Introduction to EEG and MEG source modelling

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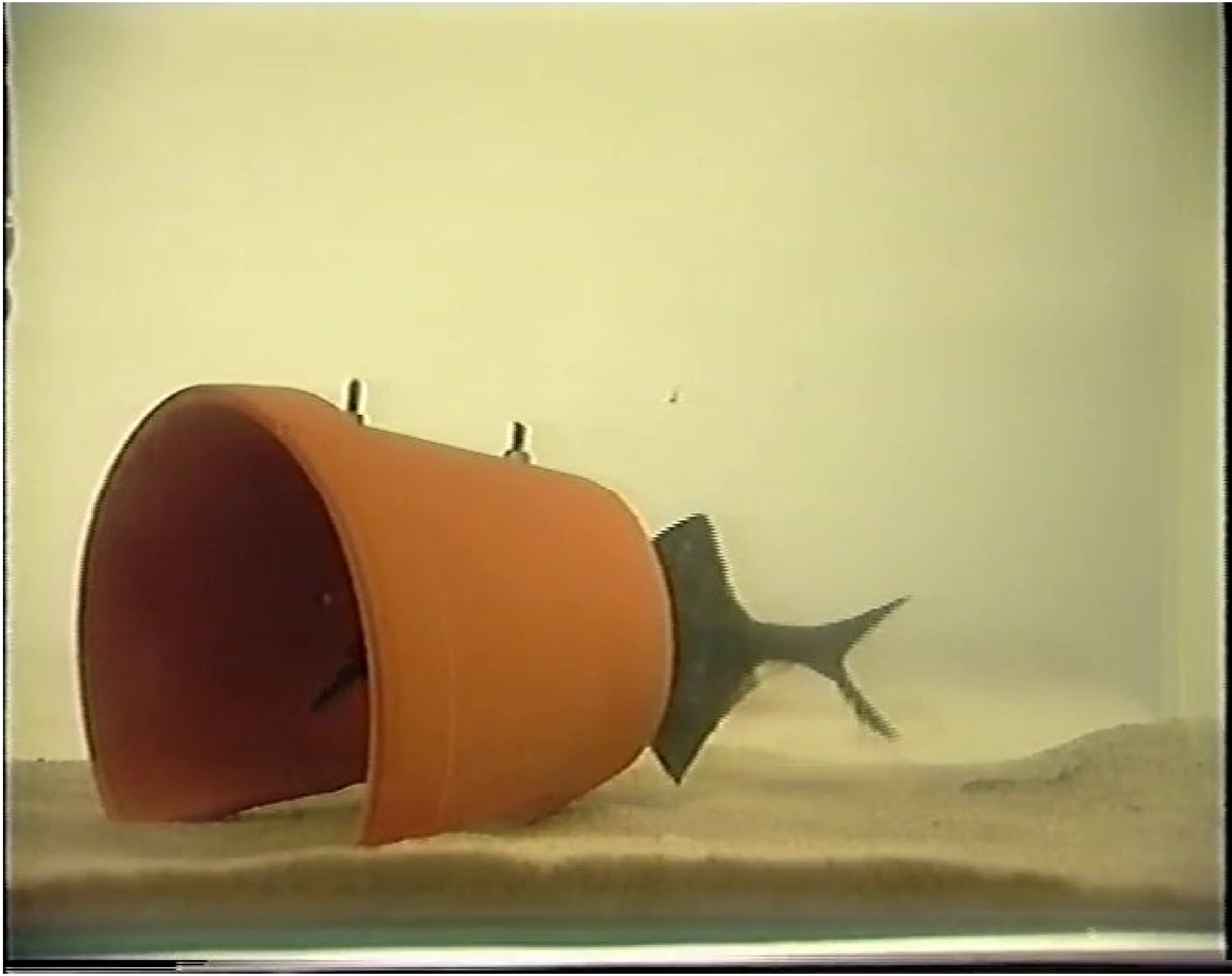
Outline

- Motivation
- Source and volume conduction models
  - using anatomical information
  - aligning sensors with anatomy
- Source reconstruction
  - equivalent dipole fitting
  - distributed models
  - scanning methods
- Summary



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Source and volume conduction models

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Summary

Motivation 1

Strong points of EEG and MEG

- Temporal resolution (~1 ms)
- Characterize individual components of ERP
- Oscillatory activity
- Disentangle dynamics of cortical networks

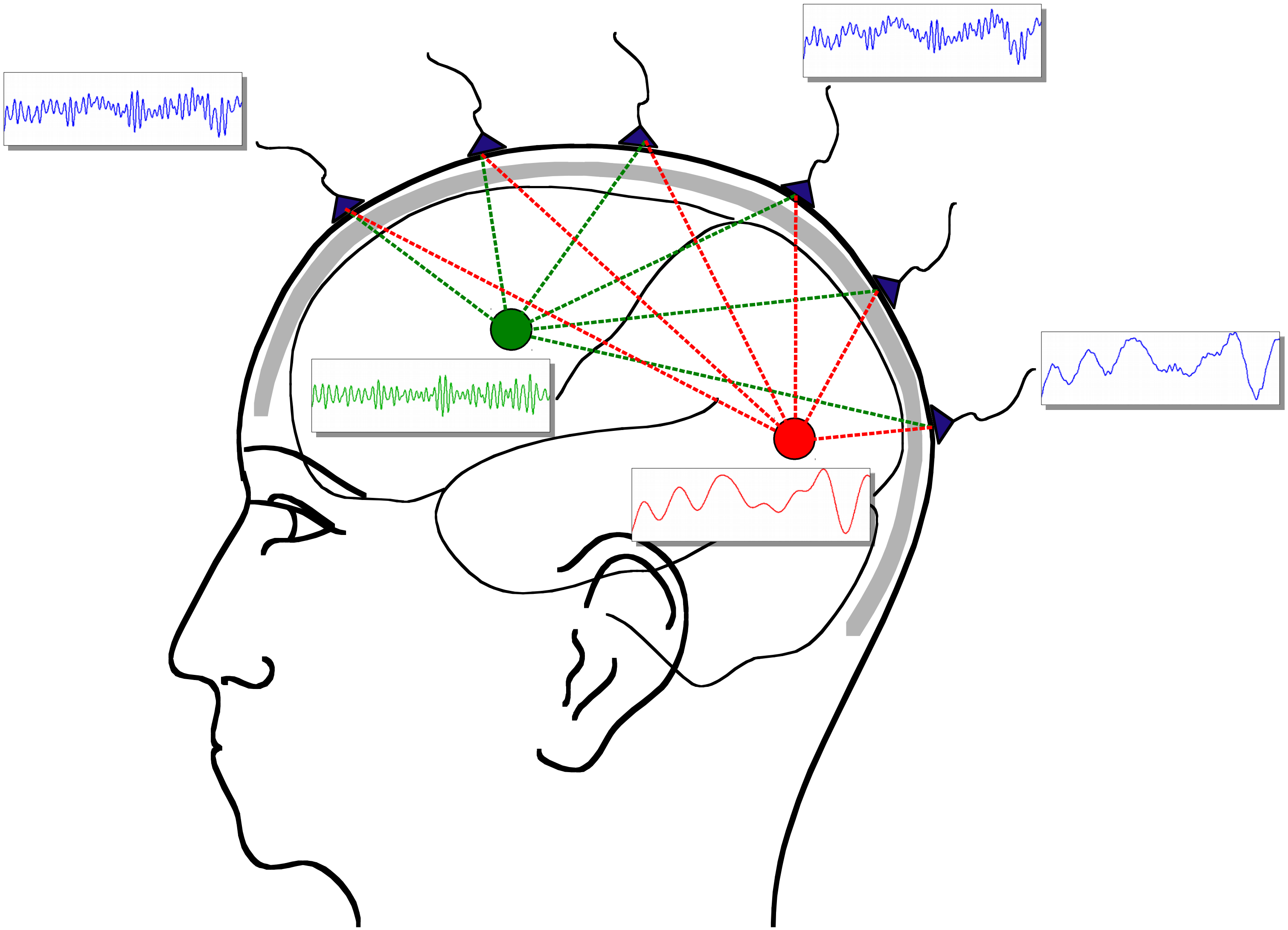
Weak points of EEG and MEG

- Measurement on outside of brain
- Overlap of components
- Low spatial resolution

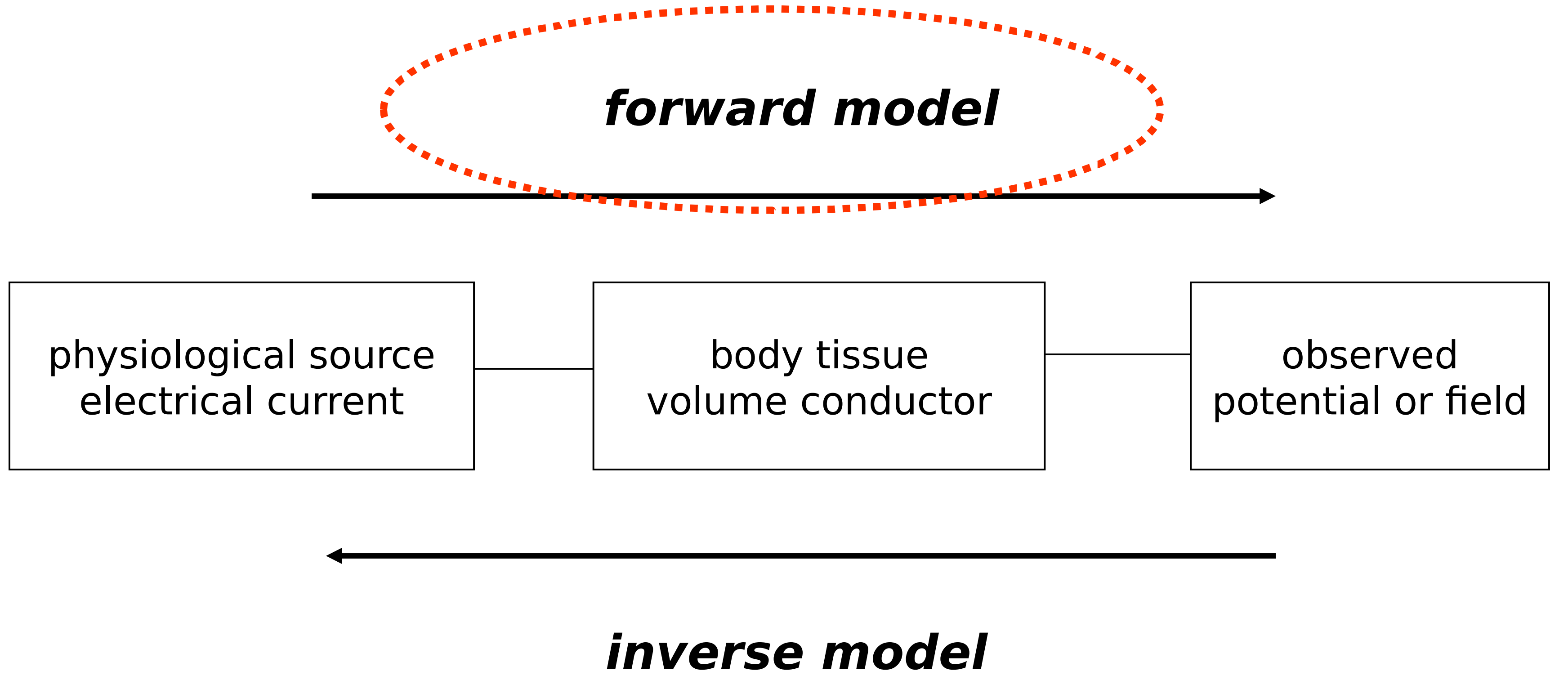
Motivation 2

- If you find a ERP/ERF component, you want to characterize it in physiological terms
  - Time or frequency are the “natural” characteristics
  - “Location” requires interpretation of the scalp topography
- Forward and inverse modelling helps to interpret the topography
- Forward and inverse modelling helps to disentangle overlapping source timeseries

Superposition of source activity



Biophysical source modelling: overview



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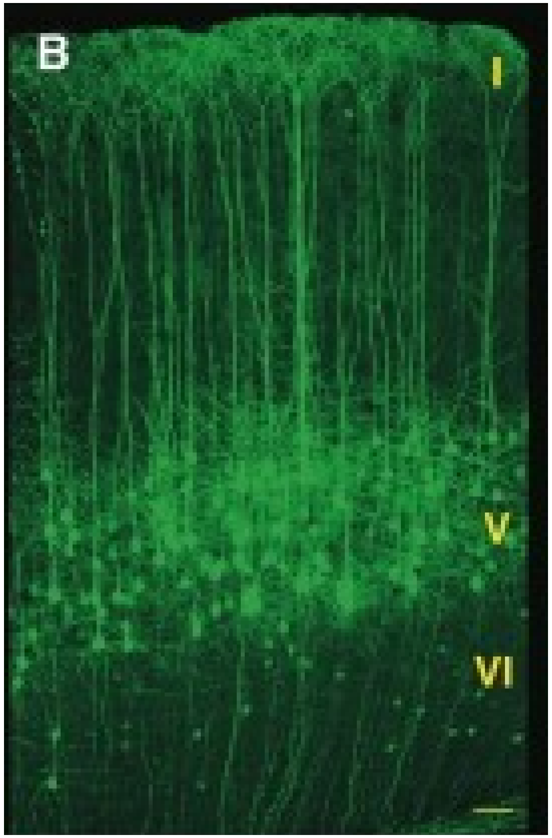
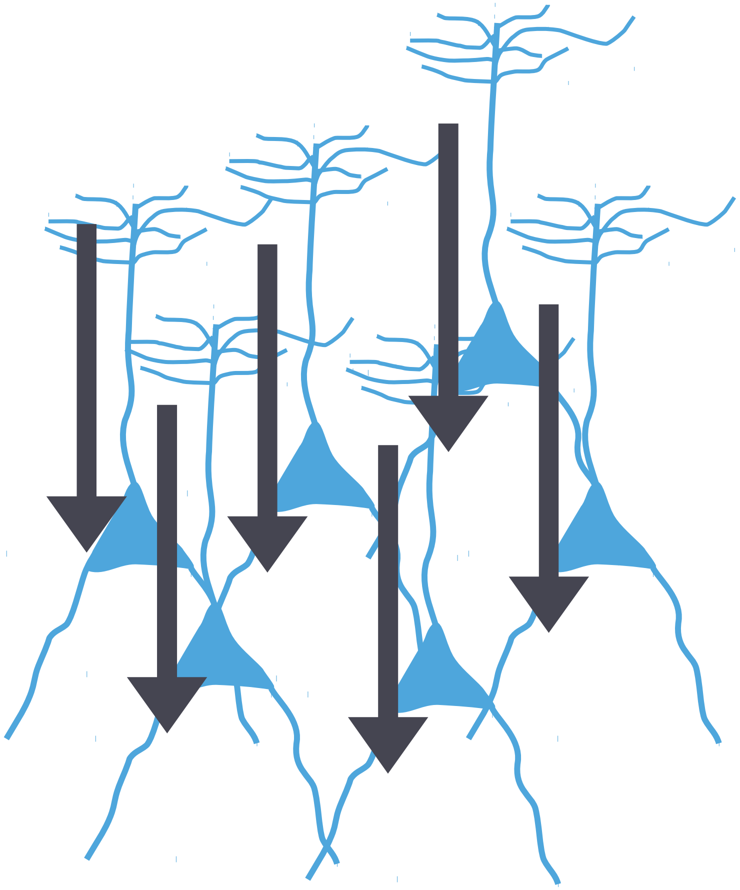
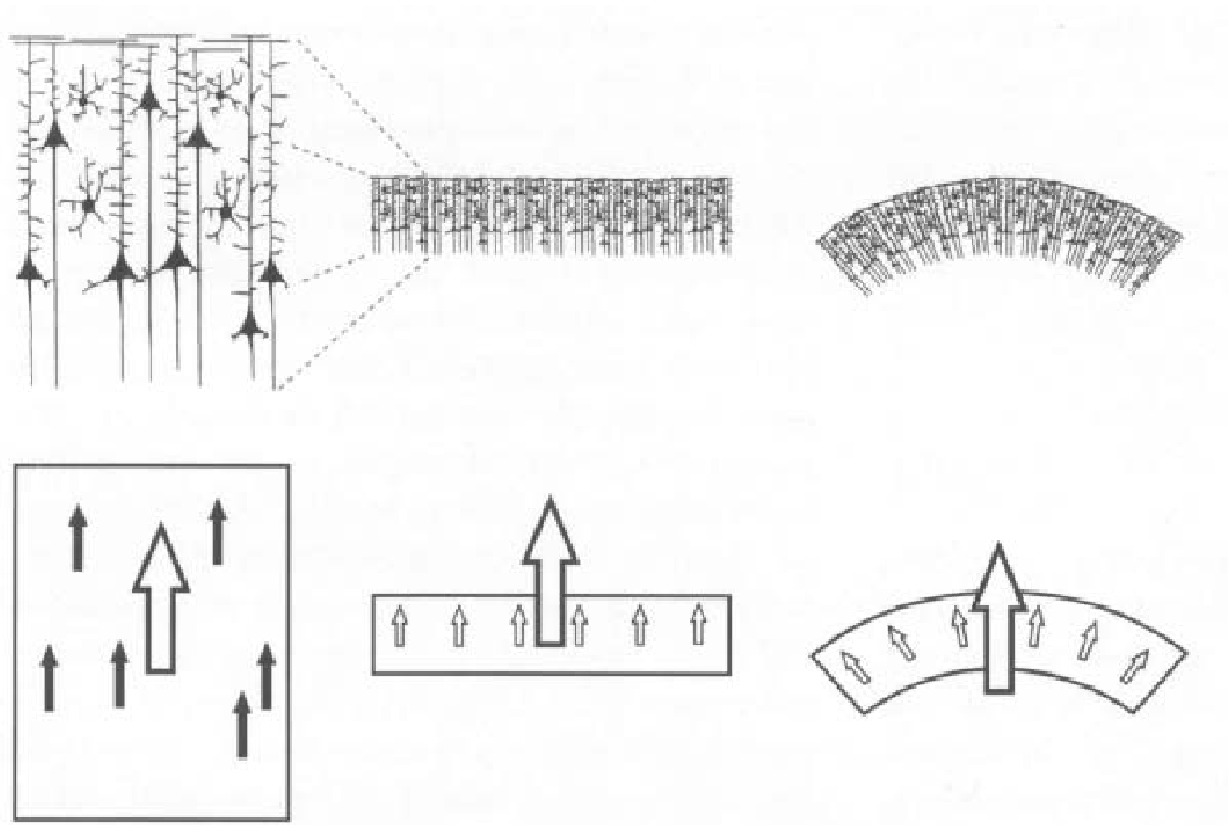
What produces the electric current





Equivalent current dipoles



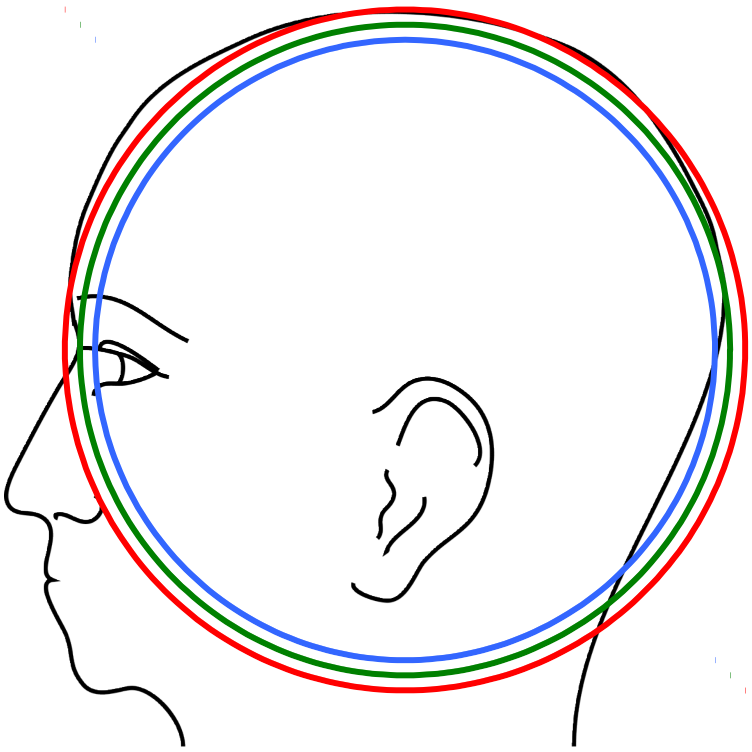
Volume conductor

described electrical properties of tissue

describes geometrical model of the head

describes **how** the currents flow, not where they originate from

same volume conductor for EEG as for MEG, but also for tDCS, tACS, TMS, …



Volume conductor

Computational methods for volume conduction problem that allow for realistic geometries

BEM *Boundary Element Method*

FEM *Finite Element Method*

FDM *Finite Difference Method*

Volume conductor: Boundary Element Method

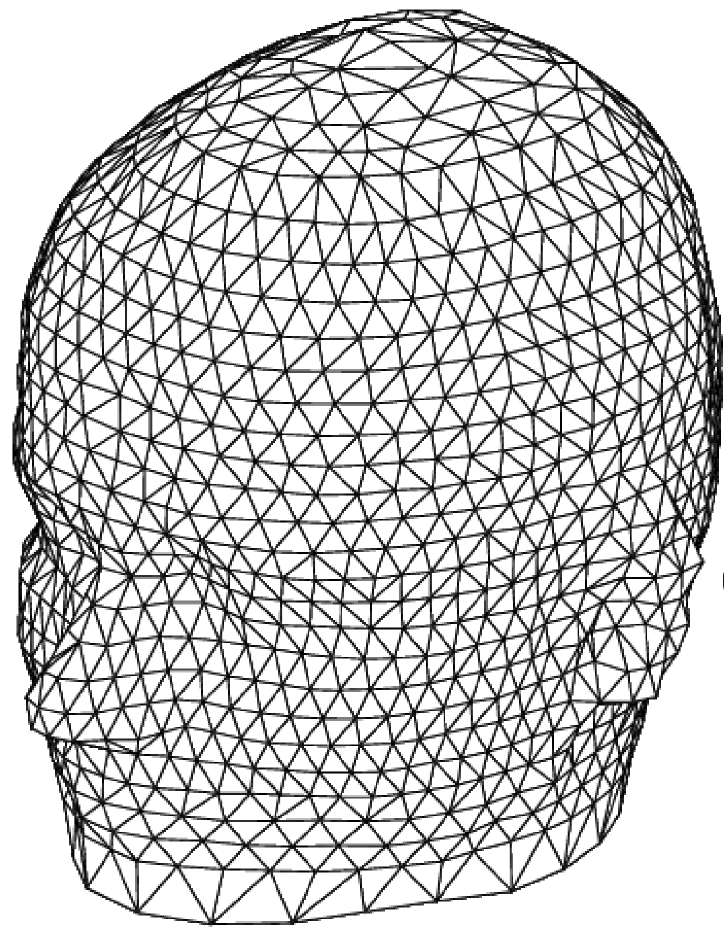
Each compartment is

- homogenous
- isotropic

Important tissues

- skin
- skull
- brain
- (CSF)

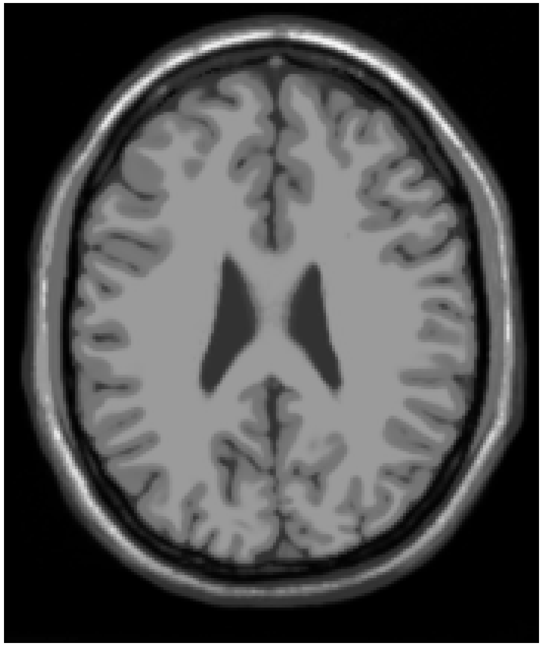
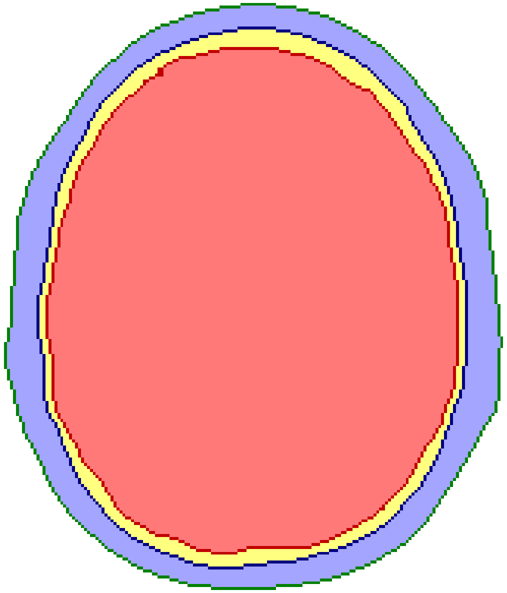
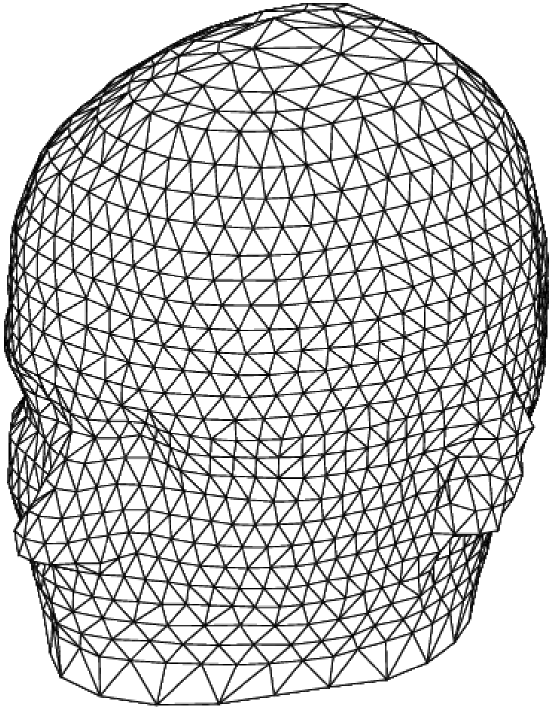
Triangulated surfaces describe boundaries



Volume conductor: Boundary Element Method

Construction of geometry

- segmentation in different tissue types
- extract surface description
- downsample to reasonable number of triangles

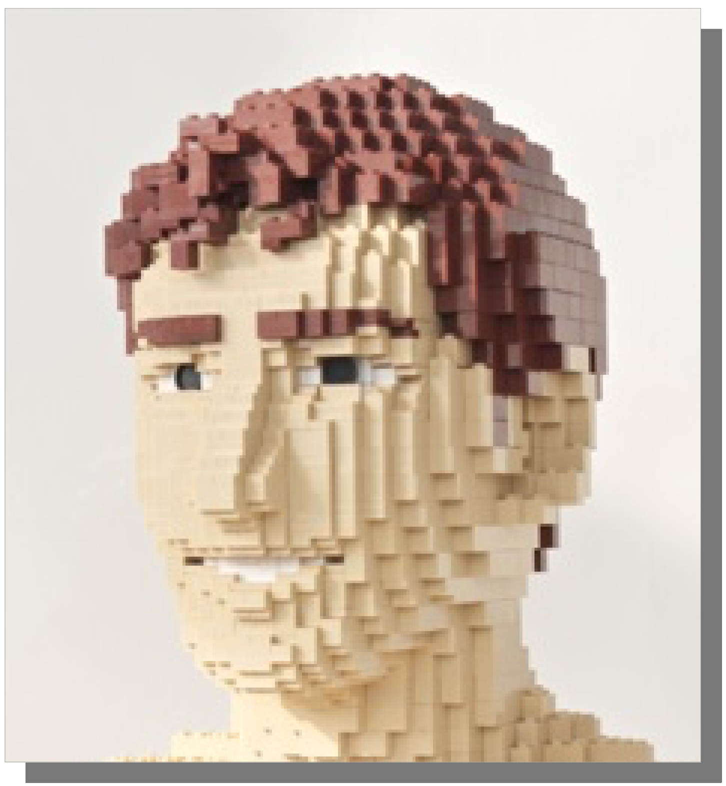




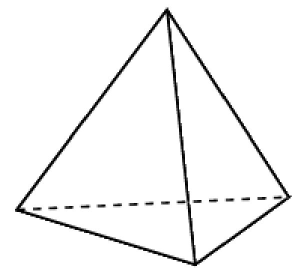
Volume conductor: Boundary Element Method

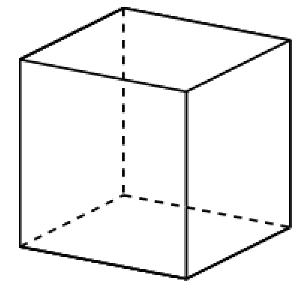
- Construction of geometry
  - segmentation in different tissue types
  - extract surface description
  - downsample to reasonable number of triangles
- Computation of model
  - independent of source model
  - only one lengthy computation
  - fast during application to real data
- Can also include more complex geometrical details
  - ventricles
  - holes in skull

Volume conductor: Finite Element Method

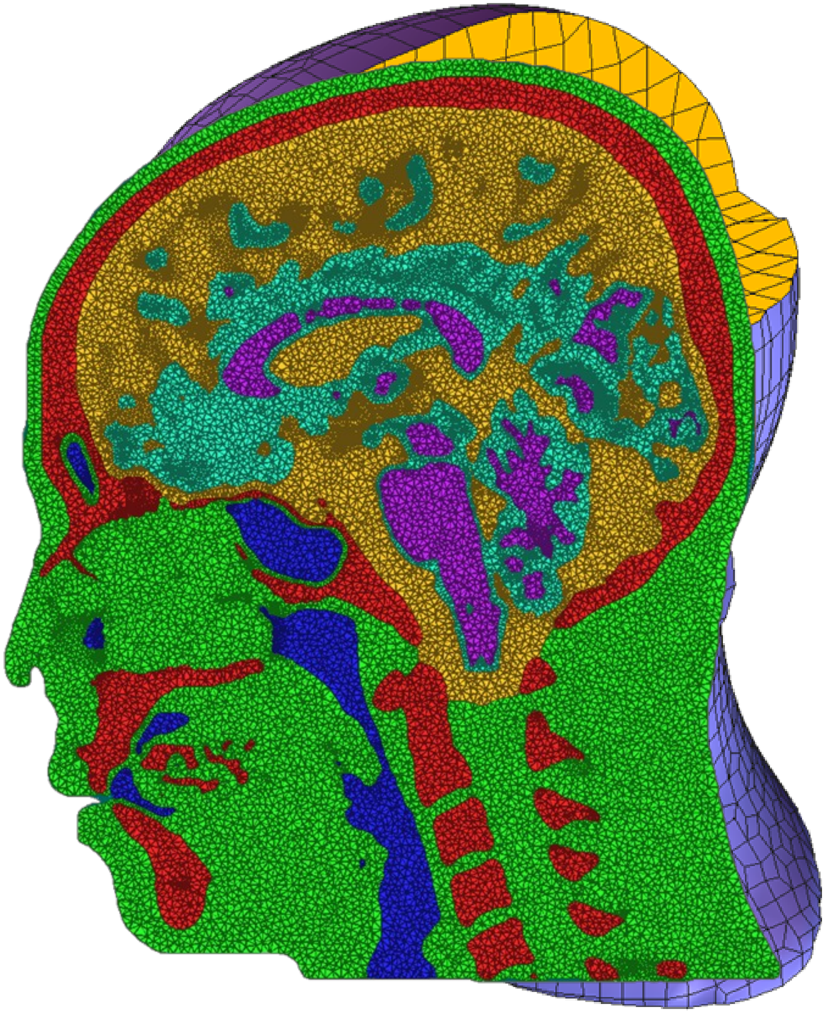
Tesselation of 3D volume in
tetraeders or hexaheders







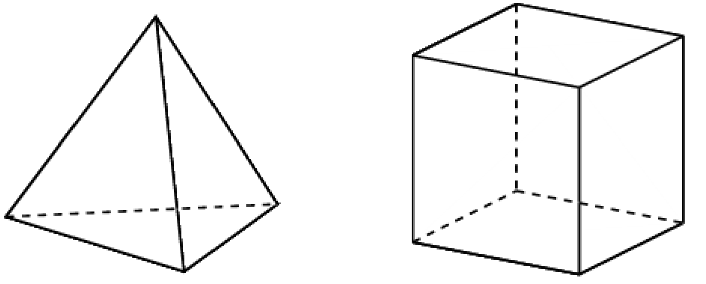
Volume conductor: Finite Element Method



tetraeders hexaheders

Volume conductor: Finite Element Method

Tesselation of 3D volume in tetraeders or hexaheders



Each element can have its own conductivity

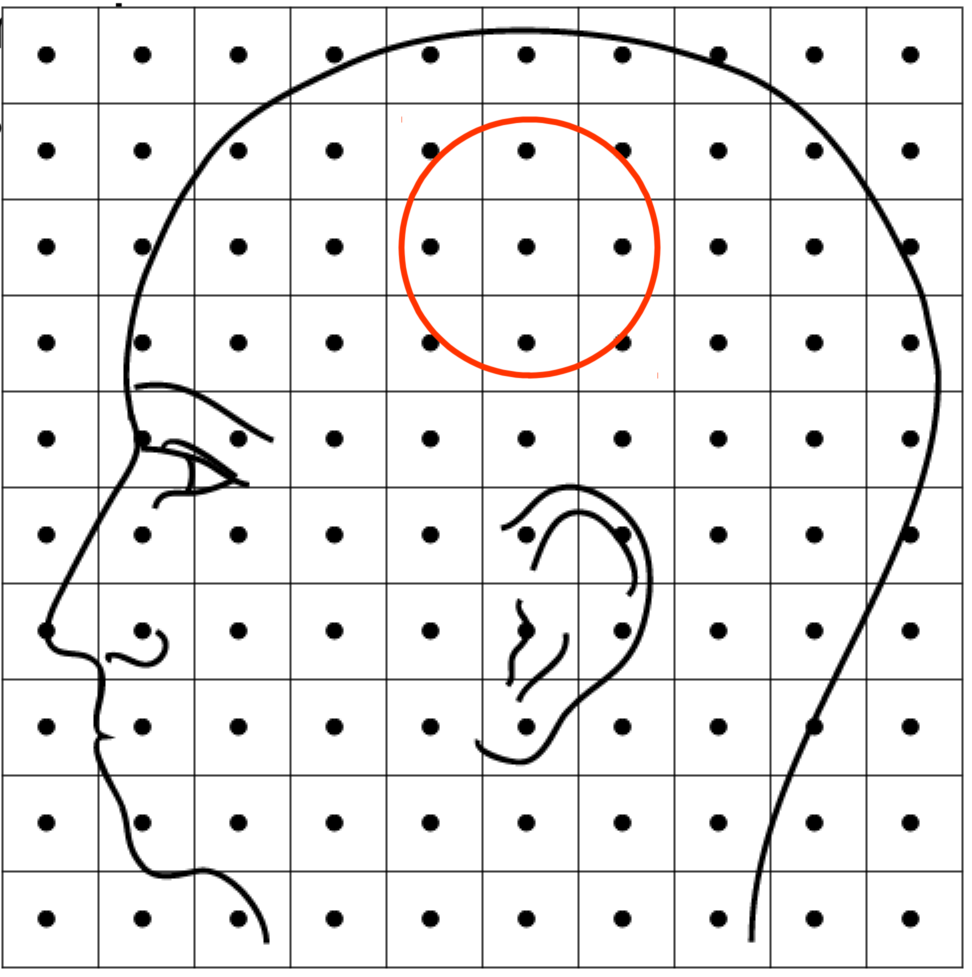
FEM is the most accurate numerical method but computationally quite expensive

Geometrical processing not as simple as BEM

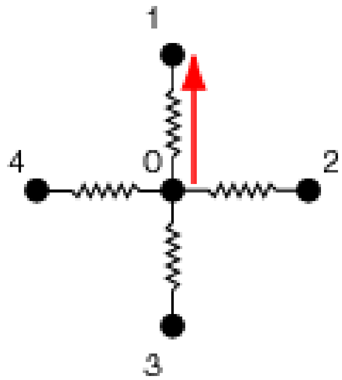
Volume conductor: Finite Difference Method

Easy to com

Not very us



Volume conductor: Finite Difference Method



$$\left.\begin{array}{l} I_1 + I_2 + I_3 + I_4 = 0 \\ V = I^*R \end{array}\right\} \Rightarrow$$

$$\Delta V_1/R_1 + \Delta V_2\,/R_2 + \Delta V_3\,/R_3 + \Delta V_4\,/R_4 = 0 \quad \Rightarrow$$

$$(V_1\text{-}V_0)/R_1 + (V_2\text{-}V_0)/R_2 + (V_3\text{-}V_0)/R_3 + (V_4\text{-}V_0)/R_4 = 0$$

Volume conductor: Finite Difference Method

Unknown potential Vi at each node

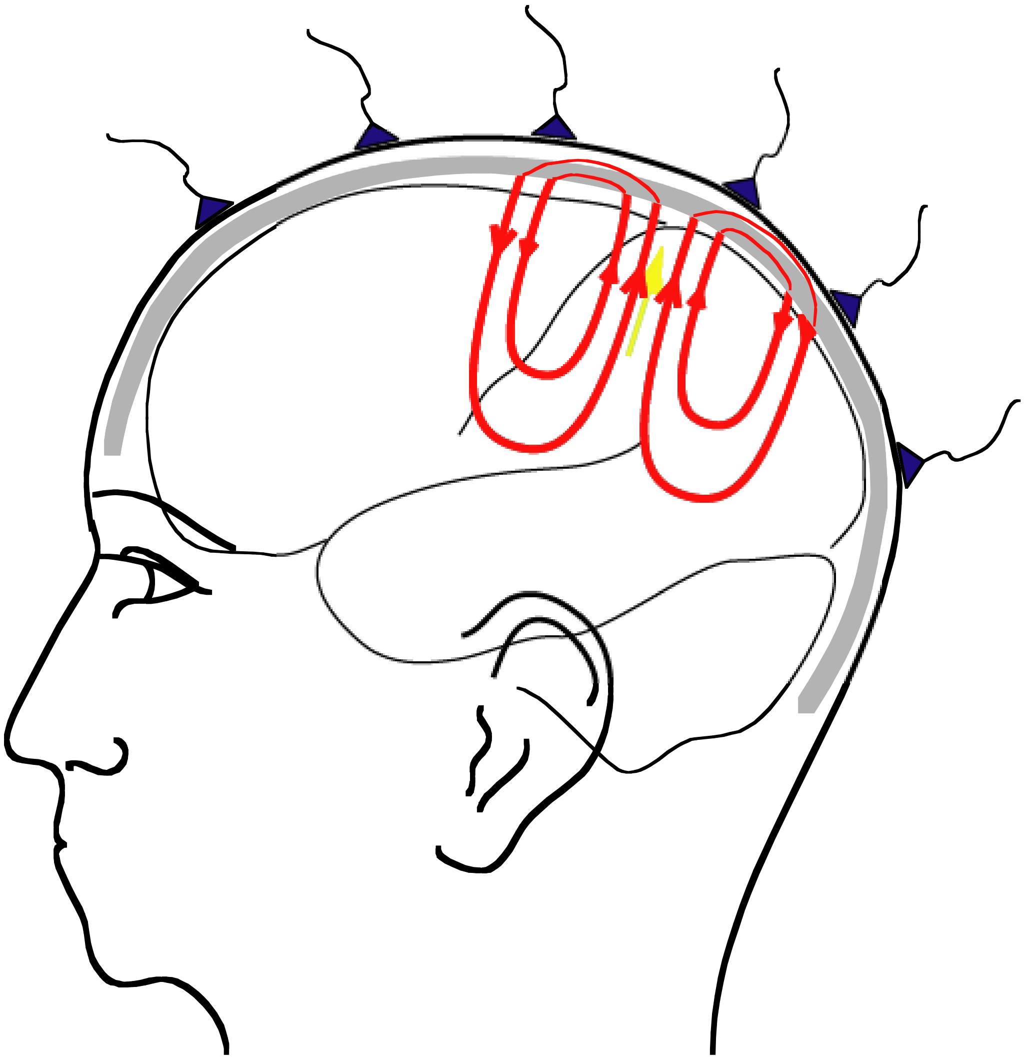
Linear equation for each node

- approx. 100x100x100 = 1.000.000 linear equations
- just as many unknown potentials

Inject some current +I and –I at two of the nodes

Solve for unknown potential

EEG volume conduction



EEG volume conduction

Potential difference between electrodes corresponds to current flowing through skin

Only tiny fraction of current passes through skull

Therefore the model should describe the skull and skin as accurately as possible

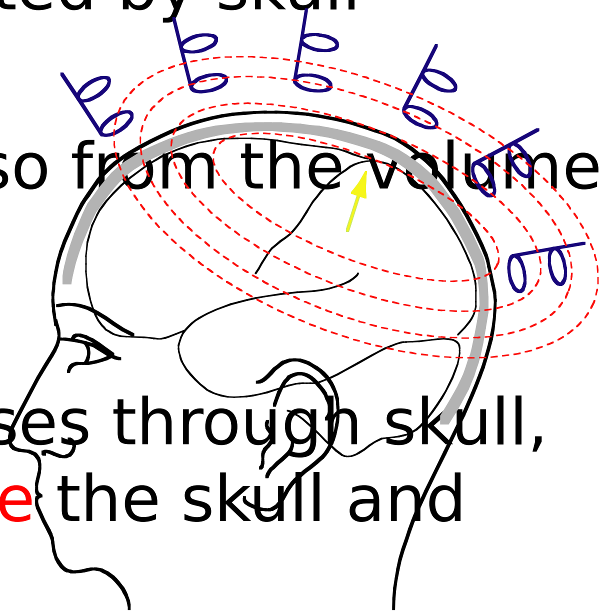
MEG volume conduction

MEG measures magnetic field over the scalp

Mistorted by skull

M ut also from the volume

O passes through skull,
gnore the skull and



Practical differences between EEG and MEG

fixed sensor positions in MEG

flexible cap in EEG

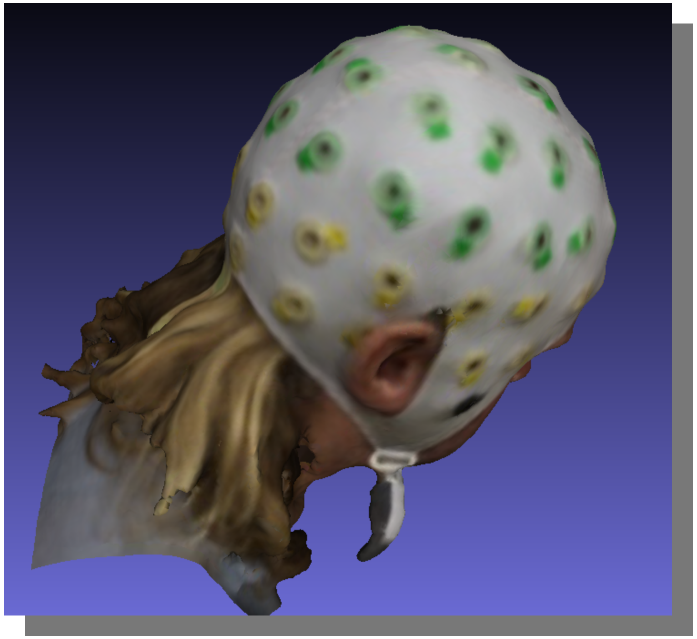
MEG requires head size to be known in analysis

- using individual anatomical MRI
- position of sensors is accurately known

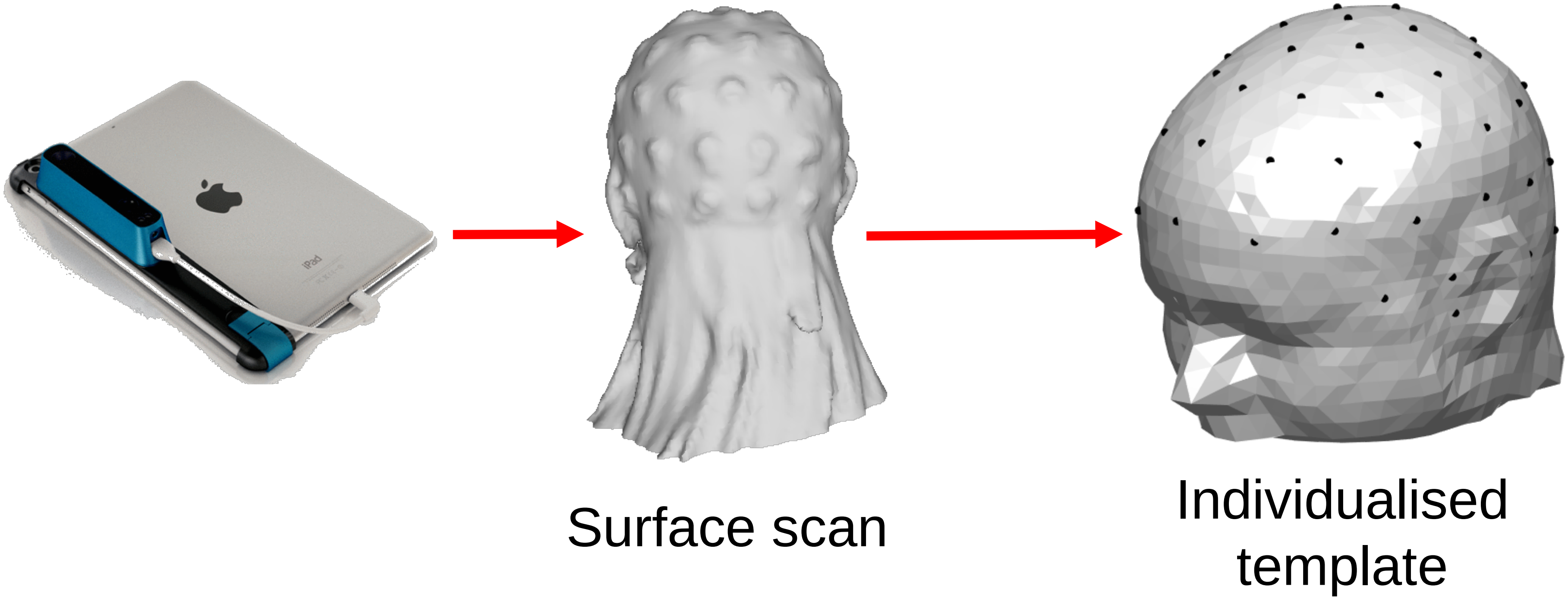
EEG requires the electrode positions to be known in analysis

Obtaining geometrical data

3D scanning instead of MRI

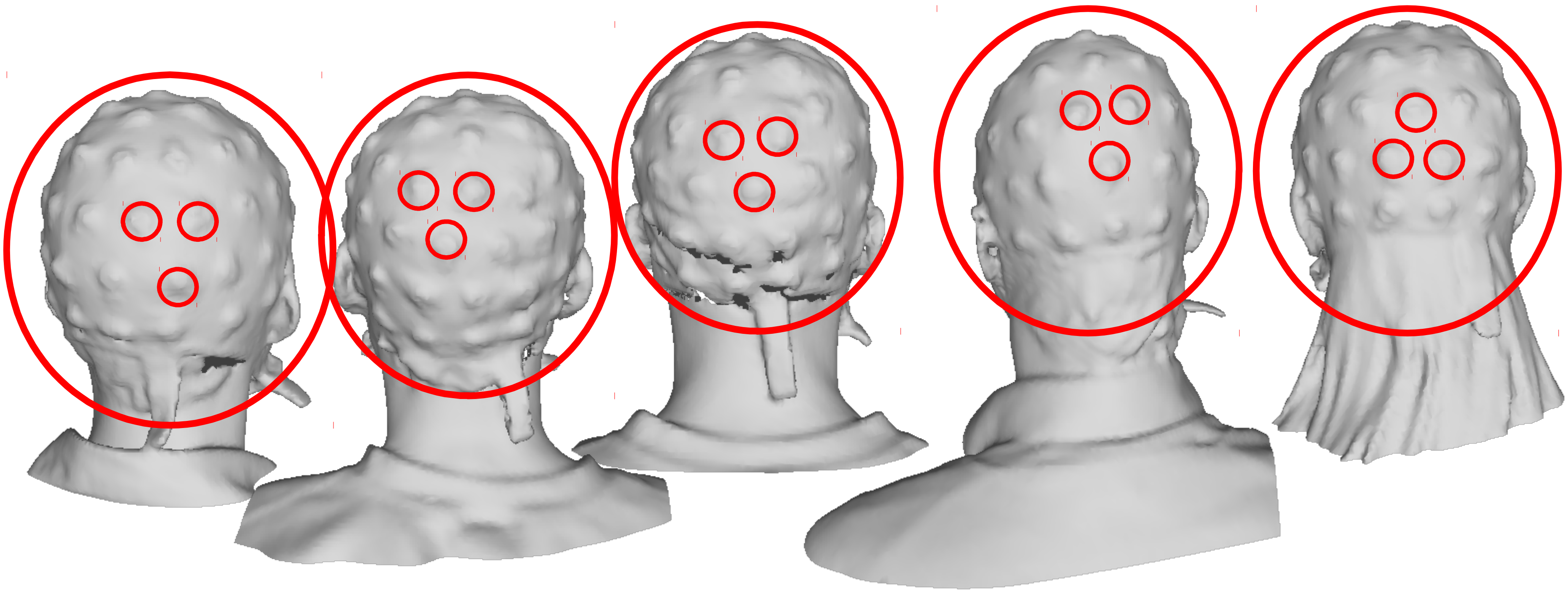


3D scanning - pipeline for EEG modelling



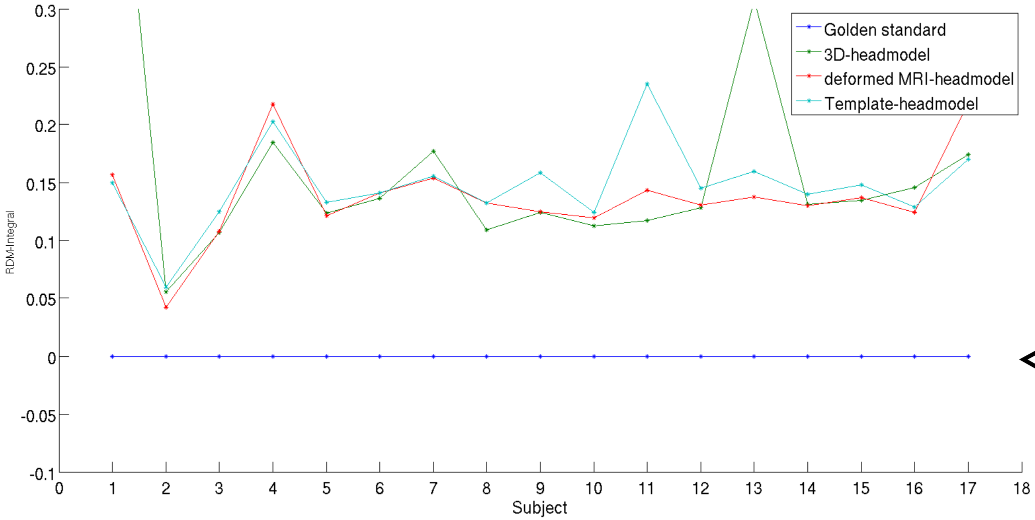
3D scanning

ChildBrain
ADVANCING BRAIN RESEARCH IN CHILDREN'S DEVELOPMENTAL NEUROCOGNITIVE DISORDERS



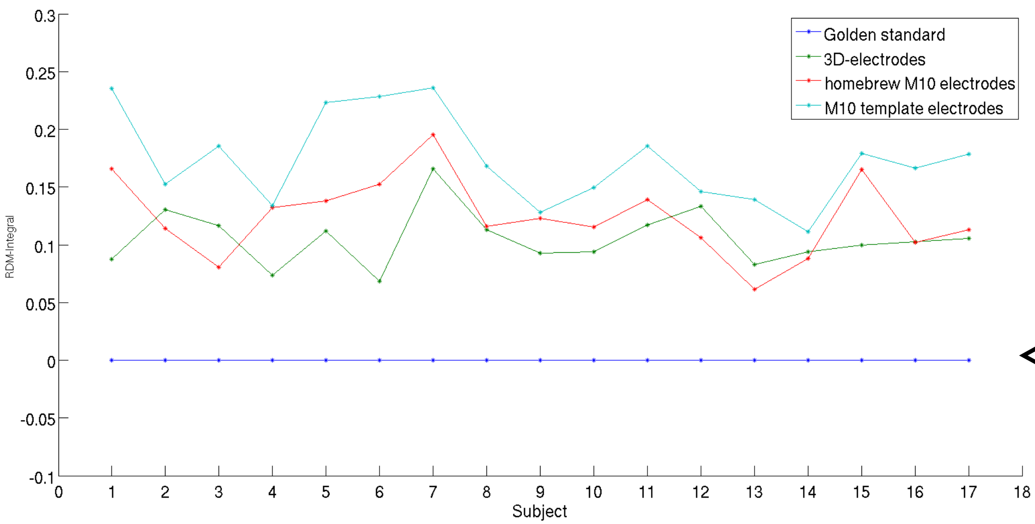
Homölle & Oostenveld
in preparation

3D scanning – EEG source model accuracy



comparing head models

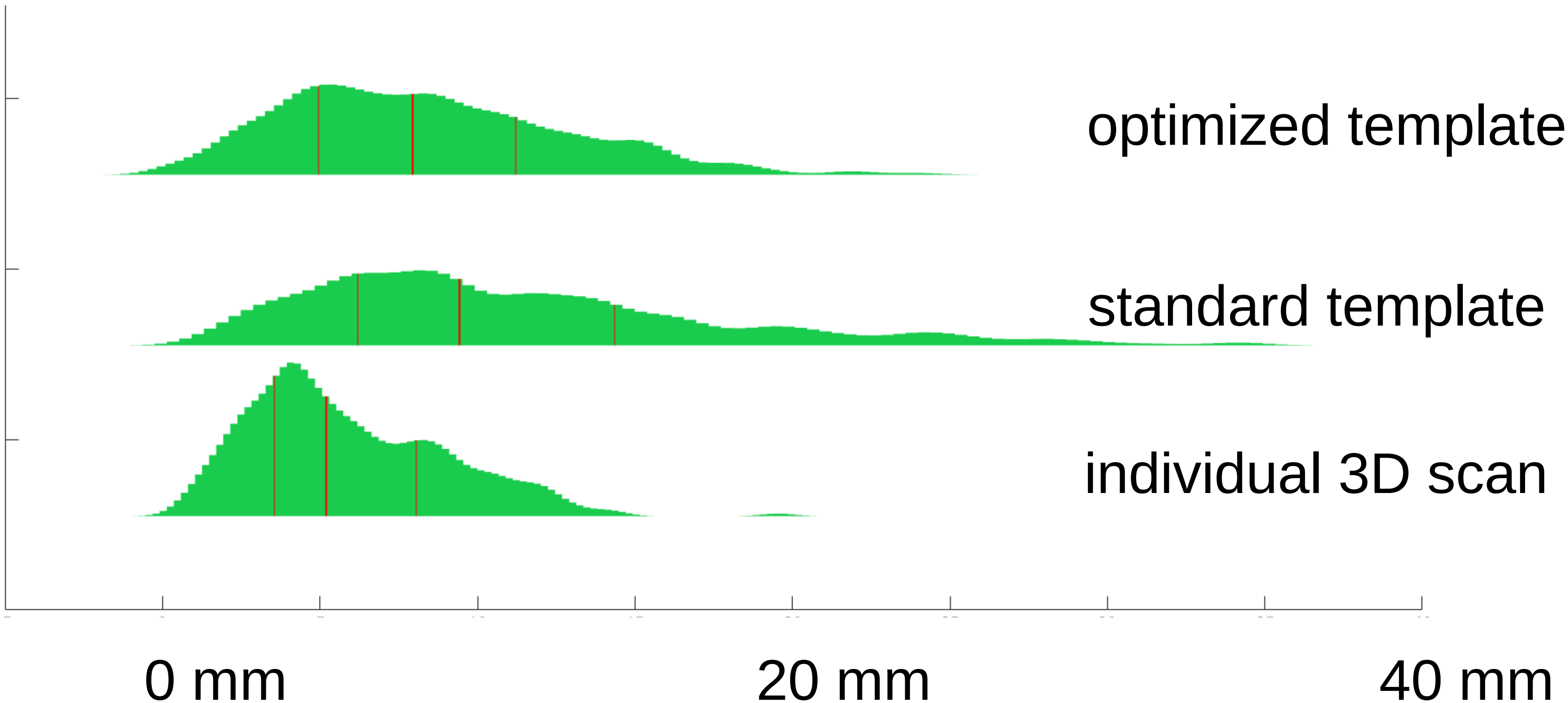
MRI+polhemus



comparing electrode locations

MRI+polhemus

3D scanning - Electrode position accuracy



Homölle & Oostenveld
in preparation

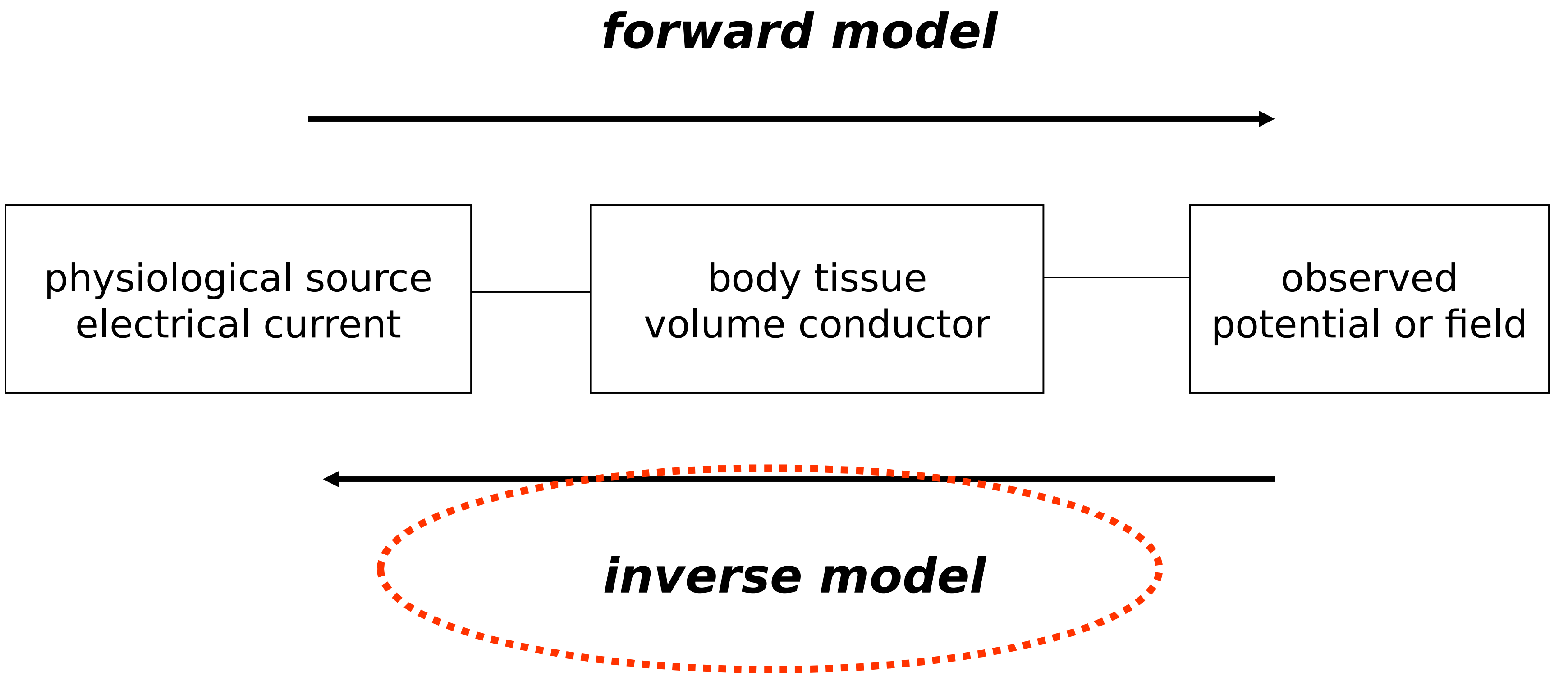
Forward modeling - summary

Using geometrical data
- scalp, skull and brain tissue
- locations at which MEG/EEG data is recorded

Measure geometrical dat
- ideally with MRI and Polhemus
- optionally with 3-D scanner

Mathematical volume conduction models

Biophysical source modelling: overview



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Source reconstruction – overview of methods

Single and multiple dipole models

- Minimize error between model and measured potential/field

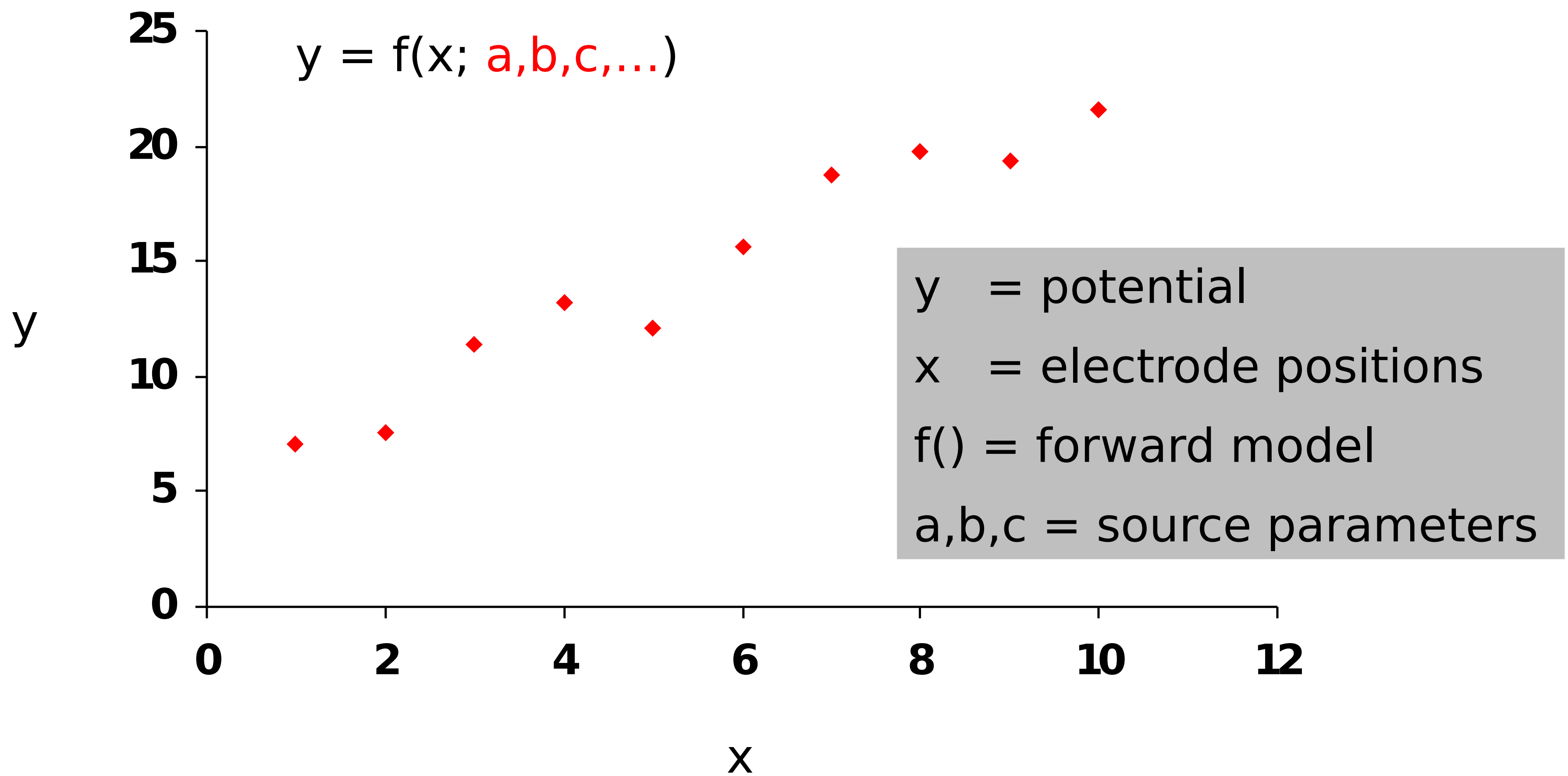
Distributed source models

- Perfect fit of model to the measured potential/field
- Additional constraint on source smoothness, power or amplitude

Spatial filtering

- Scan the whole brain with a single dipole and compute the filter output at every location
- Beamforming (e.g. LCMV, SAM, DICS)
- Multiple Signal Classification (MUSIC)

Single or multiple dipole models - Parameter estimation



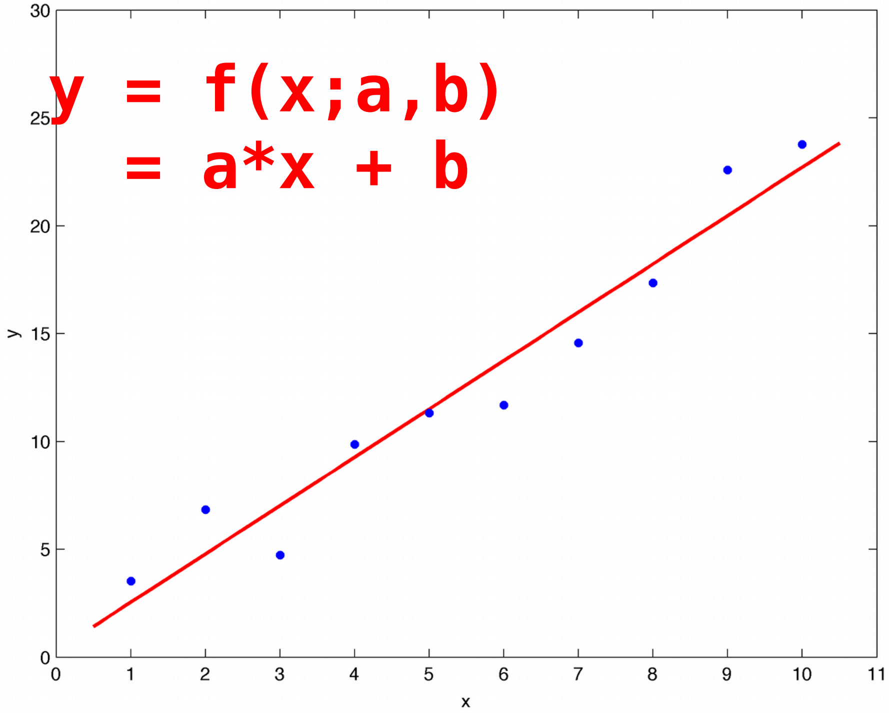
Parameter estimation: dipole parameters

source model with few parameters

- position
- orientation
- strength

compute the model data

minimize difference between actual and model data



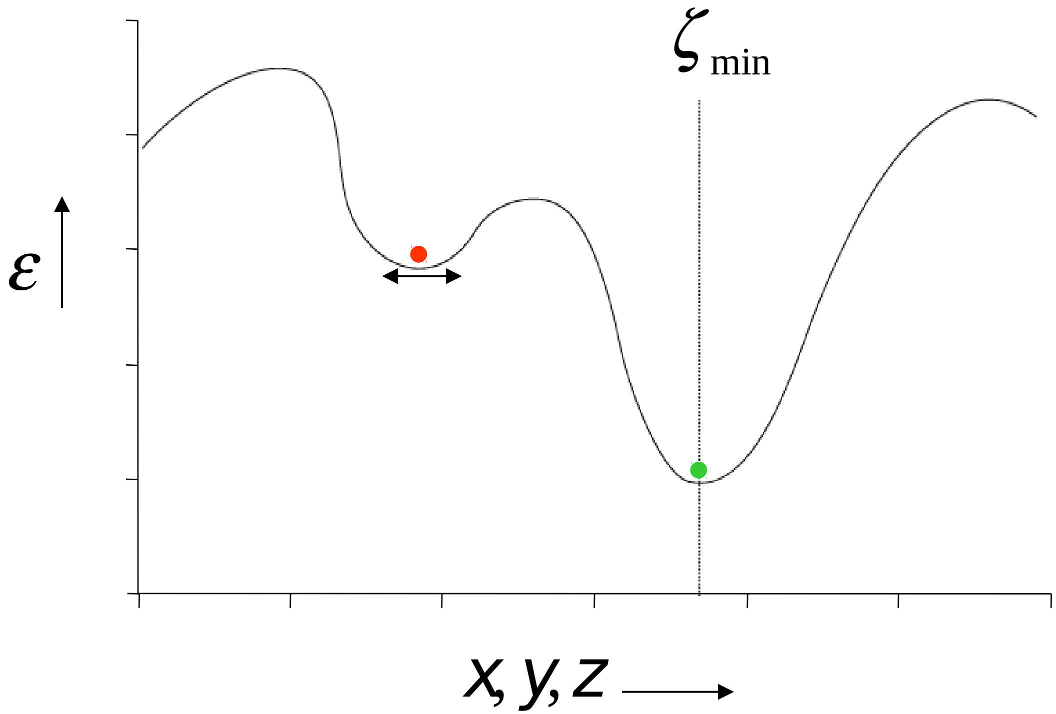
Non-linear parameters: grid search

- One dimension, e.g. location along medial-lateral
  - 100 possible locations
- Two dimensions, e.g. med-lat + inf-sup
  - 100x100=10.000
- Three dimensions
  - 100x100x100 = 1.000.000 = 10^6

- Two dipoles, each with three dimensions
  - 100x100x100x100x100x100 = 10^{12}

Optimization of non-linear parameters

$$\varepsilon rror(x,y,z) = \sum_{i=1}^{N} \left(Y_i(x,y,z) - V_i\right)^2 \Rightarrow \min_{x,y,z}\left(\varepsilon rror(x,y,z)\right)$$



Single or multiple dipole models - Strategies

- Single dipole:
  - scan the whole brain, followed by iterative optimization
- Two dipoles:
  - scan with symmetric pair, use that as starting point for iterative optimization
- More dipoles:
  - sequential dipole fitting

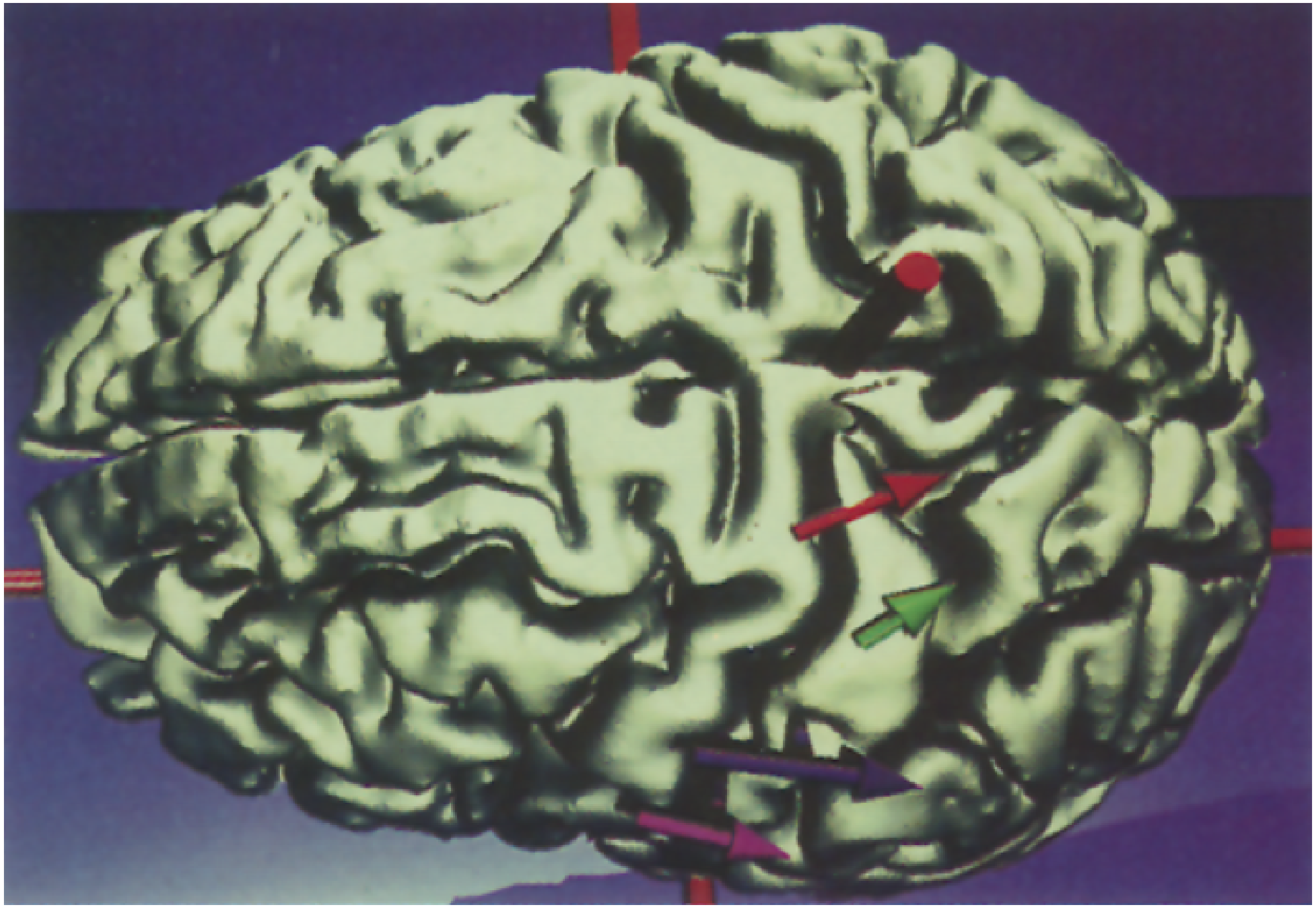
Sequential dipole fitting: spread of cortical activity

- Assume that activity starts “small”
  - explain earliest ERP component with single equivalent current dipole
- Assume later activity to be more widespread
  - add ECDs to explain later ERP components
  - estimate position of new dipoles
  - re-estimate the activity of all dipoles

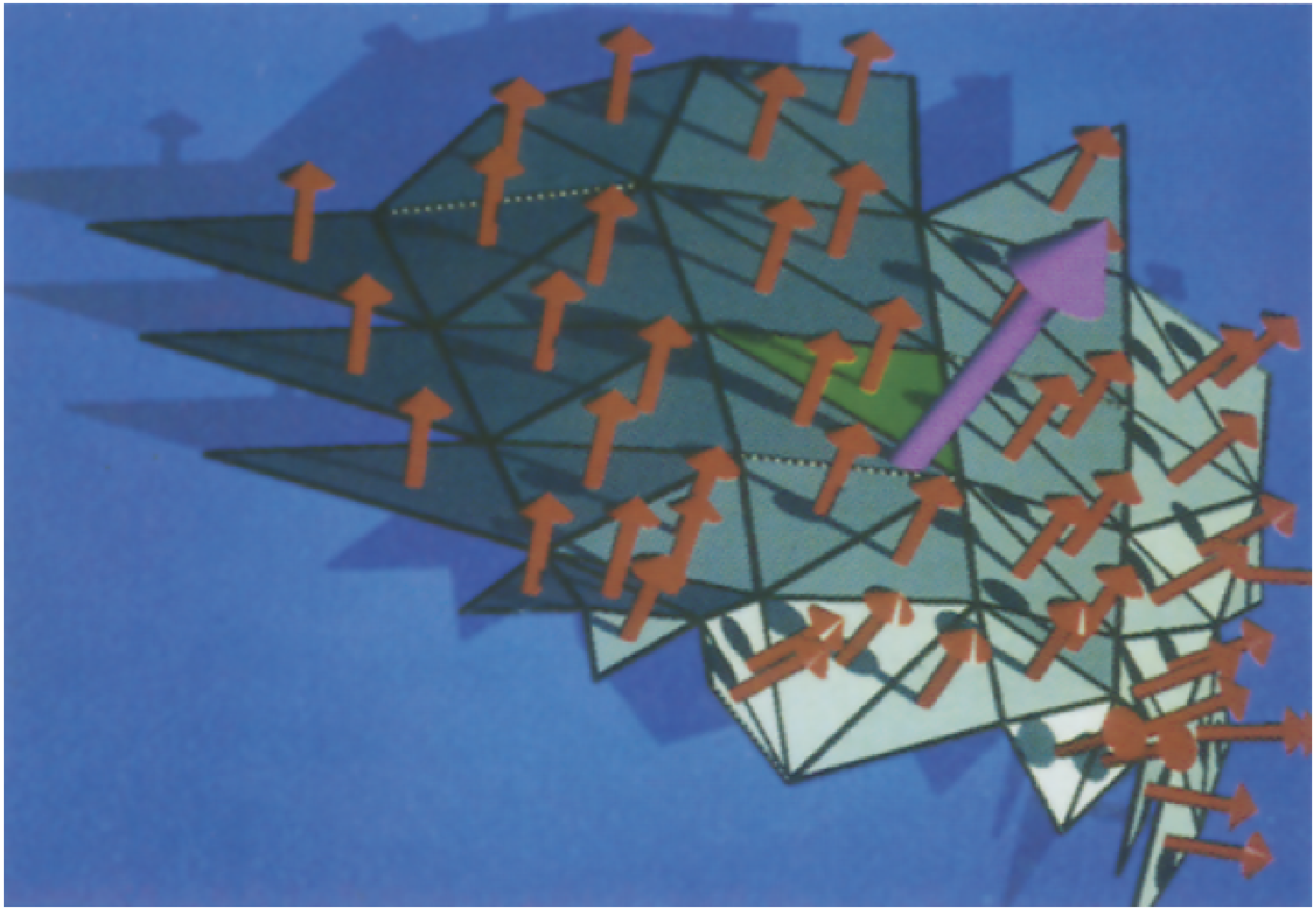
Distributed source model

- Position of the source is not estimated as such
  - Pre-defined grid (3D volume or on cortical sheet)
- Strength is estimated
  - In principle easy to solve, however…
  - More “unknowns” (parameters) than “knowns” (measurements)
  - Infinite number of solutions can explain the data perfectly
  - Additional constraints required

Distributed source model



Distributed source model

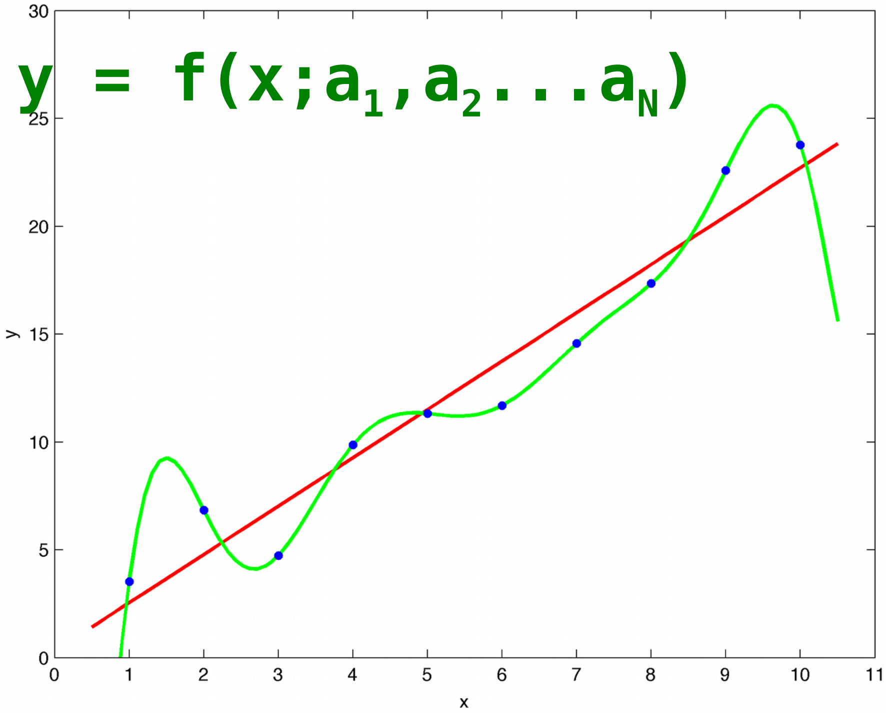


Distributed source model: linear estimation

distributed source model with **many dipoles** throughout the whole brain

estimate the strength of all dipoles

data and noise can be perfectly explained



Distributed source model: regularization

$$V = G \times q + Noise$$

$$\min_q \{ \| V - G \times q \|^2 \} = 0 \ !!$$

Regularized linear estimation:

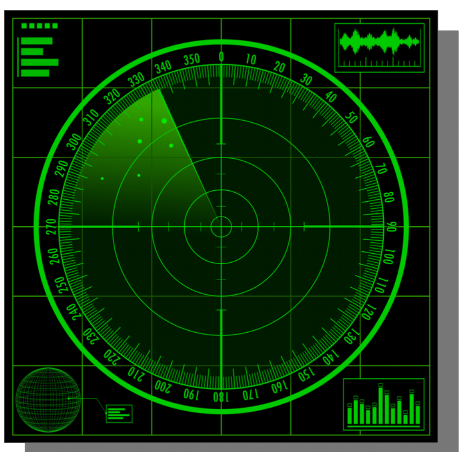
$$\rightarrow \min_q \{ \underbrace{\| V - G \times q \|^2}_{\text{mismatch with data}} + \lambda \times \underbrace{\| D \times q \|^2}_{\text{mismatch with prior assumptions}} \}$$

Scanning methods

- Position of the source is not estimated as such
- For each (possible) source position, an estimate of the activity is computed

- Construct a “spatial filter”
  - No explicit assumptions about source constraints (implicit: single dipole)
  - Assumption that sources that contribute to the data should be uncorrelated

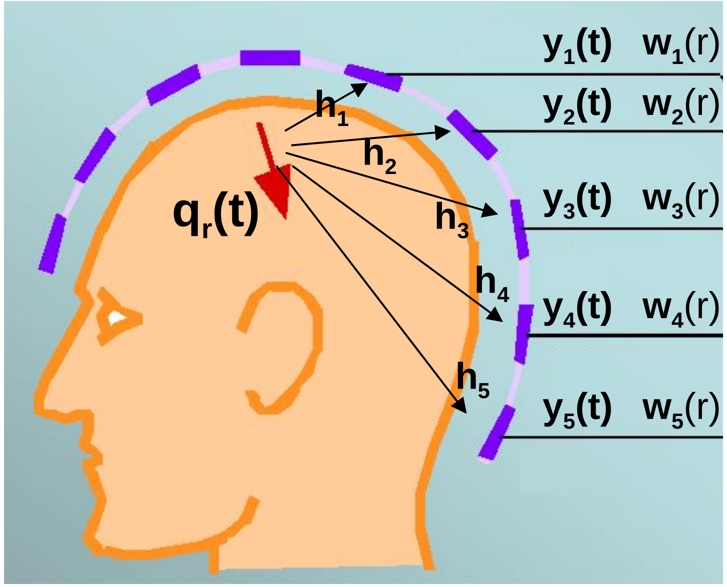
Scanning with a beamformer filter



Beamformer: the question

What is the activity of a source **q**, at a location **r**, given the data **y**?

We estimate **q** with a spatial filter **w**



$$\hat{q}_r(t) = \mathbf{w}(r)^T \mathbf{y}(t)$$

Summary 1

- Forward modelling
  - Required for the interpretation of scalp topographies
  - Different methods with varying accuracy
- Inverse modelling
  - Estimate source location and timecourse from data
- Assumptions on source locations
  - Single or multiple point-like source
  - Distributed source
- Assumptions on source and noise timecourse
  - Uncorrelated (and dipolar)

Summary 2

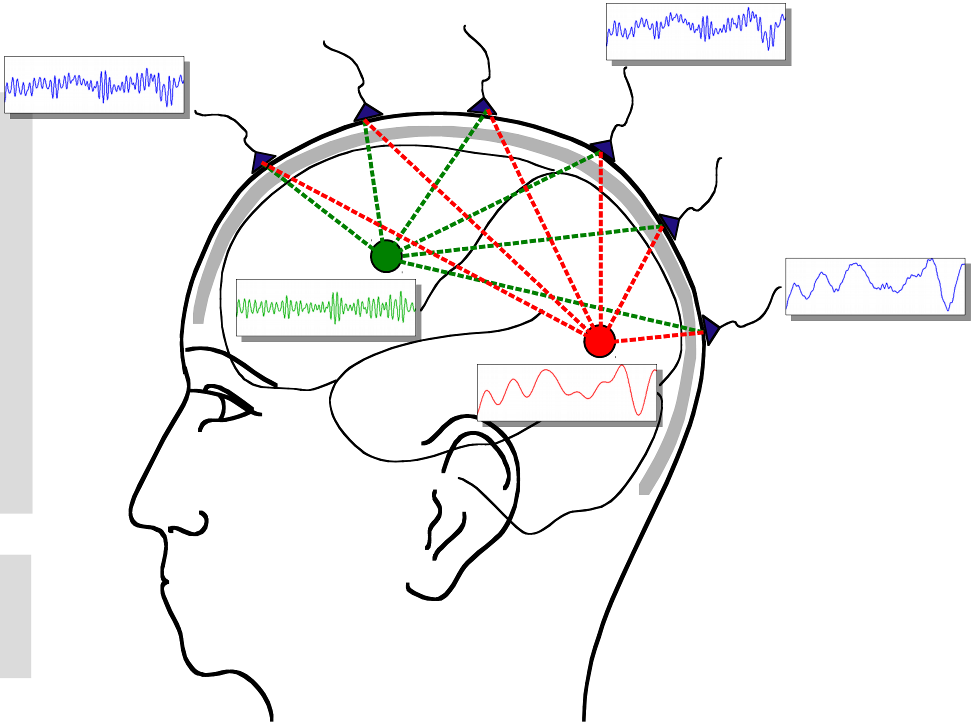
Source analysis is not only about the “where” but also about untangling the “what”, the “when” and the “how”

timecourse of activity
-> ERP

spectral characteristics
-> power spectrum

temporal changes in power
-> time-frequency response (TFR)

spatial distribution of activity over the head
-> source reconstruction



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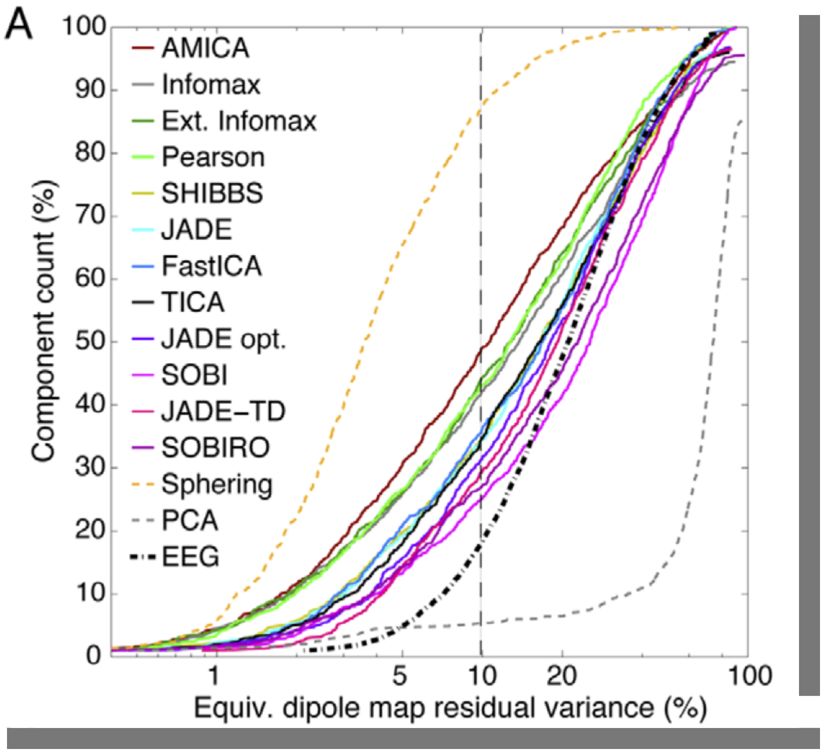
Independent components are dipolar



Delorme et al. *Independent EEG sources are dipolar*. PLoS One. 2012.

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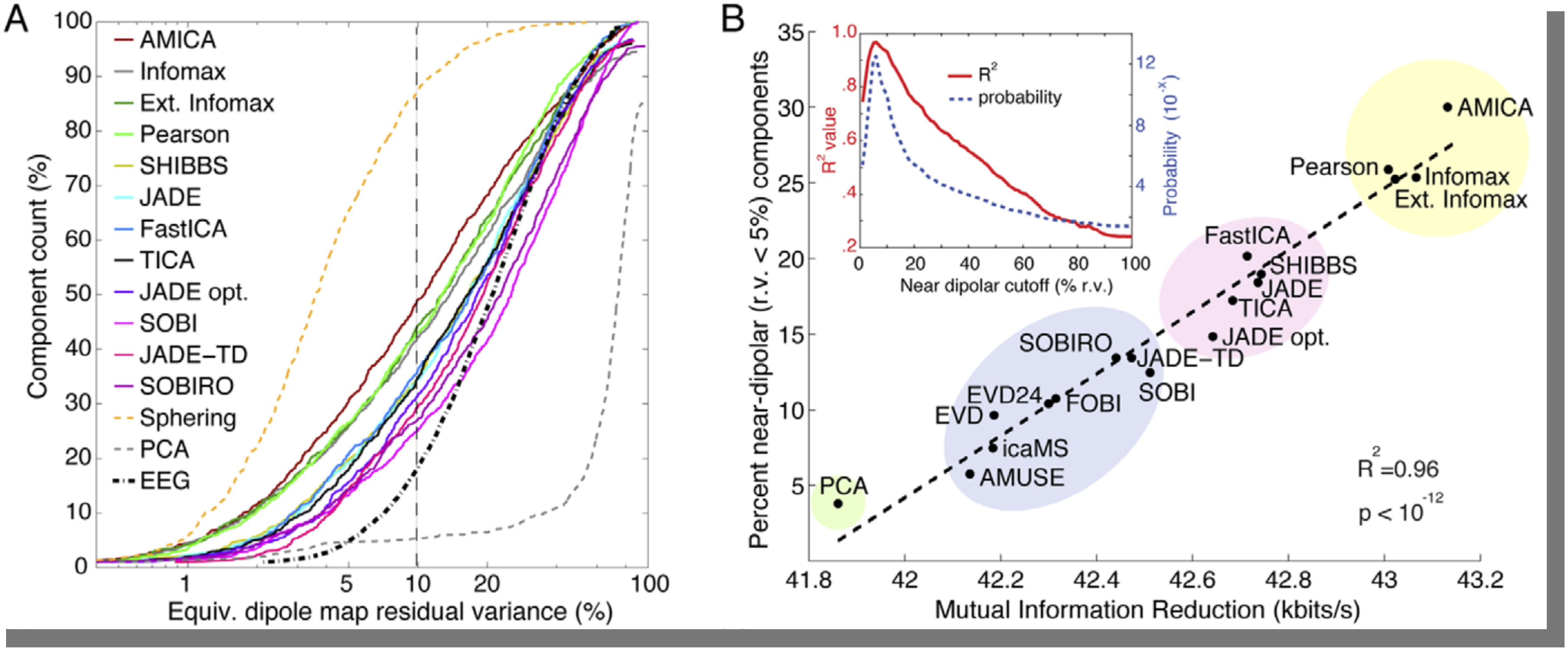

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