Forward and Inverse EEG Source Modeling

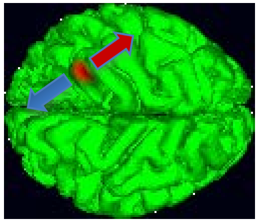
Swartz
Center for
Computational
Neuroscience

Scott Makeig

Institute for Neural Computation, UCSD

EEGLAB Tokyo

September, 2017

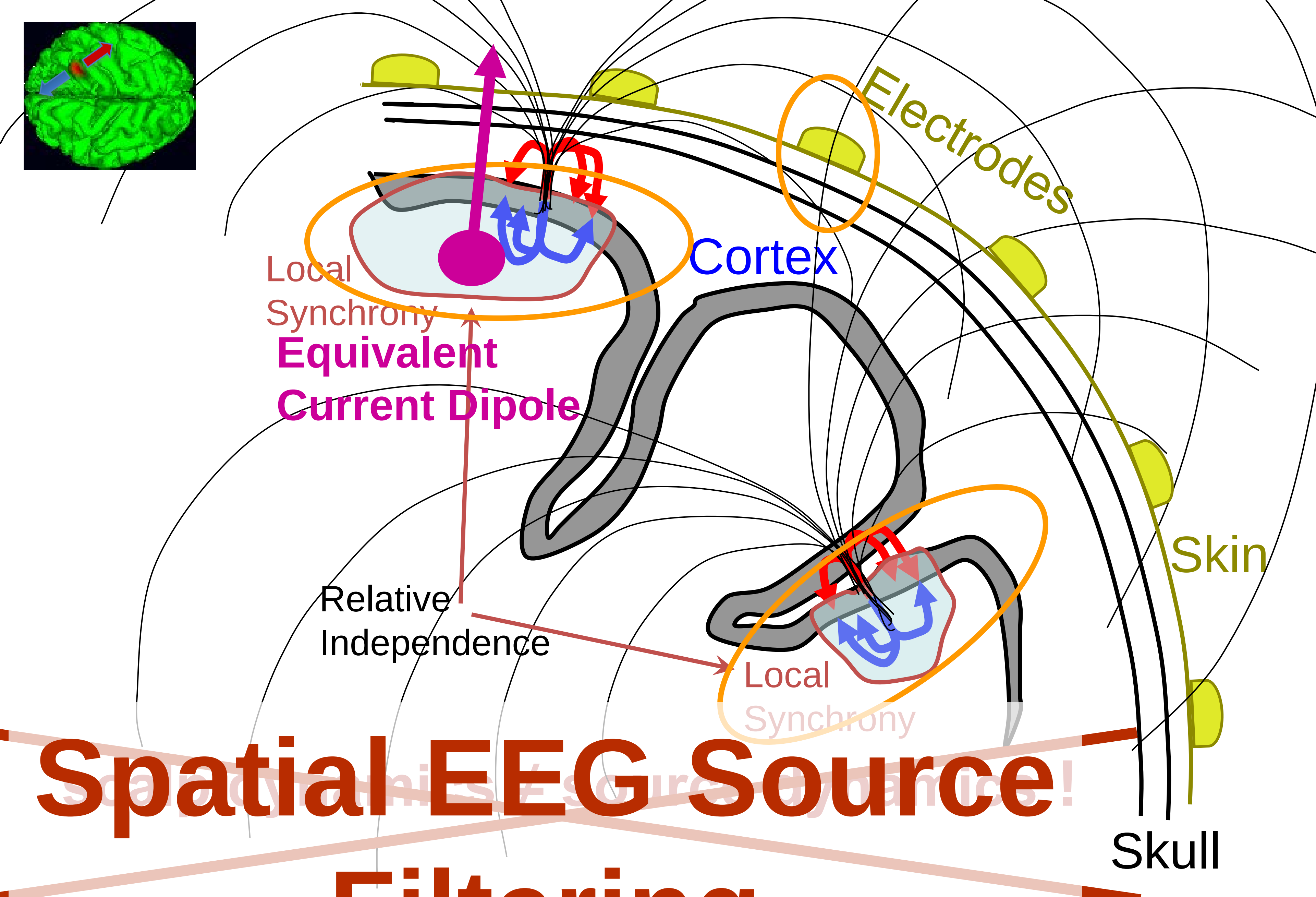


Motivation

- Why perform ICA?
- Why fit dipoles or distribution source models?
- Why measure EEG?!

- To obtain information about brain processes…
  - Time course of activities that produce the EEG signals
  - Locations of the activities that produce the EEG signals

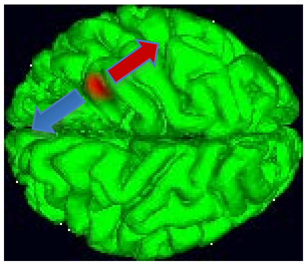
Spatial EEG Source Filtering



S. Makeig 2007

EEG source modeling

Source Space



electrical currents

Forward head model

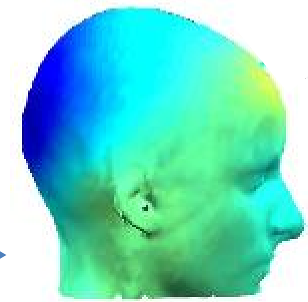
forward problem →

volume conduction through body tissues

← **inverse** problem

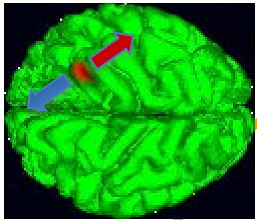
Inverse localization method

Sensor Space

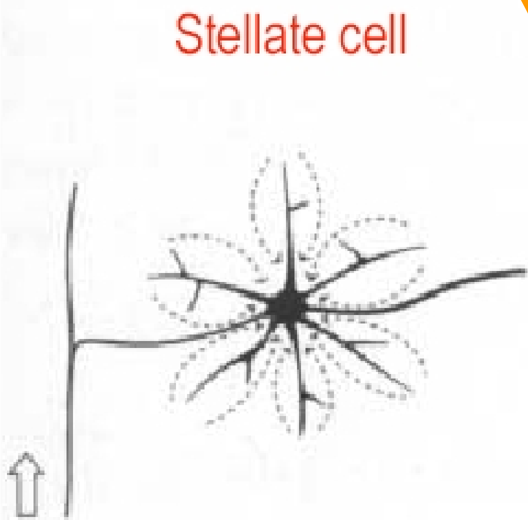


recorded potentials

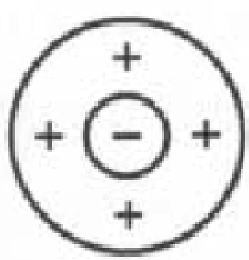
R. Oostenveld, & S. Makeig, 2016

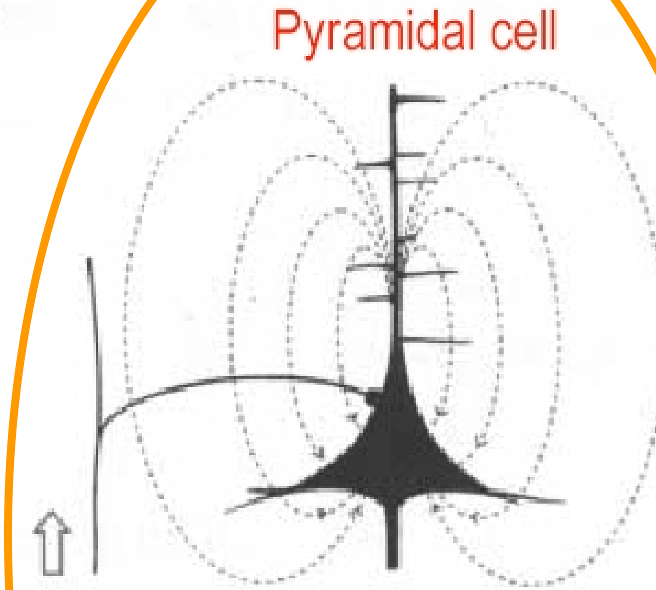


Peri-neuronal currents

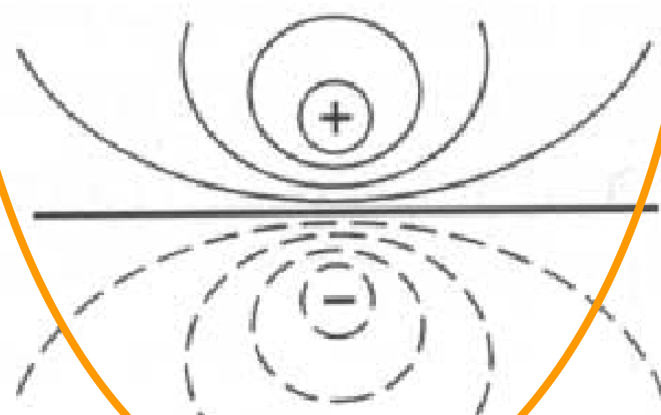


Closed field

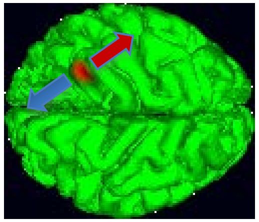




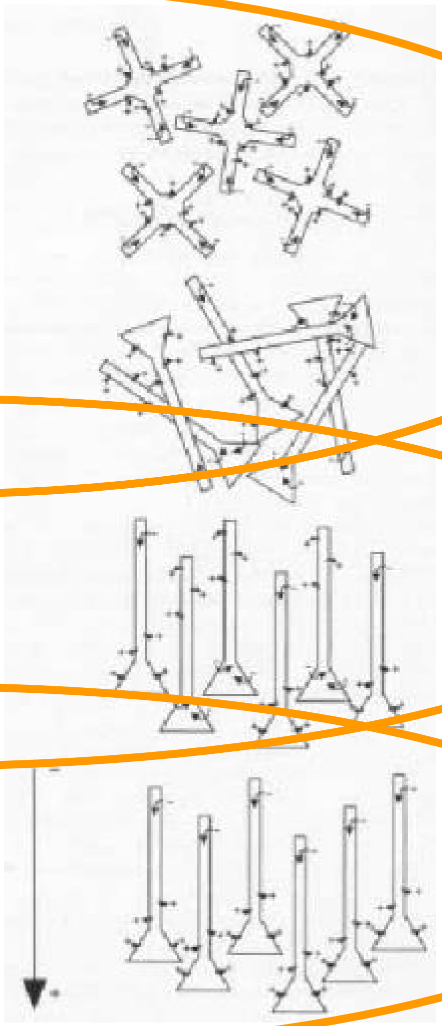
Open field



R. Oostenveld, 2007



Symmetry, orientation and activation



radially symmetric, i.e.
randomly-oriented

Closed field

asynchronously activated

Phase cancellation

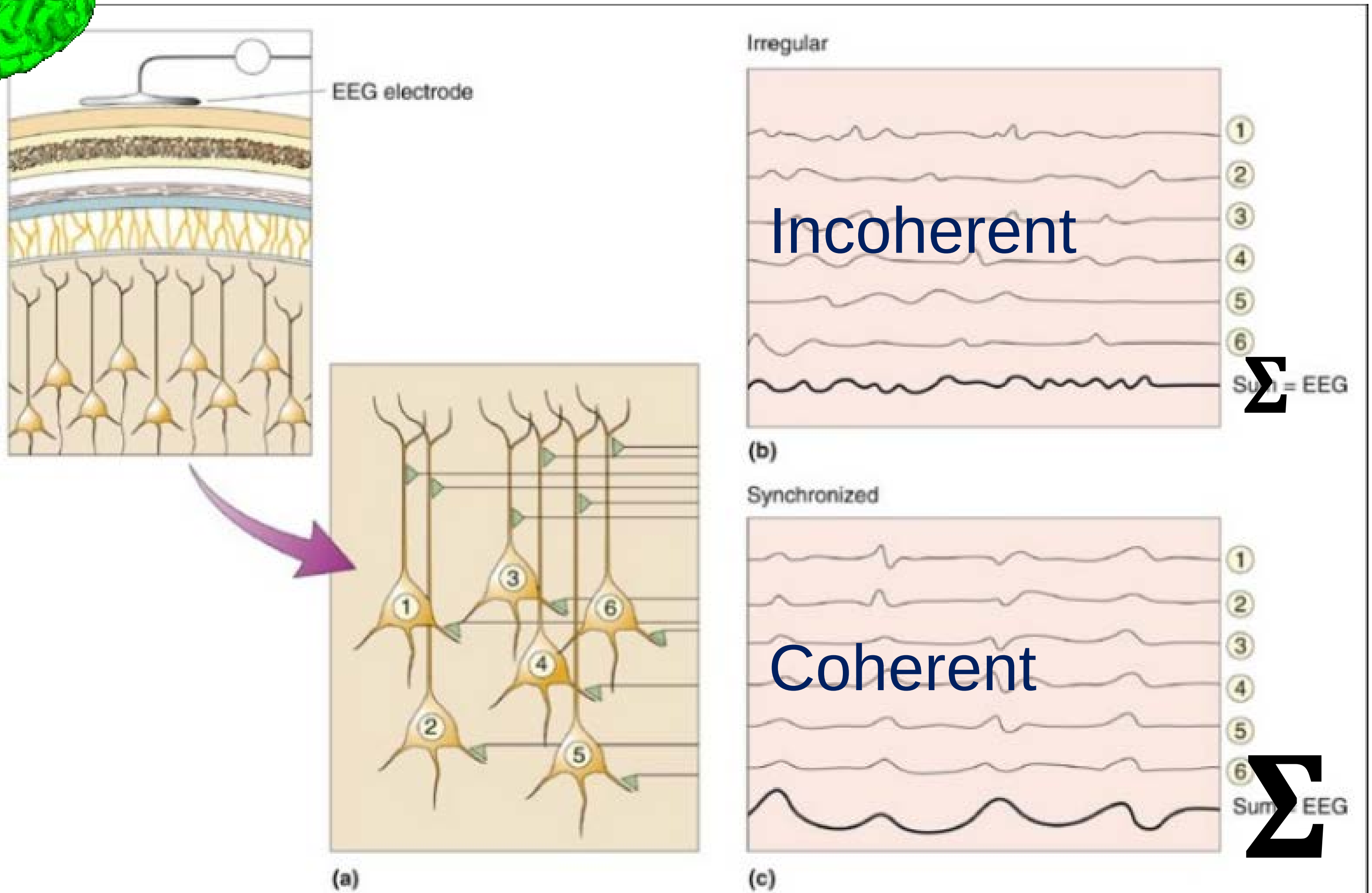
synchronously activated
parallel-oriented

Open field

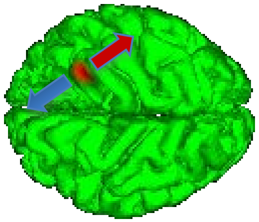
Awhen recorded at a distance, dipolar field components dominate

R. Oostenveld, 2007

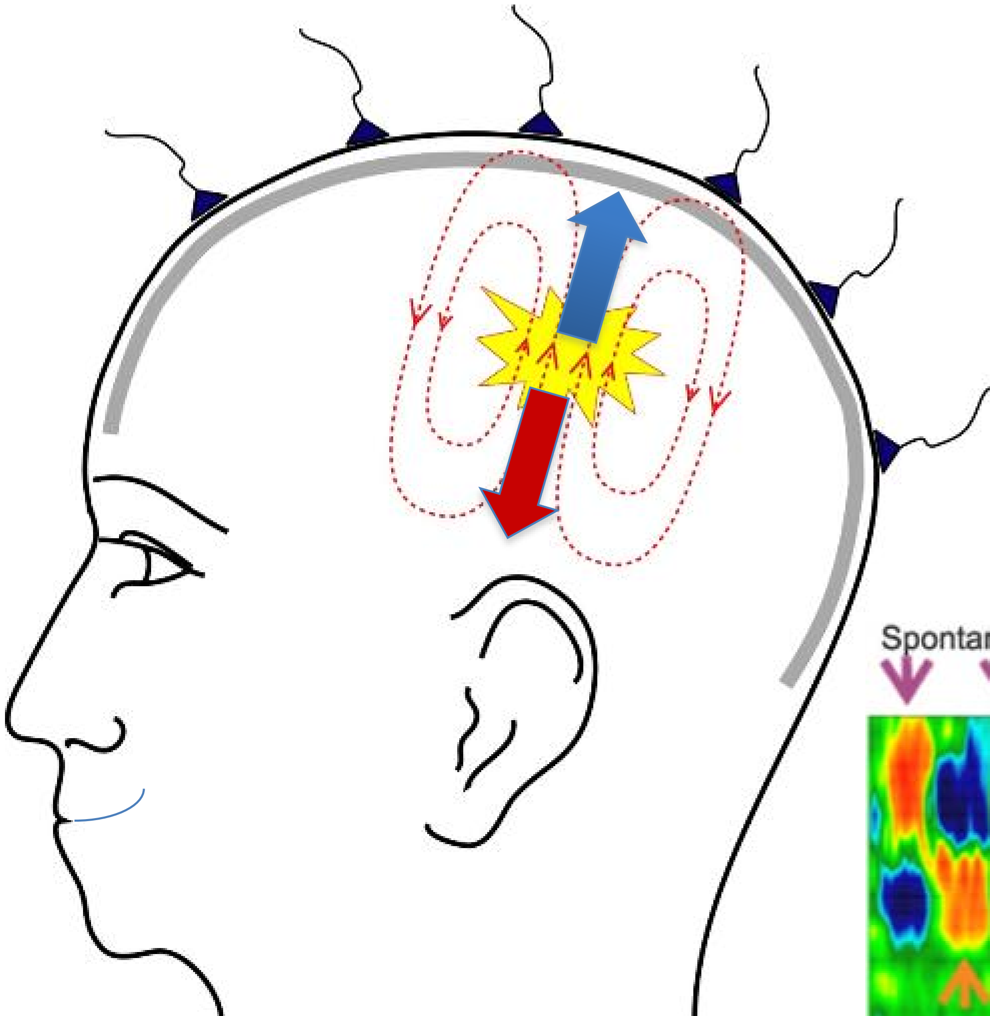
EEG Effective Sources

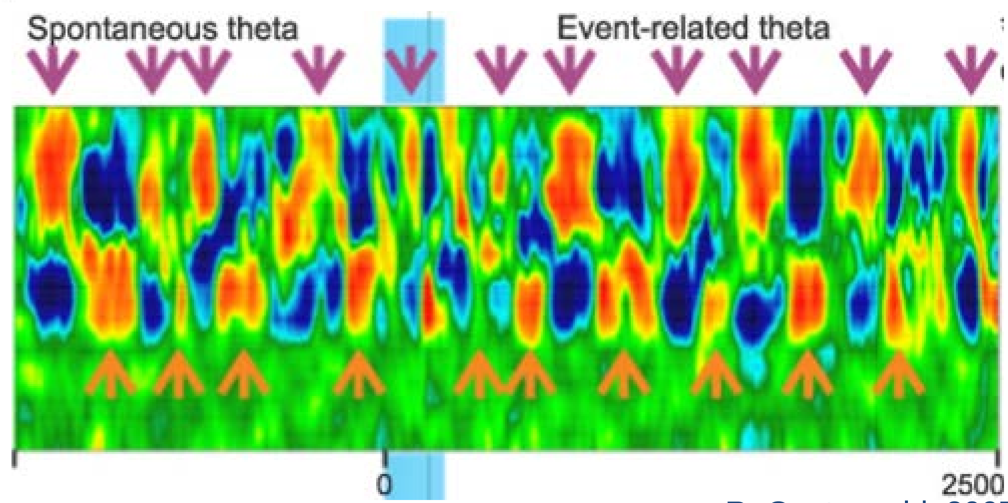


Many neurons need to sum their local field activities to be detectable at EEG electrodes. Synchronized neural activity produces large far field signals.

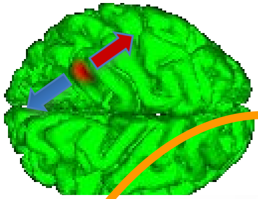


EEG volume conduction of dipolar field patterns ➔ effective sources

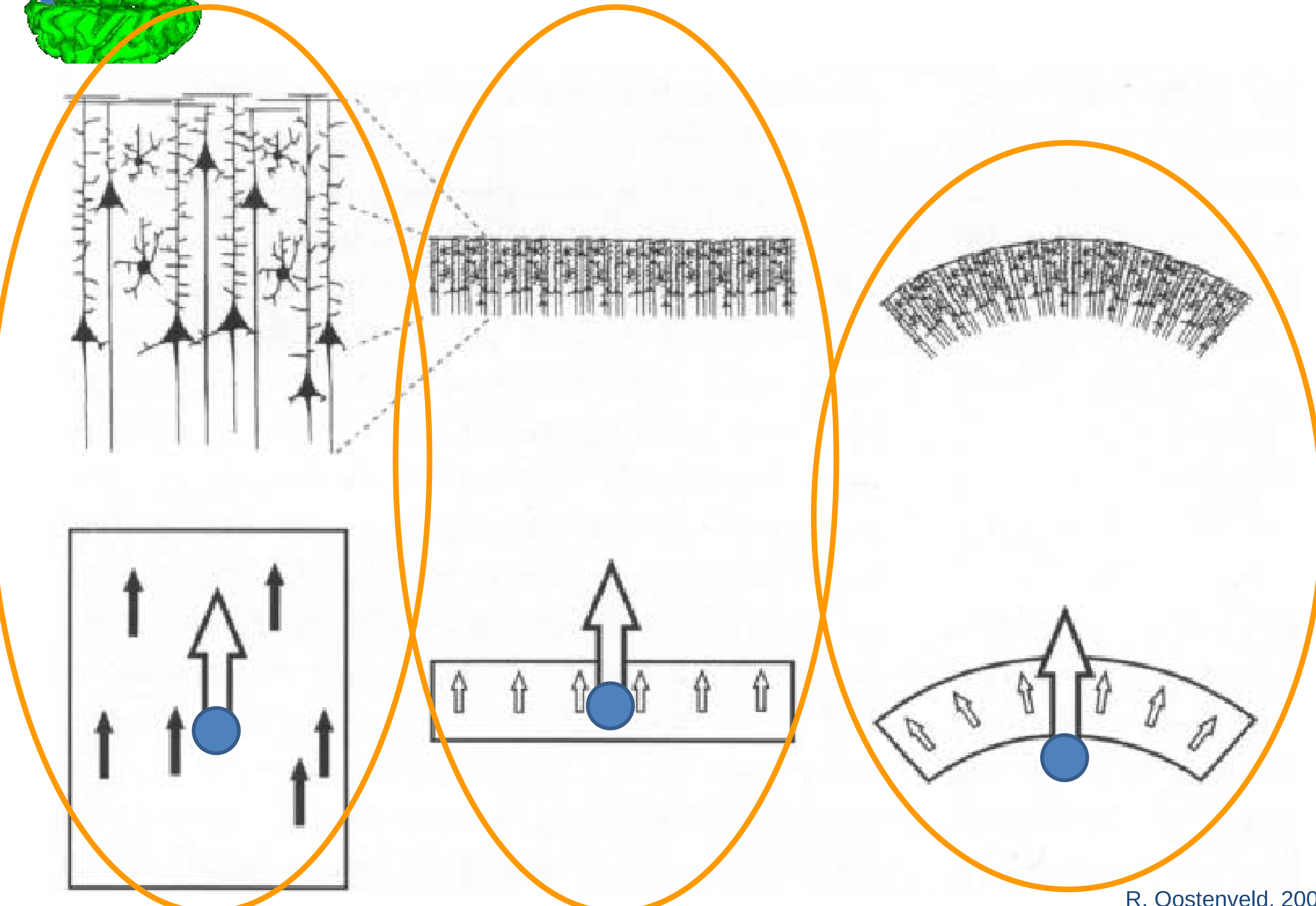




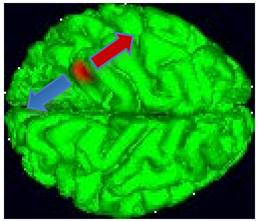
R. Oostenveld, 2007



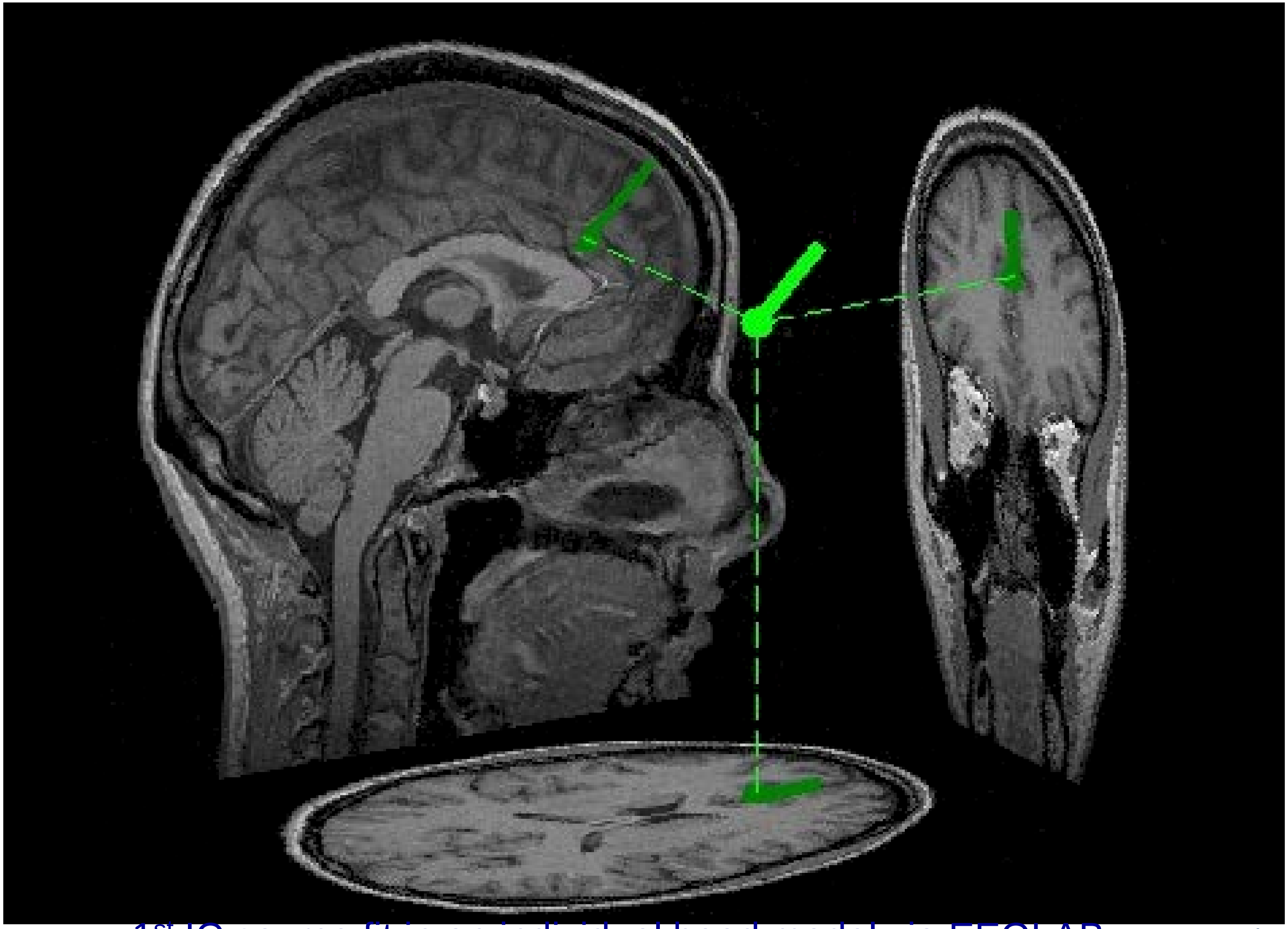
The *equivalent* current dipole



R. Oostenveld, 2007



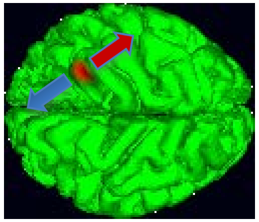
Equivalent current dipole modeling

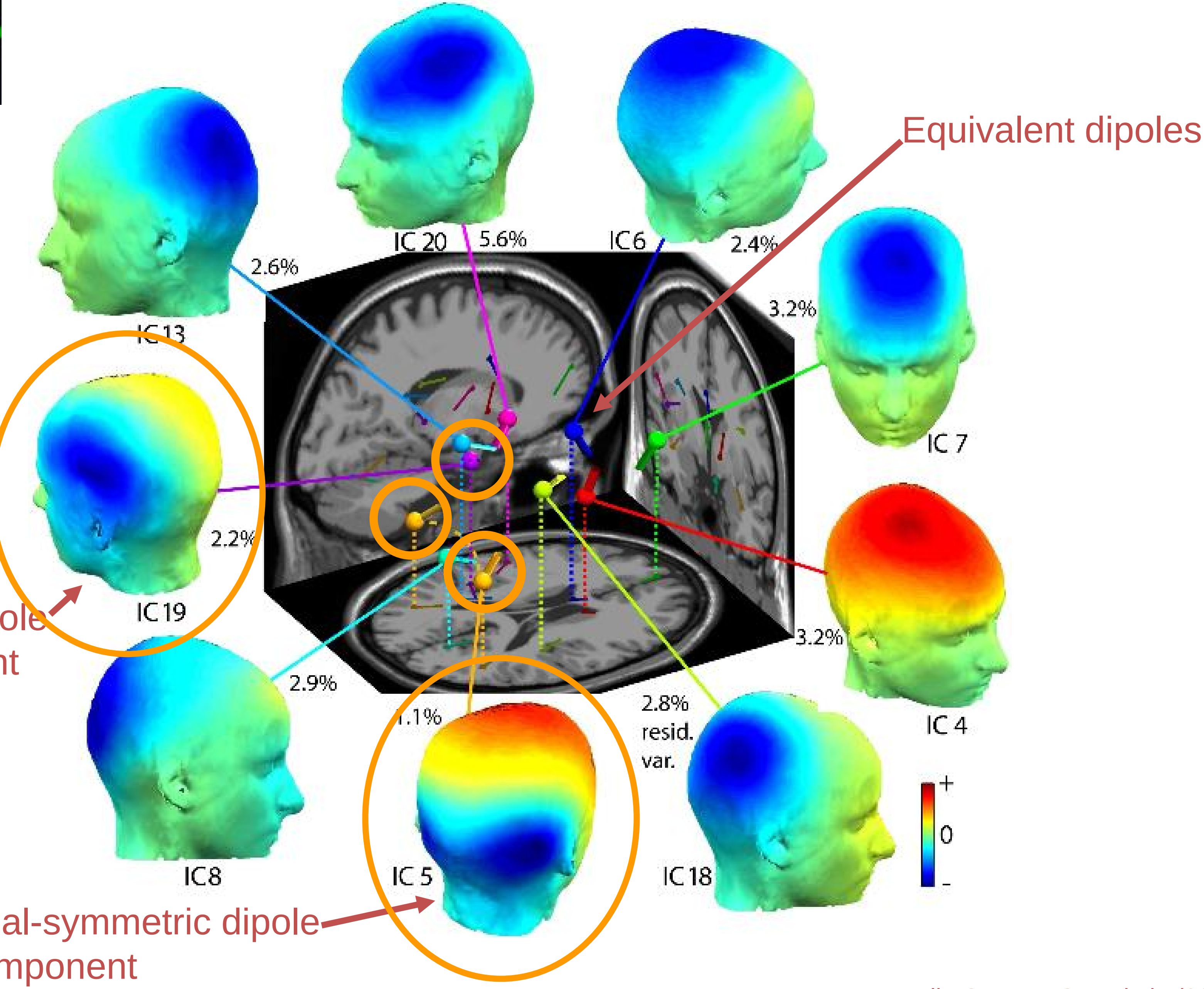


1st IC source fit in an individual head model via EEGLAB

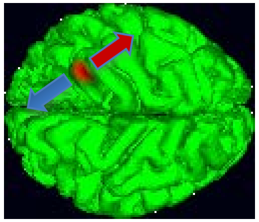
A. Delorme, ~2007

Independent cortical components





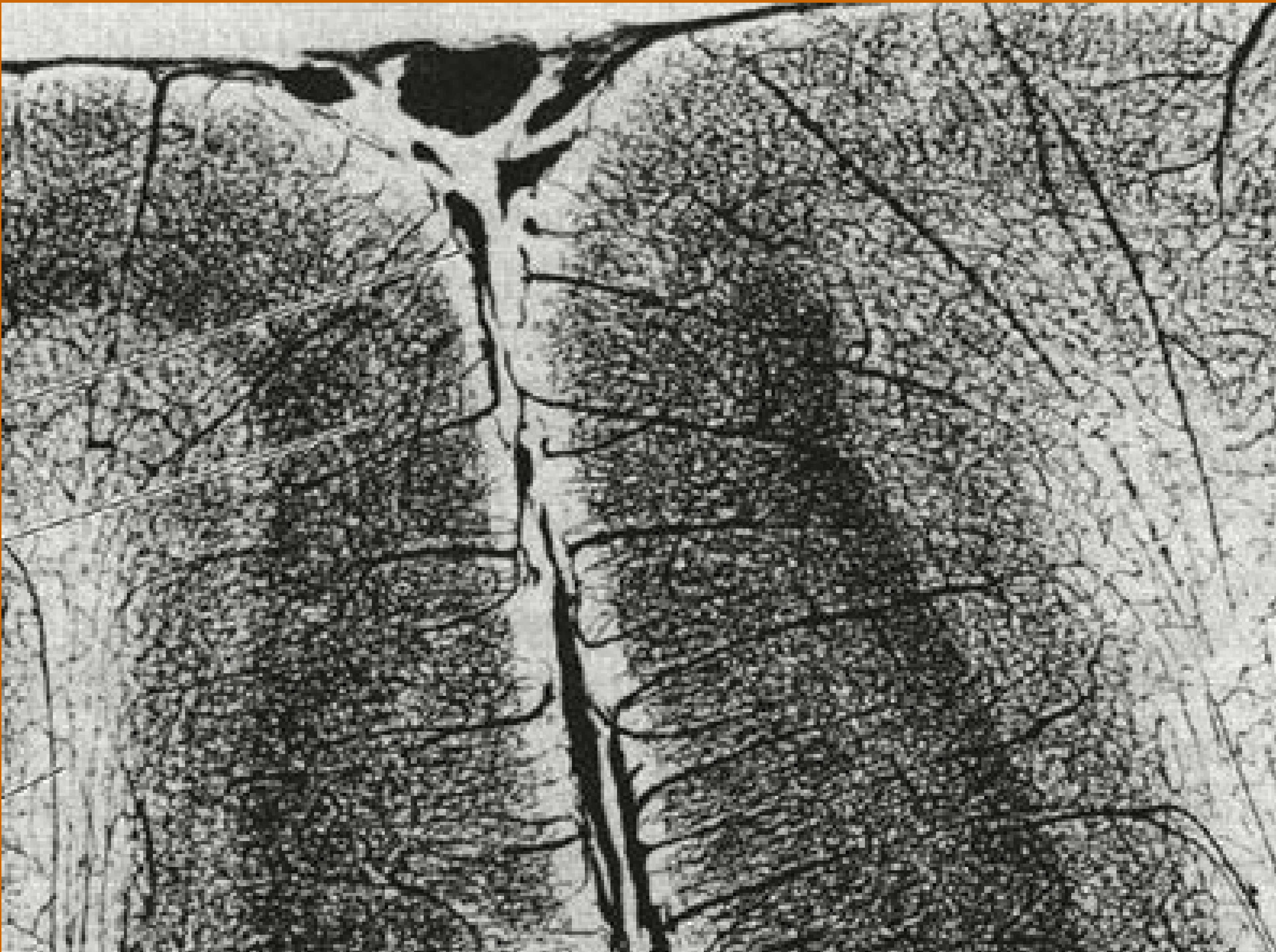
Julie Onton & S. Makeig (2006)

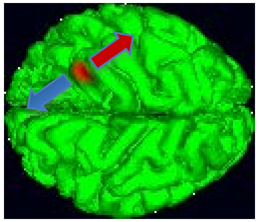


Equivalent current dipole modeling

- **Physical/mathematical motivation**
  – Any current distribution can be written as a multipole expansion
  – First term: monopole (must be 0)
  – Second term: dipole
  – Higher order terms: quadrupole, octopole, …
  – **In far-field recordings, the dipolar term dominates.**
- For convenience + accuracy, therefore
  – **Dipoles** can be used as building blocks in distributed EEG effective source models

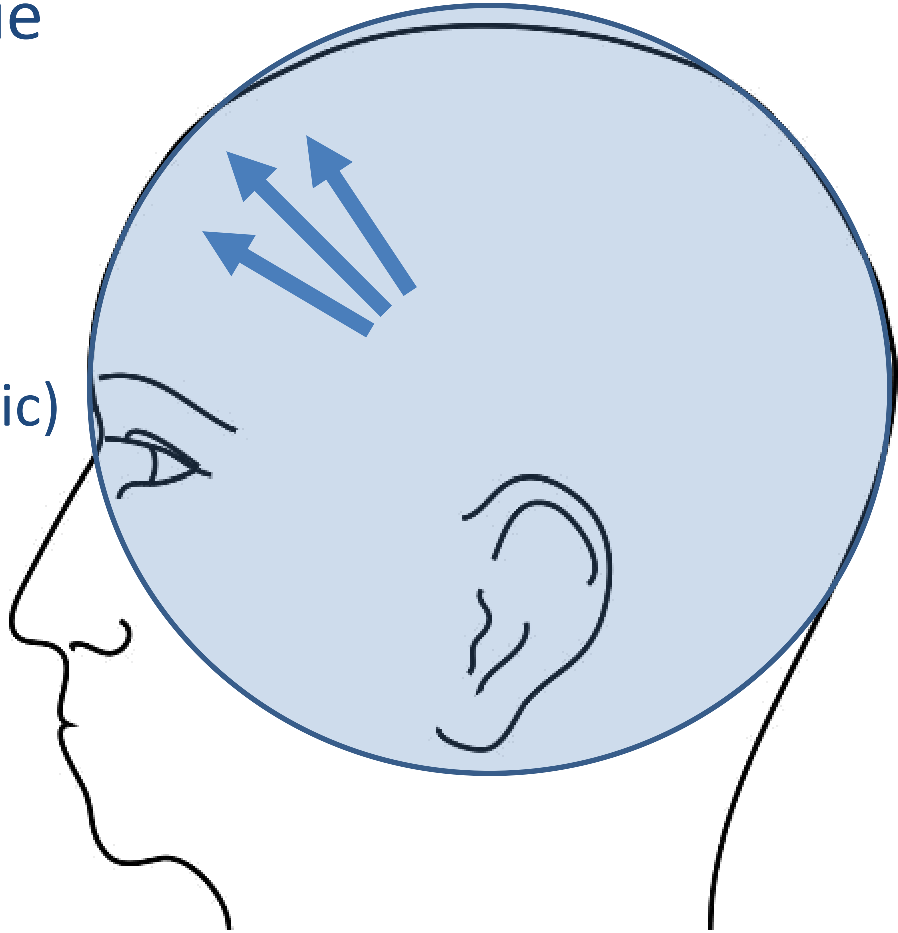
R. Oostenveld, & S. Makeig, 2016





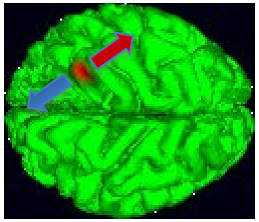
Forward Head Models

- Electrical properties of tissue
  - Conductivity
  - Anisotropy
- Geometrical description
  - Spherical model? (less realistic)
  - Realistically shaped model



→ A **forward model** describes
how the currents flow
from all possible points of origin

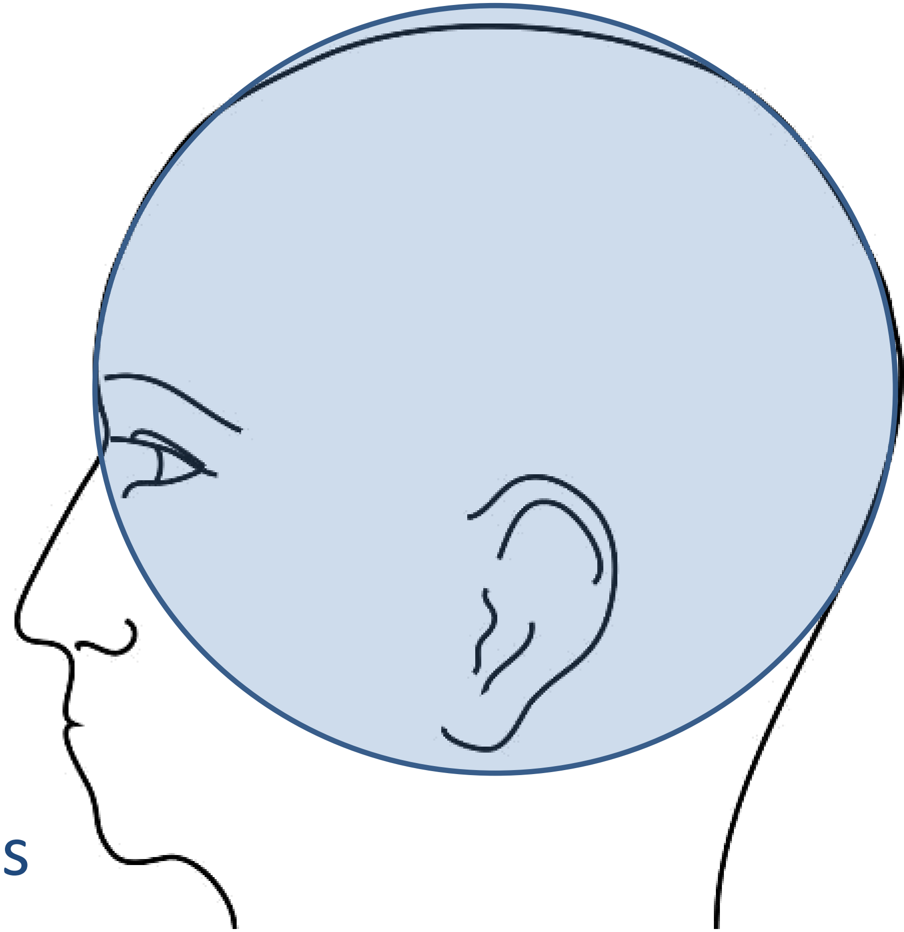
R. Oostenveld, & S. Makeig, 2016



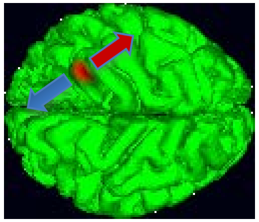
Forward Head Models

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

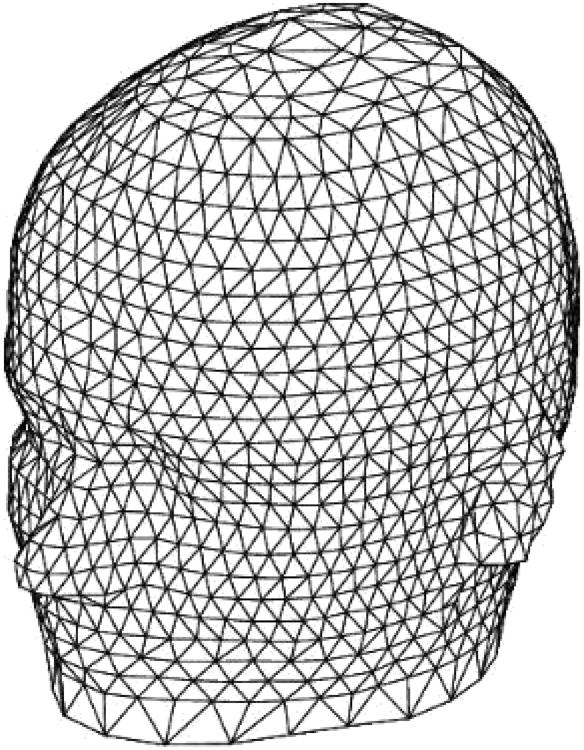
- Disadvantages of the **spherical** model
  - inaccurate in some regions
  - difficult to align to head



R. Oostenveld, & S. Makeig, 2016



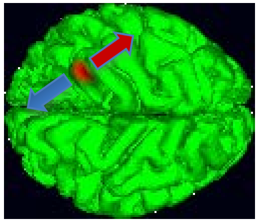
Forward Head Models



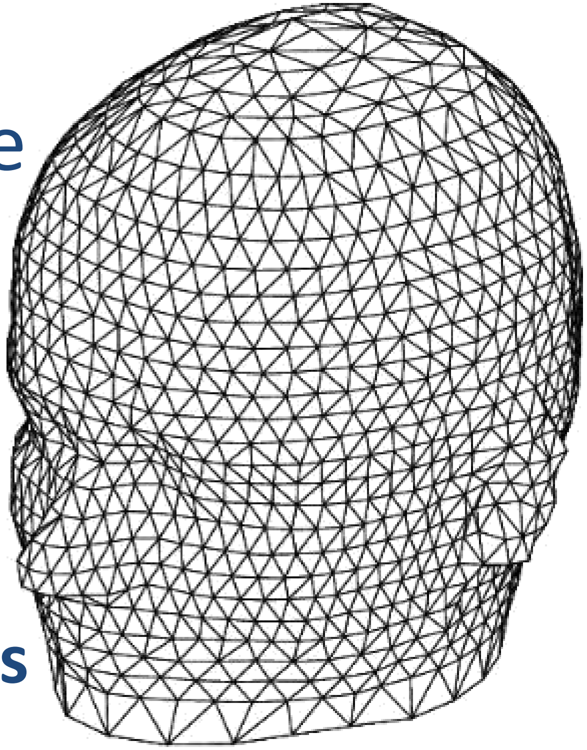
- Advantages of a **realistic** head model
  - accurate solution for EEG
- Disadvantages of a **realistic** model
  - more work
  - computationally slower
  - numerically instable?
  - Difficult for inter-individual comparisons

→ The pragmatic (easy, cheap) solution is to use a standard (mean) realistic head model (MNI).

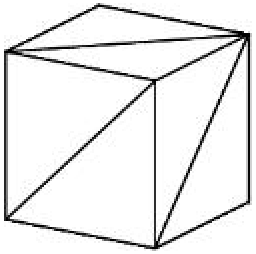
R. Oostenveld, & S. Makeig, 2016



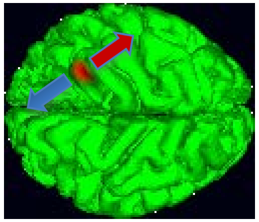
Forward Head Models



- Computational methods for volume conduction problem that allow realistic geometries
  - **Boundary Element Method (BEM) models**
  - **Finite Element Method (FEM) models**
- Geometrical description
  - **Triangles** (2-D) → BEM
  - **Tetrahedra** (3-D) → FEM



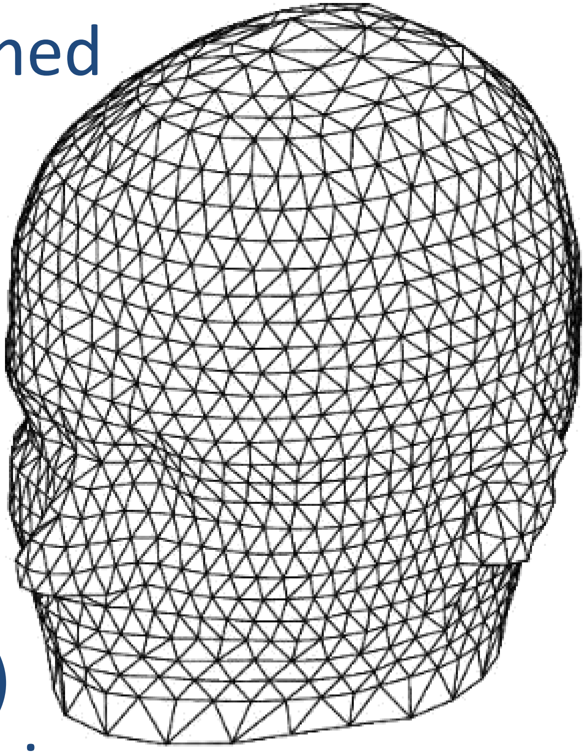
R. Oostenveld, & S. Makeig, 2016



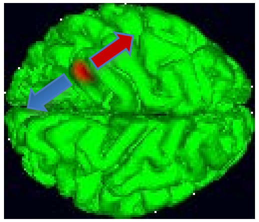
Forward Head Models: BEM

- **Boundary Element Method (BEM)** models
  - description of head geometry by tissue compartments
  - Tissue in each compartment is assumed
    - homogenous
    - isotropic

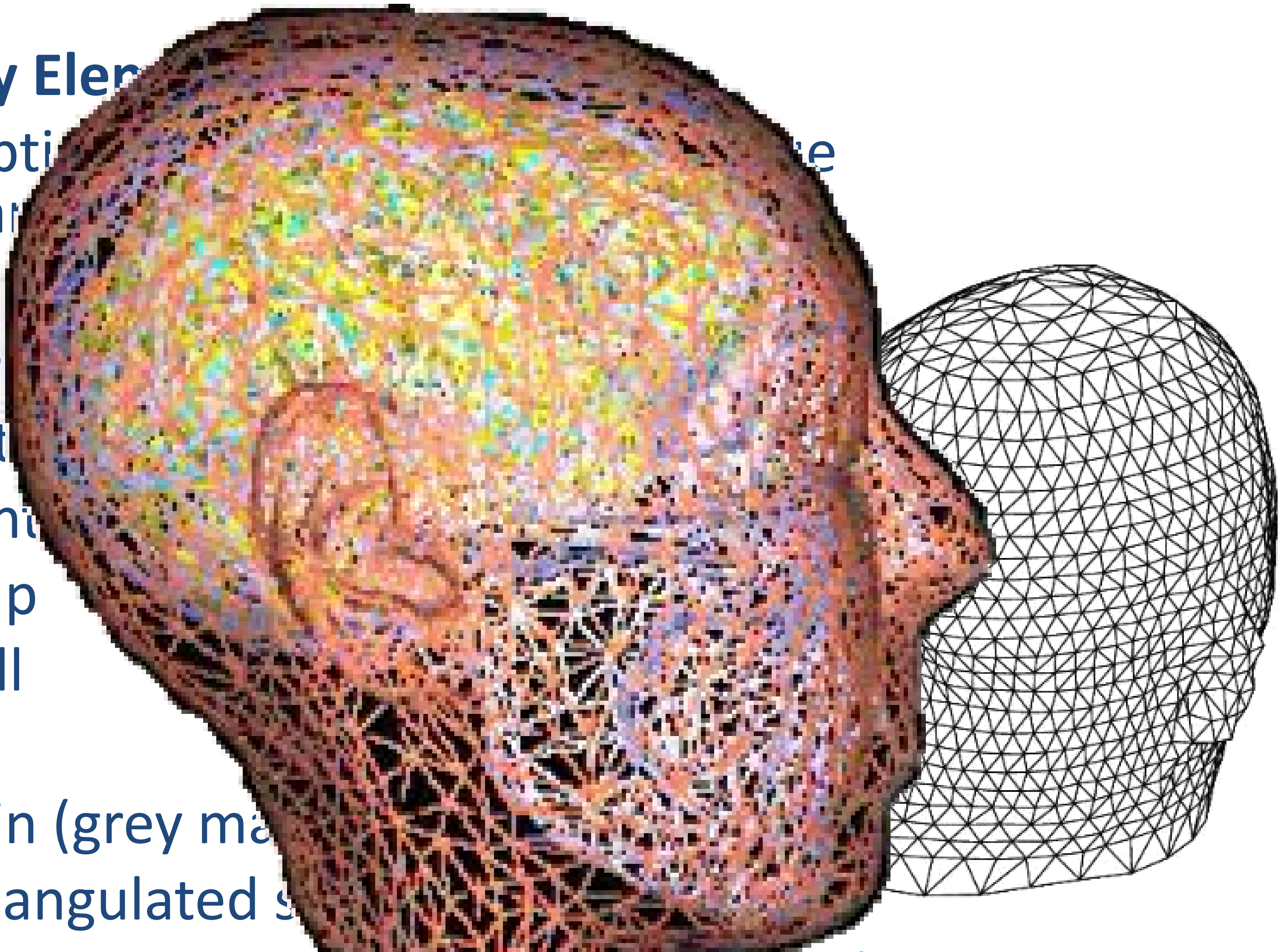
  Important tissue types
    - Scalp
    - Skull
    - CSF
    - Brain (grey matter / white matter)
  - Use triangulated surfaces as boundaries
  - Each surface should be closed (no holes)



R. Oostenveld, & S. Makeig, 2016

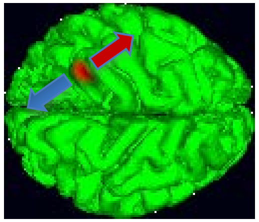


Forward Head Models: BEM



- **Boundary Elem**
  - descripti... e compar
  - Tissue
    - hom
    - isot
  - Important
    - Scalp
    - Skull
    - CSF
    - Brain (grey ma
  - Use triangulated s
  - Each surface should be closed (no holes)

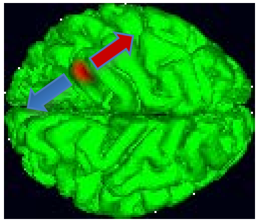
R. Oostenveld, & S. Makeig, 2016



Forward head models: Modeling the skull

- **Potential differences between electrodes** measures summed current flowing through scalp
  - – However, only a tiny fraction of *brain source currents* pass through the skull
  - – Therefore a forward head model should describe *brain, skull,* and *scalp tissues* as accurately as possible.

R. Oostenveld, & S. Makeig, 2016

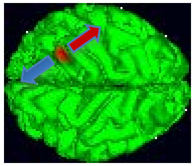


Forward head models: Modeling the skull

- **Problems with skull modeling**
  - Poorly visible in the anatomic MRI (T2) image
  - Thickness varies regionally
  - Conductivity is not homogeneous
  - Complex geometry at front and base of skull

→ **Skull conductivity** variable & unknown

R. Oostenveld, & S. Makeig, 2016

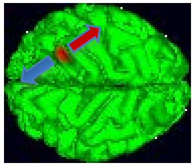


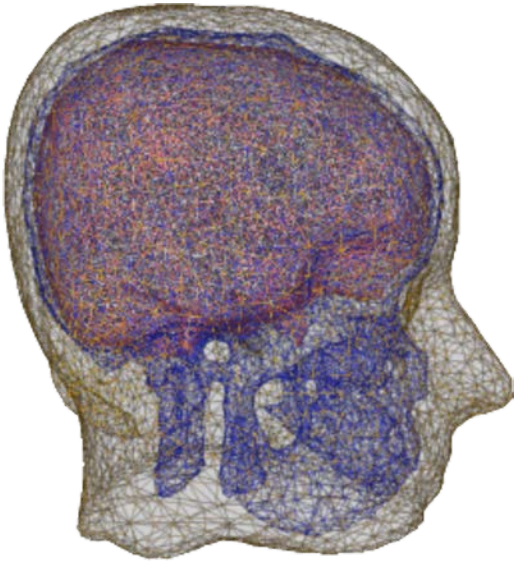
Volume conductor: FEM

To make a Finite Element Method (FEM) head model:

- **Tesselate the 3-D volume into solid tetrahedra**
  - Contains a large number of 3-D elements
  - Each tetrahedron can have its own conductivity
  - Each tetrahedron can have its own *anisotropy* (direction-dependent conductivity differences)
- **FEM is the more complete numerical method** (> BEM)
  - But is computationally expensive
  - Note: Accurate conductivities are not known, particularly for skull (and scalp?).

R. Oostenveld, & S. Makeig, 2016





Head Modeling Errors

Electrode & MRI Co-registration errors

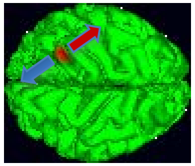
HeaD Geometry Errors

EXCLUSION of white matter

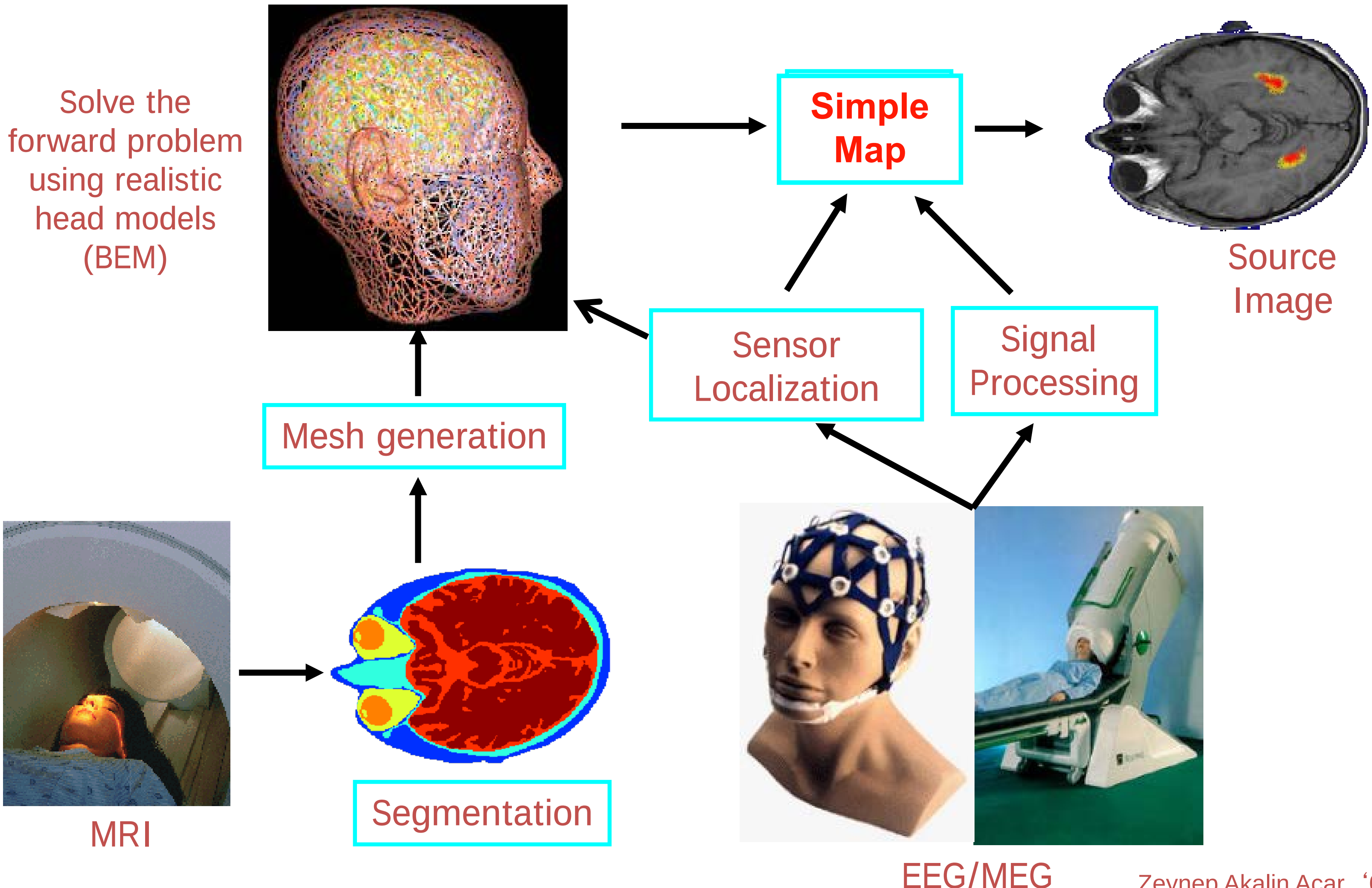
Two Few electrodes

Poor distribution of electrodes

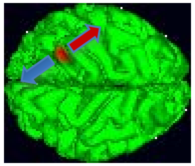
→ mis-estimation of skull conductivity



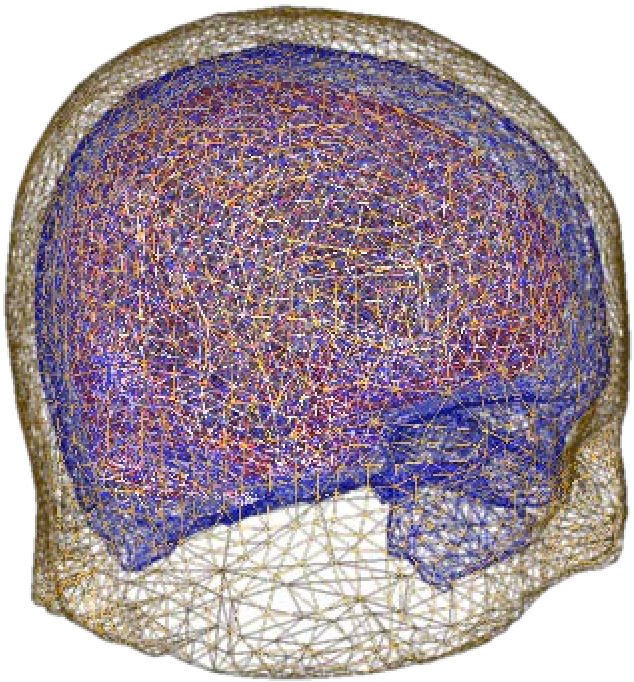
Electromagnetic source localization using realistic head models (Dipfit, NFT)



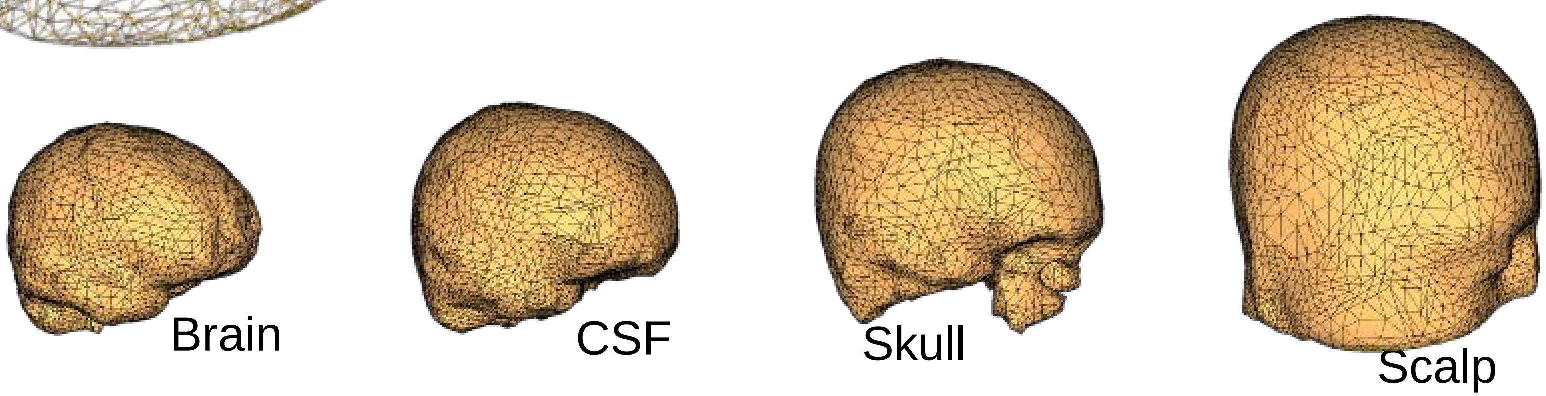
Zeynep Akalin Acar, ‘06



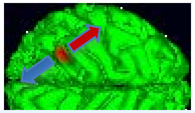
The MNI Head Model

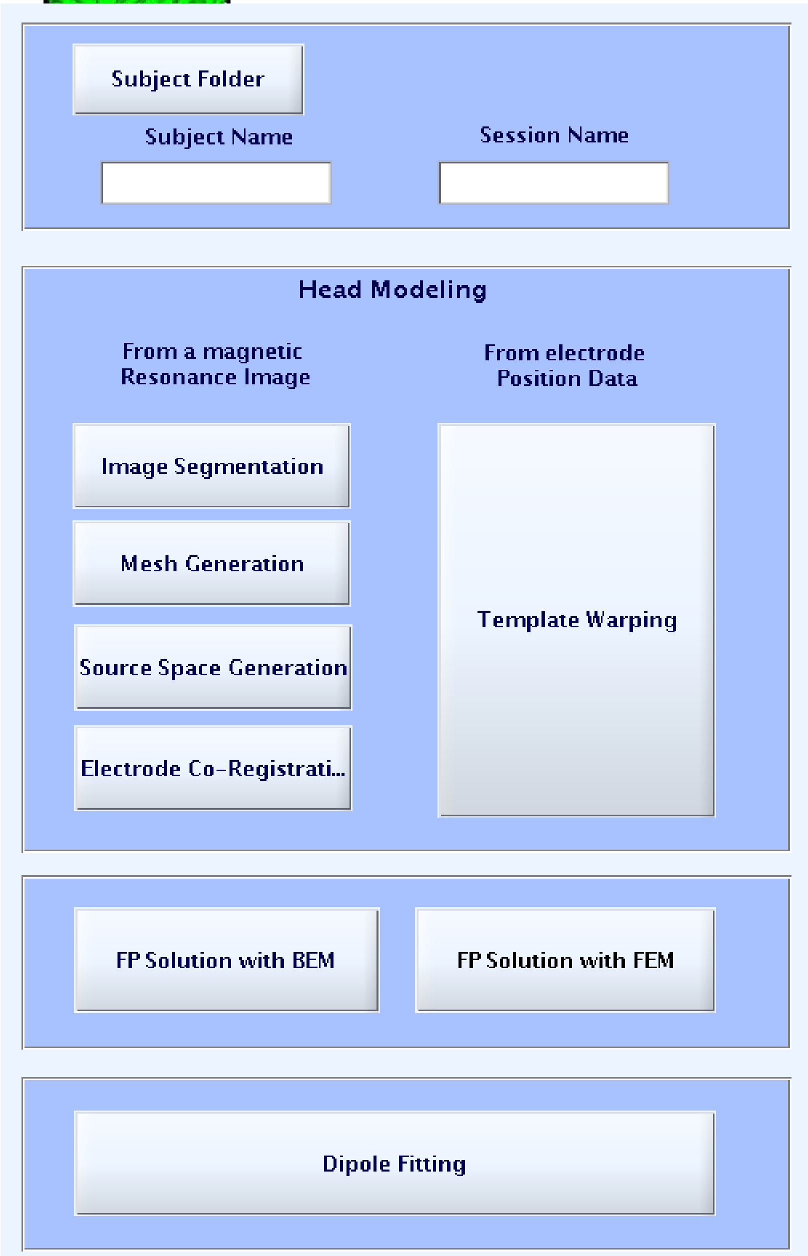


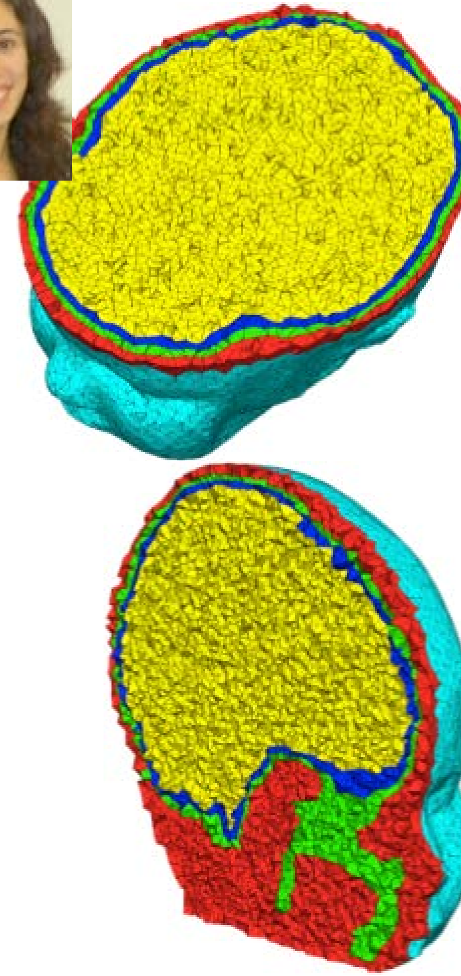
- 4-layer
  - 16856 nodes
  - 33696 elements
- 3-layer
  - 12730 nodes
  - 25448 elements



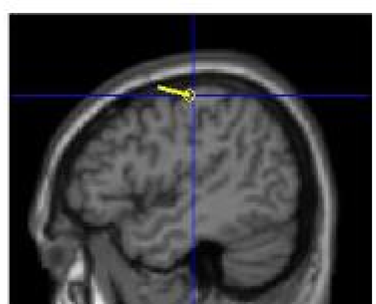
NFT





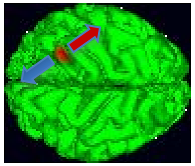


FEM models

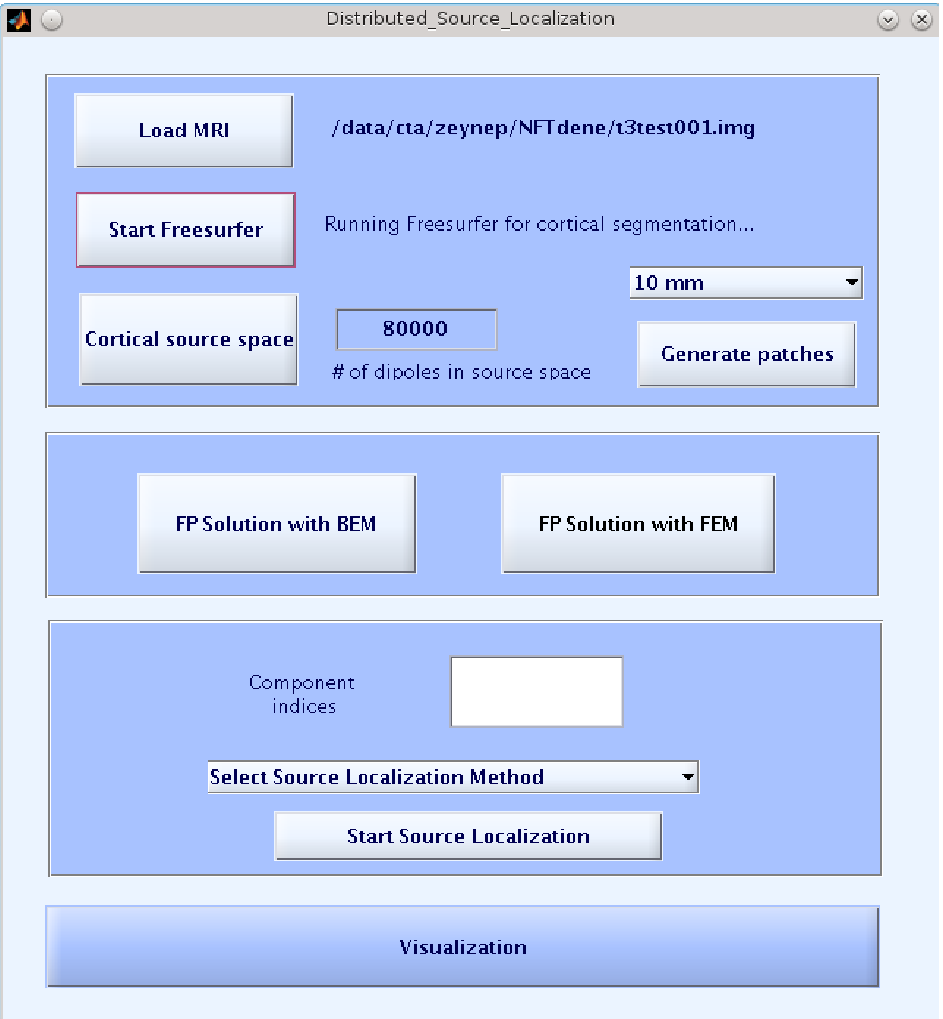


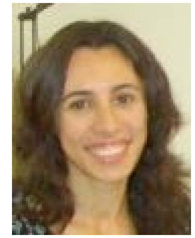
BEM models

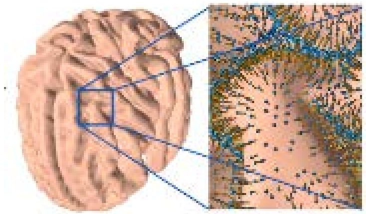
Akalin Acar & Makeig, 2010



NIST

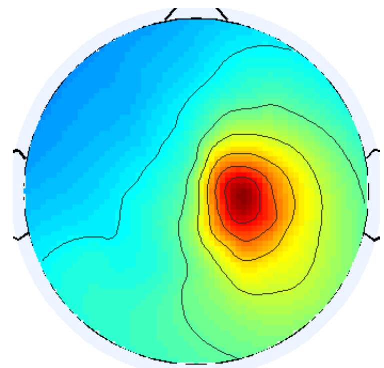




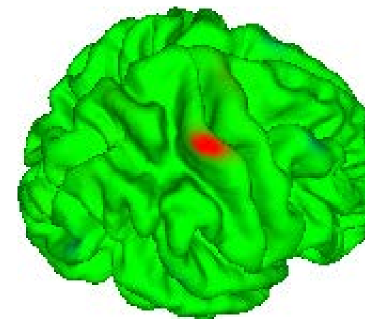


Source space

Scalp map

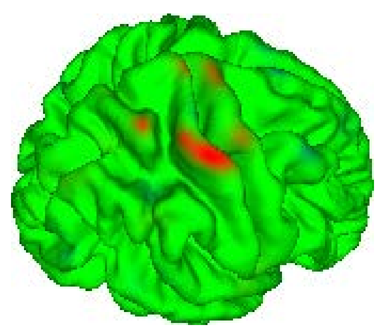


SCS

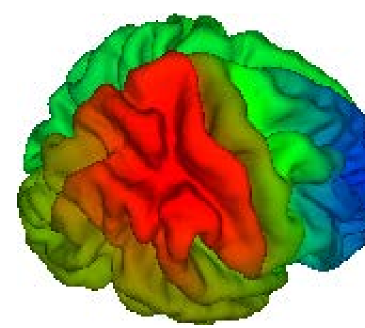


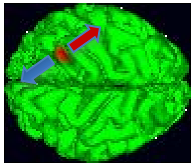
Cheng Cao, 2012

Patch-based SBL



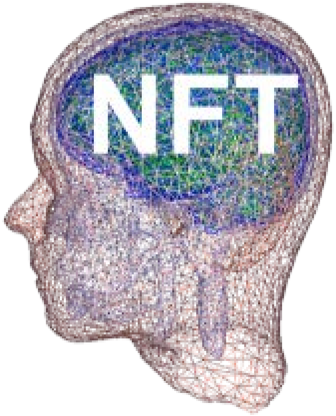
sLORETA

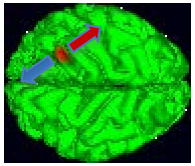




Head Model Generation Summary

- **Subject-specific Head Model (NFT)**
  - From whole head T1 weighted MR of the subject
  - 4-layer realistic BEM model
- **MNI Template Head model (DIPFIT)**
  - From the MNI head
  - 3-layer and 4-layer template BEM model
- **Warped MNI Template Head Model (NFT)**
  - Warp MNI template to EEG sensors
- **Spherical Head model (no longer in use)**
  - 3-layer concentric spheres
  - Fitted to EEG sensor locations
  - Not accurate

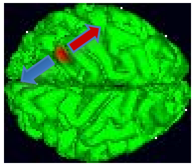




Inverse source localization

- **Single and multiple dipole models**
  - Minimize error between the model and the measured potential/field
- **Distributed dipole models**
  - Seek perfect fit to the measured potential or field
  - Must minimize **some additional source constraint**
    - LORETA assumes a smooth source current distribution
    - Minimum Norm (L2), min. total cortical $|current|^2$
    - Minimum Current (L1) min. total cortical |current|
    - Note: L2/L1 need some weighting scheme to keep source models from being too broad & superficial.

R. Oostenveld, & S. Makeig, 2016



Inverse methods

Spatial filtering approaches

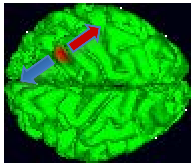
- **Scan whole brain** with single dipole and compute the filter output at every location (using sensor covariance)
  - MUSIC
  - *Beamforming* (e.g. LCMV, SAM, DICS)

- **Perform ICA decomposition** (higher-order statistics) on the continuous data.
  - ICA gives the projections of the sources to the scalp surface → **'simple' maps**!

→ICA solves 'the first half' of the inverse problem 'What?'

→ICA gives 'simple' source maps, helping to locate 'Where?

R. Oostenveld, & S. Makeig, 2016



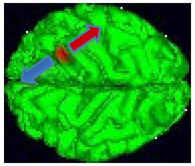
Single or multiple dipole models

- Manipulate source parameters to **minimize error** between measured and model data
  - The **position** of each source
  - The **orientation** of each source
  - The **strength (magnitude)** of each source

- **Dipole orientation** and **strength** together correspond to the "**dipole moment**," estimated linearly
- **Dipole position** is estimated non-linearly by

  source parameter estimation

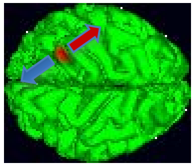
R. Oostenveld, & S. Makeig, 2016



DIPFIT: Dipole fitting 1. Grid search

1. Coarse fit step

- Define a grid with possible dipole locations
- Compute optimal dipole moment at each location
- Compute value of goal-function (fit to given map)
- Plot value of goal-function on the grid → find best fit.
- Number of evaluations:
  - single dipole, 1 cm grid: ~4,000
  - single dipole, ½ cm grid: ~32,000
  - BUT two dipoles, 1 cm grid: ~16,000,000



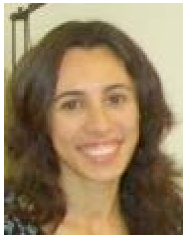
DIPFIT: Dipole fitting 2. Nonlinear search

2. Fine fit step

Start with the initial guess from coarse fitting

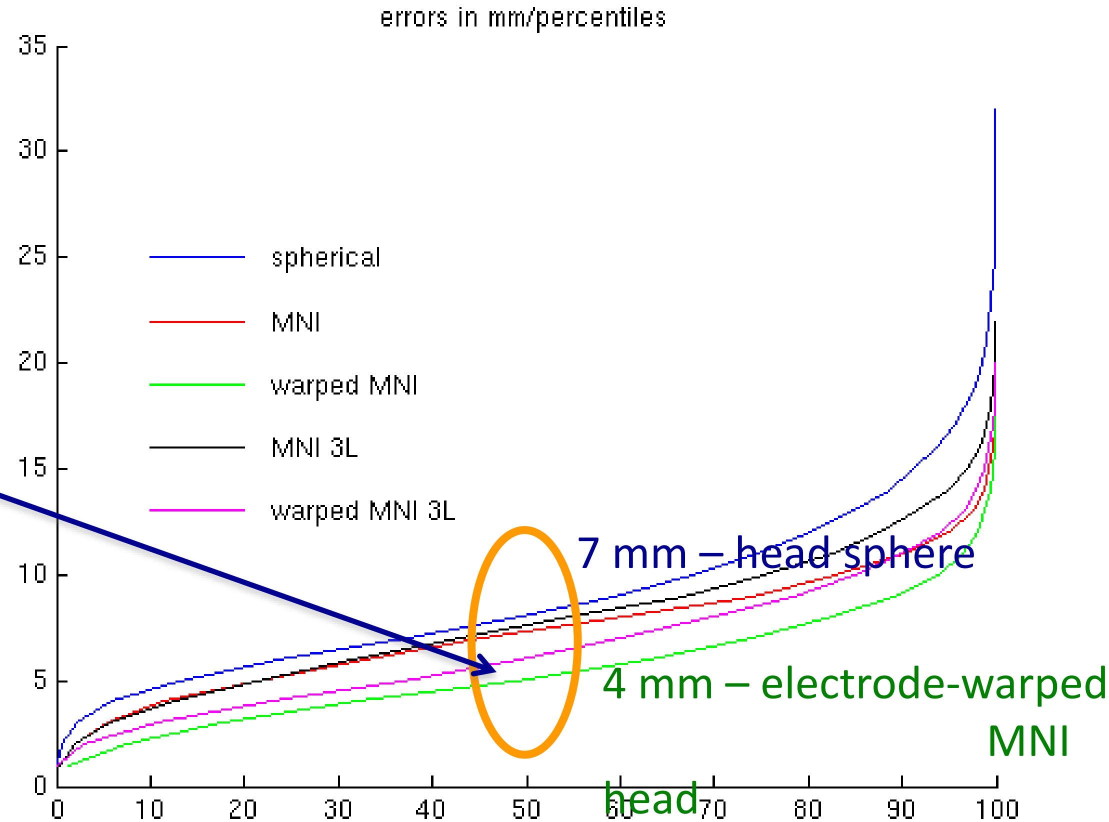
- Evaluate the local derivative of the goal (fit) function
- Then "walk down hill" to the most optimal solution

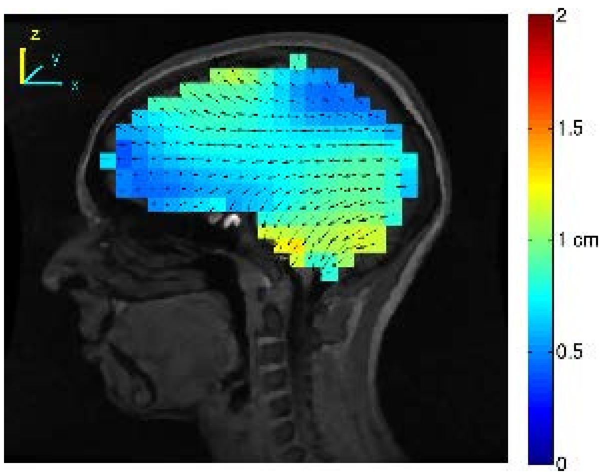
Number of iterative steps required = ~100



Effect of Template Head Model Choice On Estimated Dipole Locations

By Simulation: The median geometric error in dipole localization using the MNI template head model warped to measured electrode positions is only 4 mm.

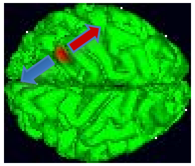




BUT Additional dipole error contributors:

- Electrode co-registration error
- ICA numerical error (not enough data?)
- Source model geometry error
- **Conductance value error** (skull) !

Z. Akalin Acar & S Makeig, 2013



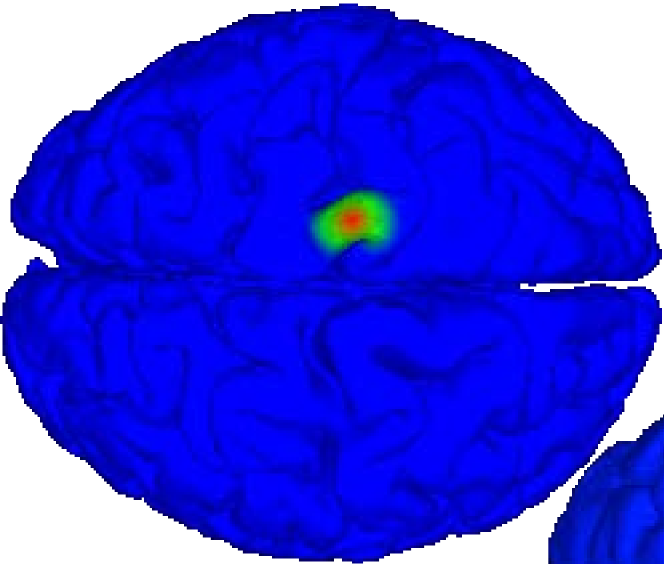
Distributed source models

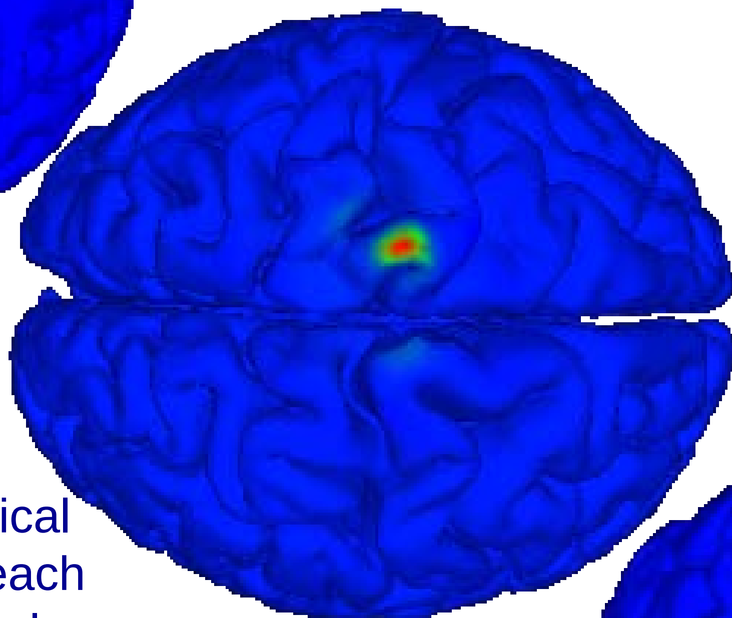
- The position of the source is not estimated as a whole
- Instead, On a pre-defined *source space* grid (3-D volume or cortical 2-D sheet)
  - Dipole strength is estimated *at each grid element*
  - In principle, a linear problem, easy to solve, BUT…
    - More "unknowns" (parameters) than "knowns" (channels, measurements), so …
    - An infinite number of solutions can explain the data perfectly (not necessarily physiologically plausible!)
  - **Therefore**, additional source constraints are required …

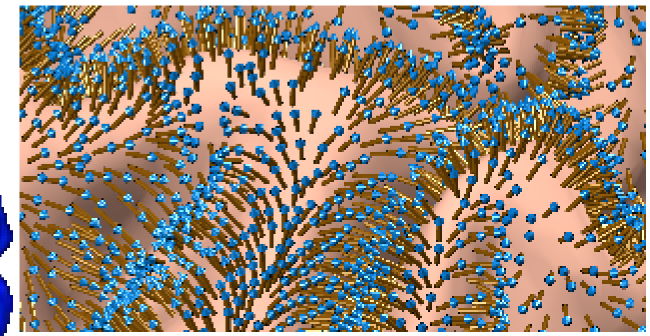
R. Oostenveld, & S. Makeig, 2016

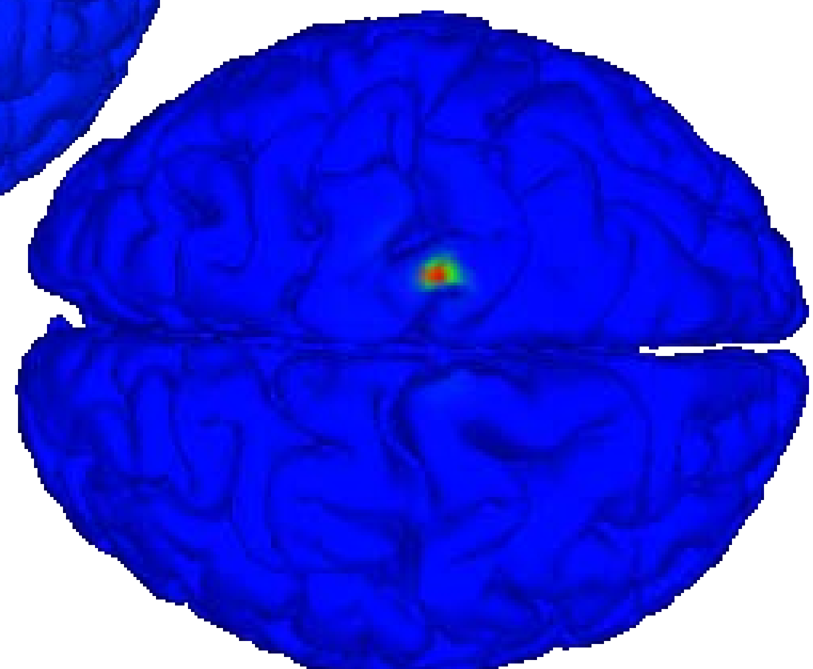
High-Resolution Distributed Source Localization

using a multiscale patch basis



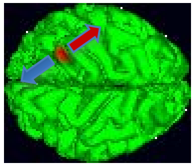






0. Build a high-res. cortical surface mesh; give each voxel an oriented dipole.
1. Compute a ‘dictionary’ of Gaussian patches conforming to the cortical surface centered at each cortical mesh voxel.
2. Use a ‘sparsifying’ approach to find the sum of the *fewest* of these patches that together produce the given source scalp or grid map.

Zeynep Akalin Acar,, S. Makeig, G. Worrell, ’09-’16



Summary

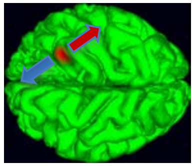
- An electromagnetic **forward head model** is required to interpret the sources of scalp maps
- Interpretation of scalp maps in terms of brain source distributions is "**inverse** source estimation"

→ Mathematical techniques are available to aid in interpreting scalp maps as arising from particular brain sources

→ These require an **inverse source model**, i.e. assumptions about the possible locations and nature of the sources (i.e., what attributes make them ***physiologically plausible***).

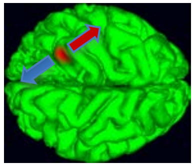
→ Then search for the ***most plausible*** source model.

R. Oostenveld, & S. Makeig, 2016



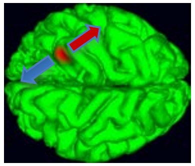
Summary

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



Summary

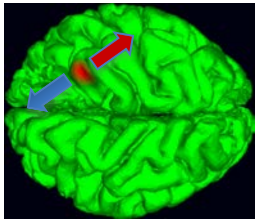
- **If we have MRI of the subject …**
  - Subject specific head model
  - Distributed source localization
- **If we don' t have the MRI head image …**
  - Warped 4-layer MNI model (NFT)
  - Dipole source localization
- **Skull conductivity estimation** is *as important* as the head model used (SCALE)
- **White matter** modeling does not have a huge effect on source localization.



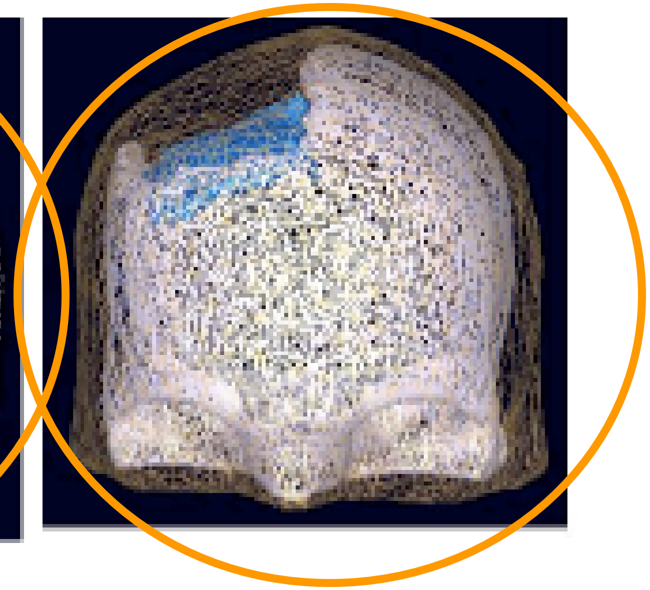
Acknowledgments

This presentation by Scott Makeig from materials by

- **Robert Oostenveld** (Donders Institute, Nijmegen)
- **Zeynep Akalin Acar** (SCCN, UCSD)
- **Arnaud Delorme** (SCCN)

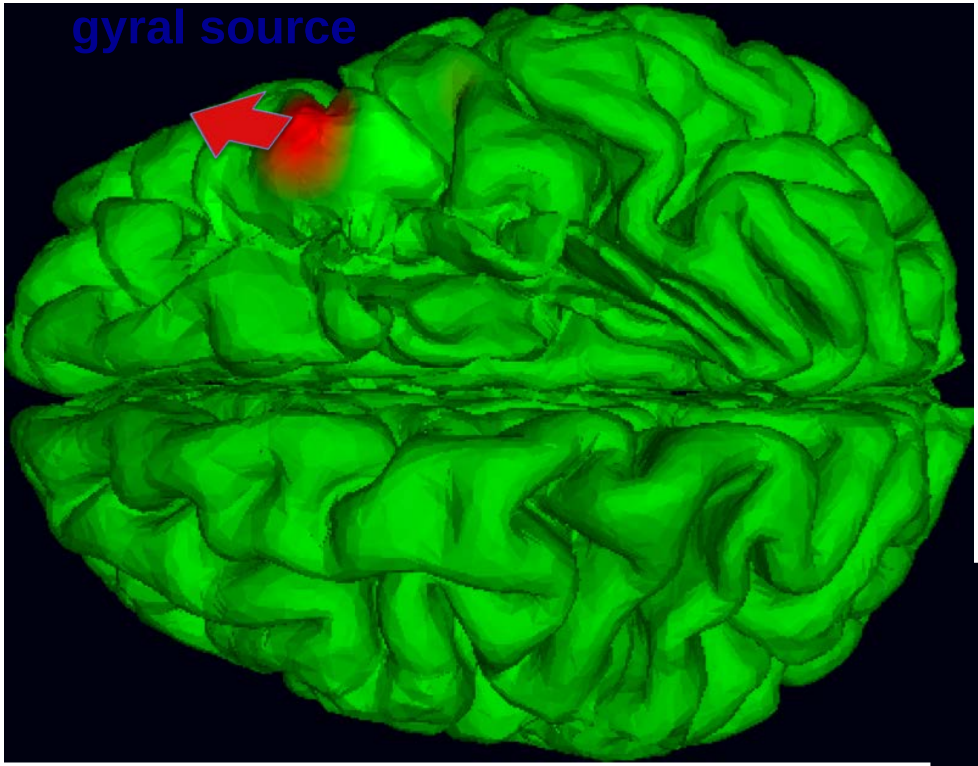


Mapping sources of intracranial data recorded to plan brain surgery



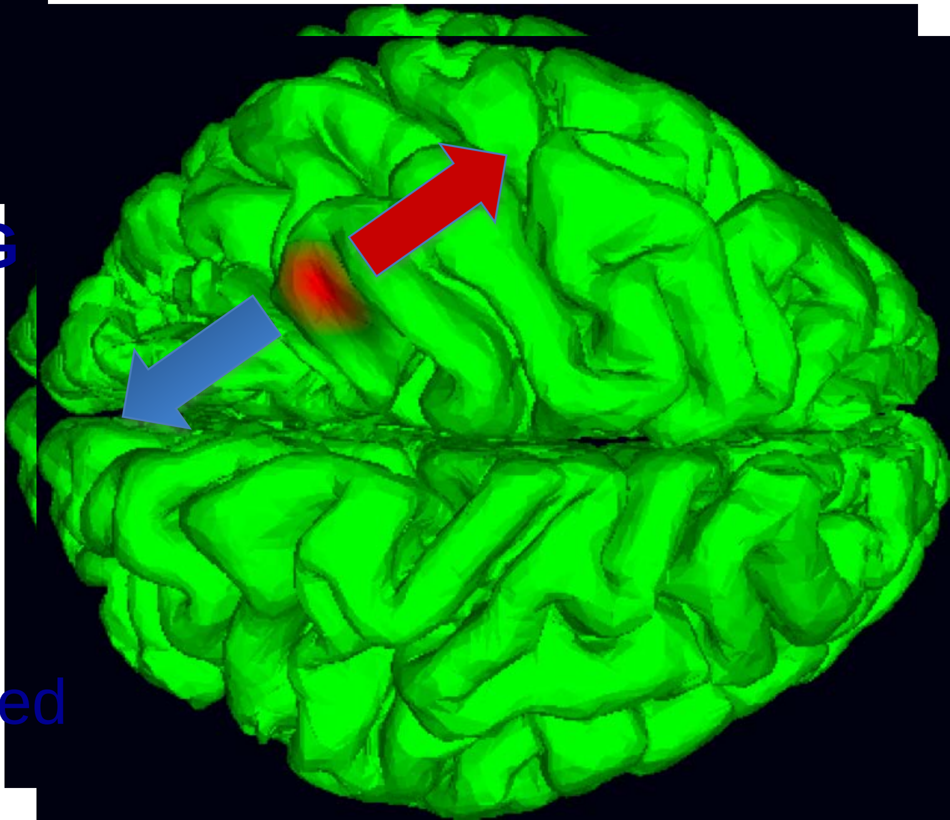
Non-conductive ‘plastic layer’ (the ECoG electrode sheet and strip)

Zeynep Akalin Acar,, S. Makeig, G. Worrell, ’09-’16



ECoG
Data Source
Decomposition by ICA

sulcal source



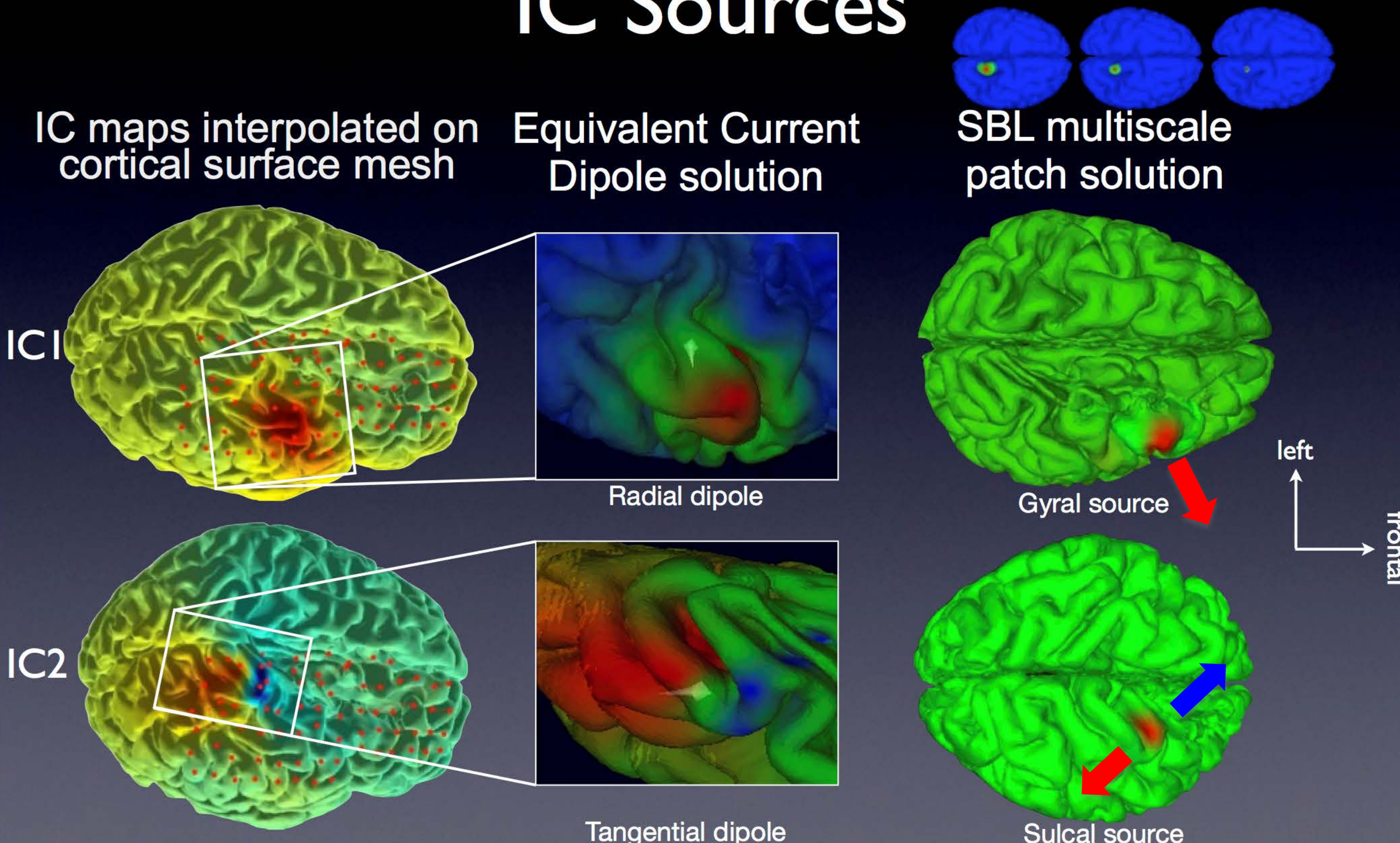
Given ECoG data from an ECoG grid:

0. Apply ICA to ECoG data.

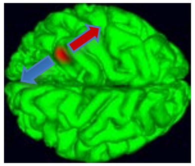
1.Can find radially oriented ‘gyral’ ECoG sources (left)

2.Can also find tangentially oriented ‘sulcal’ ECoG sources (right).

SBL Localization of Epileptogenic IC Sources

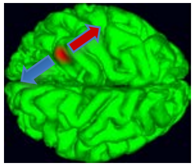


Akalin Acar, et al (2009) *IEEE EMBC*

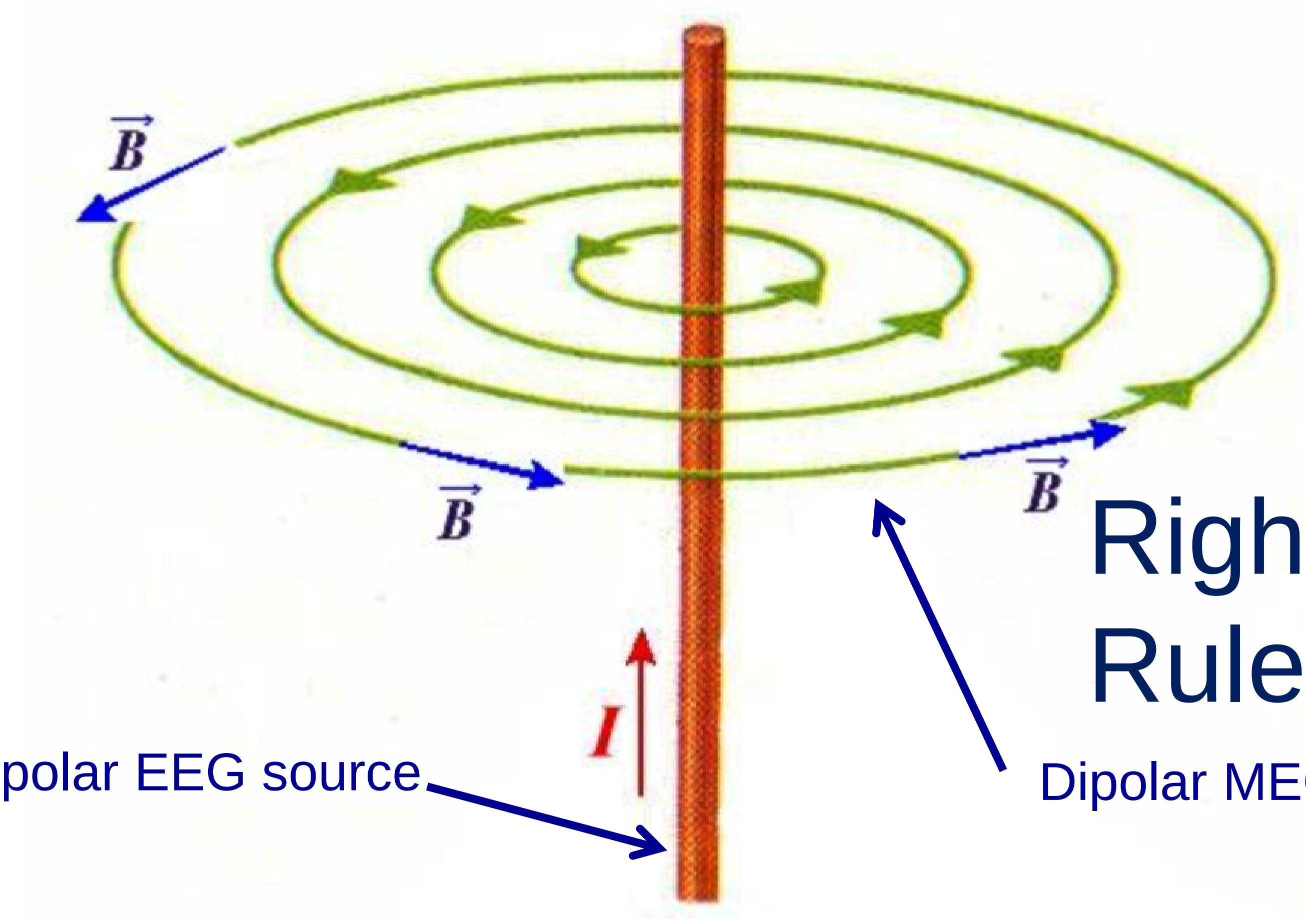


EEG vs. fMRI

- EEG measures extra-cellular potentials
  – Indexing **synchronous neuronal activity** (*phase*)
- fMRI measures BOLD (blood oxygenation level diff.)
  – Indexing **local energy consumption** (*amplitude*)
- Different characteristics
  – Generators different (neural currents, blood flow)
  – Time course differences (***BOLD is slow***)



EEG versus MEG
Electric current ←→ magnetic field

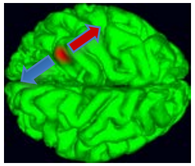


Right Hand Rule

Dipolar EEG source

Dipolar MEG field

R. Oostenveld, & S. Makeig, 2016

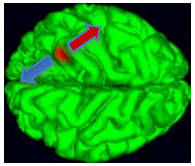


MEG volume conduction

- Measures sum of fields associated with
  – *Primary* currents
  – but also *secondary currents* at current distortions !
- However, only a fraction of the currents pass through the poorly conductive skull.
  – Therefore skull and scalp may be ~neglected in the MEG forward model (**simpler source imaging**).
- Local conductivity assumption near the dipole are important, so

→ **Both the geometries AND the conductivity of head model tissues are important in MEG forward models !**

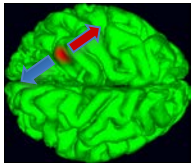
R. Oostenveld, & S. Makeig, 2016



Differences between EEG and MEG

- EEG scalp projection more blurred by volume conduction
- **BUT** MEG is insensitive to radial sources!!
- → **Therefore – EEG sees more sources!**
- EEG may be more noisy (electrode-skin impedance ~)
- but MEG is more sensitive to environmental fields!
- MEG requires no electrode gel
- but MEG requires the head to remain fixed !
- MEG is **MUCH more expen$$$ive** than EEG!

R. Oostenveld, & S. Makeig, 2016



Differences between EEG and MEG

- EEG sees potential differences, requires choice of reference electrode – but **ICA makes the data reference-free.**
- MEG sensor measures have no common reference
- MEG can use a simpler but still somewhat accurate forward model
  – E.g., a multiple non-concentric sphere model,

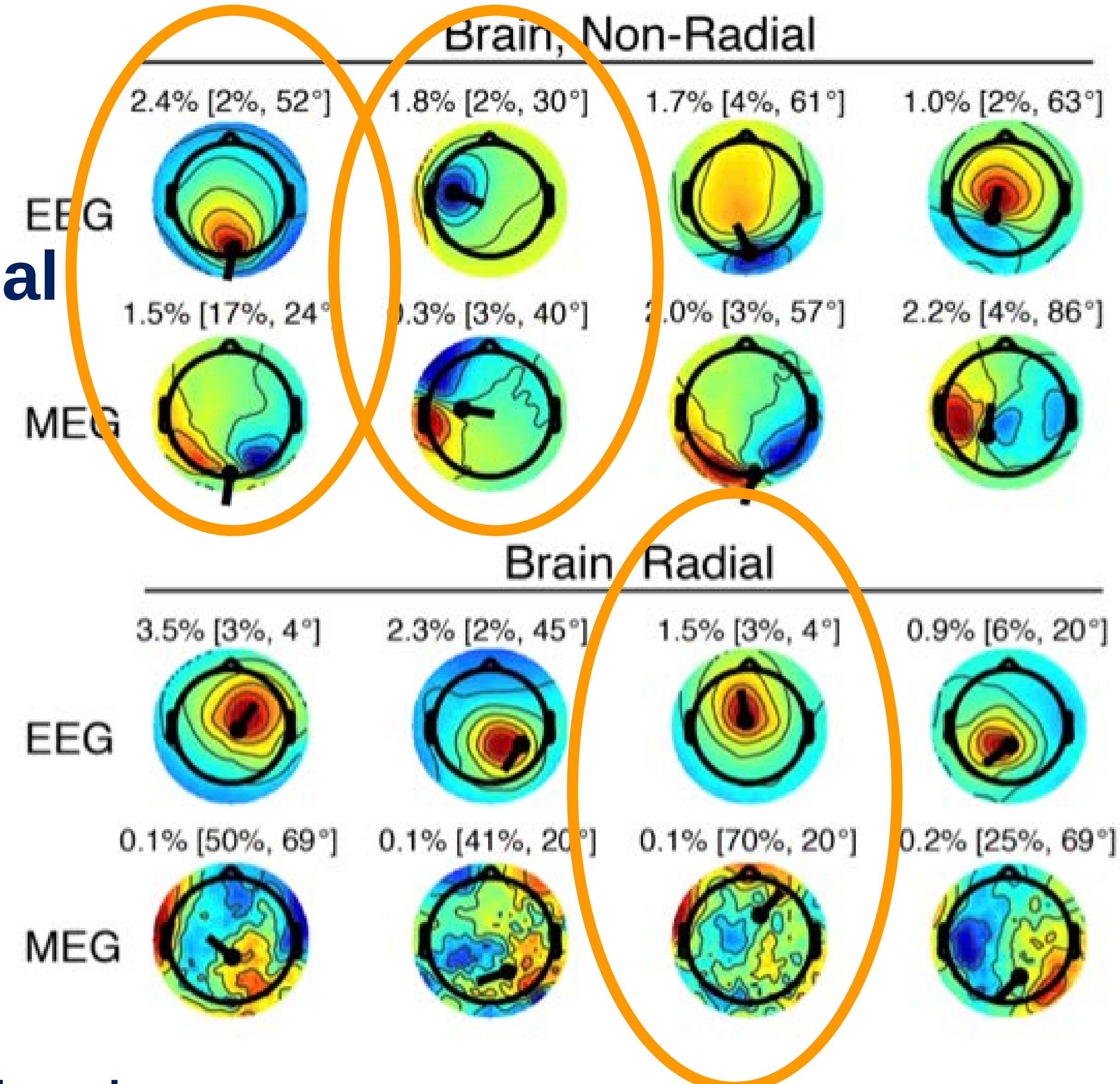
  Here, each sensor has its own local sphere fitted to the head position of brain relative to MEG sensors
  – But may vary when/if the head moves
  – Must be individually fit for each session

R. Oostenveld, & S. Makeig, 2016

EEG+MEG Joint ICA Decomposition

Tangential Sources

Radial Sources



MEEG plug-in

J. Iversen & S. Makeig, 2014