MIND NEUROTECH 101 WORKSHOP

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INTRO AND THEORY BASICS

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EEG (ELECTROENCEPHALOGRAM)

WHAT DOES IT MEASURE?

- Measures the summed electrical activity of neurons in the brain

- Neuronal communication involves action potentials (electrical impulses) postsynaptic potentials, creating small voltage changes that can be detected on the scalp

- Due to the low amplitude of these signals, they are easily affected by noise and external interference

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EEG (ELECTROENCEPHALOGRAM)

SIGNAL CHARACTERISTICS

- **Domain:** EEG signals are typically analyzed as **voltage (microvolts, µV) over time (milliseconds or seconds)**

- **Frequency Range:** Brain activity consists of different frequency bands, each associated with distinct cognitive states:
  - **Delta** (0.5 - 4 Hz): Deep sleep
  - **Theta** (4 - 8 Hz): Light sleep/relaxation/creativity
  - **Alpha** (8 - 12 Hz): Calm wakefulness/meditative states
  - **Beta** (12 - 30 Hz): Active thinking/focus
  - **Gamma** (30 - 100 Hz): Higher cognitive functions/sensory processing

- These frequency bands are extracted using filters (e.g., band-pass filters to isolate specific ranges)

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COMMON NOISE AND ARTIFACTS

- Since EEG signals are very low amplitude (10-100 μV), they are highly susceptible to external noise and artifacts

- Proper signal preprocessing is necessary to extract meaningful information

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Different Types of Types of Noise and Artifacts

Artifact Type	Description	Solution
Electromyographic (EMG) Noise	Muscle movements generate electrical activity, especially in the forehead and jaw.	Ask subjects to relax and minimize movements.
Eye Blink Artifacts (EOG)	Eye movements cause large slow deflections in the EEG signal.	Use Independent Component Analysis (ICA) to remove eye-related components.
Power Line Noise (50/60 Hz)	Electrical interference from surrounding devices.	Apply notch filtering at 50/60 Hz.
Electrode Pop Artifacts	Sudden disconnections in the electrode lead to spikes in the signal.	Ensure good skin-electrode contact and stable connections.
Sweat Artifacts	Slow drifts due to sweat affecting electrode impedance.	Use a high-pass filter (>0.5 Hz) to remove slow drifts.
Motion Artifacts	Movement of the head or body causes slow fluctuations.	Minimize movement and use reference electrodes.

ARTIFACT REMOVAL TECHNIQUES & EEG VISUALIZATION

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ARTIFACT REMOVAL TECHNIQUES

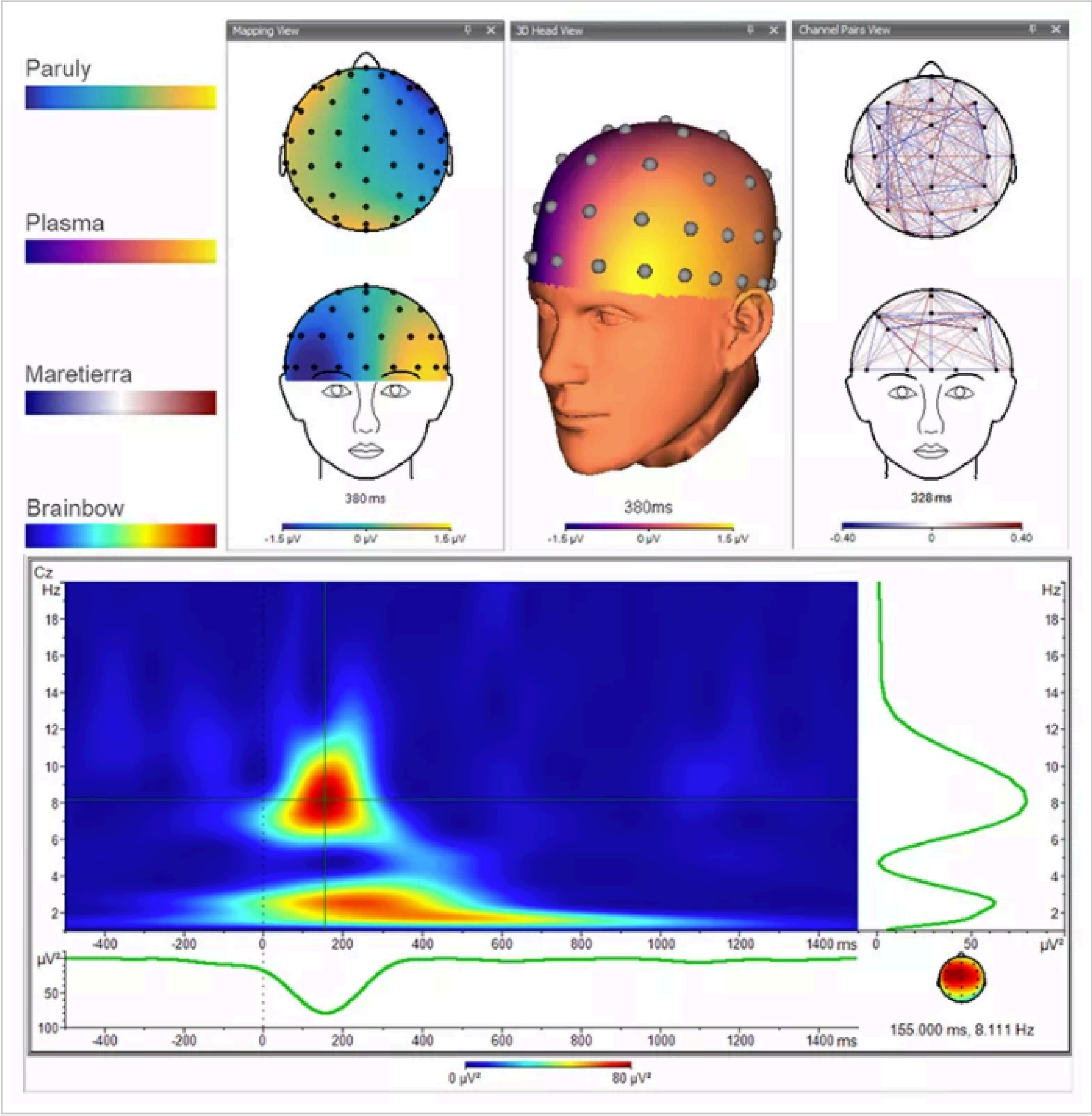
- **Filtering:**
  - Band-pass filters eliminate unwanted frequencies outside specific brainwave ranges.
- **Independent Component Analysis (ICA):**
  - Decomposes EEG signals to separate noise (e.g., eye blinks, muscle activity) from neural data.
- **Re-referencing:**
  - Enhances signal clarity by using average or linked-mastoid reference electrodes.

POST-CLEANING EEG VISUALIZATION

- **Time-Series Plots (µV vs. Time)**
  - Visualizes a single channel over time
  - Detects spikes, slow drifts, unusual patterns

- **Topographic Maps (EEG Topomaps)**
  - Heatmap of voltage distribution across the scalp
  - Identifies regions with strongest activity

- **Spectrograms (Frequency Plots) & Power Spectral Density (PSD)**
  - Displays frequency changes over time
  - Ideal for sleep, cognitive, and motor movement analysis



BANDPASS FILTERING

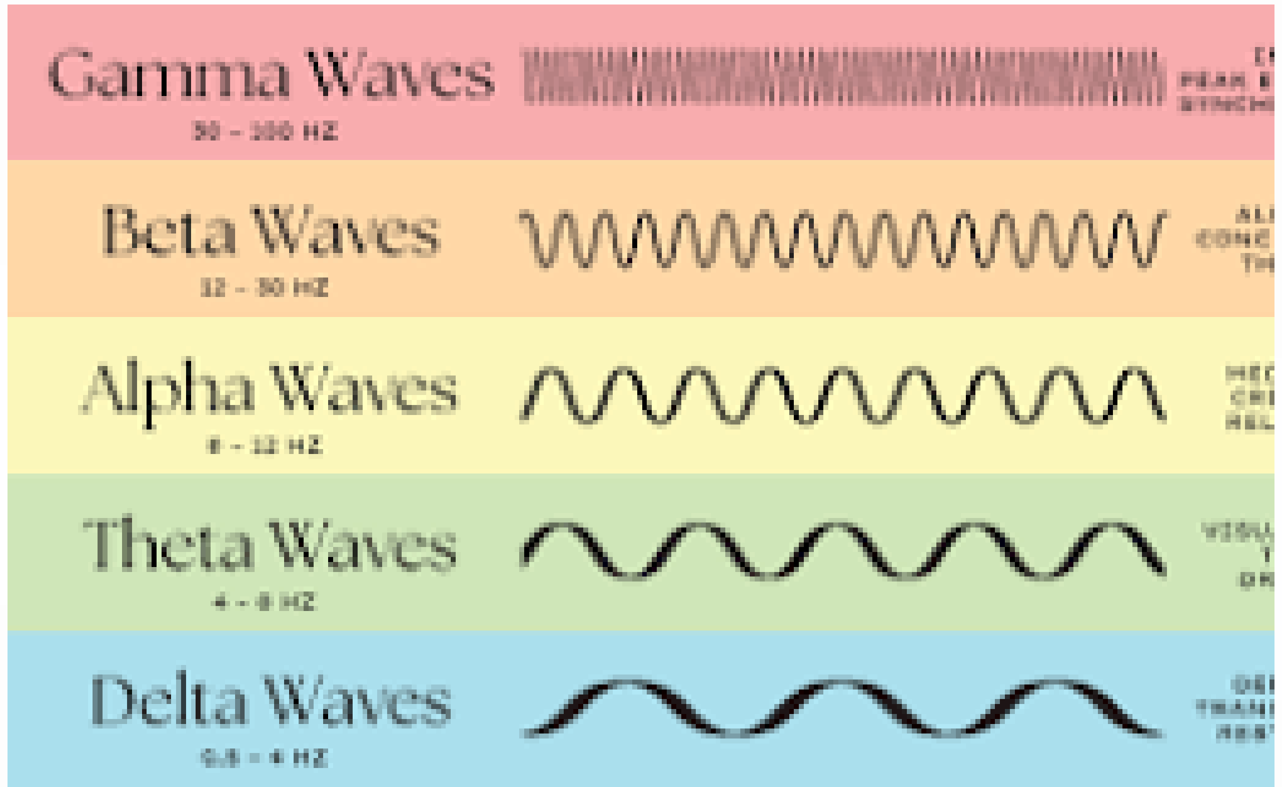
BANDPASS FILTERING THEORY

- EEG signals are often contaminated with noise and artifacts from various sources
- Filters are used to remove unwanted frequencies to isolate the brain's electrical activity of interest, **these are called bandpass filters**. They **clean** the data.
- Allows frequencies within a specific range to pass through while attenuating frequencies outside this range.
- Combines the characteristics of both low-pass and high-pass filters

BANDPASS FILTERING THEORY

In the context of EEG, common frequency bands of interest include:

- **Delta (0.5-4 Hz)**: Associated with deep sleep.
- **Theta (4-8 Hz):** Related to drowsiness and meditation.
- **Alpha (8-13 Hz)**: Linked to relaxed, wakeful states.
- **Beta (13-30 Hz):** Associated with active thinking and focus.
- **Gamma (30-100 Hz):** Related to high-level cognitive functioning.



BANDPASS FILTER

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What is the purpose/advantage?

- Isolates specific frequency bands of interest (e.g., alpha, beta waves) while eliminating unwanted frequencies.
- What are the applications?
  - **Frequency Analysis:** Isolates brainwave rhythms (alpha, beta, delta, theta) for cognitive studies
  - **Event-Related Potentials (ERPs)**: Enhances analysis of neural responses to stimuli.
  - **Artifact Removal:** Reduces noise and low-frequency drifts. Artifacts are things we do not want, and are distorting the signals quality.
  - **Baseline Drift Removal:** Minimizes slow drifts obscuring neural activity.

CHALLENGES AND RISKS

1. **Overfiltering:** Aggressive filtering may distort signals or remove valuable components, this can remove the shape and overall context to the signal.
2. **Misaligned Cutoff Frequencies:** Incorrect settings can filter out essential neural oscillations.
3. **Incomplete Drift Removal:** Filtering alone may not fully correct baseline drift.
4. **Artifact Persistence:** May require additional preprocessing for complex artifacts (e.g., muscle activity). Bandpass filtering is generally considered the bare minimum.
5. **Inconsistent Filtering:** Applying different filters across segments/channels can skew results.

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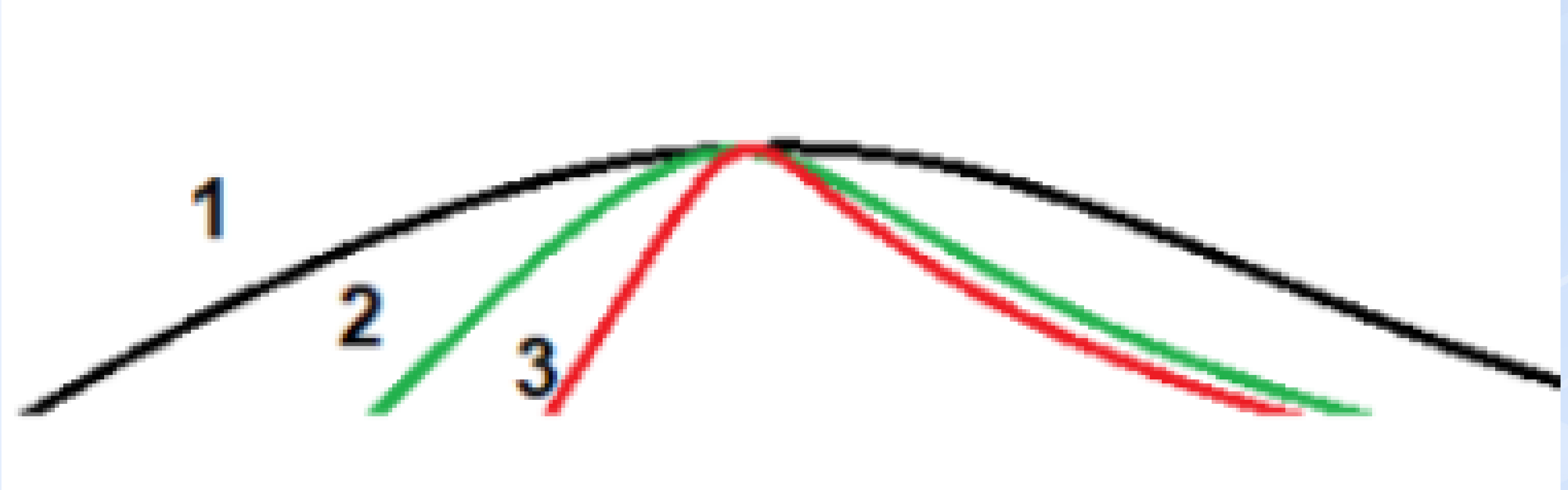
IMPLEMENTATION

The primary parameters of a band-pass filter are:

- **Lower Cutoff Frequency:** The lower bound of the passband.
- **Upper Cutoff Frequency:** The upper bound of the passband.
- **Order of the Filter:** Determines the steepness of the filter's response and its attenuation outside the passband
  - Generally, orders of 2-6 are common and higher filters generally have a faster roll-off rate, better attenuation of higher frequencies, and better noise rejection.
  - Disadvantages include slower calculations
- Lets checkout the code

Different Order Filters Visualized



TASK FOR EXPLORATION

1. **Filter Order:** Change order=5 to order=3 or order=8 and observe the effects on sharpness and phase distortion.
2. **Cutoff Frequencies:**
   - Set cutoff_high = 0.5 Hz and cutoff_low = 7 Hz.
   - Compare outcomes with original settings.
3. **Visualization:**
   - Plot both original and filtered signals on the same graph.
   - Analyze changes in frequency components.

EXPECTED OBSERVATIONS AND DISCUSSIONS

Lower Cutoff Frequencies:

- Allows more low-frequency components.
- Retains slow drifts.

Higher Cutoff Frequencies:

- Preserves more high-frequency components.
- Reduces low-frequency noise.

Filter Order:

- Higher order sharpens roll-off but risks phase distortion (timing becomes off because its more computationally expensive to do).
- Lower order smooths transition but reduces selectivity.

VISUALIZATION

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MATPLOTLIB CRASH COURSE

- Matplotlib is a data visualization package that allows you to visualize data through graphing them.

- **Importing Libraries: import matplotlib.pyplot as plt** imports the pyplot module from Matplotlib, providing an easy interface to create and display plots.

- **Plotting Data:** plt.plot(X_AXIS, Y_AXIS, '-', label="") is used to plot the data.
  - **X_AXIS and Y_AXIS** represent the array of values to be plotted on the x and y axis respectively,
  - **'-'** specifies using a solid line to connect the points.
  - The **label =** argument is used to assign a name to the line, which can later be displayed in a legend.

```
import matplotlib
# matplotlib.use('TkAgg')                           # Use TkAgg backend for interactive plotting
import matplotlib.pyplot as plt


plt.plot( *args: X_AXIS, Y_AXIS, '-', label="")  # '-' gives a smooth line
plt.legend()
plt.show()
```

MATPLOTLIB CRASH COURSE

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- **Adding a Legend:** The plt.legend() function adds a legend to the plot, which uses the labels specified in the label argument of plt.plot() to differentiate different data series.
- **Displaying the Plot:** plt.show() displays the plot in an interactive window, allowing you to visualize the graph.
- **Customization Options:** You can further customize the plot by adding titles, axis labels, and gridlines. For example, plt.title("Title of the Graph"), plt.xlabel("X-axis label"), plt.ylabel("Y-axis label"), etc.

```
import matplotlib
# matplotlib.use('TkAgg')                          # Use TkAgg backend for interactive plotting
import matplotlib.pyplot as plt


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```

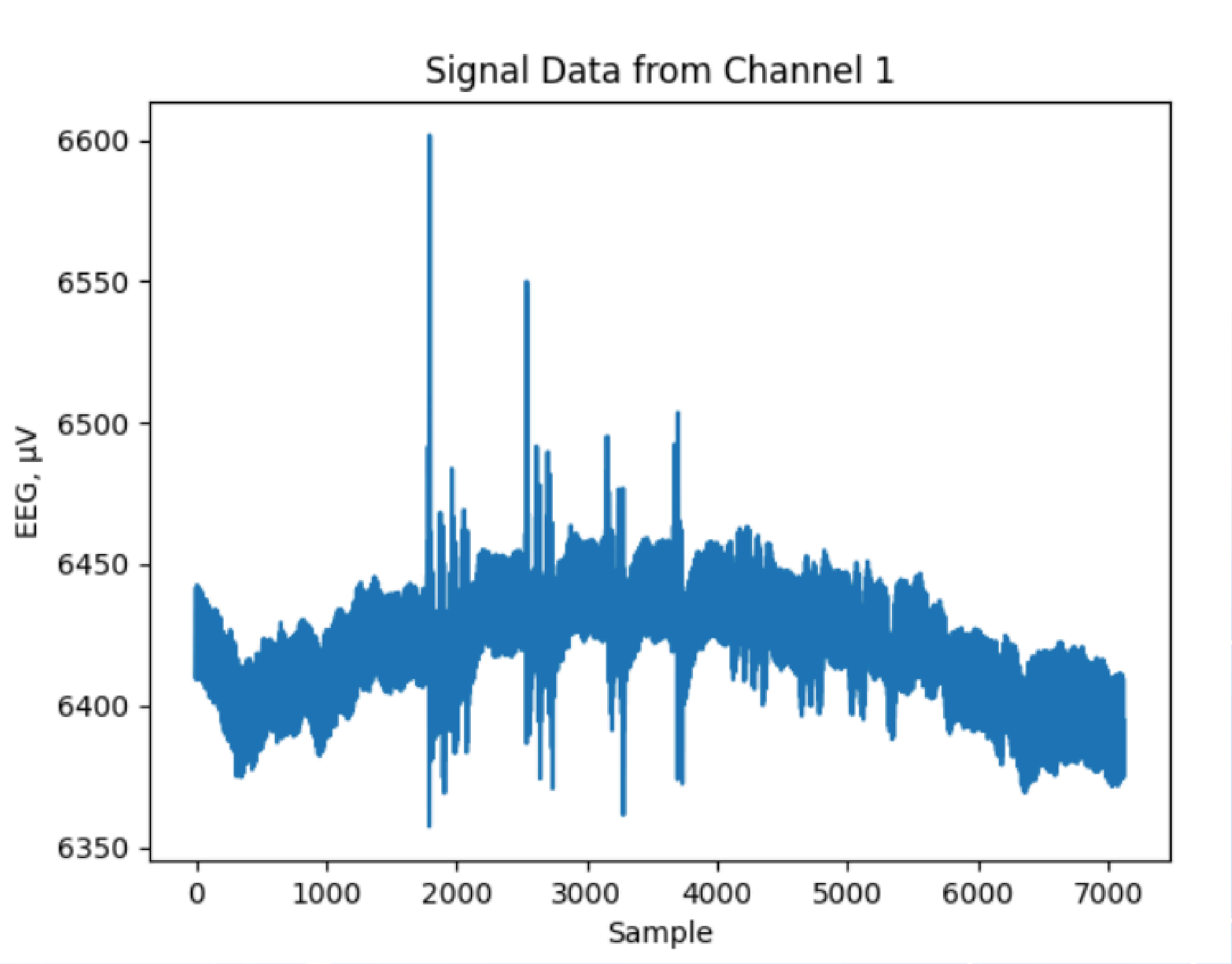
SIMPLE CHANNEL PLOT

Representation

- Line plot shows EEG signal from one electrode over time
    - **X-axis:** Time (samples)
    - **Y-axis:** EEG amplitude (µV)

Utility

- Visualizes continuous time-series data
- Helps observe brain activity changes over time
- Detects noise, artifacts, and distortions in EEG
- Enables visual inspection of brain wave patterns
- Useful for debugging and verifying preprocessing steps (e.g., filtering effectiveness)



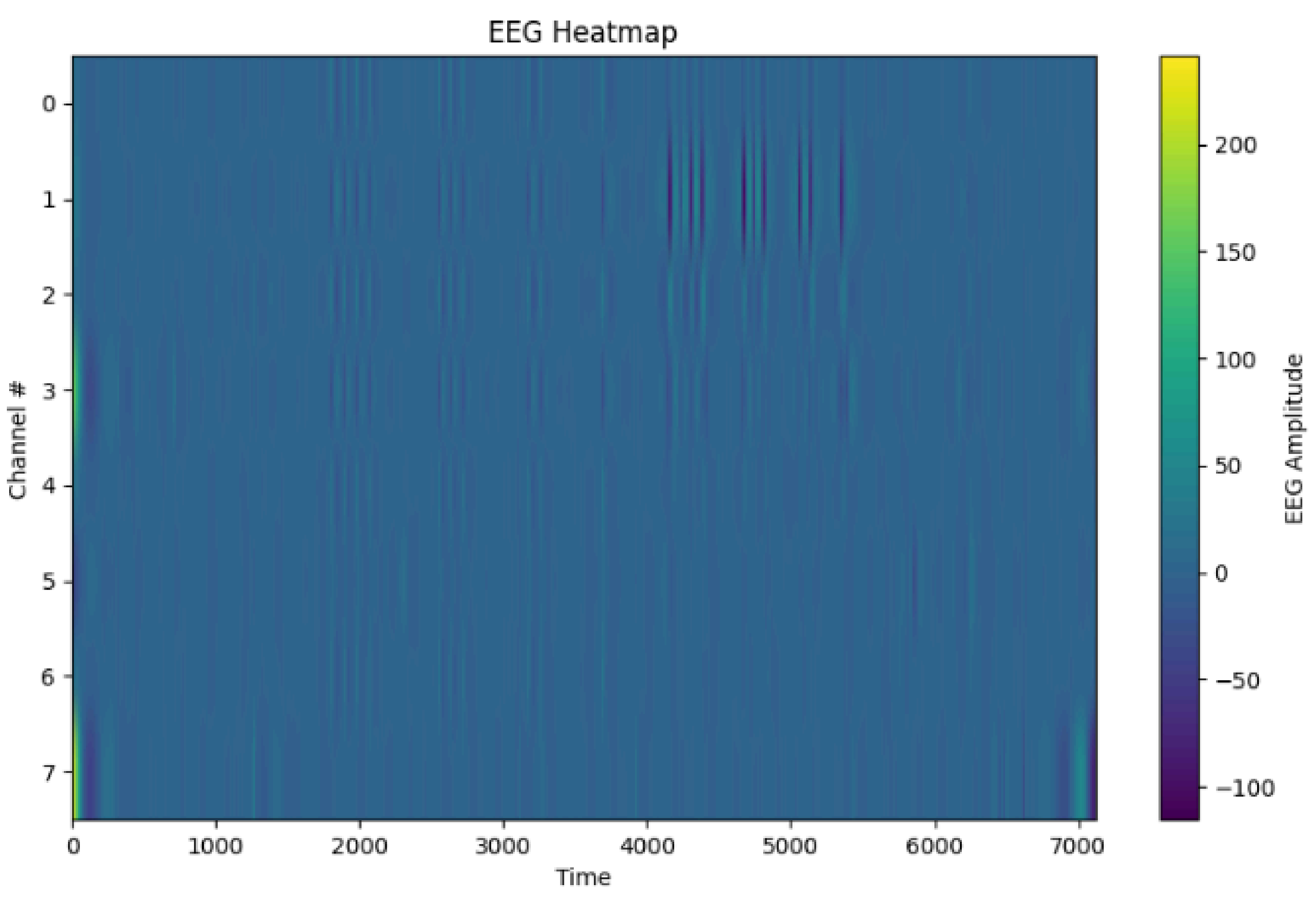
CODE IMPLEMENTATION

```
plt.plot(channel_data_bp_filtered)
plt.title("Channel Data after Band-pass Filter " + str(cutoff_high) + "-" + str(cutoff_low) + "Hz")
plt.ylabel('EEG, µV')
plt.xlabel('Sample')
plt.show()
```

HEATMAP PLOT

Representation

- Heatmap shows spatiotemporal (signal location and time) EEG data across all channels
  - **X-axis:** Time (each column = time point)
  - **Y-axis:** EEG channels (each row = electrode)
  - **Color intensity:** EEG amplitude (μV), reveals activity variation across time and channels



Utility

- Gives a broad overview of brain activity across electrodes
- Reveals patterns, trends, and outliers
- Detects artifacts (e.g., blinks, muscle movement, interference)
- Aids in comparing activity across different brain regions

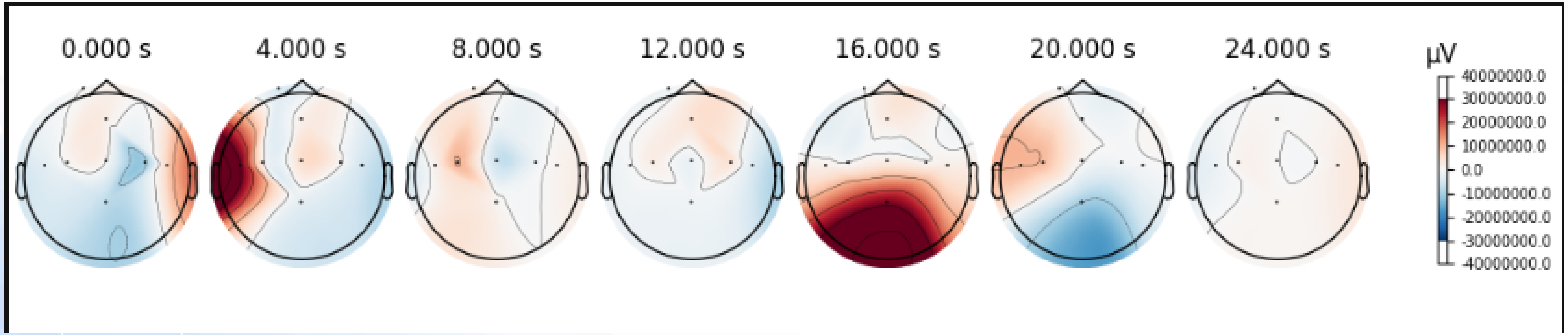
CODE IMPLEMENTATION

```
plt.figure(figsize=(10,6))
heatmap = plt.imshow(eeg_data_filtered.T,cmap="viridis",aspect = "auto")
plt.colorbar(heatmap,label="EEG Amplitude")
plt.xlabel("Time")
plt.ylabel("Channel #")
plt.title("EEG Heatmap")
```

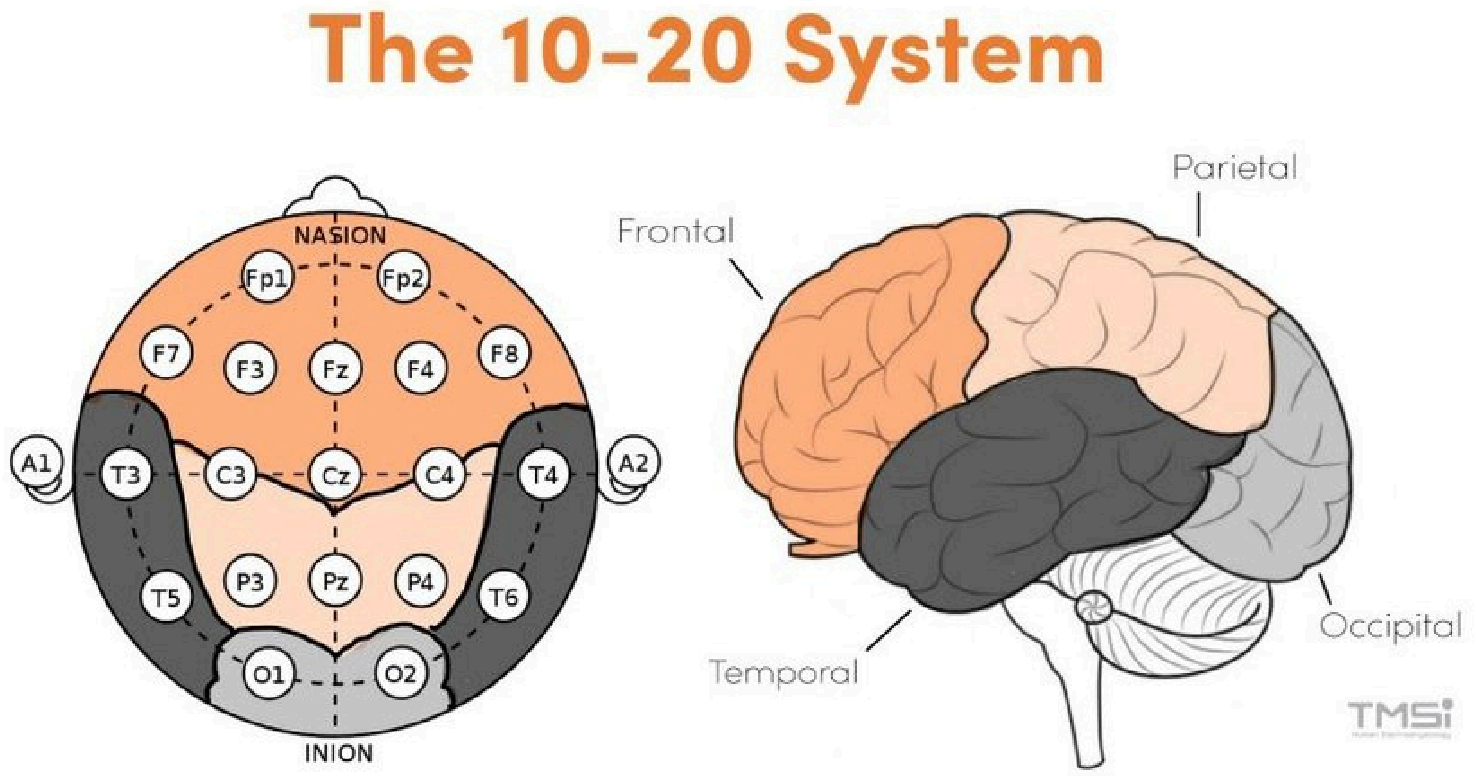
TOPOMAP PLOT

Overview

- EEG signals are recorded from **scalp electrodes and visualized using topographical maps** (topomaps)
- Topomaps show the spatial distribution of electrical activity across brain regions
- Visualization requires a predefined electrode layout called a montage to ensure accurate spatial mapping



TOPOMAP PLOT



System vs. Montage (Necessary Terminology)

- **System**:
  - Refers to the electrode placement scheme
  - Example: **International 10-20 System**
    - Globally standardized method
    - Positions electrodes based on head size percentages
    - Provides spatial coverage of brain areas (frontal, parietal, occipital, etc.)
    - Electrode labels (e.g., Fp1, Cz, O2) correspond to specific brain regions

- **Montage:**
  - Refers to how EEG signals are referenced and displayed
  - Defines the relationship between electrode signals
  - Common types:
    - Monopolar (Referential): Each electrode is referenced to a common point (e.g., linked ears, mastoids, or Cz)
    - Bipolar: Difference between pairs of electrodes is calculated

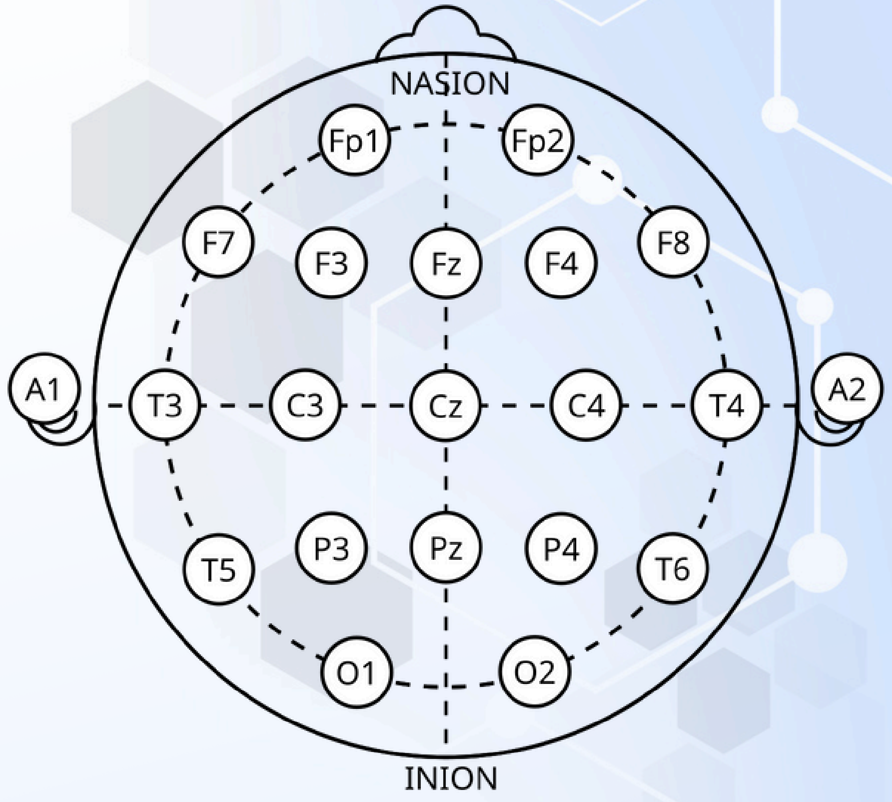
ELECTRODE PLACEMENT (EXTRA)

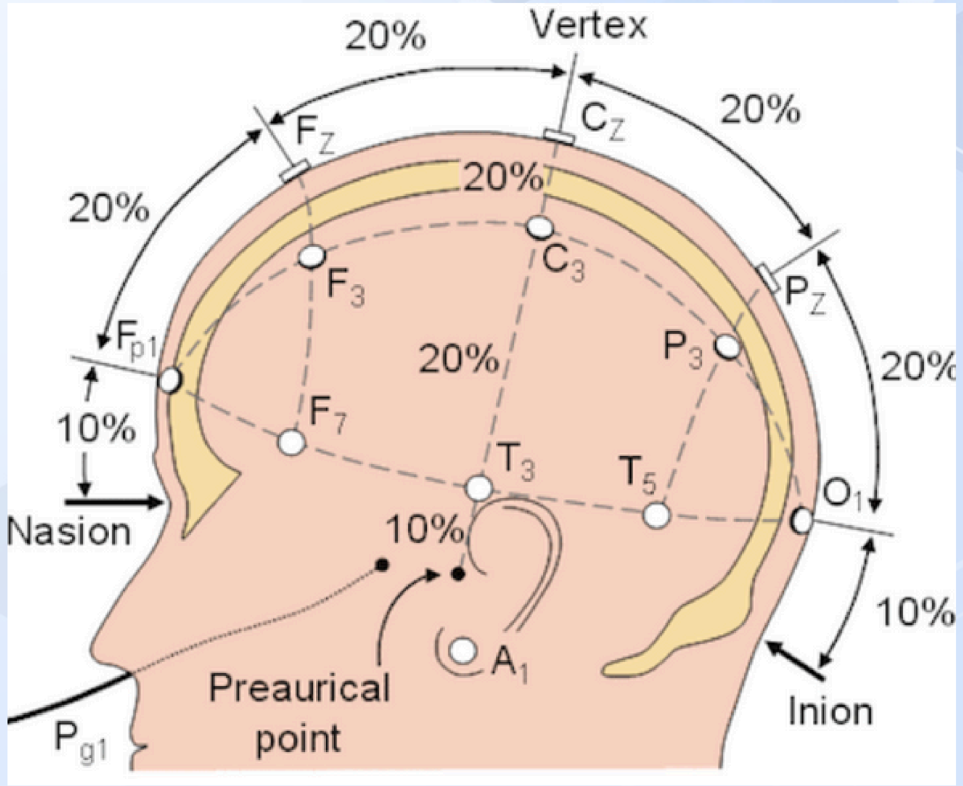
- Electrodes are placed based on percentages of head size

- Electrode Naming:
  - **Fp (Frontal Pole)** – Forehead region
  - **F (Frontal)** – Frontal lobe
  - **C (Central)** – Motor and sensory cortex
  - **P (Parietal)** – Sensory processing
  - **O (Occipital)** – Visual cortex
  - **T (Temporal)** – Auditory and memory processing

- Left-side electrodes are numbered odd (e.g., Fp1, C3), while right-side electrodes are numbered even (e.g., Fp2, C4)

- Reference electrodes (e.g., M1, M2, A1, A2) are placed on non-active regions, such as the mastoid bone, your earlobe, to improve signal clarity





TOPOMAP PLOT

Why Montages/Systems Matter

- Systems ensure consistent electrode positioning across subjects and datasets
- Montages affect signal interpretation by altering how electrical potentials are referenced
- Both are essential for accurate EEG visualization, analysis, and comparison in topomap creation

CODE IMPLEMENTATION

```
import mne
data_after_band_pass_filter = np.array(eeg_data_filtered)
data_after_band_pass_filter = data_after_band_pass_filter.reshape((8, 7120))
data_after_band_pass_filter = pd.DataFrame(data_after_band_pass_filter)
standard_montage = mne.channels.make_standard_montage('standard_alphabetic')
n_channels = 8
fake_info = mne.create_info(
    ch_names=["Fp1", "Fz", "Cz", "Pz", "T3", "C3", "C4", "T4"],  # Names of the 8 channels
    sfreq=250.,  # Sampling frequency in Hz (e.g., 250 samples per second)
    ch_types='eeg',  # Specify that the data type is EEG
    )
print(fake_info)
fake_evoked = mne.EvokedArray(data_after_band_pass_filter, fake_info)
fake_evoked.set_montage(standard_montage, on_missing='ignore')
times_to_plot = np.arange(0, 28., 4)
fake_evoked.plot_topomap(times_to_plot, ch_type="eeg", ncols=len(times_to_plot), nrows="auto")
```

SMOOTHING FILTERS

OVERVIEW

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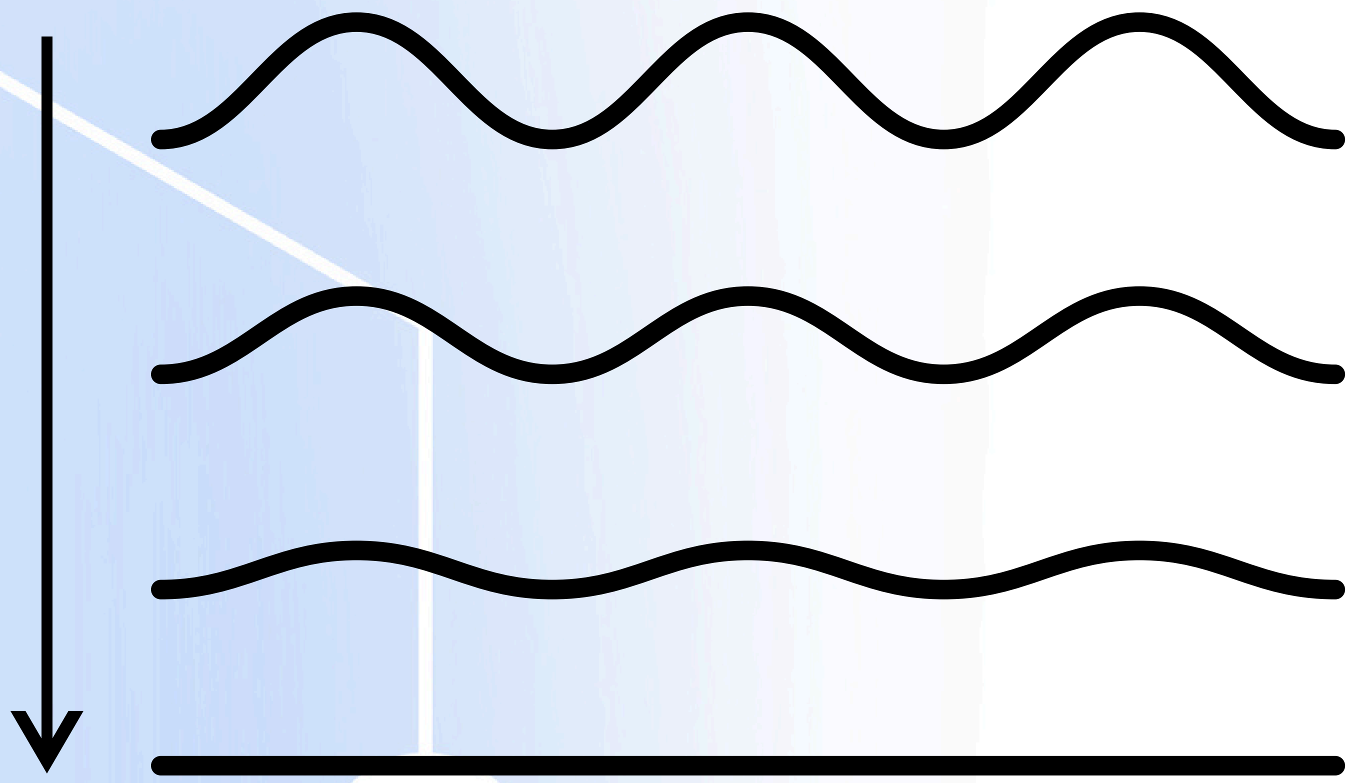
- Smoothing filters are essential tools in EEG signal processing, used to reduce noise and highlight underlying patterns.
- Makes data that looks overwhelming and unreadable into something more digestable
- These filters work by averaging or weighting neighboring data points to create a smoother representation of the signal.

AVERAGE FILTER

- **What is the purpose:**
  - Improves the signal-to-noise ratio by computing the mean of nearby samples, reducing high-frequency noise.

- **How does it work?**
  - Each data point is replaced with the average value of its neighboring data points within a defined window.



PROS AND CONS

Pros

- Smooths out high-frequency noise and minor fluctuations.
- Easy to implement.
- Visualizes slower oscillatory patterns (e.g., alpha, beta, delta waves) by using a larger time window.

Cons

- The overall detail and resolution is reduced with larger windows.
- Over-smoothing may lead to signal distortion
- Average filters introduce a time delay since they use future values in a window to compute the present output

MEDIAN FILTER

- **What is the purpose?**
  - Reduces noise and outliers by replacing each data point with the median of its neighboring values.
- **How does it work?**
  - Effective at removing impulsive noise (e.g., spikes) while preserving sharp features like ERPs.

Median represents the most middle value in a set of data when ordered

PROS AND CONS

MIND

Pros

- Removes transient artifacts and impulsive noise.
- Preserves event-related potentials and sharp features.
- Useful for baseline correction.

Cons

- Not suited for smoothing continuous noise or baseline drift.
- May distort signal features with large window sizes (oversmoothing)
- Ineffective for non-impulsive noise.

OBSERVATIONS FROM CODE

Average Filter

- Increase Window Size:
  - Observation: Signal becomes smoother, reducing noise and detail.
  - Discussion: Useful for noisy signals but risks over-smoothing.
- Decrease Window Size:
  - Observation: Retains more signal detail with minor smoothing.
  - Discussion: Suitable for preserving fine structures.

OBSERVATIONS FROM CODE

Median Filter

- Increase Window Size:
  - Observation: Removes more noise but risks blurring important features.
  - Discussion: Effective for intense noise spikes but may distort edges.
- Decrease Window Size:
  - Observation: Maintains finer details while reducing noise.
  - Discussion: Ideal for signals with light noise or fine details.

FREQUENCY ANALYSIS

OVERVIEW OF FREQUENCY ANALYSIS

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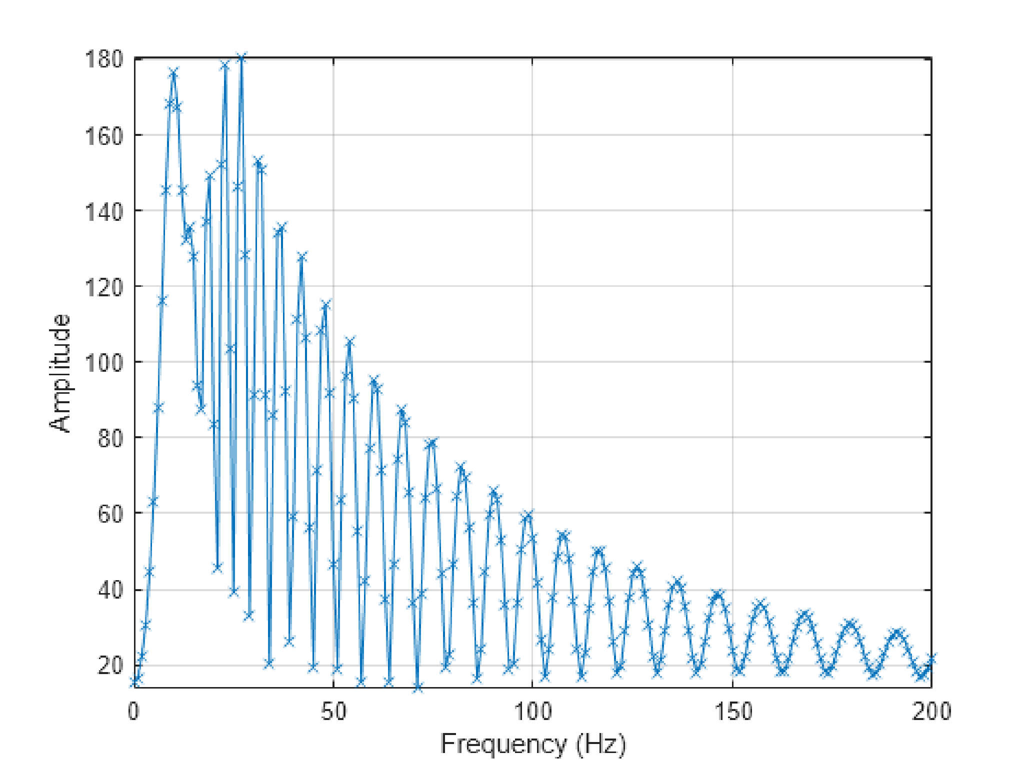
- Frequency analysis for EEG is a fundamental technique that unveils the distribution of different frequency components within the brain's electrical activity. This analysis involves transforming EEG signals from the time domain to the frequency domain, typically using the Fast Fourier Transform (FFT) algorithm.

- Recap: Key EEG frequency bands:
  - **Delta (0.5-4 Hz):** Deep sleep, unconsciousness.
  - **Theta (4-8 Hz):** Drowsiness, meditation.
  - **Alpha (8-13 Hz):** Relaxed wakefulness.
  - **Beta (13-30 Hz):** Active cognition, alertness.
  - **Gamma (30-100 Hz):** High-level information processing.

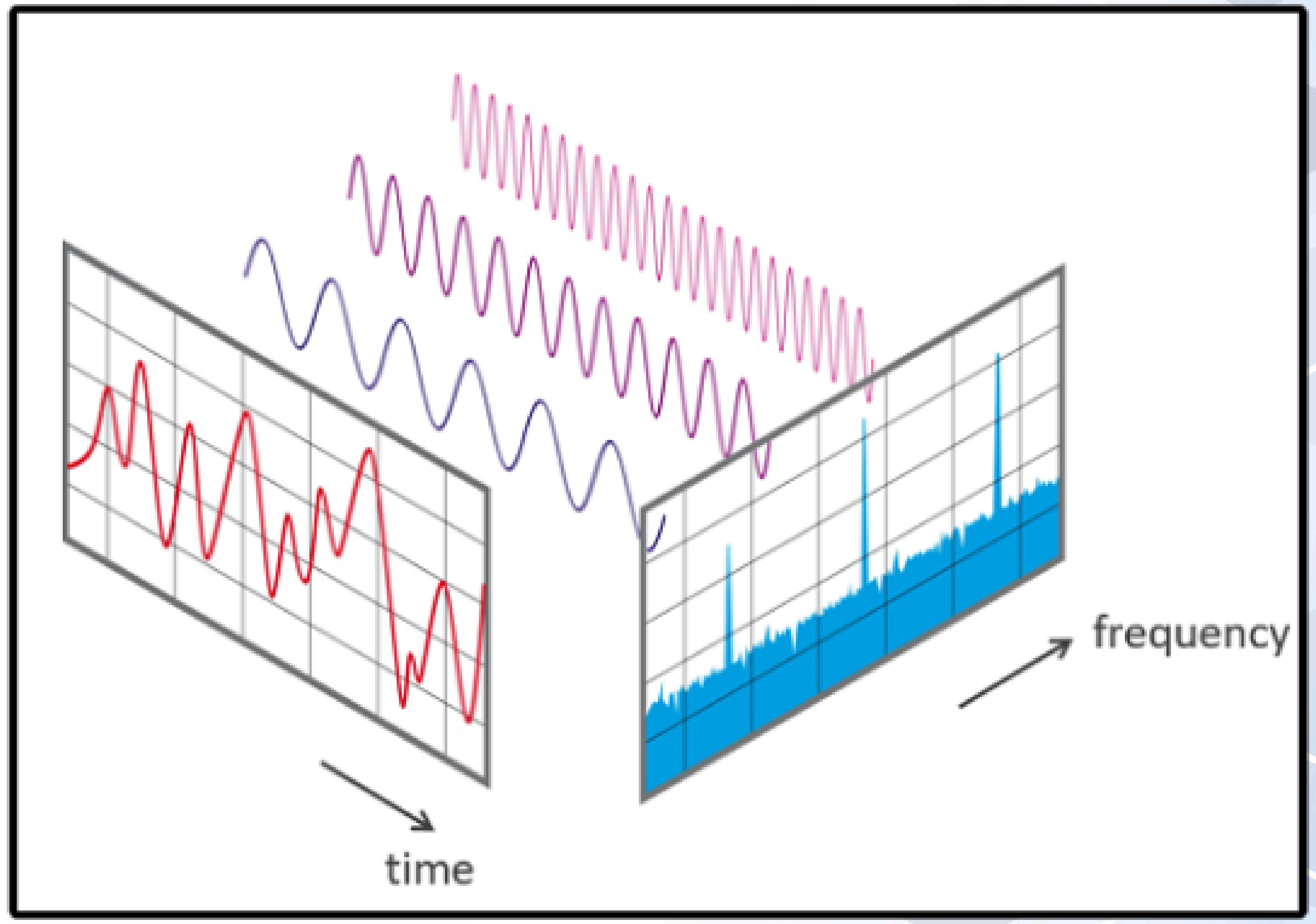


- Applications of Frequency Analysis
  - Identifying anomalies or irregularities in frequency patterns.
  - Diagnosing neurological conditions (e.g., epilepsy, sleep disorders).
  - Exploring cognitive states and neural processes

THE FAST FOURIER TRANSFORM (FFT)

MIND

- **What is FFT?**
  - A mathematical method that converts a signal from the time domain (how it changes over time) into the frequency domain (which frequencies are present).
    - It translates a **Voltage/Time Graph** to a **Voltage/Frequency Graph** over a locked time frame.



- **Why Use It for EEG?**
  - Brain activity has unique patterns in different frequency bands (like 8–12 Hz for alpha).
  - FFT lets us see these hidden patterns and analyze how strong each one is.
  - **An example:** Direct application of FFT is useful for detecting alpha waves, which spike when you close your eyes and relax.

THE FAST FOURIER TRANSFORM (FFT)

- **How Does It Work?**
  - Takes your signal (like voltage over time) and breaks it down into sine waves of different frequencies.
  - Outputs a graph showing which frequencies are present and how powerful each one is.

- **Real-Life Analogy:**
  - Like turning a song into its individual notes—FFT tells you what "notes" (frequencies) are playing in your brain signal.
  - Its telling you how many D notes are being played at a given window of the song vs how many G notes.

FFT PROS

1. **Breaks Down Signals:** Turns complex brain signals into simpler frequency parts.
2. **Focuses on Brain Waves:** Helps us look at specific types of brain activity (like alpha or beta waves).
3. **Reveals Brain Rhythms:** Shows repeating patterns linked to brain functions like focus or relaxation.
4. **Tracks Responses to Stimuli:** Can show how the brain reacts to things like lights or sounds.
5. **Shows Power of Frequencies:** Helps measure how strong each brain wave is (Power Spectral Density).
6. **Spots Noise:** Can help detect unwanted signals (like blinking) vs. real brain activity.
7. **Adds Frequency Insight:** Gives info about brain wave types while keeping some time detail.

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FFT CONS

1. **Loses Time Detail:** You get frequency info, but less clarity about when it happened.
2. **Spreads Frequencies:** If the signal isn't clean or steady, frequencies can mix.
3. **Short Segments = Less Accurate:** Analyzing small chunks of data can distort the results.
4. **Brain Signals Change:** FFT assumes steady signals, but the brain changes all the time.
5. **Sensitive to Noise:** Artifacts (like muscle movements) can mess up frequency results.
6. **Rigid Frequency Bands:** Using fixed bands (like 8–12 Hz for alpha) may miss personal differences.

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TASKS FOR EXPLORATION FOR FFT

1. **Apply band-pass filters with ranges** (e.g., 1-10 Hz, 5-15 Hz) and observe frequency spectrum changes.

2. **Vary data lengths** (e.g., 0.5 seconds, 2 seconds) to analyze the effects on resolution details.

THE HILBERT TRANSFORM

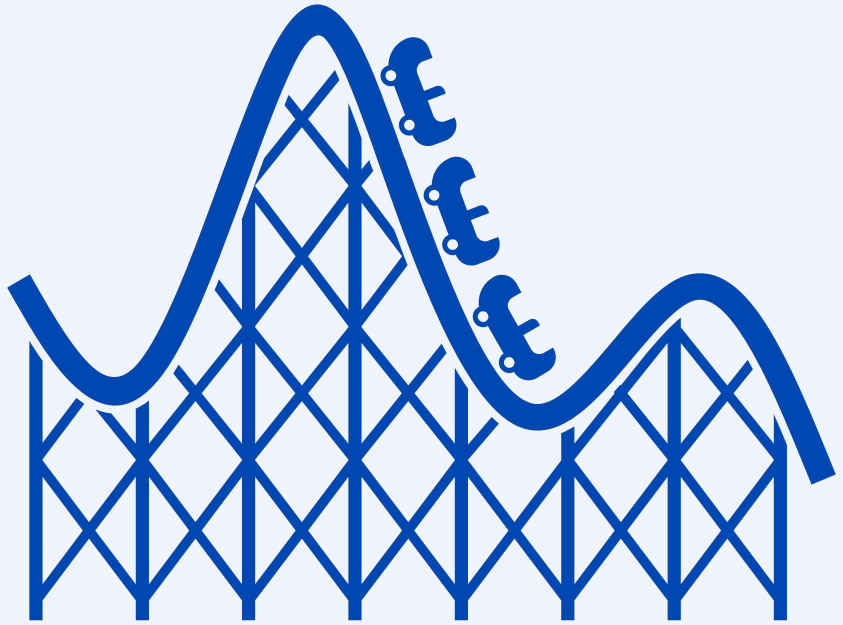
MIND

- **What is the Hilbert Transform?**
  - A method that gives us a way to track how a signal’s amplitude and phase change over time. Phase change meaning the change over the shape of the wave (Crest vs Trough)
  - Creates something called the analytic signal, which helps highlight hidden patterns in EEG data. Its outlines the shape of the original signal and is often called and amplitude envelope

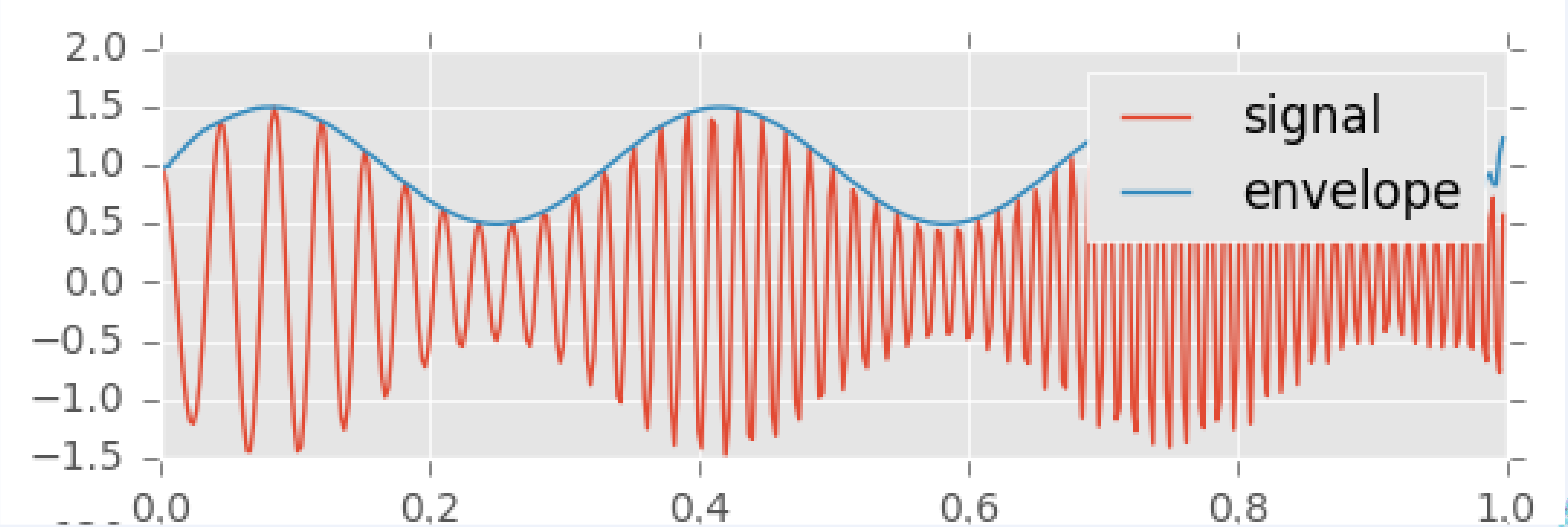
- **Why Use It for EEG?**
  - It helps us understand the "shape" of brain waves—not just how strong they are, but how they move and relate to each other over time.
  - Useful for studying how different brain rhythms interact, especially during tasks or mental states.

THE HILBERT TRANSFORM

- **What Does It Show?**
  - Instantaneous amplitude: How strong the brain signal is at each moment.
  - Instantaneous phase: Where you are in the brain wave cycle at each point.
  - Can reveal connections between brain areas or interactions between frequencies (like slow waves controlling faster ones).
- **Real-Life Analogy: A Roller Coaster Ride**
  - The **track** is your **brain signal**.
  - The **height** of the car = **amplitude** (signal strength).
  - Your **position** on the track = **phase** (where you are in the wave).
  - The Hilbert Transform shows how high and where the signal is on its wave path at every moment—like watching a roller coaster in slow motion.



THE HILBERT TRANSFORM



HILBERT PROS

1. **Tracks Signal Strength & Rhythm:** Shows how the brain wave's size (amplitude) and timing (phase) change over time.
2. **Links Brain Waves:** Helps study how slow and fast brain waves influence each other.
3. **Cross-Band Interactions:** Reveals how different frequencies work together.
4. **Brain Connectivity:** Can show how brain regions are connected through shared timing.

HILBERT CONS

1. **Filtering Can Distort Data:** Preprocessing may mess with phase info.
2. **Phase Confusion:** Can't tell if a wave is rising or falling—only where it is in the cycle. You know the position, but not the direction its moving.
3. **Sensitive to Noise:** Works best with clean signals; noise can throw it off, really easily, and especially with EEGs, noise is everywhere.
    - Implies we need to do a lot of cleaning (smoothing and band-pass filters, and maybe even machine learning models)

TASKS FOR EXPLORATION FOR HILBERT

1. **Apply band-pass filters with ranges** (e.g., 1-10 Hz, 5-15 Hz) and observe frequency spectrum changes.

2. **Vary data lengths** (e.g., 0.5 seconds, 2 seconds) to analyze the effects on resolution details.

MIND

LETS SEE THIS IN ACTION!

We have seen a lot of theory, lets end it off with how it works in action with a project the MIND Development Team has been working on!