Forward and inverse models

Localizing sources using DIPFIT

Robert Oostenveld

Donders Institute for Brain, Cognition and Behaviour

Nijmegen, The Netherland

F. C. Donders Centre

Swartz Center for Computational Neuroscience

DIPFIT: localizing dipoles

- Motivation
- Ingredients
  - Source model
  - Volume conductor model
    - Analytical (spherical model)
    - Numerical (realistic model)
  - Comparison EEG and MEG
- Inverse modeling
  - Single and multiple dipole fitting
  - Distributed source models

DIPFIT: localizing dipoles

- Motivation
- Ingredients
  - Source model
  - Volume conductor model
    - Analytical (spherical model)
    - Numerical (realistic model)
  - Comparison EEG and MEG
- Inverse modeling
  - Single and multiple dipole fitting
  - Distributed source models

F. C. Donders Centre

Swartz Center for Computational Neuroscience

Motivation

- Why fit dipoles?
- Why measure EEG?
- Why do ICA?

- Get extra information about brain processes
  - Time course of activity ----> **EEG**
  - Location of activity ----> **fMRI**

Difference between EEG and fMRI

- EEG measures post-synaptic potentials
  - related to synchronized neuronal input
- fMRI measures BOLD
  - related to energy consumption

- Different characteristics in the time domain
- Different generators

- Timecourse *and* location

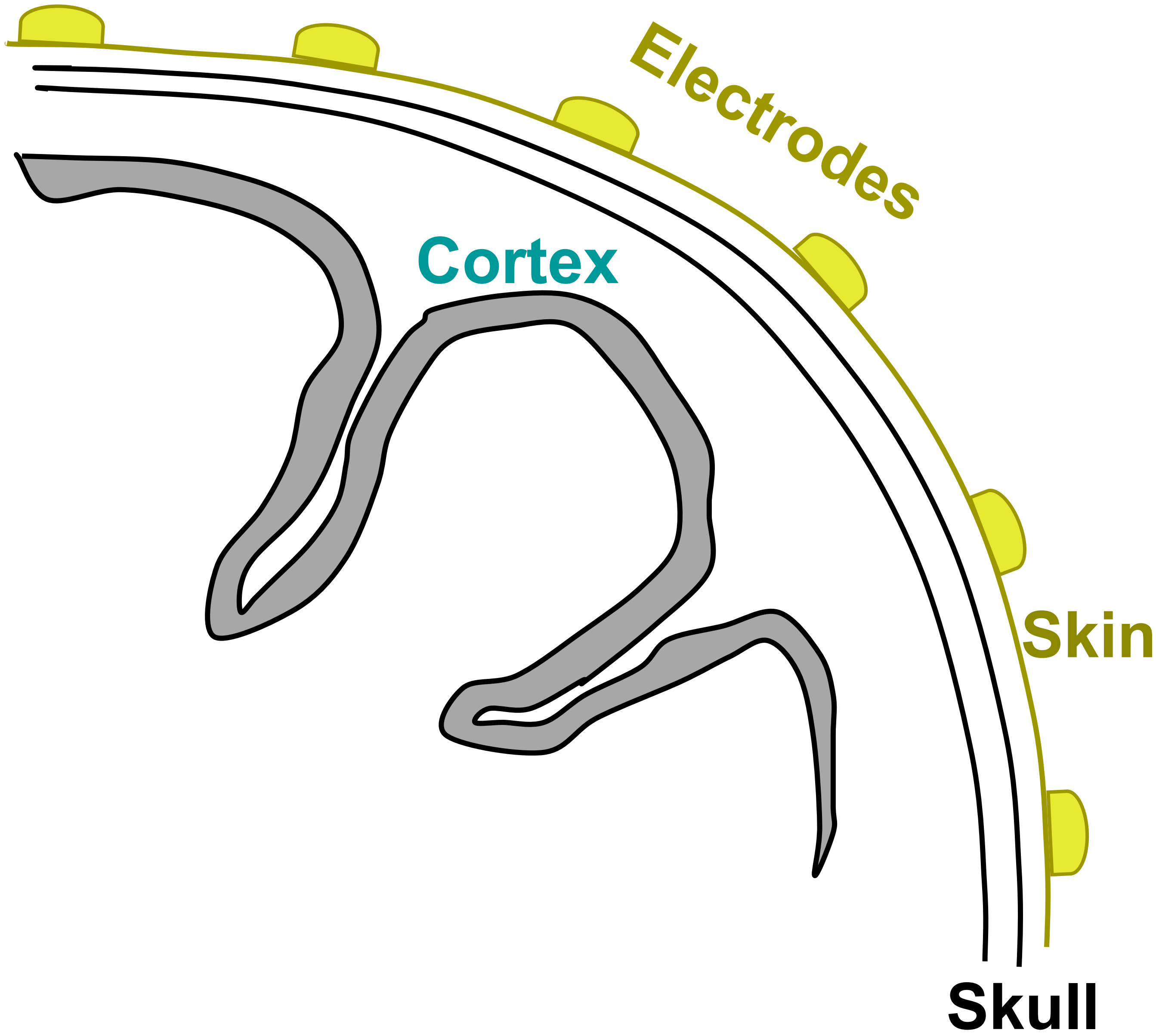
Why EEG: extra information

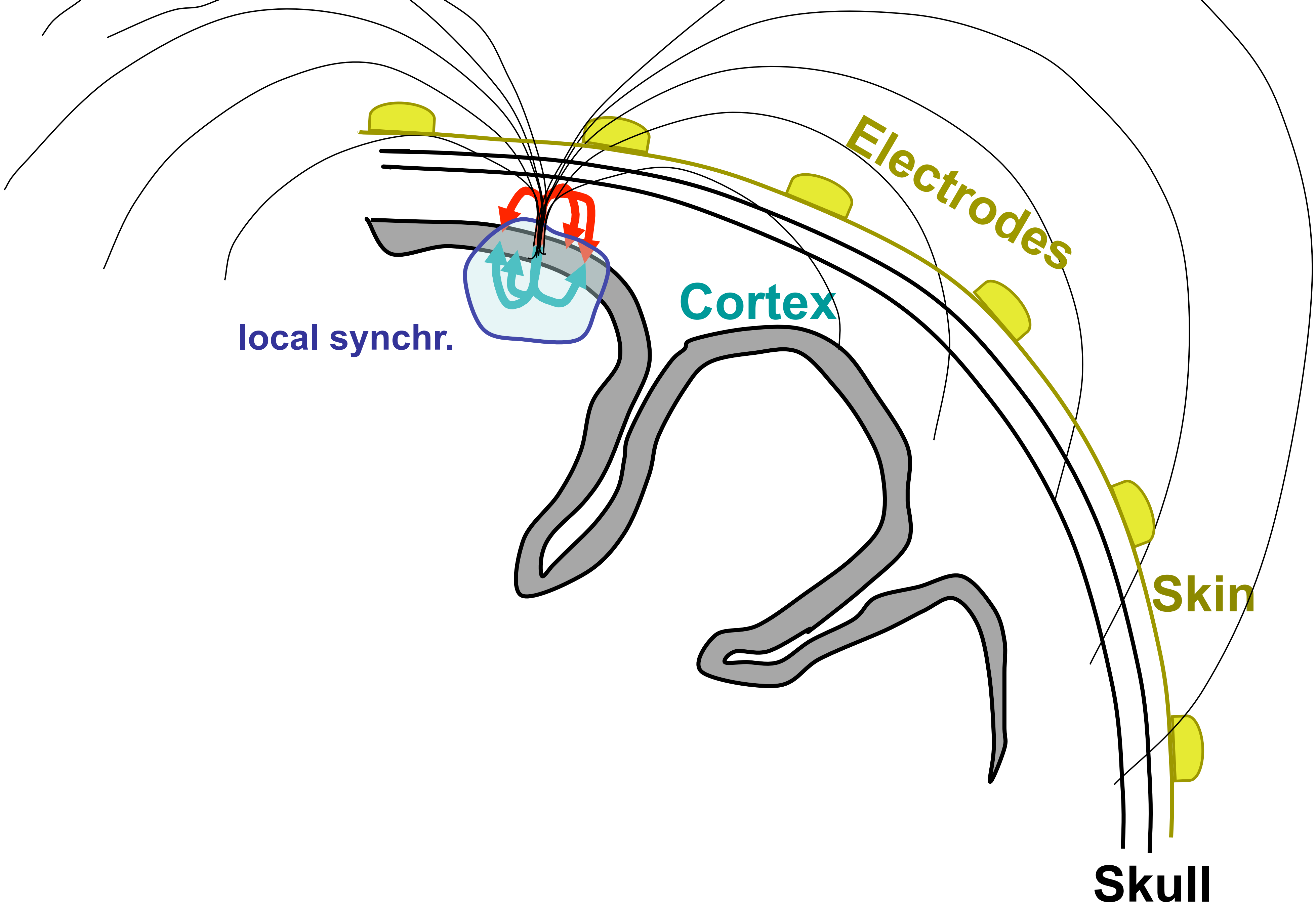
- Timecourse
  - ERSP
  - ERP
- Topography
  - Scalp distribution
  - Underlying generators

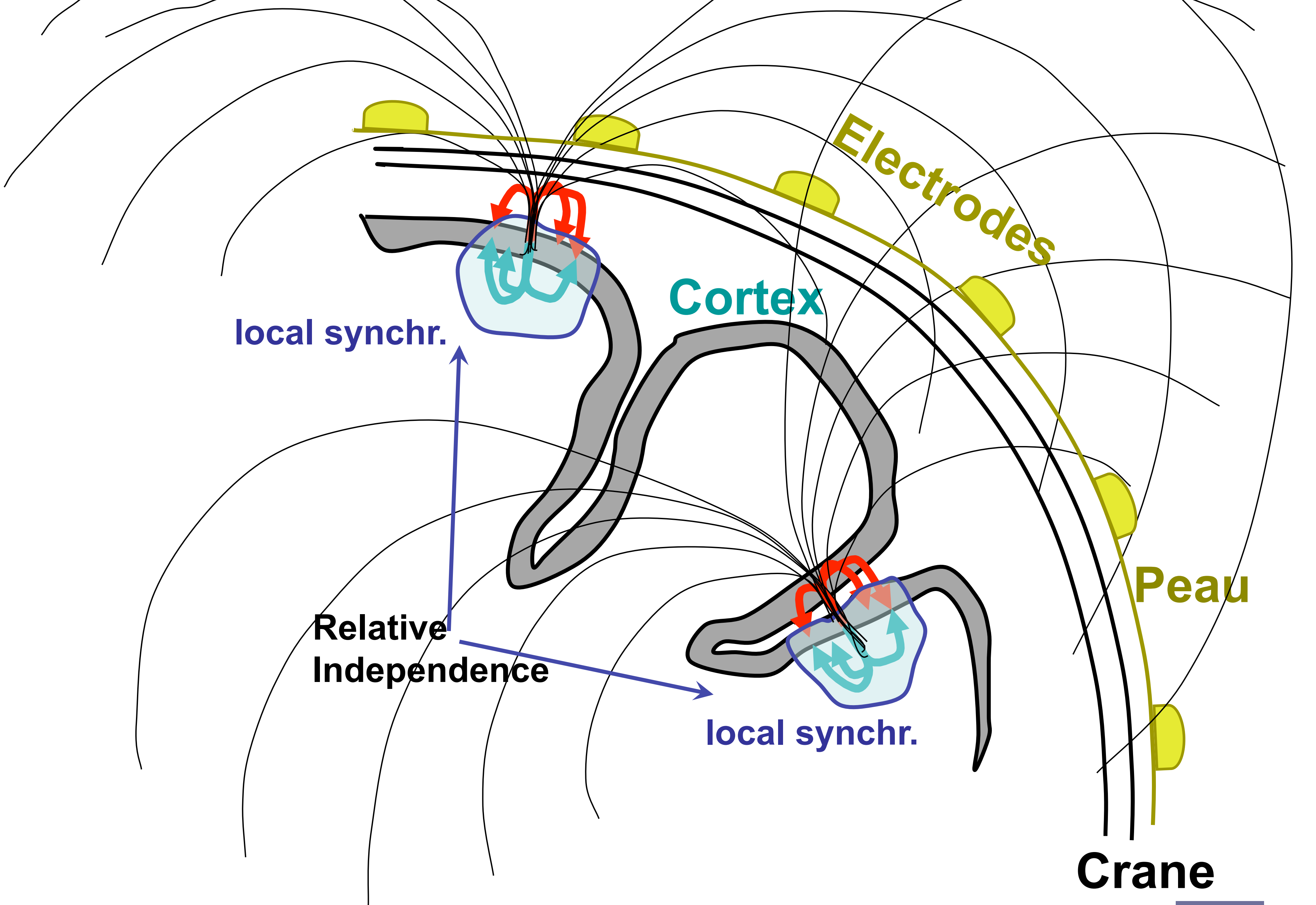
ICA

F. C. Donders Centre

Swartz Center for Computational Neuroscience

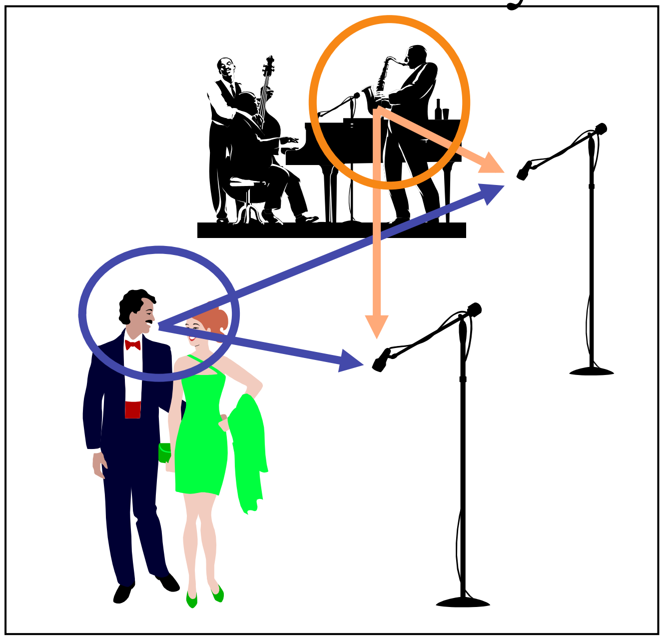

Electrodes
Cortex
Skin
Skull


Electrodes
Cortex
local synchr.
Skin
Skull

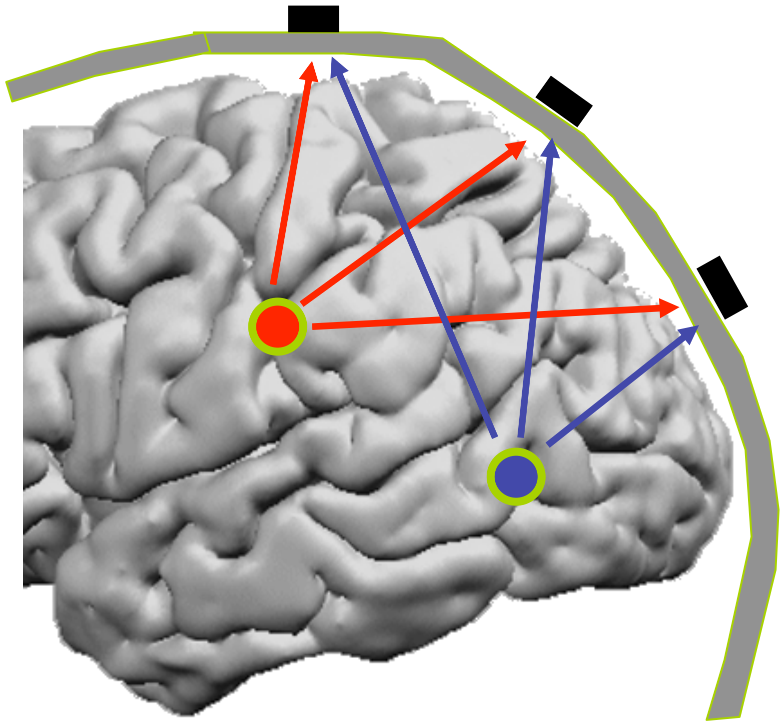

Electrodes
Cortex
local synchr.
Peau
Relative
Independence
local synchr.
Crane

Independent component analysis

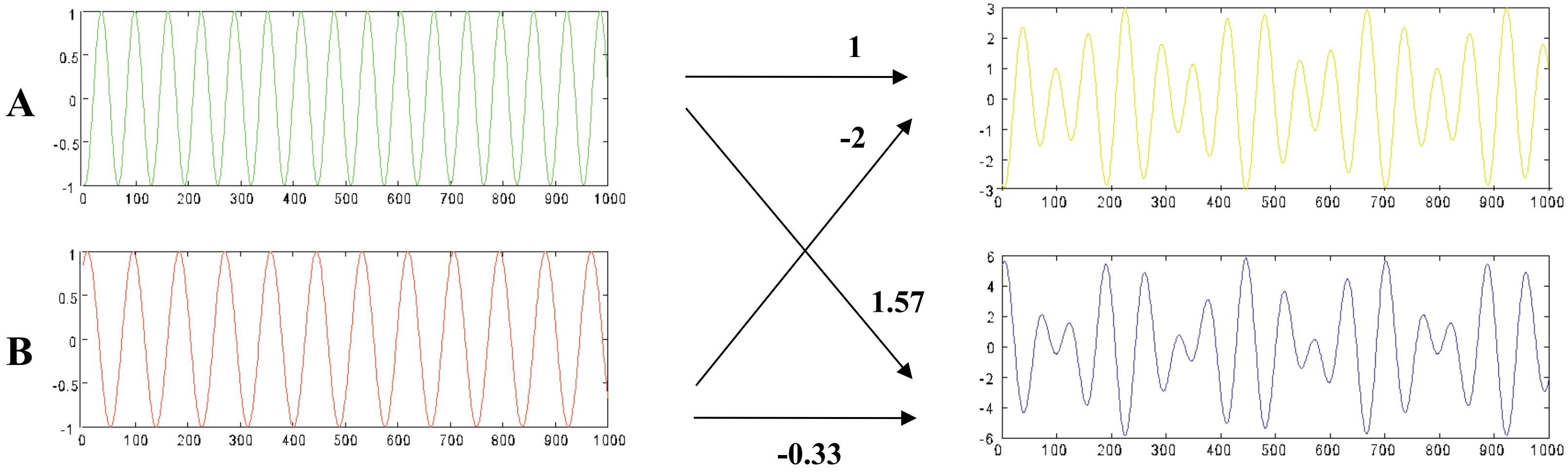
Cocktail Party



Mixture of Brain source activity



Infomax ICA



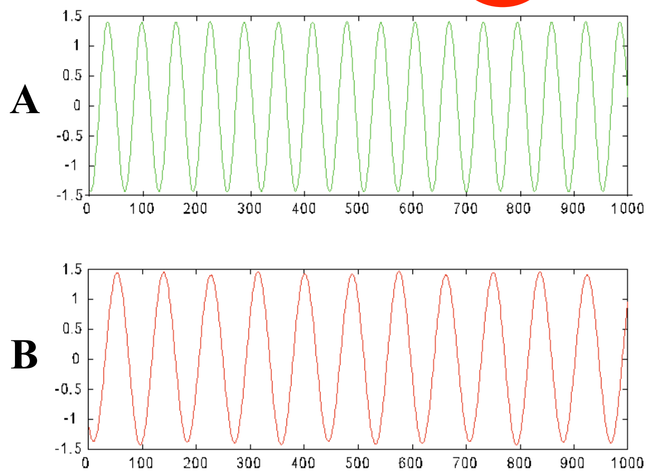
$Y=[A;B]$

Linear Combination

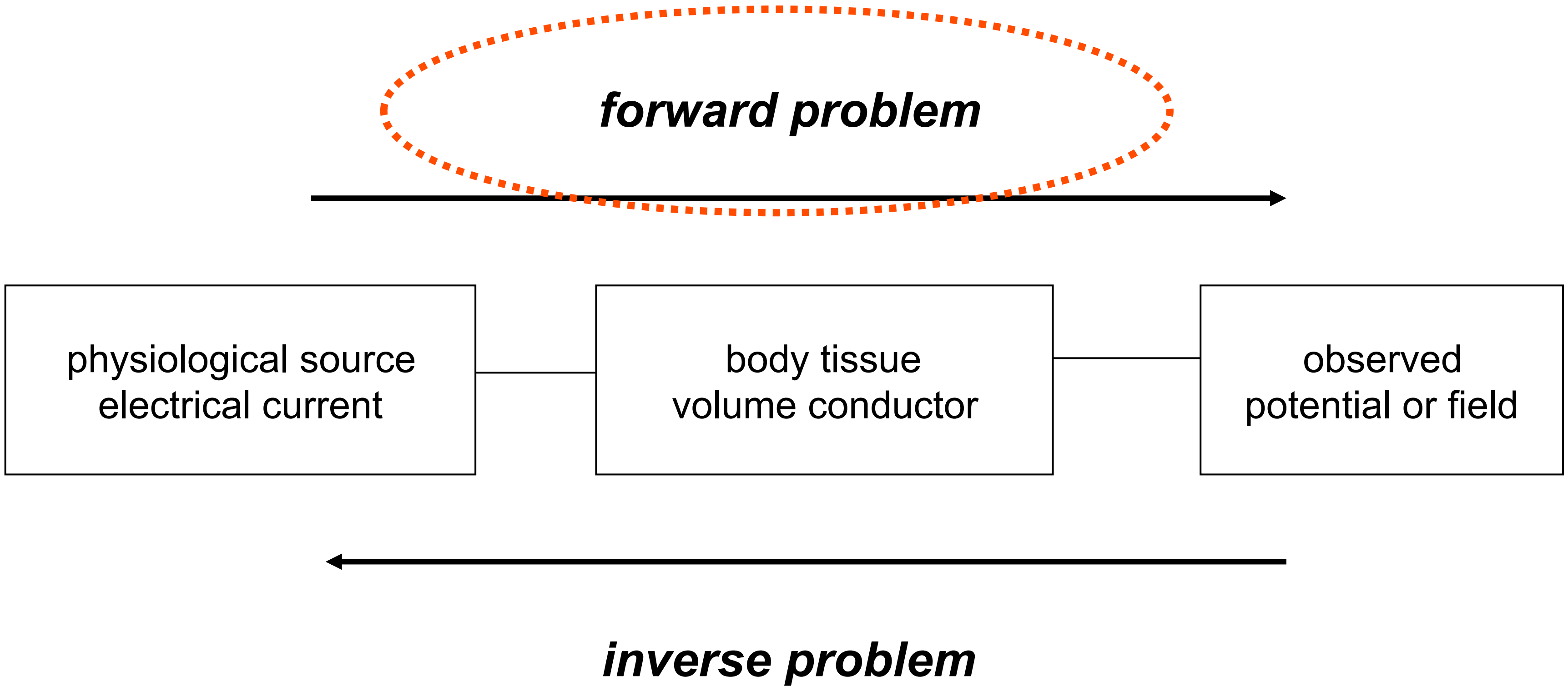
$X=YW$

ICA

$\tilde{Y}=W^{-1}\tilde{X}$



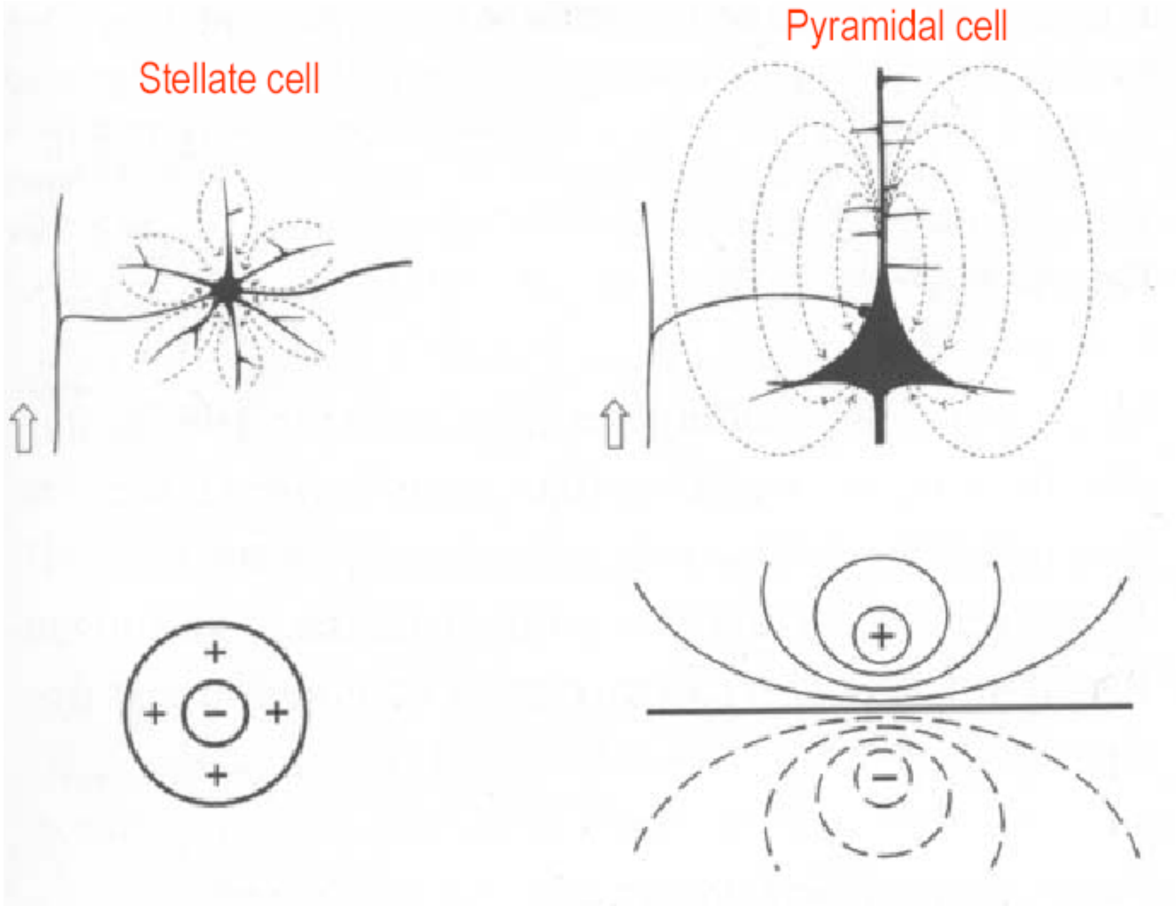
Source modelling



Overview

- Motivation
- Ingredients
  - Source model
  - Volume conductor model
    - Analytical (spherical model)
    - Numerical (realistic model)
  - Comparison EEG and MEG
- Inverse modeling
  - Single and multiple dipole fitting
  - Distributed source models

Neuronal currents



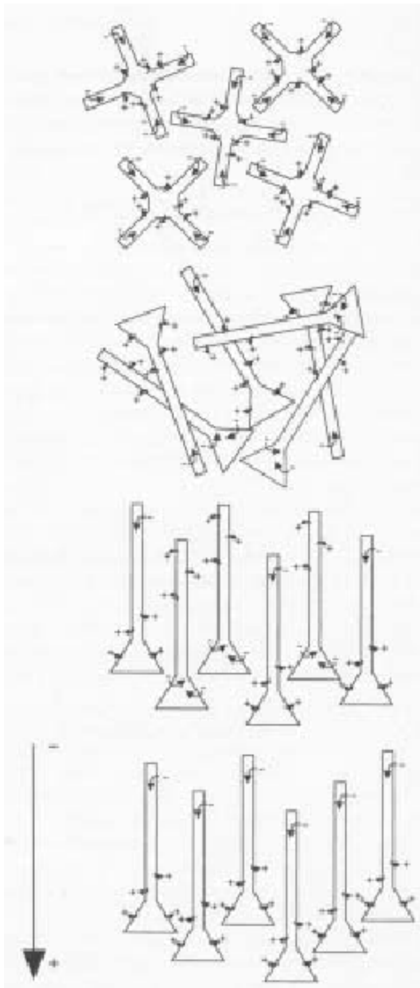
Symmetry, orientation and activation

radial symmetric

random oriented

asynchronously activated

synchronously activated
parallel oriented



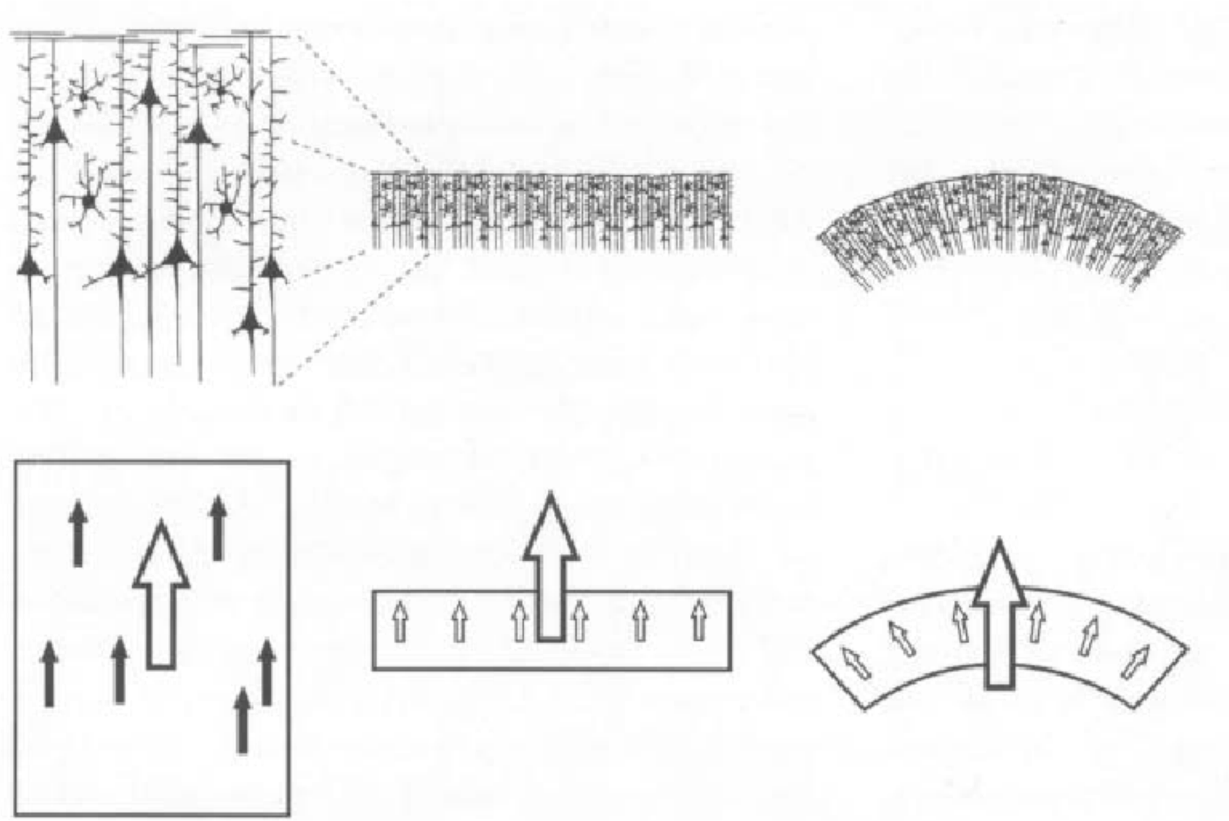
F. C. Donders Centre

Swartz Center for Computational Neuroscience

Motivation for current dipoles

- Neurophysiological motivation

Equivalent current dipoles



Motivation for current dipoles

- Neurophysiological motivation
- Physical/mathematical motivation
  - Any current distribution can be written as a multipole expansion
  - First term: monopole (must be zero)
  - Second term: dipole
  - Higher order terms: quadrupole, octupole

Motivation for current dipoles

- Neurophysiological motivation

- Physical/mathematical motivation
  - Any current distribution can be written as a multipole expansion
  - First term: monopole (must be zero)
  - Second term: dipole
  - Higher order terms: quadrupole, octupole

- Convenience
  - dipoles can be used as building block in distributed source models

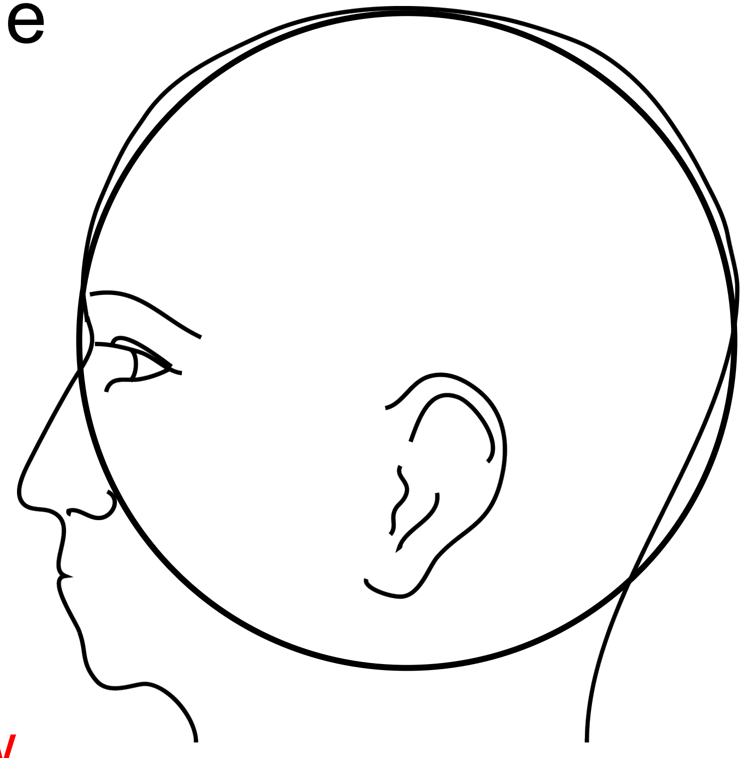
Overview

- Motivation and background
- Forward modeling
  - Source model
  - Volume conductor model
    - Analytical (spherical model)
    - Numerical (realistic model)
  - Comparison EEG and MEG
- Inverse modeling
  - Single and multiple dipole fitting
  - Distributed source models
  - Spatial filtering

Volume conductor

- electrical properties of tissue
- geometrical description

- spherical model
- realistic shaped model



→ Describes how the currents flow,
not where they originate from

Volume conductor

- Advantages spherical model
  - mathematically accurate
  - reasonably accurate
  - computationally fast
  - easy to use

- Disadvantages spherical model
  - inacurate, esp. in some regions
  - difficult alignment with anatomy

Volume conductor

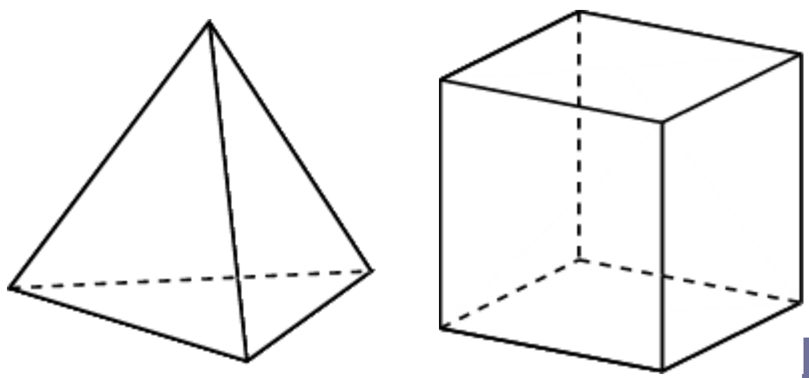
- Advantages realistic model
  - accurate solution for EEG
- Disadvantages realistic model
  - more work
  - individual anatomical MRI required
  - computationally slow(er)
  - numerically instable
  - difficult in interindividual comparison

→The pragmatic solution is to use a standard realistic headmodel for EEG

Realistic volume conductor

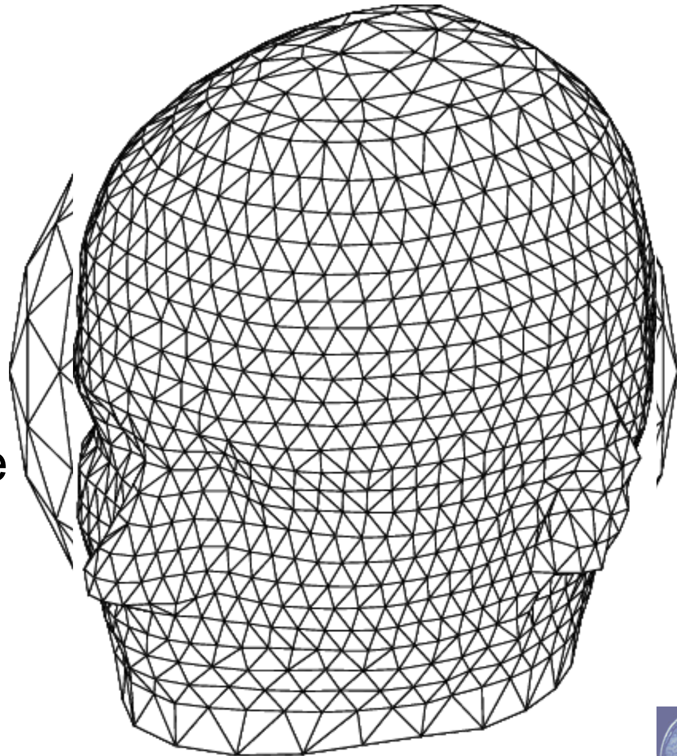
- Computational methods for volume conduction problem that allow realistic geometries
  - Boundary Element Method (BEM)
  - Finite Element Method (FEM)

- Geometrical description
  - triangles
  - tetraeders/voxels



Volume conductor: BEM

- Boundary Element Method
  - description of geometry by compartments
  - each compartment is
    - homogenous
    - isotropic
  - important tissues
    - skin
    - skull
    - brain
    - (CSF)
  - triangulated surfaces as boundarie
  - surfaces should be closed



Volume conductor: FEM

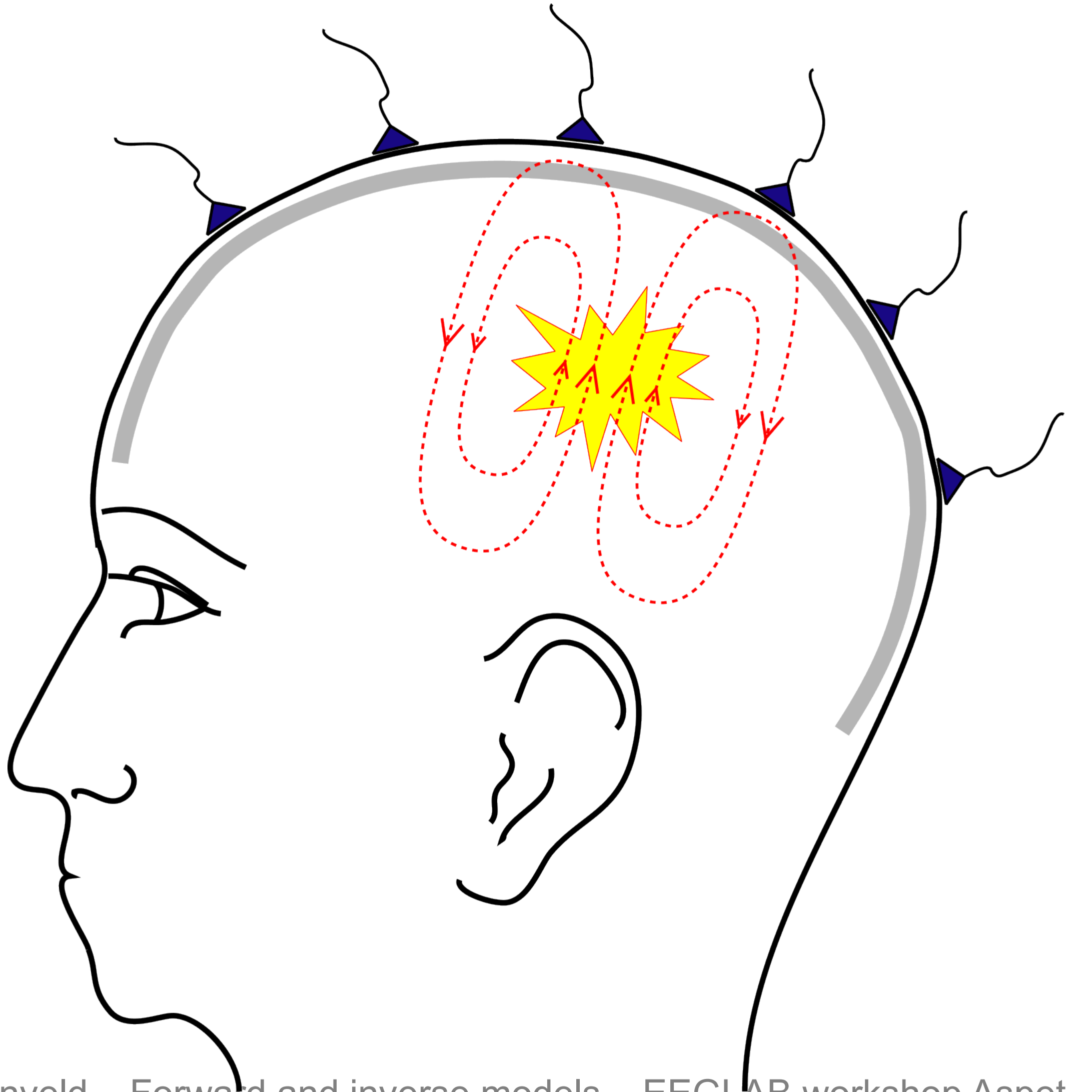
- Tesselation of 3D volume in tetraeders
- Large number of elements
- Each tetraeder can have its own conductivity

- FEM is most accurate numerical method
- Computationally expensive
- Accurate conductivities are not (well) known

Overview

- Motivation and background
- Forward modeling
  - Source model
  - Volume conductor model
    - Analytical (spherical model)
    - Numerical (realistic model)
  - Comparison EEG and MEG
- Inverse modeling
  - Single and multiple dipole fitting
  - Distributed source models
  - Spatial filtering

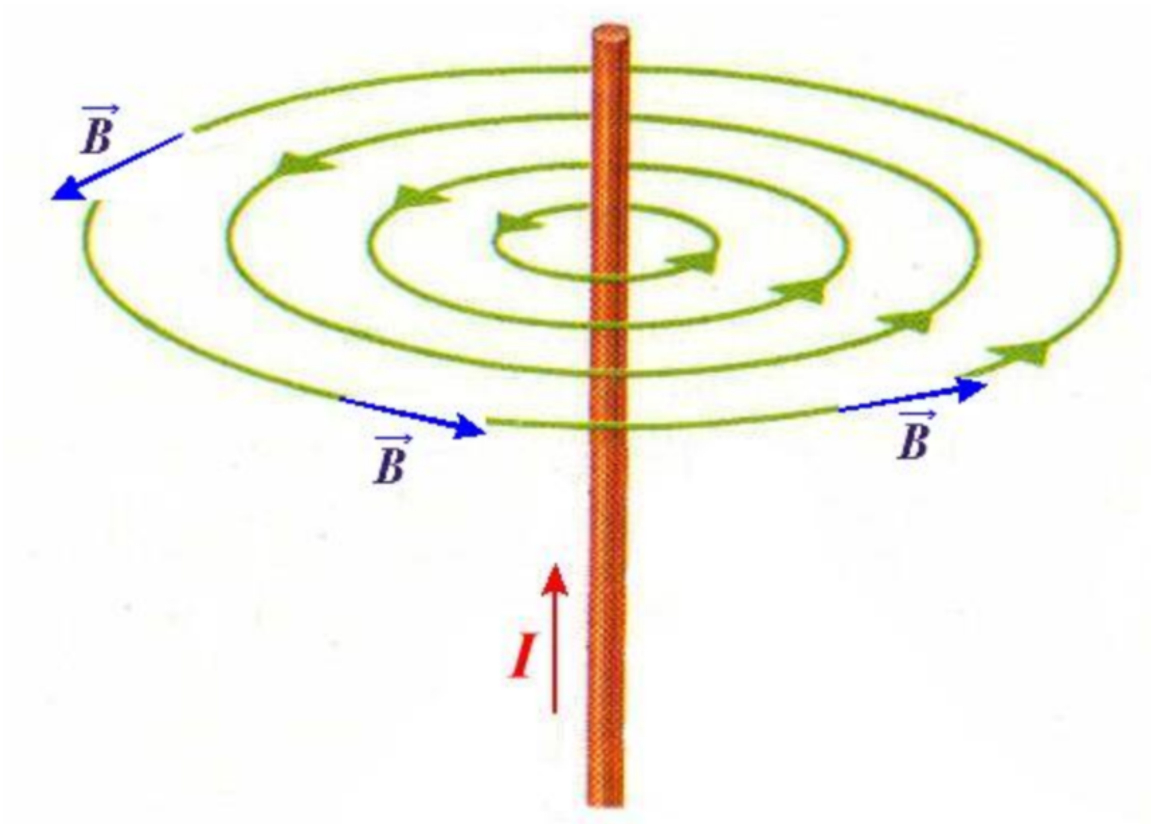
EEG volume conduction



EEG volume conduction

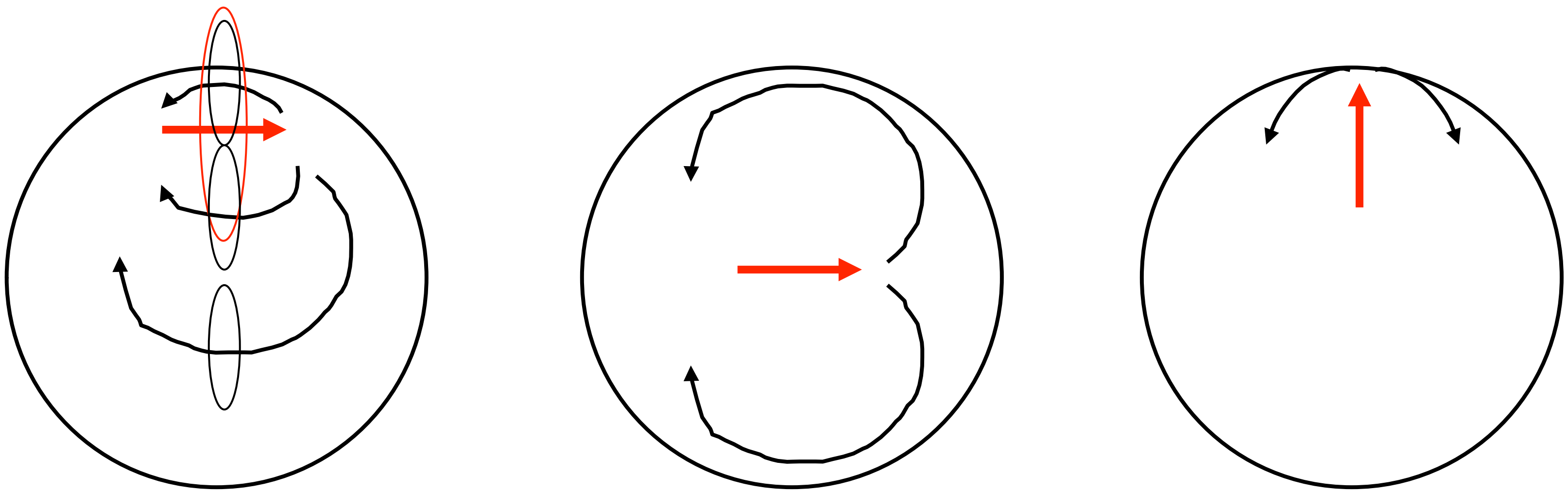
- Potential difference between electrodes corresponds to current flowing through skin
- Only tiny fraction of current passes through skull
- Therefore the model should describe skull and skin as accurately as possible
- Problems with skull
  - Not visible in anatomical MRI
  - Thickness varies
  - Conductivity is not homogeneous
  - Complex geometry at base of skull

Electric current → magnetic field



MEG volume conduction

- Measures sum of fields associated with
  - Primary currents
  - Secondary currents !!!



MEG volume conduction

- Only tiny fraction of current passes through the poorly conductive skull
- Therefore skull and skin can be neglected in the MEG model
- Local conductivity around dipole important
  - geometry
  - conductivity

Differences between EEG and MEG

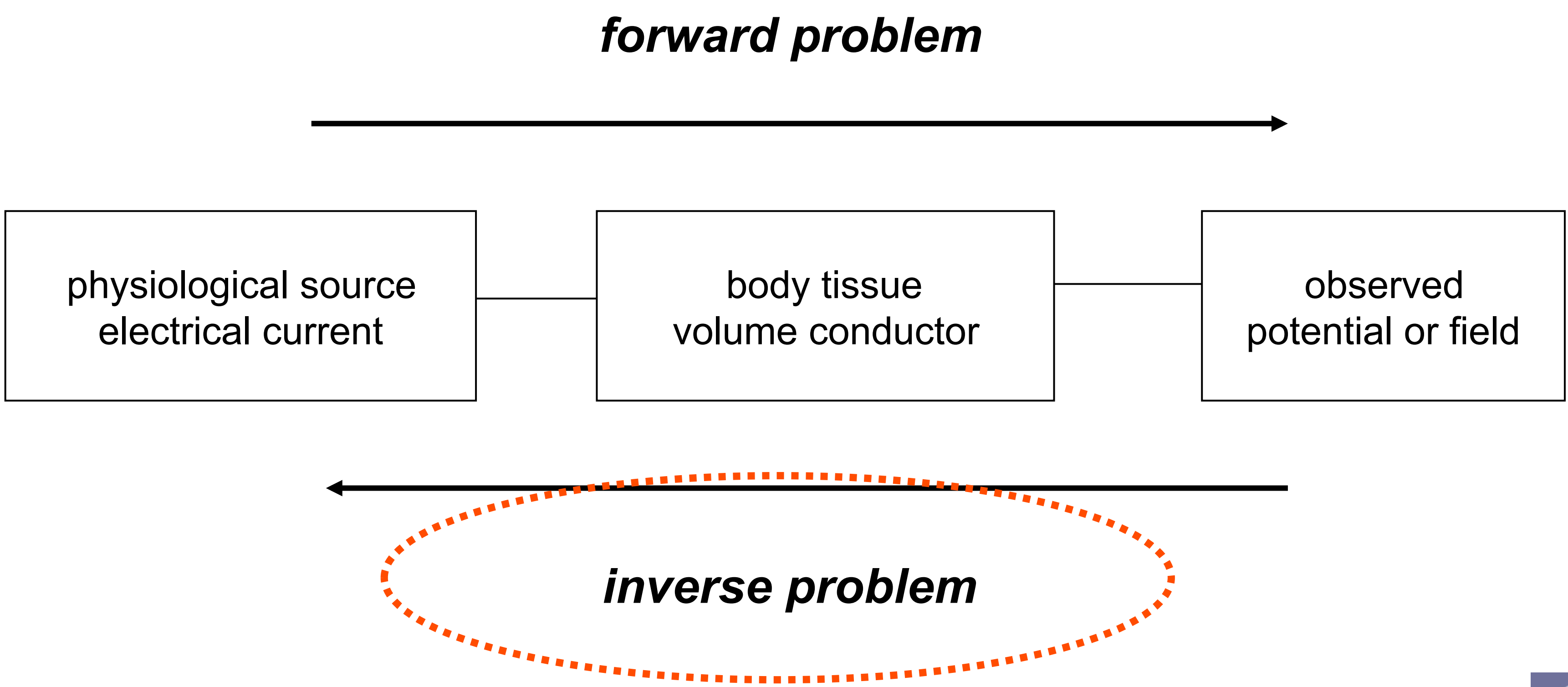
- more blurred
- deep sources
- electrode noise
- reference electrode
- fixed to head
- skull+skin important for modelling

- no radial or deep sources
- environmental noise
- independent sensors
- head can move
- skull+skin not important

Overview

- Motivation
- Forward modeling
  - Source model
  - Volume conductor model
    - Analytical (spherical model)
    - Numerical (realistic model)
  - Comparison EEG and MEG
- Inverse modeling
  - Single and multiple dipole fitting
  - Distributed source models

Source modelling



Inverse methods

- Single and multiple dipole models
  - Minimize error between model and measured potential/field
- Distributed dipole models
  - Perfect fit of model to the measured potential/field
  - Minimize additional constraint on sources
  - LORETA (smoothness)
  - Minimum Norm (L2)
  - Minimum Current (L1)
- Spatial filtering
  - Scan whole brain with single dipole and compute the filter output at every location
  - MUSIC
  - Beamforming (e.g. LCMV, SAM, DICS)

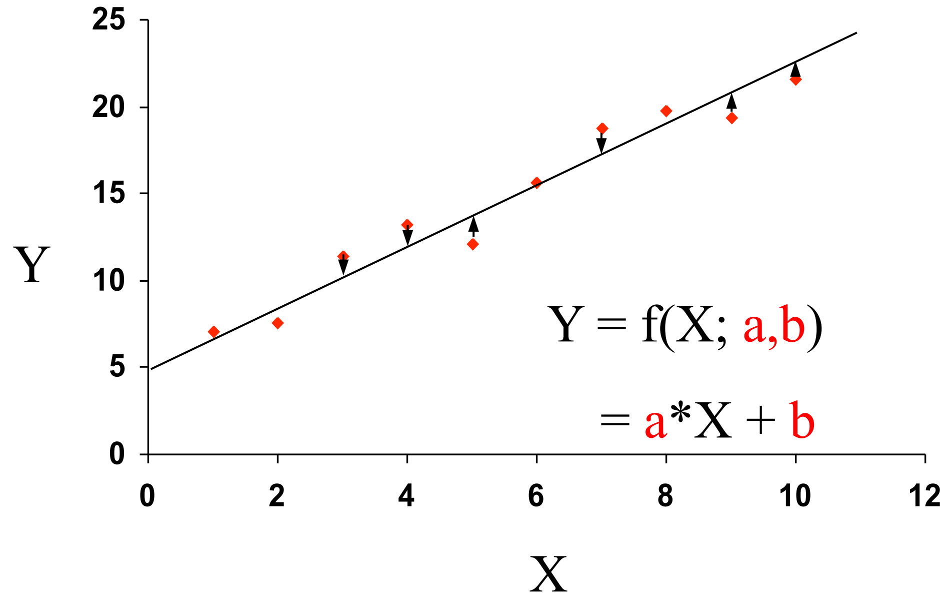
Overview

- Motivation and background
- Forward modeling
  - Source model
  - Volume conductor model
    - Analytical (spherical model)
    - Numerical (realistic model)
  - Comparison EEG and MEG
- Inverse modeling
  - Single and multiple dipole fitting
  - Distributed source models
  - Spatial filtering

Single or multiple dipole models

- Manipulate source parameters to minimize error between measured and model data
  - Location of each source
  - Orientation of each source
  - Strength of each source
- Orientation and strength together correspond to the "dipole moment" and can be estimated linearly
- Position is estimated non-linearly
- Source parameter estimation

Parameter estimation



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

Parameter estimation: model

measured potential

$$V_i = V(\vec{r}_i) + \text{noise}$$

forward model for the data

$$Y_i = Y(r_i;\zeta) + \text{noise}$$

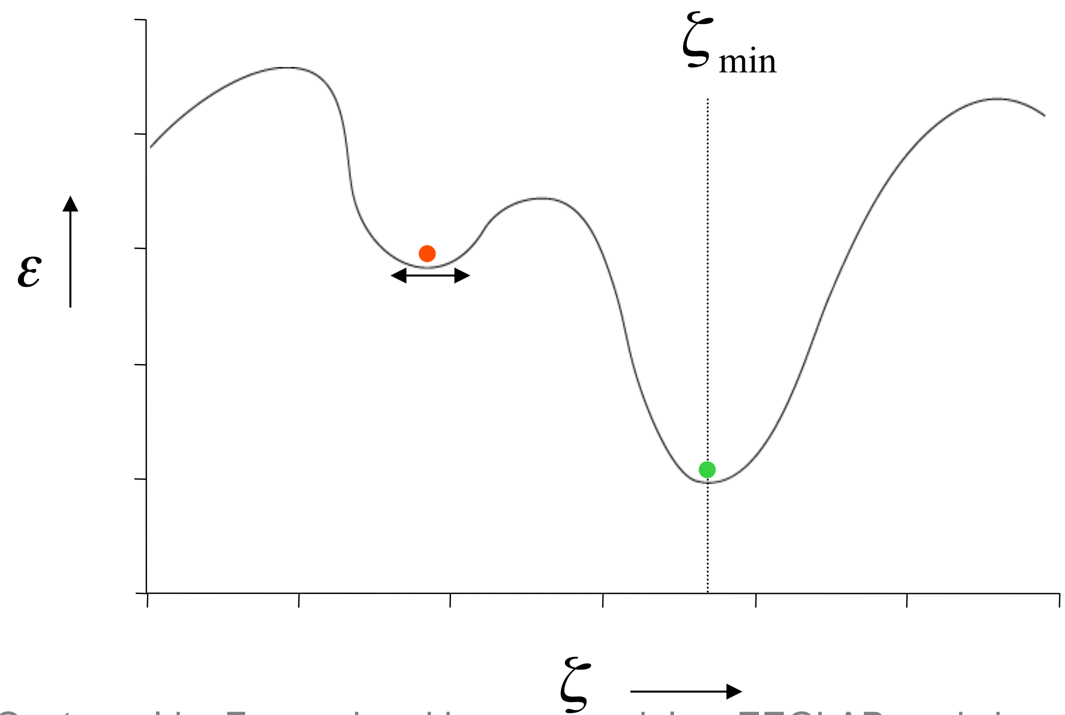
select "optimal" model

$$\min_{\zeta} \left\{ \sum_{i=1}^{N} (Y(r_i;\zeta) - V(r_i))^2 \right\}$$

Select optimal model

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

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



Dipole *scanning*: grid search

- define grid with allowed dipole locations
- compute optimal dipole moment for each location
- compute value of goal-function
- plot value of goal-function on grid

- number of evaluations:
  - single dipole, 1 cm grid: ~4 000
  - single dipole, ½ cm grid: ~32 000
  - two dipoles, 1cm grid: ~16 000 000

Dipole *fitting*: nonlinear search

- start with an initial guess
- evaluate the local derivative of goal-function
- “walk down hill” to the most optimal solution

- number of evaluations: ~100

Overview

- Motivation and background
- Forward modeling
  - Source model
  - Volume conductor model
    - Analytical (spherical model)
    - Numerical (realistic model)
  - Comparison EEG and MEG
- Inverse modeling
  - Single and multiple dipole fitting
  - Distributed source models
  - Spatial filtering

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
  - Linear estimation problem

Distributed source model

- Linear estimation

$$\vec{\Psi} = q_1\vec{\Psi}_1 + q_2\vec{\Psi}_2 + \ldots \quad = \begin{bmatrix} \Psi_{1,1} & \Psi_{2,1} & \cdots \\ \Psi_{1,2} & \Psi_{2,2} & \cdots \\ \vdots & \vdots & \ddots \\ \Psi_{1,N} & \Psi_{2,N} & \cdots \end{bmatrix} \cdot \begin{bmatrix} q_1 \\ q_2 \\ \vdots \end{bmatrix} \quad = \mathrm{L} \cdot \vec{q}$$

$$\vec{q} = \mathrm{L}^{-1} \cdot \vec{\Psi}$$

Distributed source model

$$V = L \cdot q + Noise$$

$$\min_q \{\| V - L \cdot q \|^2\} = 0 \;\; !!$$

- Regularized linear estimation:

$$\min_q \{\| V - L \cdot q \|^2 + \lambda^2 \cdot \| D \cdot q \|^2\}$$

- Constrained linear estimation:

$$\min_q \{q^T \cdot W \cdot q\} \quad \text{while} \quad \| V - L \cdot q \|^2 = 0$$

Overview

- Motivation and background
- Forward modeling
  - Source model
  - Volume conductor model
    - Analytical (spherical model)
    - Numerical (realistic model)
  - Comparison EEG and MEG
- Inverse modeling
  - Single and multiple dipole fitting
  - Distributed source models
  - Spatial filtering

Spatial filtering

- position of the source as such is not estimated
- scanning the whole brain
  - single dipole as source
  - estimate activity at each grid location
    - that explains a part of the data
    - that supresses other activity
- various methods
  - multiple signal classification (MUSIC)
  - beamforming
  - LCMV, SAM, DICS, …
- not a distributed source model, but a distributed representation of the single dipole estimate
- unmixing of data into “signal source” and “noise sources” using assumptions on temporal relation between sources

Summary 1

- Forward modelling
  - Required for the interpretation of scalp topographies
  - Interpretation of scalp topography *is* "source estimation"
  - Mathematical techniques are available that aid in interpreting scalp topographies -> inverse modeling

Summary 2

- Inverse modeling
  - Model assumption for volume conductor
  - Model assumption for source (I.e. dipole)
  - Additional assumptions on source
    - Single point-like source
    - Multiple point-like sources
    - Distributed source
  - Different mathematical solutions
    - Dipole fitting (linear and nonlinear)
    - Linear estimation (regularized)