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Introduction to EEG and MEG

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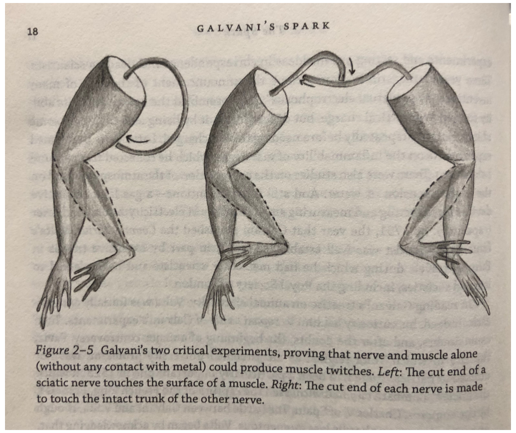
1. MEG and EEG: Historical and Technical Background

Historical and Technical Background of EEG

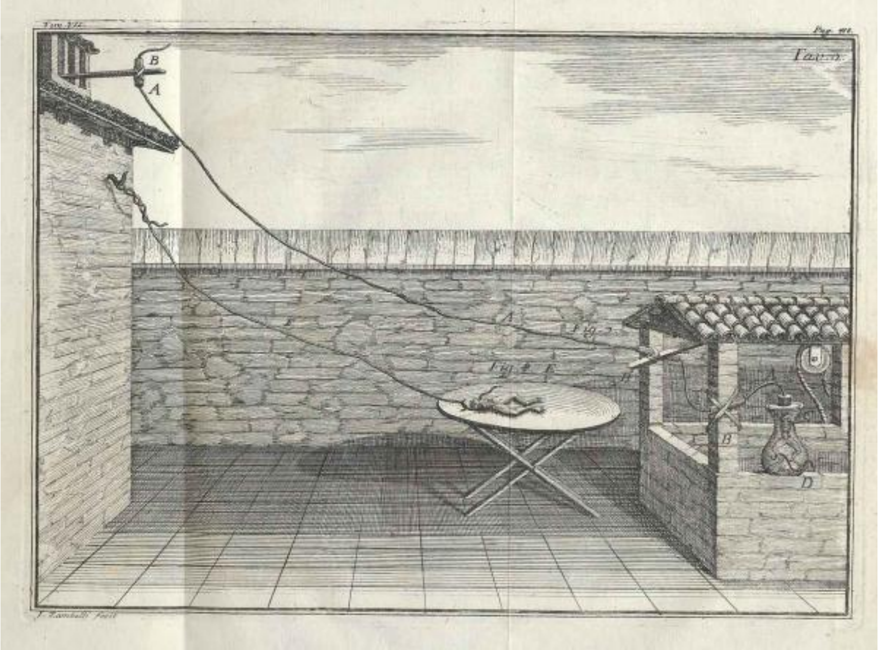
- 1780: Galvani’s demonstration of muscle-nerve interactions
- 1870: Hitzig and Fritsch stimulated cortex in a dog and found that the contralateral muscles moved
- 1873: David Ferrier built on Hitzig-Fritsch’s work and topographically mapped motor function in various animals

Understandable that electrical stimulation of the brain produces a response, but can a spontaneous brain activity be recorded?



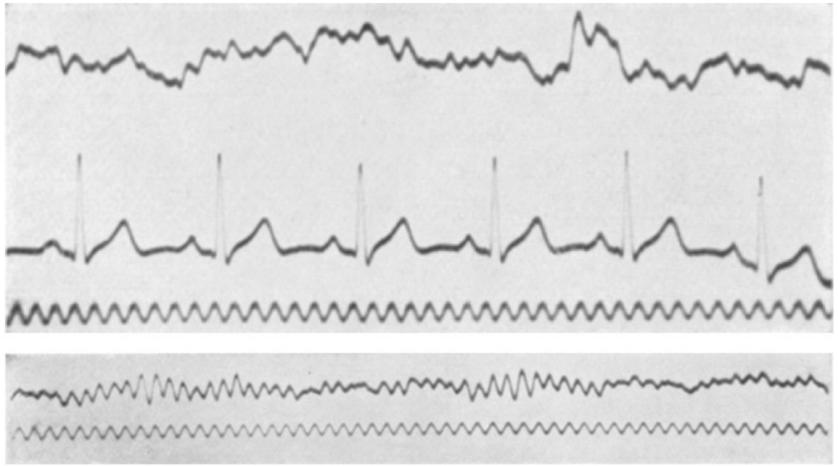
18 GALVANI'S SPARK

Figure 2–5 Galvani’s two critical experiments, proving that nerve and muscle alone (without any contact with metal) could produce muscle twitches. *Left*: The cut end of a sciatic nerve touches the surface of a muscle. *Right*: The cut end of each nerve is made to touch the intact trunk of the other nerve.



Historical and Technical Background of EEG

- 1875: Richard Caton did the first invasive recordings of brain activity and used a galvanometer to detect electrical signals in rabbit and monkey cortex
- 1929: Hans Berger recorded the first human EEG by measuring electric potentials between two electrodes placed at the scalp.
- 1934: Edgar Adrian reproduced Berger's findings.



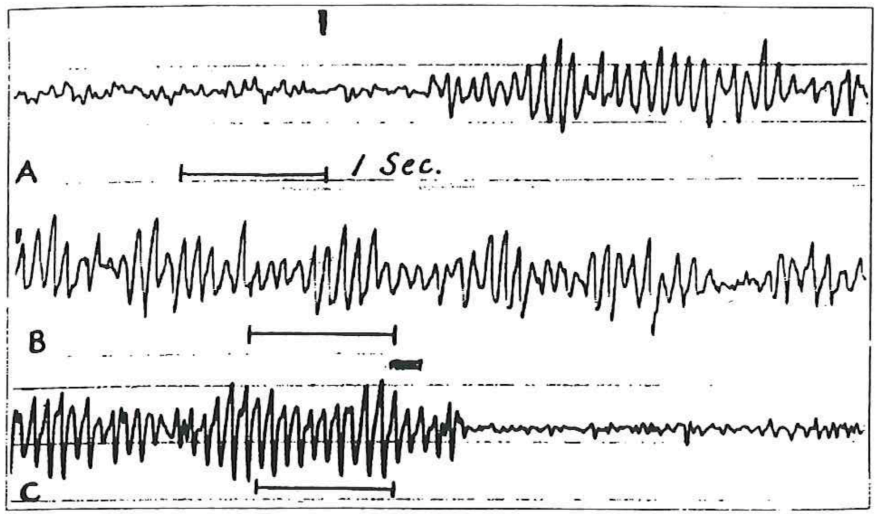


FIGURE 15.6. *A human electroencephalogram made by Adrian. In Row A, the subject started with his eyes open and then closed them, producing larger brain waves. In Row B, the eyes were open but the head was in a dark box. Row C shows how the large rhythmic waves change to faster and smaller activity when the subject again opens his eyes. (From Adrian, 1934; courtesy of the American Medical Association.)*

Historical and Technical Background of EEG

- 1935-36: The first unambiguous sensory (auditory) evoked potentials" were recorded (in Boston) by Hallowell and Pauline

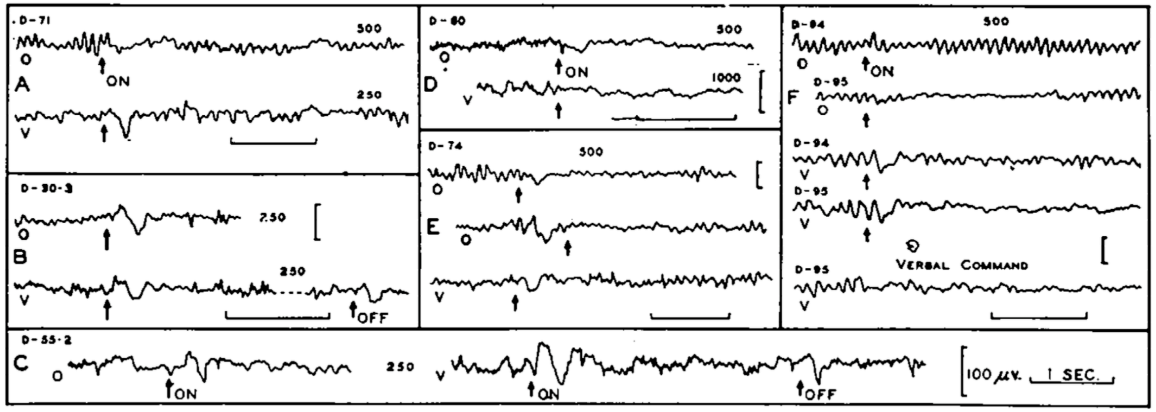


FIG. 1. On-effects and modifications of spontaneous rhythms in response to sounds.

- Much excitement and research focused on identifying various cognitive ERP components and developing methods recording and analyzing the ERPs in cognitive experiments.
  Various auditory, visual, somatosensory evoked potentials have been identified
  Specific peaks/troughs have been labeled as either P or N followed the time in milliseconds when they are seen.

- Note that these are single trial data – no averaging across trials t 1962 (Galambos, Sheatz)!

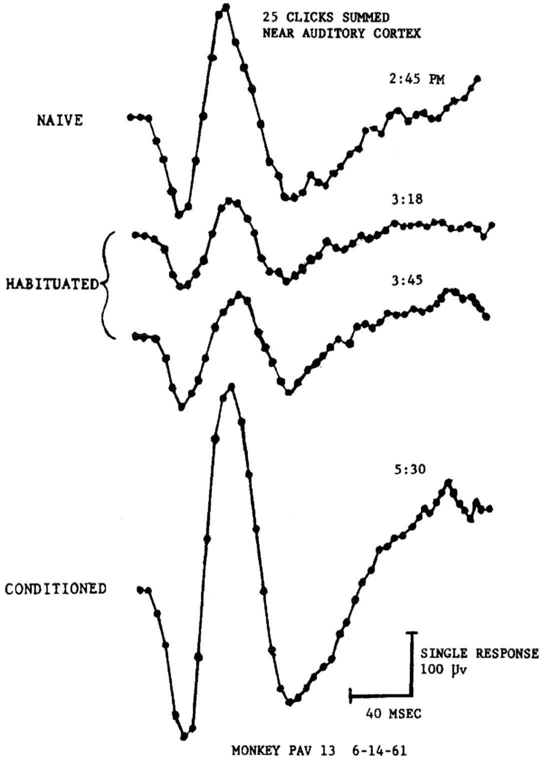


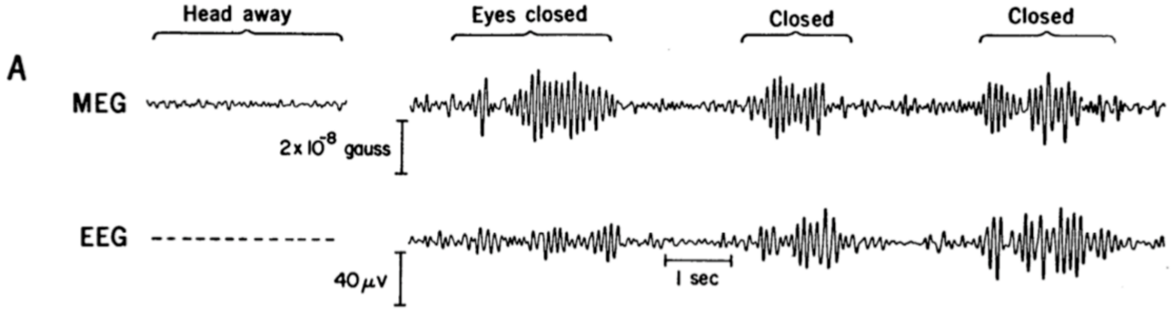
FIG. 1. Click-evoked responses averaged by computer. Bipolar recording from cortex of inferior bank of superior temporal gyrus in monkey.

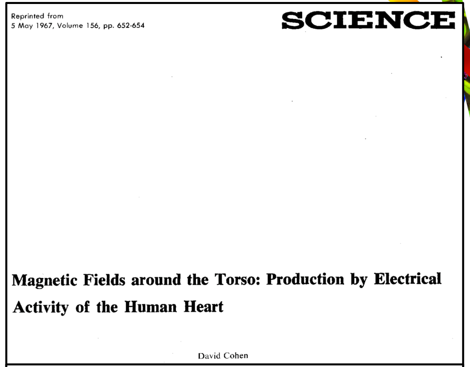
Historical and Technical Background of MEG

- Back in the mid 60s, David Cohen started constructing an elaborate 5-layer magnetically shielded room. First started recording the heart signal (MCG) and then signals (alpha rhythms) from the brain. Early measurements were done using a copper induction coil.
  - First brain MEG measurements required thousands of averages with concurrent phase-locked EEG measurements.

- Late 1960s: Jim Zimmerman developed the first practical SQUIDs for biomagnetism
  - SQUID = Superconducting Quantum Interference Devices

- By 1971, David Cohen and Jim Zimmerman were able to record from the brain



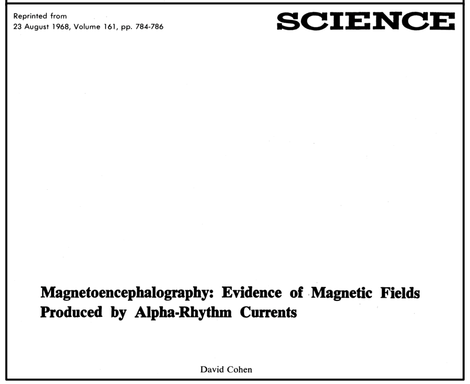


Reprinted from
5 May 1967, Volume 156, pp. 652-654

SCIENCE

Magnetic Fields around the Torso: Production by Electrical Activity of the Human Heart

David Cohen



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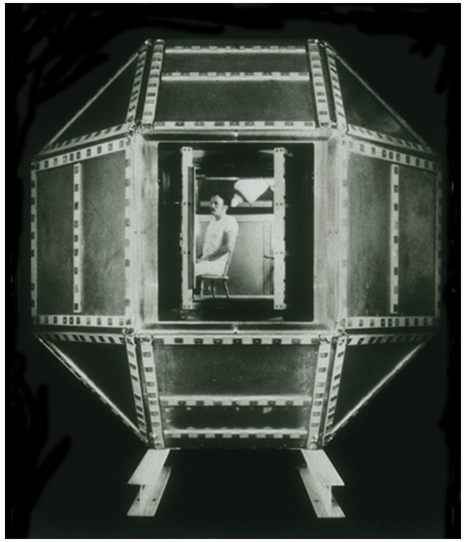
23 August 1968, Volume 161, pp. 784-786

SCIENCE

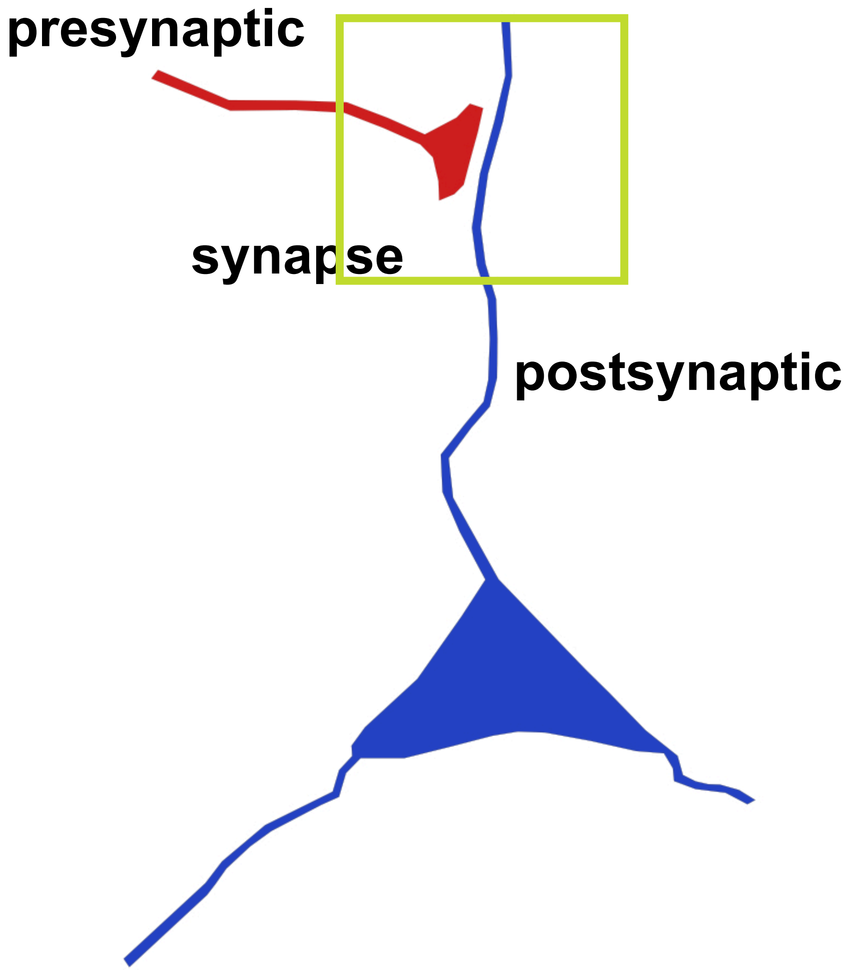
Magnetoencephalography: Evidence of Magnetic Fields Produced by Alpha-Rhythm Currents

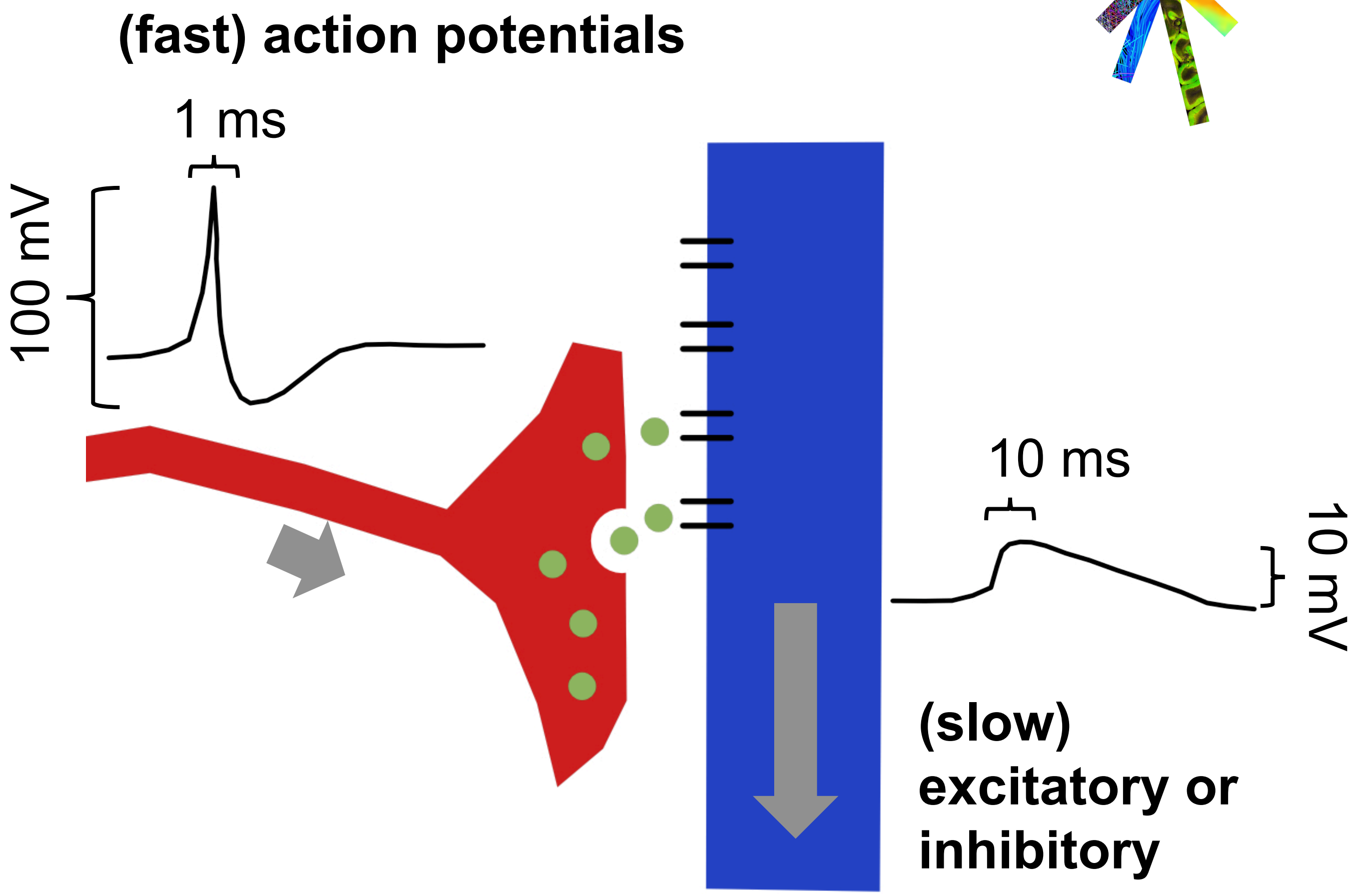
David Cohen



2. Neural Sources of MEG and EEG

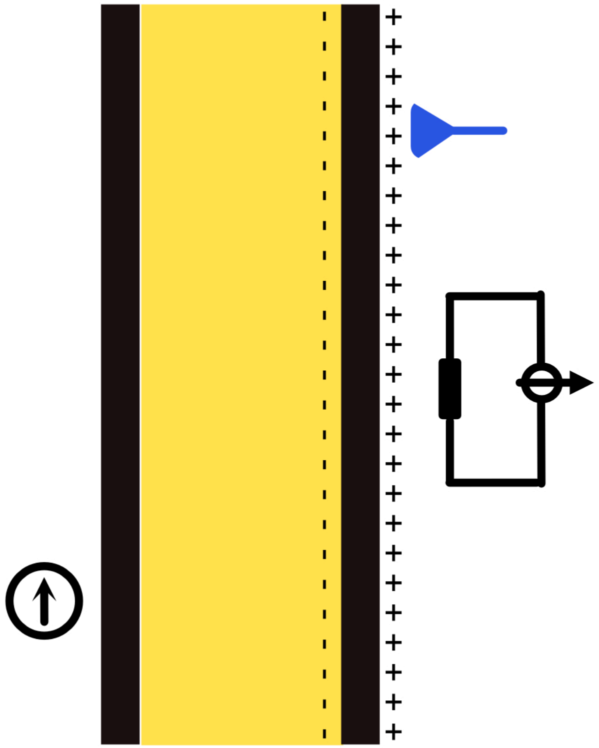
Pre-synaptic and post-synaptic potentials





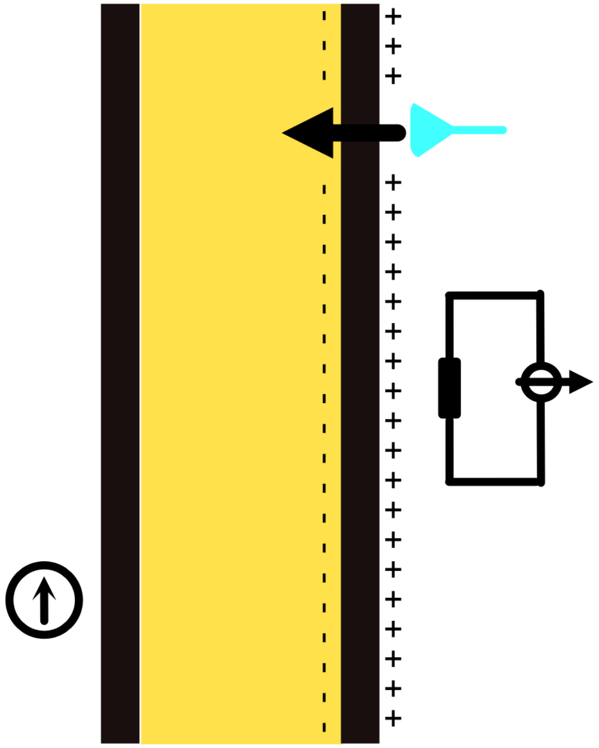
(slow) excitatory or inhibitory postsynaptic potentials (EPSP, IPSP)

Neurons as current dipoles



Based on
EEG: Basic Principles, Clinical Applications and Related Fields
by Niedermeyer & Lopes da Silva

Neurons as current dipoles



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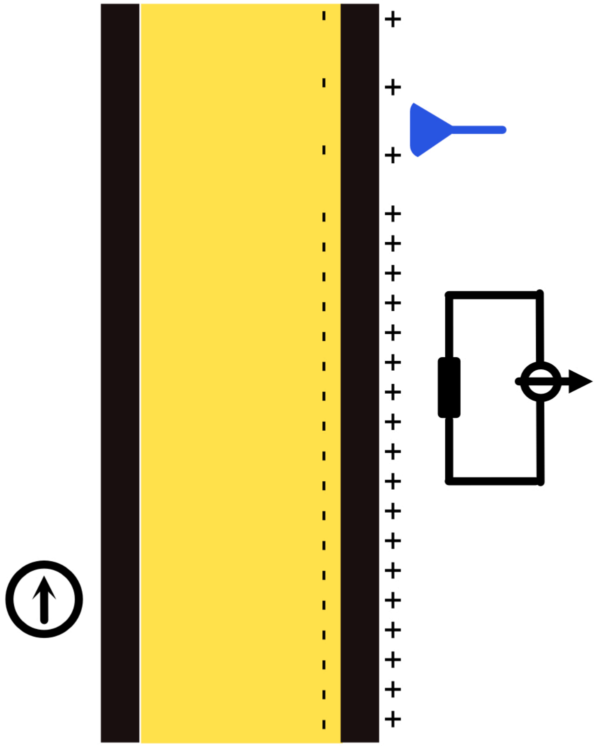
Neurons as current dipoles



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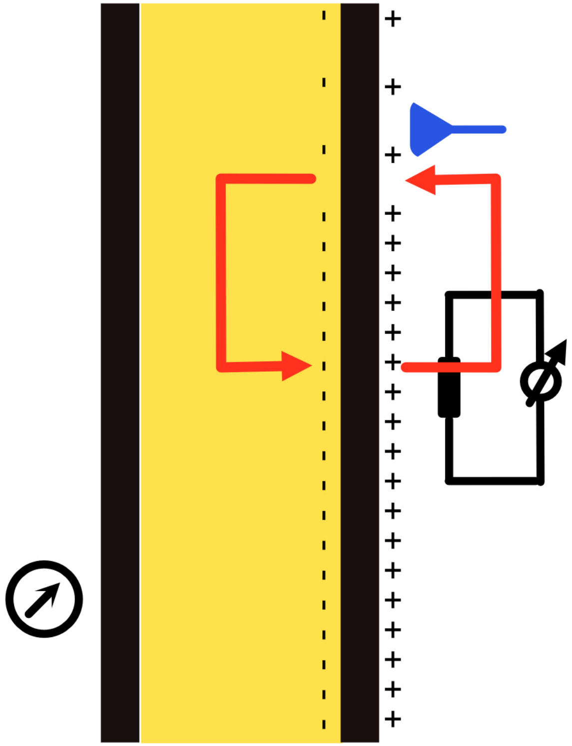
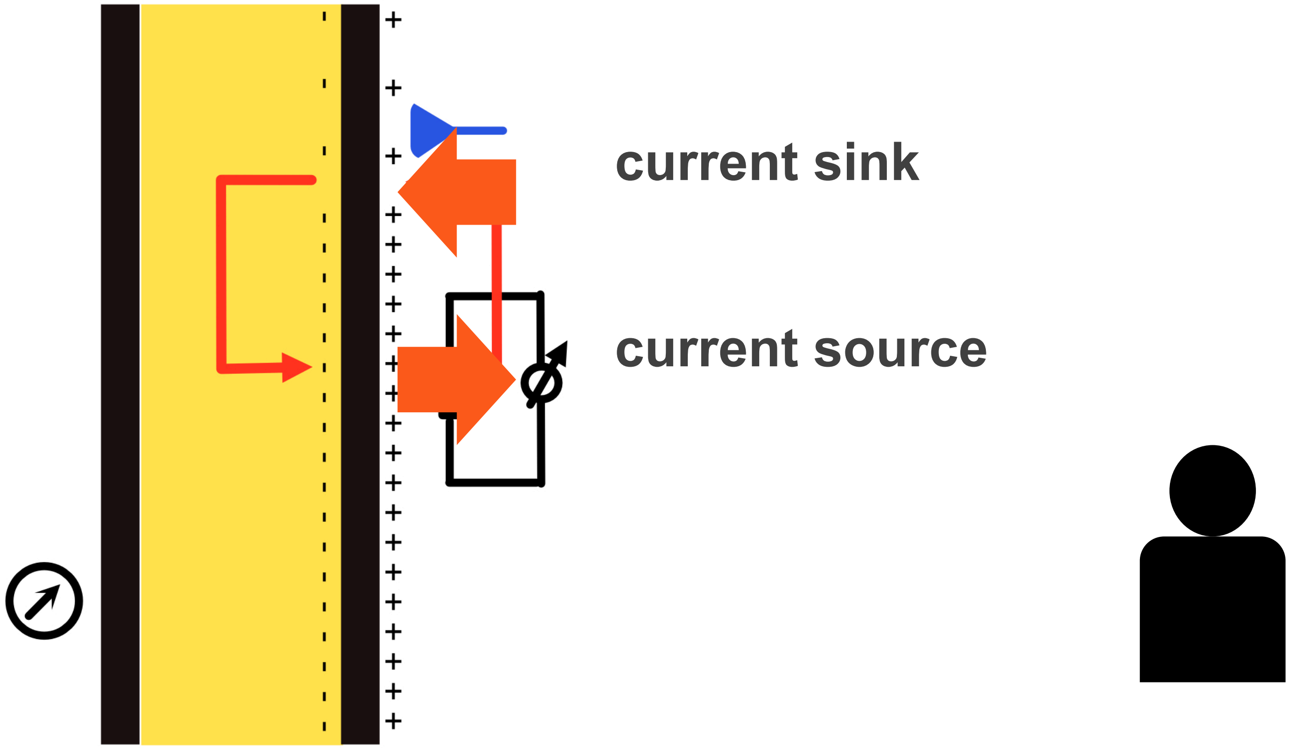
Neurons as current dipoles

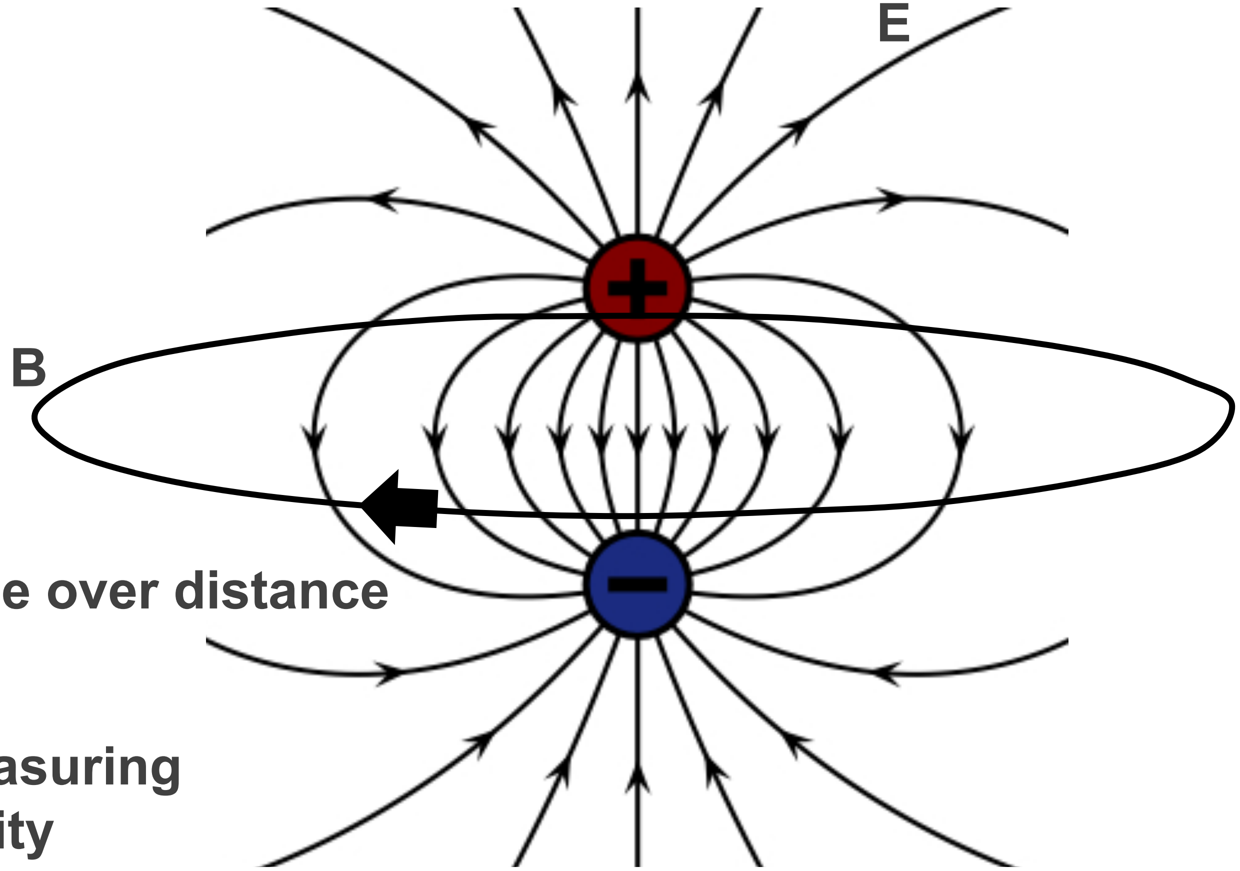


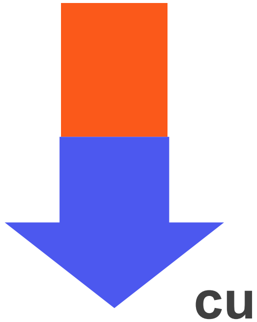
Neurons as current dipoles



Note: Current sources and sinks are defined wrt a viewer in the extracellular space

Neurons as current dipoles



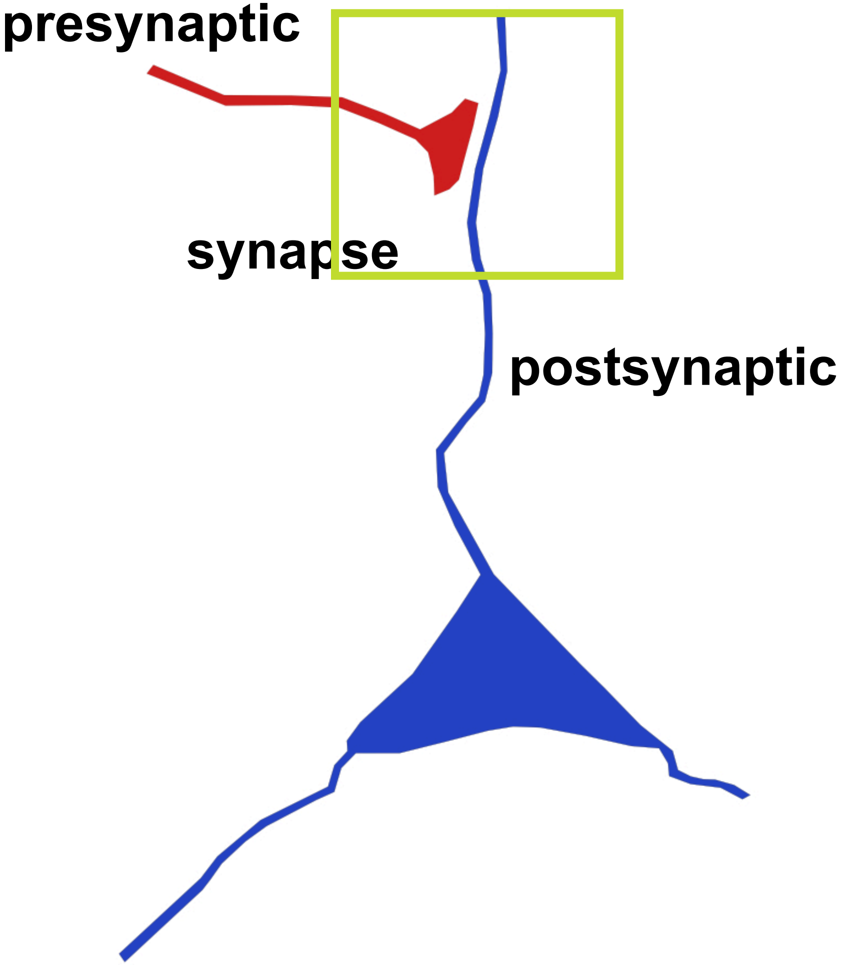


current source

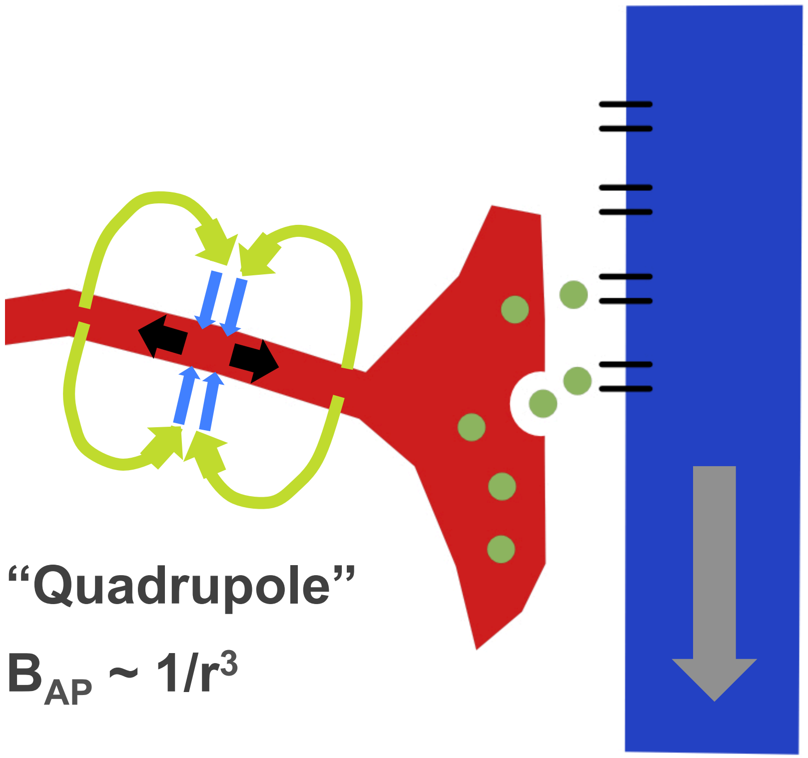
current sink

- Current dipoles
- Separation of charge over distance
- Unit: nA.m
- Fundamental to measuring and recording activity with EEG and MEG
- Note that current dipole ≠ magnetic dipole
  - magnetic dipoles are equivalent to a small current loop

Fields from different currents



(fast) action potentials



“Quadrupole”

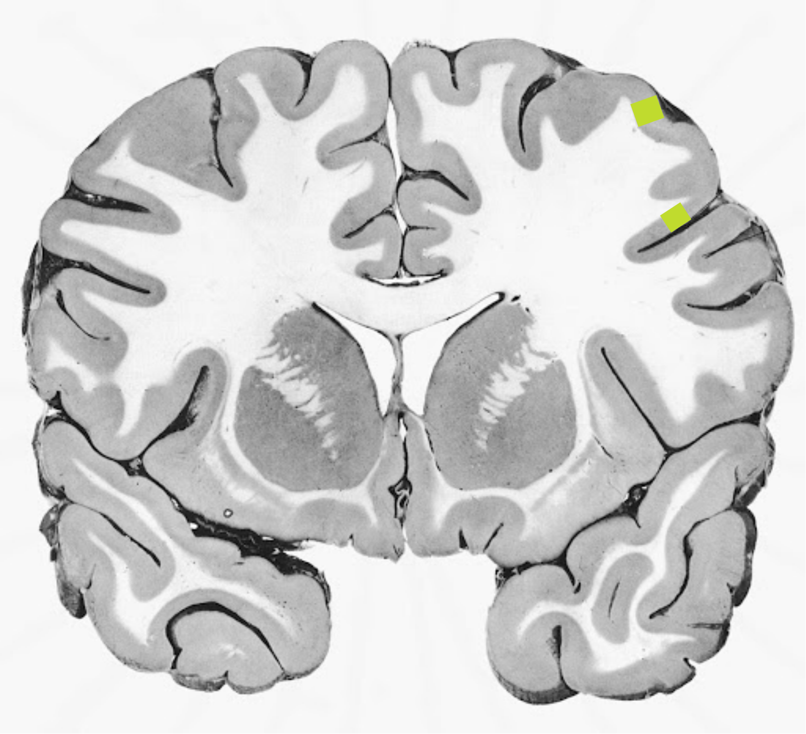
$B_{AP} \sim 1/r^3$

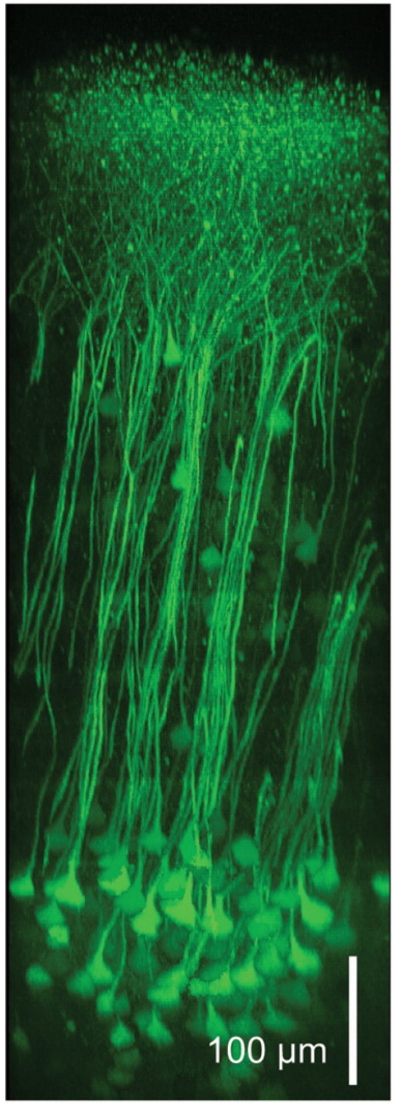
“Dipole”

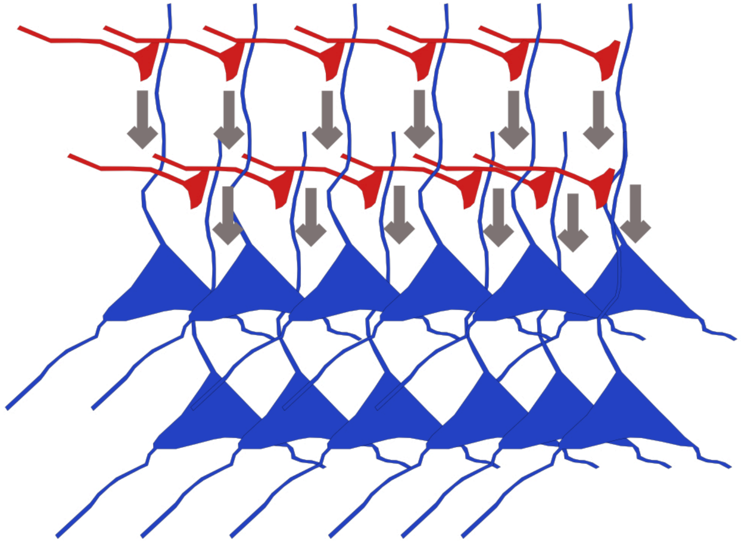
$B_{PSP} \sim 1/r^2$

(slow) excitatory or inhibitory postsynaptic potentials (EPSP, IPSP)

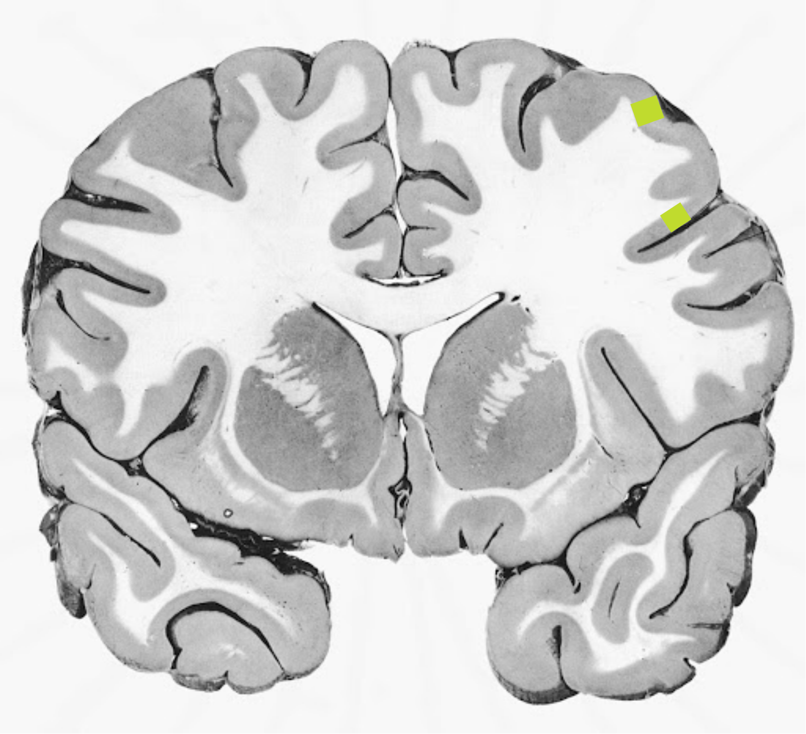
Population activity

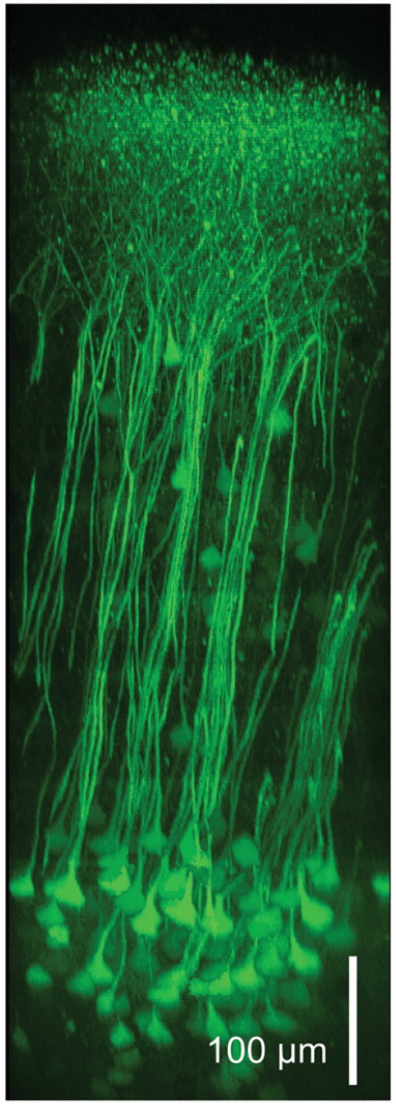


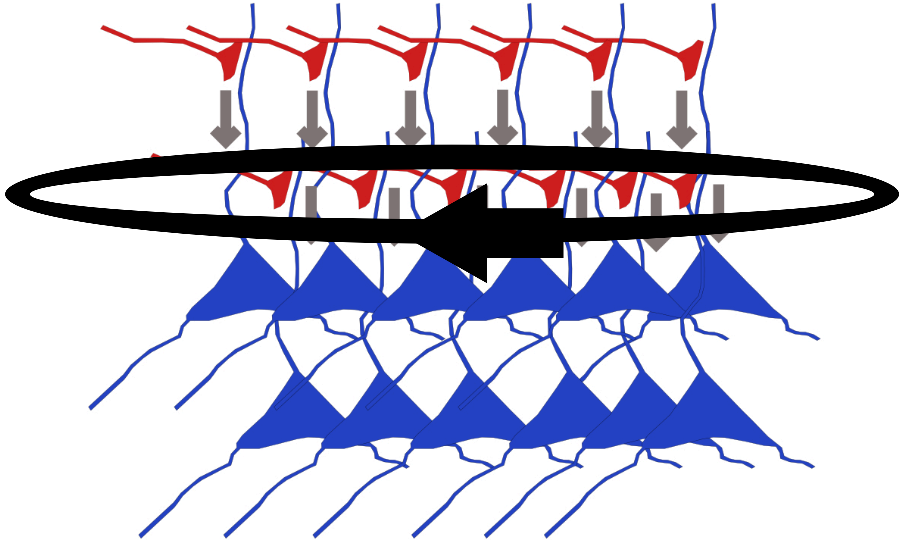




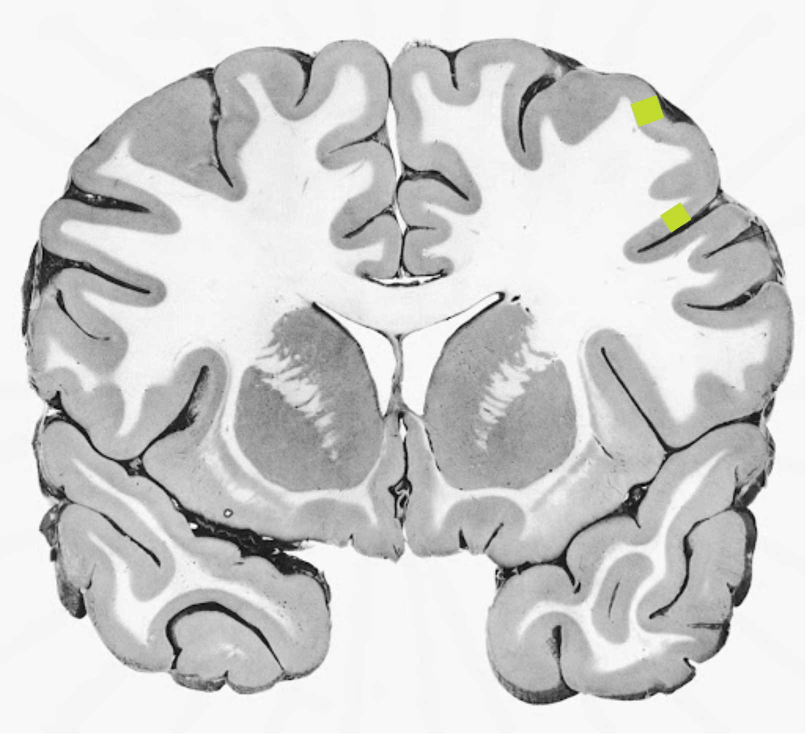
Neuron populations

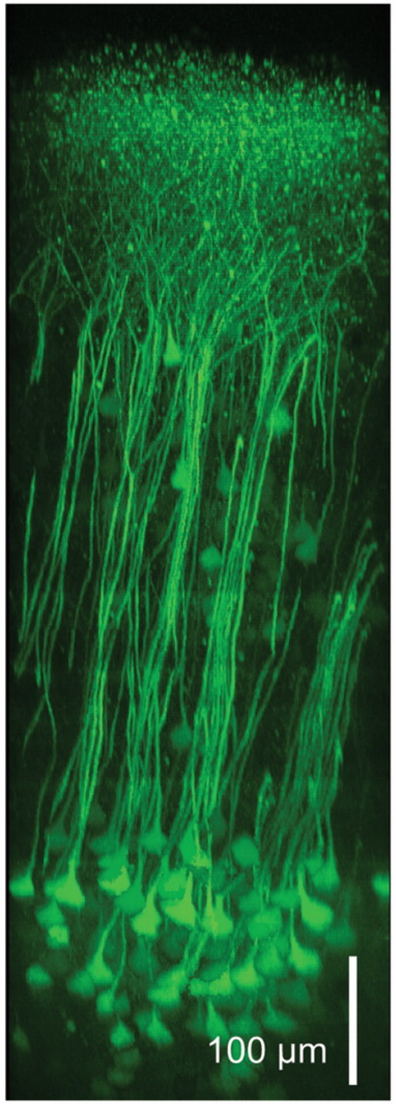




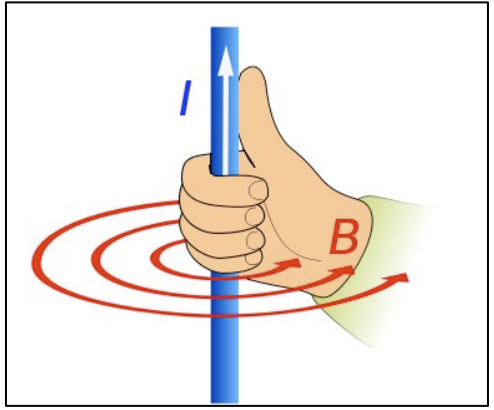


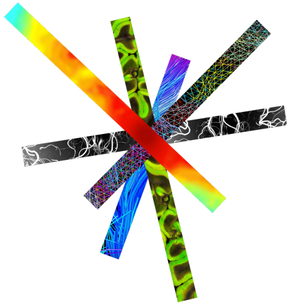
Neuron populations

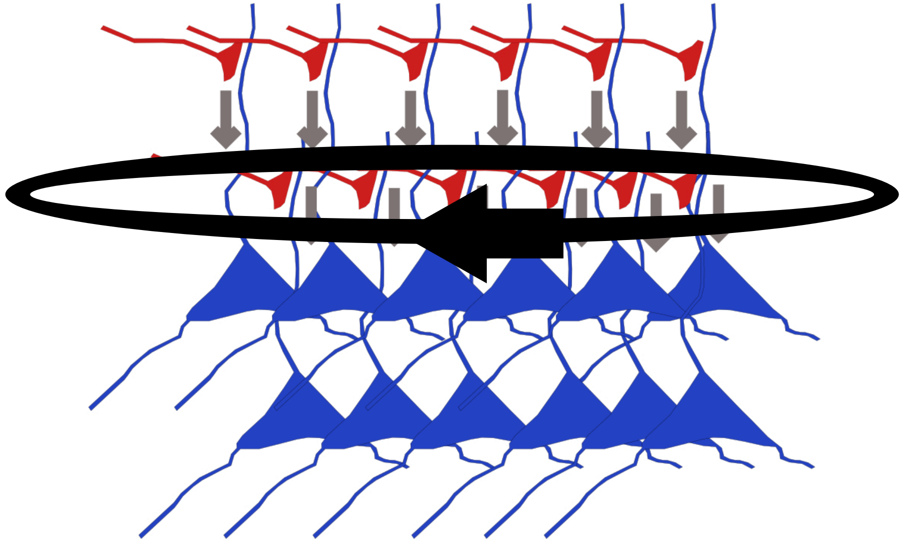




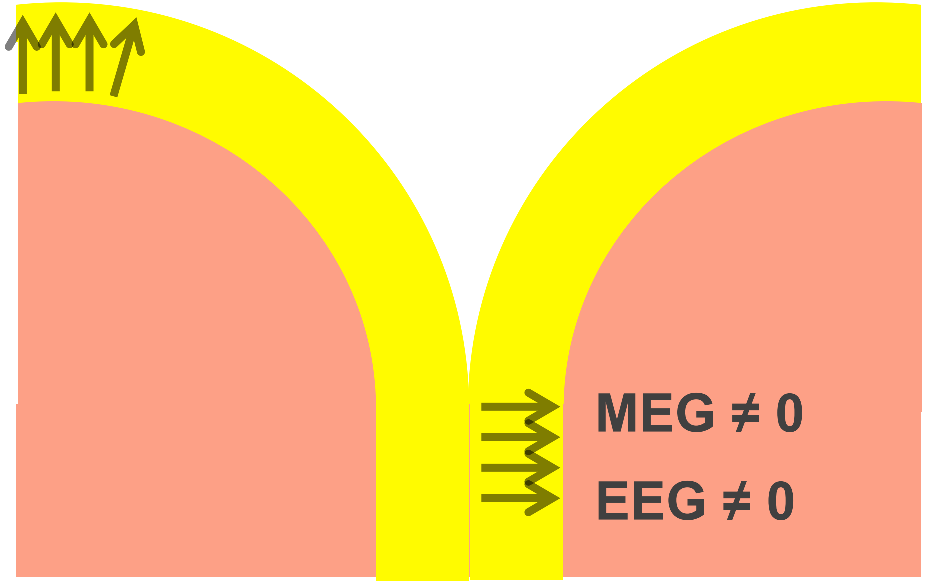
Right Hand Rule







Radial and Tangential Dipoles



MEG = 0

EEG ≠ 0

MEG ≠ 0

EEG ≠ 0

Numbers

- EEG: 0.1-100 μV

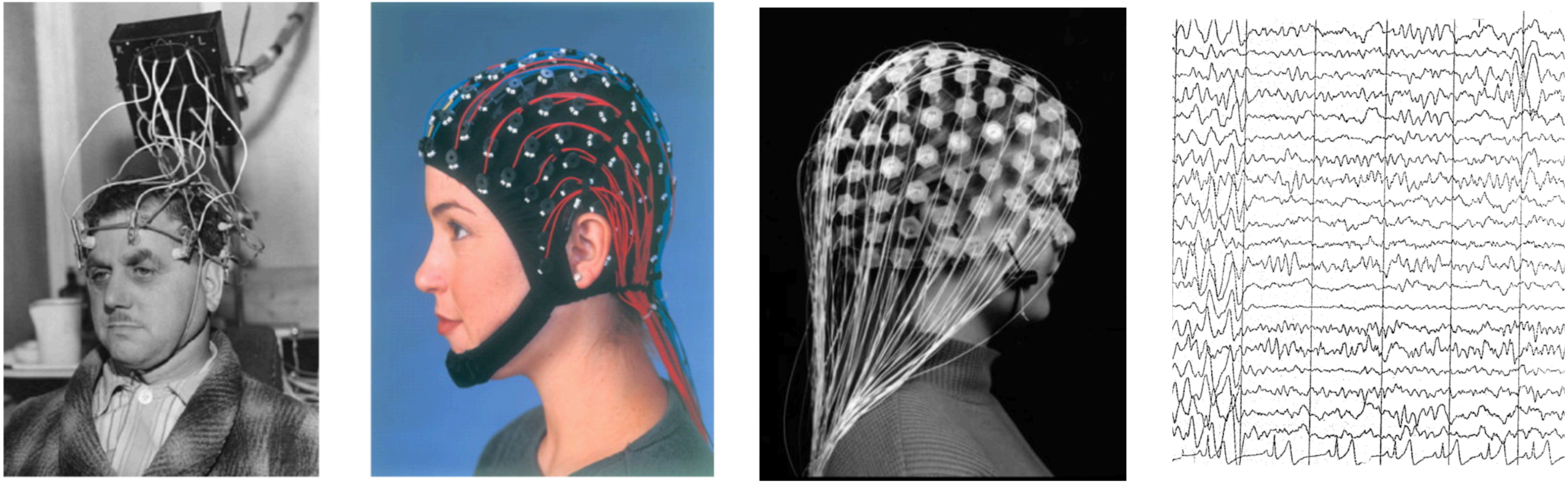
- MEG: 1 fT – 3 pT
  Earth's magnetic field: 10^{-6} Tesla (~ μT)
  Fridge magnets: ~ mT
  MRI scanners: ~ 3 Tesla

- Current density = Current dipole moment density
  Current density in brain tissue is constant across species and across brain regions ≈ 1 nA.m/mm2
  Invariance in current dipole moment density across brain structures and species: Physiological constraint for neuroimaging, Murakami & Okada, Neuroimage 2015

- Dipole moment for measurable cortical generators in humans Q ≈ 10 nA.m
  (Hamalainen 1993)
  For a single pyramidal neuron, q ≈ 0.2 pA.m
  (Murakami & Okada 2006)
  ~50,000 synchronously firing cortical neurons generate a detectable signal

3. Practicalities of EEG and MEG acquisition

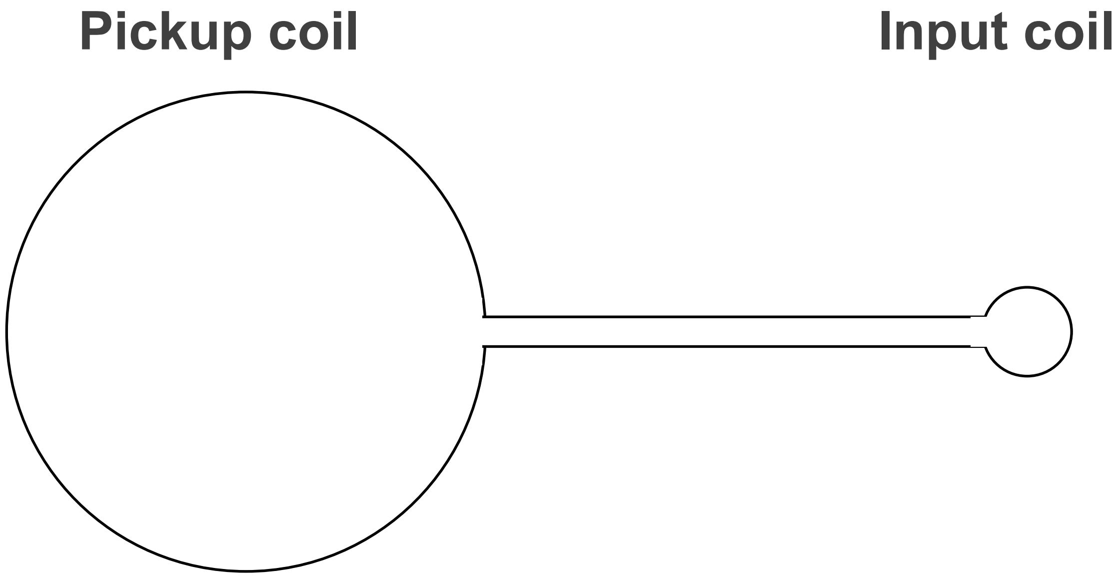
Practicalities of recording EEG



Practicalities of recording MEG

- MEG measures magnetic fields with highly sophisticated sensors
- SQUID = Superconducting Quantum Interference Devices
- SQUID-based MEG sensors need to be shielded, cooled and tuned
- SQUID noise ~ 2.5 fT/√Hz
- Instrumentation is expensive
- Magnetic fields can originate from:
  - Magnetic materials (let’s keep these out of the MEG)
  - Electric currents (neuronal currents)

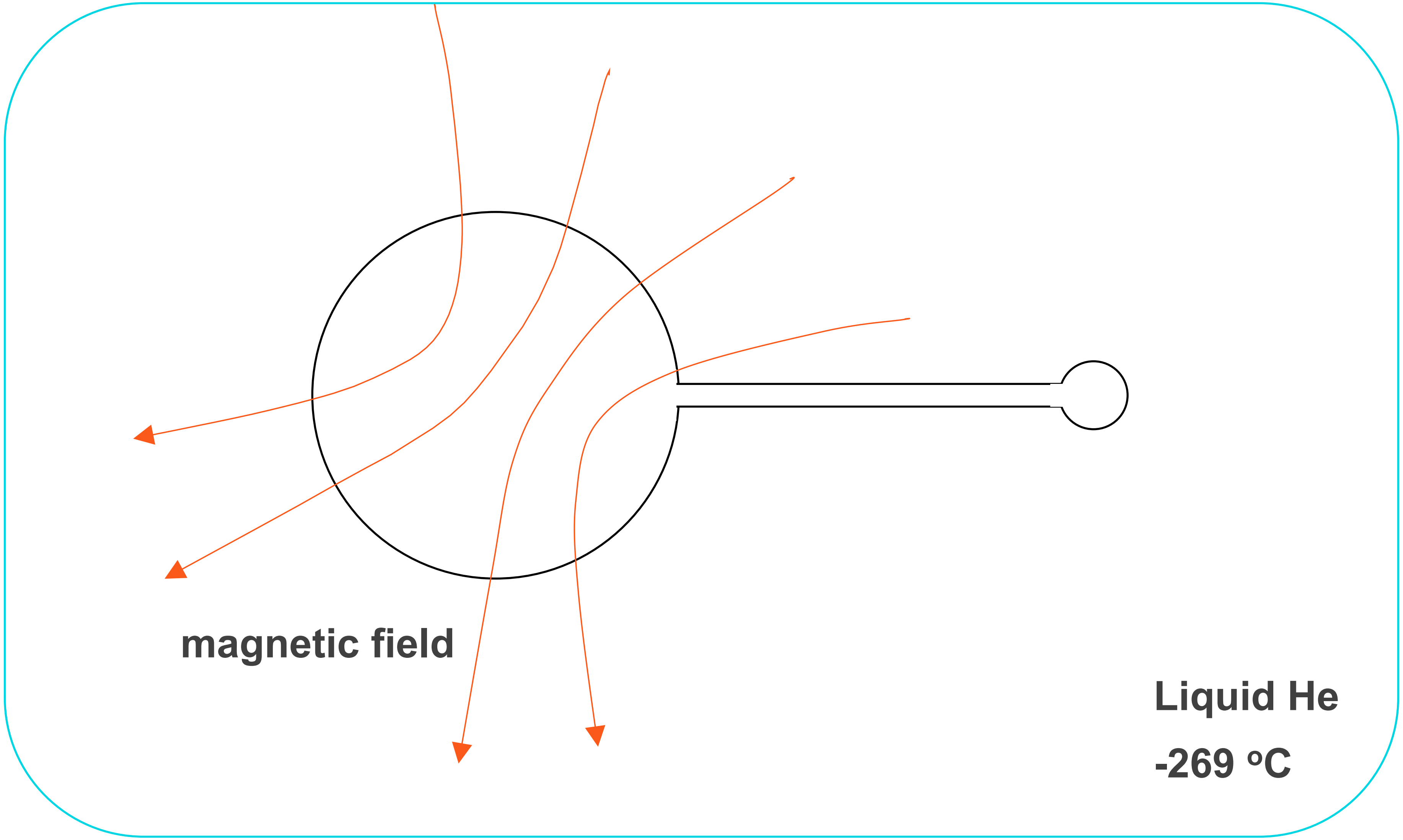
Practicalities of recording MEG: MEG sensors



Since magnetic fields are so small, amplify the field with a flux transformer

Whole thing is made of a superconducting metal

Practicalities of recording MEG: MEG sensors



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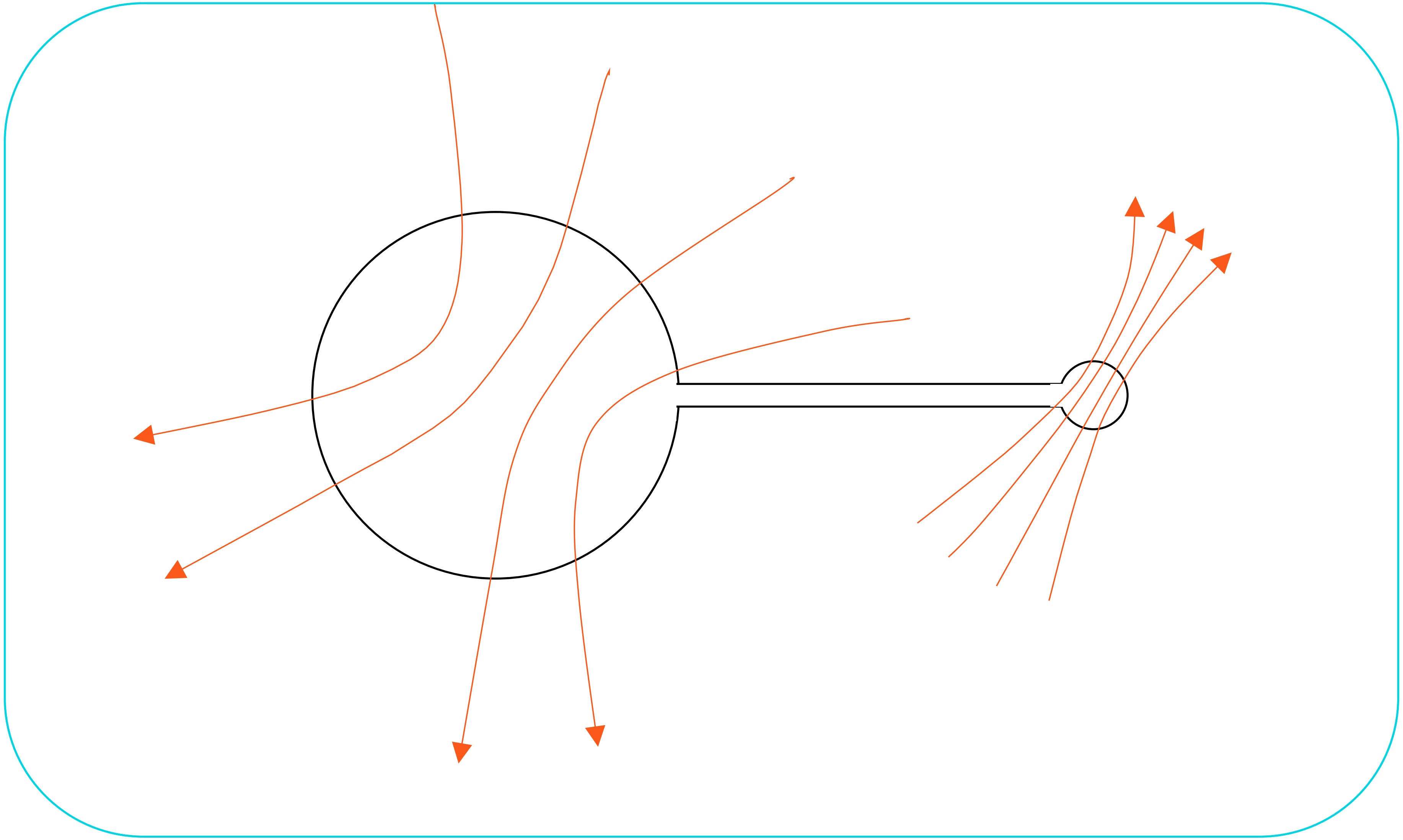
Practicalities of recording MEG: MEG sensors



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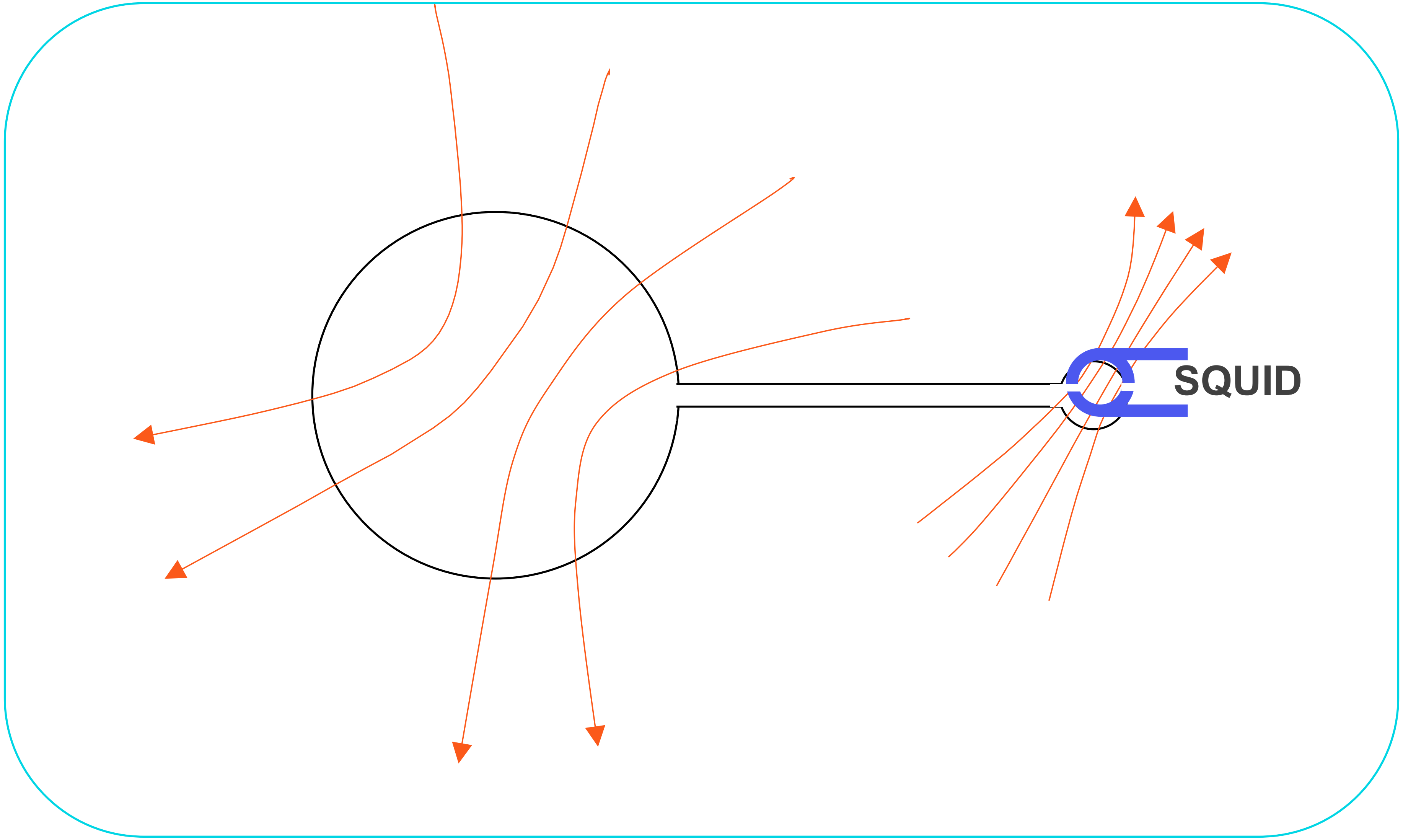
Practicalities of recording MEG: MEG sensors

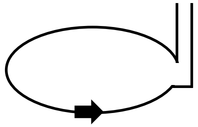


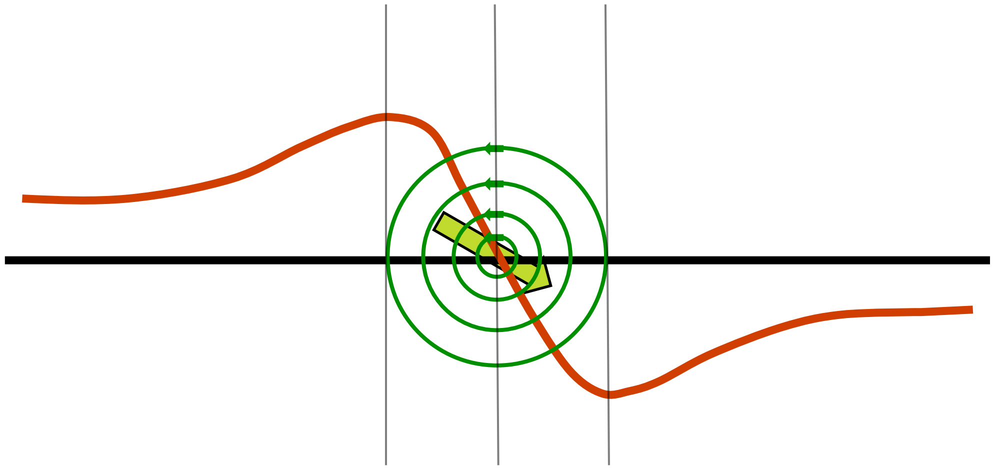
Practicalities of recording MEG: MEG sensors

- Sometimes magnetic material is accidentally brought close to the SQUID
- The SQUID gets a “flux trap” (MEG jargon!)
- Need to transiently heat the sensor above the critical temp by applying an electric heater pulse
- “Heating the sensor” is a super-common first step prior to MEG acquisition.

Magnetometers vs Gradiometers

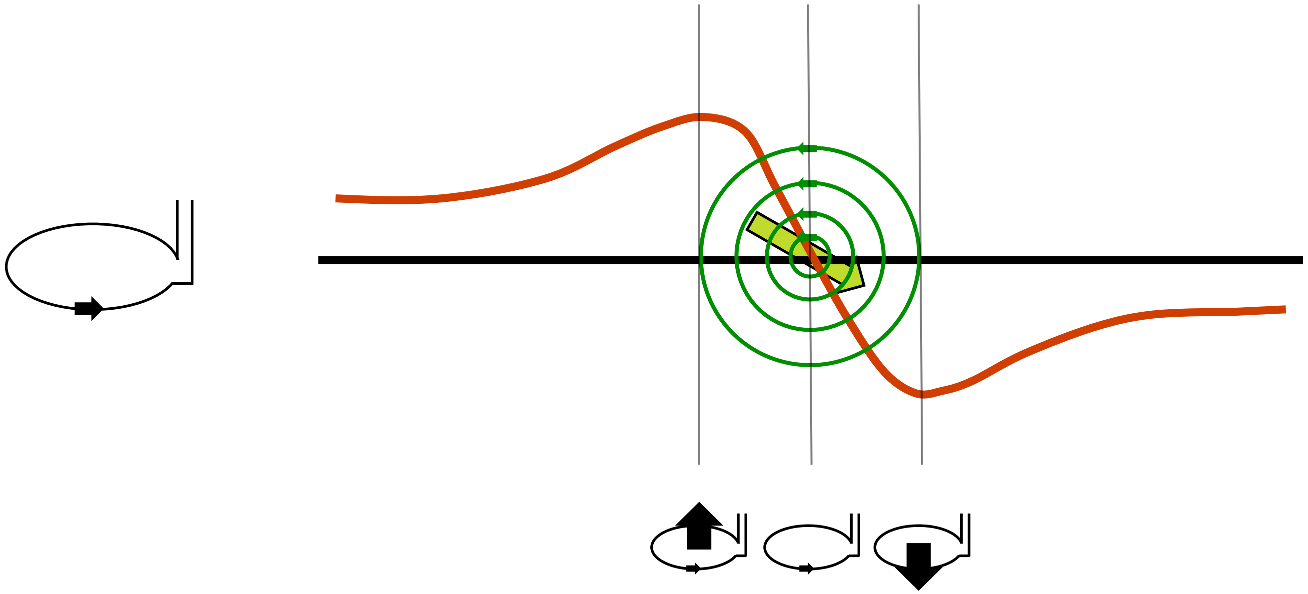
magnetometer



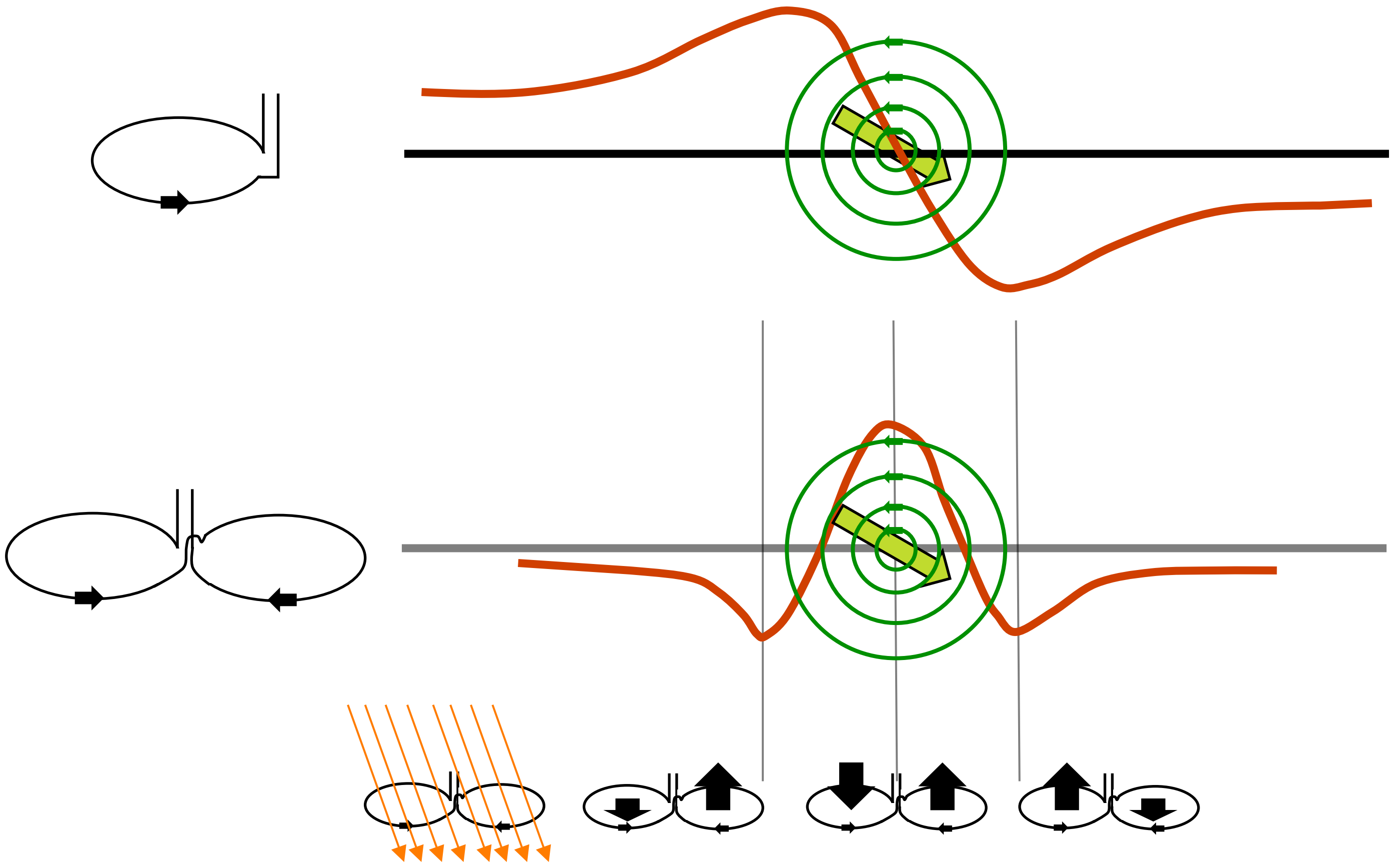


Magnetometers vs Gradiometers

magnetometer



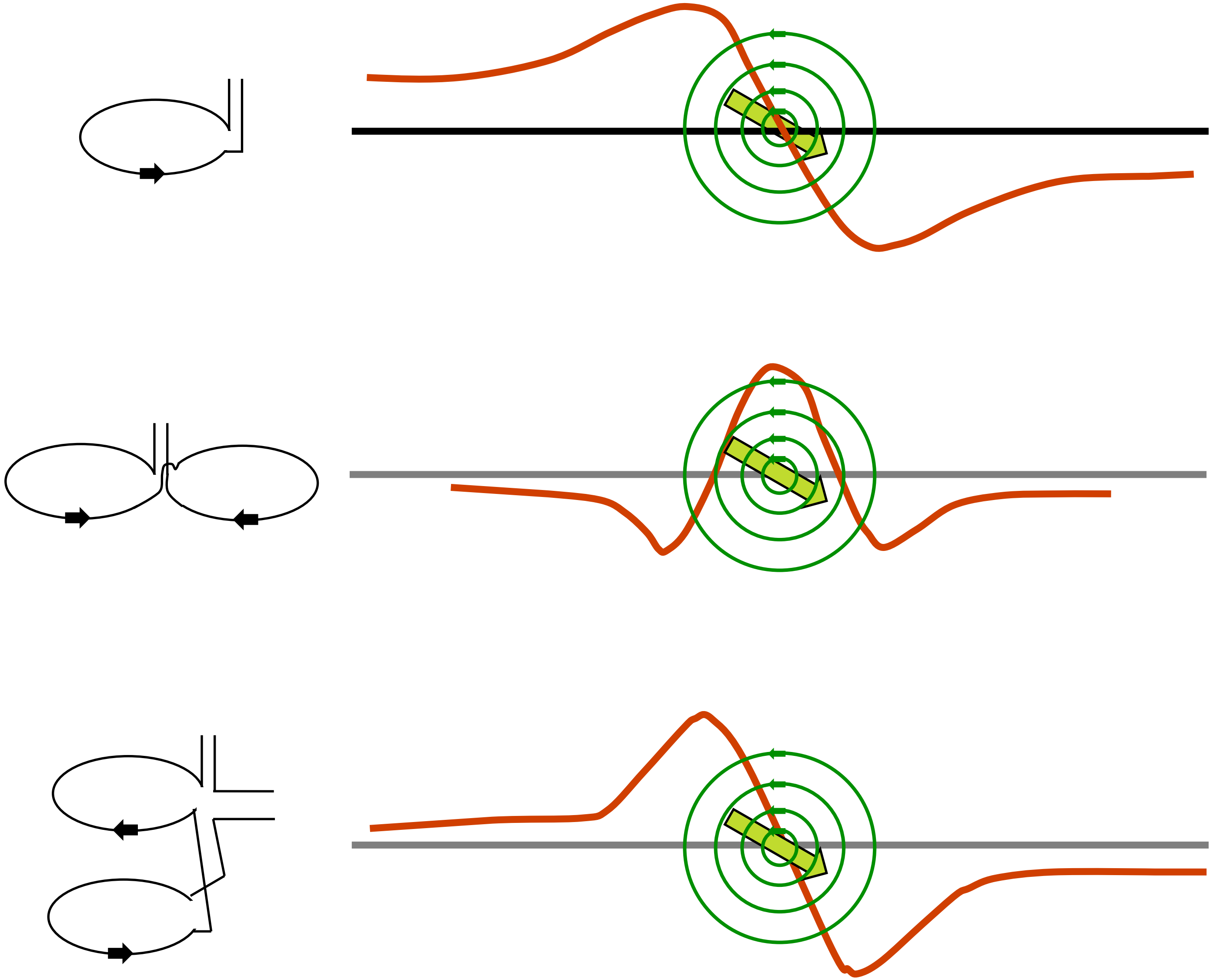
Magnetometers vs Gradiometers



magnetometer

planar
gradiometer

Magnetometers vs Gradiometers

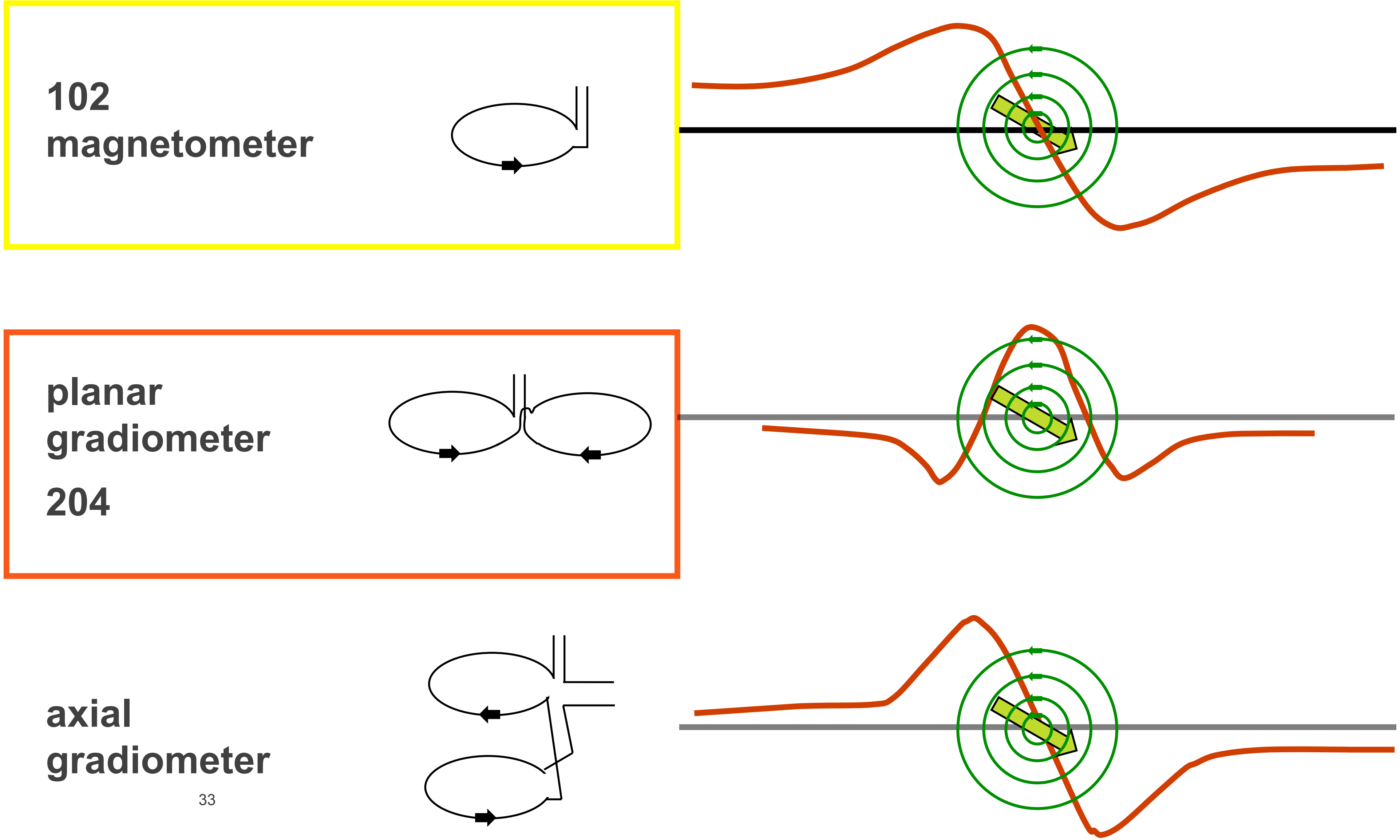


magnetometer

planar gradiometer

axial gradiometer

Neuromag MEG at Martinos Center: 306-ch system



102
magnetometer

planar
gradiometer
204

axial
gradiometer

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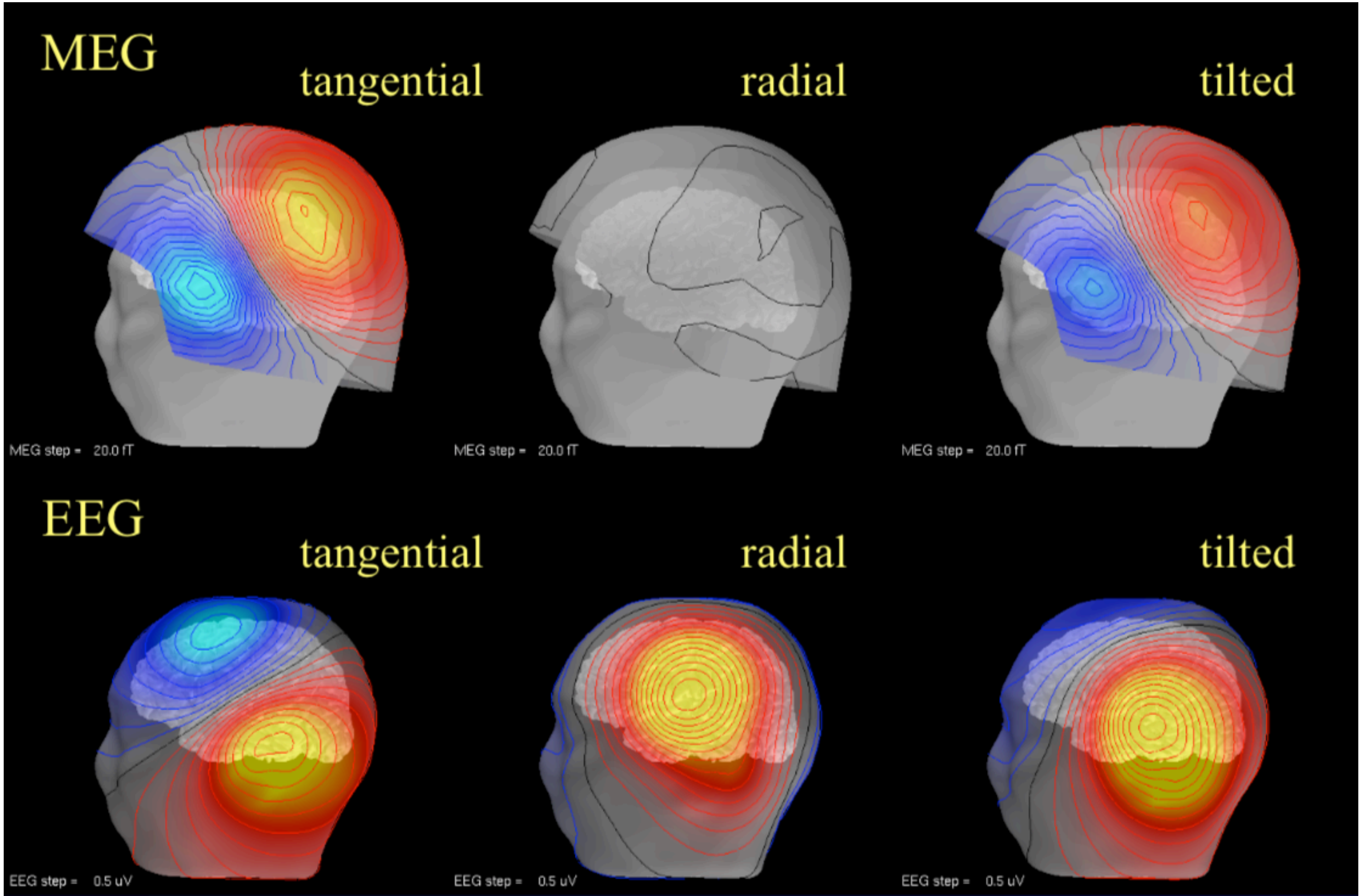
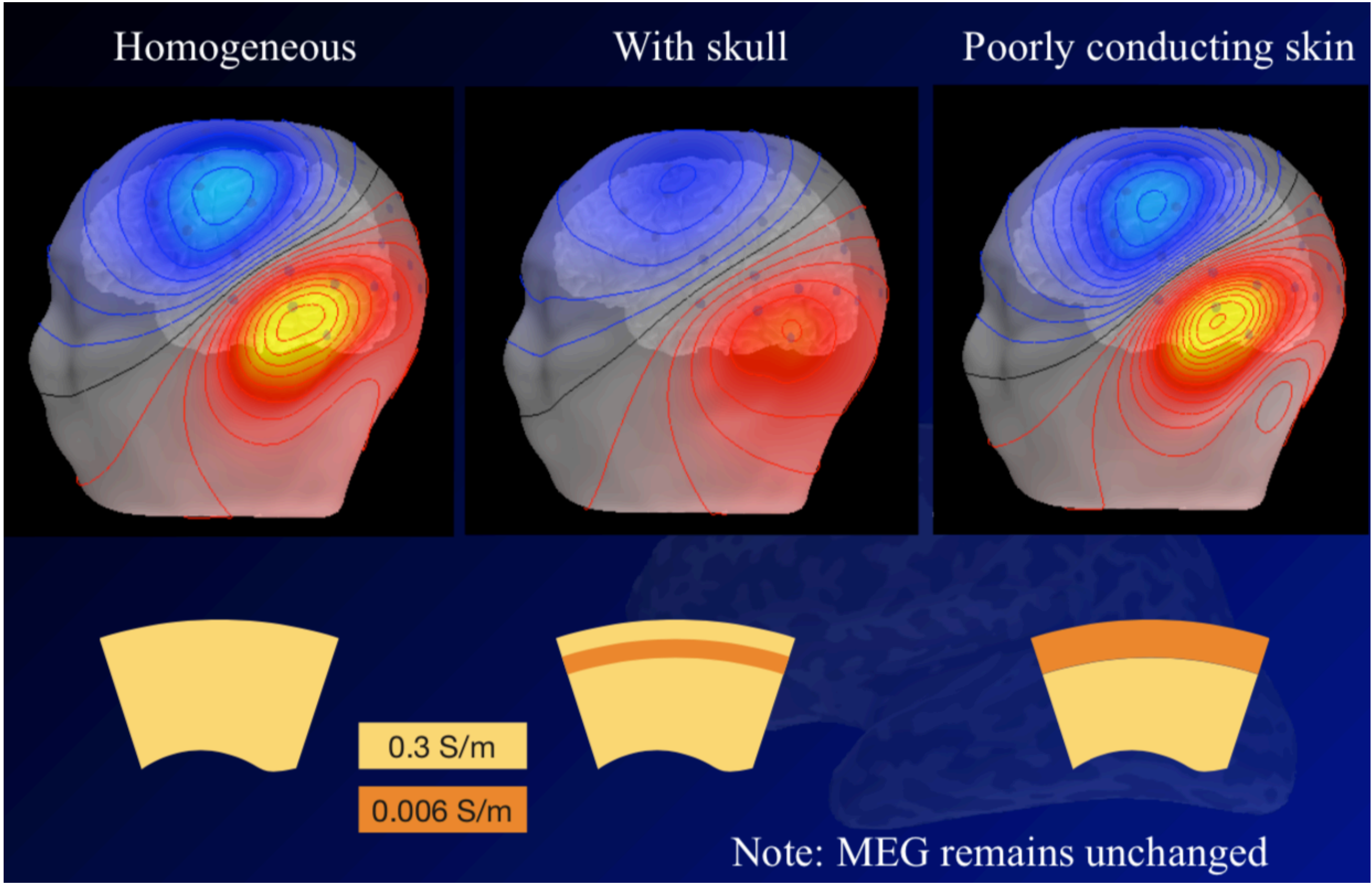
Tangential, Radial and Tilted sources



Slide courtesy M. Hamalainen

Effect of conductivities on EEG



Note: MEG remains unchanged

Slide courtesy

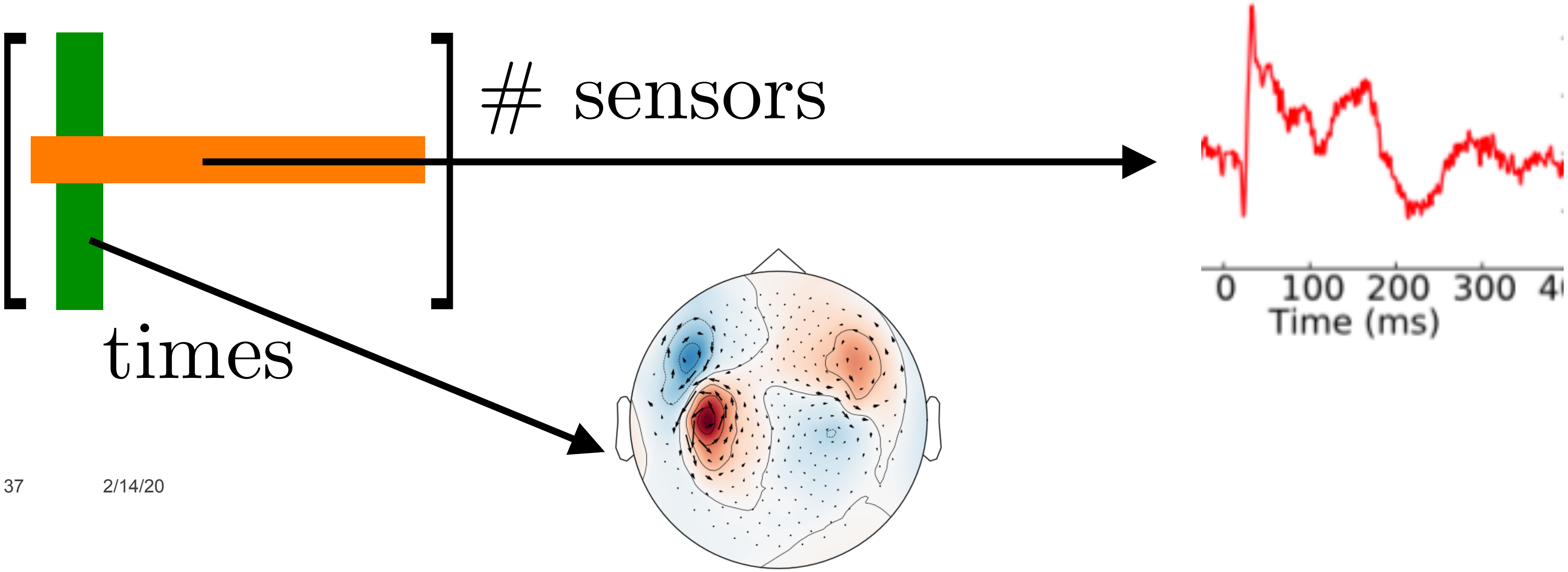
M. Hamalainen

4. Mininum norm source estimation from EEG and MEG measurements

Distributed source framework

$$M = GX + E$$

MEEG data (measurements)



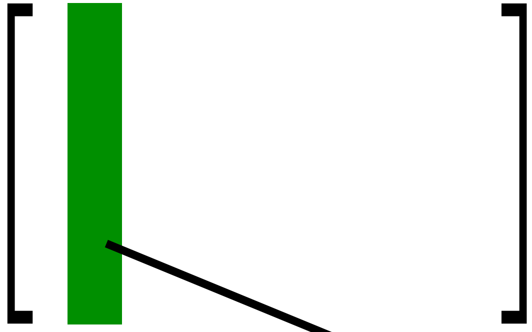
sensors

times

Distributed source framework

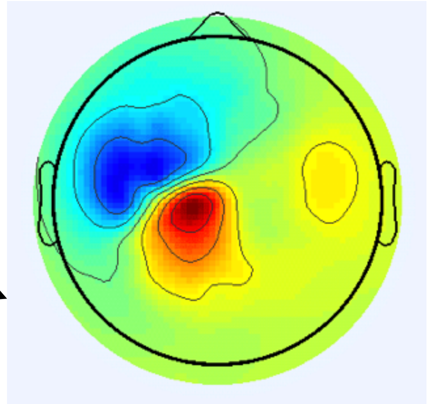
$$\mathrm{M} = \mathrm{G}\mathrm{X} + \mathrm{E}$$

Gain matrix (leadfield)



$\#$ sensors

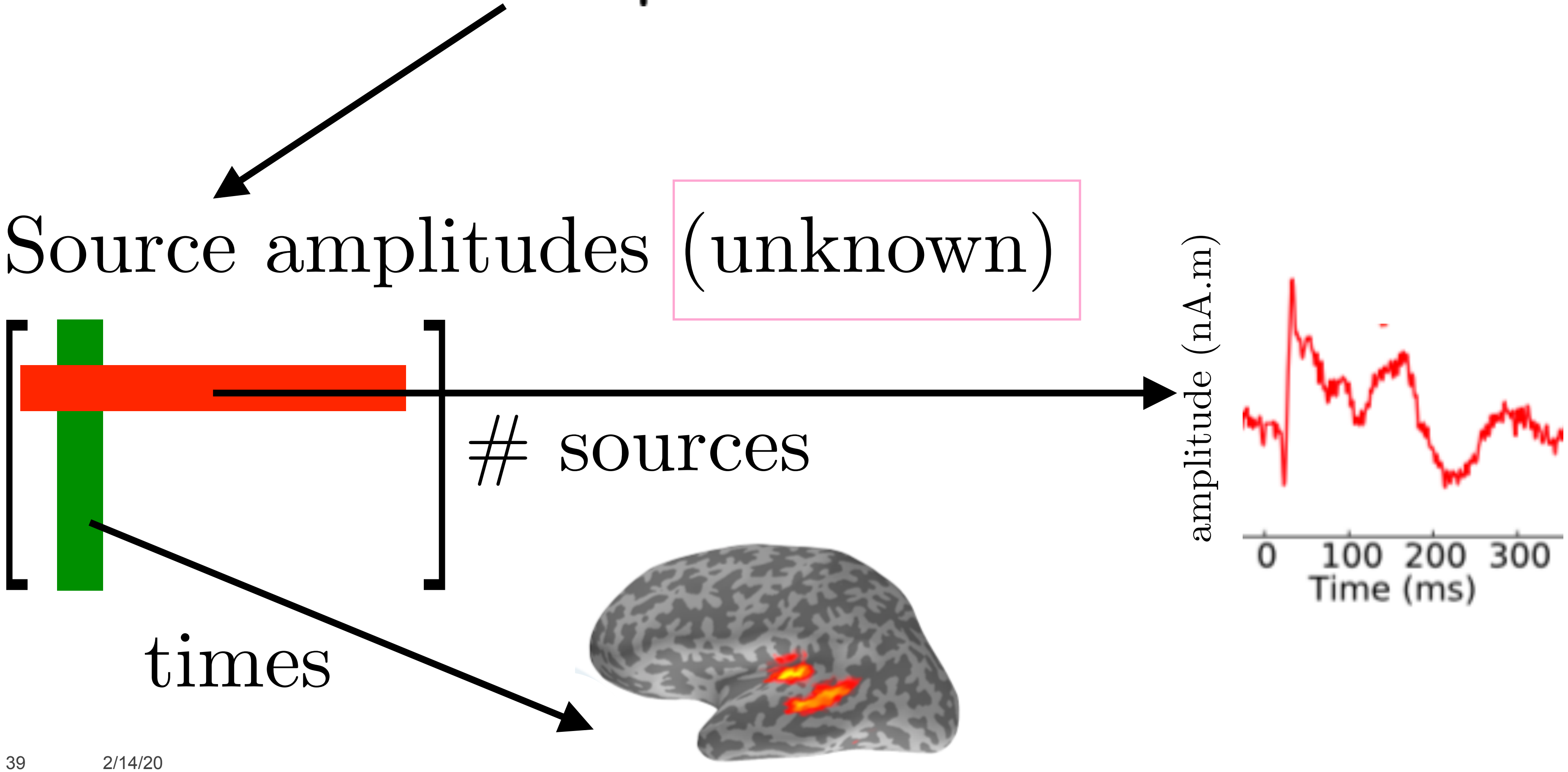
$\#$ sources



“forward” field for a single dipole

Distributed source framework

$$\mathrm{M} = \mathrm{G}\mathrm{X} + \mathrm{E}$$



Source amplitudes (unknown)

sources

times

Distributed source framework

$$\mathrm{M} = \mathrm{G}\mathrm{X} + \mathrm{E}$$

$$noise$$

$$\begin{array}{cc} \left[\begin{array}{ccc} \quad & \quad & \quad \\ & & \\ & & \end{array} \right] & \#\ \text{sensors} \\ \text{times} & \end{array}$$

Minimum Norm Solution

- We have a grid of dipoles on the surface or in a volume
- Underdetermined problem! $\boxed{n_{sources} > n_{measurements}}$
- Need to find an optimal solution given the data
- Find the current distribution with the smallest overall amplitude that can explain the measurements (in the L2 norm sense)

$$\mathrm{M} = \mathrm{GX} + \mathrm{E}$$

$$X^* = \arg\min ||M - GX||^2 + \lambda ||X||^2$$

Hamalainen et al 1994

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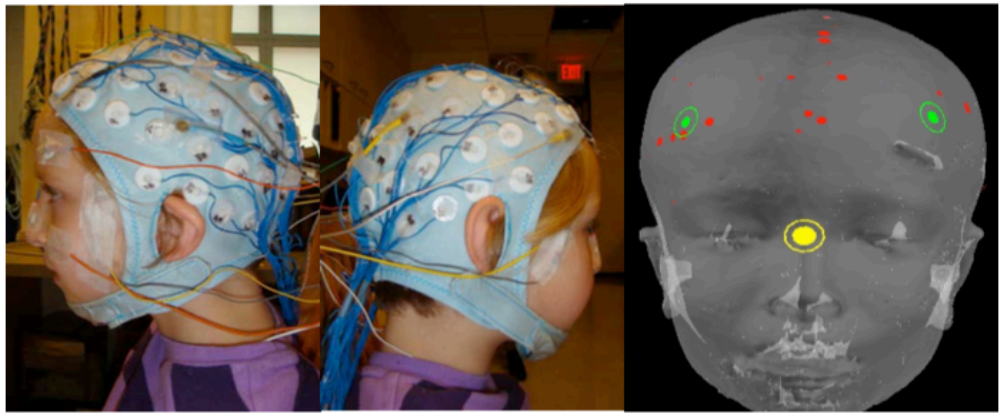
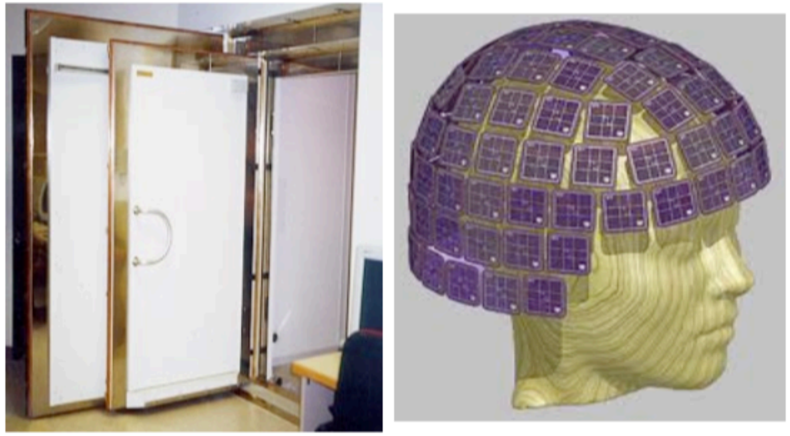
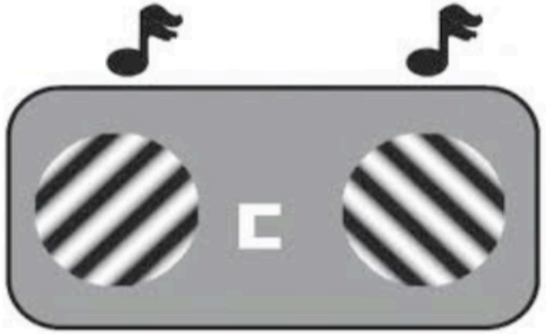
4. Processing EEG and MEG data

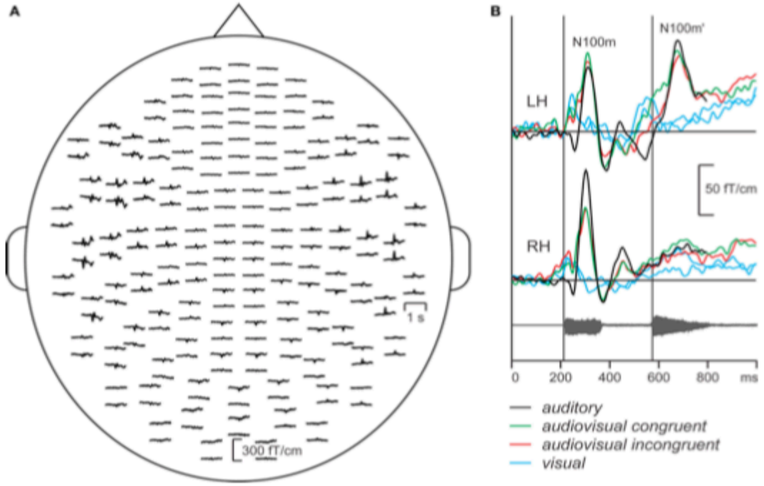
Basic MEEG Acquisition



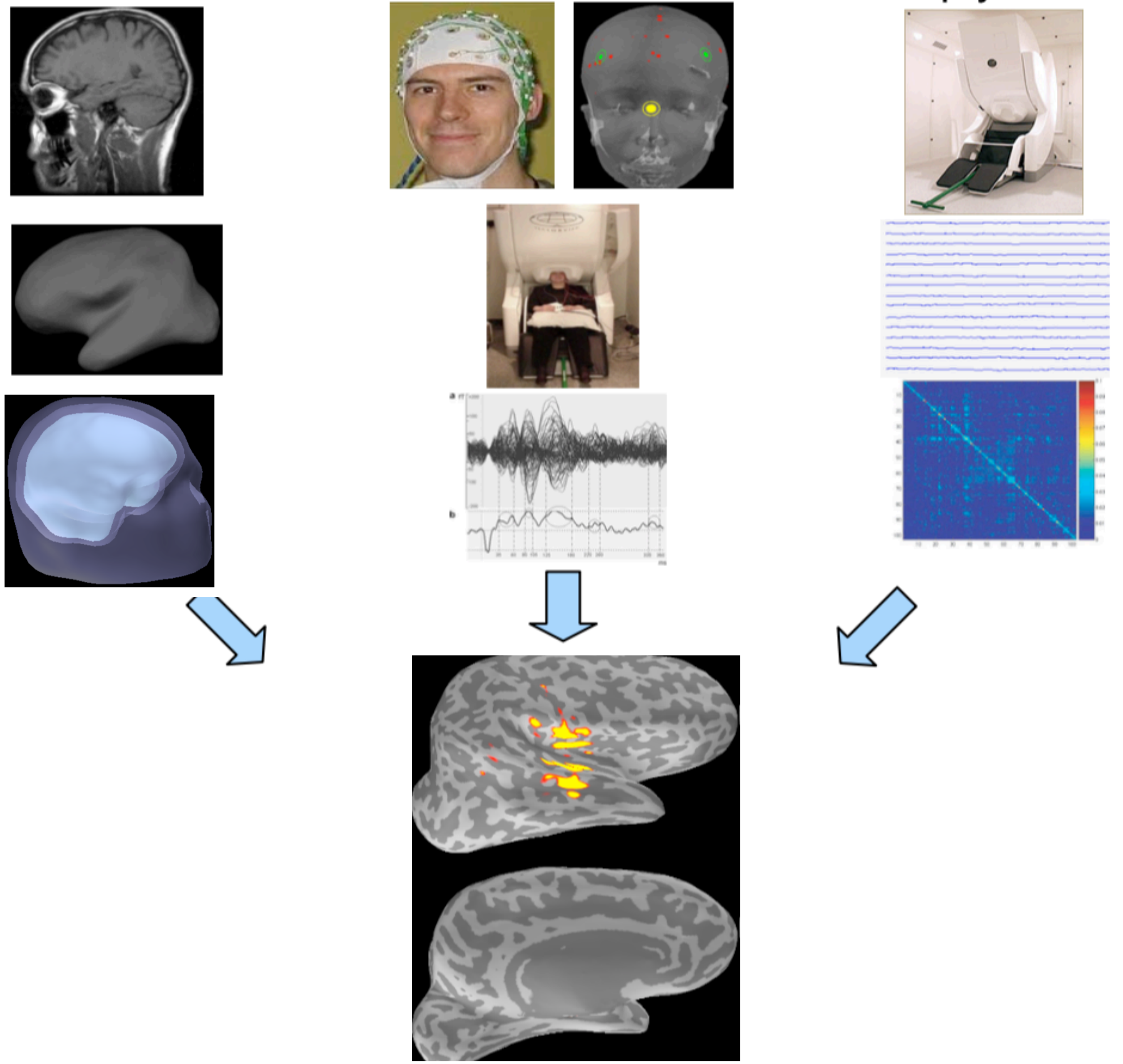


Brain Response





Pipeline



MRI

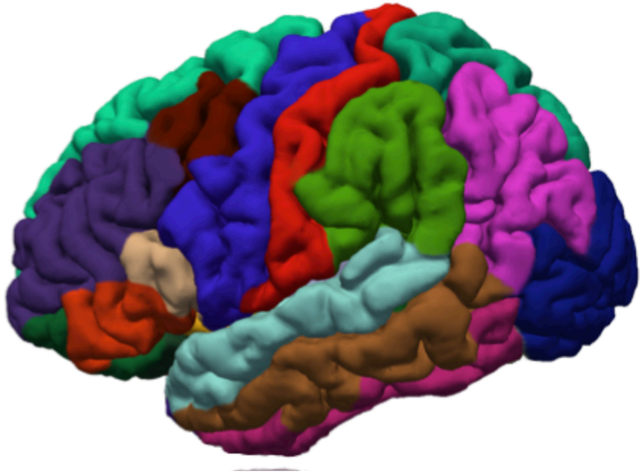
MEEG

Empty Room

Software packages

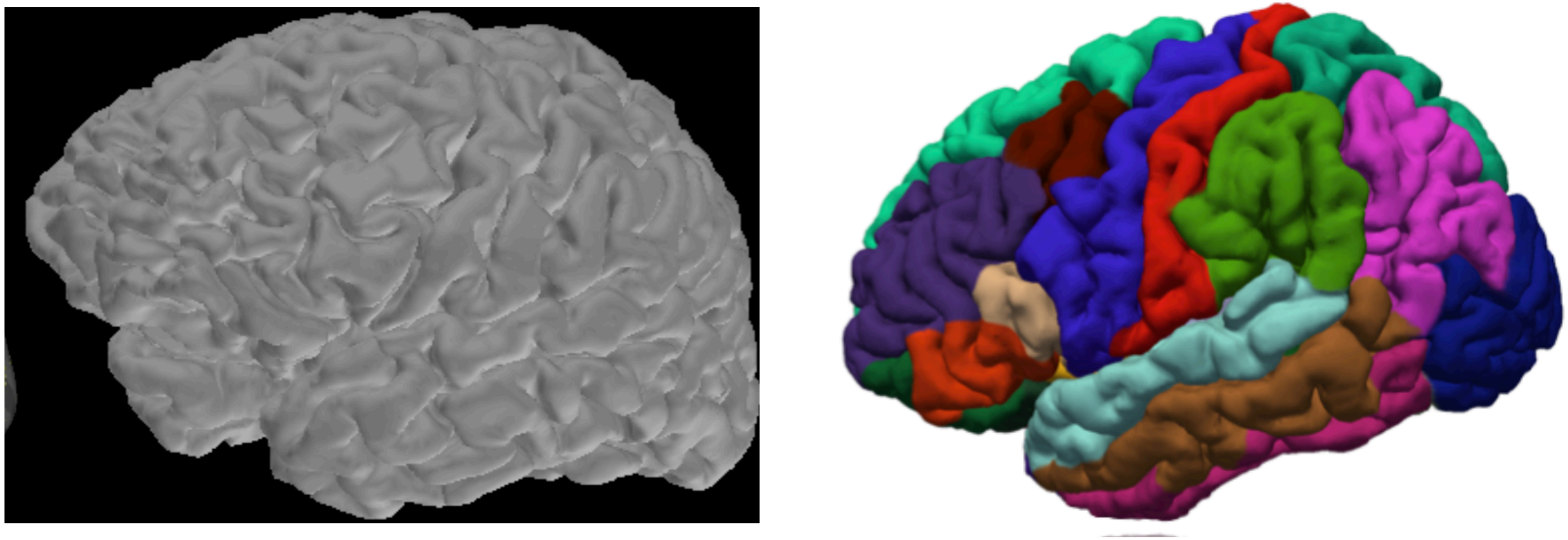
- Freesurfer: https://surfer.nmr.mgh.harvard.edu
- MNE-Python: https://mne.tools/stable/index.html
- MNE-C
- MNE-MATLAB
- EEGLab
- FieldTrip

MNE
MEG + EEG ANALYSIS & VISUALIZATION



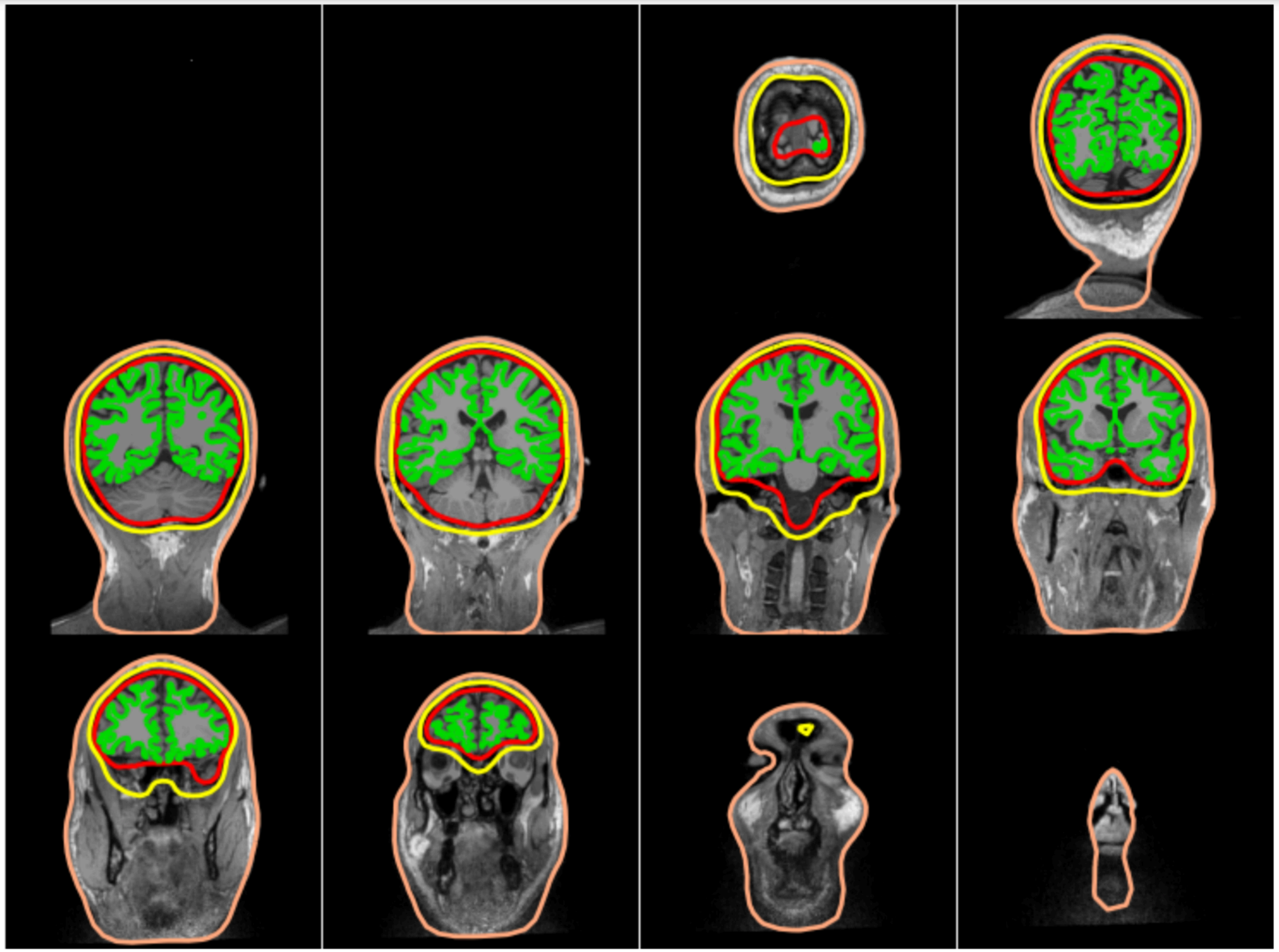
MRI Preprocessing

- Run Freesurfer `recon-all`
- White matter, gray matter, inflated surfaces

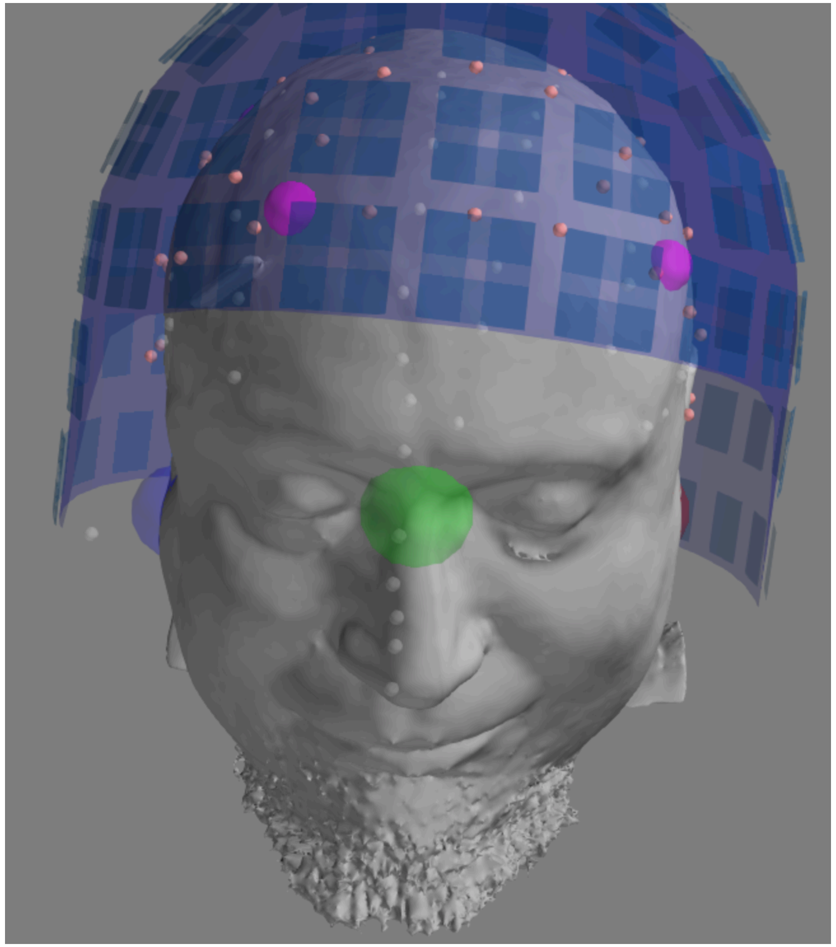


Make the boundary-element model (BEM)

- BEM surfaces: triangulations of the interfaces between the different tissues
- Head geometry, conductivities
- Independent of MEG data/head pos
- Needed for forward computation
- Use command line tools:
    - `mne_watershed_bem`
    - `mne_flash_bem`
- Or use `mne` Python:
    - `mne.bem.make_watershed_bem`
    - `mne.bem.make_flash_bem`
    - `mne.viz.plot_bem`



Co-Register the MRI head model to the head position recorded during the MEG



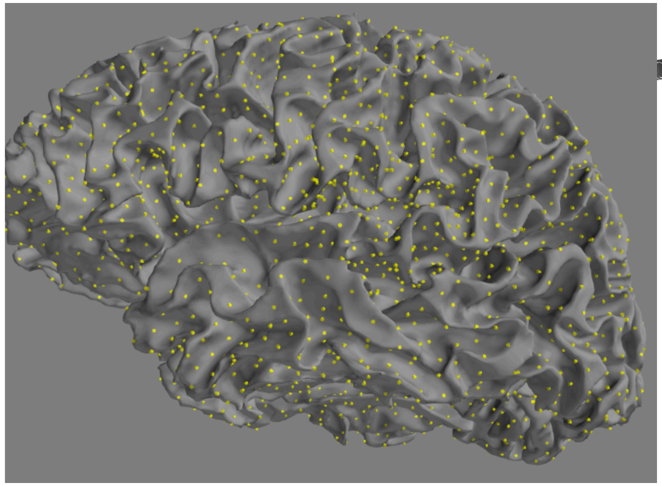
- `Mne` python: `mne.gui.coregistration` or
- Command line: `mne coreg`
- `mne_analyze`

- This will position the head and the MEEG sensors in a common coordinate system
- `“-trans.fif” file`
  (coordinate transformation)

Compute the Source Space

- Define the position and orientation of the candidate source locations
- Surface-based source space
  candidate dipoles are confined to a surface
  `mne.setup_source_space`
- Volume source space
  `mne.setup_volume_source_space`

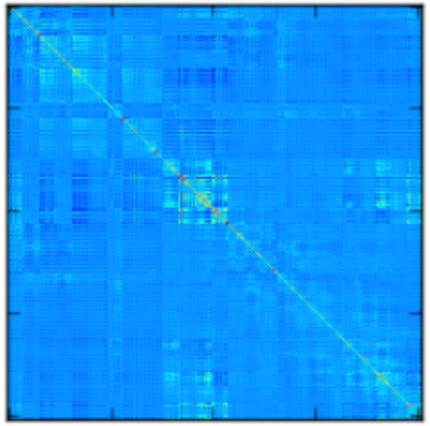
Surface Source Space



Volume Source Space

Compute the forward operator and the noise cov

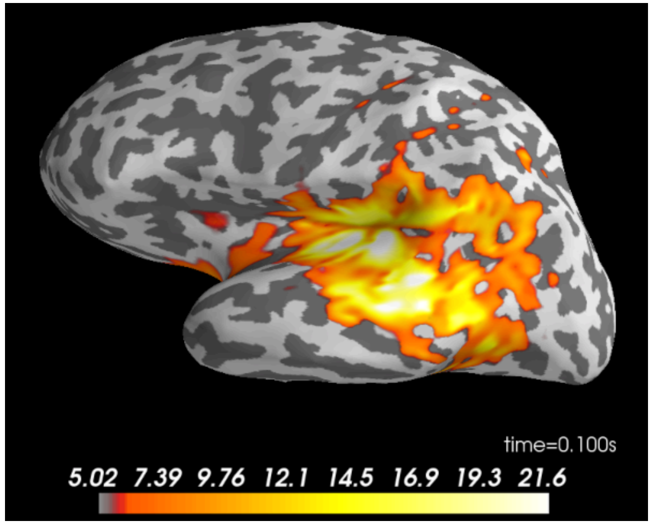
- Also called the gain matrix or the leadfield matrix
- **`mne.make_forward_solution`**
- Noise covariance matrix can be obtained either from the empty room or from the baseline period of the data
- **`mne.compute_raw_covariance`**
- **`mne.compute_covariance`**
- Should I regularize the noise covariance matrix?
  The estimated covariance might be unstable and induce correlations between the estimates

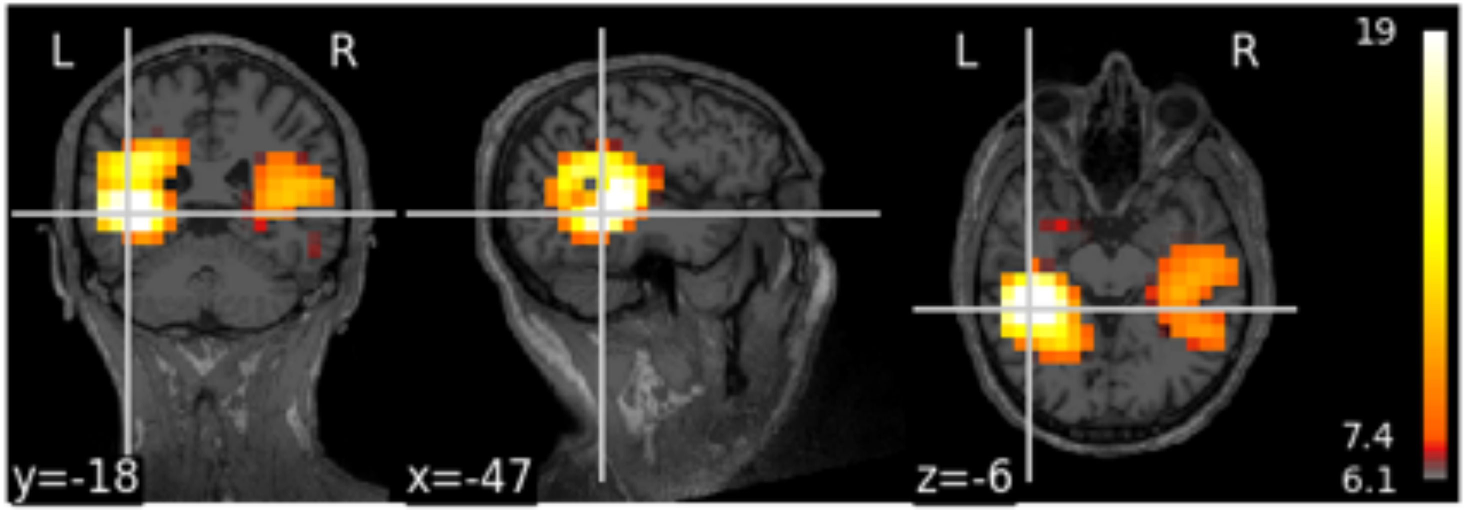


- **`mne.minimum_norm.inverse_operator`**

Compute inverse solution

- Apply the inverse operator to the MEEG data
- **`mne.minimum_norm.apply_inverse`**
- Returns a source estimate (either a surface source estimate or a volume source estimate)





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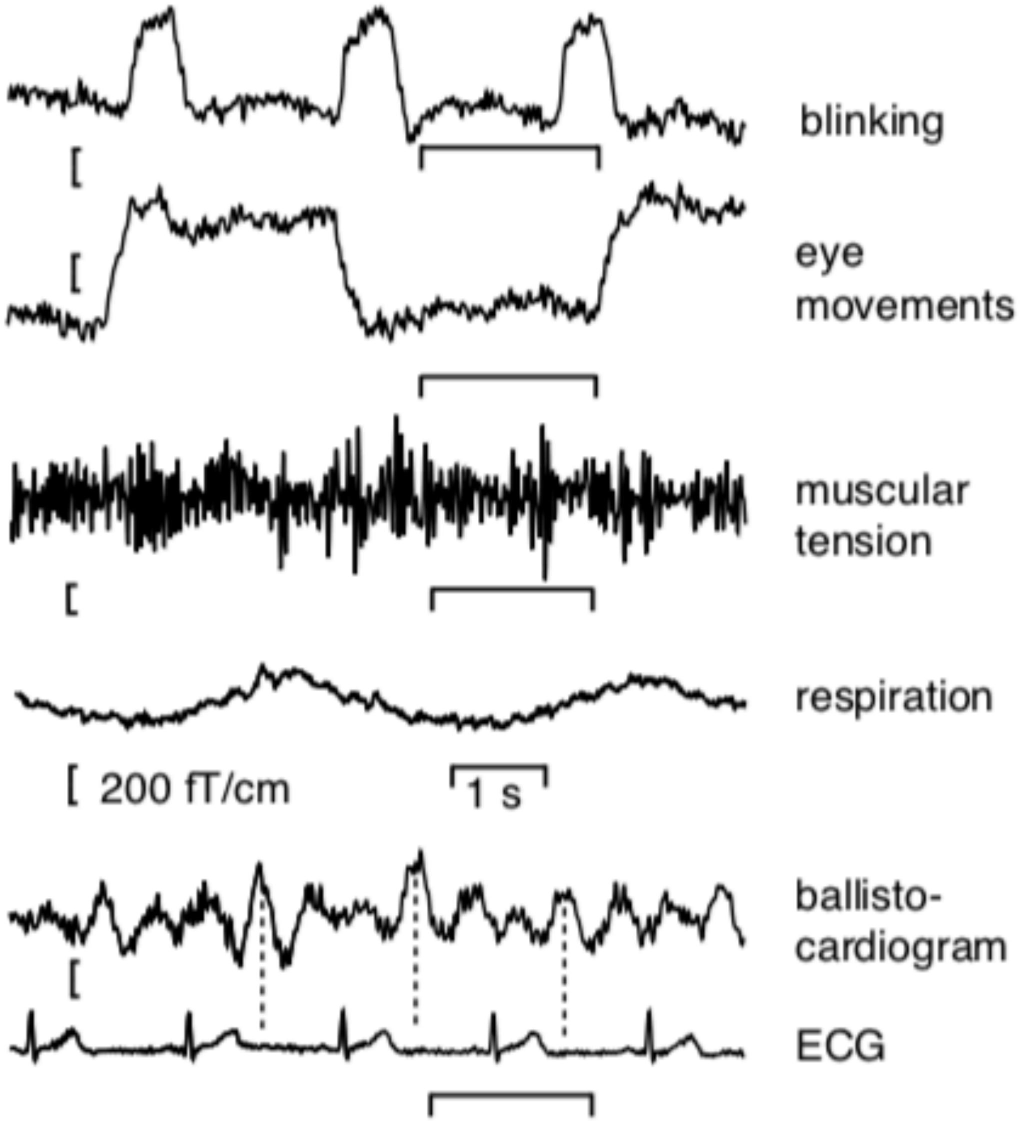
Artifacts



Artifact Removal Methods

- Signal Space Projection (SSP)
- Independent Component Analysis (ICA)
- Don’t forget that ICA assumes that the sources are statistically independent
  Only independence is at work

4. What can I see with MEEG?

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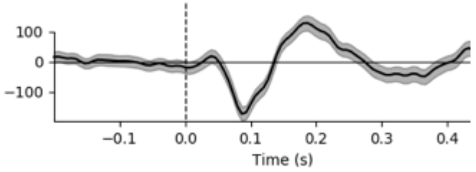
TIME

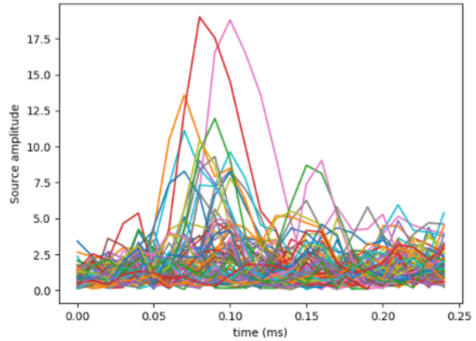
Time (Good temporal resolution!)

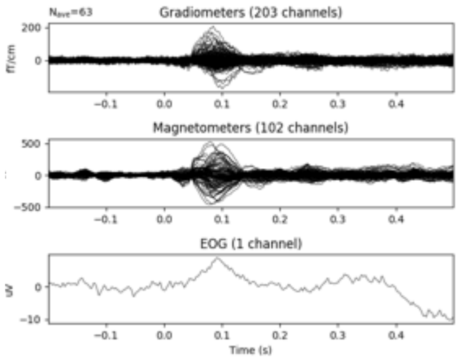
Event Related Potentials and Fields

Epoched Data

Source Estimates



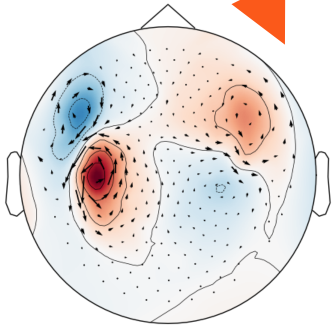


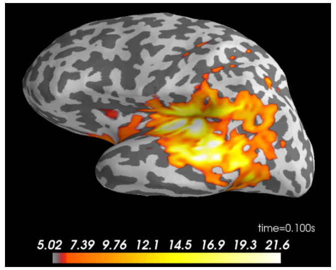


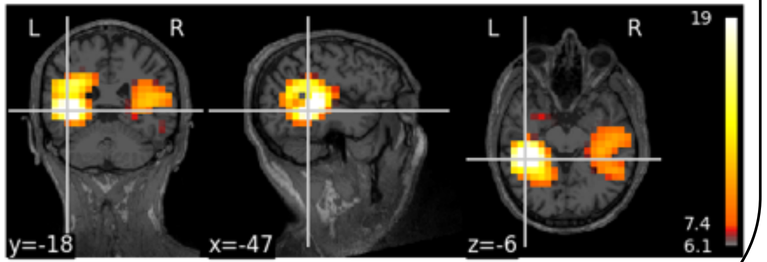
SPACE

Source space

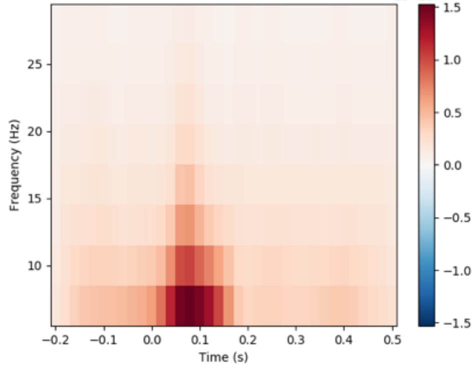
Sensor space



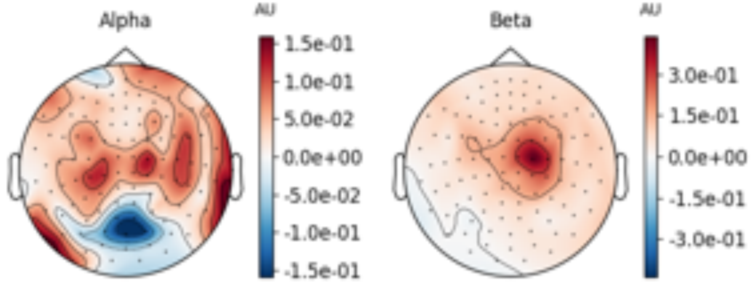




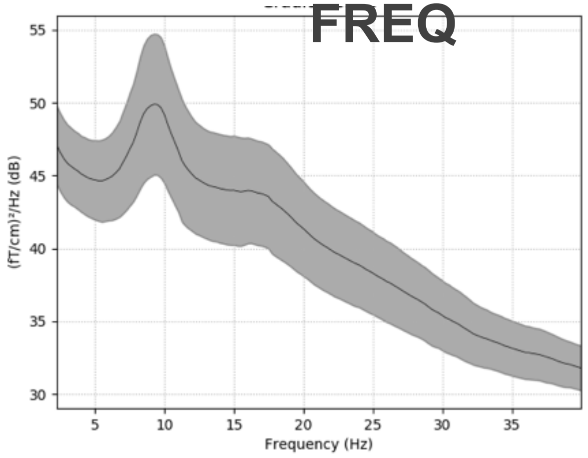
TIME + FREQ



SPACE + FREQ



FREQ



To Summarize

- EEG detects electric fields due to neuronal activity, MEG detects the corresponding magnetic field
- They are sensitive to differently oriented sources (MEG – tangential dipoles, EEG – both radial and tangential)
- Goal of the neuromagnetic inverse problem is to estimate the current source density underlying the measured MEEG data
- Current density in the cortex is approximately a constant: 1 nA.m/mm2 (Murakami & Okada 2016)
- (Helmholtz 1953): Even if you know the magnetic/electric potential precisely everywhere outside the head, you cannot recover the primary current distribution uniquely
- Prerequisite for most localization studies is the solution of the forward problem
- There are ambiguities in the solution of the inverse problem – the results depend crucially on the assumptions of the source modeling
- Size of the activated region in the source images need not related to the actual dimensions of the source but rather reflects an intrinsic limitation of the imaging method.
- <u>“Different source estimation methods give converging evidence when interpreted correctly” – M. Hamalainen</u>

THANK YOU!