Forward and Inverse EEG Source Modeling

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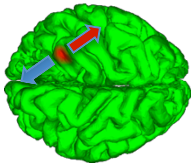
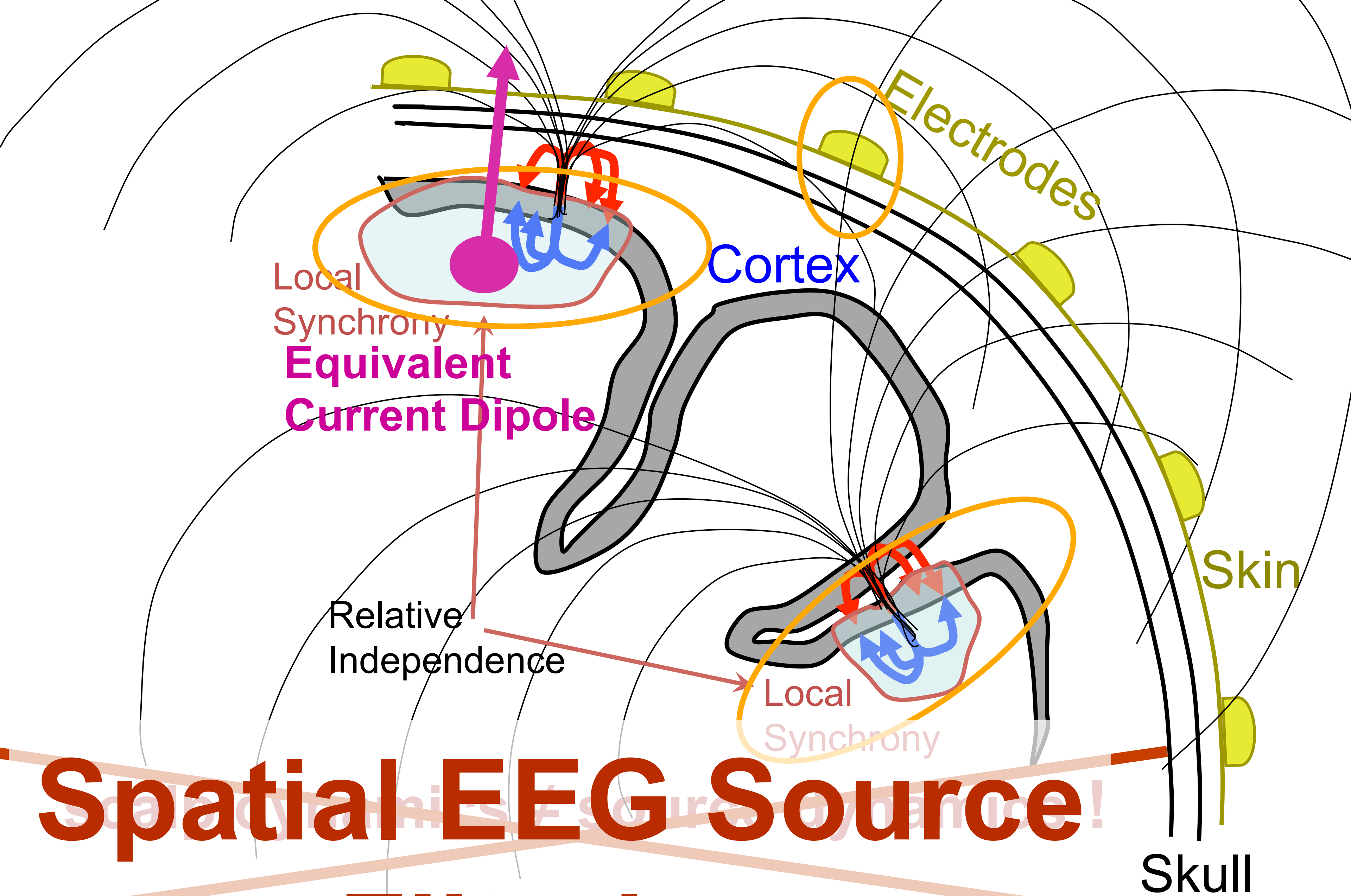


Motivation

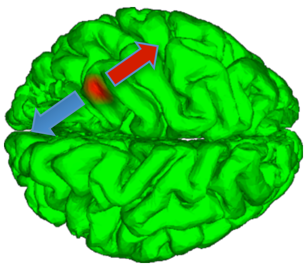
- Why measure EEG?
- Why perform ICA?
- Why fit dipoles?
- To obtain information about brain processes…
  - Time course of activity →EEG, MEG
  - Location of activity → fMRI, MEG, & EEG



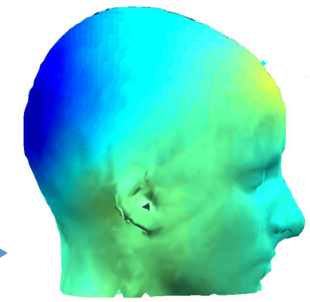
Spatial EEG Source Filtering

S. Makeig 2007

EEG source modeling



forward problem →

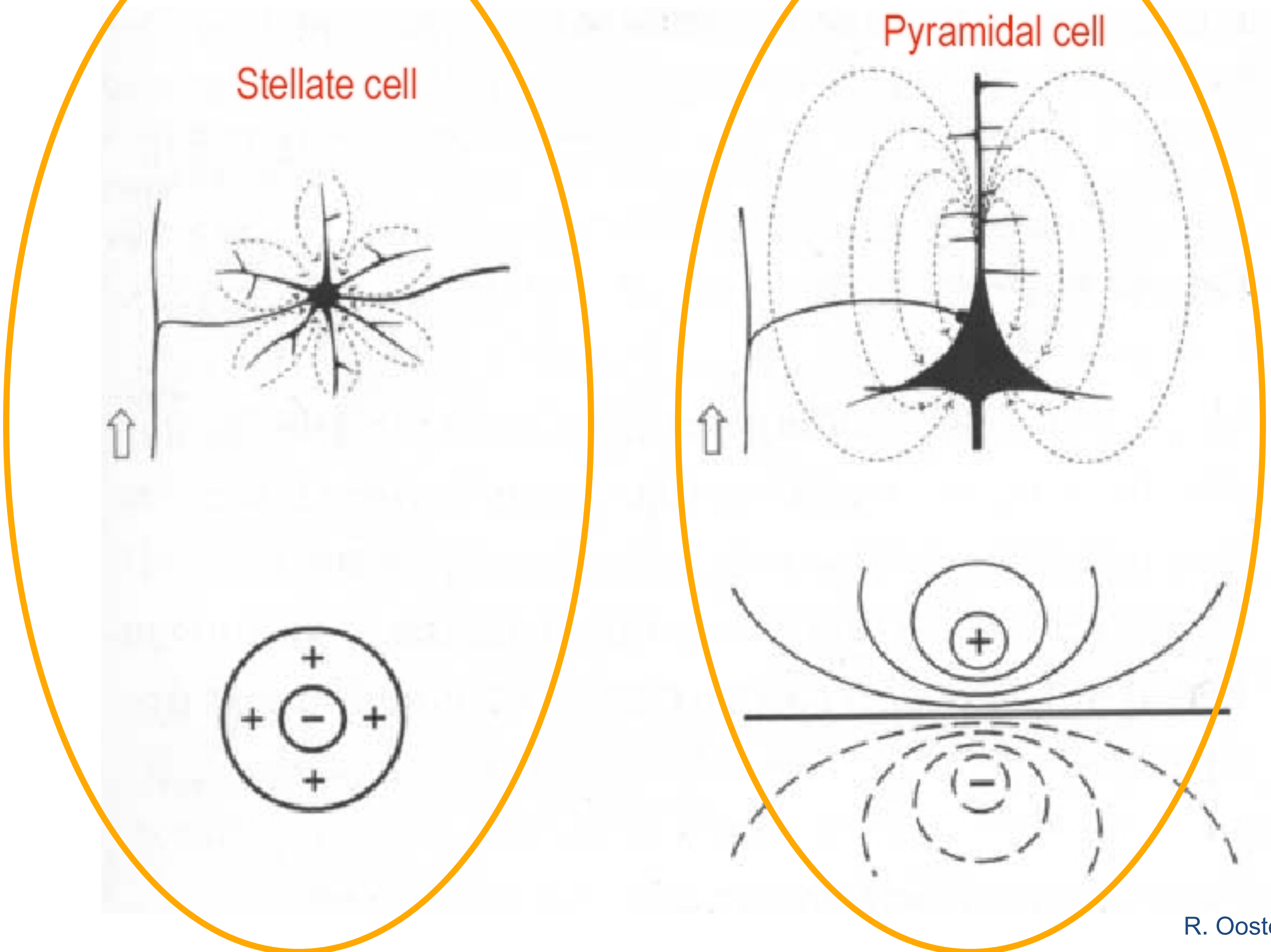


physiological source electrical current	body tissue volume conductor	observed potential or field

← **inverse** problem

R. Oostenveld, & S. Makeig, 2016

Peri-neuronal currents



R. Oostenveld, 2007

Symmetry, orientation and activation

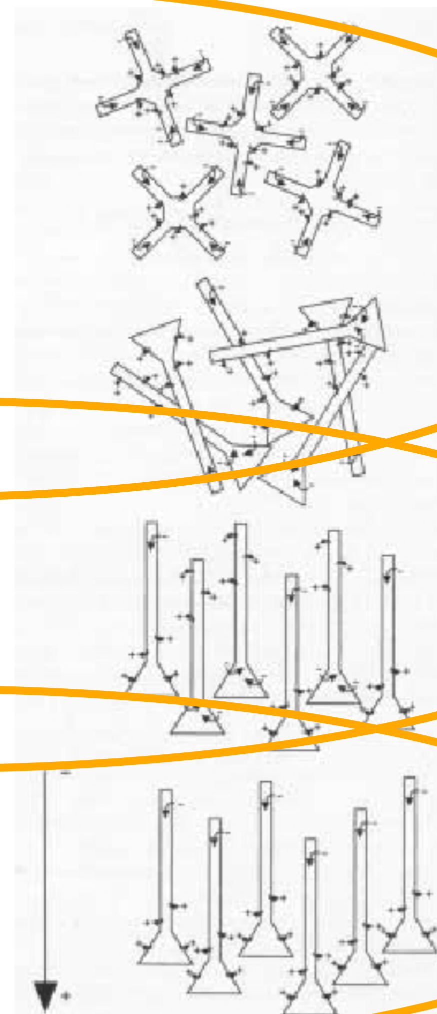
radially symmetric, i.e.

randomly-oriented

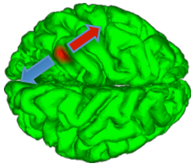
asynchronously activated

synchronously activated

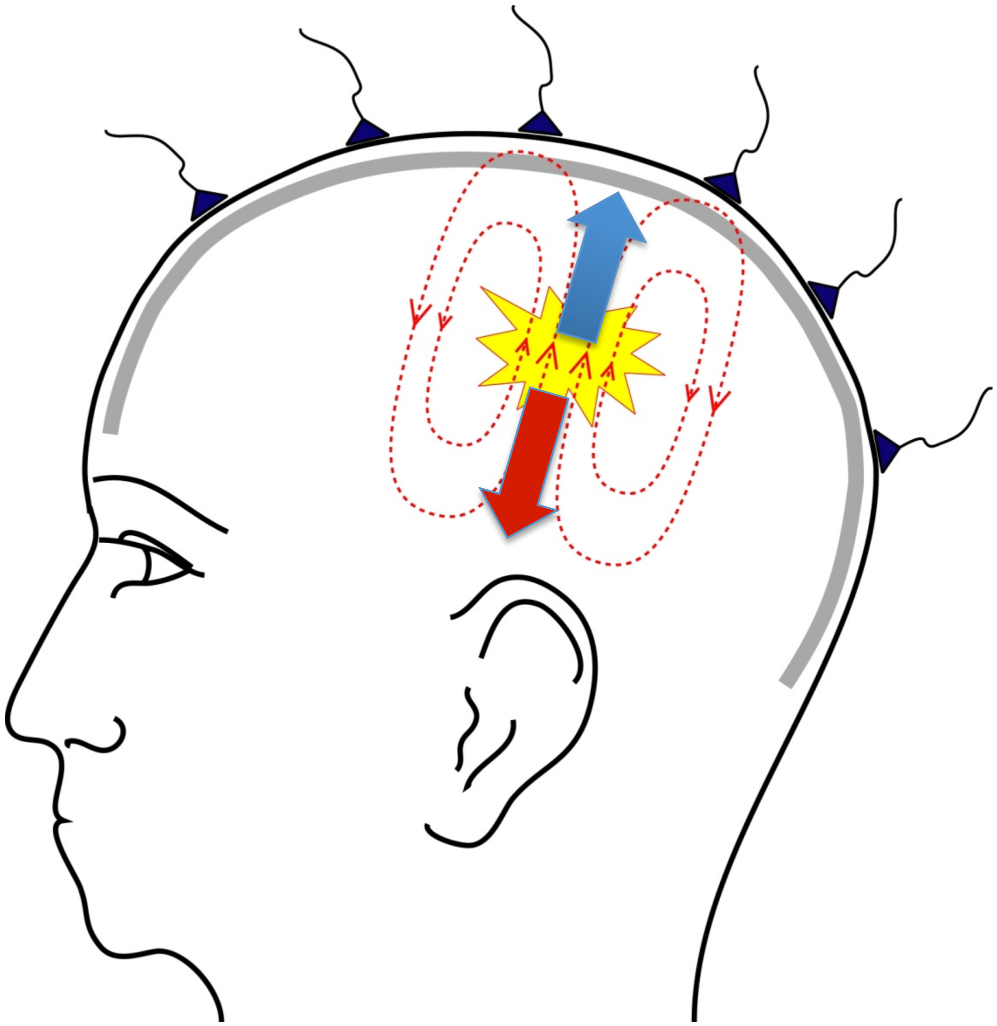
parallel-oriented



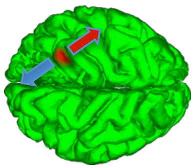
R. Oostenveld, 2007



EEG volume conduction → dipolar field patterns



R. Oostenveld, 2007



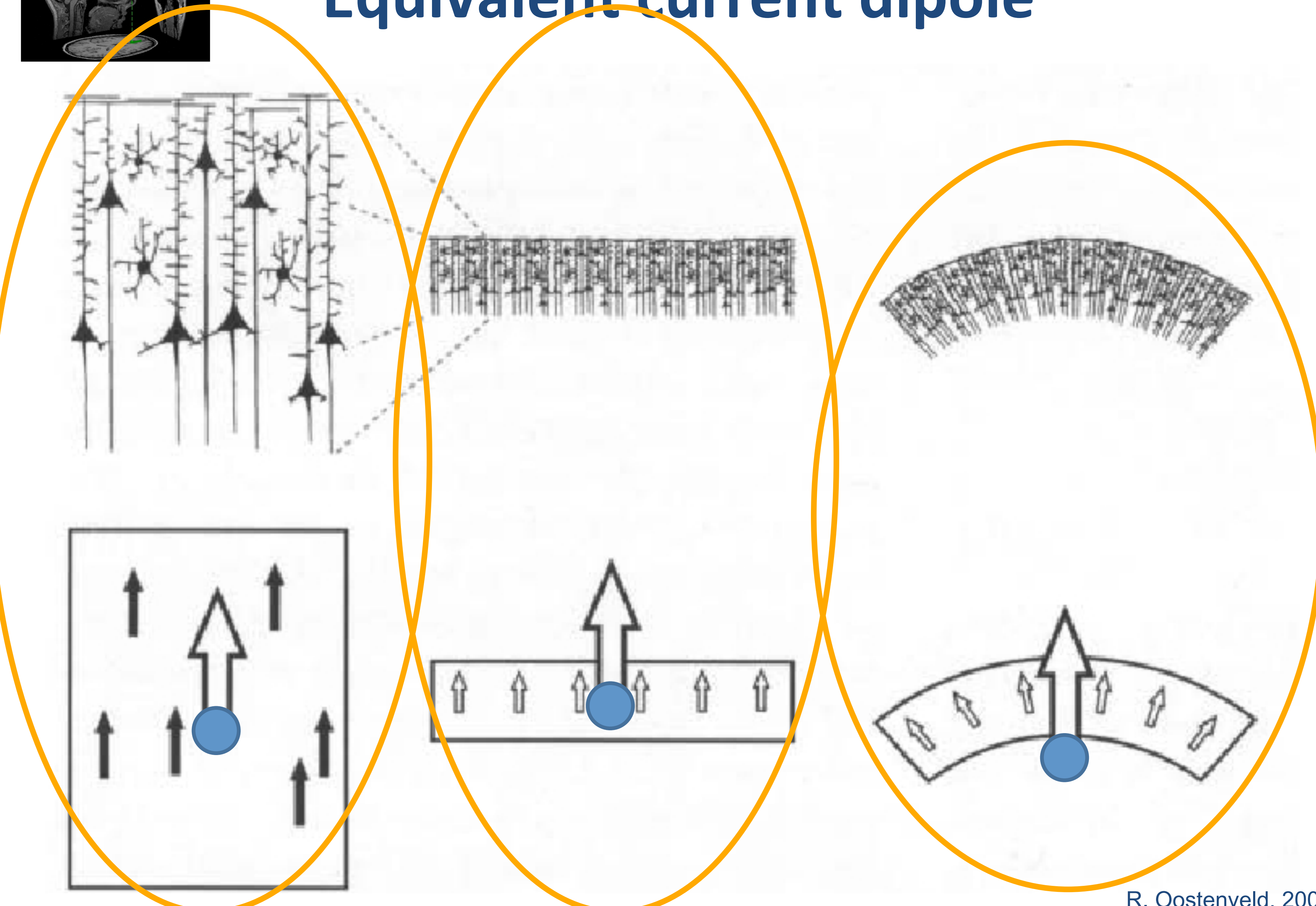
EEG volume conduction

- **Potential differences between electrodes** measures summed current flowing through scalp
  - 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.
- **Problems with skull**
  - Poorly visible in anatomical MRI (T2) images
  - Thickness varies regionally
  - Conductivity is not homogeneous
  - Complex geometry at front and base of skull

  → **Individual skull conductivity** variable & unknown

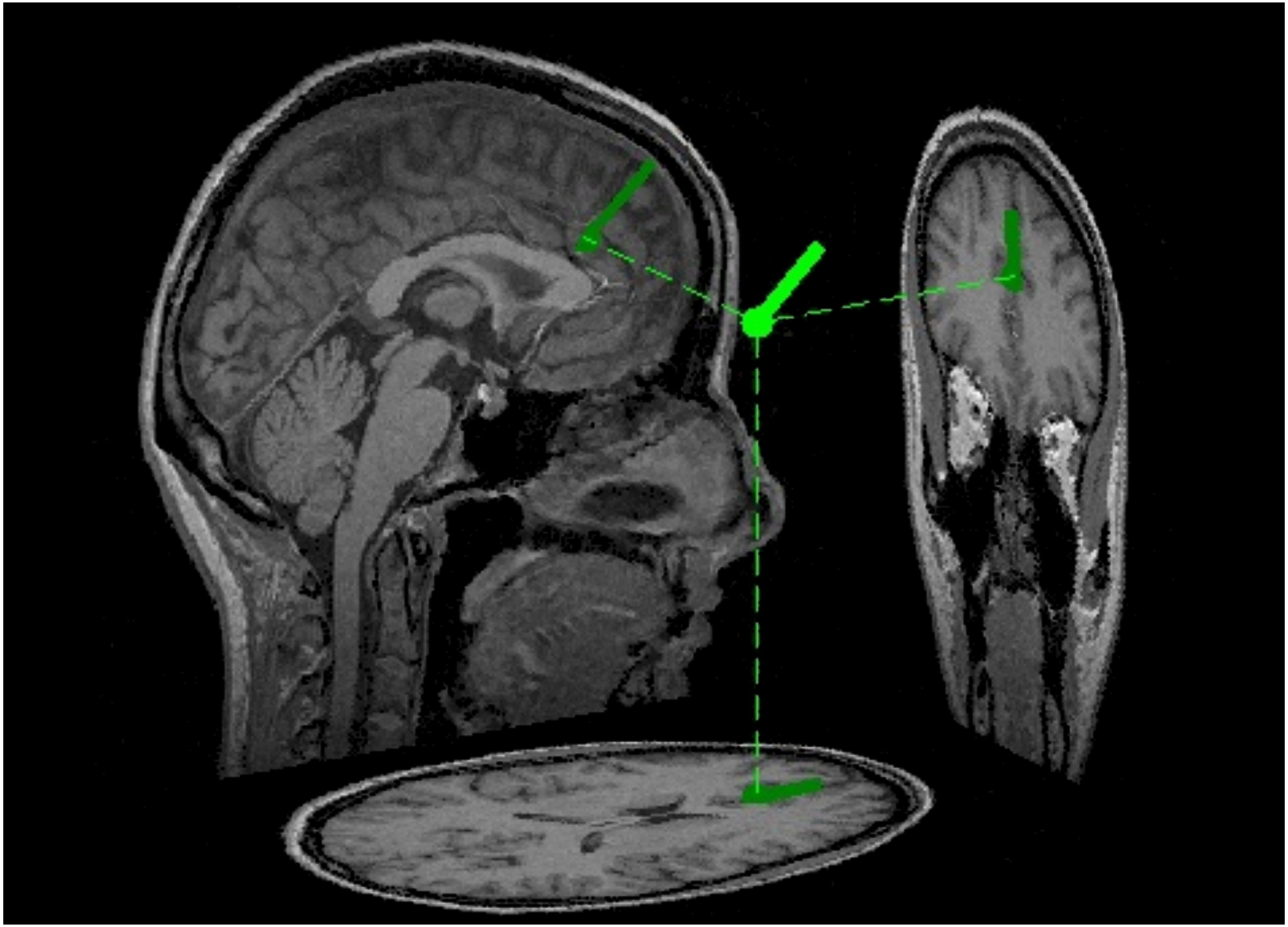
R. Oostenveld, & S. Makeig, 2016

Equivalent current dipole



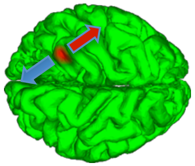
R. Oostenveld, 2007

Equivalent current dipole



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

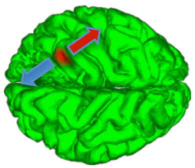
A. Delorme, ~2007



Equivalent current dipole

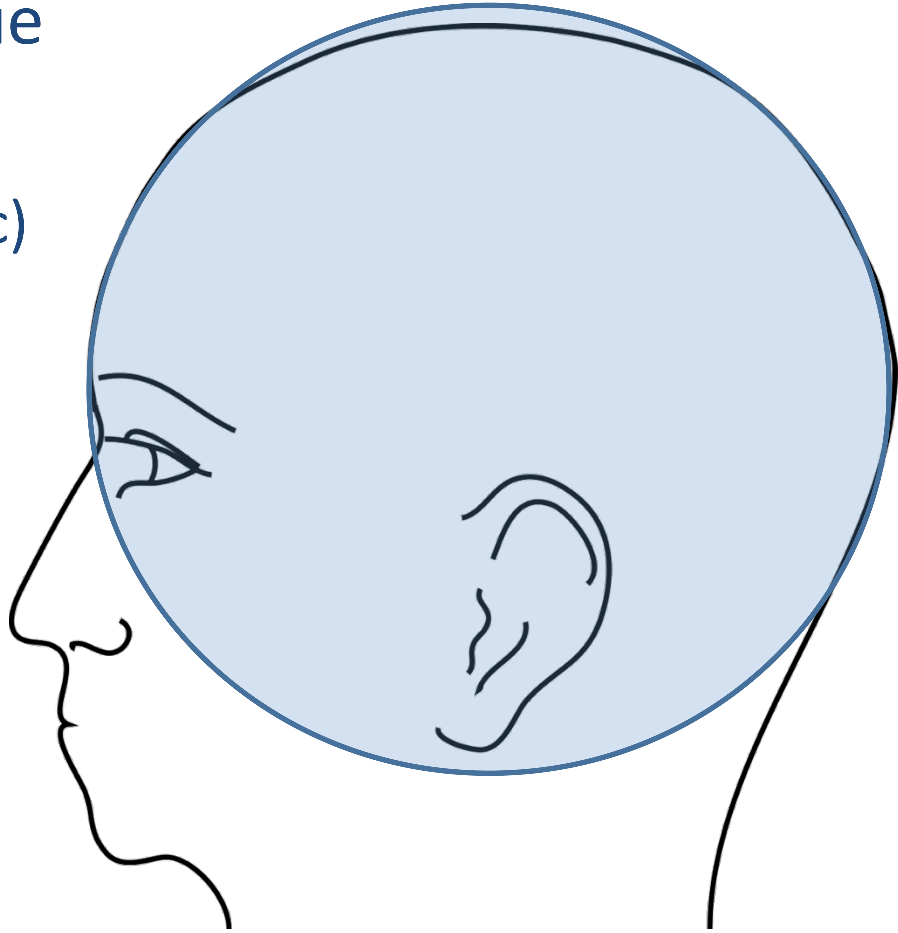
- Physical/mathematical motivation
  - Any current distribution can be written as a multipole expansion
  - First term: monopole (must be 0)
  - Second term: dipole
  - Higher order terms: quadrupole, octopole, …
  - **In far-field recordings, the dipolar term dominates.**
- For convenience + accuracy,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

R. Oostenveld, & S. Makeig, 2016

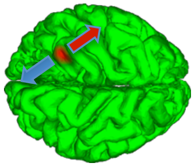


Volume conductor

- Electrical properties of tissue
- Geometrical description
  - spherical model (less realistic)
  - realistically shaped model

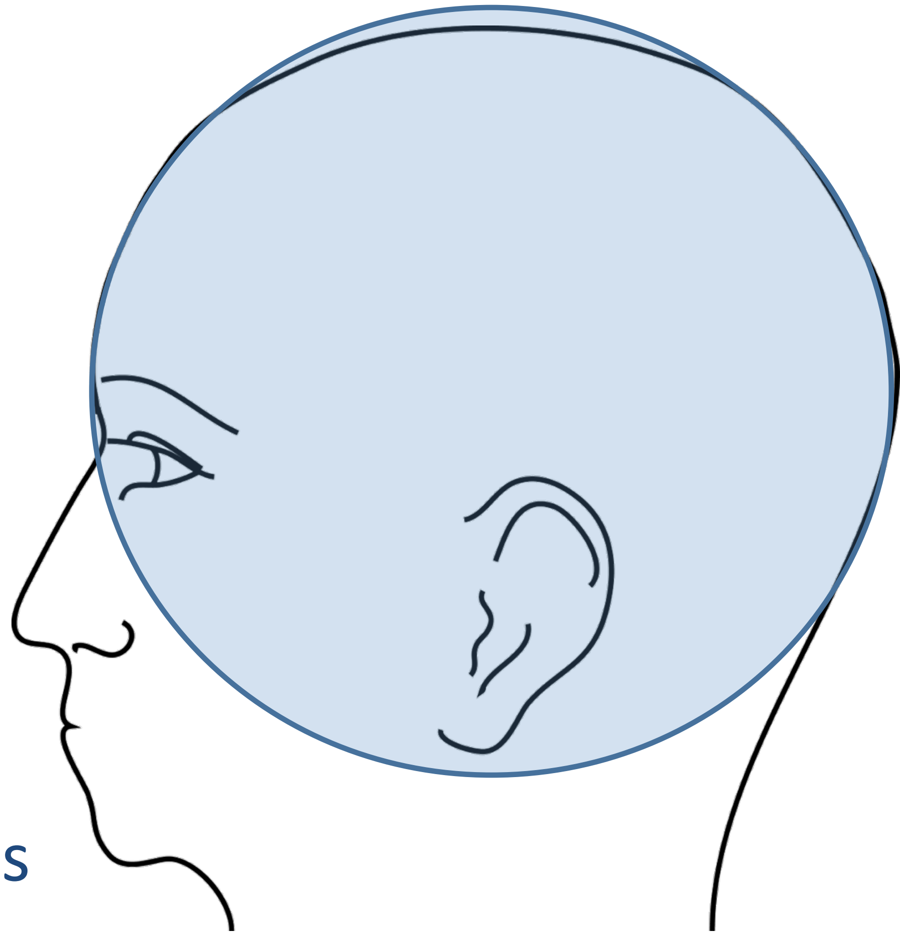


→ A **forward model** describes
how the currents flow,
not where they originate



Volume conductor

- 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



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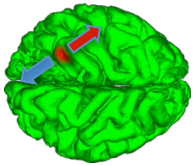
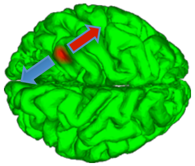


Volume conductor

- 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

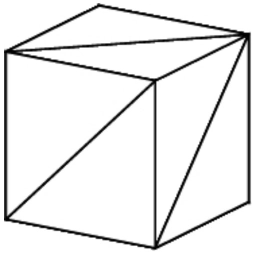
→ **The pragmatic (easy, cheap) solution is to use a standard (mean) realistic head model (MNI).**

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



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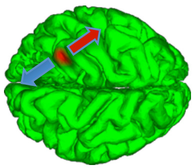
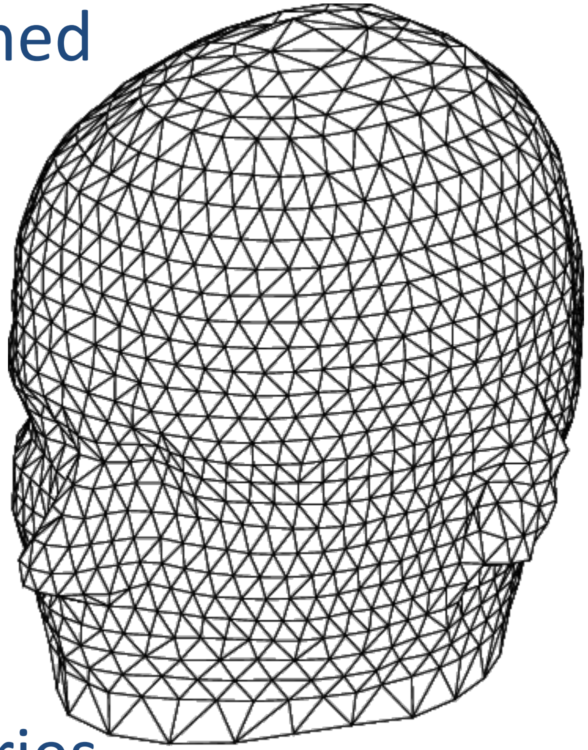


Volume conductor: BEM

- **Boundary Element Method** 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

Volume conductor: BEM

- **Boundary Elen**
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    compar
  - Tissue
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  Important
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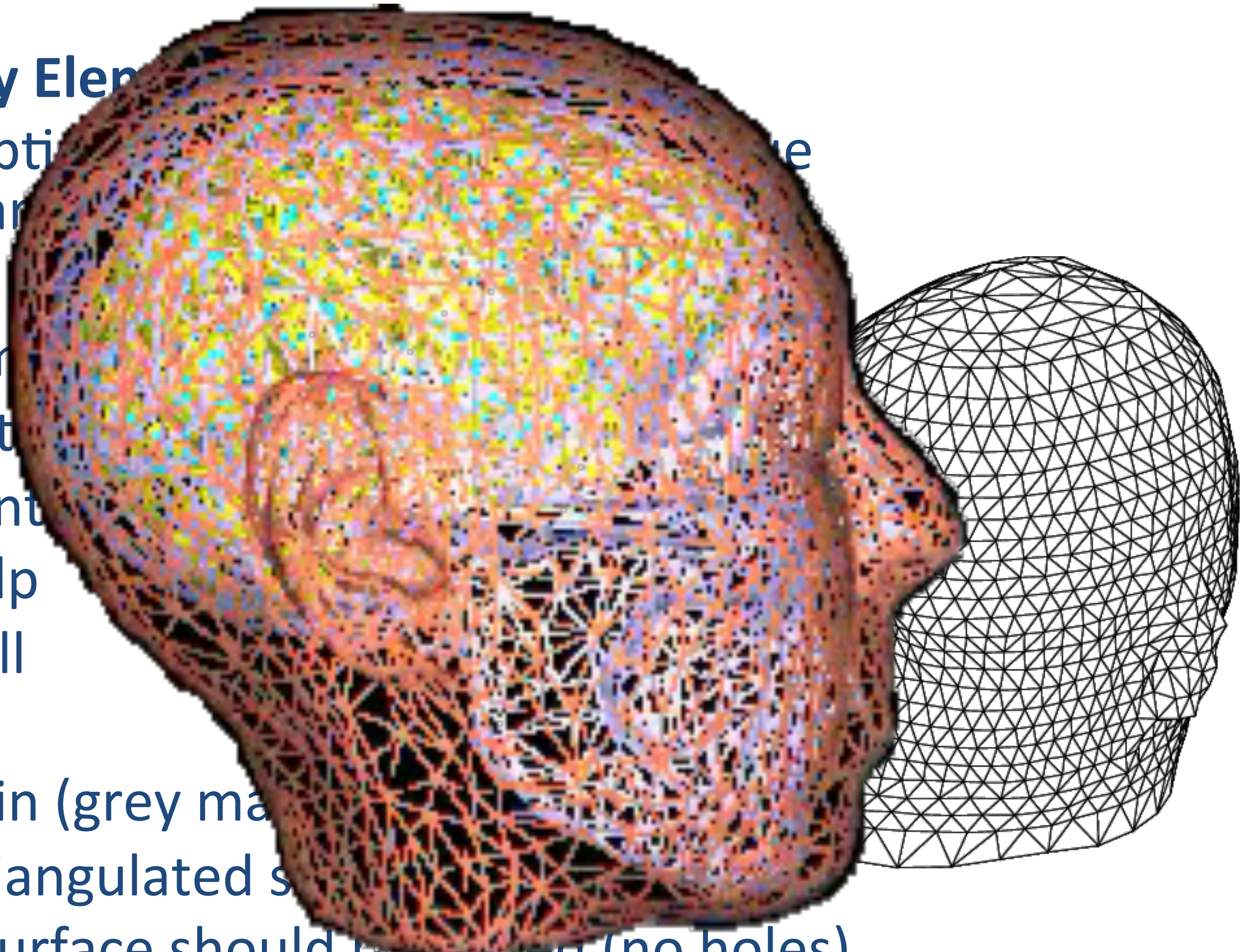

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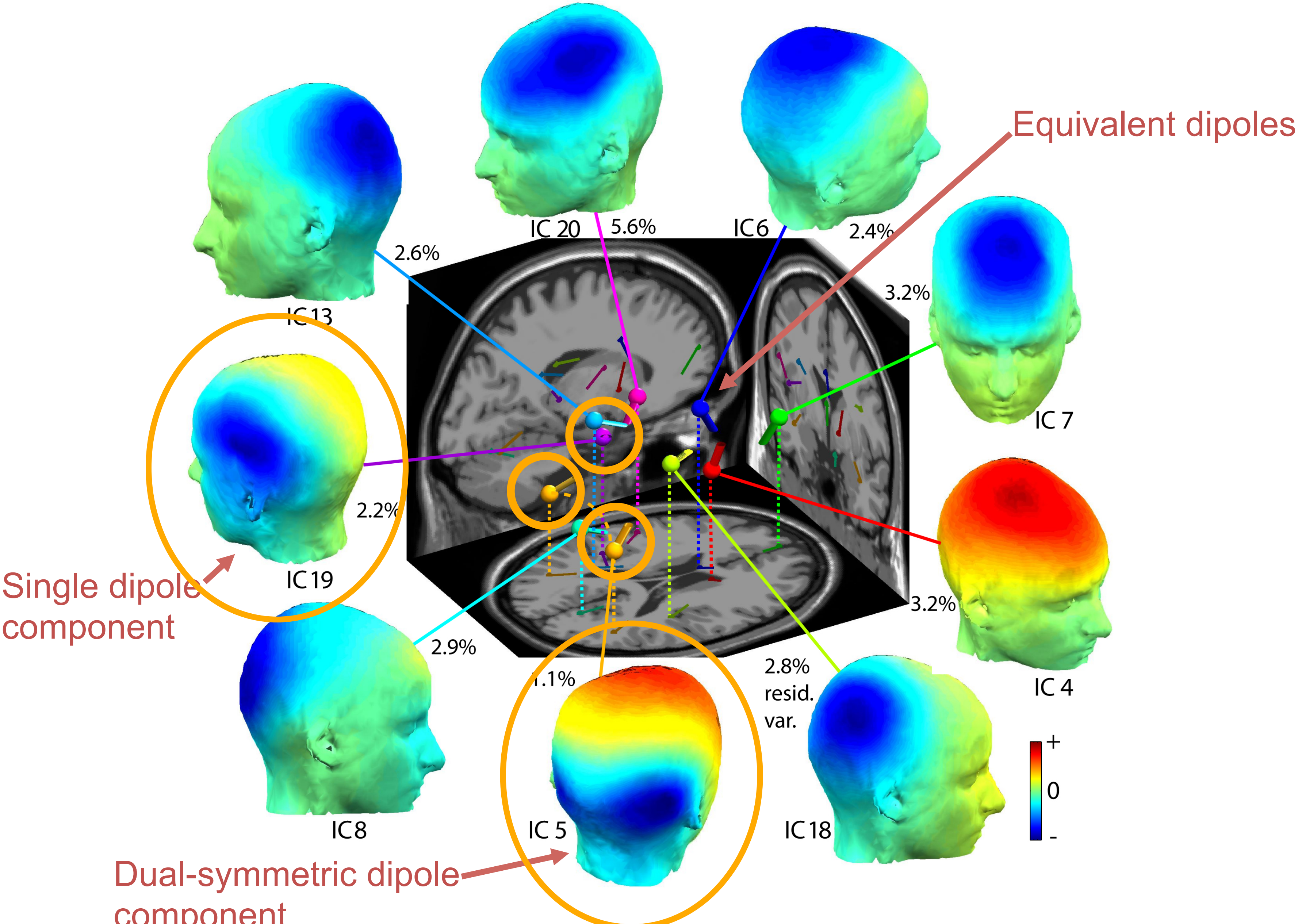
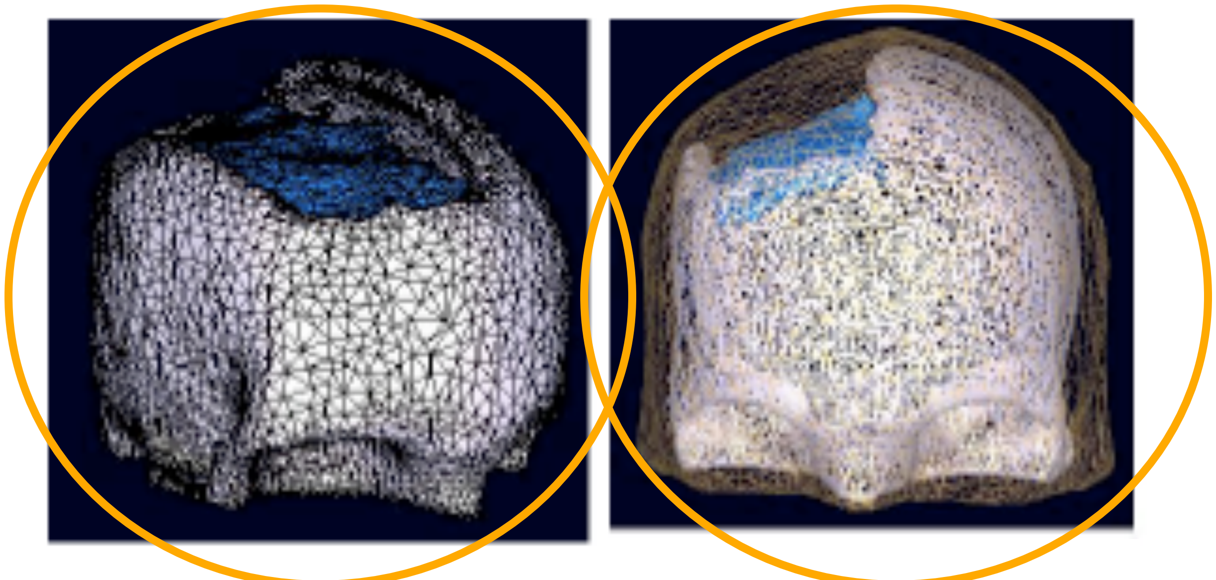
Independent cortical components



Julie Onton & S. Makeig (2006)

Electromagnetic source localization using realistic head models – here to map sources of intracranial data recorded to plan brain surgery

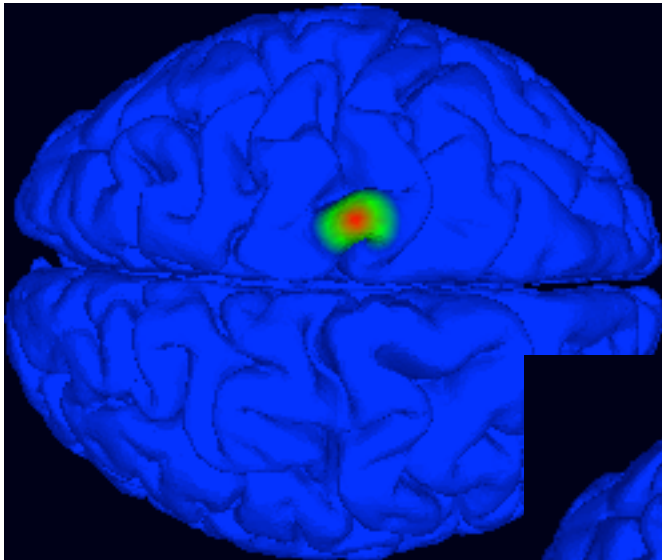


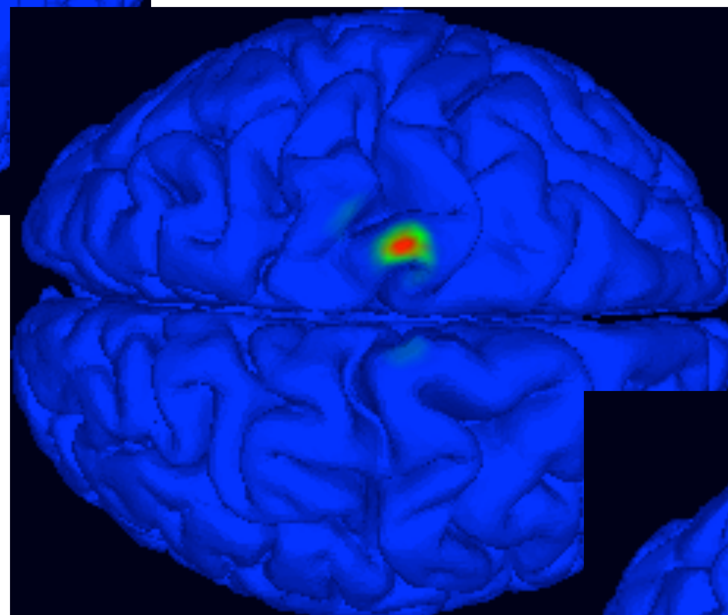
Non-conductive ‘plastic layer’ (the ECoG electrode sheet and strip)

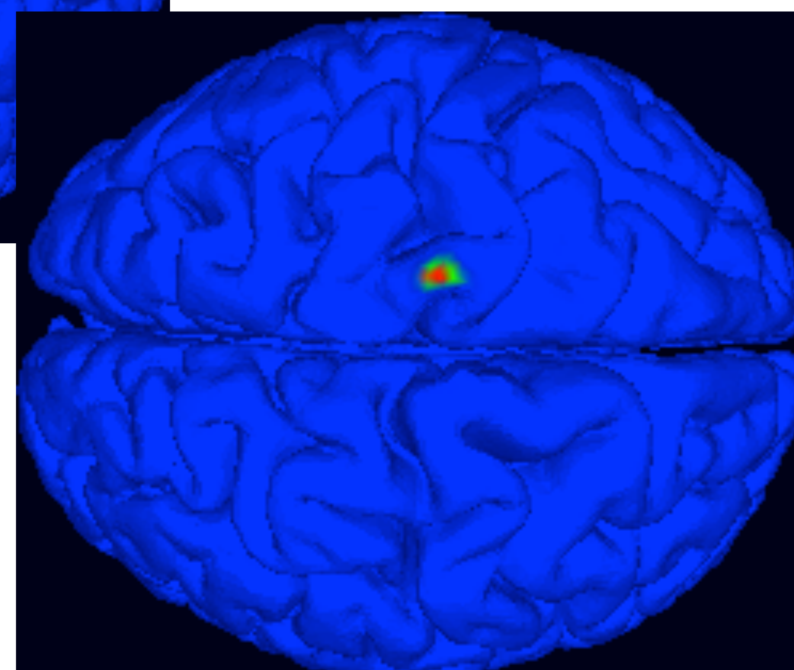
Zeynep Akalin Acar,, S. Makeig, G. Worrell, ’09-’16

Distributed source localization

Multiscale patch basis







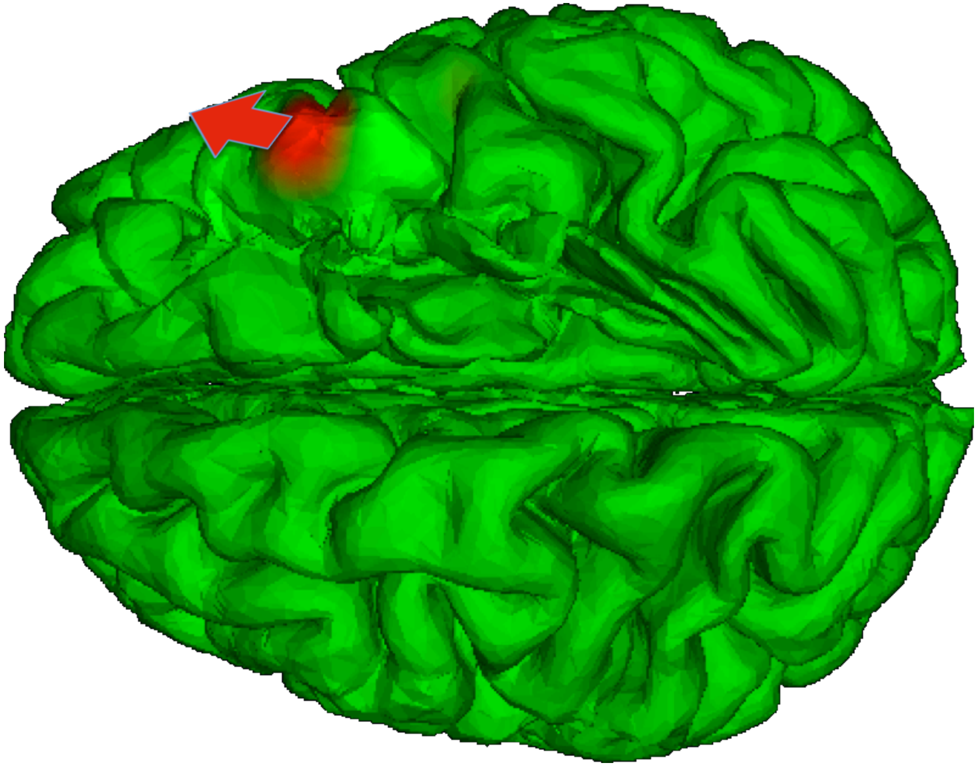
Inverse Approach

1. Compute 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 which produces the given source scalp map.

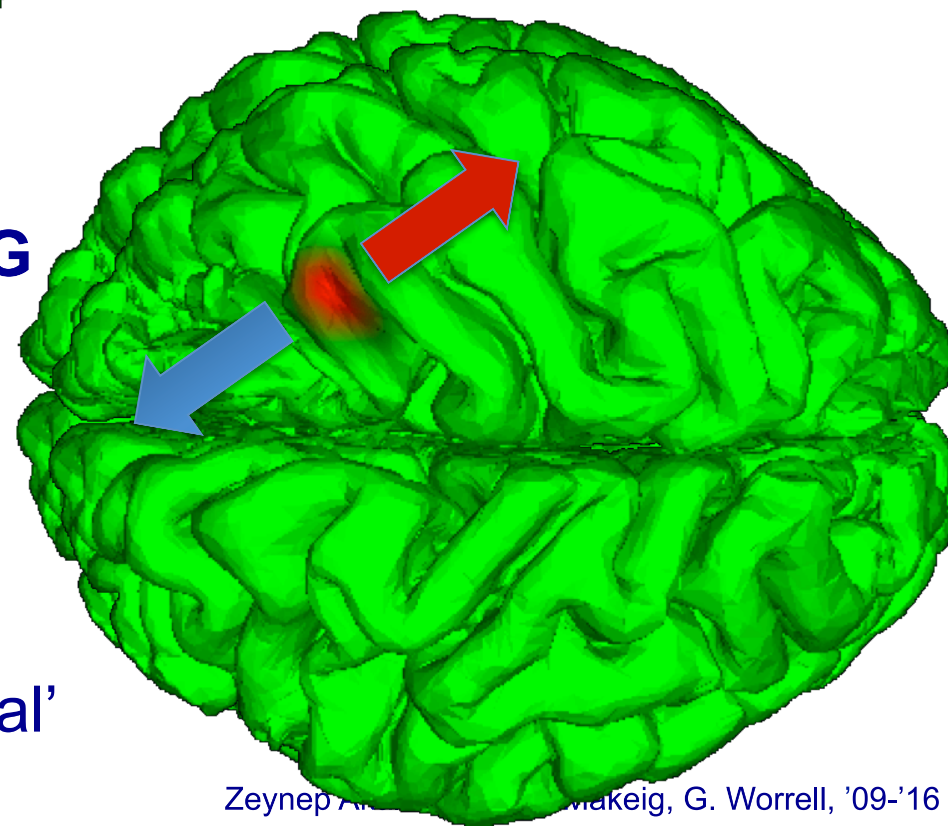
Zeynep Akalin Acar,, S. Makeig, G. Worrell, ’09-’16

ECoG Data Source Decomposition by ICA

gyral source



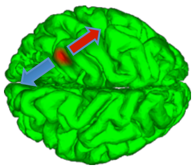
sulcal source



Given ECoG data from an ECoG grid:

0. Apply ICA to ECoG data.
1. Find radially oriented ‘gyral’ sources (left)
2. Find tangentially oriented ‘sulcal’ sources (right).

Zeynep A… akeig, G. Worrell, ’09-’16

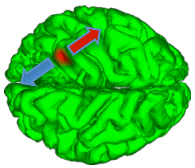


Volume conductor: FEM

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 accurate numerical method (> BEM)
  – But is computationally expensive
  – Note: Accurate conductivities are not known, particularly for skull (and scalp?).

R. Oostenveld, & S. Makeig, 2016

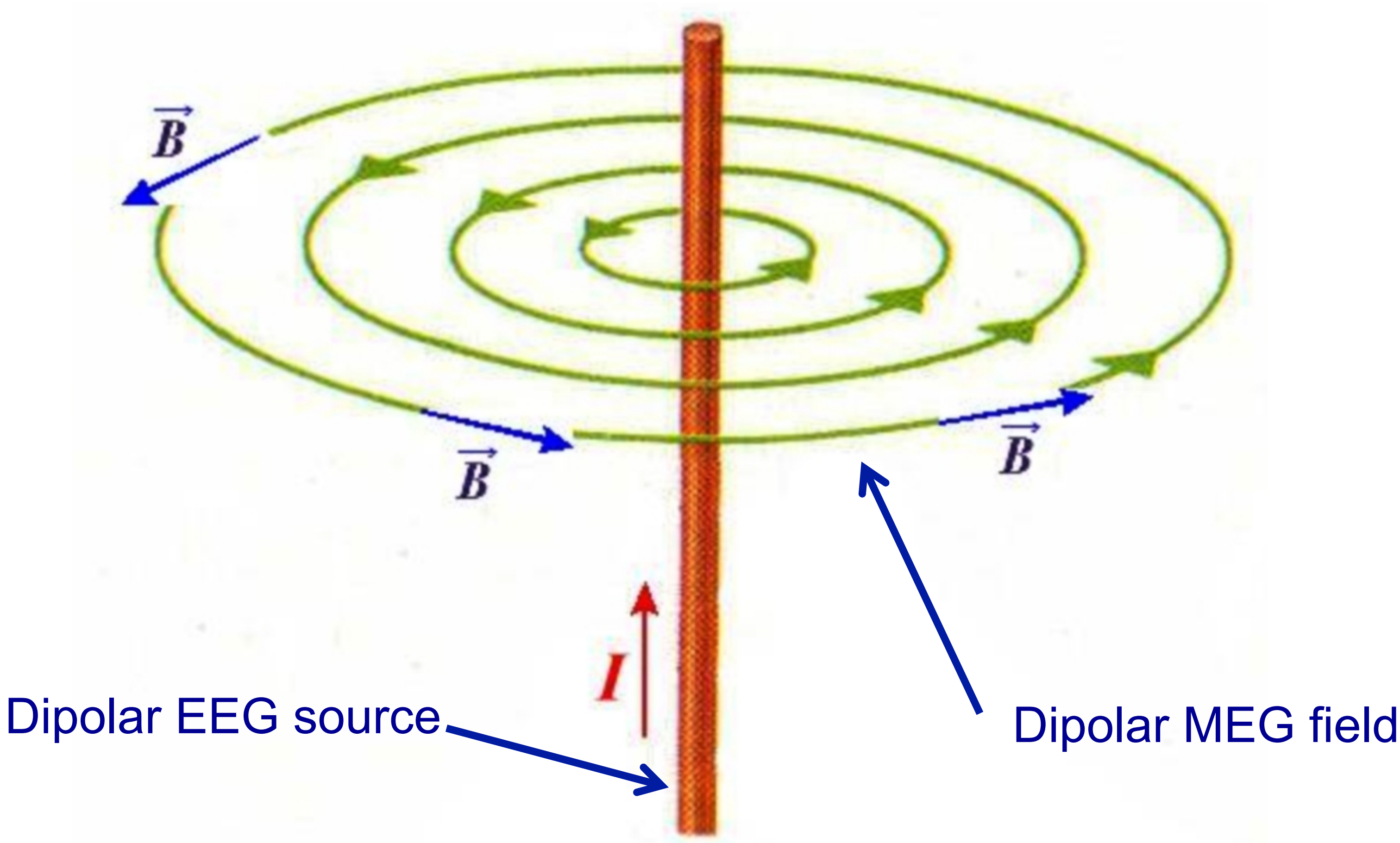


EEG and fMRI

- 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***)

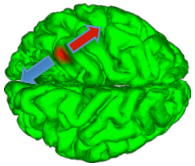
R. Oostenveld, & S. Makeig, 2016

EEG and MEG
Electric current <-> magnetic field



The right-hand rule relating EEG to MEG

R. Oostenveld, & S. Makeig, 2016

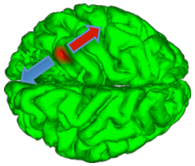


MEG volume conduction

- Measures sum of fields associated with
  - Primary currents
  - BUT also *secondary currents* at current distortions !
- However, only a tiny fraction of current passes through the poorly conductive skull.
  - Therefore skull and scalp can be ~neglected in the MEG model (simpler source imaging).
- Local conductivity assumption around dipole important

  → Geometry & conductivity of head model important

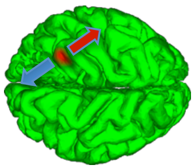
R. Oostenveld, & S. Makeig, 2016



Differences between EEG and MEG

- EEG scalp projection more blurred from volume conduction
- **BUT** MEG is insensitive to radial sources!!
- → **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 expensive than EEG!

R. Oostenveld, & S. Makeig, 2016

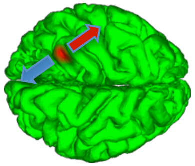


Differences between EEG and MEG

- 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

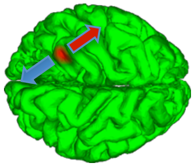
R. Oostenveld, & S. Makeig, 2016



Inverse methods

- **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)

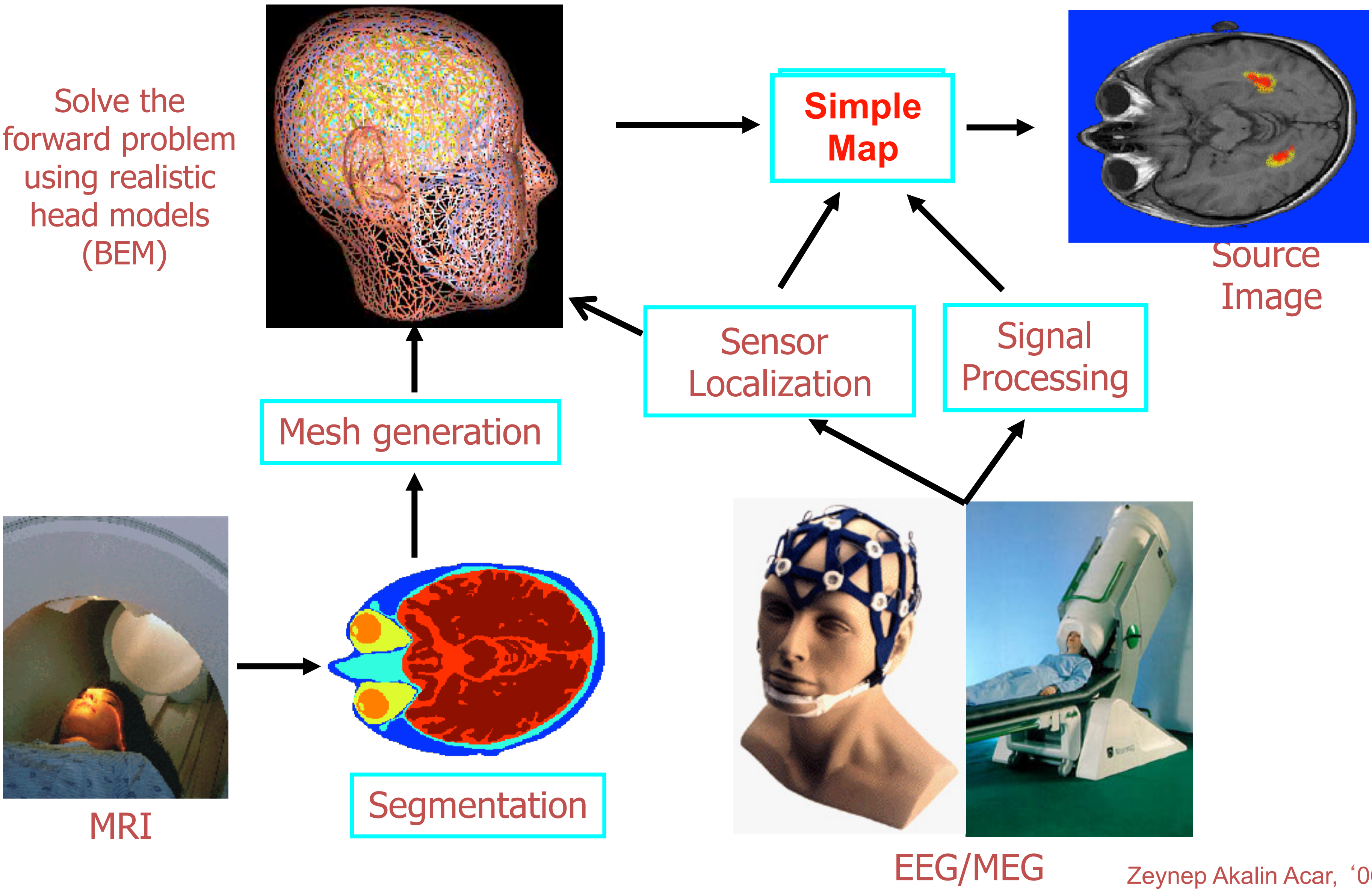
- **Perform ICA decomposition** (higher-order statistics) on the continuous data.
  - ICA gives the projections of the sources to the scalp surface → '**simple**' **maps**!

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

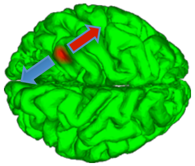
→ ICA gives 'simple' source maps, helping to locate 'Where?

R. Oostenveld, & S. Makeig, 2016

Electromagnetic source localization using realistic head models (NFT)



Zeynep Akalin Acar, '06



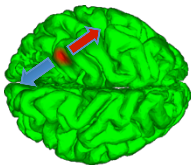
Single or multiple dipole models

- 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

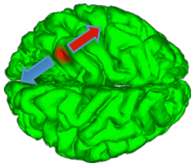


DIPFIT: Dipole fitting 1. Grid search

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

R. Oostenveld, & S. Makeig, 2016



DIPFIT: Dipole fitting 2. Nonlinear search

2. Fine fit step

Start with the initial guess from coarse fitting

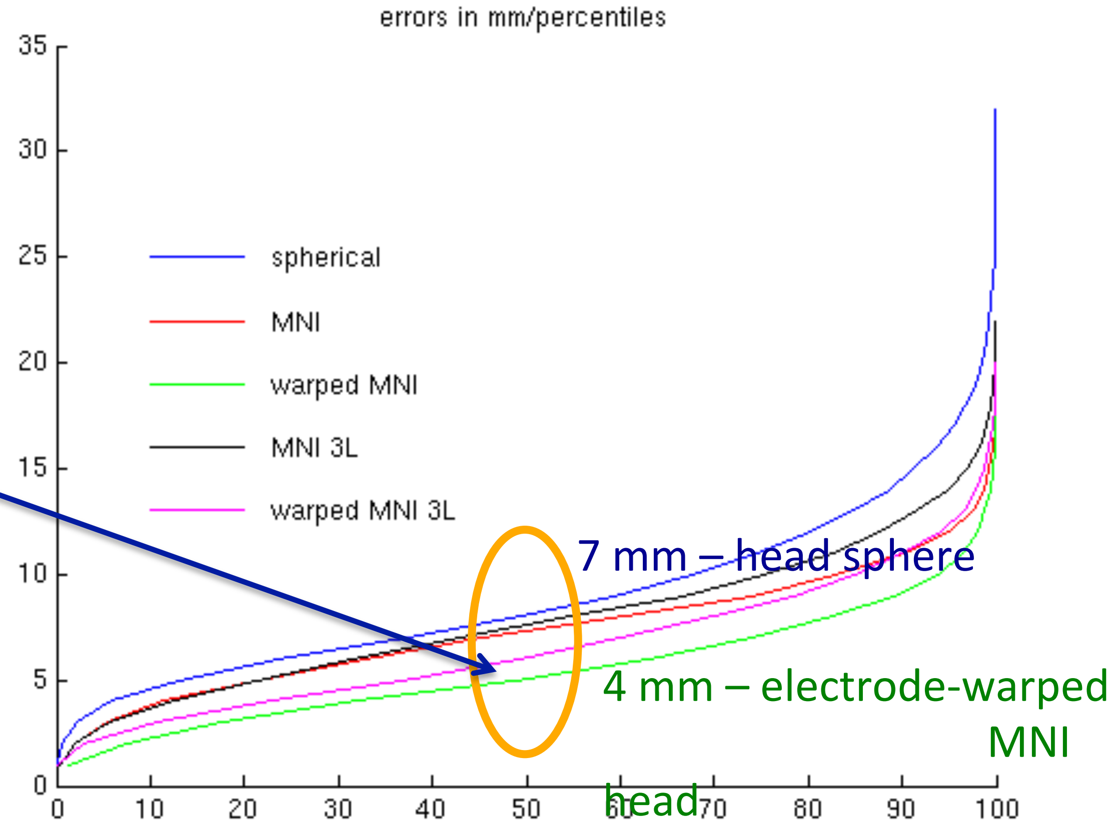
- Evaluate the local derivative of the goal (fit) function
- Then "walk down hill" to the most optimal solution

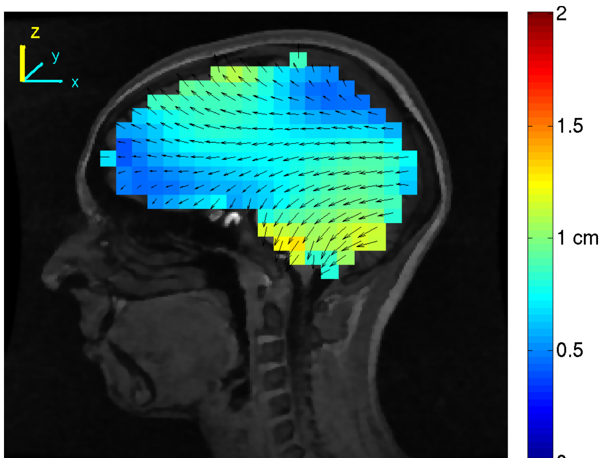
Number of iterative steps required = ~100

R. Oostenveld, & S. Makeig, 2016

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.

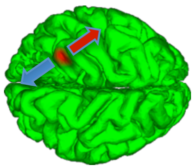




BUT Additional dipole error contributors:

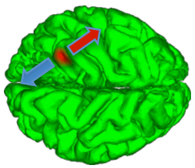
- Electrode co-registration error
- ICA numerical error (not enough data?)
- Source model geometry error
- Conductance value error (skull)

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 …



Summary

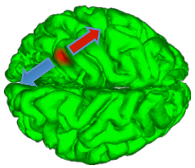
- An electromagnetic **forward head model** is required to interpret the sources of scalp maps
- Interpretation of scalp maps in terms of brain source distributions is "**inverse** source estimation"

→ 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)

R. Oostenveld, 2007

Acknowledgments

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