Localizing the sources of ERP topographies

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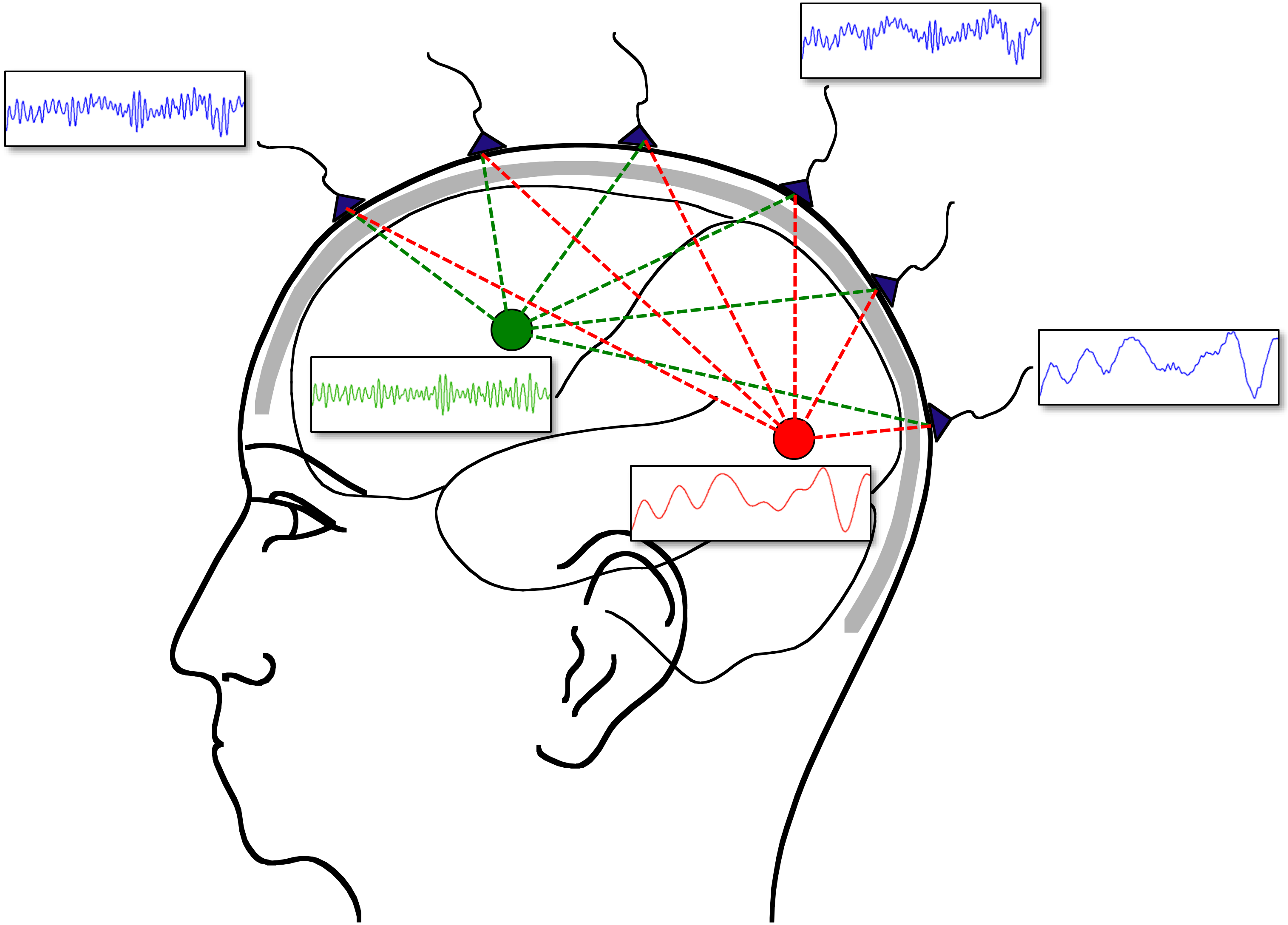
African Brain Data Network

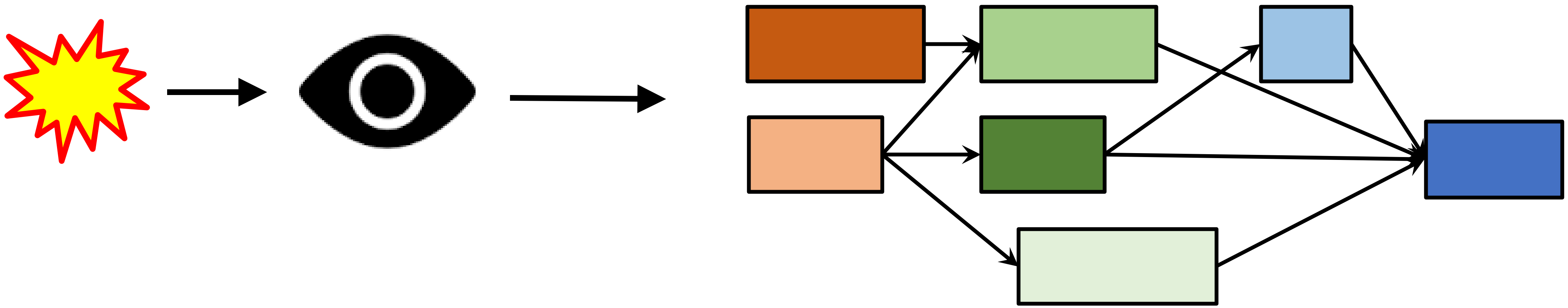
Superposition of source activity



Overview

- Motivation and background
- Forward modeling
  - Source model
  - Volume conductor model
- Inverse modeling - biophysical models
  - Single and multiple dipole fitting
  - Distributed source models
  - Beamforming

ERP components reveal the *when* and *where*



Different functions in different brain areas.

The brain is a hierarchical functional network.

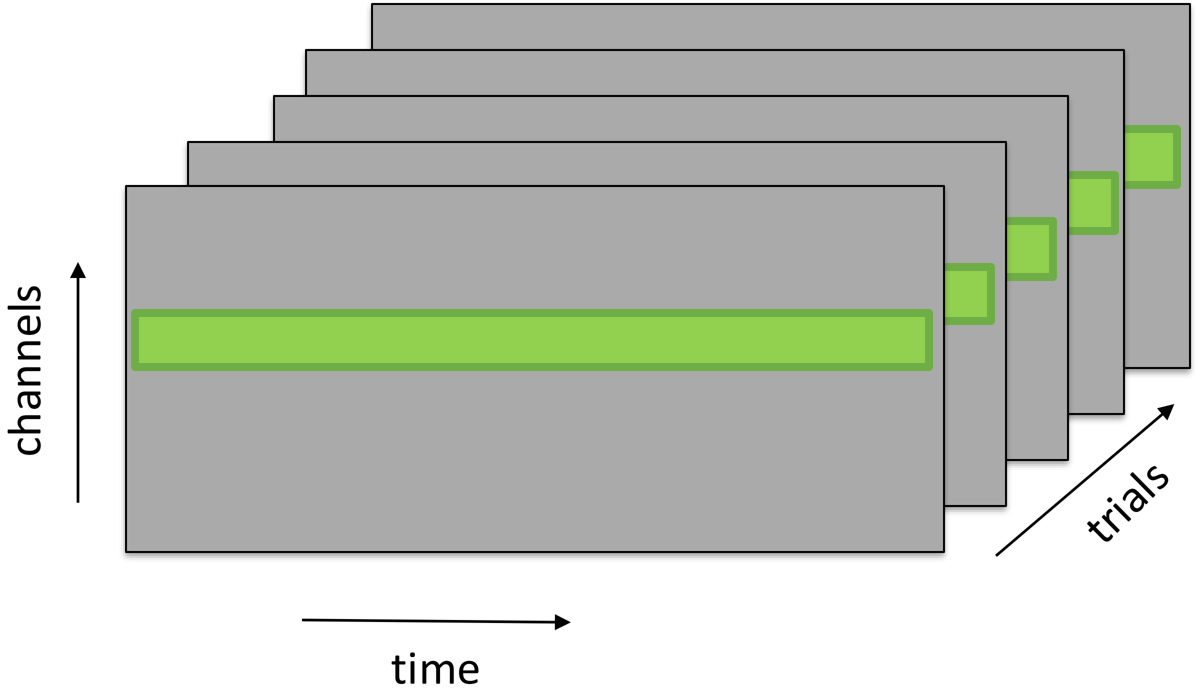
Serial/sequential and parallel processing at different times/latencies in different areas.

Identifying the latency and topography of ERP components helps to disentangle functional networks.

One channel, all time points

When does specific brain activity start (in one condition)?

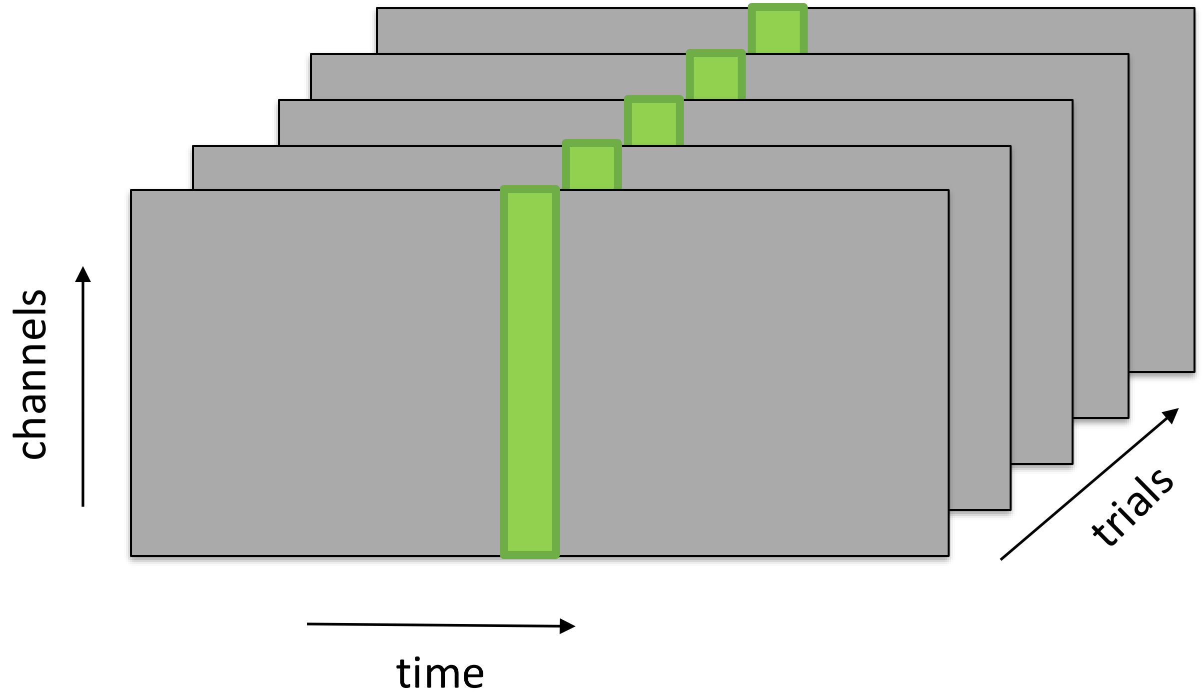
When is the activity different between conditions?



All channels, one time point

What is the *topographic distribution* (in one condition) at latency t ?

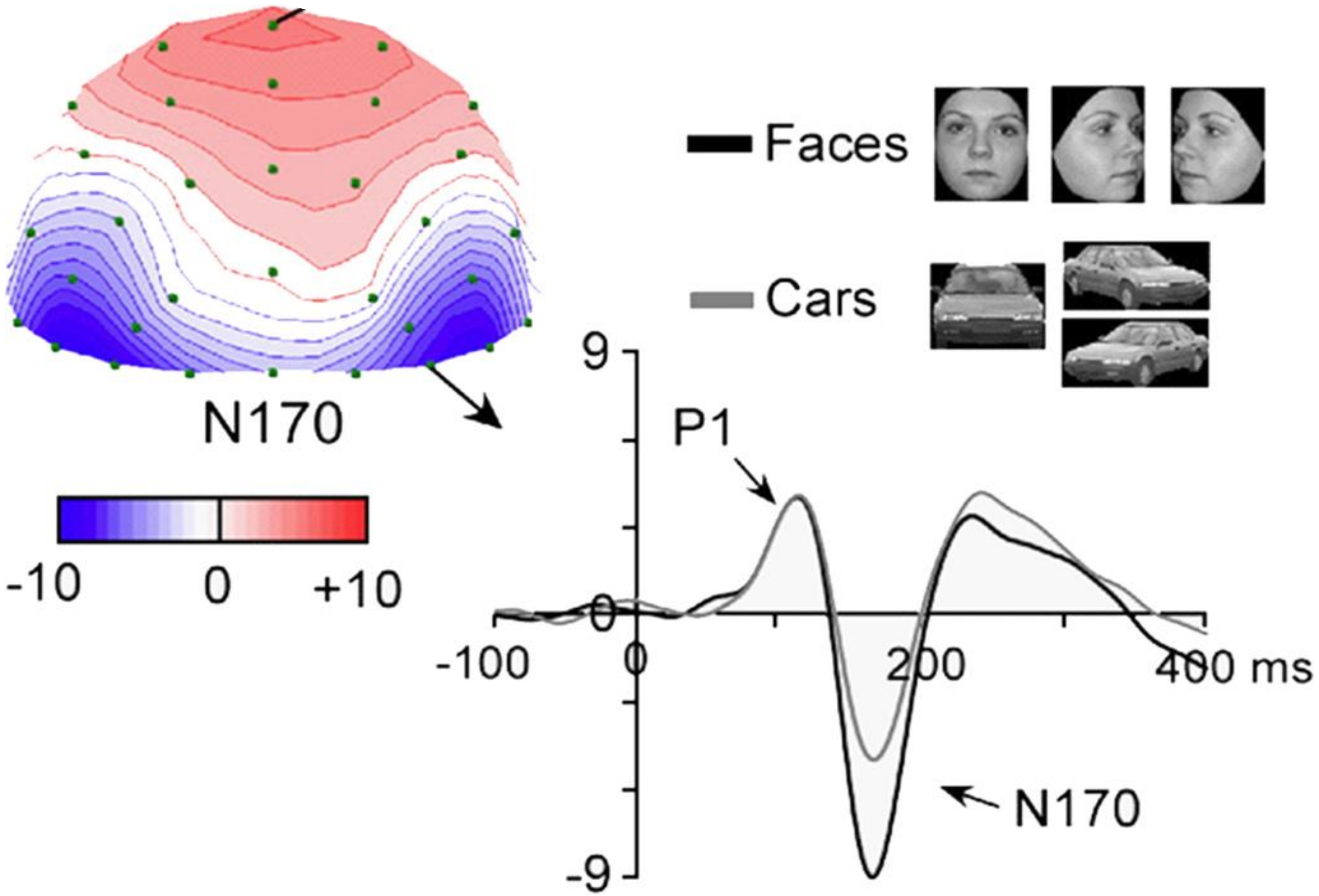
What is the *topographic distribution* of the difference at latency t ?



ERP difference waves to localize face-selective brain areas

The N170 is an ERP response specific for faces, when contrasted to other visual stimuli.

The N170 originates from the fusiform face area (FFA) which is located on the ventral surface of the brain.

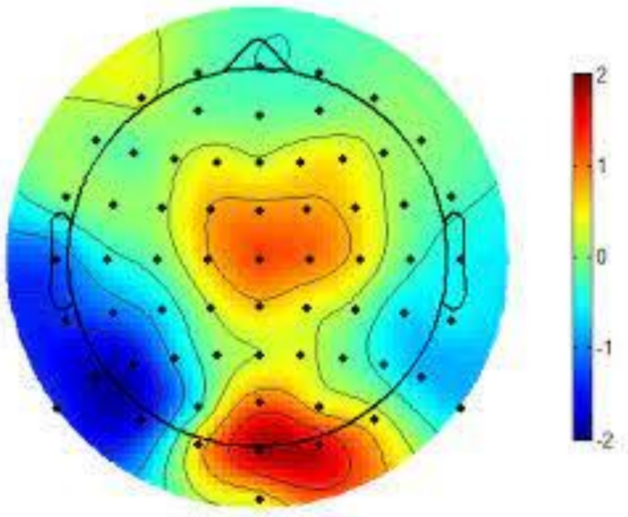


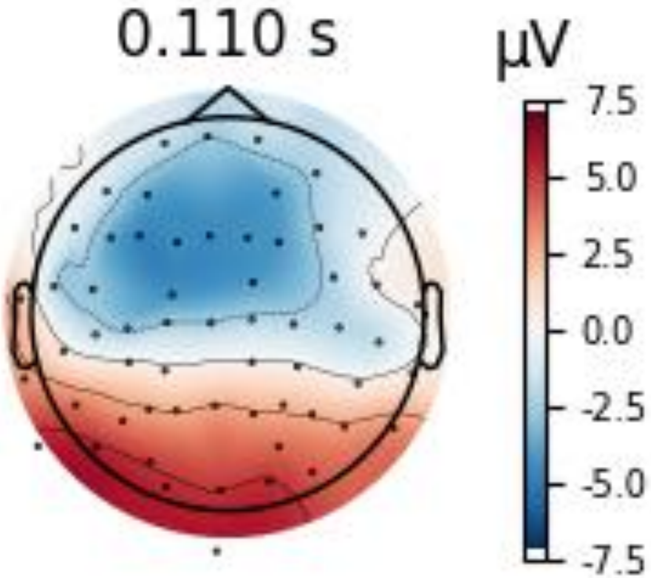
Kuefner et al. (2010), https://doi.org/10.3389/neuro.09.067.2009

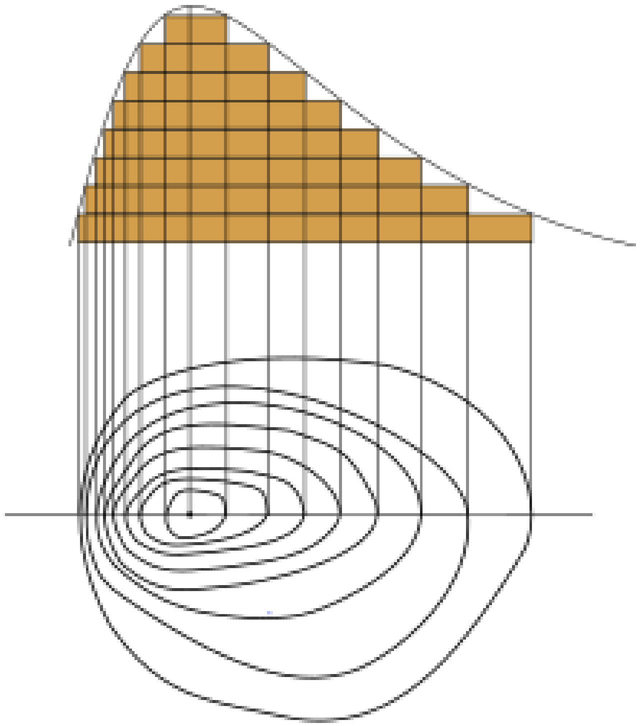
Localizing and understanding the ERP

- If you find a ERP 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 modeling helps to interpret the topography
- Forward and inverse modeling helps to disentangle overlapping source timeseries

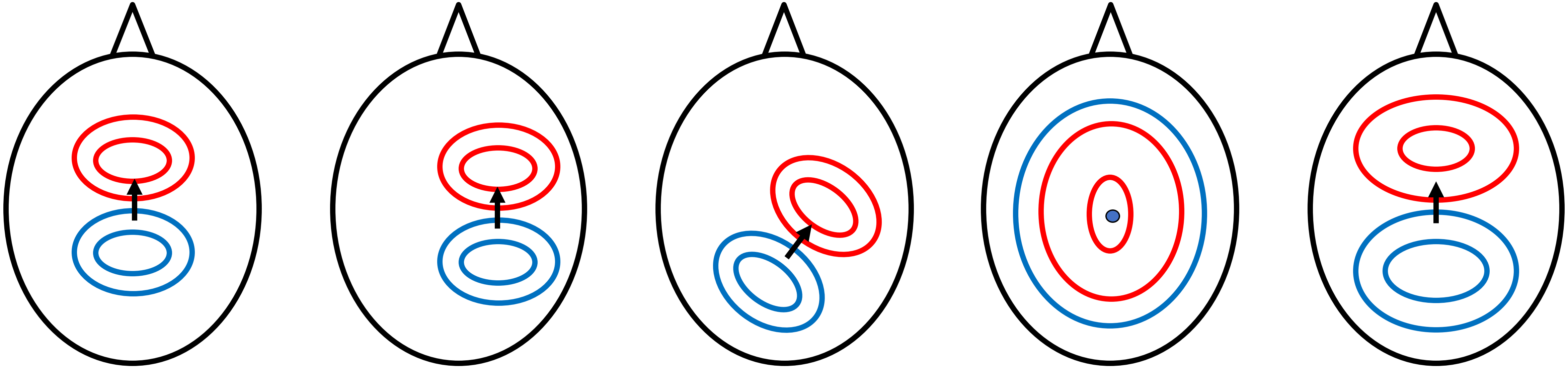
ERP topographies – colors and contour lines



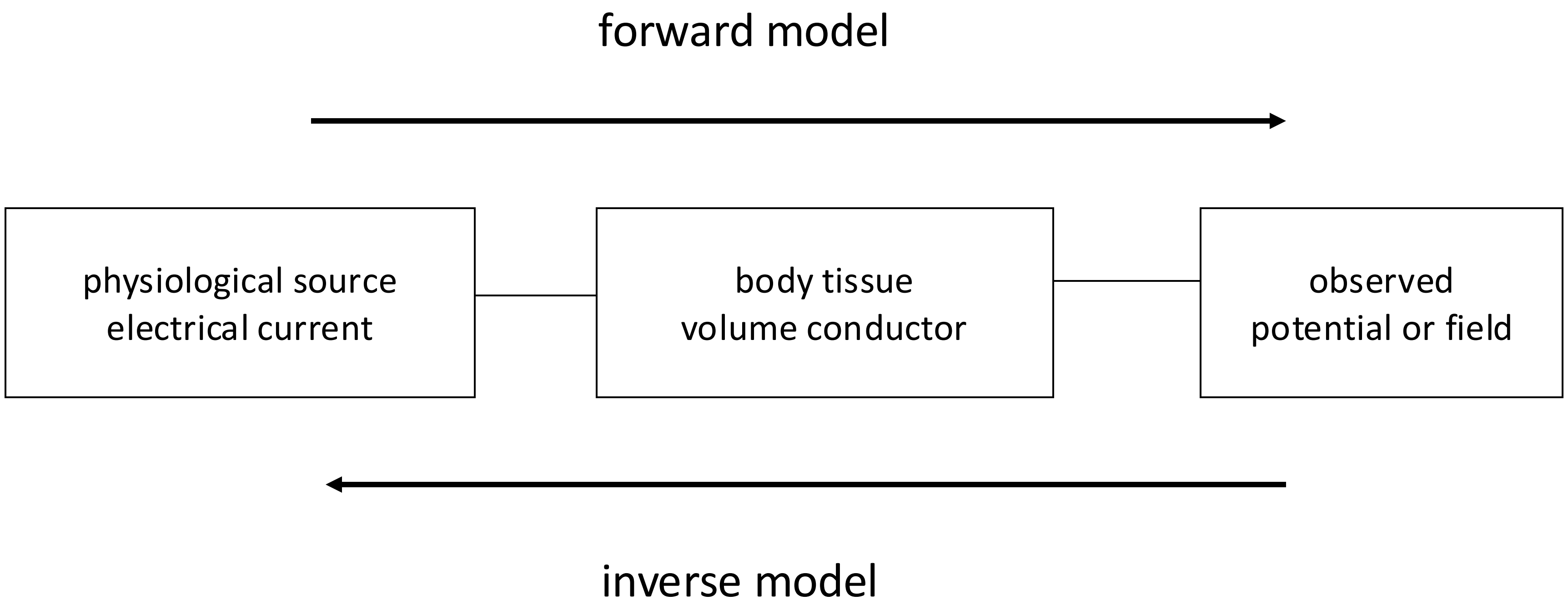




Forward models and ERP topograpies



Biophysical source modelling: overview



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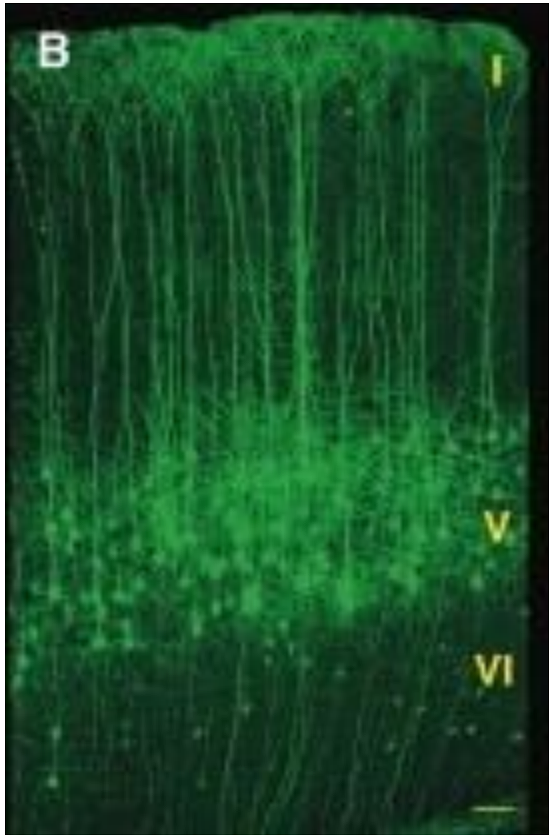
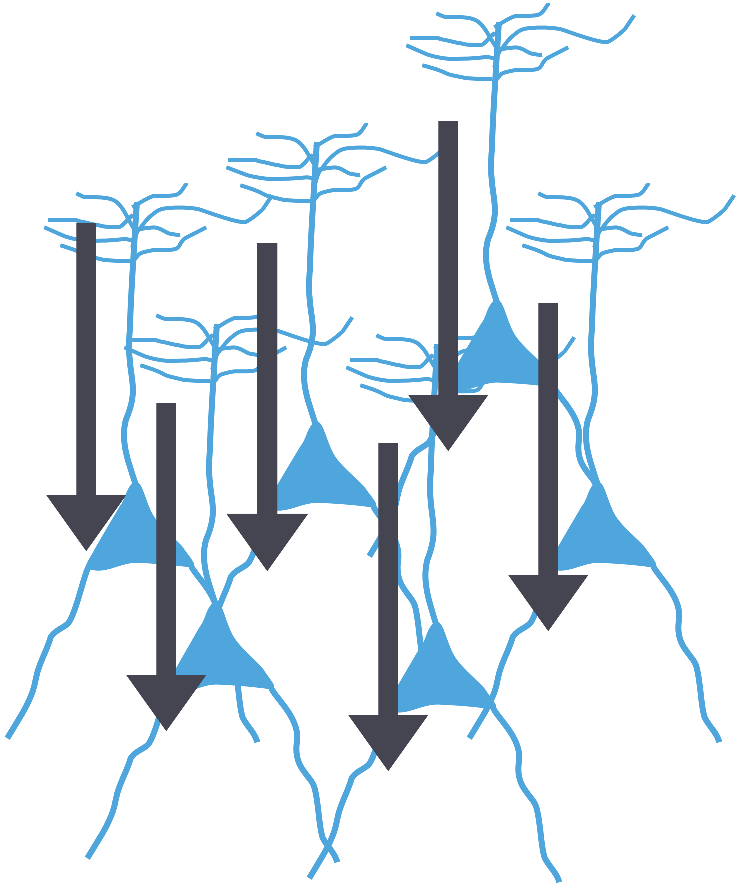
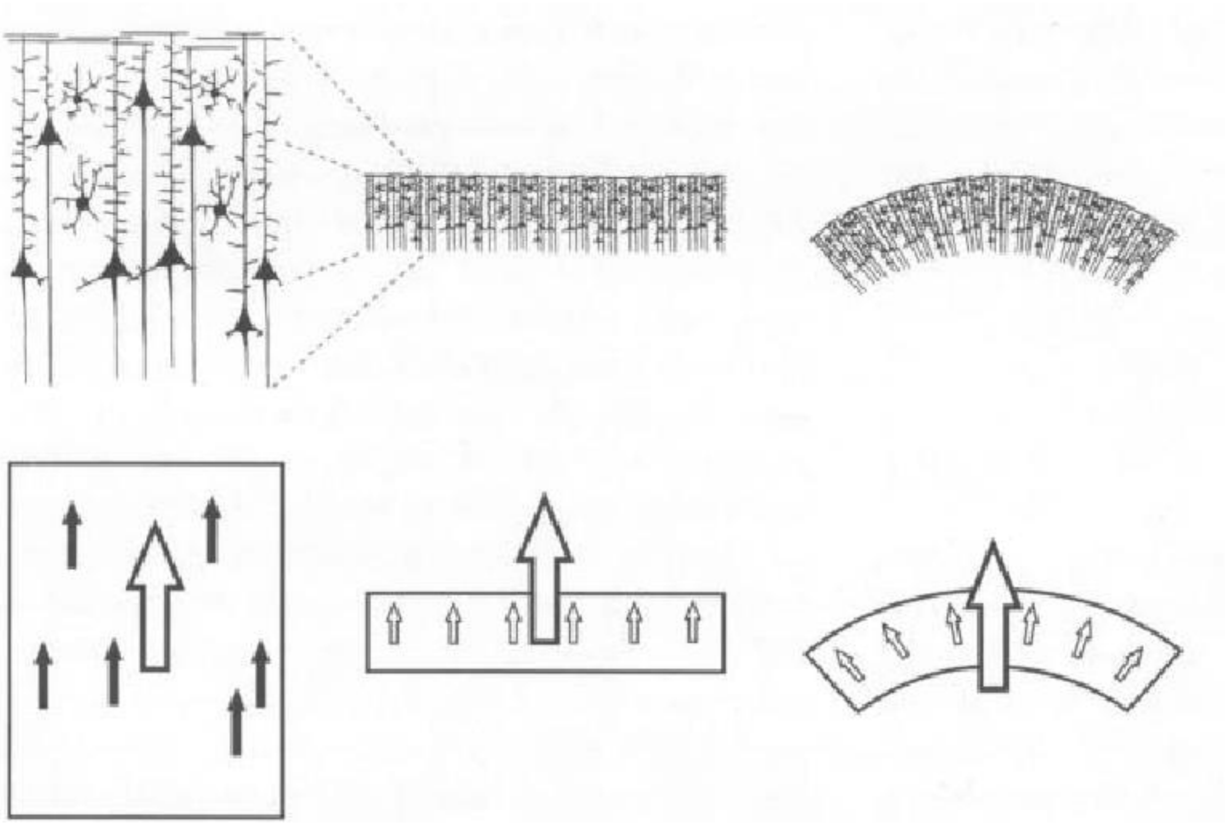
What produces the electric current





Equivalent current dipoles



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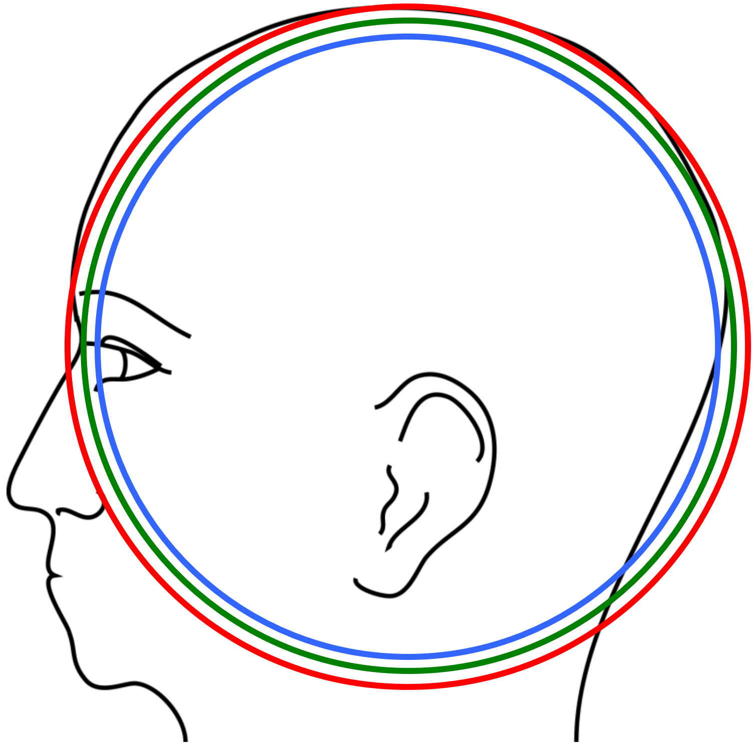
Volume conductor

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

Analytic computational methods for volume conduction problem for simple geometries, like a sphere.

Numerical computational methods for volume conduction problem allow for realistic geometries.

BEM = Boundary Element Method

FEM = Finite Element Method

Volume conductor: Boundary Element Method

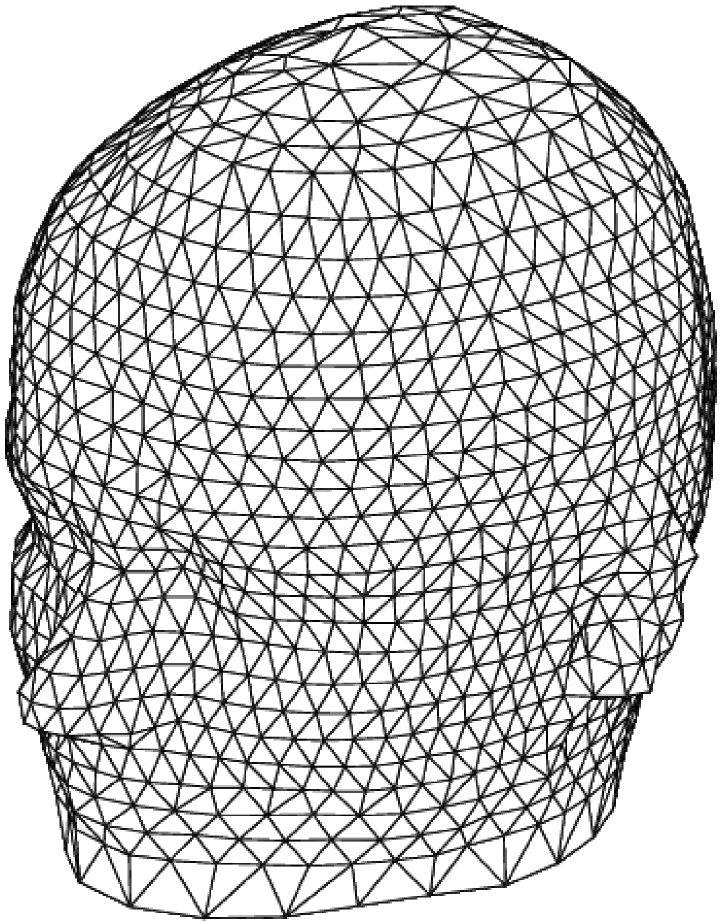
Each compartment is

- homogenous
- isotropic

Important tissues

- skin
- skull
- brain
- (CSF)

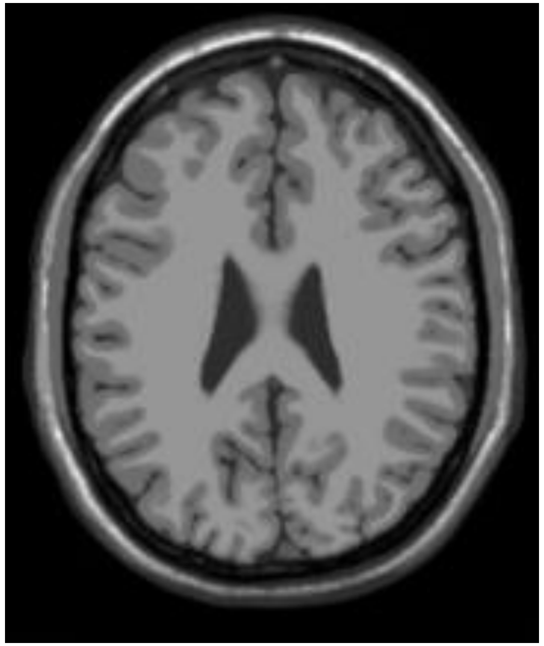
Triangulated surfaces describe boundaries

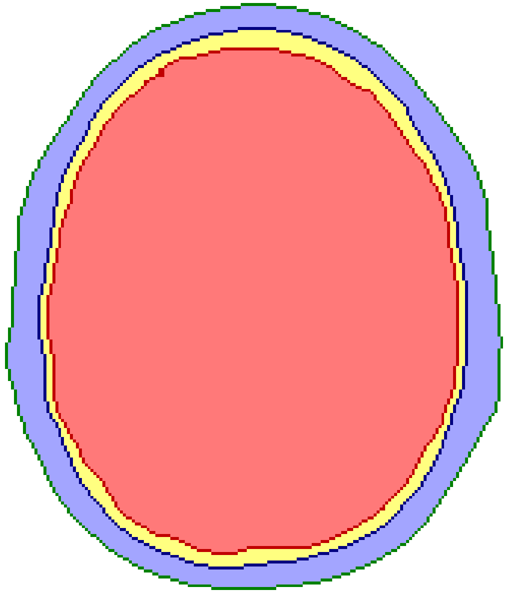


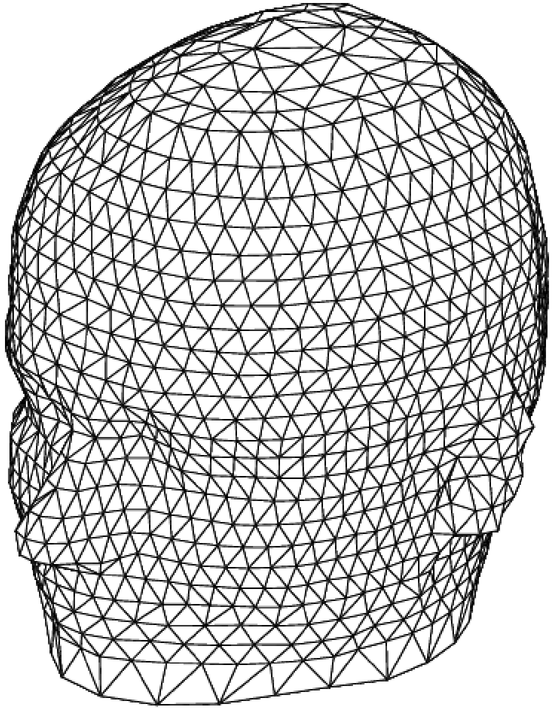
Volume conductor: Boundary Element Method

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

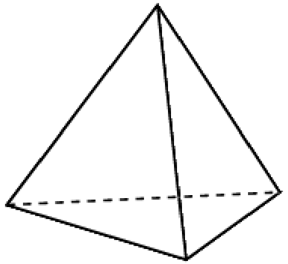
- segmentation in different tissue types
- extract surface description
- downsample to reasonable number of triangles

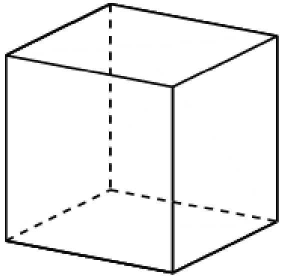
BEM computation of the volume conduction model

- independent of source model

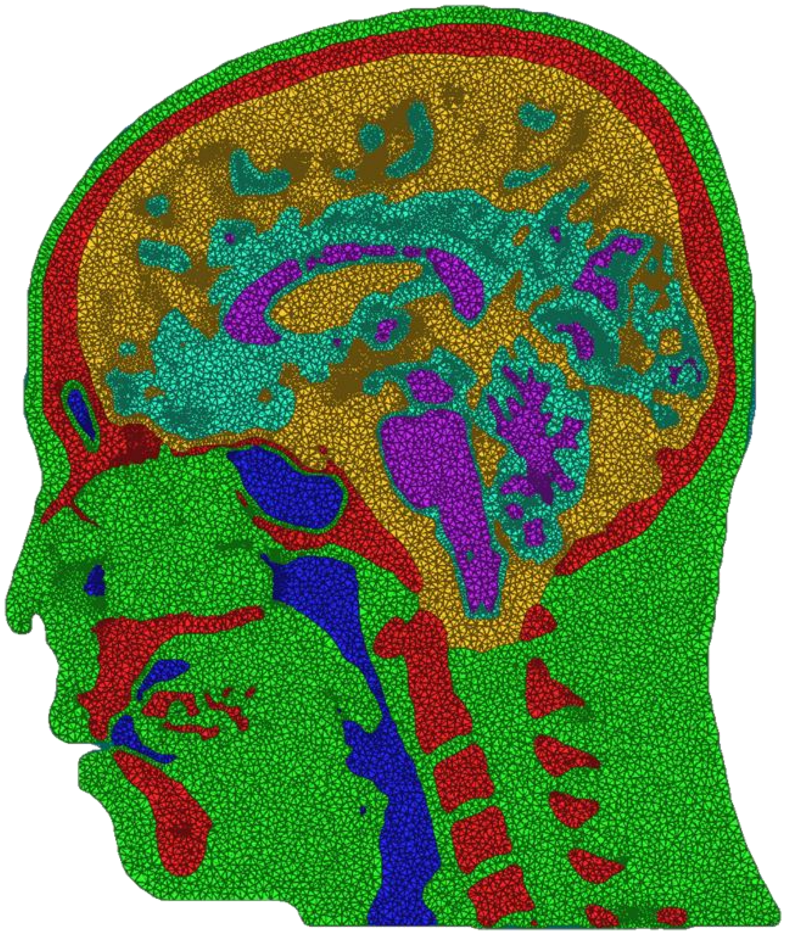
Volume conductor: Finite Element Method

Tesselation of 3D volume in
tetraeders or hexaheders

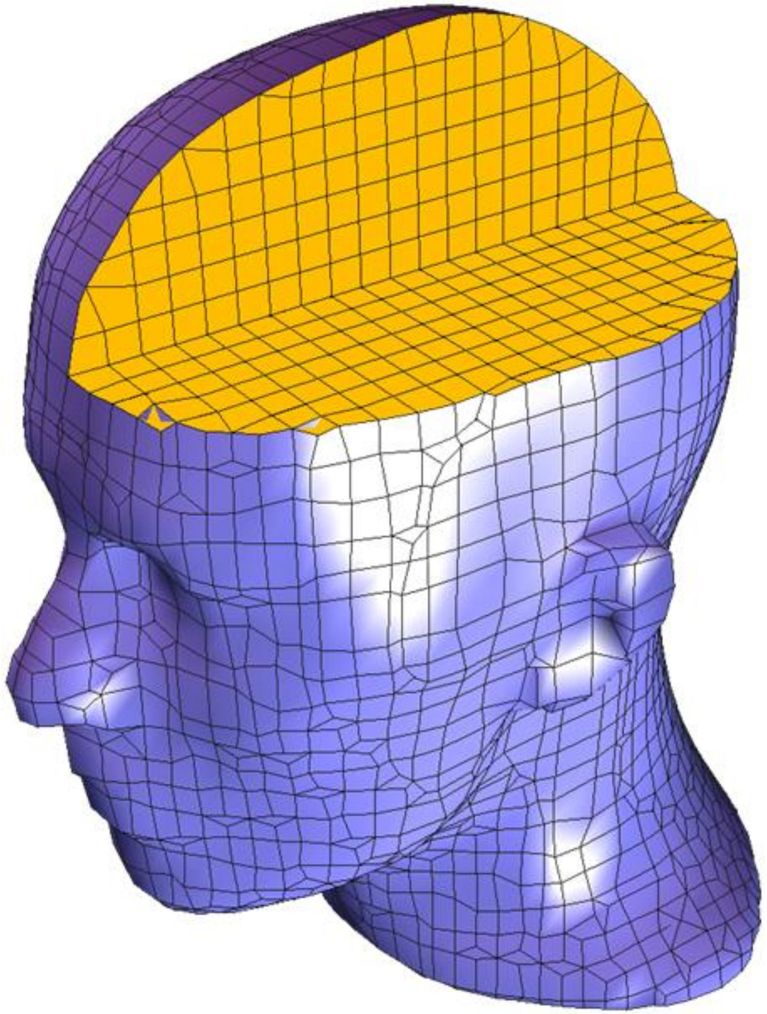




Volume conductor: Finite Element Method



tetraeders



hexaheders

Volume conductor: Finite Element Method

Tesselation of 3D volume in
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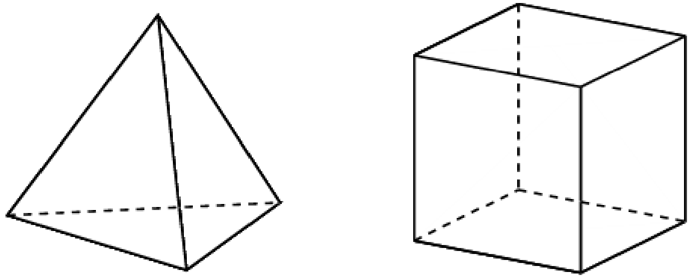


Each element can have its own conductivity

FEM is the most accurate numerical method but computationally quite expensive

Geometrical processing not as simple as BEM

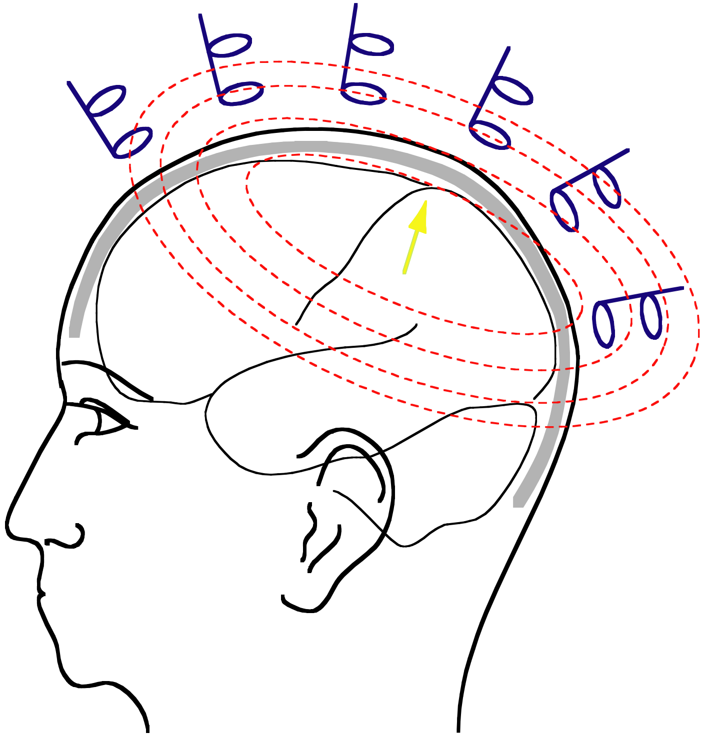
EEG volume conduction

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

Magnetoencephalography (MEG)



MEG volume conduction

MEG measures magnetic field over the scalp

Magnetic field itself is not distorted by skull

Only tiny fraction of current passes through skull, therefore the model can ignore the skull and skin

Magnetic field from ECDs but also from the volume currents

Overview

Motivation and background

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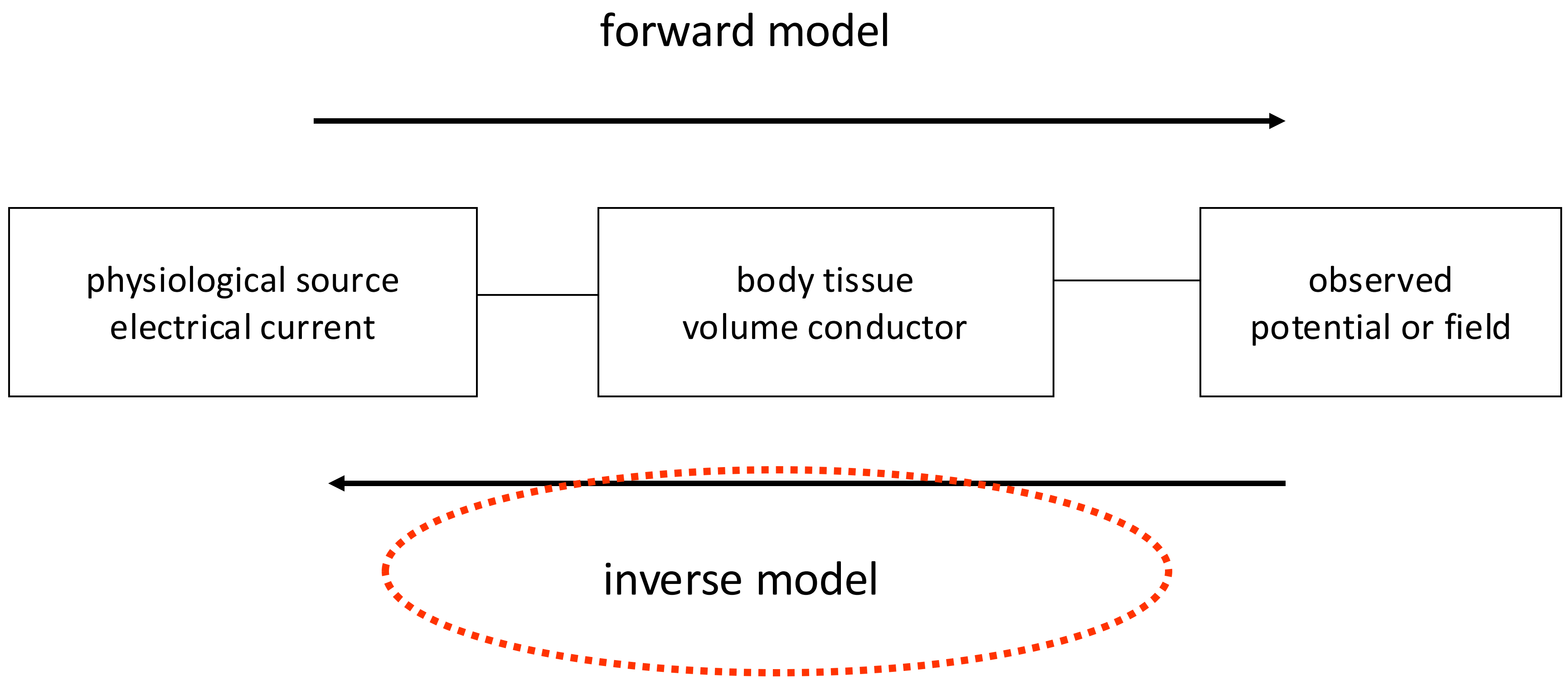
- Volume conductor model

Inverse modeling - biophysical models

- Single and multiple dipole fitting
- Distributed source models
- Beamforming

Biophysical source modelling: overview



Inverse localization: demo

Inverse 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)

Overview

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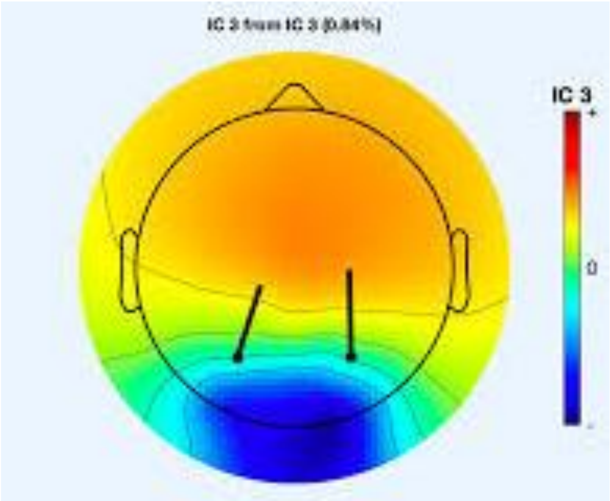
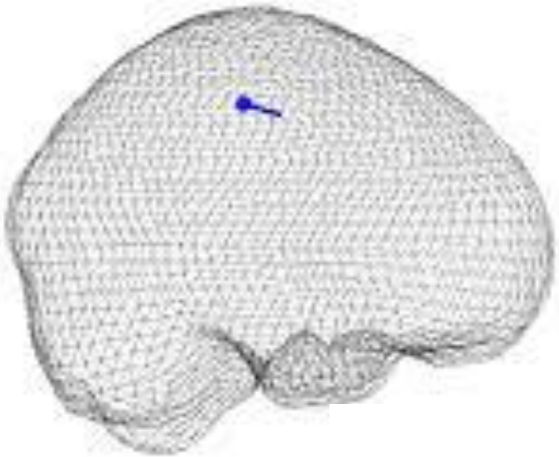
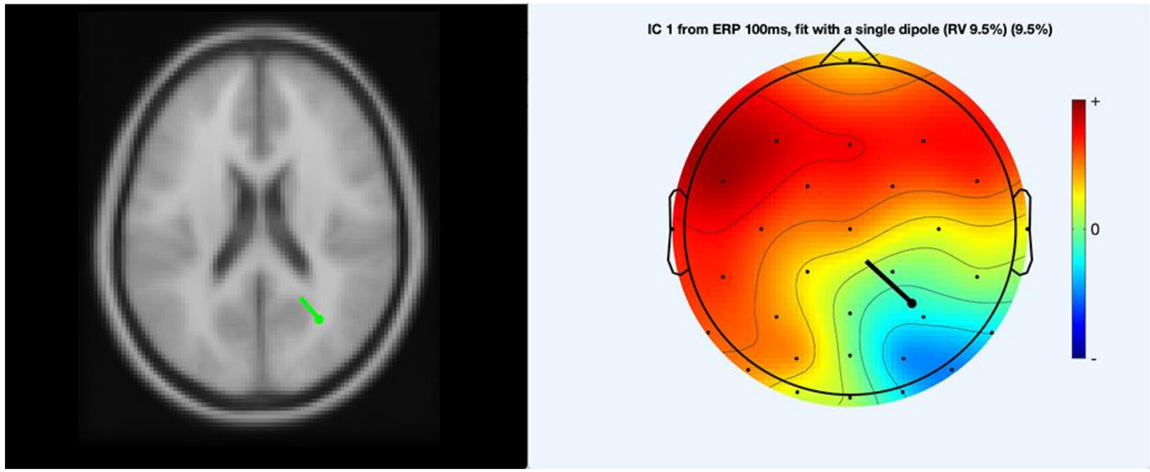
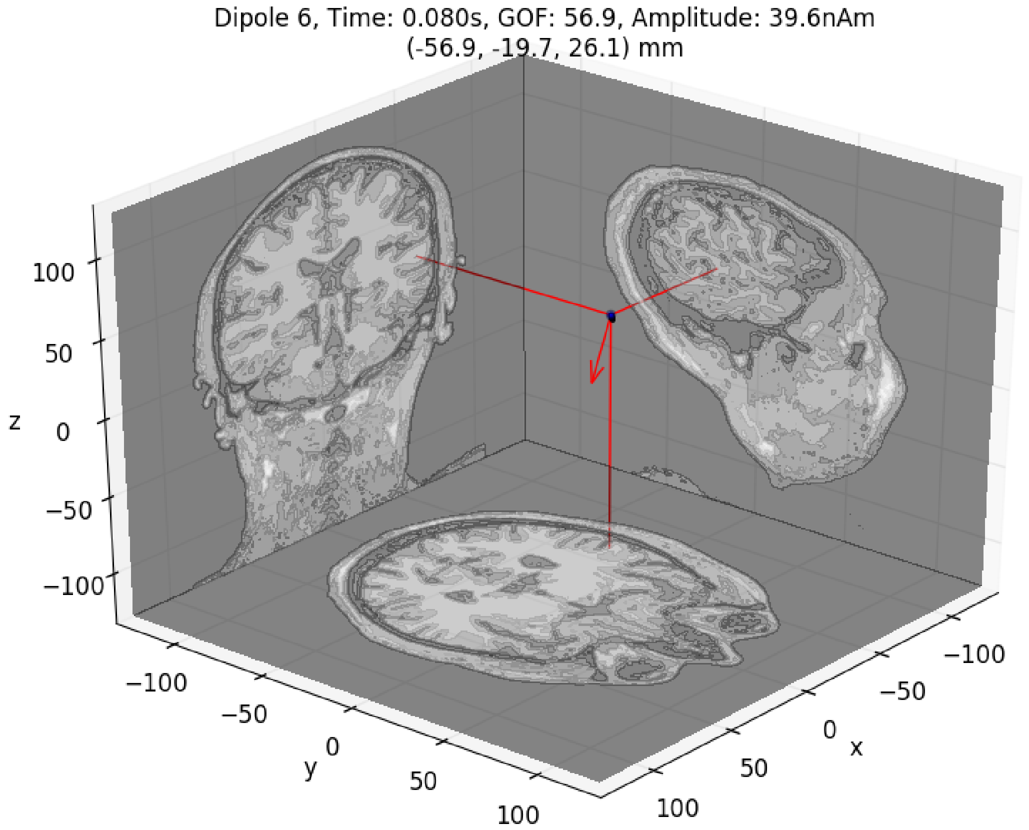
Dipole fitting

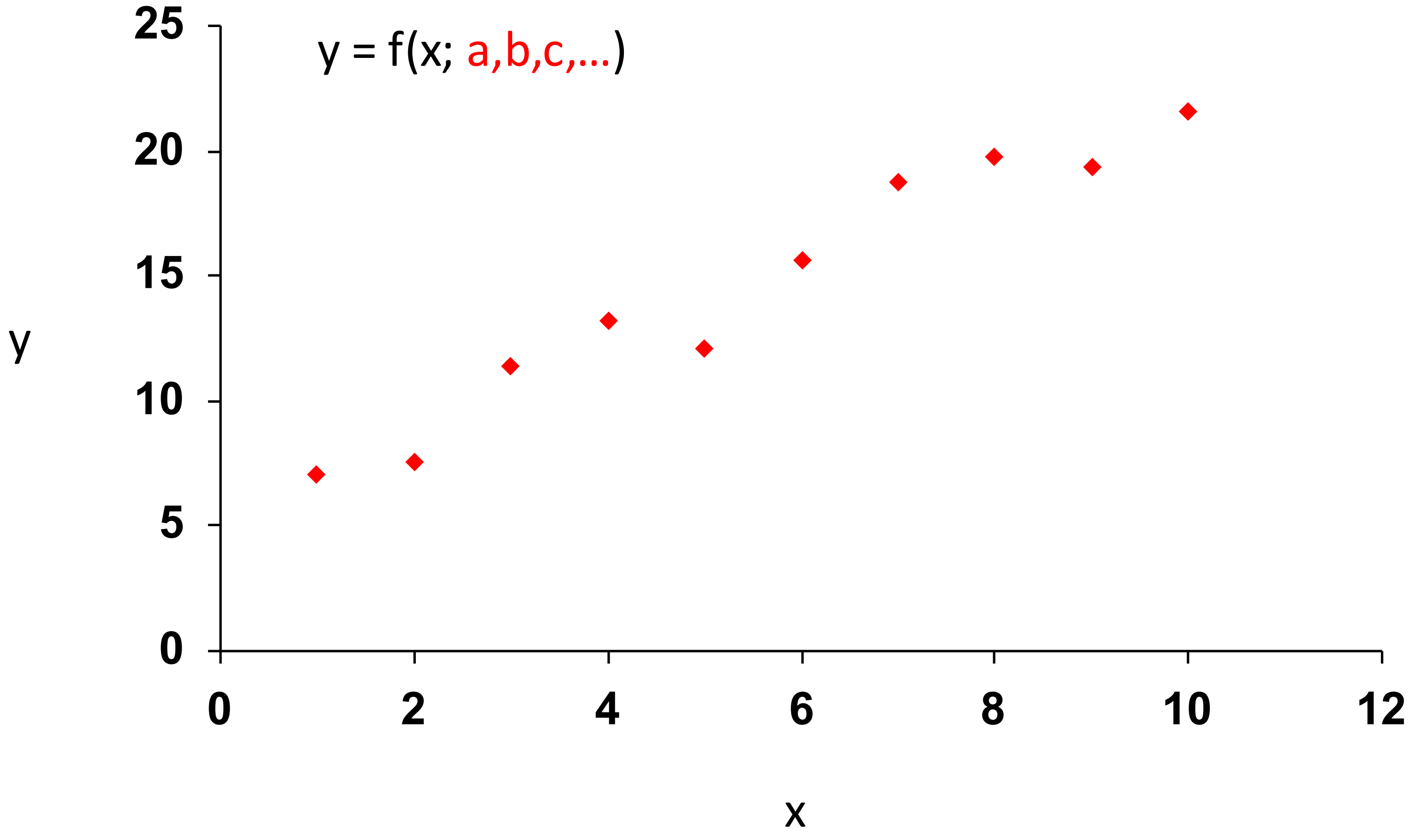








Single or multiple dipole models - Parameter estimation



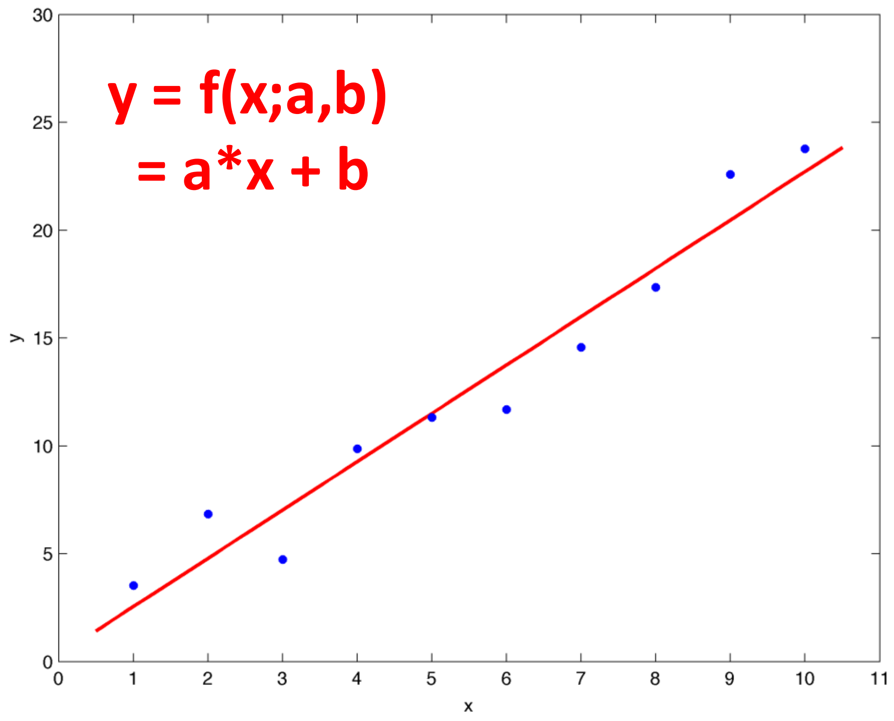
Parameter estimation: dipole parameters

source model with
few parameters

- position
- orientation
- strength

compute the model data

minimize difference
between actual and model
data



Dipole model: linear estimation

$$Y = L_1X_1 + L_2X_2 + ... + L_nX_n + \text{noise}$$

$$Y = L\,X + \text{noise}$$

Y is the data, for example 64x500 samples

L is the leadfield matrix, for example 64x3

X is the strength of the source, for example 3x500

The noise is the same size as the data

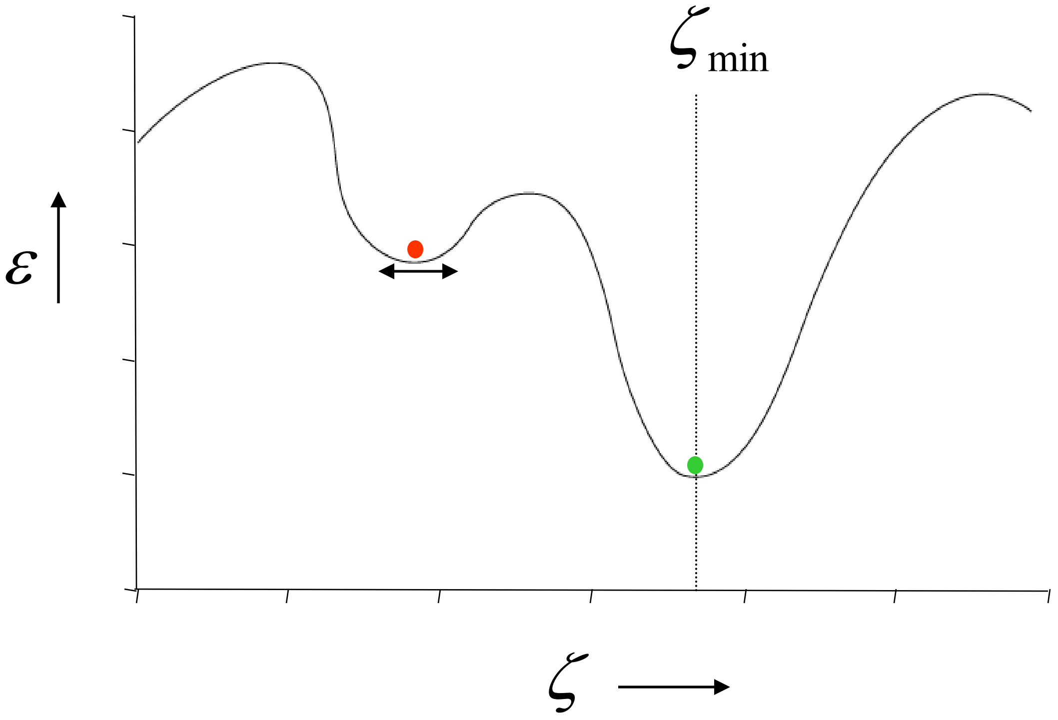
The leadfield L depends on the position of the source

We compare the model data Y with the measured data

Non-linear parameters

$$\varepsilon rror(\zeta) = \sum_{i=1}^{N} \left(Y_i(\zeta) - V_i\right)^2 \quad \Rightarrow \quad \min_{\zeta}\left(\varepsilon rror(\zeta)\right)$$

$$\zeta = a, b, c, \ldots$$



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

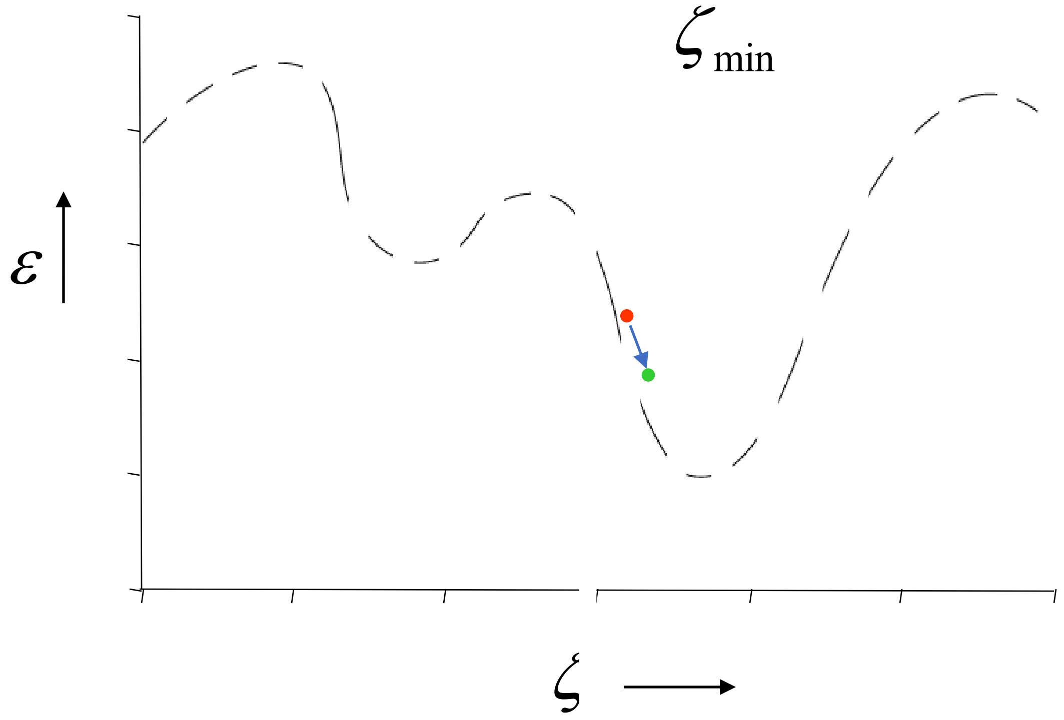
Two dipoles, each with three dimensions

100x100x100x100x100x100 = 10^{12}

Non-linear parameters: gradient descent optimization

$$\varepsilon rror(\zeta) = \square_{i=1}^{N} \left(Y_i(\zeta) - V_i\right)^2 \quad \Rightarrow \quad \min_{\zeta}\left(\varepsilon rror(\zeta)\right)$$

$$\zeta = a, b, c, \ldots$$



Single or multiple dipole models - Strategies

Single dipole:

scan the whole brain, followed by iterative optimization

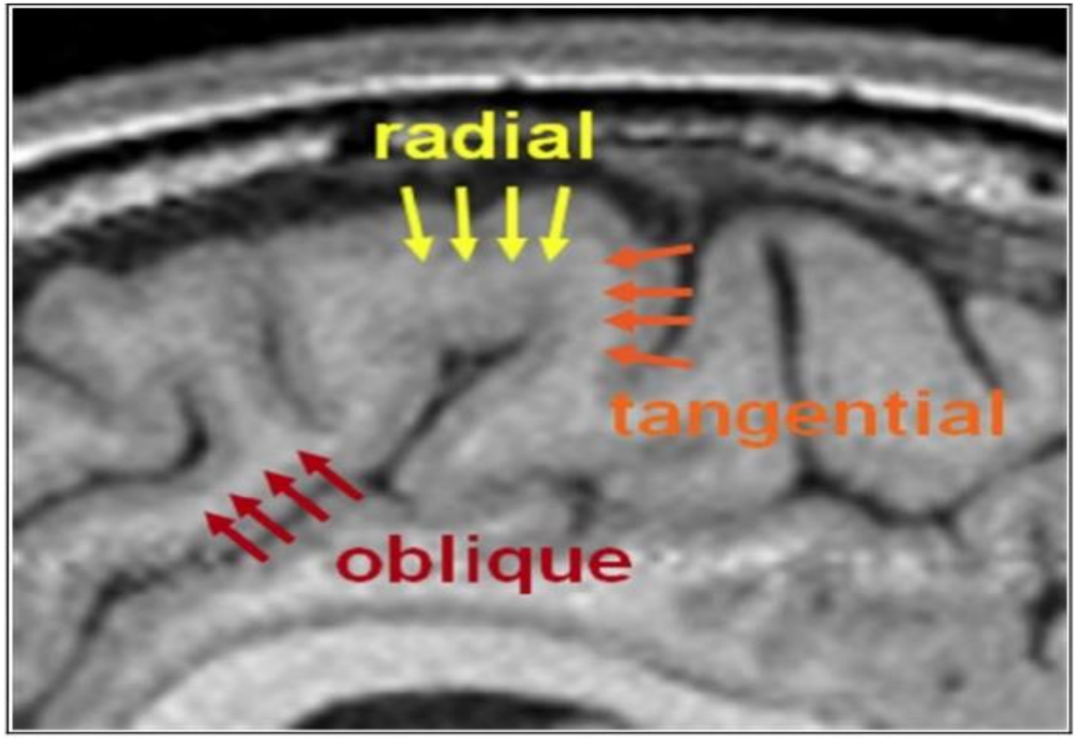
Two dipoles:

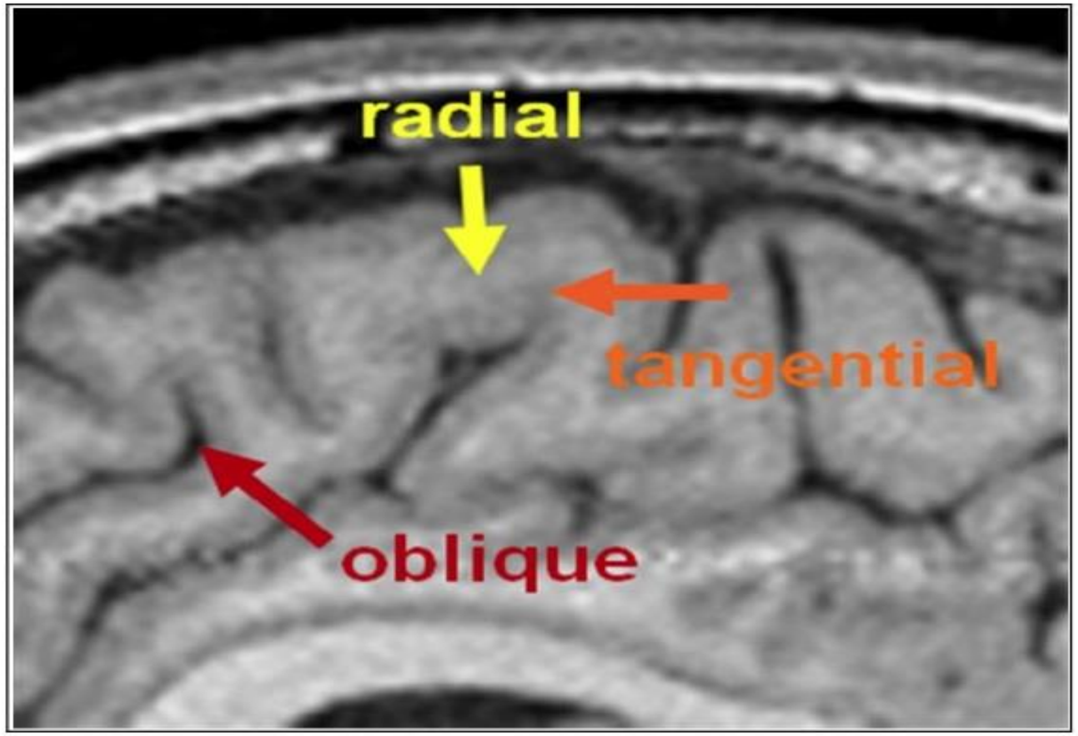
scan with symmetric pair, use that as starting point for iterative optimization

More dipoles:

sequential dipole fitting

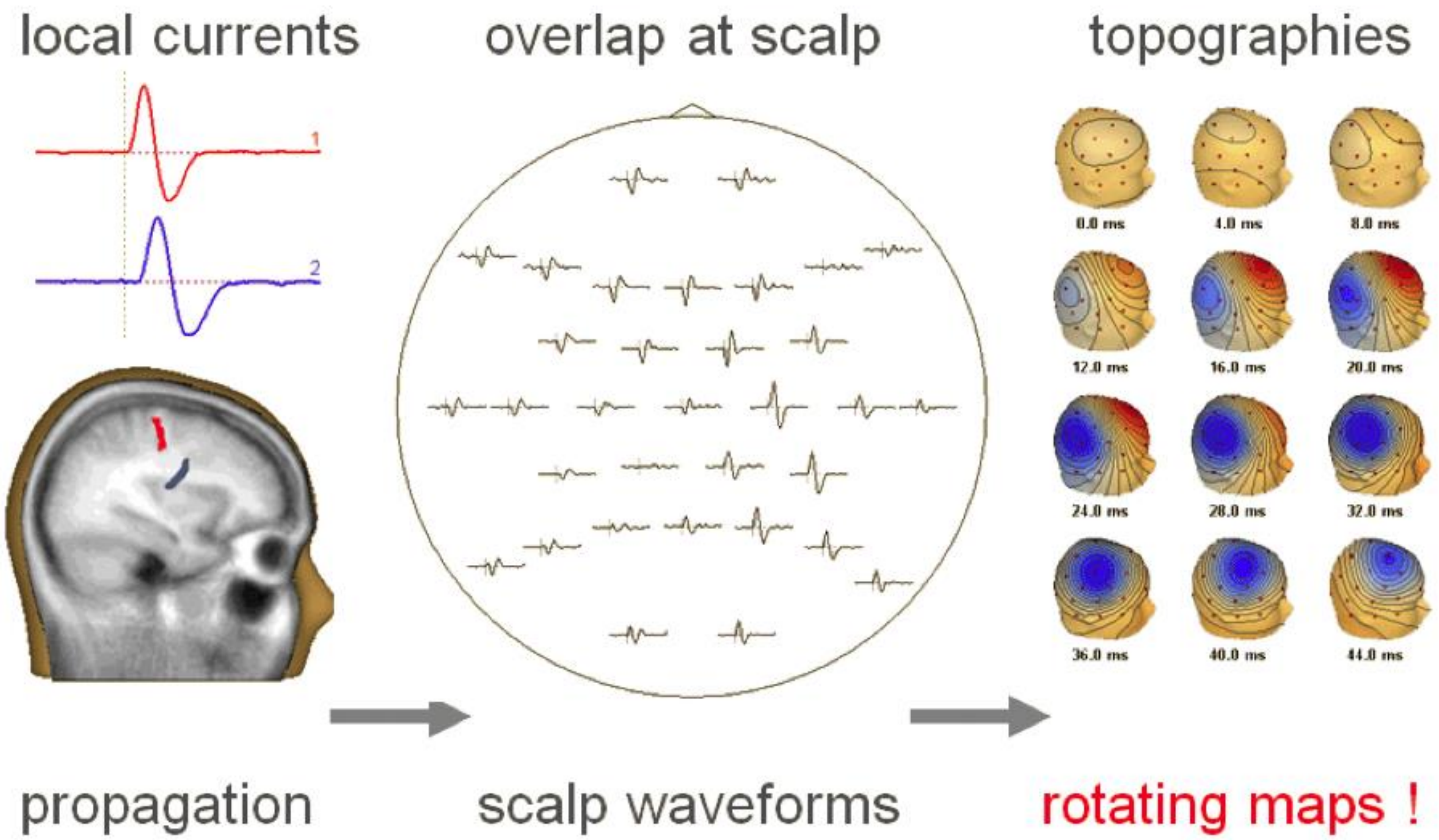
Sequential dipole fitting





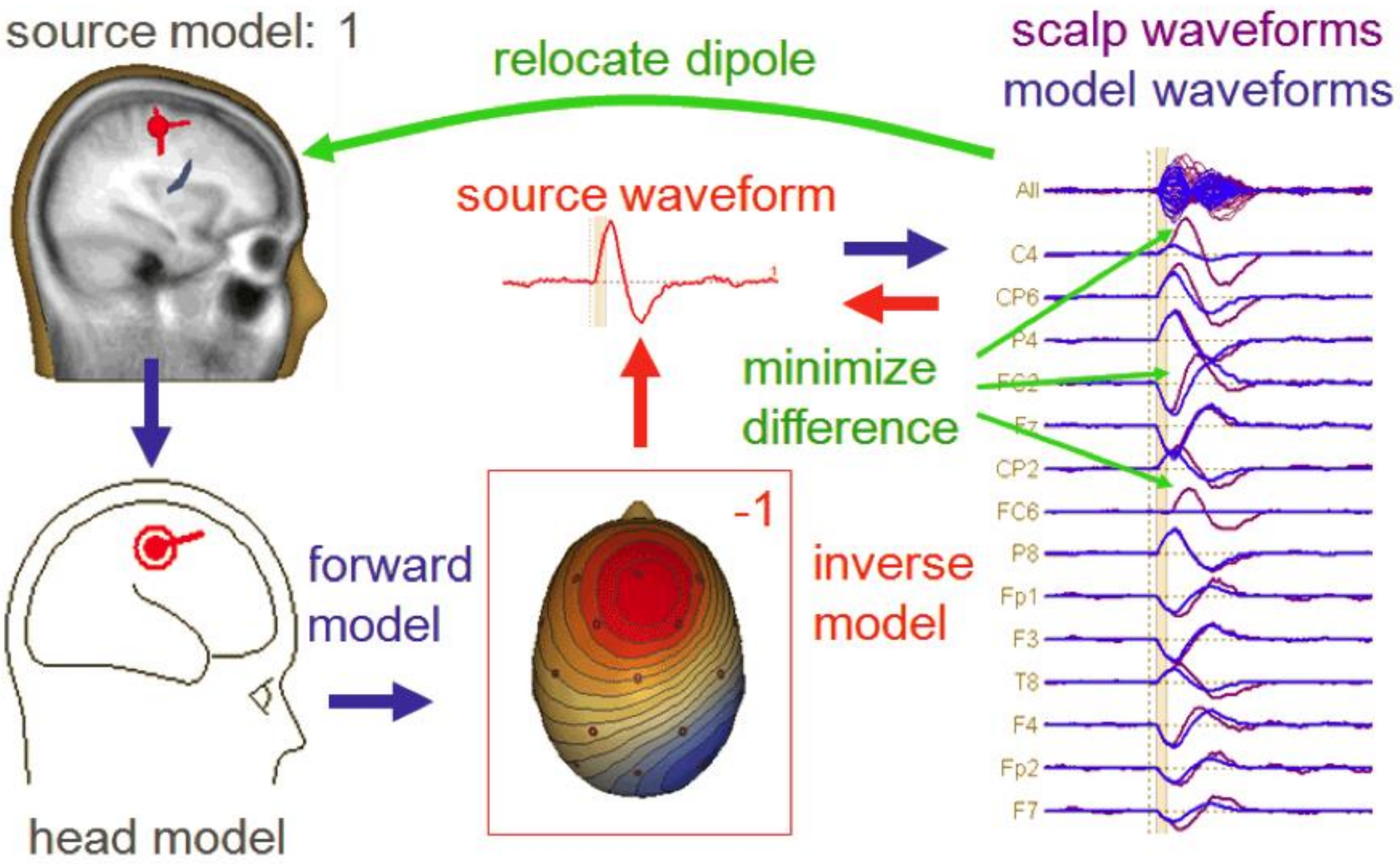
BESA manual

Sequential dipole fitting



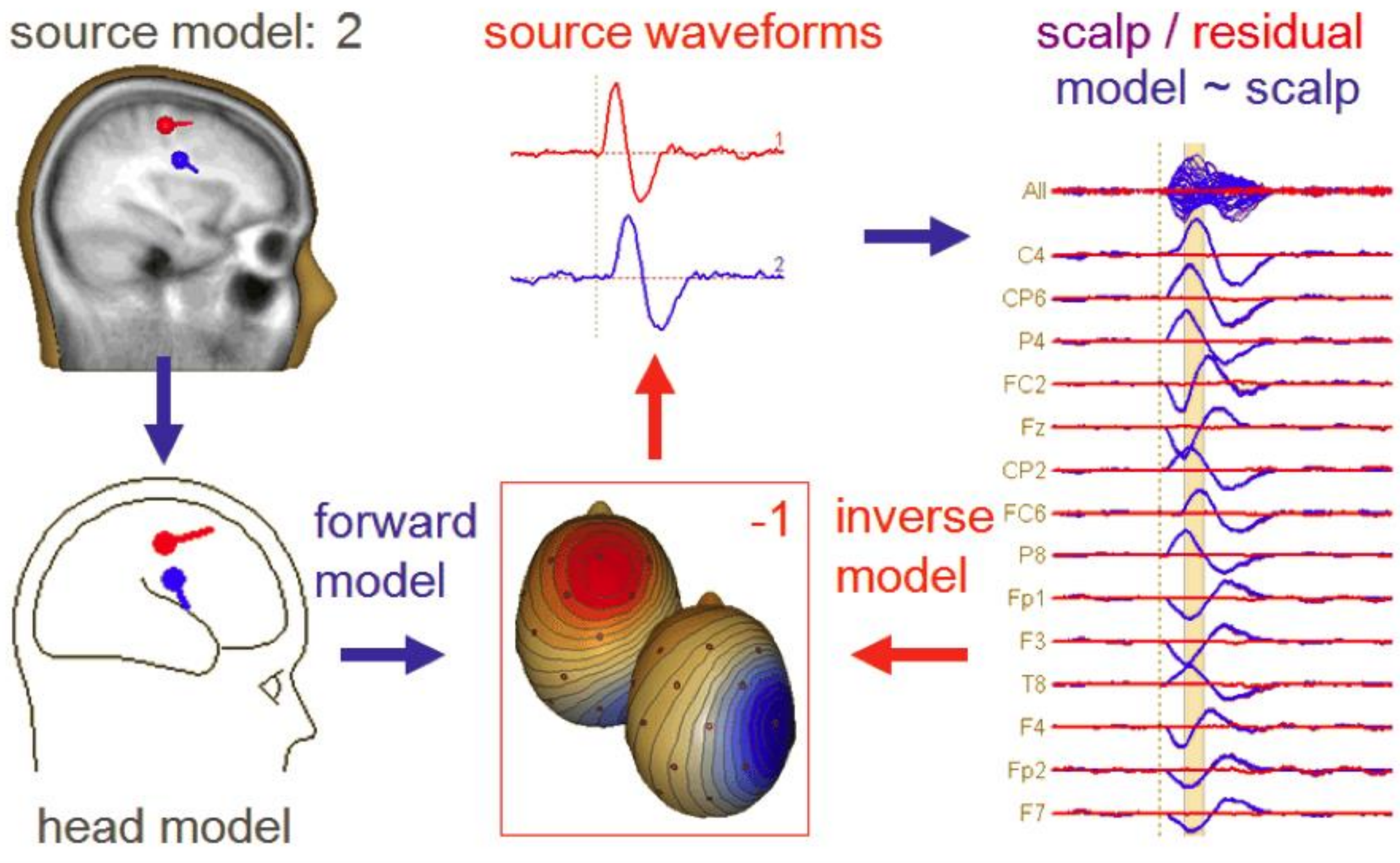
BESA manual

Sequential dipole fitting



BESA manual

Sequential dipole fitting



BESA manual

Sequential dipole fitting to explain spread of 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

Iterative and interactive (hence subjective) process

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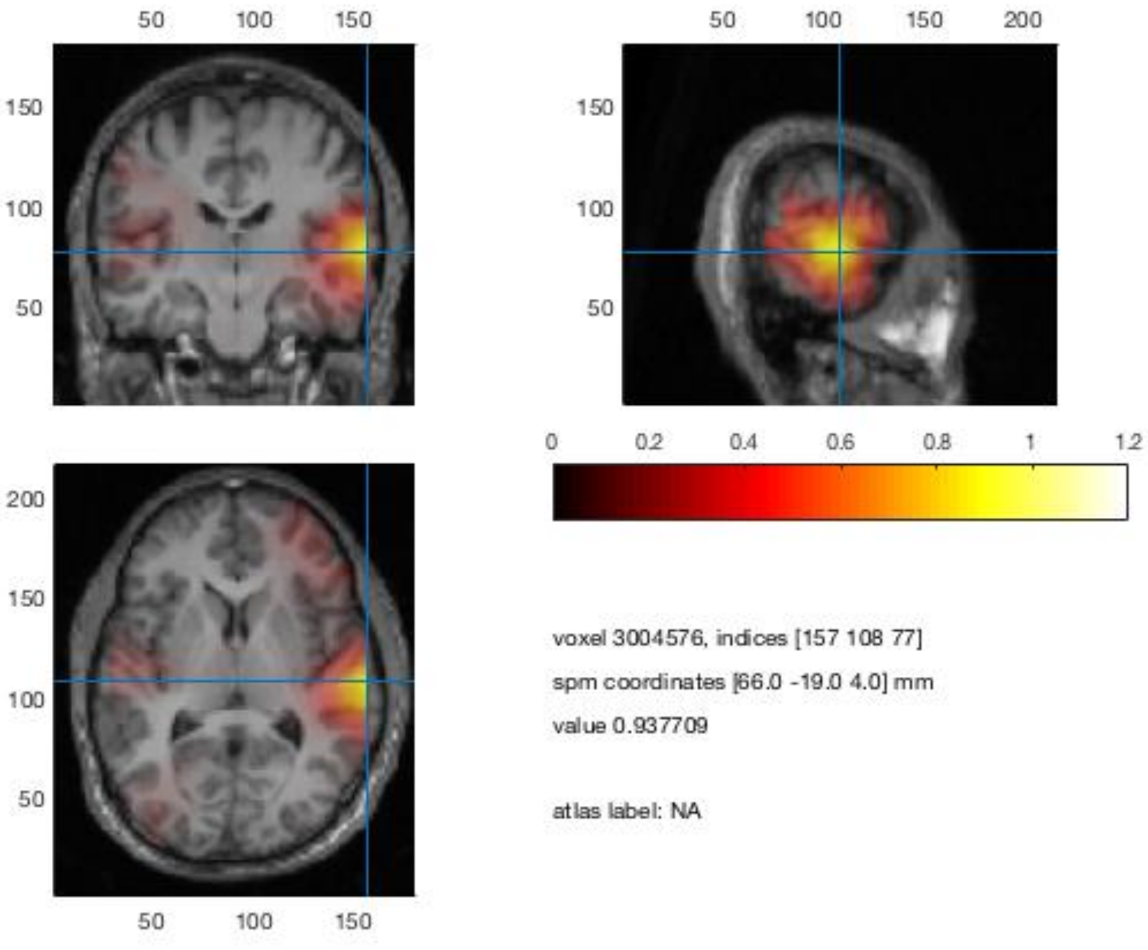
  - **Distributed source models and beamforming**

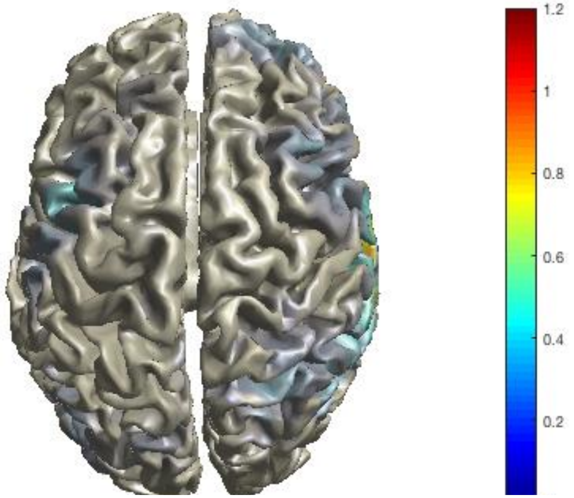
Distributed source models and beamforming

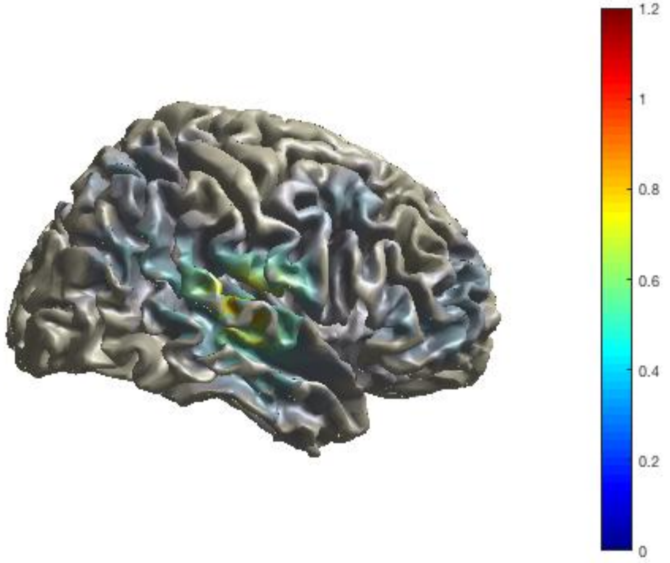
With dipole fitting we assume a single or a few point like sources (ECDs)

But what if we assume that there can be activity distributed over the whole brain?

Distributed source models and beamforming





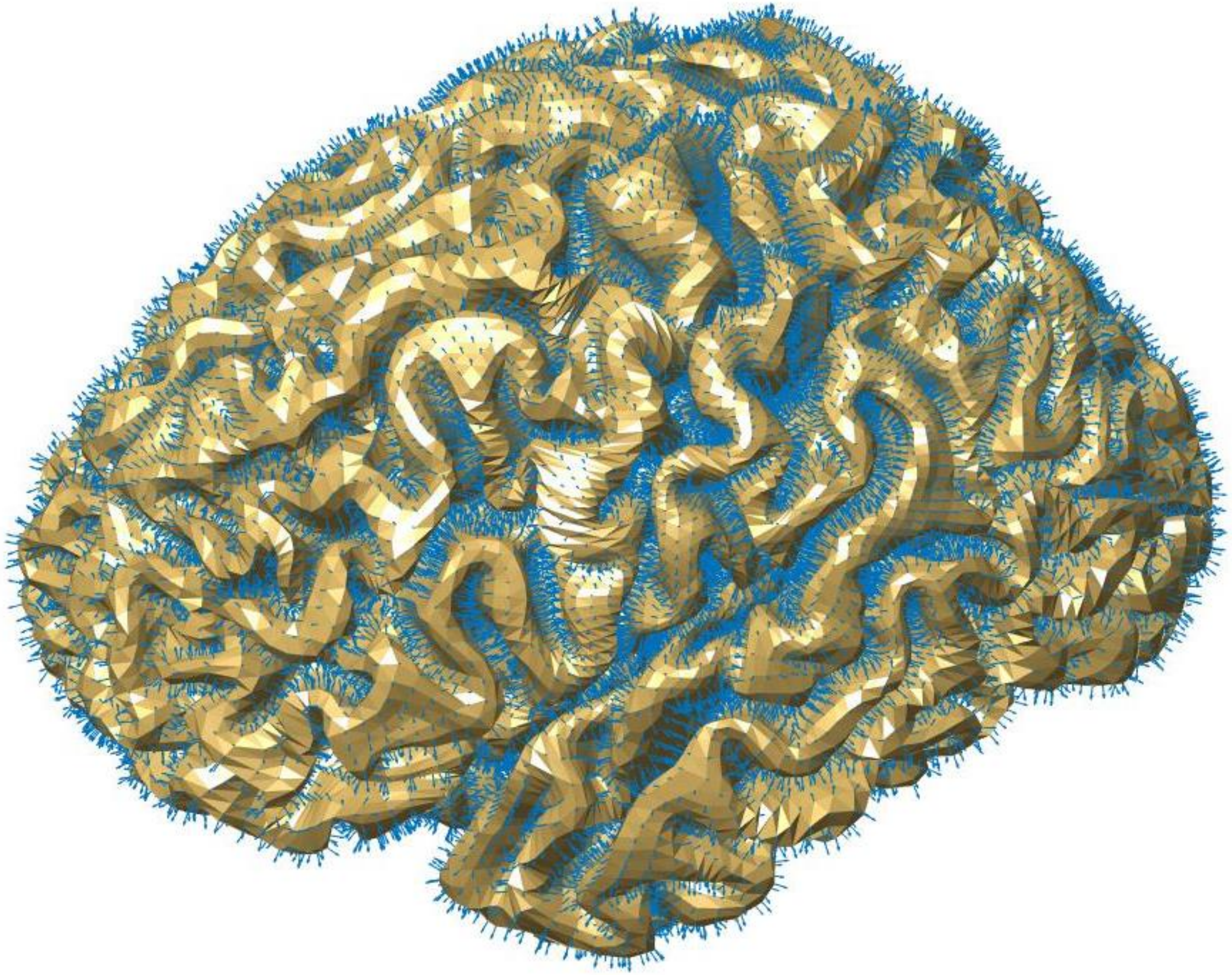


Distributed source models and beamforming

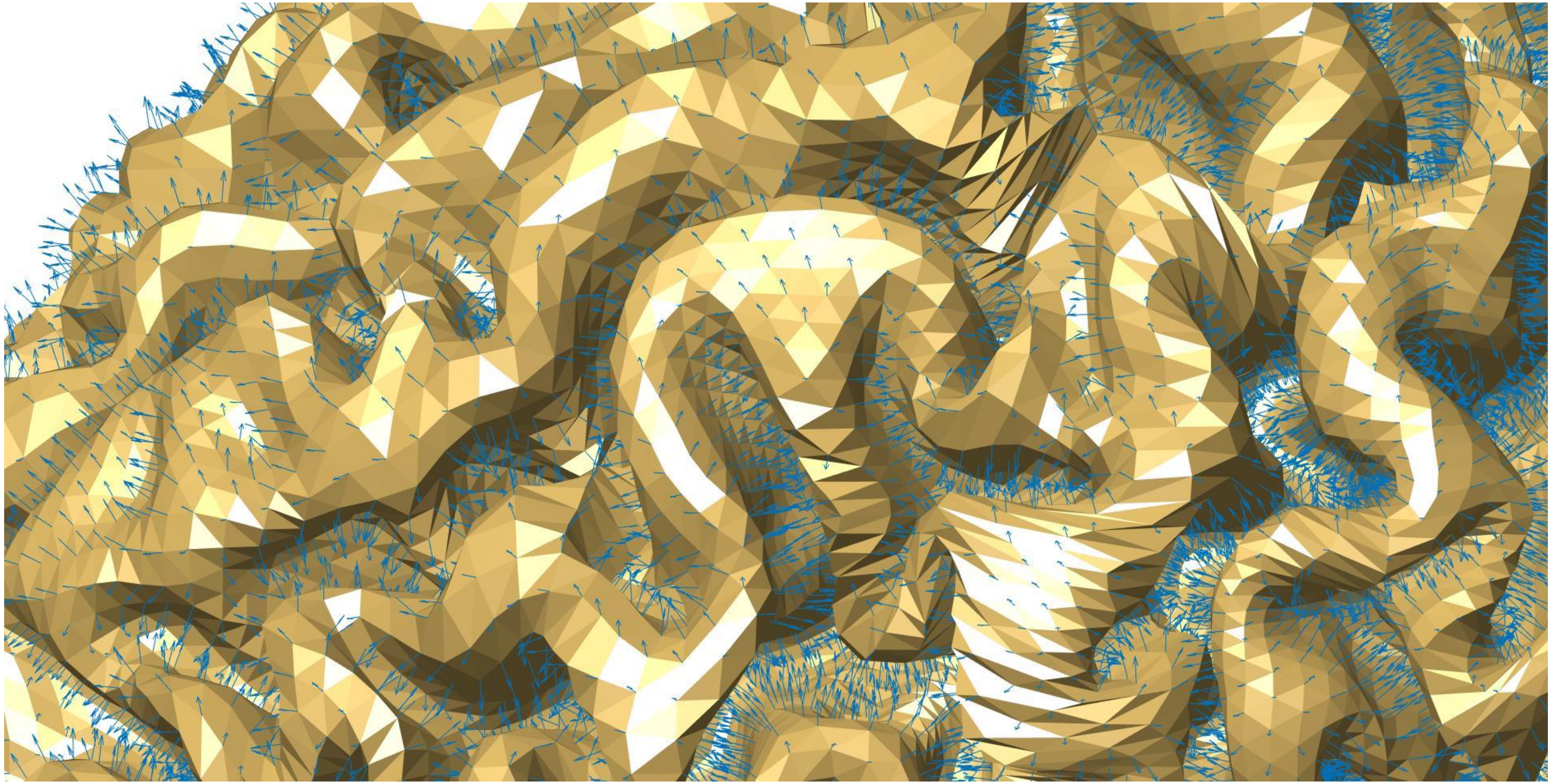
- Position of the source is not estimated as such
  - We can assume a pre-defined grid (3D volume or on cortical sheet)

- We can estimate the strength at every location
  - In principle easy to solve, however…
  - More “unknowns” than “knowns”
  - Infinite number of solutions can explain the data perfectly
  - Additional constraintsor assumptions are required

Distributed source model



Distributed source model



Distributed source model: linear estimation

$$Y = L_1X_1 + L_2X_2 + \ldots + \ldots + \ldots + \ldots + \ldots + \ldots + \ldots + L_nX_n + \text{noise}$$

$$Y = L\,X + \text{noise}$$

Y is the data, for example 64x500 samples

L is the leadfield matrix, for example 64x8000

X is the strength of the source, for example 8000x500

We now have to estimate 8000x500 parameters, from 64x500 data points

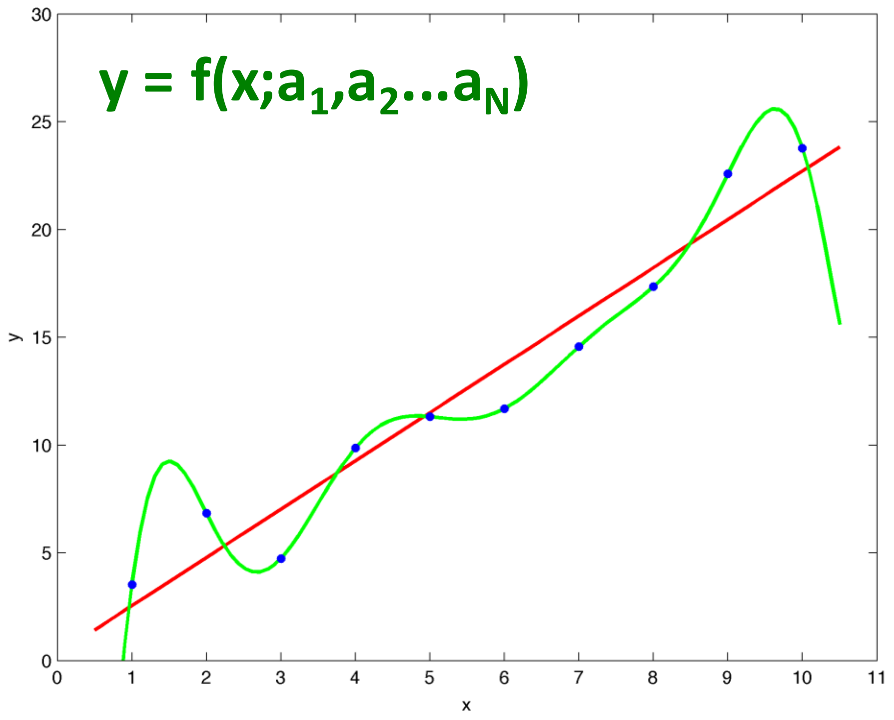
This is an overdetermined linear system

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 estimation

To find a unique solution to the overdetermined problem we make additional assumptions.

The general assumption is that we want to have the “simplest” solution, so the solution with the minimal overall “norm”.

The “norm” expresses the overall amplitude or power of all the sources distributed in the brain.

We compute the Minimum Norm Estimate (MNE).

We can use additional assumptions about the noise and distribution.

Beamforming

With beamforming we also assume that there can be activity everywhere in the brain.

Rather than computing the activity at all locations simultaneously, we compute it for each location seperately.

We scan the whole brain, and for each location we compute a “spatial filter”.

This also requires extra assumptions: that the sources are uncorrelated, which is not always the case in reality.

Which source localization method to use

Dipole fitting

Distributed source estimation using MNE

Distributed source estimation using beamforming

Each of them has different assumptions on the actual sources.

Your data is different from others' data, so the method that is best for you might be different as well.

Let's discuss some practical guidelines for selecting a method…

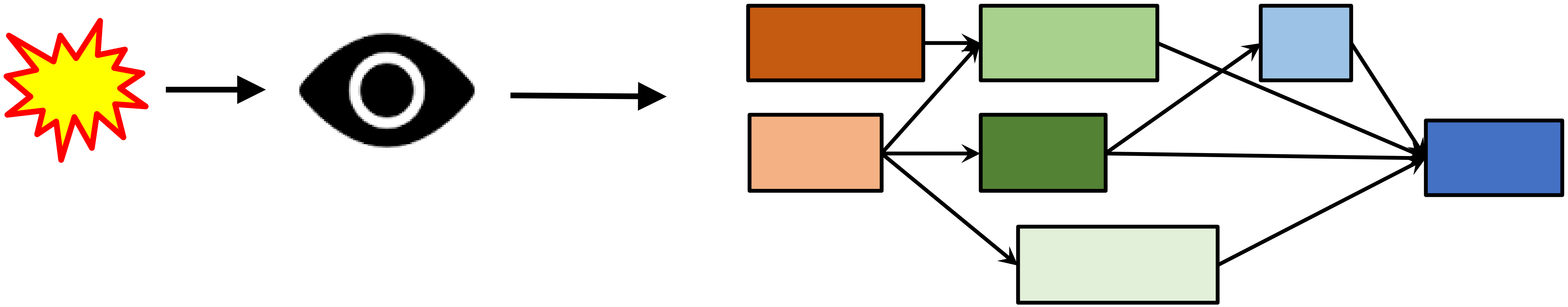
Localizing and understanding the ERP

If you find a ERP component, you want to characterize it in physiological terms

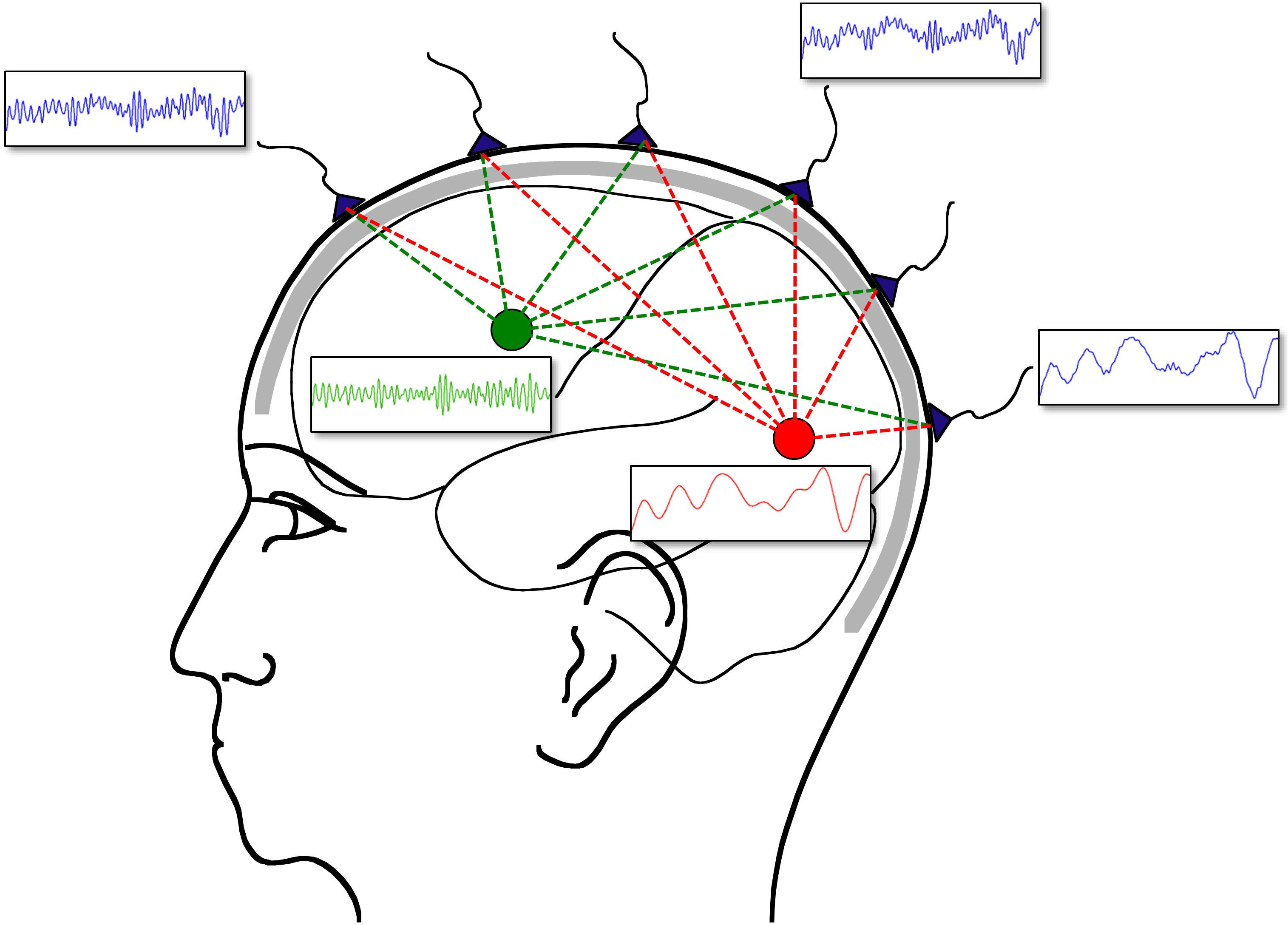
- Time is the "natural" characteristic of the ERP
- "Location" requires interpretation of the scalp topography

Forward and inverse modeling helps to interpret the **spatial distribution**

Forward and inverse modeling helps to disentangle overlapping source **timeseries**



Localize *and* disentangle the source activity



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