows' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 amplitudes_back = (2.0 / rows) * abs(data_back_fft[:rows//2, :2])
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'rows' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 fig, axes = subplots(figsize=(6, 5), ncols=1, nrows=no_win, sharex=
  False)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'subplots' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 names = df_back.columns[:2]
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'df_back' is not defined
2
3 Detailed traceback:
```

```
4 File "<string>", line 1, in <module>
```

```
1 for index, ax in enumerate(axes.flat):
2     axes[index].plot(freqs, amplitudes_back[:, index])
3     axes[index].set_xlim(0, 8)
4     axes[index].set(ylabel=f'Amplitude {names[index]}')
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'axes' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 axes[index].set(xlabel='Frequency (Hz)');
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'axes' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 show()
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'show' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

We can see that in these two channels, the main amplitude contributions lie in the low frequencies, below 2 Hz.

Let us compare the corresponding figure for the case of seizure activity:

```
1 data_epil_fft = fft(data_epil, axis=0)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'fft' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 fig, axes = subplots(figsize=(6, 5), ncols=1, nrows=no_win, sharex=
  False)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'subplots' is not defined
2
```

Time Series

```
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 names = df_epil.columns[:2]
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'df_epil' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 amplitudes_epil = (2.0 / rows) * abs(data_epil_fft[:rows//2, :2])
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'rows' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 for index, ax in enumerate(axes.flat):
2     axes[index].plot(freqs, amplitudes_epil[:, index])
3     axes[index].set_xlim(0, 12)
4     axes[index].set(ylabel=f'Amplitude {names[index]}')
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'axes' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 axes[index].set(xlabel='Frequency (Hz)');
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'axes' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 show()
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'show' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

The main frequency of the epileptic rhythm is between 2 and 3 Hz.

As we can see above in the Fourier spectra above, the amplitudes are high for low frequencies and tend to decrease with increasing frequency. Sometimes it is useful to see the high frequencies enhanced. This can be achieved with a logarithmic plot of the powers.

```
1 fig, axes = subplots(figsize=(6, 6), ncols=1, nrows=no_win, sharex=False)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'subplots' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 for index, ax in enumerate(axes.flat):
2
3     axes[index].plot(freqs, amplitudes_back[:, index])
4     axes[index].set_xlim(0, 30)
5     axes[index].set(ylabel=f'Amplitude {names[index]}')
6     axes[index].set_yscale('log')
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'axes' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 axes[no_win-1].set(xlabel='Frequency (Hz)');
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'axes' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 fig.suptitle('Logarithmic Fourier Spectra of Background EEG', fontsize
  =16);
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'fig' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 show()
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'show' is not defined
2
```



```
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

And for the seizure data:

```
1 fig, axes = subplots(figsize=(6, 10), ncols=1, nrows=no_win, sharex=
  False)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'subplots' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 for index, ax in enumerate(axes.flat):
2
3     axes[index].plot(freqs, amplitudes_epil[:, index])
4     axes[index].set_xlim(0, 30)
5     axes[index].set_ylabel=f'Power {names[index]}')
6     axes[index].set_yscale('log')
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'axes' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 axes[no_win-1].set(xlabel='Frequency (Hz)');
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'axes' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 fig.suptitle('Logarithmic Fourier Spectra of Seizure EEG', fontsize=16)
  ;
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'fig' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 show()
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'show' is not defined
2
```

```
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

In the spectrum of the absence data, it is now more obvious that there are further maxima at 6, 9, 12, and perhaps 15Hz. These are integer multiples or ‘harmonics’ of the basic frequency at around 3Hz, also referred to as the fundamental frequency.

A feature that can be used as a summary statistic, is to calculate the **band power** for each channel. The band power can be obtained as the sum of all powers within a specified range of frequencies, also called the ‘band’. The band power thus represents a single number.

DIY2: Fourier spectra of filtered data

Calculate and display the Fourier spectra of the first two channels filtered between 4 and 12 Hz for the absence seizure data. Can you find harmonics?

```
1 data_epil_filt = data_filter(data_epil, sr, 4, 12)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'data_epil' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 data_epil_fft = fft(data_epil_filt, axis=0)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'fft' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 rows = data_epil.shape[0]
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'data_epil' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 freqs = (sr/2)*linspace(0, 1, int(rows/2))
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'rows' is not defined
2
3 Detailed traceback:
```

```
4 File "<string>", line 1, in <module>
```

```
1 amplitudes_epil = (2.0 / rows) * abs(data_epil_fft[:rows//2, :no_win])
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'rows' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 fig, axes = subplots(figsize=(6, 10), ncols=1, nrows=no_win, sharex=
  False)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'subplots' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 for index, ax in enumerate(axes.flat):
2     axes[index].plot(freqs, amplitudes_epil[:, index])
3     axes[index].set_xlim(0, 12)
4     axes[index].set(ylabel=f'Amplitudes {names[index]}')
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'axes' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 axes[no_win-1].set(xlabel='Frequency (Hz)');
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'axes' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 fig.suptitle('Fourier Spectra of Seizure EEG', fontsize=16);
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'fig' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 show()
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'show' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

Cross-Correlation Matrix

As one example of a multivariate analysis of time series data, we can calculate the cross-correlation matrix.

Here it is done for the background:

```
1 corr_matrix_back = corrcoef(data_back, rowvar=False)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'data_back' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 fill_diagonal(corr_matrix_back, 0)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'corr_matrix_back' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 fig, ax = subplots(figsize = (8,8))
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'subplots' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 im = ax.imshow(corr_matrix_back, cmap='coolwarm');
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 fig.colorbar(im, orientation='horizontal', shrink=0.68);
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'fig' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 show()
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'show' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

The diagonal is set to zero. This is done to improve the visual display. If left to one, the diagonal tends to dominate the visual impression even though it is trivial and nothing can be learned from it.

Looking at the non-diagonal elements, we find:

- two strongly correlated series (indices 5 and 7)
- two strongly anti-correlated series (indices 3 and 4)
- a block of pronounced correlations between series with indices 4 through 9)

DIY3: Display the correlation matrix for the seizure data

Calculate the correlation matrix for the seizure data and compare the correlation pattern to the one from the background data.

```
1 corr_matrix_epil = corrccoef(data_epil, rowvar=False)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'data_epil' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 fill_diagonal(corr_matrix_epil, 0)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'corr_matrix_epil' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 fig, ax = subplots(figsize = (8,8))
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'subplots' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 im = ax.imshow(corr_matrix_epil, cmap='coolwarm');
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 fig.colorbar(im, orientation='horizontal', shrink=0.68);
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'fig' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 show()
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'show' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

We find - a number of pairs of strongly correlated series - two strongly anti-correlated series (indices 3 and 4) - a block of pronounced correlations between series with indices 4 through 9).

So interestingly, while the time series changes dramatically in shape, the correlation pattern still shows some qualitative resemblance.

All results shown so far, represent the recording of the segment of 6 seconds chosen at the beginning. The human brain produces time-dependent voltage changes 24 hours a day and as seeing only a few seconds is only a partial view. The next step to investigate is to show how the features found for one segment vary over time.

Exercises

End of chapter Exercises

Pathological Human Brain Rhythms

Look at the image of brain activity from a child at the start of an epileptic seizure. It shows 4 seconds of evolution of the first 10 channels of a seizure rhythm at sampling rate $sr=1024$.

```
1 path = 'data/P1_Seizure1.csv'
2
3 data = read_csv(path, delimiter=r"\s+")
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'read_csv' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 data_P1 = data.to_numpy()
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'data' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 sr = 1024
2
3 period = 4
4
5 channels = 10
6
7 plot_series(data_P1[:sr*period, :channels], sr);
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'data_P1' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 show()
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'show' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

Using the code from this lesson, import the data from the file `P1_Seizure1.csv` and generate an overview of uni- and multivariate features in the following form:

1. Pick the first two seconds of the recording as background, the last two second as epileptic seizure rhythm. Use the first ten channels in both cases. Data should have the shape (2048, 10).
2. Filter the data to get rid of frequencies below 1 Hz and frequencies faster than 20 Hz.
3. Plot time series of both.
4. Fourier transform both filtered data sets and display the Fourier spectra of the first 4 channels. What are the strongest frequencies in the two sets?
5. Plot the correlation matrices of both data sets. Which challes show the strongest change in correlations?

```
1 from pandas import read_csv
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords):  
  ModuleNotFoundError: No module named 'pandas'  
2  
3 Detailed traceback:  
4   File "<string>", line 1, in <module>  
5   File "/home/runner/.local/share/renv/cache/v5/R-4.2/x86_64-pc-linux-  
    gnu/reticulate/1.24/ffdf27627a3c1537478073c43b6e7980/reticulate/  
    python/rpytools/loader.py", line 39, in _import_hook  
6     module = _import(
```

```
1 from numpy import arange, zeros, linspace, sin, pi, c_, mean, var,  
  array  
2  
3 from numpy import correlate, corrcoef, fill_diagonal, amin, amax,  
  asarray  
4  
5 from numpy import around, triu_indices  
6  
7 from numpy.ma import masked_less, masked_greater  
8  
9 from scipy.fftpack import fft
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords):  
  ModuleNotFoundError: No module named 'scipy'  
2  
3 Detailed traceback:  
4   File "<string>", line 1, in <module>  
5   File "/home/runner/.local/share/renv/cache/v5/R-4.2/x86_64-pc-linux-  
    gnu/reticulate/1.24/ffdf27627a3c1537478073c43b6e7980/reticulate/  
    python/rpytools/loader.py", line 39, in _import_hook  
6     module = _import(
```



```
1 from matplotlib.pyplot import subplots, yticks, legend, axis, figure, show
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords):  
  ModuleNotFoundError: No module named 'matplotlib'  
2  
3 Detailed traceback:  
4   File "<string>", line 1, in <module>  
5   File "/home/runner/.local/share/renv/cache/v5/R-4.2/x86_64-pc-linux-gnu/reticulate/1.24/ffdf27627a3c1537478073c43b6e7980/reticulate/python/rpytools/loader.py", line 39, in _import_hook  
6     module = _import(
```

Q1

Extract data for first and last two seconds

```
1 sr = 1024  
2  
3 duration = 2 # seconds  
4 data_n = data.to_numpy()  
5  
6 # dat_back = data.iloc[:duration*sr, :10]
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:  
  name 'data' is not defined  
2  
3 Detailed traceback:  
4   File "<string>", line 1, in <module>
```

```
1 dat_back = data_n[:duration*sr, :10]
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:  
  name 'data_n' is not defined  
2  
3 Detailed traceback:  
4   File "<string>", line 1, in <module>
```

```
1 dat_epil = data_n[data_n.shape[0] - duration*sr:, :10]
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:  
  name 'data_n' is not defined  
2  
3 Detailed traceback:  
4   File "<string>", line 1, in <module>
```

```
1 time = linspace(0, 1, duration*sr)
2
3 print(dat_back.shape, dat_epil.shape, time.shape)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
   name 'dat_back' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

Q2 and Q3

Filter and display data

```
1 def data_filter(data, sr, low, high):
2     """
3     Filtering of multiple time series.
4
5     data: nxm numpy array. Rows are time points, columns are recordings
6     sr: sampling rate, same time units as period
7
8     low: Low cut-off frequency (high-pass filter)
9     high: High cut-off frequency (low-pass filter)
10
11     return: filtered data
12     """
13
14     from scipy.signal import butter, sosfilt
15
16     order = 5
17
18     filter_settings = [low, high, order]
19
20     sos = butter(order, (low, high), btype='bandpass', fs=sr, output='
        sos')
21
22     data_filtered = zeros((data.shape[0], data.shape[1]))
23
24     for index, column in enumerate(data.transpose()):
25         forward = sosfilt(sos, column)
26         backwards = sosfilt(sos, forward[-1::-1])
27         data_filtered[:, index] = backwards[-1::-1]
28
29     return data_filtered
```

```
1 dat_back_filt = data_filter(dat_back, sr, 1, 20)
2 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
```

```
name 'dat_back' is not defined
3
4 Detailed traceback:
5   File "<string>", line 1, in <module>
6   (fig, ax) = plot_series(dat_back_filt, sr)
7   Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
8     name 'dat_back_filt' is not defined
9
10 Detailed traceback:
11   File "<string>", line 1, in <module>
12   fig.suptitle('First two seconds: Background EEG', fontsize=16);
13   Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
14     name 'fig' is not defined
15
16 Detailed traceback:
17   File "<string>", line 1, in <module>
18   show()
19   Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
20     name 'show' is not defined
21
22 Detailed traceback:
23   File "<string>", line 1, in <module>
```

```
1 dat_epil_filt = data_filter(dat_epil, sr, 1, 20)
2 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
3   name 'dat_epil' is not defined
4
5 Detailed traceback:
6   File "<string>", line 1, in <module>
7   (fig, ax) = plot_series(dat_epil_filt, sr)
8   Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
9     name 'dat_epil_filt' is not defined
10
11 Detailed traceback:
12   File "<string>", line 1, in <module>
13   fig.suptitle('Last 2 seconds: Seizure EEG', fontsize=16);
14   Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
15     name 'fig' is not defined
16
17 Detailed traceback:
18   File "<string>", line 1, in <module>
19   show()
20   Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
21     name 'show' is not defined
22
23 Detailed traceback:
24   File "<string>", line 1, in <module>
```

Q4**Fourier Transform**

```
1 rows = dat_back.shape[0]
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'dat_back' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 dat_back_fft = fft(dat_back_filt, axis=0)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'fft' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 powers_back2 = (2.0 / rows) * abs(dat_back_fft[:rows//2, :])
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'rows' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 dat_epil_fft = fft(dat_epil_filt, axis=0)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'fft' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 powers_epil2 = (2.0 / rows) * abs(dat_epil_fft[:rows//2, :])
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'rows' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

You can see the frequencies with largest power visually from a display of the Fourier spectrum. Here is an example code how to extract those values for each channel using Numpy functions.

```
1 # Get the maxima of powers for each channel
2
3 powermax_back2 = amax(powers_back2, axis=0)
4 powermax_epil2 = amax(powers_epil2, axis=0)
5
6
7 # Get the frequency index of that maximum
8
9 powermax_back2_index = zeros(powers_back2.shape[1])
10
11 for ind, pow in enumerate(list(powers_back2.transpose())):
12     pow_ind = list(pow).index(powermax_back2[ind])
13     powermax_back2_index[ind] = pow_ind
14
15 powermax_epil2_index = zeros(powers_epil2.shape[1])
16
17 for ind, pow in enumerate(list(powers_epil2.transpose())):
18     pow_ind = list(pow).index(powermax_epil2[ind])
19     powermax_epil2_index[ind] = pow_ind
20
21
22
23 powermax_back2_freq = asarray(powermax_back2_index)*(sr / 2 /
24     powers_back2.shape[0])
25 powermax_epil2_freq = asarray(powermax_epil2_index)*(sr / 2 /
26     powers_epil2.shape[0])
27
28 print('Frequencies of max power in background (Hz): ', '\n', around(
29     powermax_back2_freq, decimals=1))
30 print('')
31 print('Frequencies of max power in seizure (Hz): ', '\n', around(
32     powermax_epil2_freq, decimals=1))
33
34 #print(powermax_back2_freq, '\n', powermax_epil2_freq)
35
36 fig, ax = subplots(nrows=2, figsize=(6,9))
37
38 binwidth = 1
39
40 (counts1, bins1, bars1) = ax[0].hist(powermax_back2_freq, bins=arange
41     (0, 50 + binwidth, binwidth))
42 ax[0].set_xlim(0, 30)
43 ax[0].set_ylim(0, 10)
44 ax[0].set_xlabel('Frequency (Hz), Background')
45
46 (counts2, bins2, bars2) = ax[1].hist(powermax_epil2_freq, bins=arange
47     (0, 50 + binwidth, binwidth))
48 ax[1].set_xlim(0, 30)
49 ax[1].set_ylim(0, 10)
50 ax[1].set_xlabel('Frequency (Hz), Seizure');
```

```
46 show()
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'powers_back2' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'powers_epil2' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'powers_back2' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'powers_back2' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'powers_epil2' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'powers_epil2' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'powermax_back2_index' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'powermax_epil2_index' is not defined
2
3 Detailed traceback:
4 File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'powermax_back2_freq' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'powermax_epil2_freq' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'subplots' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'show' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

Fourier spectrum with max frequency

```
1 print('Maximum count: background: ', amax(counts1))
2
3 print('Maximum count: seizure:    ', amax(counts2))
4
5 print('Frequency with maximum count: background: ', '10-11 Hz')
6
7 print('Frequency with maximum count: seizure:    ', ' 7- 8 Hz')
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'counts1' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'counts2' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 Frequency with maximum count: background: 10-11 Hz
```


2	Frequency with maximum count: seizure:	7- 8 Hz
---	--	---------

```
1 freqs = (sr/2)*linspace(0, 1, int(rows/2))
2 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'rows' is not defined
3
4 Detailed traceback:
5   File "<string>", line 1, in <module>
6   fig, axes = subplots(figsize=(6, 14), ncols=1, nrows=4, sharex=False)
7
8 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'subplots' is not defined
9
10 Detailed traceback:
11   File "<string>", line 1, in <module>
12   axes[0].plot(freqs, powers_back2[:, 3])
13 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'axes' is not defined
14
15 Detailed traceback:
16   File "<string>", line 1, in <module>
17   axes[0].set_xlim(0, 20)
18 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'axes' is not defined
19
20 Detailed traceback:
21   File "<string>", line 1, in <module>
22   axes[0].set_ylim(0, 12)
23 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'axes' is not defined
24
25 Detailed traceback:
26   File "<string>", line 1, in <module>
27   axes[0].set(ylabel=f'Power channel 3')
28 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'axes' is not defined
29
30 Detailed traceback:
31   File "<string>", line 1, in <module>
32   axes[0].set(xlabel='Frequency (Hz)');
33 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'axes' is not defined
34
35 Detailed traceback:
36   File "<string>", line 1, in <module>
37   axes[1].plot(time, dat_back_filt[:, 3], c='r')
38 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'axes' is not defined
39
40 Detailed traceback:
41   File "<string>", line 1, in <module>
```

```
42 axes[1].set(xlabel='Time (s)');
43 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
   name 'axes' is not defined
44
45 Detailed traceback:
46   File "<string>", line 1, in <module>
47 axes[1].set_ylim(-50, 60)
48 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
   name 'axes' is not defined
49
50 Detailed traceback:
51   File "<string>", line 1, in <module>
52 axes[2].plot(freqs, powers_epil2[:, 3])
53 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
   name 'axes' is not defined
54
55 Detailed traceback:
56   File "<string>", line 1, in <module>
57 axes[2].set_xlim(0, 20)
58 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
   name 'axes' is not defined
59
60 Detailed traceback:
61   File "<string>", line 1, in <module>
62 axes[2].set_ylim(0, 12)
63 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
   name 'axes' is not defined
64
65 Detailed traceback:
66   File "<string>", line 1, in <module>
67 axes[2].set(ylabel='Power channel index 1')
68 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
   name 'axes' is not defined
69
70 Detailed traceback:
71   File "<string>", line 1, in <module>
72 axes[2].set(xlabel='Frequency (Hz)');
73 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
   name 'axes' is not defined
74
75 Detailed traceback:
76   File "<string>", line 1, in <module>
77 axes[3].plot(time, dat_epil_filt[:, 3], c='r')
78 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
   name 'axes' is not defined
79
80 Detailed traceback:
81   File "<string>", line 1, in <module>
82 axes[3].set(xlabel='Time (s)');
83 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
   name 'axes' is not defined
```

```
84
85 Detailed traceback:
86   File "<string>", line 1, in <module>
87 axes[3].set_ylim(-50, 60)
88 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
    name 'axes' is not defined
89
90 Detailed traceback:
91   File "<string>", line 1, in <module>
92 show()
93 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
    name 'show' is not defined
94
95 Detailed traceback:
96   File "<string>", line 1, in <module>
```

Q5

Correlation Matrix

```
1 corr_matrix_back2 = corrccoef(dat_back_filt, rowvar=False)
2 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
    name 'dat_back_filt' is not defined
3
4 Detailed traceback:
5   File "<string>", line 1, in <module>
6 fill_diagonal(corr_matrix_back2, 0)
7 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
    name 'corr_matrix_back2' is not defined
8
9 Detailed traceback:
10  File "<string>", line 1, in <module>
11 corr_matrix_epil2 = corrccoef(dat_epil_filt, rowvar=False)
12 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
    name 'dat_epil_filt' is not defined
13
14 Detailed traceback:
15  File "<string>", line 1, in <module>
16 fill_diagonal(corr_matrix_epil2, 0)
17 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
    name 'corr_matrix_epil2' is not defined
18
19 Detailed traceback:
20  File "<string>", line 1, in <module>
21 fig, ax = subplots(figsize = (8,8), ncols=2)
22 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
    name 'subplots' is not defined
23
24 Detailed traceback:
```

```
25 File "<string>", line 1, in <module>
26 im1 = ax[0].imshow(corr_matrix_back2, cmap='coolwarm');
27 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
    name 'ax' is not defined
28
29 Detailed traceback:
30 File "<string>", line 1, in <module>
31 fig.colorbar(im1, ax=ax[0], orientation='horizontal', shrink=0.8)
32 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
    name 'fig' is not defined
33
34 Detailed traceback:
35 File "<string>", line 1, in <module>
36 im2 = ax[1].imshow(corr_matrix_epil2, cmap='coolwarm');
37 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
    name 'ax' is not defined
38
39 Detailed traceback:
40 File "<string>", line 1, in <module>
41 fig.colorbar(im2, ax=ax[1], orientation='horizontal', shrink=0.8);
42 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
    name 'fig' is not defined
43
44 Detailed traceback:
45 File "<string>", line 1, in <module>
46 show()
47 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
    name 'show' is not defined
48
49 Detailed traceback:
50 File "<string>", line 1, in <module>
```

Hist of Correlation Coefficients

```
1 channels = dat_back.shape[1]
2 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
    name 'dat_back' is not defined
3
4 Detailed traceback:
5 File "<string>", line 1, in <module>
6 corr_coeffs_back2 = corr_matrix_back2[triu_indices(channels, k=1)]
7 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
    name 'corr_matrix_back2' is not defined
8
9 Detailed traceback:
10 File "<string>", line 1, in <module>
11 corr_coeffs_epil2 = corr_matrix_epil2[triu_indices(channels, k=1)]
12 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
    name 'corr_matrix_epil2' is not defined
```

```
13
14 Detailed traceback:
15   File "<string>", line 1, in <module>
16   fig, ax = subplots(nrows=2)
17   Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
18     name 'subplots' is not defined
19
20 Detailed traceback:
21   File "<string>", line 1, in <module>
22   ax[0].hist(corr_coeffs_back2, bins = 12);
23   Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
24     name 'ax' is not defined
25
26 Detailed traceback:
27   File "<string>", line 1, in <module>
28   ax[0].set_xlim(-1, 1)
29   Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
30     name 'ax' is not defined
31
32 Detailed traceback:
33   File "<string>", line 1, in <module>
34   ax[1].hist(corr_coeffs_epil2, bins = 12);
35   Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
36     name 'ax' is not defined
37
38 Detailed traceback:
39   File "<string>", line 1, in <module>
40   ax[1].set_xlim(-1, 1);
41   Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
42     name 'ax' is not defined
43
44 Detailed traceback:
45   File "<string>", line 1, in <module>
```

Channel Correlations

```
1 corr_coeffs_back2_mean = mean(abs(corr_matrix_back2), axis=0)
2 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
3   name 'corr_matrix_back2' is not defined
4
5 Detailed traceback:
6   File "<string>", line 1, in <module>
7   corr_coeffs_epil2_mean = mean(abs(corr_matrix_epil2), axis=0)
```

```
7 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'corr_matrix_epil2' is not defined
8
9 Detailed traceback:
10 File "<string>", line 1, in <module>
11 fig, ax = subplots(nrows=2, figsize=(5,9))
12 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'subplots' is not defined
13
14 Detailed traceback:
15 File "<string>", line 1, in <module>
16 bins = arange(corr_coeffs_back2_mean.shape[0])
17 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'corr_coeffs_back2_mean' is not defined
18
19 Detailed traceback:
20 File "<string>", line 1, in <module>
21 ax[0].bar(bins, corr_coeffs_back2_mean);
22 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
23
24 Detailed traceback:
25 File "<string>", line 1, in <module>
26 ax[0].set_xlabel('Background')
27 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
28
29 Detailed traceback:
30 File "<string>", line 1, in <module>
31 ax[0].set_ylim(0, 0.4)
32 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
33
34 Detailed traceback:
35 File "<string>", line 1, in <module>
36 ax[1].bar(bins, corr_coeffs_epil2_mean);
37 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
38
39 Detailed traceback:
40 File "<string>", line 1, in <module>
41 ax[1].set_xlabel('Seizure')
42 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
43
44 Detailed traceback:
45 File "<string>", line 1, in <module>
46 ax[1].set_ylim(0, 0.4);
47 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
48
```

```
49 Detailed traceback:
50   File "<string>", line 1, in <module>
51 show()
52 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
   name 'show' is not defined
53
54 Detailed traceback:
55   File "<string>", line 1, in <module>
```

```
1 corr_back2_mean = mean(corr_coeffs_back2_mean)
2 corr_epil2_mean = mean(corr_coeffs_epil2_mean)
3
4 print('Average correlation background: ', around(corr_back2_mean,
   decimals=2))
5 print('Average correlation seizure:      ', around(corr_epil2_mean,
   decimals=2))
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
   name 'corr_coeffs_back2_mean' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
   name 'corr_coeffs_epil2_mean' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
   name 'corr_back2_mean' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
   name 'corr_epil2_mean' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

Channels with strongest correlations during the seizure

```
1 threshold = 0.2
2
3 corr_coeffs_epil2_large = corr_coeffs_epil2_mean > threshold
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'corr_coeffs_epil2_mean' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

```
1 corr_coeffs_epil2_large
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'corr_coeffs_epil2_large' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

A horizontal line can be used to indicate the threshold:

```
1 fig, ax = subplots()
2 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'subplots' is not defined
3
4 Detailed traceback:
5   File "<string>", line 1, in <module>
6 bins = arange(corr_coeffs_back2_mean.shape[0])
7 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'corr_coeffs_back2_mean' is not defined
8
9 Detailed traceback:
10  File "<string>", line 1, in <module>
11 ax.bar(bins, corr_coeffs_epil2_mean);
12 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
13
14 Detailed traceback:
15  File "<string>", line 1, in <module>
16 ax.set_xlabel('Seizure')
17 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
18
19 Detailed traceback:
20  File "<string>", line 1, in <module>
21 ax.set_ylim(0, 0.4);
22 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
23
24 Detailed traceback:
25  File "<string>", line 1, in <module>
26 ax.axhline(y=threshold, c='r');
27 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
  name 'ax' is not defined
28
```



```
29 Detailed traceback:
30   File "<string>", line 1, in <module>
31 show()
32 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
    name 'show' is not defined
33
34 Detailed traceback:
35   File "<string>", line 1, in <module>
```

To find the indices of the channels that are larger than the threshold (i.e. those displaying True), we can use Numpy function `nonzero`:

```
1 from numpy import nonzero
2
3 nonzero(corr_coeffs_epil2_large)
```

```
1 Error in py_call_impl(callable, dots$args, dots$keywords): NameError:
    name 'corr_coeffs_epil2_large' is not defined
2
3 Detailed traceback:
4   File "<string>", line 1, in <module>
```

Keypoints

- `plot_series` is a Python function created to display multiple timeseries plots.
- Data filtering is applied to take out specific and relevant components.
- The Fourier spectrum decomposes the time series into a sum of sine waves.
- Cross-correlation matrix is used for multivariate analysis.