Final Signal Processing project:
Sleep stages through cycles investigation with EEG data

By 3-rd year IT&BA students at UCU:
Pavelko Roman and Pastukh Yaroslav

Part 1

1.1 Introduction

Sleep - is a condition of the body and mind that typically recurs for several hours every night, in which the nervous system is relatively inactive, the eyes closed, the postural muscles relaxed, and consciousness practically suspended. Sleep is characterized by relative immobility and reduced responsiveness to environmental stimuli. This in contrast to the state of wakefulness which is characterized by presumably purposeful motor activity and the ability to respond to environmental stimuli appropriately.

In the contemporary rapidly-evolving tech-era, the importance of sleep cannot be emphasized enough, as people tend to sacrifice the crucial recovery process for extra hours of productivity, causing significant harm to the brain activity, which consequently affects the performance of all other vital functions, which make up for the equality of life from a physiological standpoints.

1.2 Role in human's biological performance

Among all of the functions sleep is responsible for as a process, the most popular and easy to think of one is restorative: it is during the sleep when humans' bodies truly relax, when the growth happens. Among the benefits of this activity, the part of the day humans spend a third of their existence in total, are majorly lower risk of cardiovascular diseases, better athletic performance, better memory consolidation and, more widely, better brain cells restoration, and, in the more modern perspective, better concentration and productivity. Most importantly, it is crucial to mention that sleep is important for recovery of the nervous system, as it largely correlates with feelings of fatigue, mood shifts and overall emotional stability.

However, not only does it perform recreational function, but also it takes part in reducing energy expenditure by lowering metabolism and thermoregulation through hypothalamic nuclei. There are cross pathways of circadian rhythms and energy metabolism; however, during REM sleep, there is increased whole-body oxygen consumption.

Researchers also think that sleep brings about memory consolidation and the plasticity of the cognitive neural networks. Learning, behavior, and cognitive performance are improved after sleep, as evidenced by functional magnetic resonance imaging on the visuomotor task performance after normal sleep.

Part 2

2.1 Data Overview

The data we have been working with can be reached by the link - the sleep-edf database containing 197 whole-night PolySomnoGraphic sleep recordings, containing EEG, EOG, chin EMG, and event markers. Some records also contain respiration and body temperature. Corresponding hypnograms (sleep patterns) were manually scored by well-trained technicians according to the Rechtschaffen and Kales manual. Since all of the files are held in the .edf (European Data Format), which is impossible to read by any of the built-in Python libraries, or even scipy/numpy, so we had to use mne to handle the peculiarities of medical time series data.

Concerning the data source, since the mne library supports working with remote files, and considering the fact that we have done the majority of the work with .ipynb notebooks, the files, yet to be processed, were downloaded remotely (on Google Colab) and from there no significant preprocessing was needed except for opening different types of files - ones with 7-channel data: 2 EEG recordings (one for Fpz-Cz, the other for EEG Pz-Oz - differing from each other by the was electrodes were placed), EOG horizontal data, Resp oro-nasal data, EMG submental recording, Temp rectal and Event marker recordings.

The *Hypnogram.edf files contain annotations of the sleep patterns that correspond to the PSGs. These patterns (hypnograms) consist of sleep stages W, R, 1, 2, 3, 4, M (Movement time) and ? (not scored). All hypnograms were manually scored by well-trained technicians (identified by the eighth letter of the hypnogram filename) according to the 1968 Rechtschaffen and Kales manual, but based on Fpz-Cz/Pz-Oz EEGs instead of C4-A1/C3-A2 EEGs.

2.2 Related work

Here we would like to mention the different methods to use for the **sleep stage classification problem**, which is described in the separate part in this paper. Most of the related methods used 30-second epochs for vigilance state or sleep stage. However, in this work, or, rather, tutorial**,** artifacts also were also considered, although not always eliminated.

Generally, each epoch is labelled with a stage mark, which later composes to a training set and is fit to ML/DL models.

Part 3

3.1 Sleep staging

The humble beginnings in sleep medicine started with a mere observation and description of various events occurring during sleep and wake. However, it was not until the development of the field of electrophysiology and the invention of electroencephalography (EEG) recordings by Hans Berger in the early part of the 20th century that we began to understand better the complexity of the brain mechanisms characterizing sleep and wake states. Sleep goes through structured and organized cycles through various stages.

The initial overnight sleep recordings were performed by Loomes and his colleagues as they faced the challenging task of describing typical sleep patterns in normal individuals. Several groups improvised this and, in turn, gave rise to the beginnings of sleep staging. However, it was only 17 years later that Aserinsky recognized rapid eye movement (REM) sleep. This led to the birth of modern methods of sleep staging.

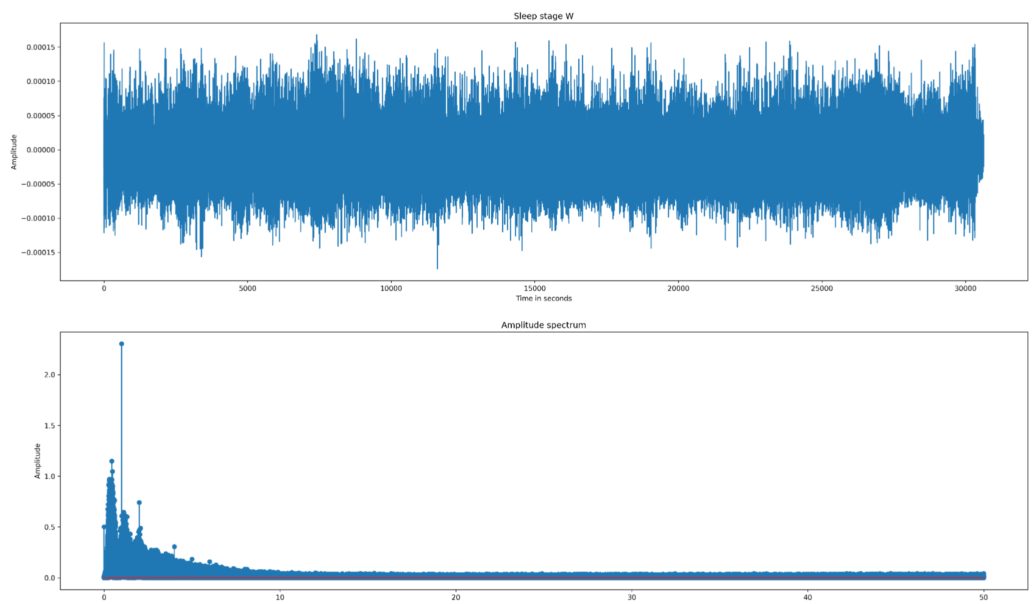
In 1968, a committee of experts chaired by Rechtschaffen and Kales established the rules for the scoring of sleep in normal human adults. From this coding, 5 sleep stages were identified: 1 REM stage and 4 NREM sleep stages. Each stage consists of a number of physiological variables, which tend to occur in concert. Subsequently, in 2004, a revision of the sleep scoring rules was commissioned by the American Academy of Sleep Medicine (AASM), which included rules for the scoring of arousals, respiratory events, sleep-related movement disorders, and cardiac events. The magnitude and distribution of the standard sleep parameters reflect the macrostructure of sleep.

3.2 Macrostructure of Sleep [each stage with graphical representation of a signal both in time- and frequency- domain]

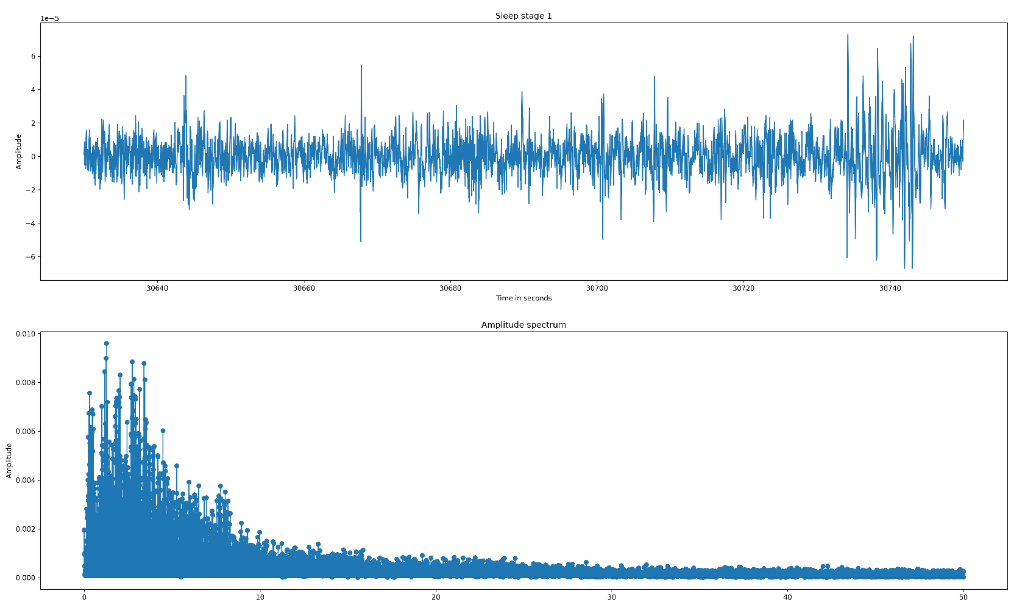
Based on sleep macrostructure, sleep can be classified into 2 main stages: ***Non-Rapid Eye Movement (NREM)*** and ***Rapid Eye Movement (REM)*** sleep. Typically, as one goes to sleep, the low-voltage fast EEG pattern of wakefulness gradually gives way to slower frequencies, as NREM sleep goes from stage *N1* (decrease in alpha) to stage *N2* (spindles, K-complexes) to stage *N3* (increasing amplitude and regularity of delta rhythm). Stage N3 is referred to as slow-wave sleep (SWS). SWS is interrupted by periods of rapid eye movement (REM, i.e., active or paradoxical) sleep. Polysomnography (PSG) is a multiparametric study that has been traditionally used to assess the architecture of sleep.

Sleep goes through multiple discrete cycles of NREM and REM sleep through any given night. In normal adults, each cycle lasts for about 90 to 120 minutes, and there are about 4 to 5 such cycles that occur during a normal 8 hour night sleep. The percentage of NREM sleep is maximum in the first part of the night, while REM sleep predominates in the second half.

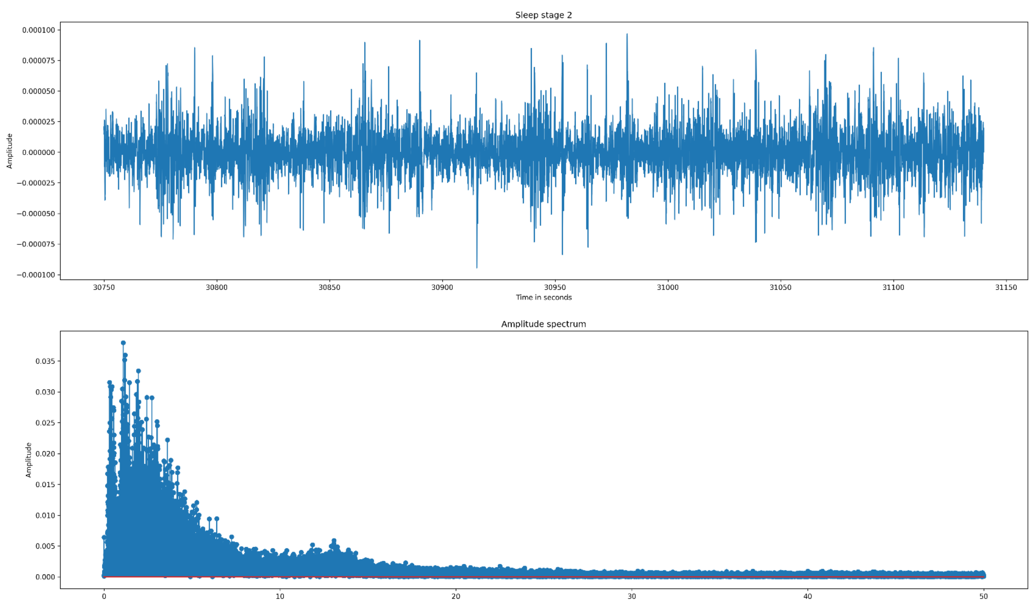
Stage wake (W) is characterized by the presence of a predominant beta rhythm over the anterior leads, and there is a posterior progression to a posterior dominant alpha rhythm (described later) over the occipital regions. This anteroposterior progression is best observed with the eyes closed and is attenuated by eye-opening. Eye blinks are frequently observed in this stage which appear as conjugate eye movements consisting of 0.5 to 2 Hz. During the transition to drowsiness, one of the first things to appear is slow lateral eye movements typically less than 0.5 Hz, and there is greater prominence of alpha rhythm with intermittent beta rhythm.



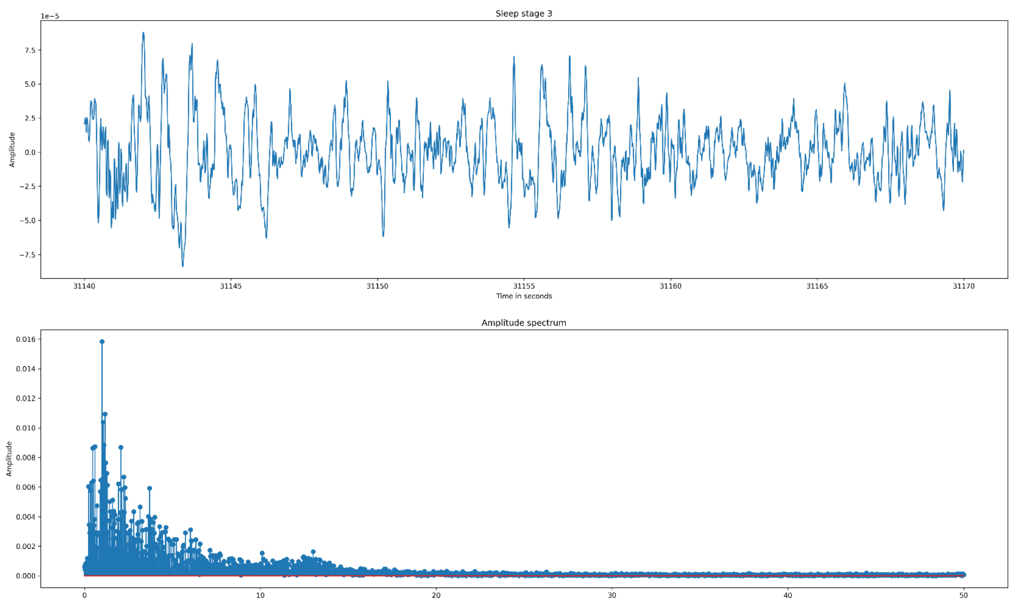
Stage 1 (N1) is characterized typically by the disappearance of the alpha (*Alpha brainwaves* (8-12 Hz.) are slower and larger. They are associated with a state of relaxation and represent the brain shifting into an idling gear, waiting to respond when needed. If we close our eyes and begin picturing something peaceful, there is an increase in alpha brainwaves) rhythm and appearance of roving eye movements, which are slow, conjugate, to and fro deflections usually lasting approximately 500 milliseconds. The EEG shows medium amplitude, mixed frequency predominantly of 4 to 7 Hz activity, and irregularly spaced bursts of slow waves.



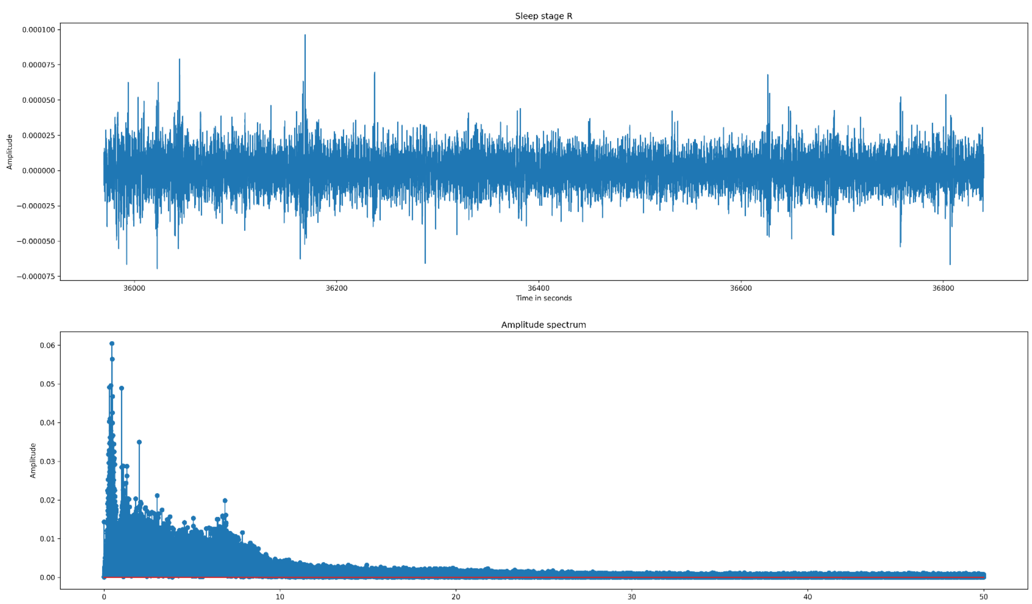
Stage 2 (N2) is characterized by the presence of bilaterally synchronous theta activity accompanied by sleep spindles or K-complexes, or both. K complexes are defined by the occurrence of a complex pattern of negative sharp wave immediately followed by a positive wave (V-shaped) standing out from the background EEG, lasting 0.5 seconds, and is most prominent in the fronto-central derivations.



Stage 3 (N3) is characterized by high amplitude, delta (*Delta brainwaves* (1-3 Hz) are the slowest, highest amplitude brain waves, and are what we experience when we are asleep. In general, different levels of awareness are associated with dominant brainwave states) slowing in the range of 0.5 to 2 Hz with amplitudes of equal to 75 microV as measured over the fronto-central derivations. K-complexes and sleep spindles may be present, but POSTs are rare. Typically, N3 sleep is scored if slowing is seen in 20% of the epoch. N3 sleep occurs most frequently during the first one-third of the night, and clinically this can be important as NREM parasomnias such as sleepwalking and night terrors are typically seen during this period.

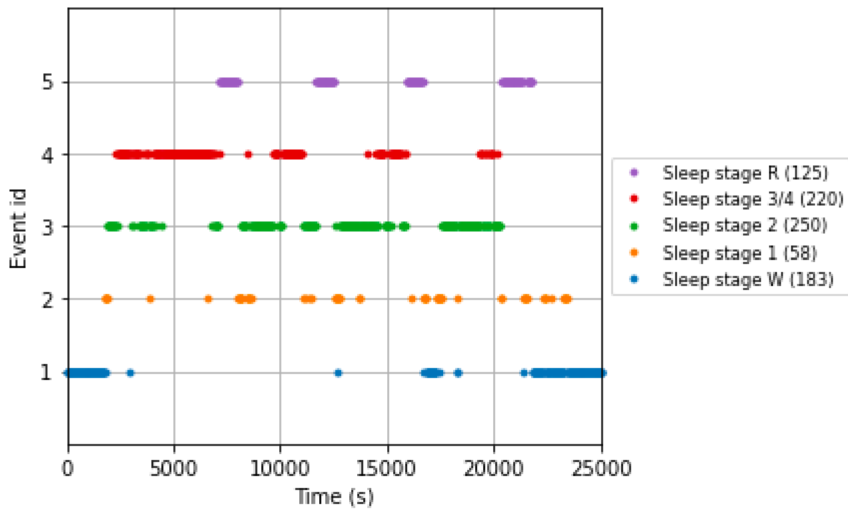


Stage REM (R) is characterized by the presence of rapid eye movements (REM), which are conjugate, irregular, and sharply contoured eye movements with an initial phase deflection usually lasting less than 500 ms. We also see diminished EMG tone and is usually the lowest of the entire recording. Sawtooth waves are seen, which are described as drains of sharply contoured or triangular, often serrated waves of 2 to 6 Hz with maximal amplitude over the central derivations and often, but not always preceded by a burst of rapid eye movements. The threshold for arousal by auditory stimuli tends to be the highest during REM. Typically, the R stage of sleep is present predominantly in the last one-third of the night and is the period where the REM parasomnias such as nightmares are typically seen.



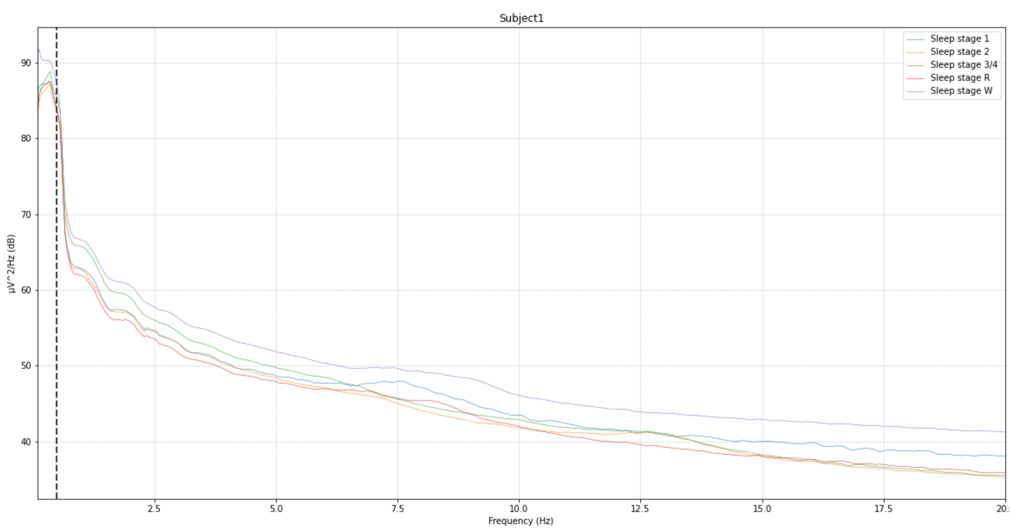
3.3 Sleep stages time distribution across full night's sleep and energy spectrum from data of a randomly picked subject

Sleep stages distribution



From the above graph (and many others, corresponding to sleep recording of other subjects), we can see that sleep stages may overlap, which we assume to be caused by the annotations of mediocre quality

Energy distribution through stages



From the energy graph we can see that at all stages lower frequencies are dominant, and also energy levels of deeper stages of sleep are lower.

Part 4

4.1 Classification

As we already know original stages classification, it makes sense to use some ML or DL techniques to make predictions on stages. We chose a Random Forest Classifier (RFC) and performed some transformations. It is quite a complex task for ML models to recognize different stages behavior as all subjects can have individual sleep specifics or issues. So further steps for our research definitely would be using some State-Of-The-Art deep learning models for signal processing. We have reached an 0.74 accuracy score using RFC with a training set consisting of 15 subjects' EEG recordings.

Also it makes sense to train such models on EEG recordings of one particular subject in order to avoid features extracting complexity for proposed models.

Here are our result's confusion matrix and classification report:

	0	1	2	3	4
0	128	9	0	0	1
1	12	13	0	0	4
2	11	28	264	36	49
3	5	2	41	243	0
4	13	14	20	0	71

	precision	recall	f1-score	support
Sleep stage W	0.76	0.93	0.83	138
Sleep stage 1	0.20	0.45	0.27	29
Sleep stage 2	0.81	0.68	0.74	388
Sleep stage 3/4	0.87	0.84	0.85	291
Sleep stage R	0.57	0.60	0.58	118
accuracy			0.75	964
macro avg	0.64	0.70	0.66	964
weighted avg	0.77	0.75	0.75	964

Part 5

5.1 Summary and Conclusions

In this project we analyzed sleep EEG recordings as a complete signal, extracted insights from it in terms of frequency dominance across different stages of sleep. We found that the signal slows down in frequency as humans go towards deeper stages of NREM, where the restorative function is said to be at its peak and where it is the most difficult to be woken up, and also - produces relative raises in amplitude; - which exactly coincides with theoretical knowledge about sleep from much earlier and established researches. We would also like to go on with the investigation of sleep in terms of working with labelled data about age of subjects - which is of particular interest knowing that as the more adult a person is, the less time they spend in REM sleep stage, and, knowingly, the less time they need for night's recovery; whether they have any sleep or general neurological disorders, and expand this base of research to, for example, capture depression through EEG data, or capture athletic performance and overall strength level of sportsmen.

We also attempted to conduct classification of sleep stages of the different samples of EEG data (30-second epochs) using ML model Random Forest Classifier, on which we reached 74% accuracy. These are only first-guess results, as there was no hyperparameter tuning yet, and we only fed a small amount of data to it.

Part 6

6.1 References

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