



Radboud University



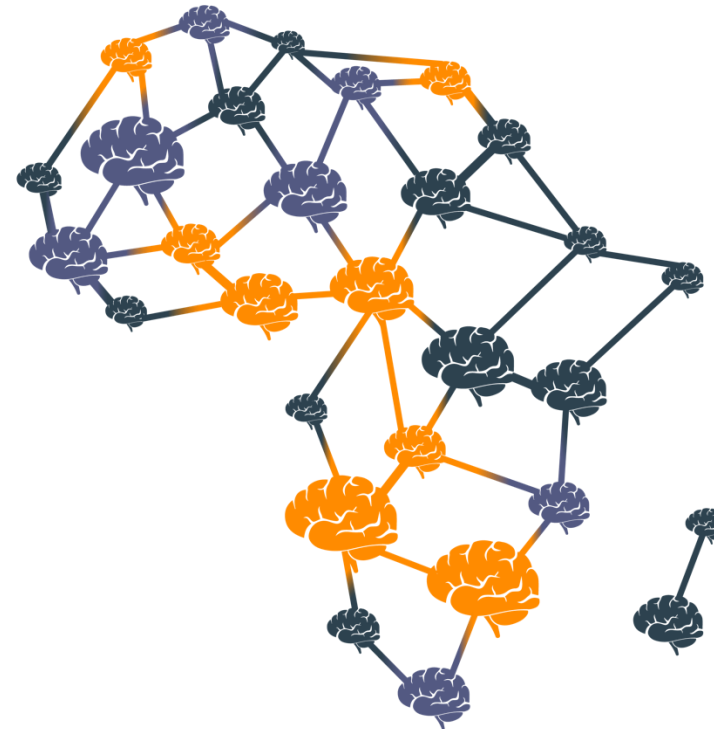
University of
Copenhagen



How does an EEG system work

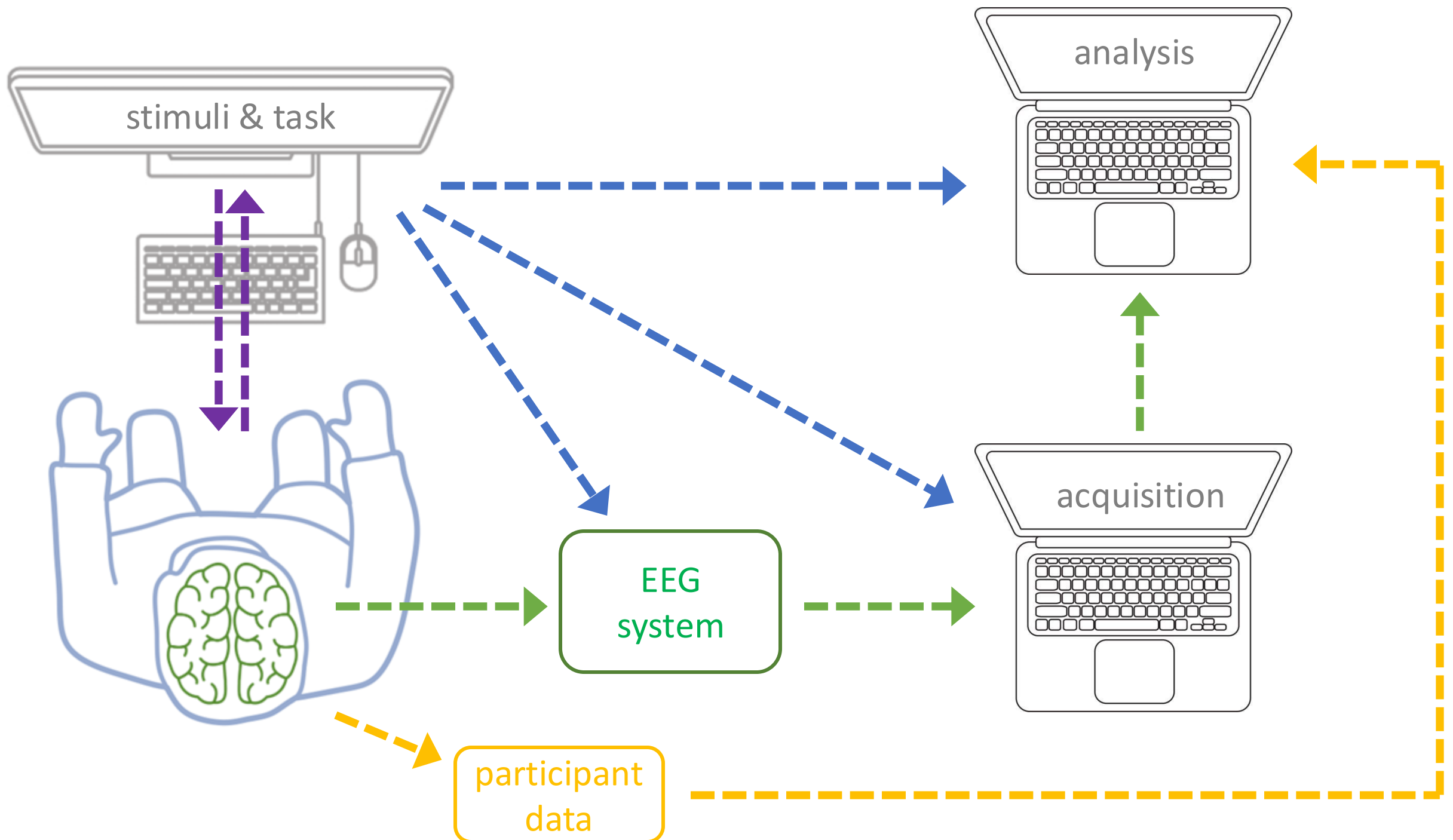
Robert Oostenveld
Mikkel C. Vinding

9-14 June 2025
Port Harcourt, Nigeria



**African
Brain
Data
Network**





What is EEG and how to record it?

EEG is a voltage difference between electrodes placed on the scalp.

It is about 1-10 micro Volt, also written as μV or as uV.

The small voltage is first amplified and then digitized.

The “EEG system” is the amplifier and digitizer hardware, and the software that comes with it. It often includes other features, such as triggers, auxiliary inputs, and impedance testing.

EEG electrodes

How do we record small voltages

An EEG electrode is not the same as an EEG channel.

The **electrode** is the small metal disk on the scalp.

The **channel** is the amplified and digitized signal.

With a multimeter we use two electrodes to record one voltage: the red is the +, the black is the – (or reference), the number is the difference.

The numbers on the screen are the digital representation of the voltage difference between the electrodes.



How do we record small voltages

We usually record the voltage of all electrodes on the scalp relative to one common “reference” electrode. This reference is placed at a location where it has very good attachment.

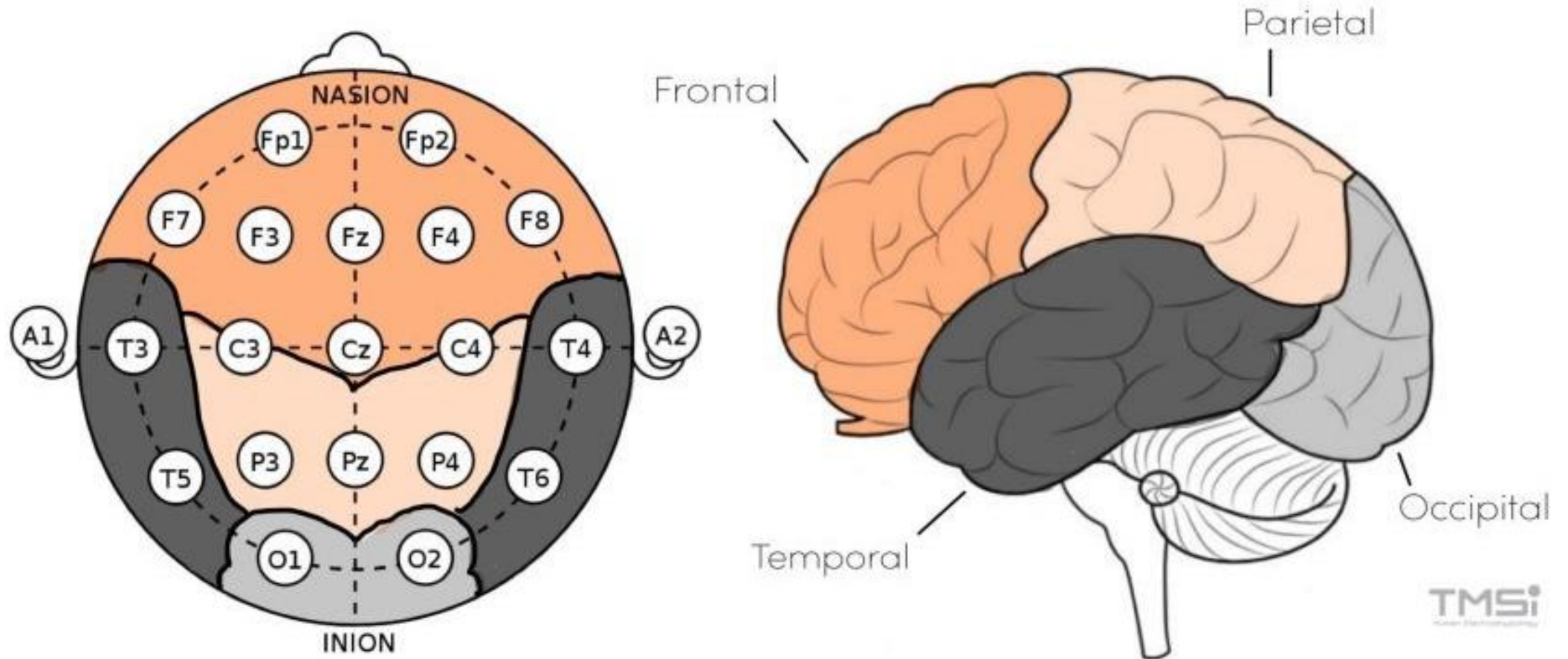
The EEG system usually also has a “ground” electrode to reduce the influence of noise.

With 21 electrodes on the scalp we record 19 channels.

With $N+2$ electrodes on the scalp we record N channels.

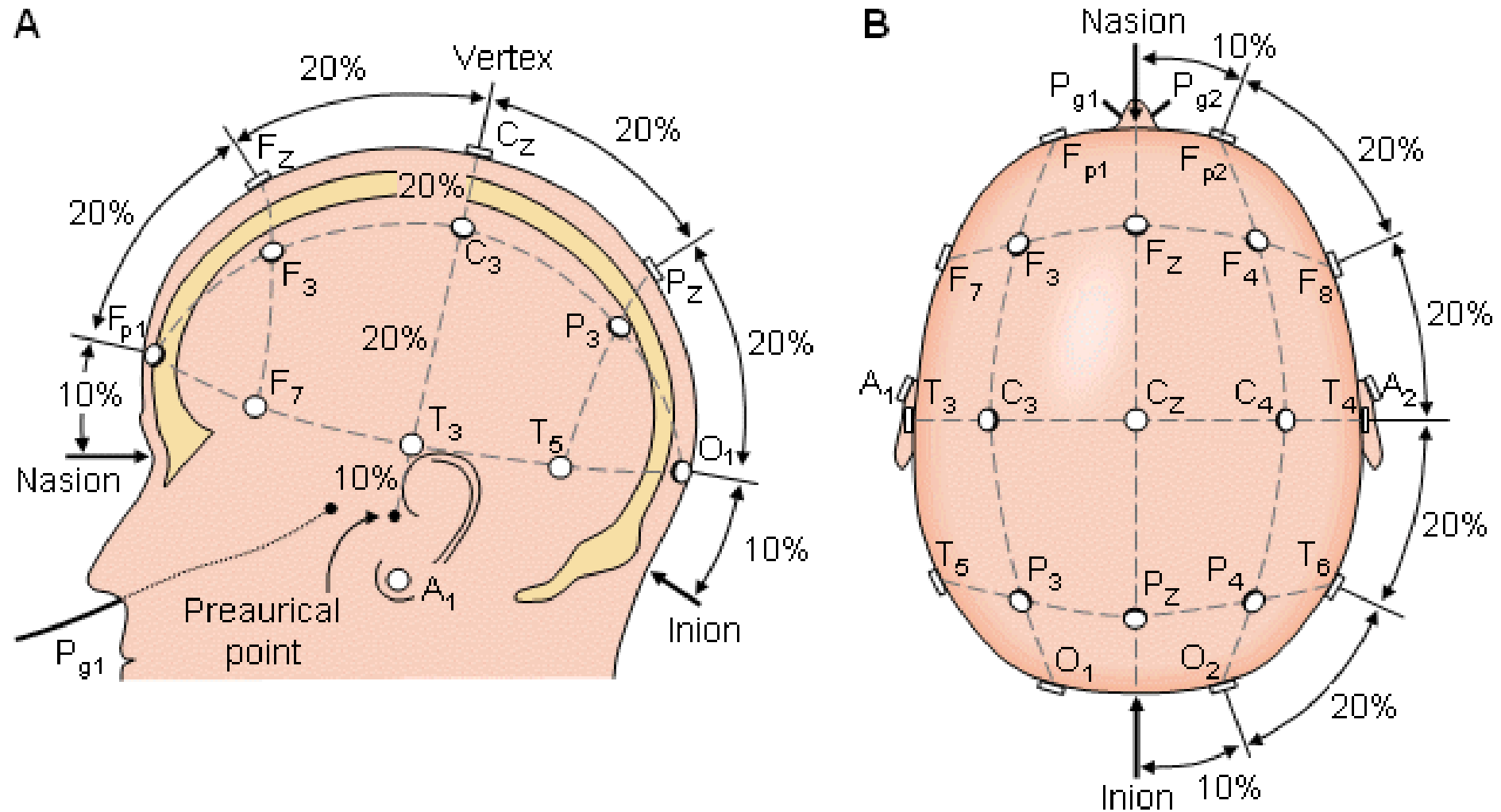
When recording larger amplitude signals (like ECG and EMG), usually $N+1$ electrodes are used for N channels. However, sometimes we also use $2*N$ bipolar channels for EMG.

The 10-20 electrode placement system - naming



Note that electrodes T3/4 are nowadays mostly called C7/8, and T5/6 are called P7/8. The ear lobes are called A1/2, the mastoids are called M1/2.

The 10-20 electrode placement system - placement



The electrode as electro-chemical interface

Small electric currents (generated in the brain) need to pass from the scalp to the electrode

Electric **current** is the displacement of electric **charge**, or charged particles.

On one side the scalp or skin of the participant.

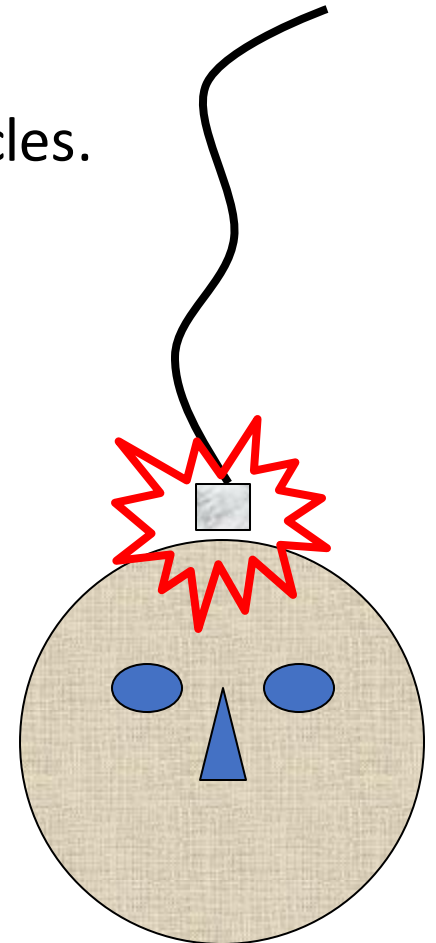
Electric current is conducted by **ions** (= dissolved salt) in the tissue

Na^+ , K^+ , Cl^-

On the other side the wire that goes to the amplifier electronics.

Electric current is conducted by **electrons** in the metal

e^-



Different connections to the participant's scalp

Electrode paste, with cup electrodes

Single-use adhesive electrodes for EMG, ECG, EOG

Electrode gel, with most common electrodes

Salt water, with sponge electrodes

Bridge electrodes

Dry electrodes

Active electrodes

Needle electrodes

Intracranial electrodes (sEEG, ECoG)



Cup electrodes

Often made of gold-plated copper

Can also be made of tin, silver, or silver-chloride



Touch-proof connectors

Female connector on the lead (=wire)

Male connector on the amplifier



Cup electrodes

You use a measuring tape to determine the positions.

You “scoop” or squeeze some electrode paste onto the electrode and stick it between the hair on the scalp.

You can use collodion glue to glue the hair over it, or to glue a small piece of gauze over it



Single-use adhesive electrodes (not common for EEG)

Placed on bare skin

For muscle, heart and eye signals

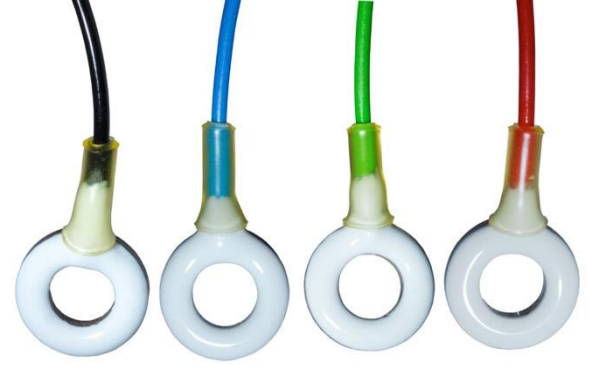
Electromyogram = EMG

Electrocardiogram = ECG

Electrooculogram = EOG



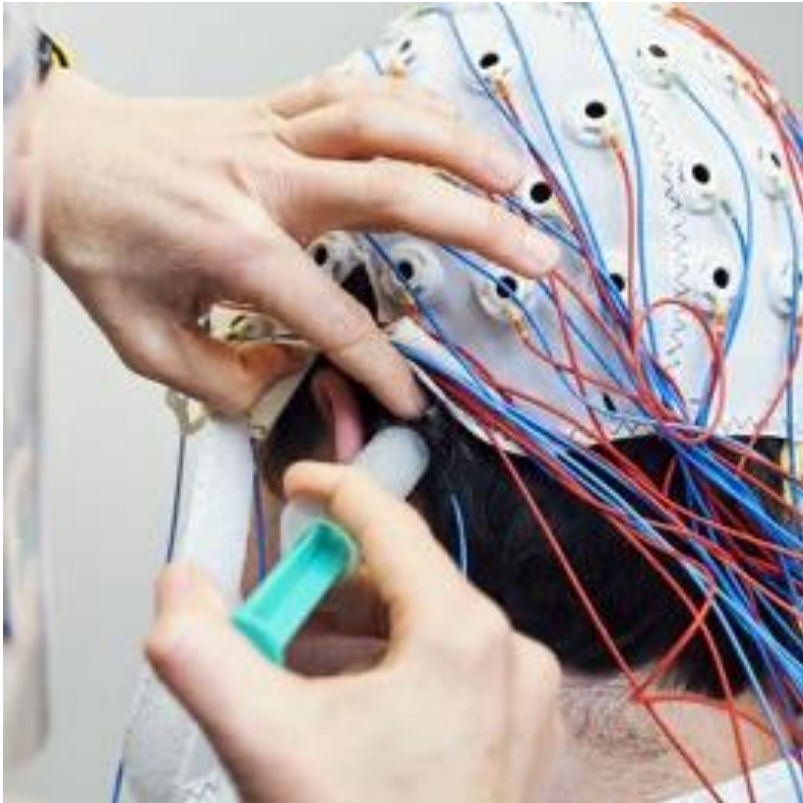
Ag/AgCl electrodes - “normal” electrodes



Ring- or pin-shaped electrodes

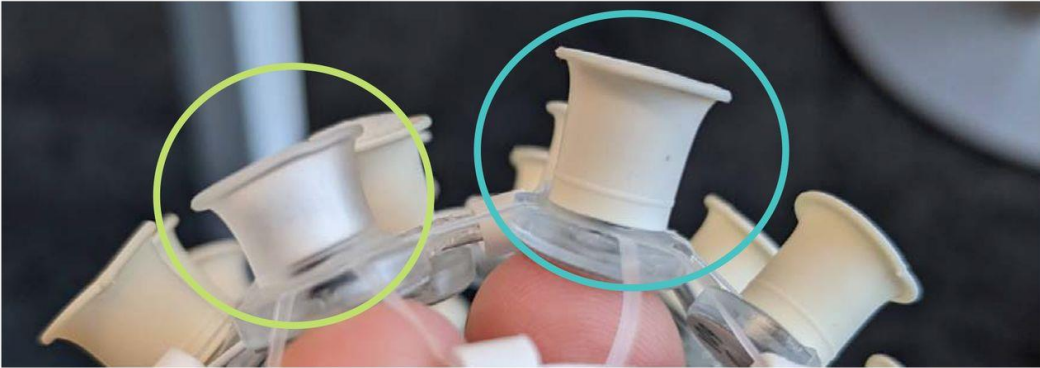
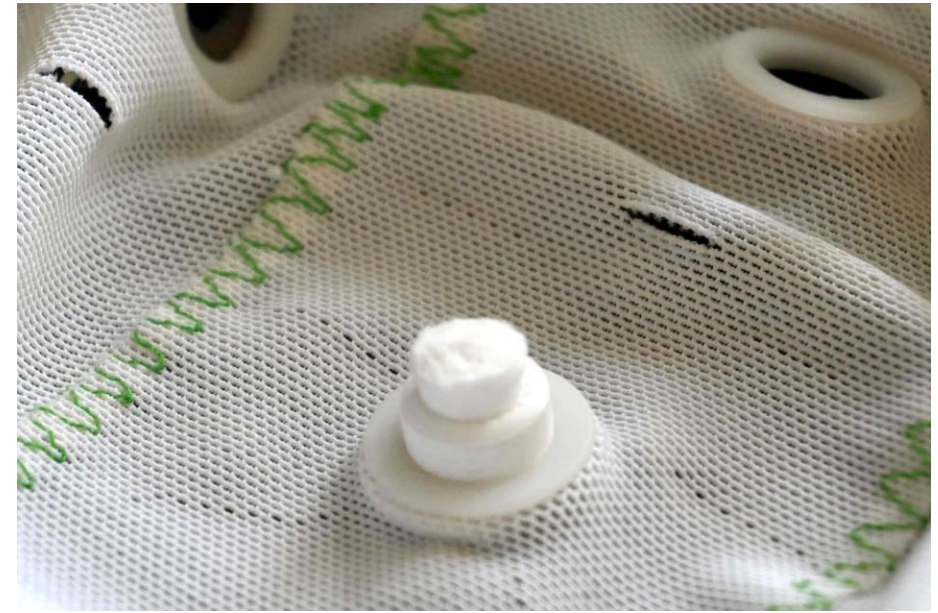
Sintered Ag/AgCl (= silver/silver-chloride)

Syringe with blunt needle to apply electrode gel through the hole



Sponge electrodes

The whole cap or net is plunged into salt water
The cap is then placed on the participant at once



Tall pedestal
(9.3 mm)

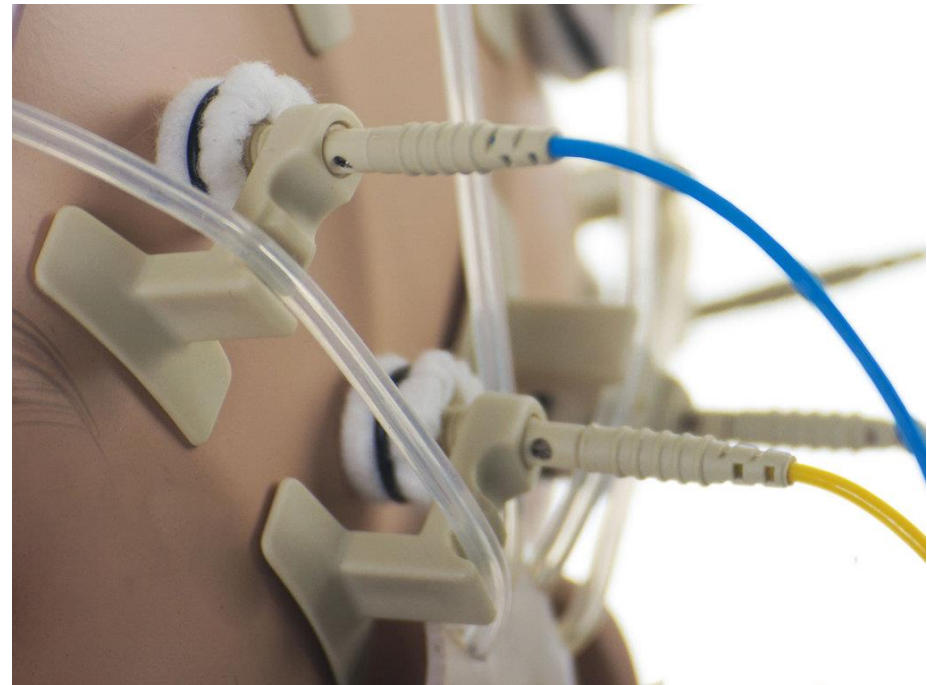


Short pedestal
(6.5 mm)



Bridge electrodes

Used for quick application of a
small number
Not so good for long recordings

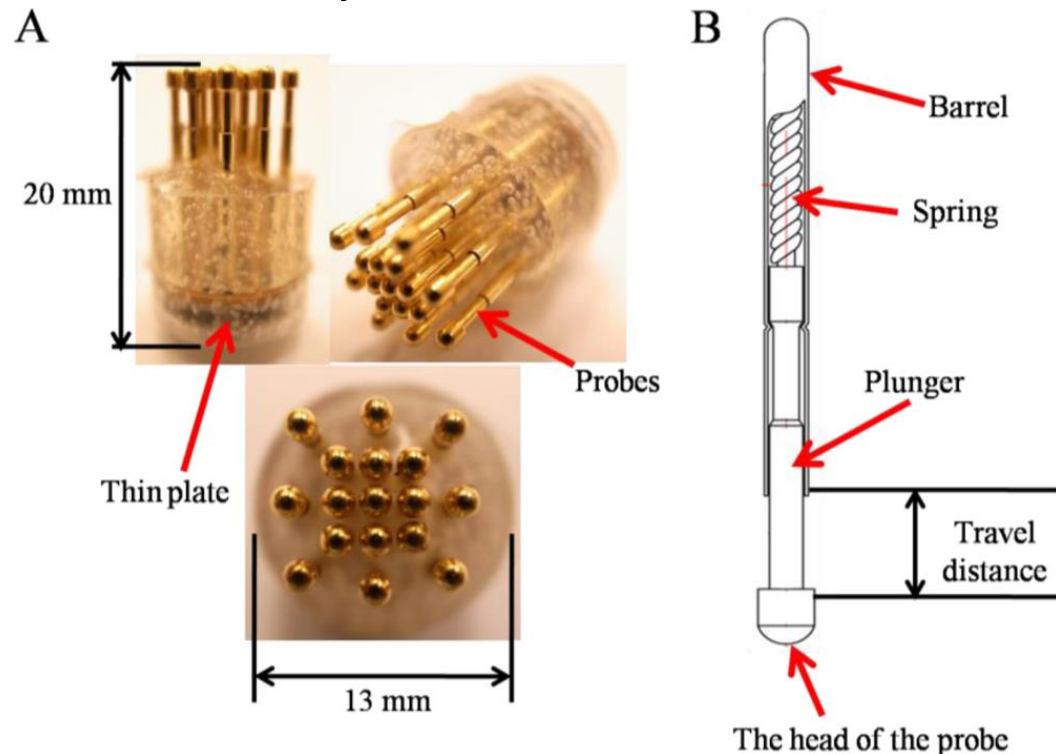


Dry electrodes

Not using gel or paste

Golg-plated pins or flexible conductive polymer

Sweat/humidity as electrolyte between the electrode and scalp to conduct the electricity



Active electrodes

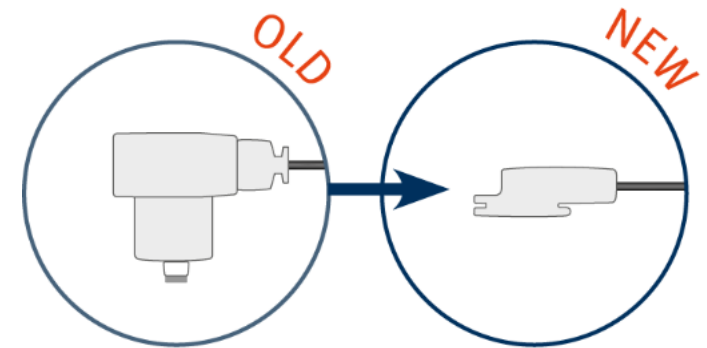
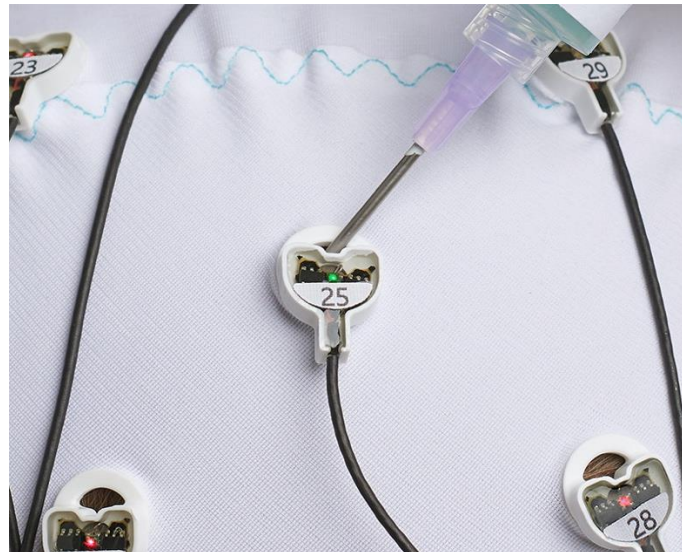
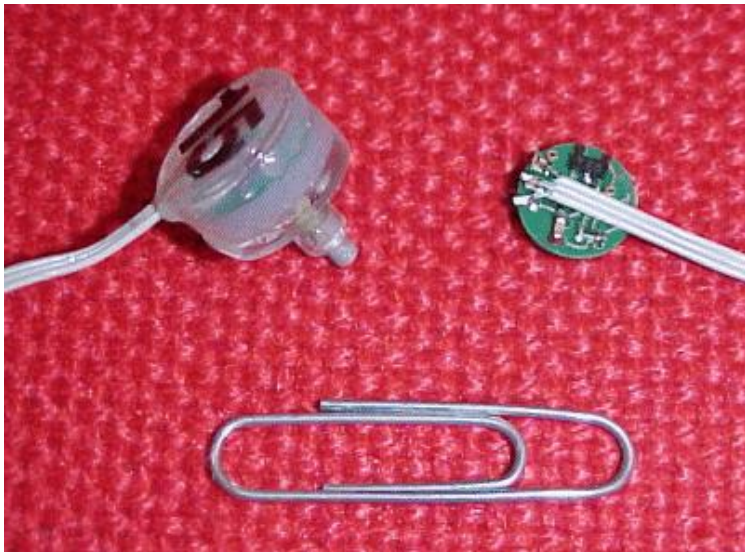
The electrode can be anything

- Ag/AgCl with gel

- Dry gold-plated electrode

- Dry conductive polymer/plastic

Small electronic circuit on the electrode to amplify the signal

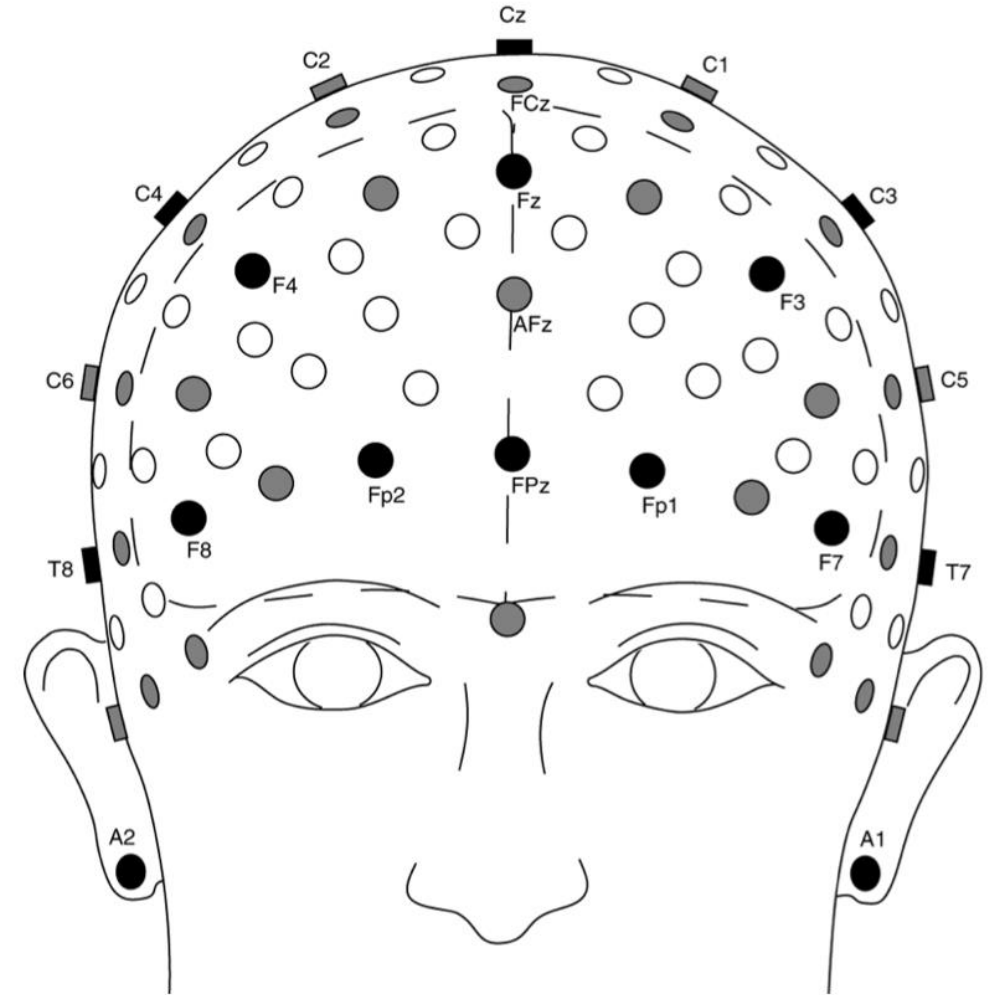
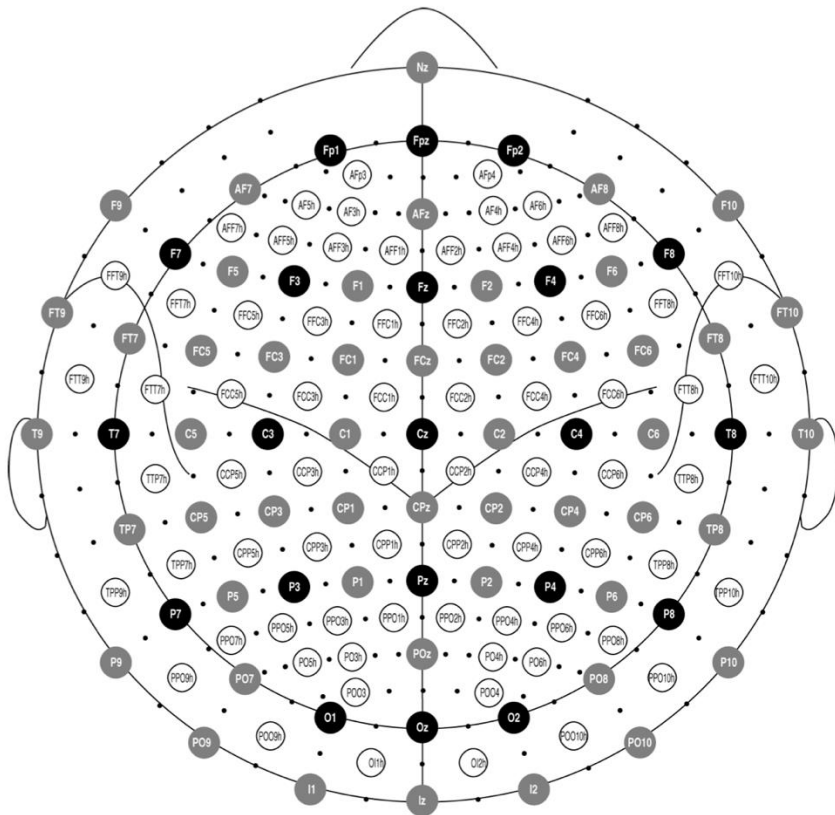


Different EEG electrode placement schemes

10-20 system, international clinical standard

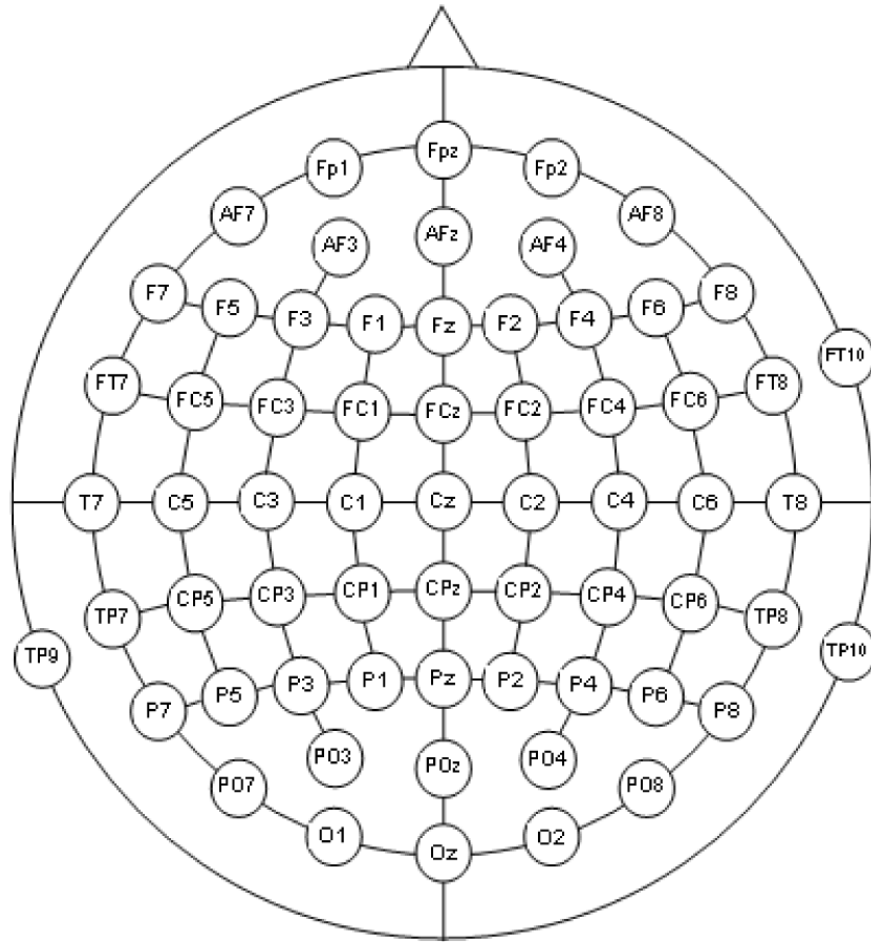
10-10 standard, extension with all 10% distances

10-5 standard, extension with 5% distances

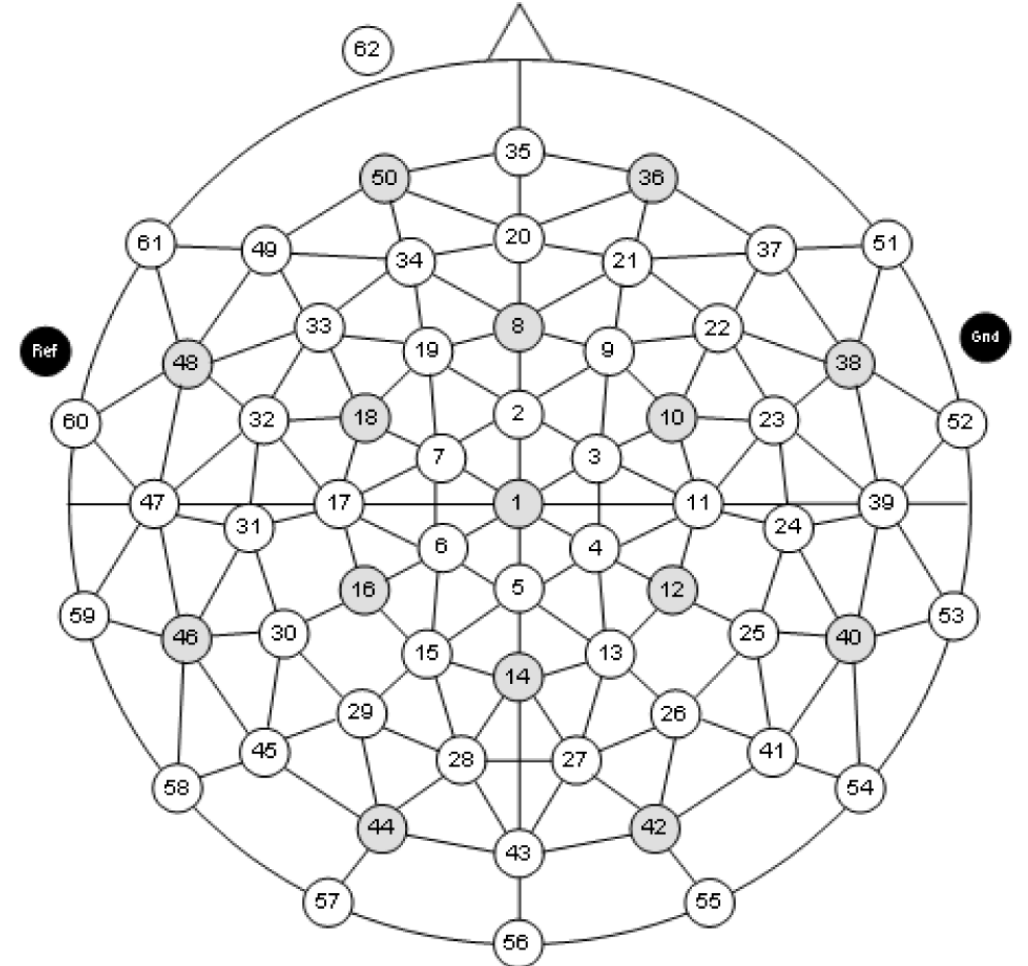


Jasper. (1958) *Electroencephalogr Clin Neurophysiol.*
Chatrian et al. (1985) *Am J EEG Technol.*
Oostenveld and Praamstra. (2001) *Clin Neurophysiol.*

Equidistant electrode placement, for example Easycap “M10”

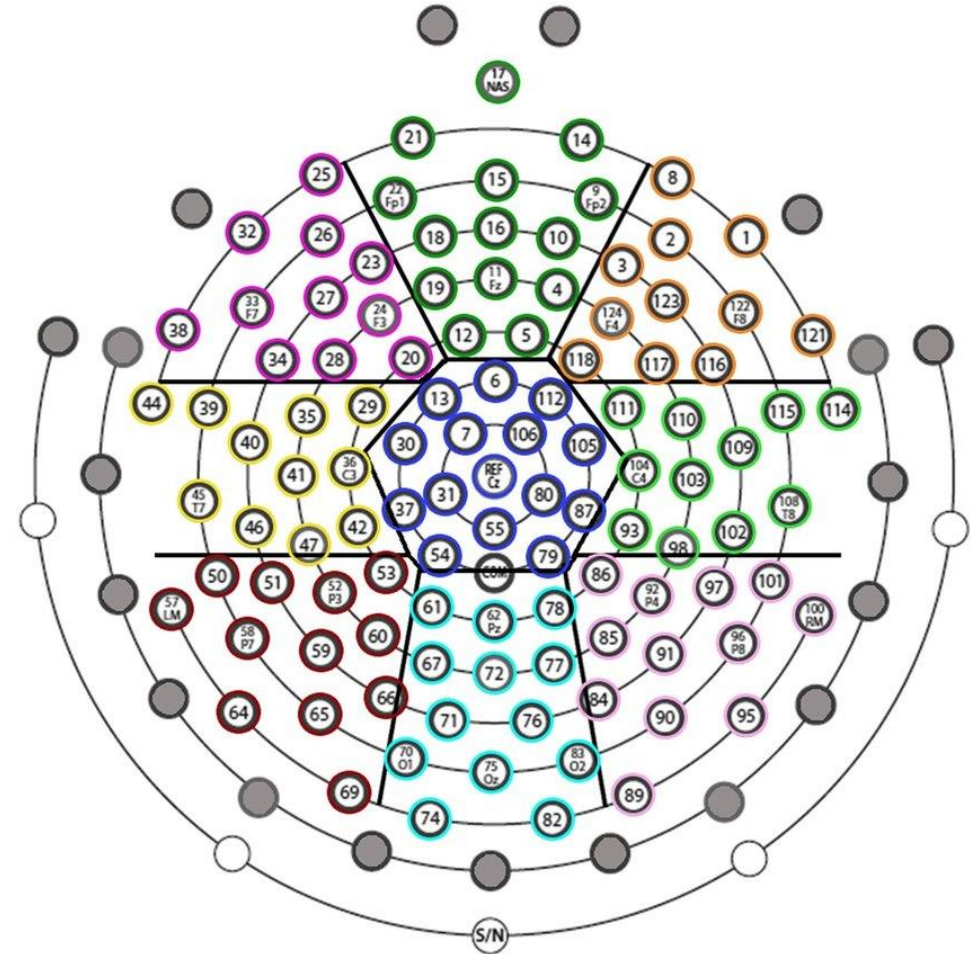


Extended 10-20 or 10-10



M10

EGI Geodesic Net - 128 or 256 electrodes



Different types of electrode caps





Radboud University



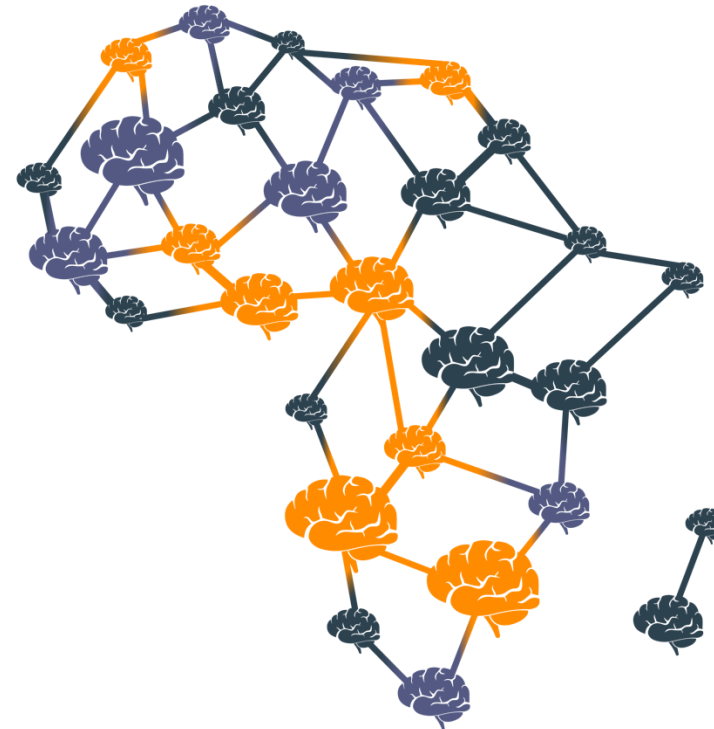
University of
Copenhagen



How does an EEG system work

Robert Oostenveld
Mikkel C. Vinding

9-14 June 2025
Port Harcourt, Nigeria



**African
Brain
Data
Network**



Discrete representation of the EEG voltage

How do we record EEG signals

The small voltage difference between EEG electrodes is first amplified and then digitized.

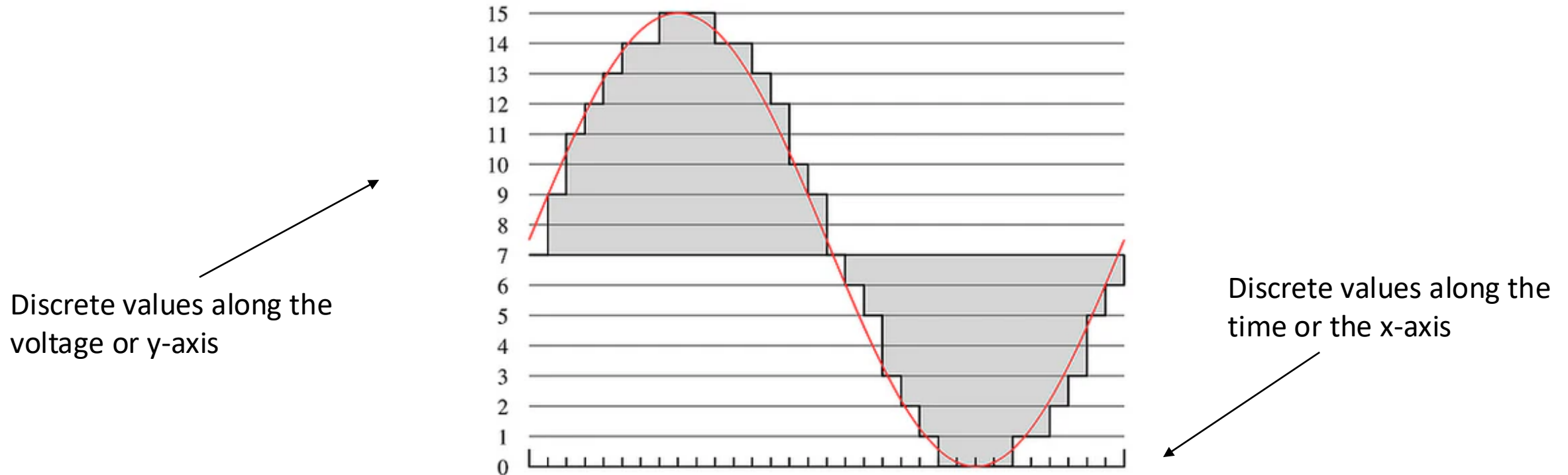
Analog = when the signal is represented as a voltage that changes over time

Digital = when the signal is represented as a number on a microcontroller or computer

Analog and digital signals

Analog signals are continuous, digital signals are sampled.

This gives a discrete representation of the values at discrete points in time.



Decimal and binary numbers

With the **decimal system** we use 10 symbols or digits: 0, 1, 2, 3, 4, 5, 6, 7, 8, 9

We place these side-by side, where we start at the right and move to the left.

3 -> this means 3 times 1

24 -> this means 4 times 1, plus 2 times 10

abc -> this means "a" times 1, plus "b" times 10, plus "c" times 100

The places in the composite number (going from right to left) represent

$10^0=1$, $10^1=10$, $10^2=10 \times 10=100$, etc.

Note that in programming 10^n is often written as 10^n .

Decimal and binary numbers

With **binary numbers** we use two digits of symbols: 0 and 1, these are called “bits”.
As with decimal numbers we interpret them from right to left.

The rightmost bit represents 0 (or 1) times 2^0

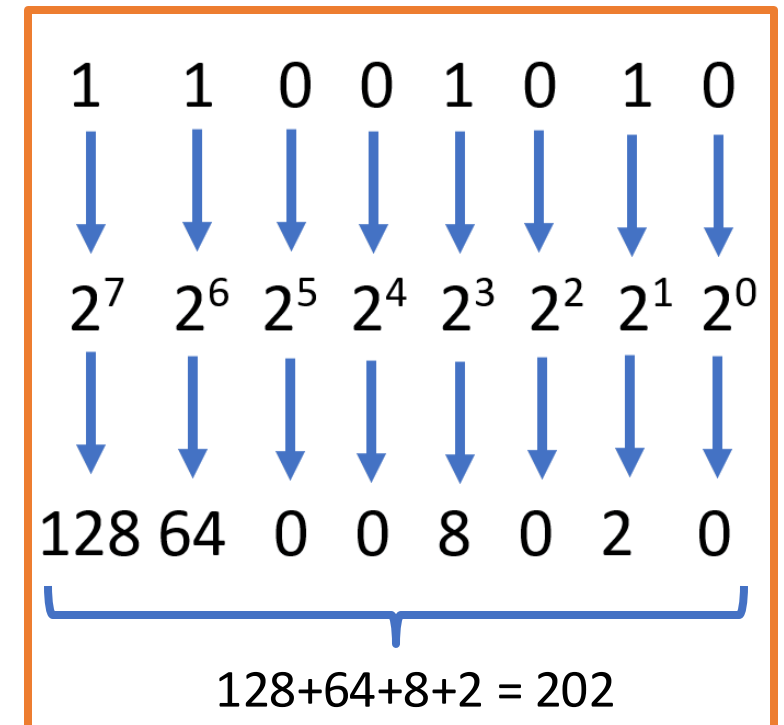
The second bit from the right represents (0 or) 1 times 2^1

Binary 00000000 = decimal 0

Binary 00000001 = decimal 1

Binary 00000010 = decimal 2

Binary 11001010 = decimal 202 (= 2+8+64+128)



Binary numbers come in different representations

8 bits integer numbers range from b00000000 to b11111111, or decimal 0 to 255

16 bit integer numbers use 16 bits and range from decimal 0 to $2^{16} - 1$

We also have 32 bit integer numbers, 64 bit integer numbers, ...

Unsigned versus signed integers:

In **signed** integers the left-most bit is not a number but represents the sign (+ or -)

So **unsigned** b11111111 is 255 and **signed** b11111111 is -127

Integer versus floating point numbers:

For decimal numbers we can write $1/3$ as approximately 1.3333 or as 1,3333 with a comma.

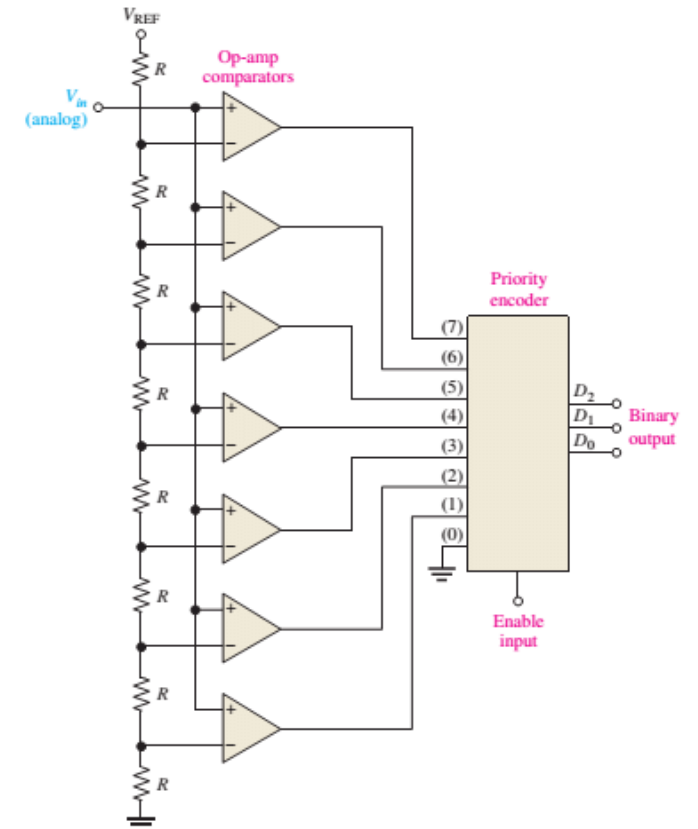
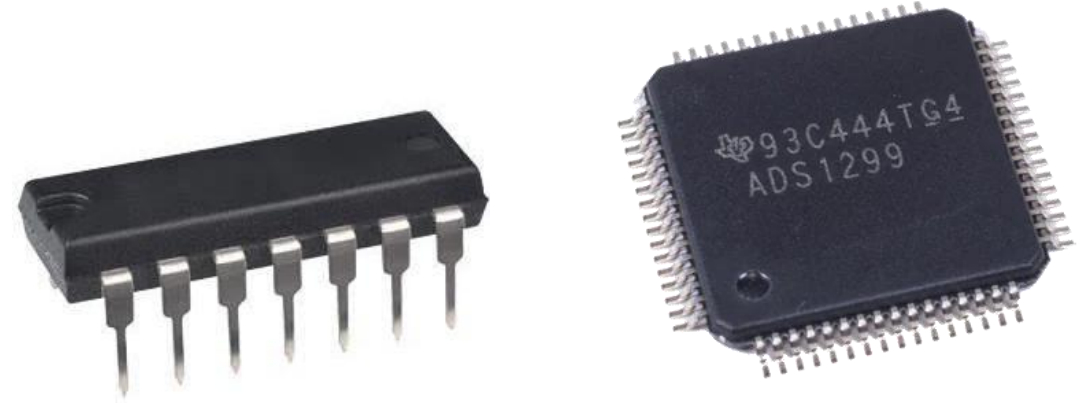
Floating point representations for binary numbers are known as “single precision” or float32, and “double precision” or float64 representations.

Analog to digital convertor (ADC)

The amplified EEG voltage difference is converted to a digital representation using an ADC. An ADC is usually a integrated circuit (IC), i.e., a chip.

These ADC chips have become very sophisticated, also incorporate the amplifier and often convert multiple channels simultaneously.

If you have multiple channels but only a single ADC, you can use a sample-and-hold mechanism.



<https://www.ti.com/product/ADS1299>

<https://www.analog.com/en/products/ad7771.html>

EEG dynamic range and artifacts



~1.000.000 Volt



1,5 Volt



1-10 micro Volt

The ratio between lightning and a battery is about 1.000.000

The ratio between a battery and the EEG signal of interest is about 1.000.000

Why are these binary representations relevant?

The ADC converts the continuous analog signal to a binary representation.

An 8-bit ADC can only represent the numbers -127 to 127, or from 0 to 255 if we assume that 128 is in the middle.

The smallest difference in the EEG that can be distinguished is 1, the largest range that can be represented is 255.

Numbers smaller than 1 will become 0, this is the “floor”.

Numbers larger than 255 will become 255, this is the “ceiling”.

The **ratio** between the smallest and largest number is relevant. For an 8 bit ADC this is $1/255$, for a 16 bit ADC this is $1/65535$ (or 96dB).

EEG dynamic range and artifacts

We have artifacts that – in order to capture them properly – require an ADC with a very large dynamic range.

16 bit is the minimum that we need for research EEG.

24 bit (or effectively 21 or 22 bit) is more common.

Furthermore, we should still try to **avoid** those artifacts if we can.

Noise-free environment, Faraday cage, short cables, shielded cables, active electrodes, smart amplifier designs, CMS/DRL, preventing movements, etc.

EEG dynamic range and noise

We want to record very small signals and signal differences.

If the sample-to-sample noise (for example from the environment) large, then we do not need small steps in the ADC.

If the sample-to-sample noise can be made small (which is what we want), then the ADC should also be able to detect small voltage differences.

The dynamic range needs to account for large artifacts, and small signals.

EEG artifacts

Other types of (physiological) bioelectricity

Muscle (EMG)

Heart (ECG)

Eye movements (EOG)

Electrodes that don't make good contact

Electrodes that move relative to the scalp

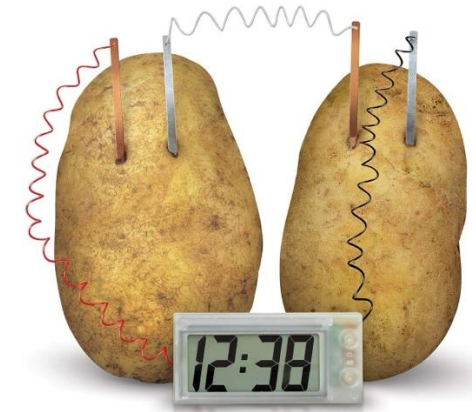
Wires that pick up artifacts and/or move

Power line noise, 50Hz electrical equipment

Electrochemical noise (sweating)

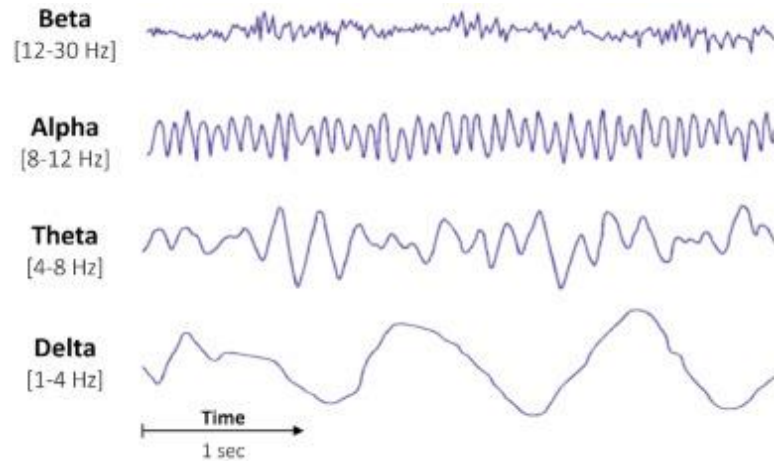
Electrostatic noise (e.g., rubbing feet over the carpet)

Some of these are mostly **common-mode**, i.e., similar on all channels



Discrete sampling over time

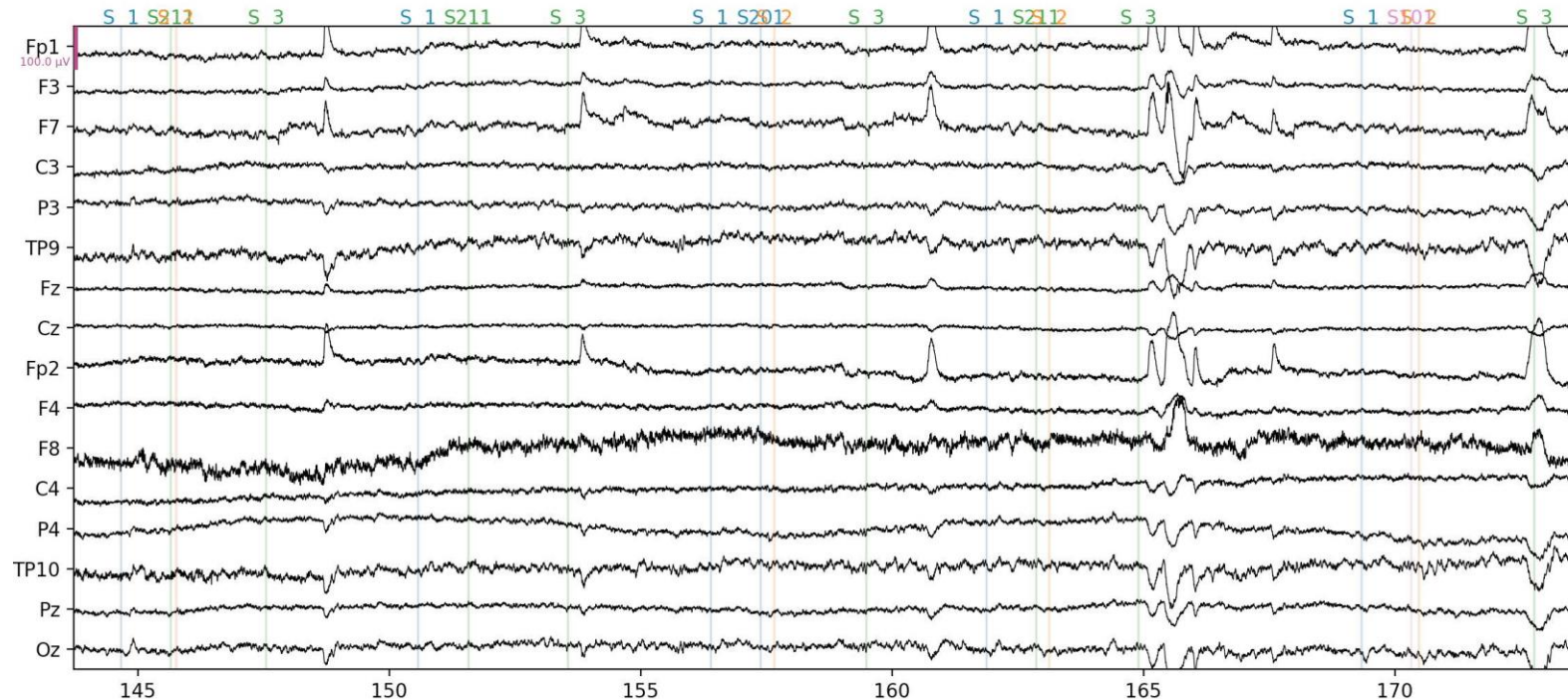
EEG time courses



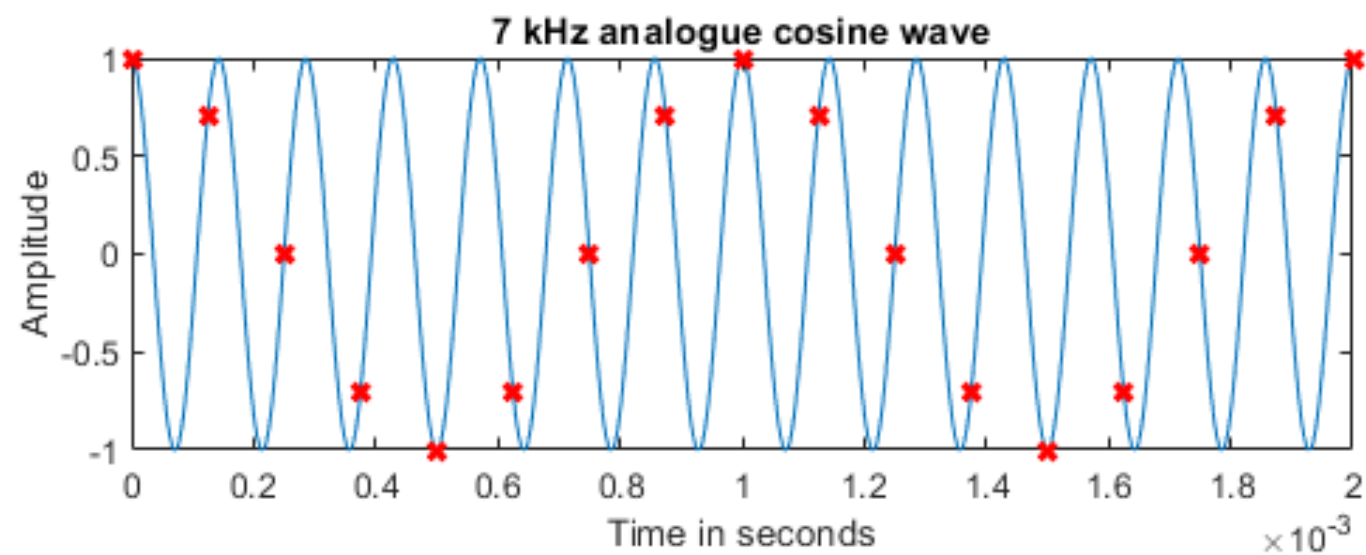
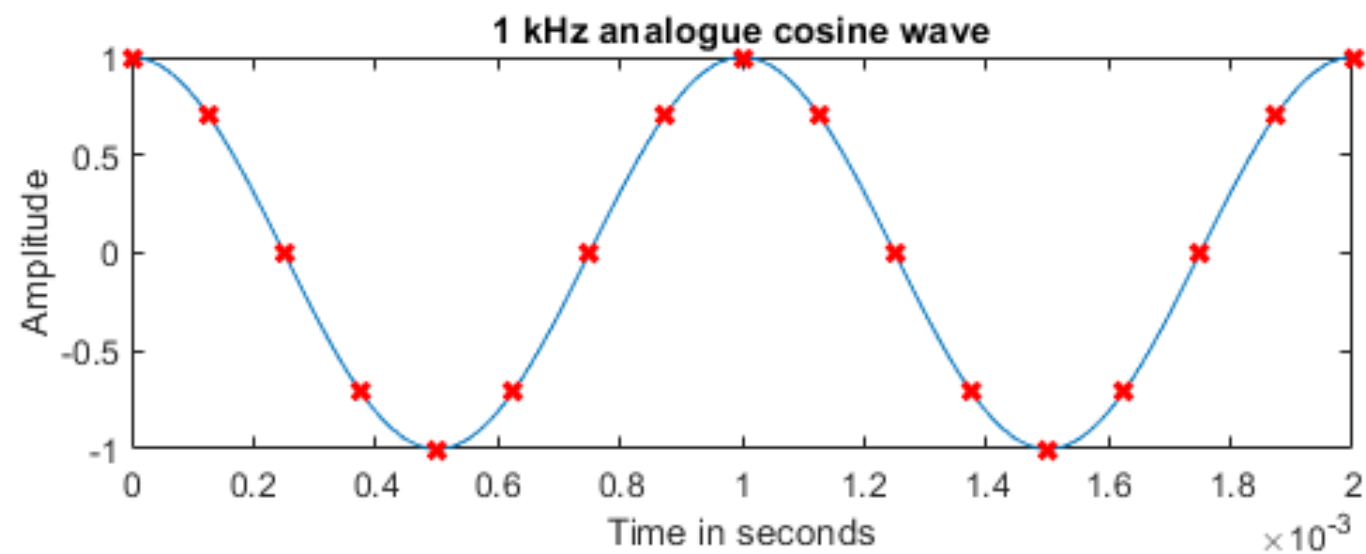
High-frequency activity in EEG can go up to 600 Hz (HFOs in epilepsy), but most of the EEG signal is below 100Hz.

We often sample at 250 or 500Hz.

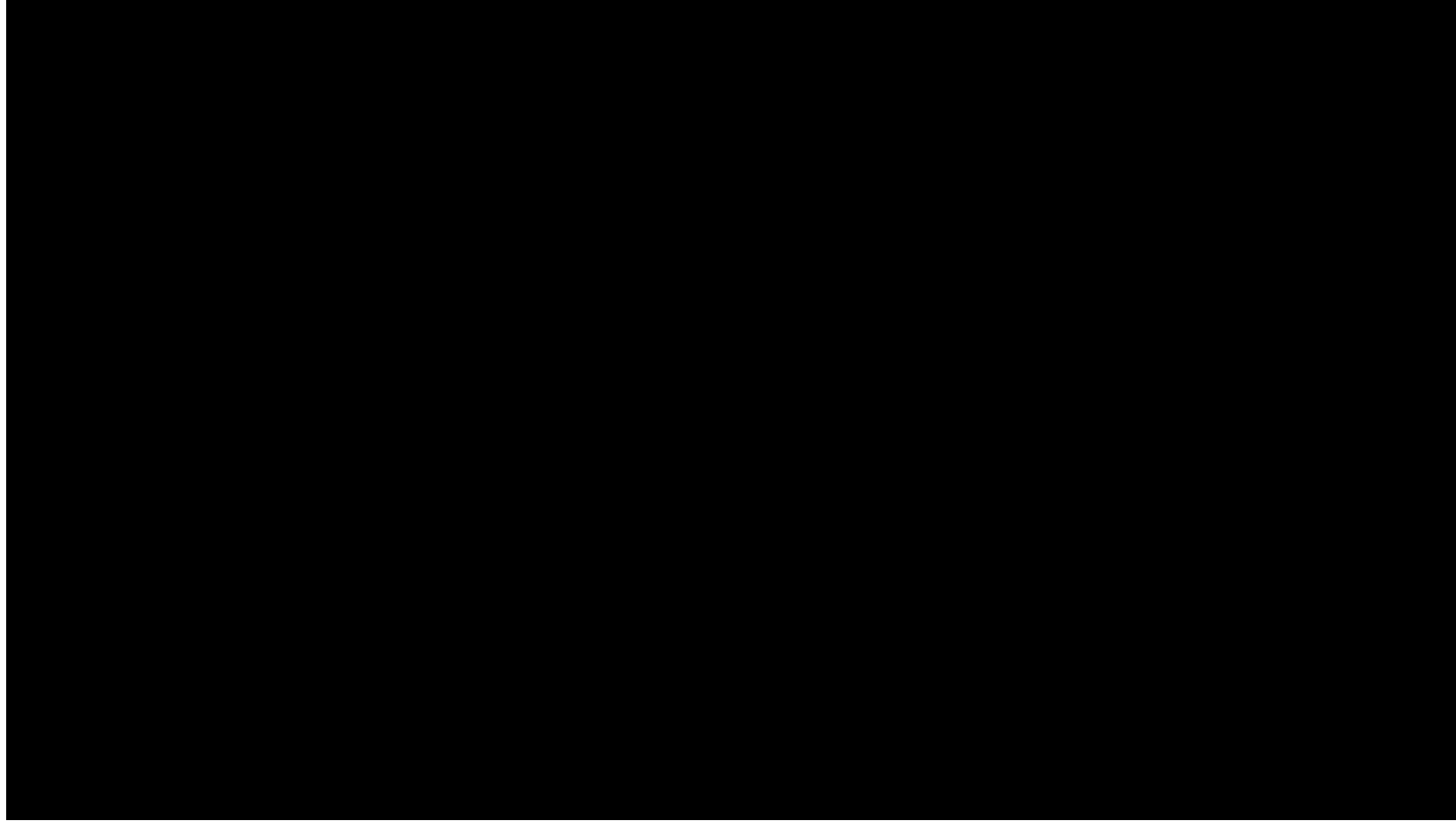
Sampling faster can help to identify artifacts, for example from muscles.



Sampling and aliasing



Sampling and aliasing



Sampling and aliasing

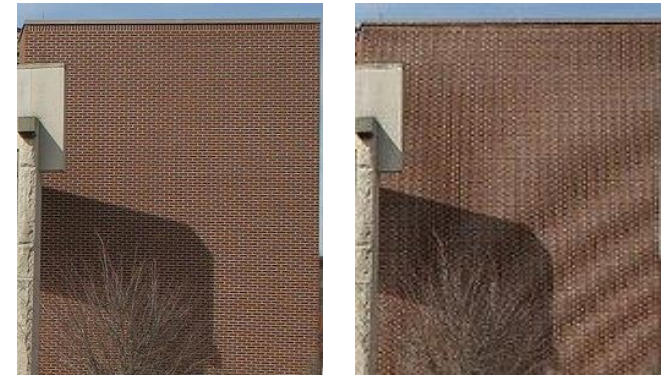
If the analog signal contains frequencies higher than the Nyquist frequency ($\frac{1}{2}$ times the sampling frequency), we cannot distinguish them in the sampled digital signal from lower frequencies. This is called “aliasing”. It happens with any sampled signal, also with photo and video.

Consequences:

- High frequency signals cannot be recorded/represented
- High frequency signals show up as low-frequency noise

Solutions:

- Apply a low-pass “anti aliasing” filter on the analog signal prior to sampling, this is commonly at $\frac{1}{3}$ or $\frac{1}{4}$ the sampling rate (so for 250Hz at 83 or 67 Hz).
- Employ “over-sampling” (sample much faster) and downsample the signal digitally



Saving data to disk

EEG to the computer

The EEG “system” consists of the electrodes, cap, amplifier, and the computer with acquisition software

The EEG data is a single number for every channel and for every sample

32 channels

500 Hz sampling rate

32x500 samples (numbers) per second

This long list of numbers can be represented as a $N_{\text{chans}} \times N_{\text{samples}}$ matrix

$$V = \begin{bmatrix} 12 & 7 & 21 & 31 & 11 \\ 45 & -2 & 14 & 27 & 19 \\ -3 & 15 & 36 & 71 & 26 \\ 4 & -13 & 55 & 34 & 15 \end{bmatrix}$$

EEG to the computer

EEG data *could* be stored in an Excel spreadsheet

This is not done for raw and continuous EEG data, as it is too large

500 samples per second, 60 seconds, 60 minutes: $3600 \times 500 = \sim 2\text{M}$ samples per hour

Metadata also needs to be stored, like

- Sampling rate

- Channel names

- Triggers

- Amplification factor

EEG data *is* stored in specific data formats

Many EEG manufacturers have their own format

EDF, BDF, BrainVision format, ...

Often a single file with a “header” and subsequent “data”

Sometimes separate files for the header and data

Example - BrainVision uses three files (.vhdr, .vmrk, .eeg)

Brain Vision Data Exchange Header File Version 1.0

; Data created by the Vision Recorder

[Common Infos]

Codepage=UTF-8

DataFile=test.eeg

MarkerFile=test.vmrk

DataFormat=BINARY

; Data orientation: MULTIPLEXED

DataOrientation=MULTIPLEXED

NumberOfChannels=32

; Sampling interval in microseconds

SamplingInterval=2000

[Binary Infos]

BinaryFormat=INT_16

[Channel Infos]

; Each entry: Ch<Channel number>

; <Resolution in "Unit">, <Unit>

; Fields are delimited by comma

; Commas in channel names are

Ch1=Fp1,,0.5,µV

Ch2=Fp2,,0.5,µV

Ch3=F3,,0.5,µV

Ch4=F4,,0.5,µV

...

Brain Vision Data Exchange Marker File, Version 1.0

[Common Infos]

Codepage=UTF-8

DataFile=test.eeg

[Marker Infos]

; Each entry: Mk<Marker number>=<Type>,<Description>,<Position in data points>,<

; Fields are delimited by commas, some fields might be omitted (empty).

; Commas in type or description text are coded as "\1".

Mk1=New Segment,,1,1,0,20131113161403794232

Mk2=Stimulus,S253,487,0,0

Mk3=Stimulus,S255,497,1,0

Mk4=Event,254,1770,1,0

Mk5=Stimulus,S255,1780,1,0

Mk6=Event,254,3253,1,0

Mk7=Stimulus,S255,3263,1,0

Mk8=Stimulus,S253,4936,1,0

Mk9=Stimulus,S255,4946,1,0

Mk10=Response,R255,6000,1,0

Mk11=Event,254,6620,1,0

Mk12=Stimulus,S255,6630,1,0

...

Some EEG file formats

ANT Neuro (.avr, .cnt, .trg)

BESA (.avr, .swf)

Biosemi BDF (.bdf)

BrainVision (.eeg, .seg, .dat, .vhdr, .vmrk)

CED - Cambridge Electronic Design (.smr)

EEGLAB (.set, .fdt)

Electrical Geodesics, Inc. (EGI) (.egis, .ave, .gave, .ses, .raw, .mff)

NeuroScan (.eeg, .cnt, .avg)

Nexstim (.nxe)

TMSi (.Poly5)

Generic formats (.edf, .gdf)

...

Brain Imaging Data Structure



The EEG data file does not contain *all* information

The age of the participant, handedness, clinical status, ...

What was the task that the participant was doing

Where were the electrodes placed

What type of amplifier was used

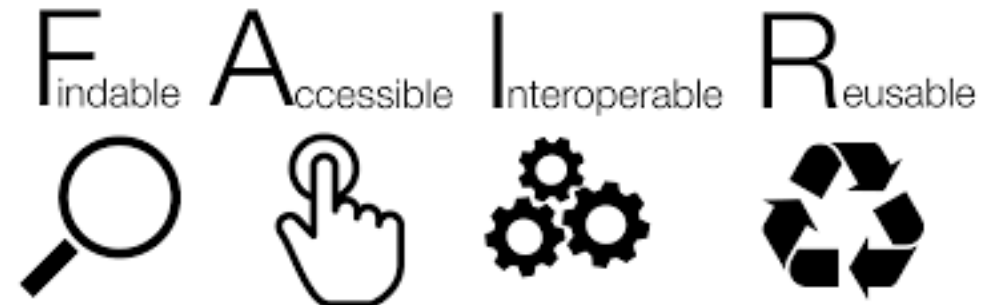
...

The EEG signal itself is the “data”, all surrounding information is “metadata”

The Brain Imaging Data Structure (BIDS) is *the* standard for organizing both the data and metadata.



Open Data



Findable

Make your data available in a catalog or repository
with a persistent identifier (DOI, handle) and metadata

Accessible

Be explicit about data usage terms (agreement with downloader)

Interoperable

Make your data human and machine readable, e.g. BIDS

Reusable

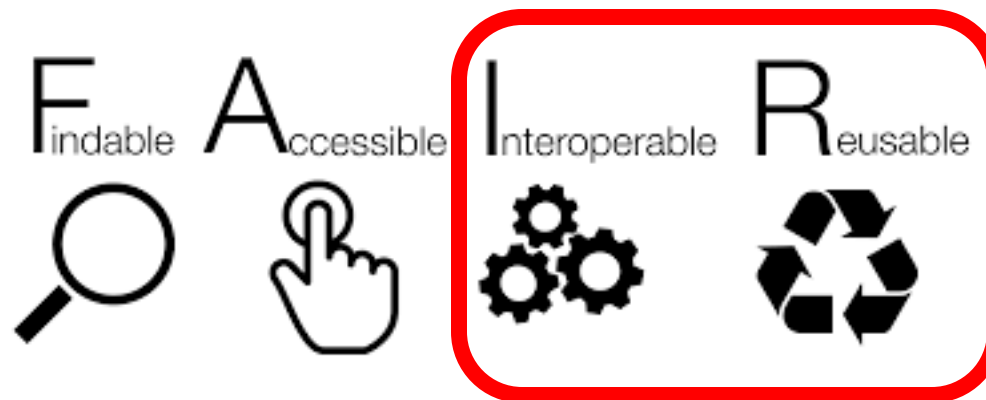
Make sure you document enough details, e.g. “data descriptor” paper
that can be cited, along with citing our data -> measurable impact!

Brain Imaging Data Structure (BIDS)

external reuse: publishing, sharing

internal reuse: archiving, curation, collaborating

Fundamental for OpenNeuro, but also used in Donders Repository and as the basis for new analysis pipelines and workflow development



<https://openneuro.org>

<https://data.donders.ru.nl>



BIDS for MRI, MEG, EEG, iEEG, PET, fNIRS
microscopy, behavior, motion, ...

Just a bunch of directories and files on disk

No special software required (although tools are available)

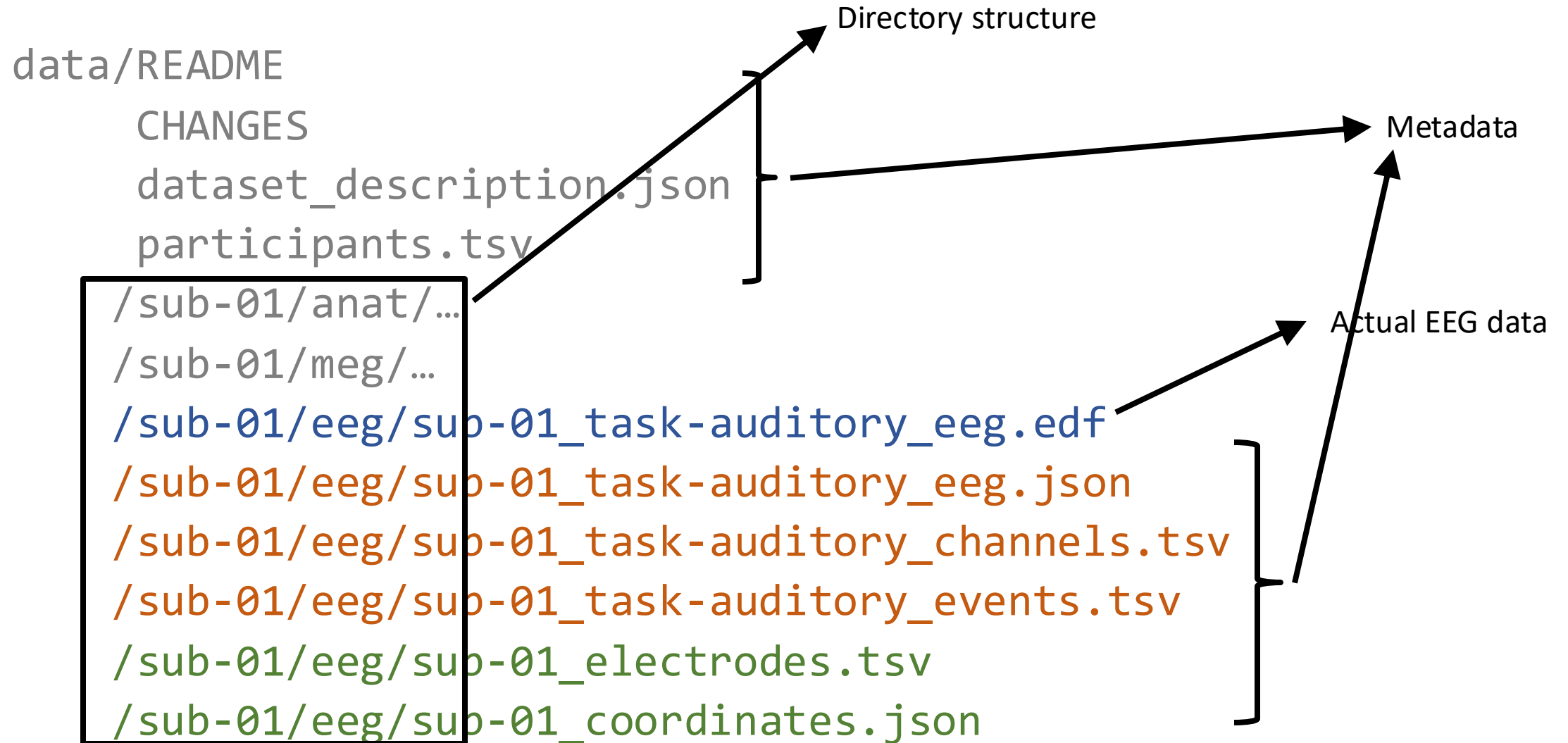
Converters:

FieldTrip data2bids, EEGLAB, MNE-BIDS

BIDScoin, Heudiconv

Processing:

MRIfqc, fMRIfprep



BIDS “sidecar” files for metadata

see also <https://github.com/bids-standard/bids-examples>

- 1) represent otherwise missing data
- 2) make it easier to query/search

As example for EEG:

_participants.tsv and json
_sessions.tsv and json
_scans.tsv and json

_eeg.json
_channels.tsv and json
_electrodes.tsv and json
_coordinates.json
_photos.jpg

```
{  
  "TaskName": "matchingpennies",  
  "TaskDescription": "The task is emulating a game of 'matching pennies'",  
  "SamplingFrequency": 5000,  
  "Manufacturer": "Brain Products",  
  "ManufacturersModelName": "BrainAmp DC",  
  "CapManufacturer": "Brain Products",  
  "CapManufacturersModelName": "actiCAP 64Ch Standard-2",  
  "EEGChannelCount": 10,  
  "EOGChannelCount": 0,  
  "ECGChannelCount": 0.
```

name	type	units	status	status_description
FC5	EEG	uV	bad	Contains high frequency noise
FC1	EEG	uV	good	n/a
C3	EEG	uV	good	n/a
CP5	EEG	uV	good	n/a
CP1	EEG	uV	good	n/a
FC2	EEG	uV	good	n/a
FC6	EEG	uV	bad	Low correlation with other channels
C4	EEG	uV	good	n/a
CP2	EEG	uV	good	n/a
CP6	EEG	uV	good	n/a

Organizing your EEG data on the computer

1. The EEG acquisition software writes the data in its own format
2. You organize the data over recordings, participants, sessions, tasks
 - a) You rename the files and put them in appropriate directories
 - b) You add the notes from the recording as txt or pdf file
3. You convert the data file to a standard format
4. You add the metadata according to the BIDS standard
5. You use the BIDS validator to check that everything is correct

This is the ideal scenario, many people stop after step 2a.