Forward and Inverse EEG Source Modeling

Scott Makeig

Institute for Neural Computation

UCSD, La Jolla CA

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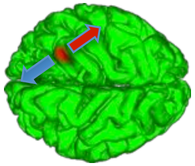

Motivation

- Why fit dipoles?
- Why measure EEG?
- Why do ICA?
- Get extra information about brain processes
  - Time course of activity ----> EEG
  - Location of activity → fMRI

Differences between EEG and fMRI

- EEG measures post-synaptic potentials
  - related to synchronized neuronal input (phase)
- fMRI measures BOLD
  - related to energy consumption (amplitude)
- Different characteristics in the time domain
- Different generators
- Time course

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Why EEG? Extra information!

- Timecourse
  - ERSP
  - ERP
  - Etc.

- Topography
  - Scalp distribution
  - Underlying source distribution

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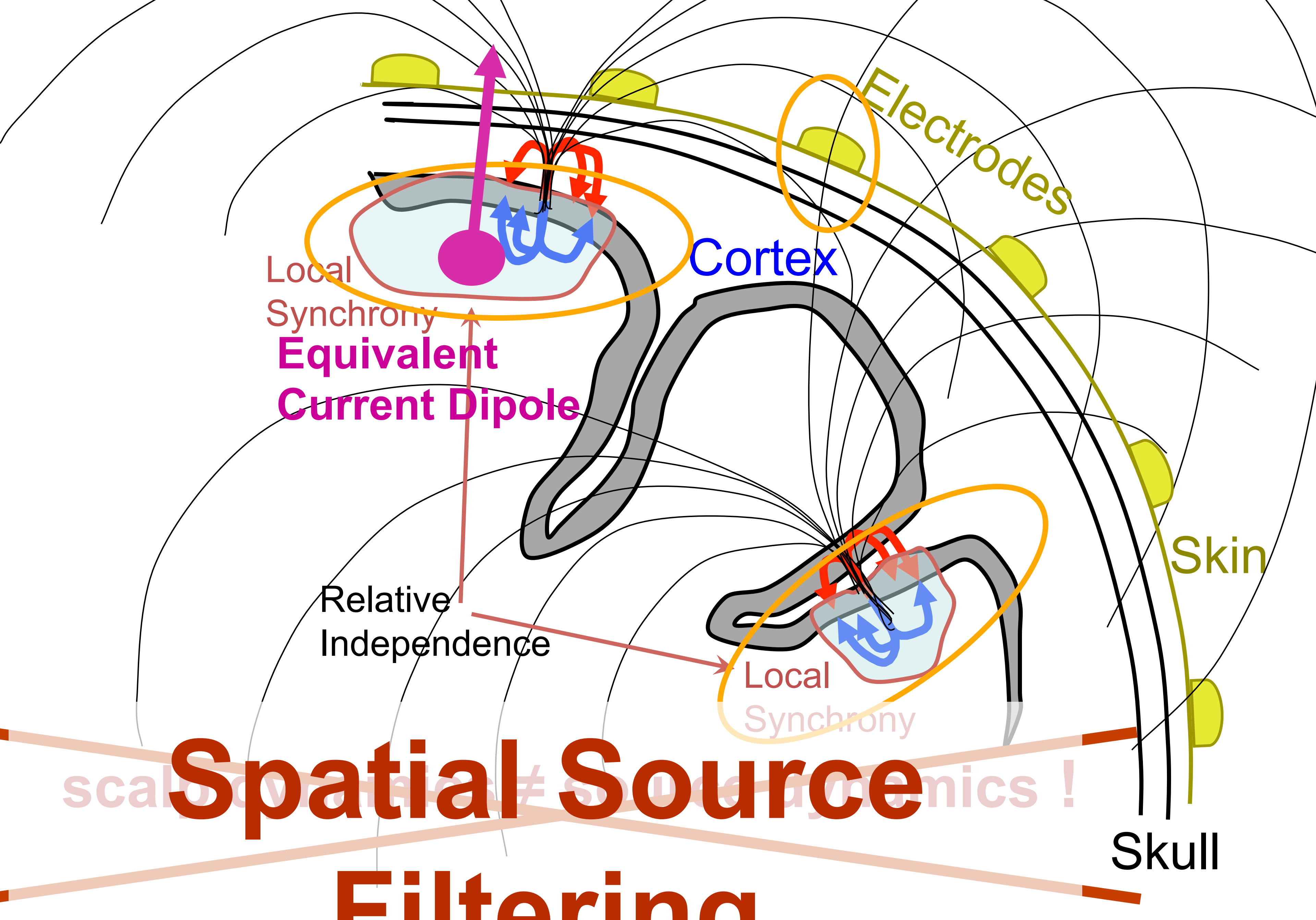

Spatial Source Filtering

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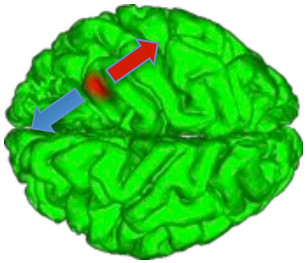
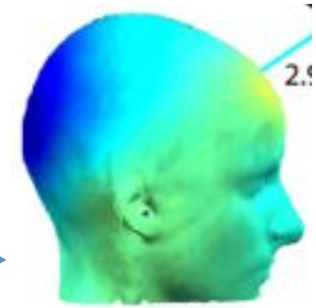
Source modeling



forward problem



physiological source
electrical current

body tissue
volume conductor

observed
potential or field

inverse problem

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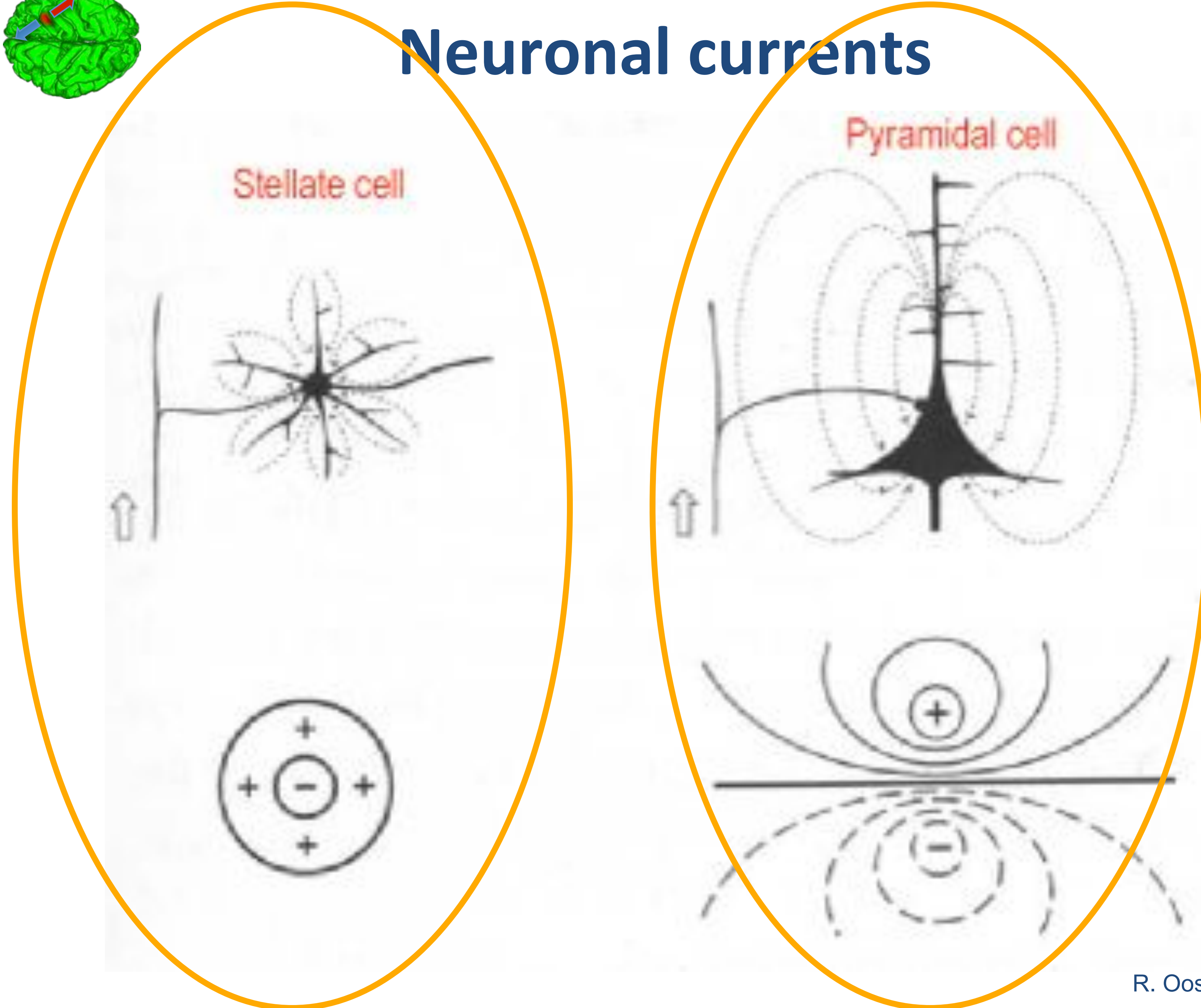
Neuronal currents



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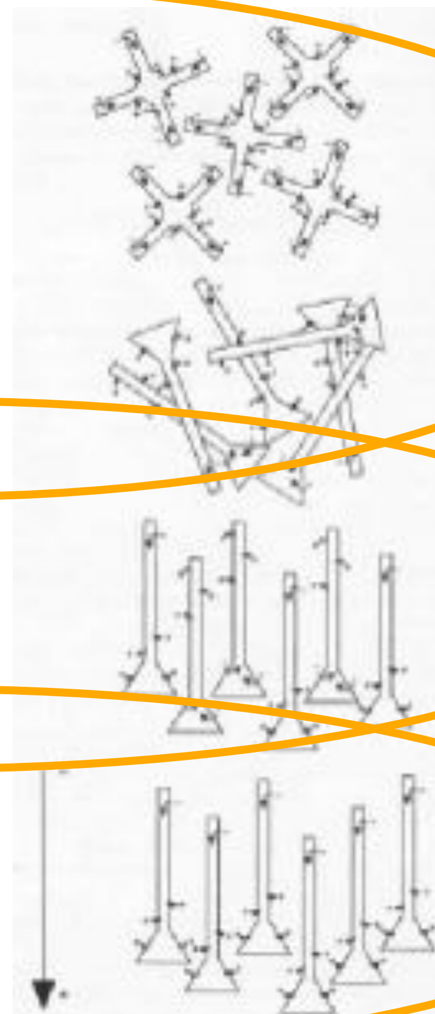
Symmetry, orientation and activation

radially symmetric, i.e.
randomly-oriented

asynchronously activated

synchronously activated
parallel-oriented



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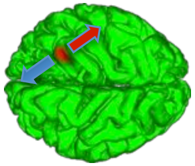
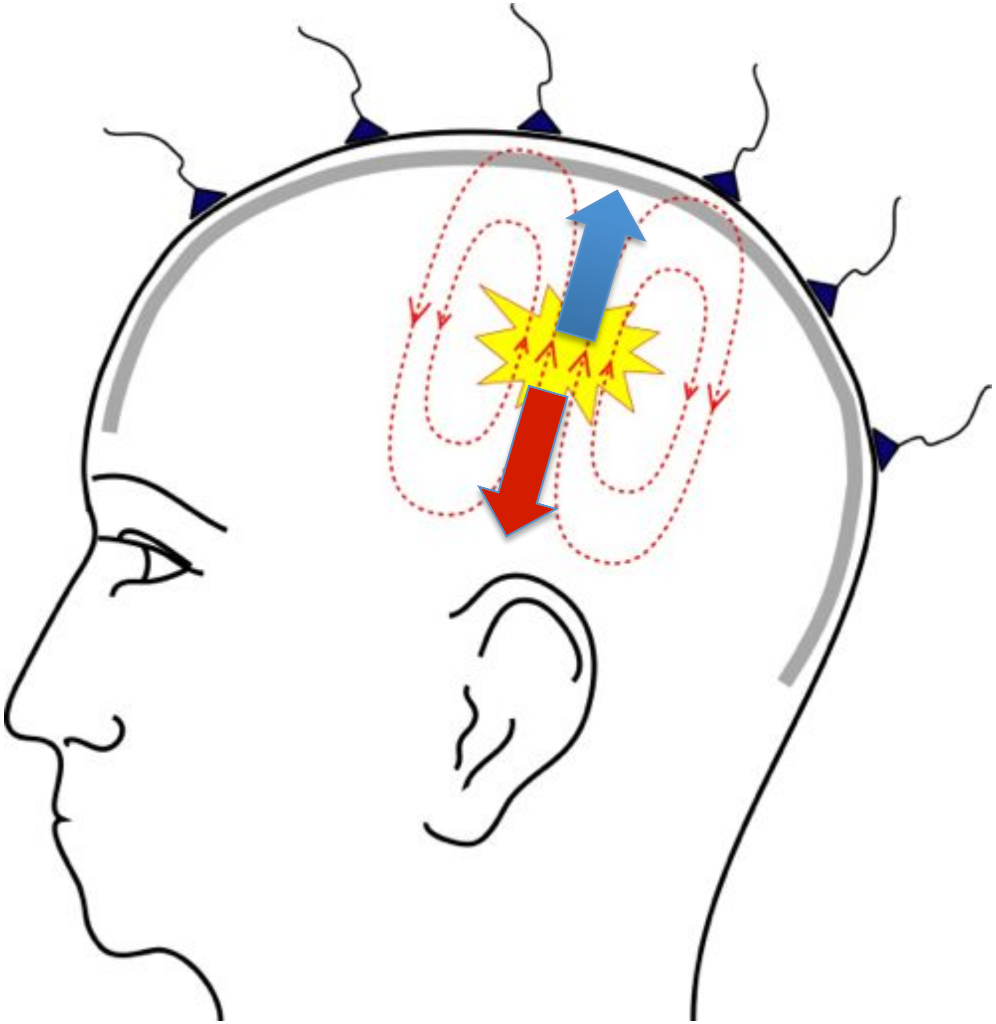


EEG volume conduction



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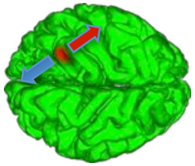

EEG volume conduction

- **Potential difference between electrodes** corresponds to current flowing through skin
  - Only tiny fraction of current passes through skull
  - Therefore the model should describe both skull and skin as accurately as possible.

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

  → Individual skull conductivity variable & unknown

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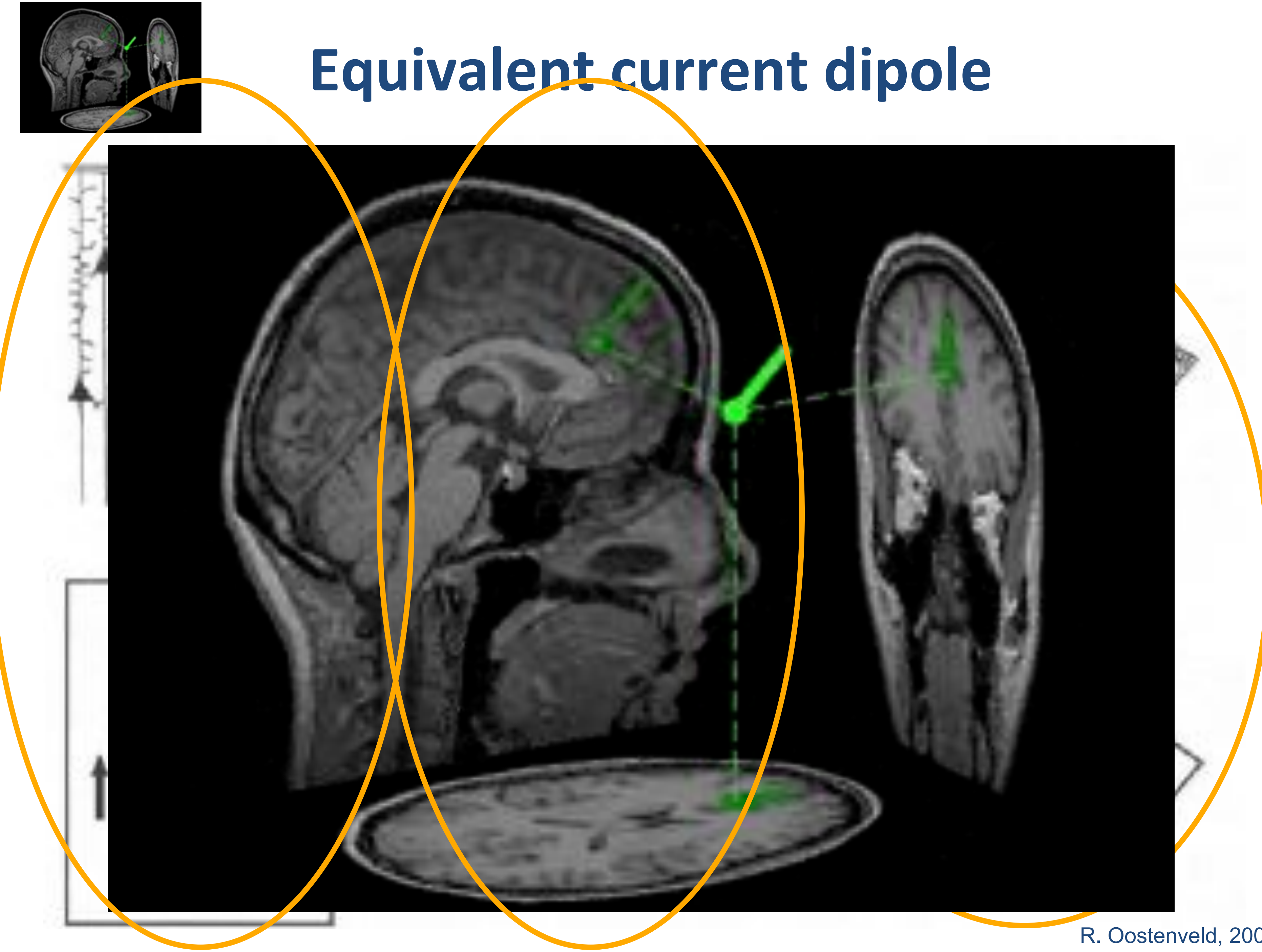
Equivalent current dipole



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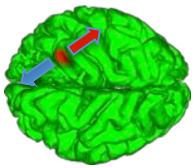

Equivalent current dipole

- 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, …
- Convenience
  - **Dipoles** can be used as building blocks in distributed source models

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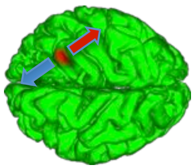
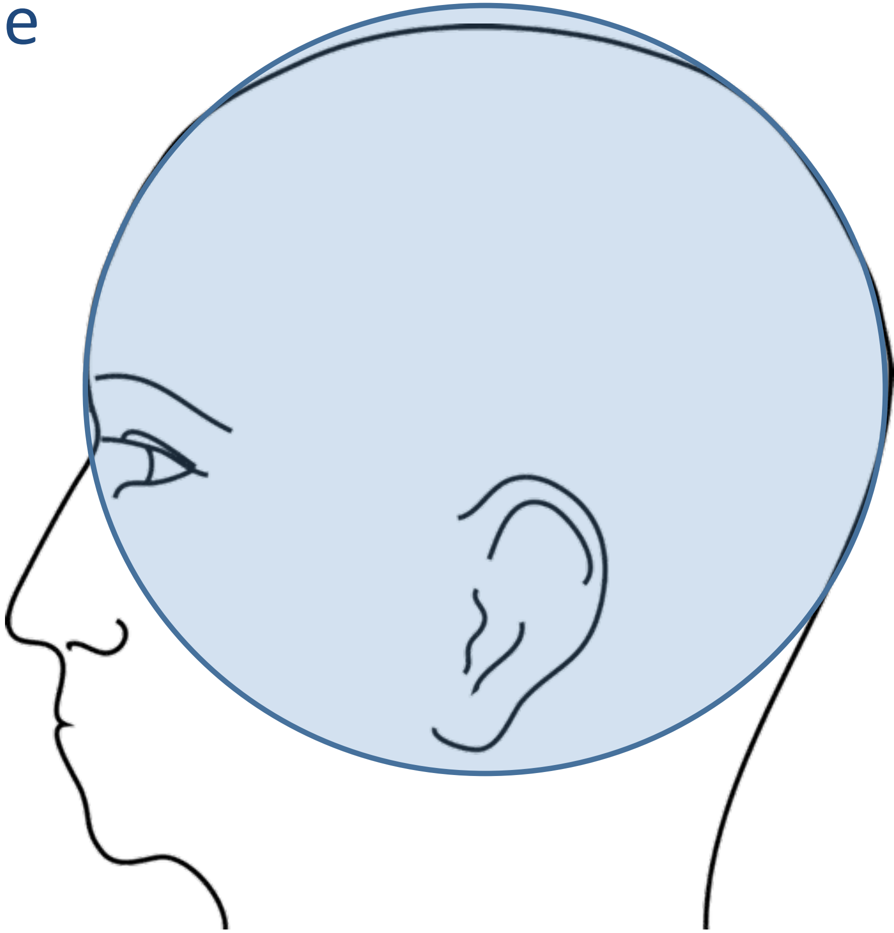


Volume conductor

- Electrical properties of tissue
- Geometrical description
  - spherical model
  - realistically shaped model

→ Forward model describes
how the currents flow,
not where they originate



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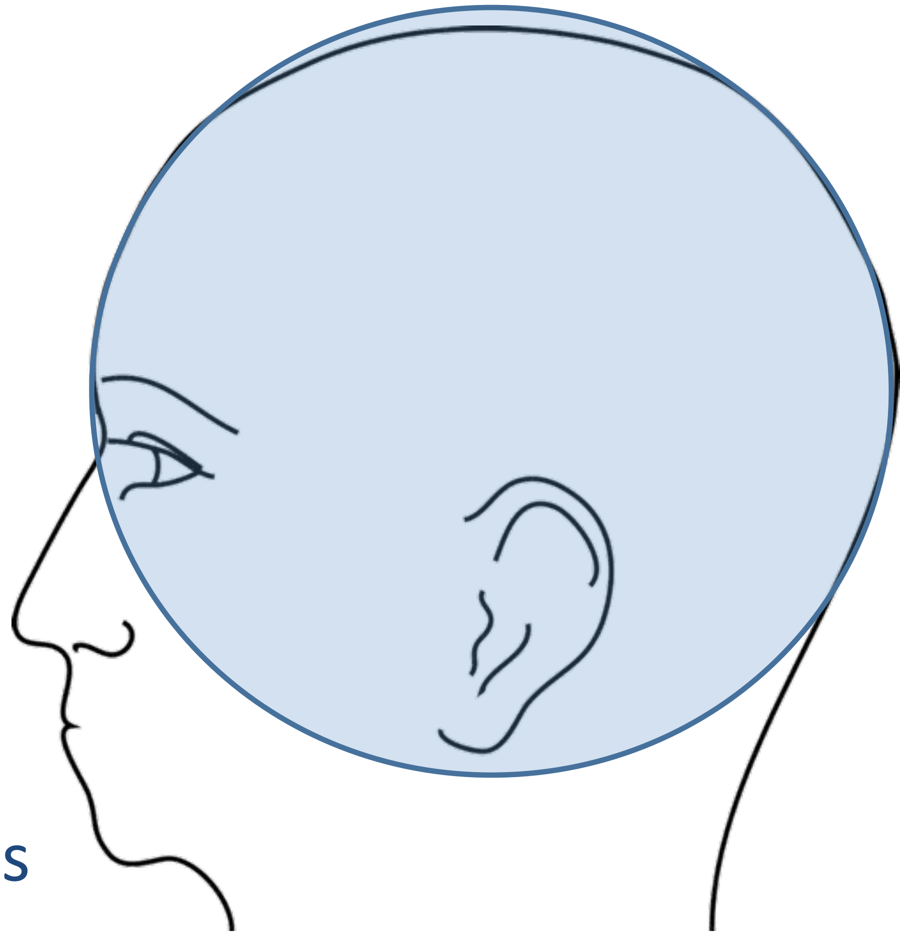
Volume conductor

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

- Disadvantages of the **spherical** model
  - inaccurate in some regions
  - difficult alignment



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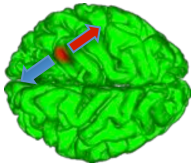

Volume conductor

- 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).

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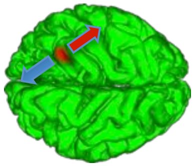

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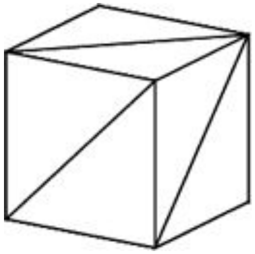
- Computational methods for volume conduction problem that allow realistic geometries
  - Boundary Element Method (BEM)
  - Finite Element Method (FEM)
- Geometrical description
  - triangles
  - tetrahedra



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Volume conductor: BEM

- Boundar
  - desc ents
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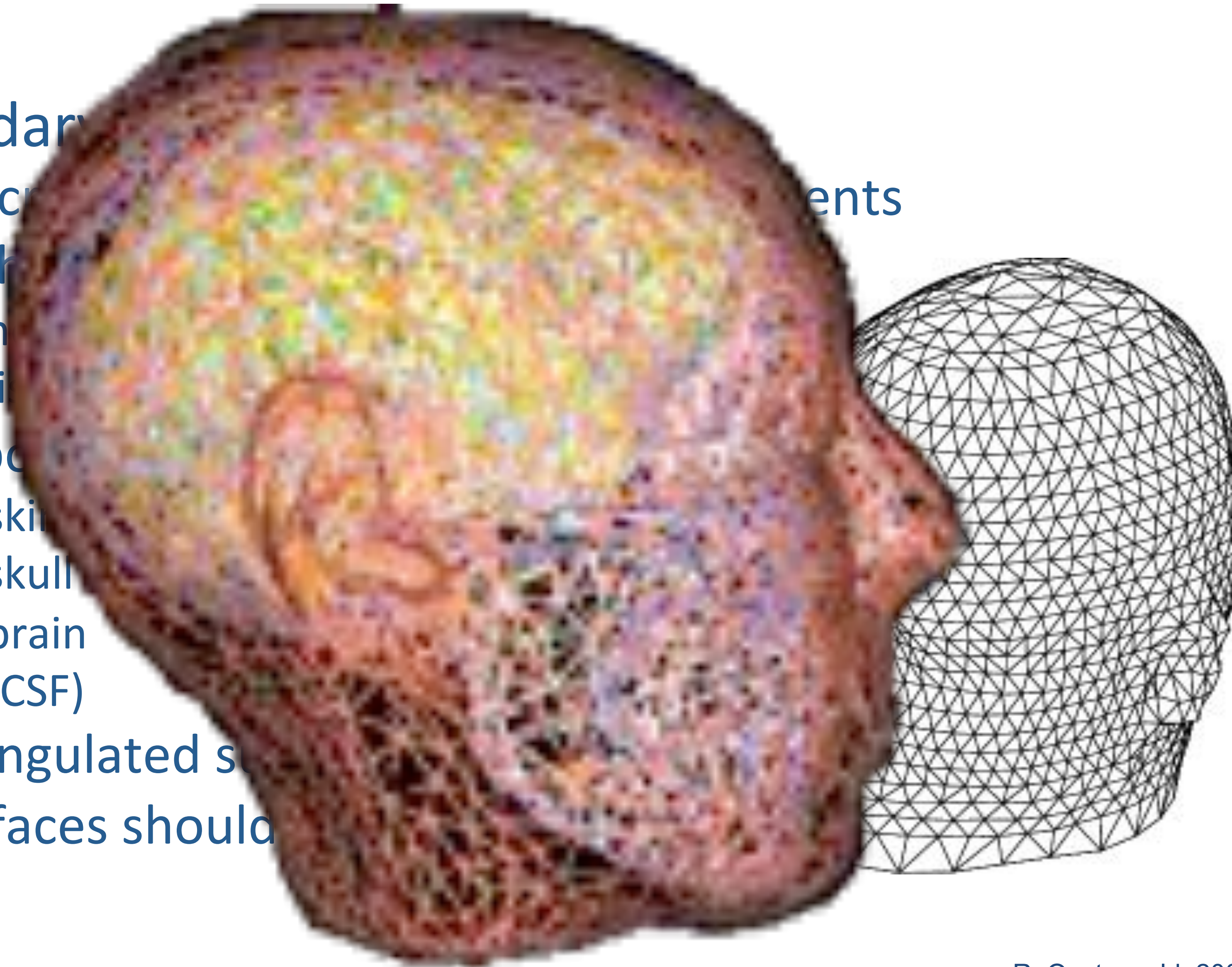
    - ski
    - skull
    - brain
    - (CSF)
  - triangulated s
  - surfaces should



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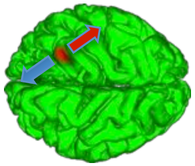

Volume conductor: FEM

- Tesselate the 3-D volume into solid tetrahedra
  - Large number of elements
  - Each tetrahedron can have its own conductivity
  - Each tetrahedron can have its own anisotropy

- FEM is most accurate numerical method
  – Computationally expensive
  – Accurate conductivities are not known

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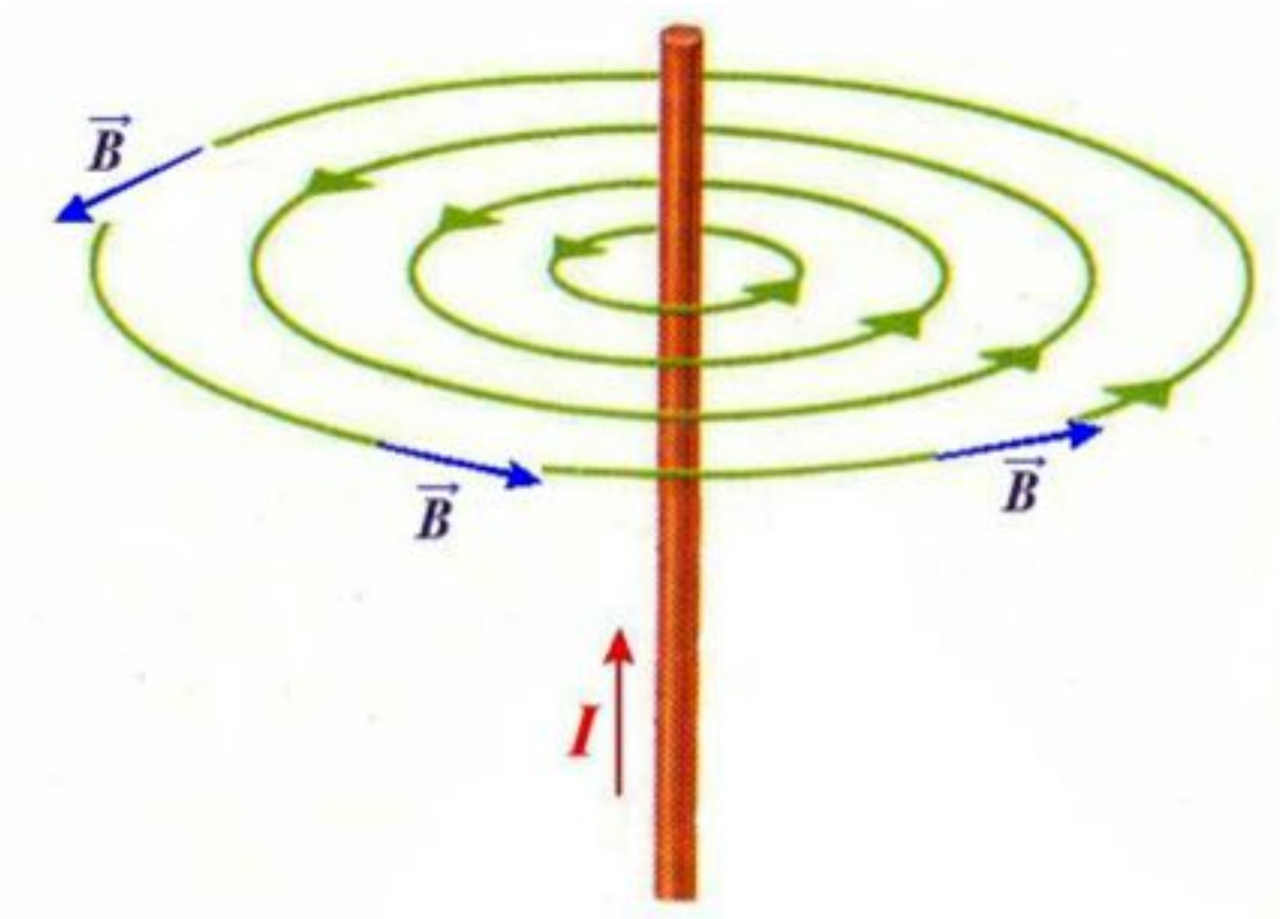
MEG: Electric current ←→ magnetic field



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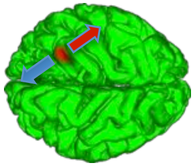

MEG volume conduction

- Measures sum of fields associated with
  - Primary currents
  - BUT also secondary currents at current distortions !!!
- But only a 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

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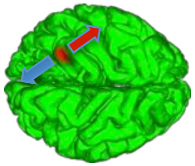

Differences between EEG and MEG

- In EEG, scalp distribution more blurred from volume conduction
- MEG is insensitive to radial sources!!
- So EEG sees more sources
- EEG is more noisy (electrode-skin impedance)
- MEG is more sensitive to environmental noise!
- MEG requires no gel
- MEG requires the head to stay fixed !
- MEG MUCH more expensive than EEG!

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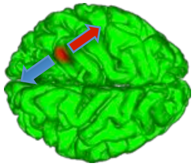
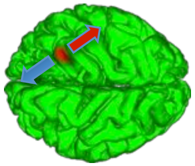


Differences between EEG and MEG

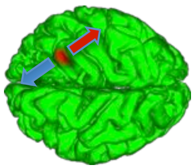
- EEG sees potential differences, requires choice of reference electrode
- MEG sensors are measured independently of each other
- MEG can use simple but somewhat accurate volume conduction model
  - E.g. multiple non-concentric sphere model,

  Here, each sensor has its own local sphere fitted to the head position of brain relative to MEG sensors
  - may vary within a long session when head moves
  - is different between sessions



Inverse methods

- **Single and multiple dipole models**
  – Minimize error between the model and the measured potential/field
- **Distributed dipole models**
  – Perfect fit of model to the measured potential/field
  – Minimize an additional constraint on sources
    - LORETA (assume a smooth distribution)
    - Minimum Norm (L2, minimum power at the cortex)
    - Minimum Current (L1, minimum current in the cortex)



Inverse methods

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

  - **Perform ICA decomposition** (higher-order statistics)
    - On the scalp maps at individual moments
    - ICA gives the projections of the sources to the scalp surface, i.e., '**simple**' **maps**!

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

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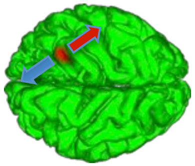

Single or multiple dipole models

- Manipulate source parameters to **minimize error** between measured and model data
  - **Position** 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 by source parameter estimation

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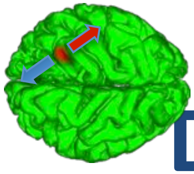

DIPFIT: Dipole scanning: 1. Grid search

- 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
  - BUT two dipoles, 1 cm grid: ~16,000,000

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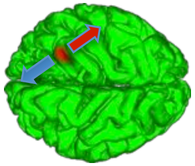


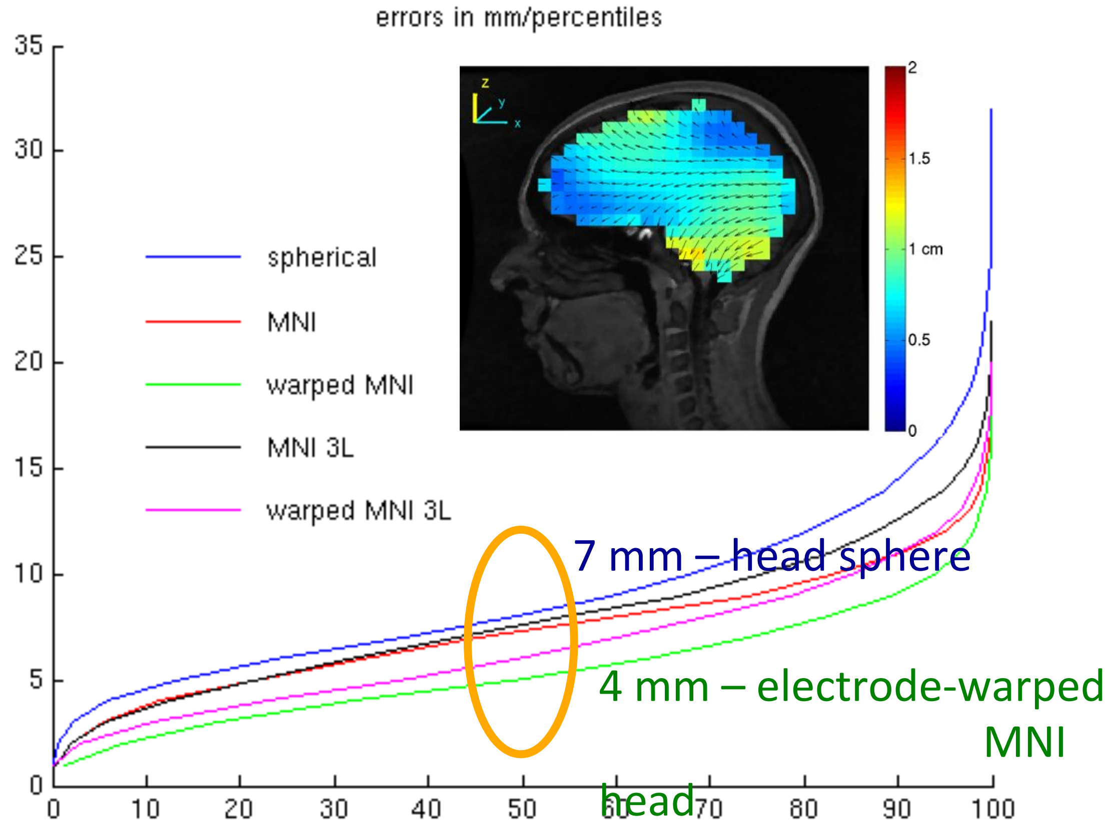
DIPFIT: Dipole fitting: 2. Nonlinear search

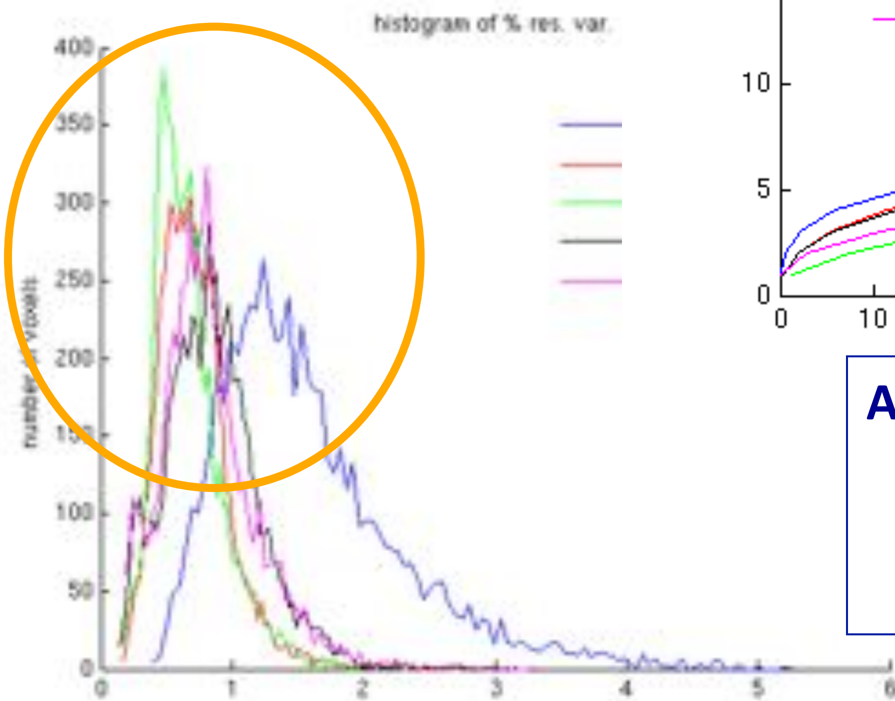
- Start with an initial guess from coarse fitting
  - evaluate the local derivative of goal-function
  - "walk down hill" to the most optimal solution

- Number of evaluations needed ~ 100

Effect of Template Head Model Choice On Estimated Dipole Locations

Median geometric error in dipole localization from using the MNI template head model warped to recorded electrode positions is 4 mm.

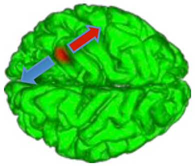




Additional dipole error contributors:

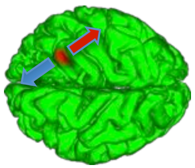
- **Electrode co-registration error**
- **ICA numerical error**
- **Source model error**

Z. Akalin Acar & S Makeig, 2011



Distributed source models

- Position of the source is not estimated as a whole
  - Pre-defined grid (3-D volume or cortical sheet)
  - Strength is *estimated at each grid element*
  - In principle, a linear problem, easy to solve, BUT…
    - More "unknowns" (parameters) than "knowns" (channels, measurements)
    - An infinite number of solutions can explain the data perfectly (not necessarily physiologically plausible!)
  - **So**, additional constraints are required …



Summary

- Forward modeling
  - Required for the interpretation of scalp topographies
  - Interpretation of scalp topographies

    is “source estimation”
  - Mathematical techniques are available

    to aid in interpreting scalp topographies

    -> inverse models

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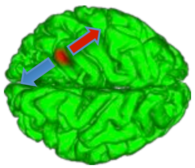

Summary

- **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)

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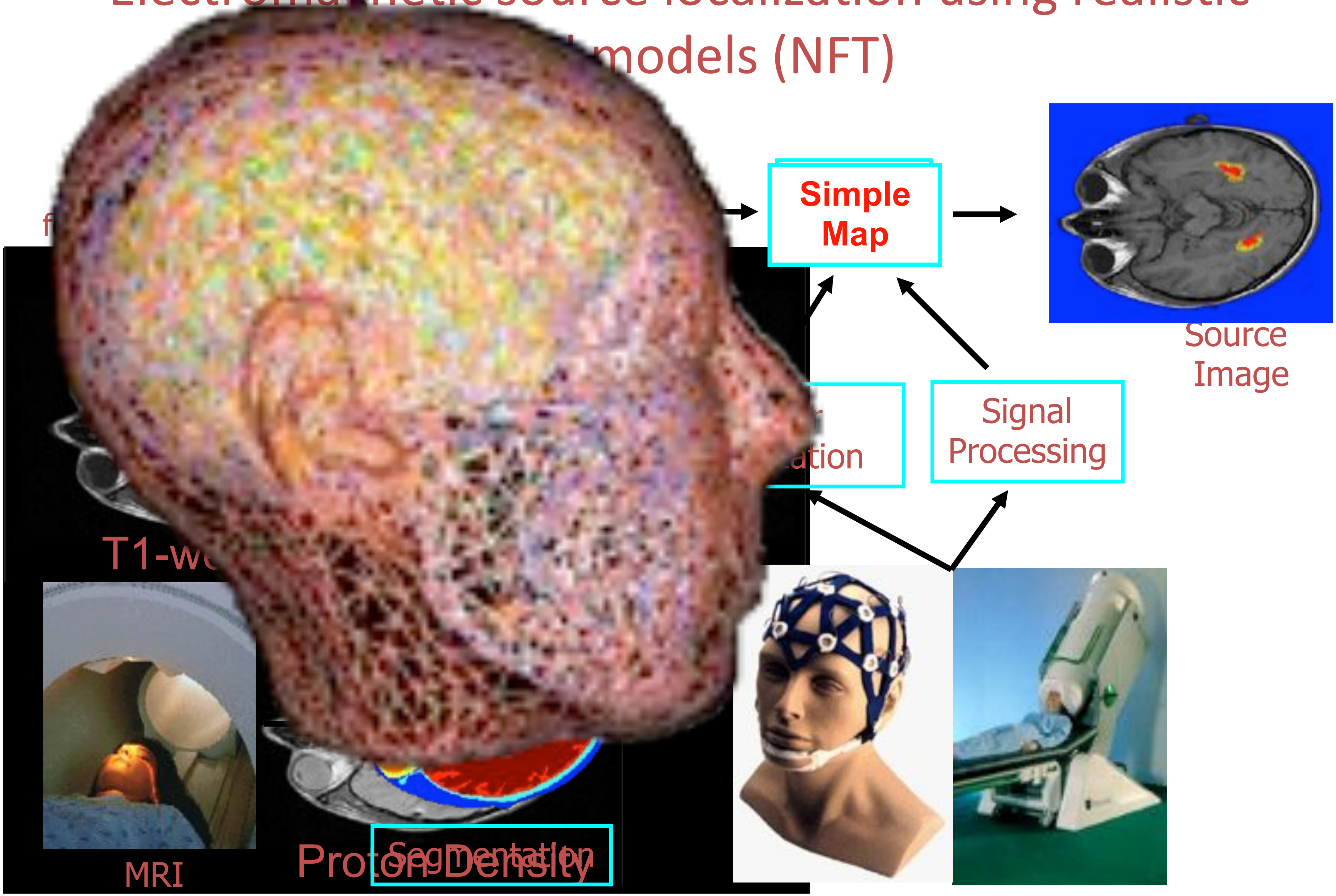
Electromagnetic source localization using realistic
models (NFT)



Zeynep Akalin Acar, '06

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