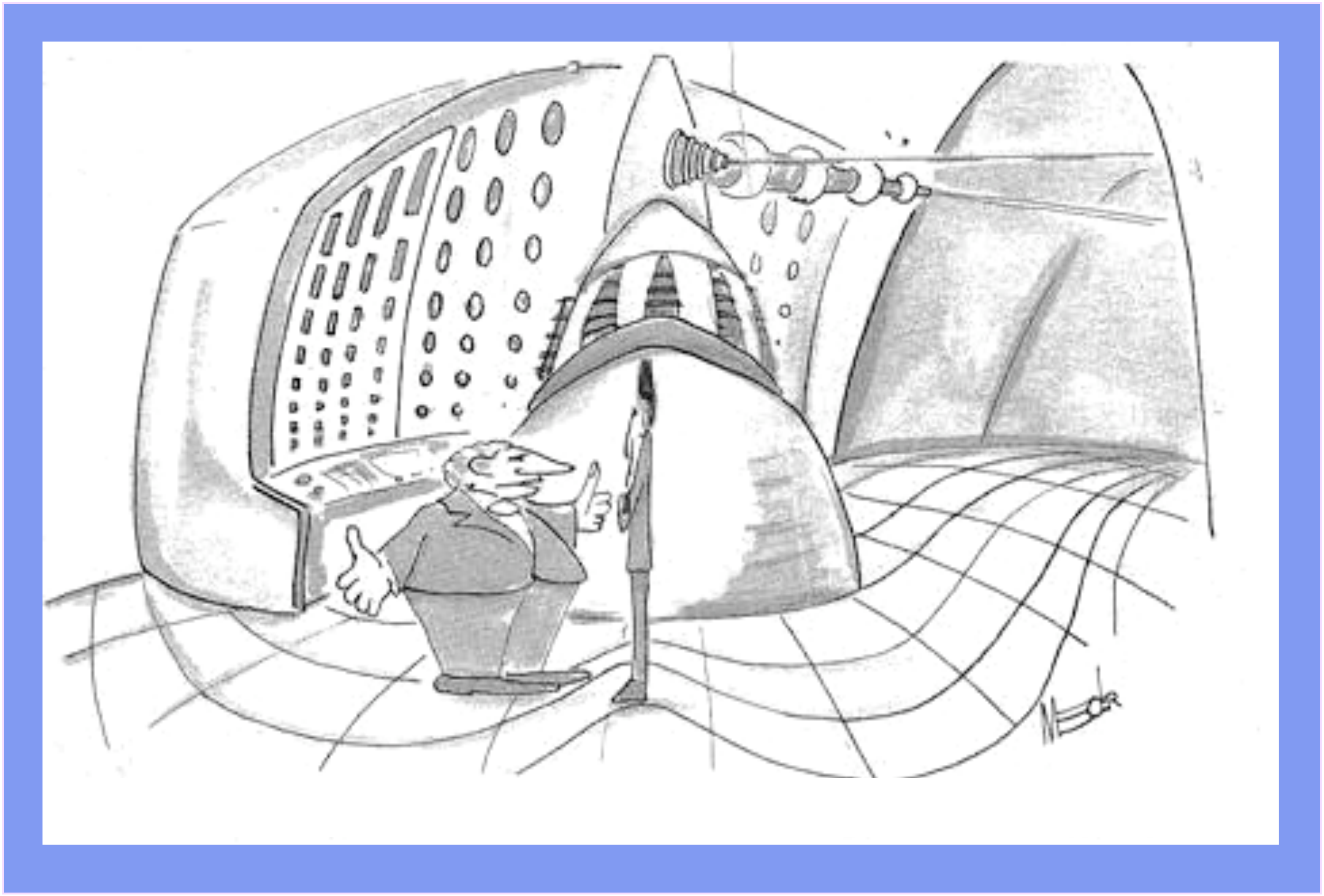
Forward and Inverse EEG Source Modeling

Scott Makeig

Institute for Neural Computation

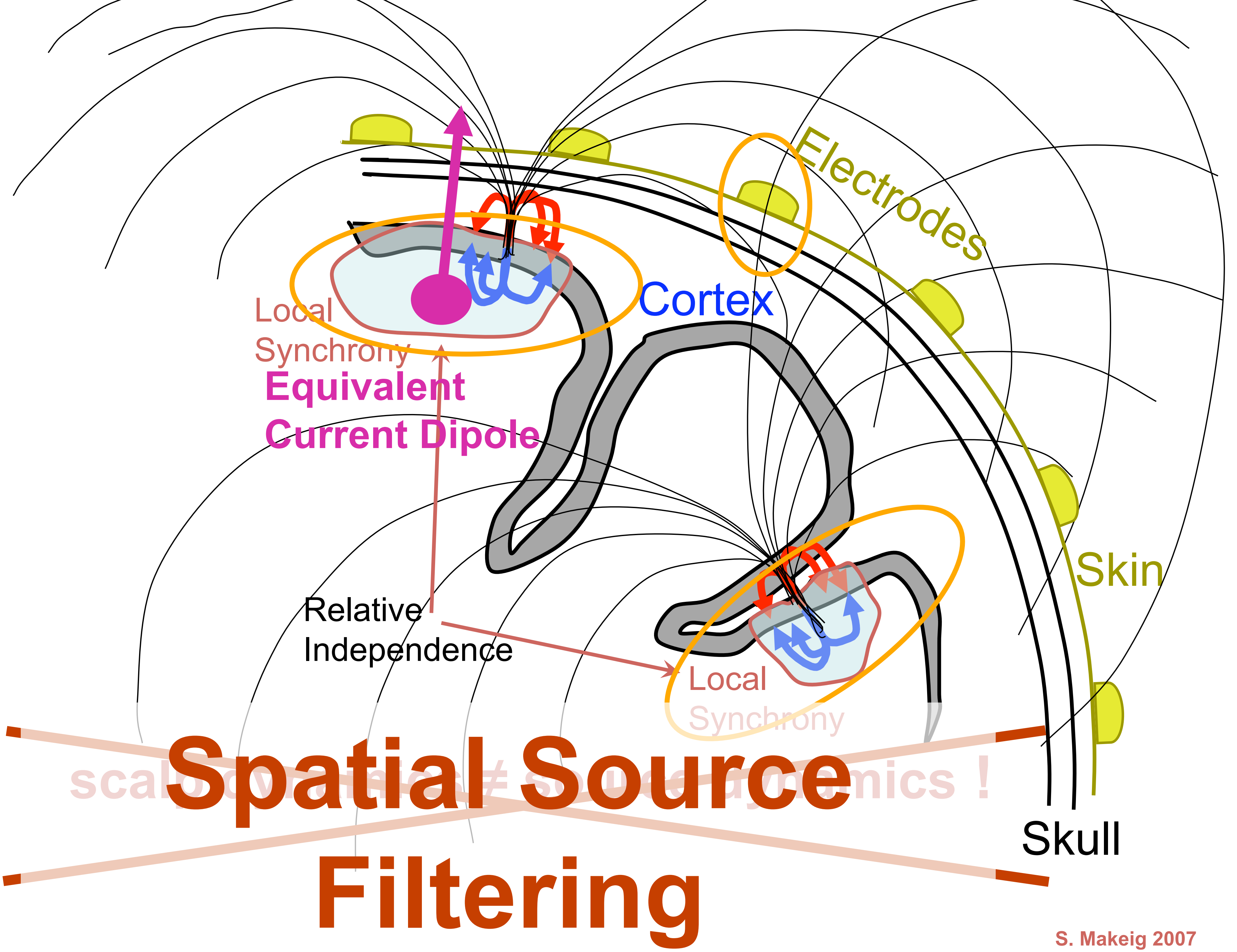
UCSD, La Jolla CA

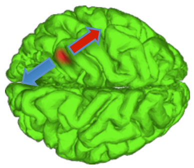
EEGLAB Workshop, Indiana University, April, 2097



"Surely, if there were gravity waves,
we would have detected them by now."

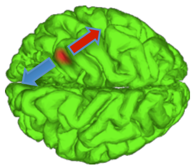
NYT → Scott Makeig, 2005


Electrodes
Cortex
Local Synchrony
Equivalent Current Dipole
Relative Independence
Local Synchrony
Skin
Skull
scalp covariance ≠ source dynamics !
Spatial Source Filtering
S. Makeig 2007

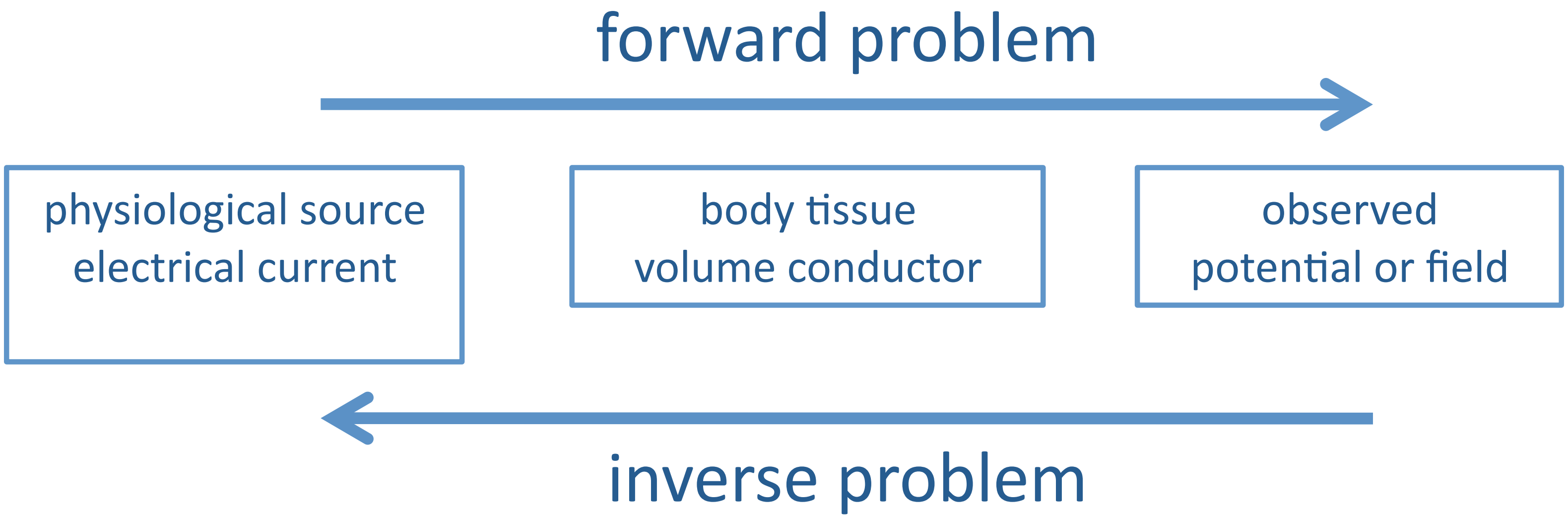


DIPFIT: Theory of forward and inverse source modeling

Robert Oostenveld
r.oostenveld@fcdonders.ru.nl



Source modeling



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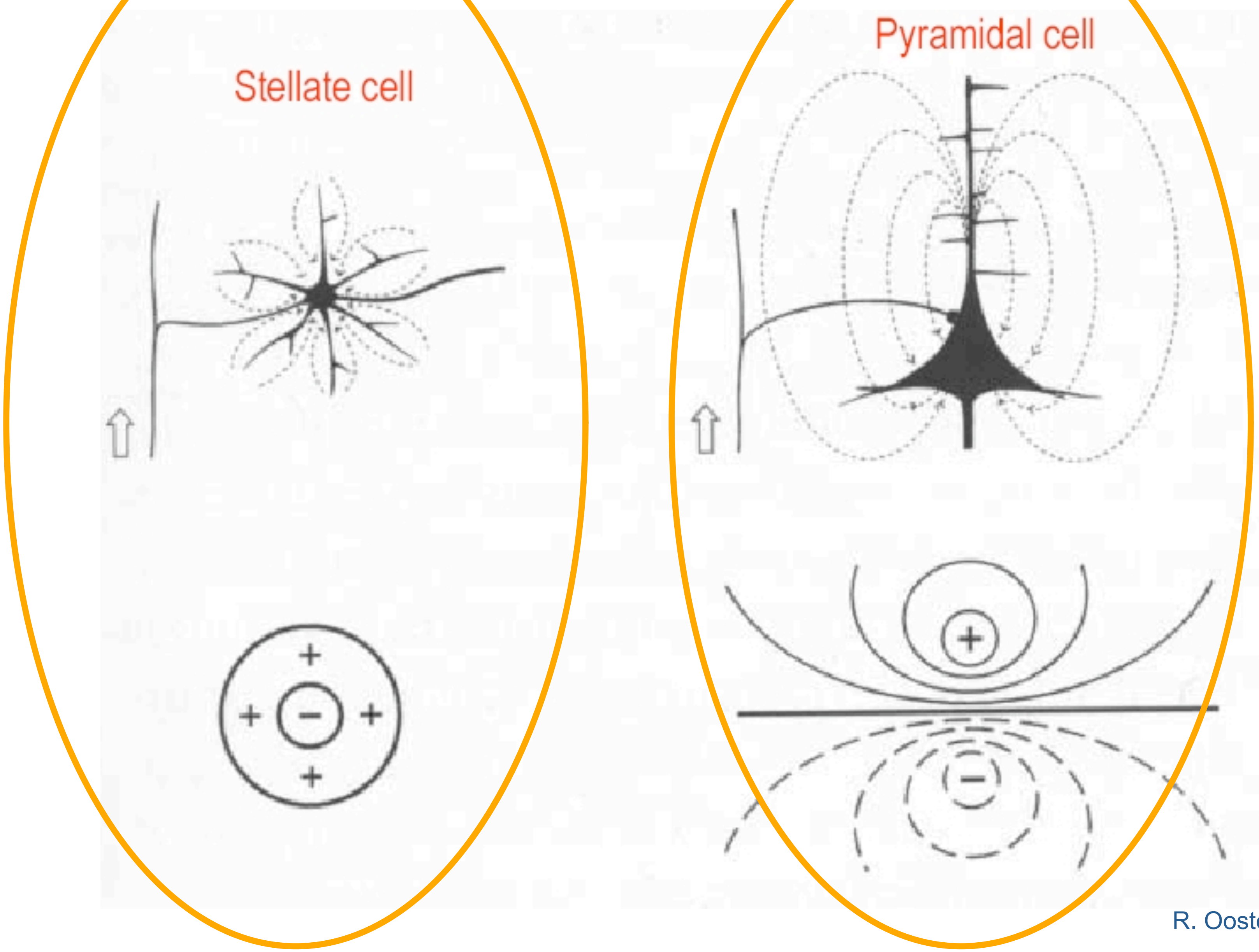
Neuronal currents



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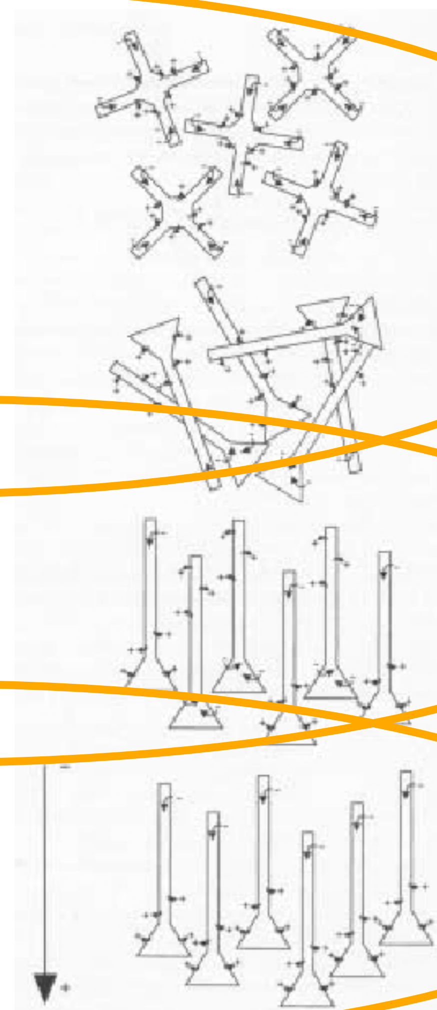
Symmetry, orientation and activation

radially symmetric, i.e.
randomly-oriented

asynchronously activated

synchronously activated
parallel-oriented



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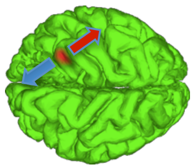
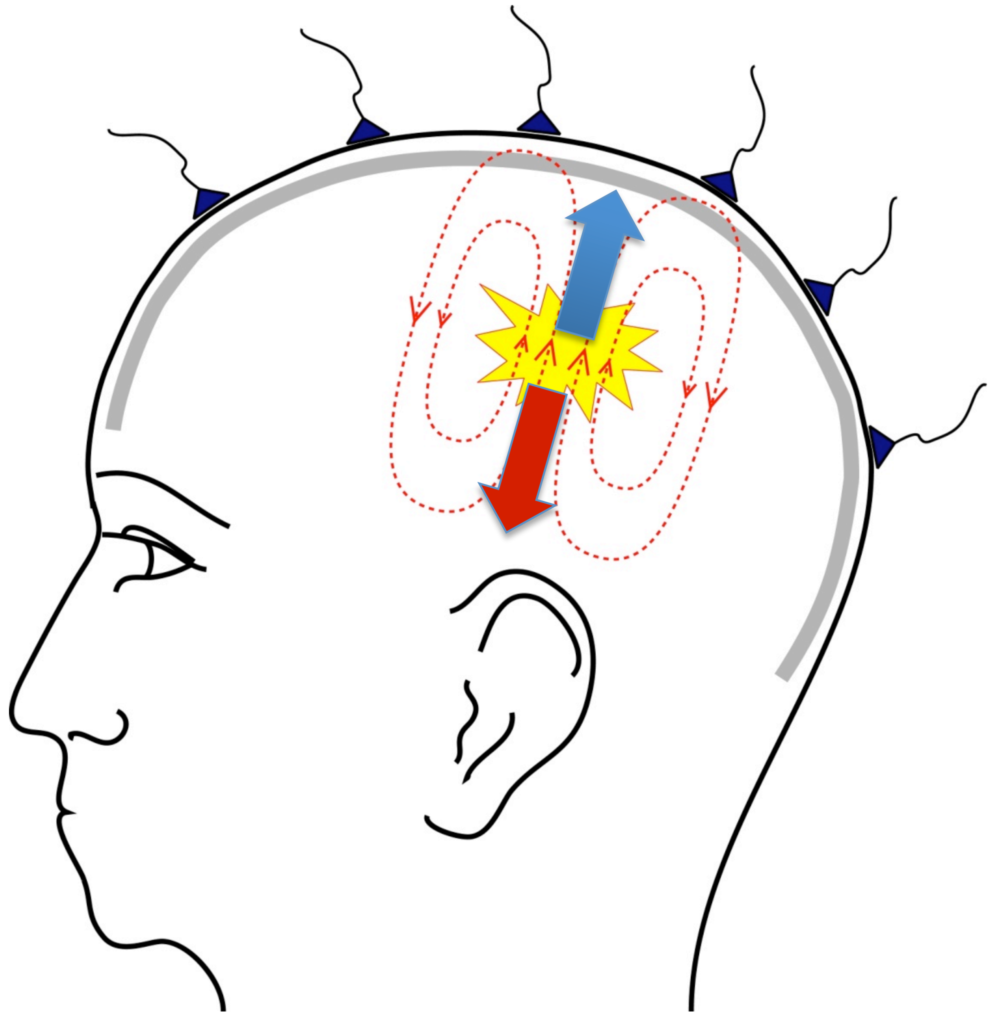


EEG volume conduction



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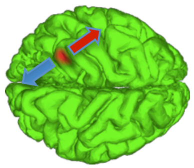

EEG volume conduction

- **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

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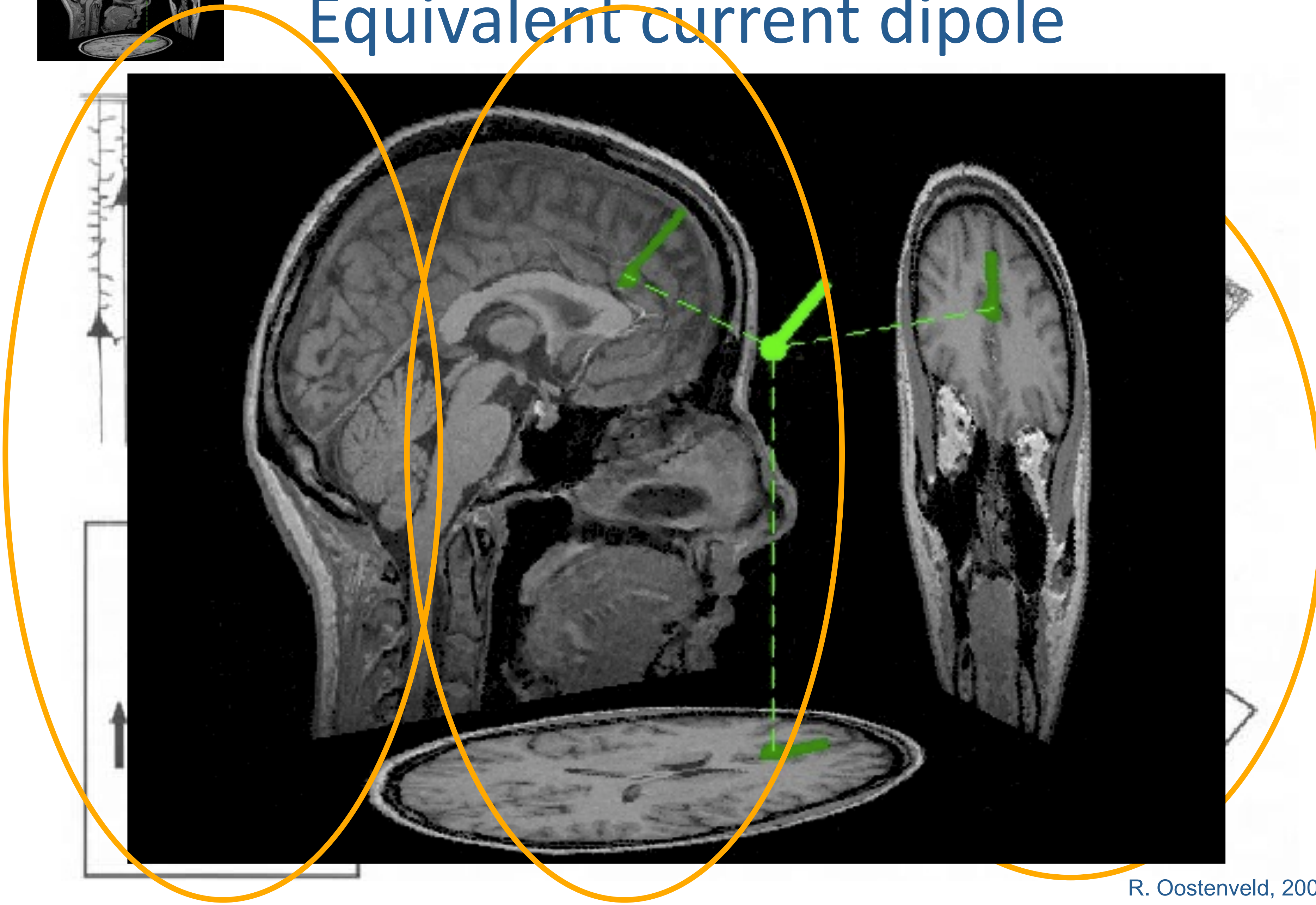
Equivalent current dipole



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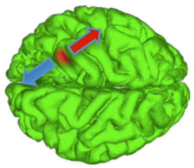

Equivalent current dipoles

- 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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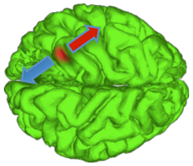
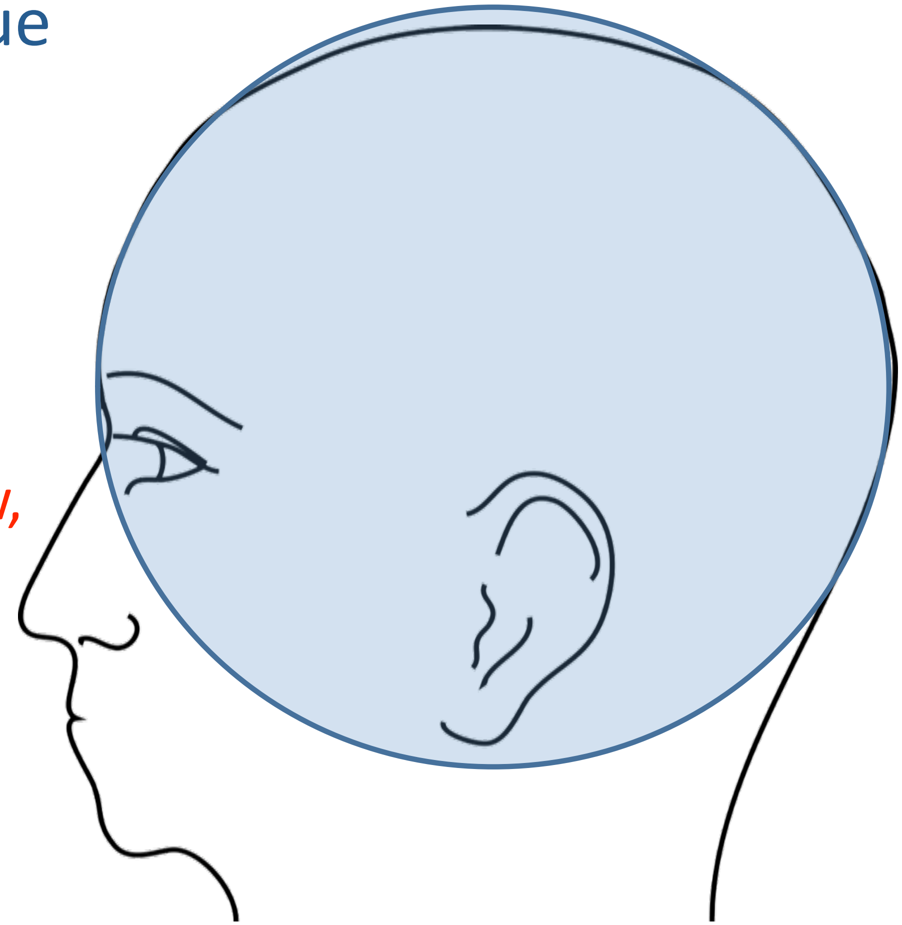


Volume conductor

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

→ Describes how the currents flow,
not where they originate



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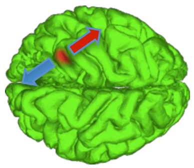
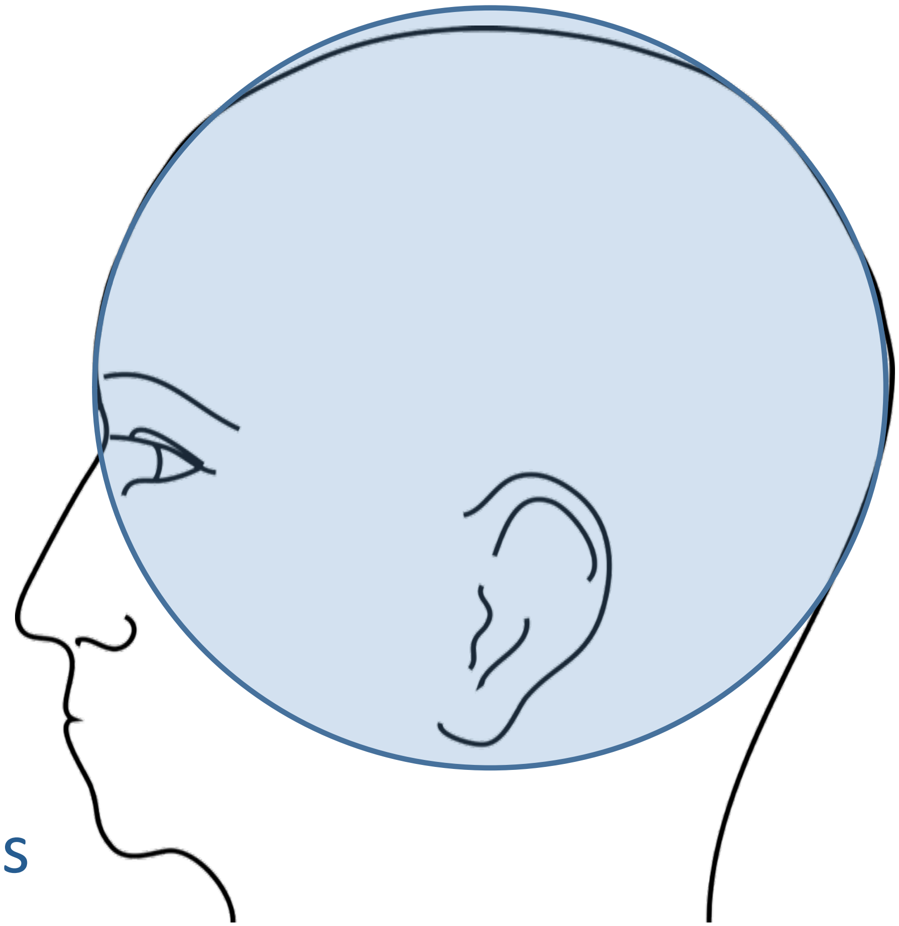


Volume conductor

- 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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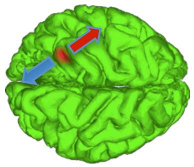

Volume conductor

- 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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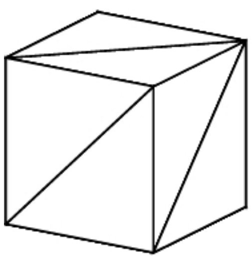
Realistic volume conductor

- 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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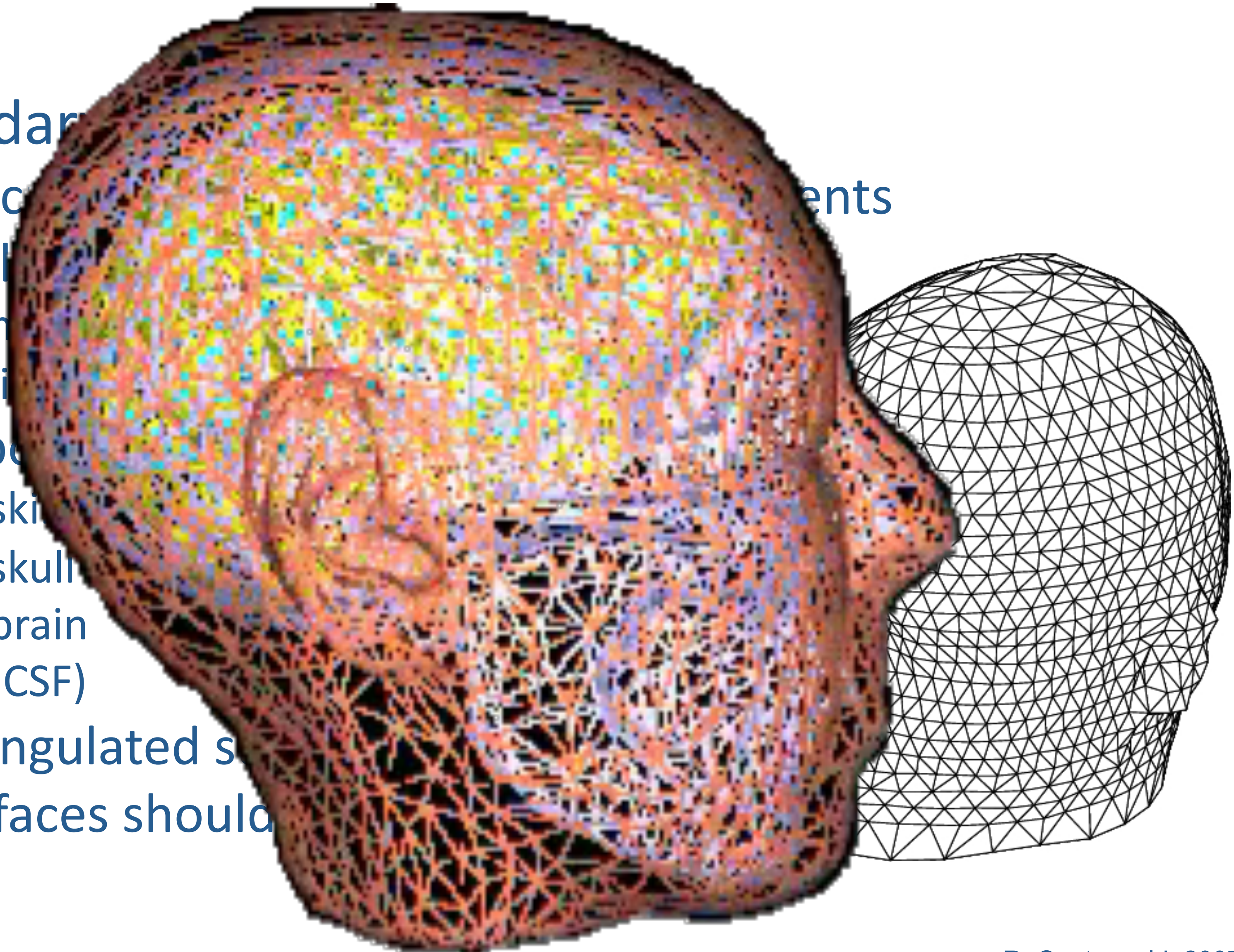
Volume conductor: BEM

- Boundar
  - desc ... ents
  - eac
    - h
    - i
  - imp
    - ski
    - skull
    - brain
    - (CSF)
  - triangulated s
  - surfaces should



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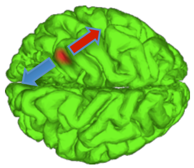

Volume conductor: FEM

- 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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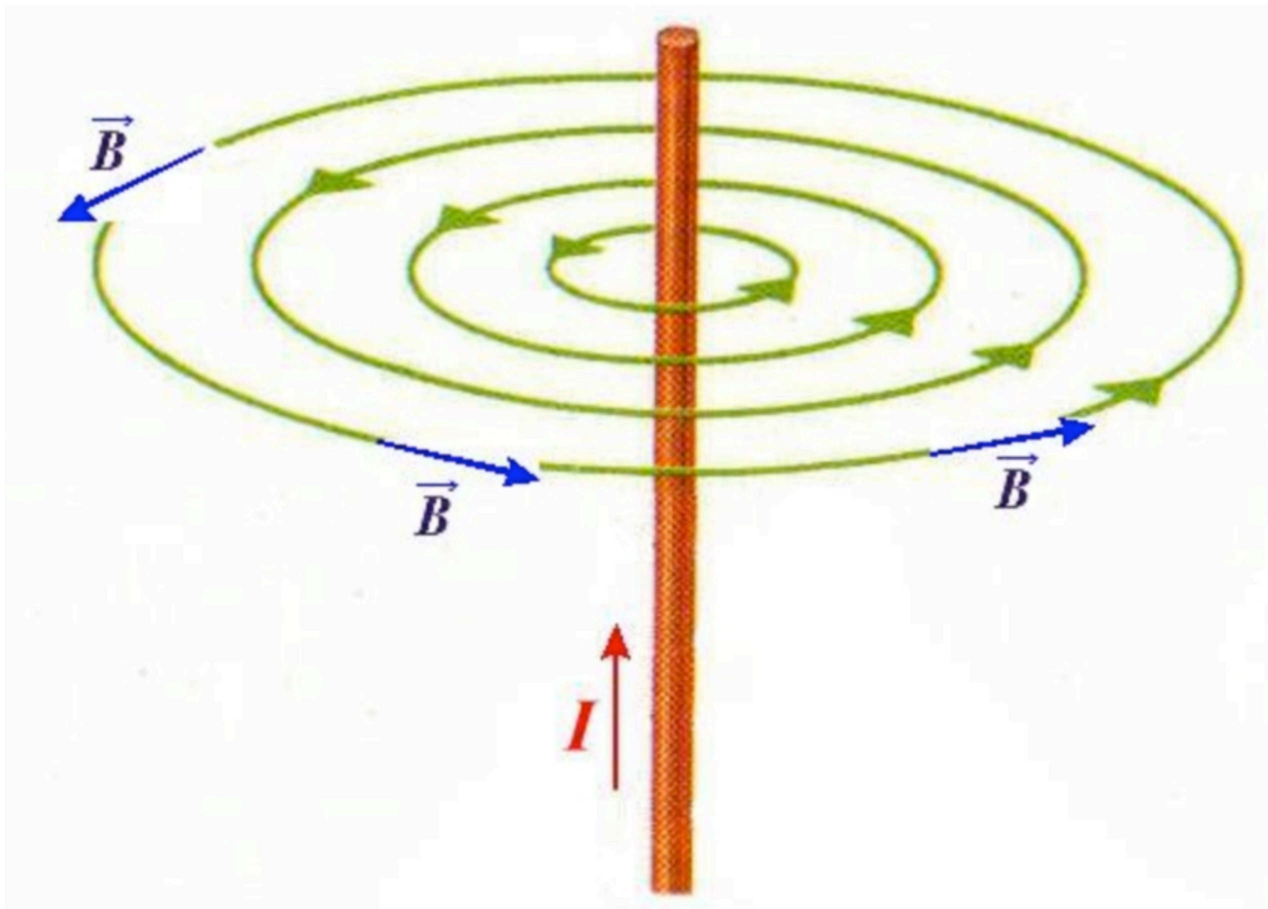
Electric current → magnetic field



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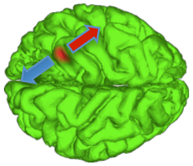

MEG volume conduction

- Measures sum of fields associated with
  - Primary currents
  - BUT also secondary currents !!!
- 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

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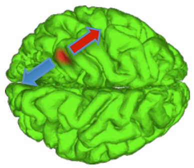

Differences between EEG and MEG

- Scalp distribution more blurred due to volume conductor in EEG
- MEG is insensitive to radial sources
- EEG sees more
- EEG more noisy in itself (electrode-skin impedance)
- MEG more sensitive to environmental noise!
- MEG requires no gel
- MEG requires the head to stay fixed !

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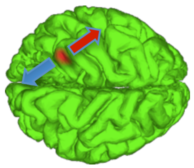

Differences between EEG and MEG

- EEG 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
  - multiple non-concentric sphere model,

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

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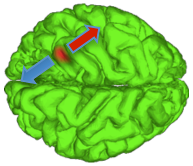

Inverse methods

- **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)

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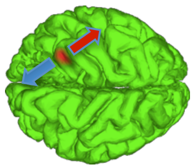

Inverse methods

- **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 / moments)
    - Of the scalp maps at individual moments
    - Of the differences in scalp maps between adjacent 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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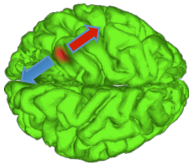

Single or multiple dipole models

- 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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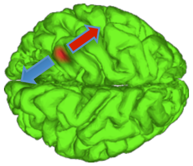

Dipole scanning: grid search

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

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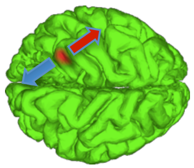

Dipole fitting: nonlinear search

- 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

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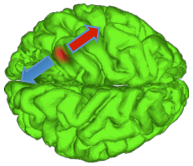

Distributed source models

- Position of the source is not estimated as such
  - 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 …

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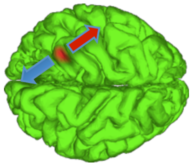

Summary

- 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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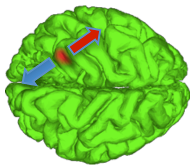
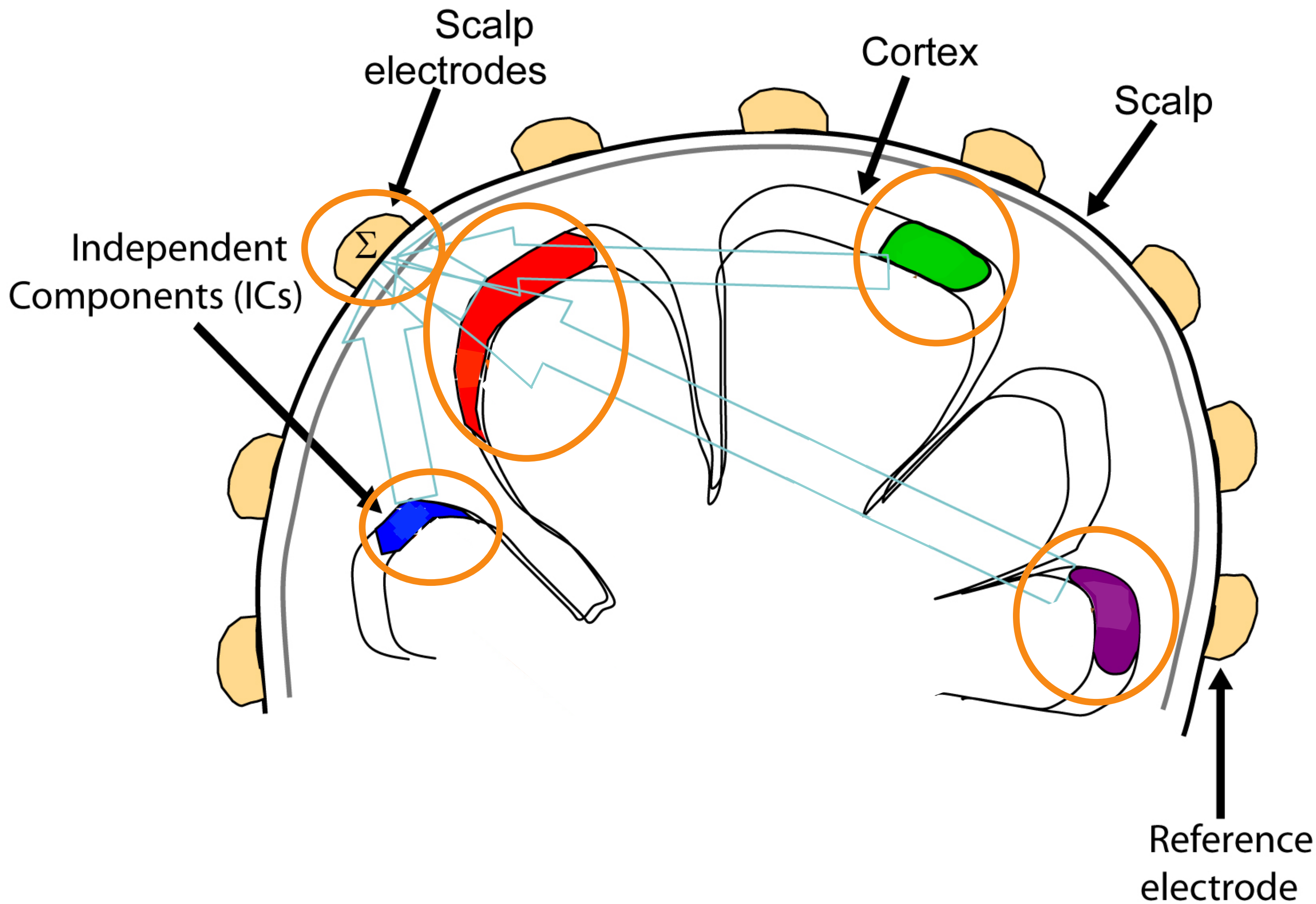


Summary

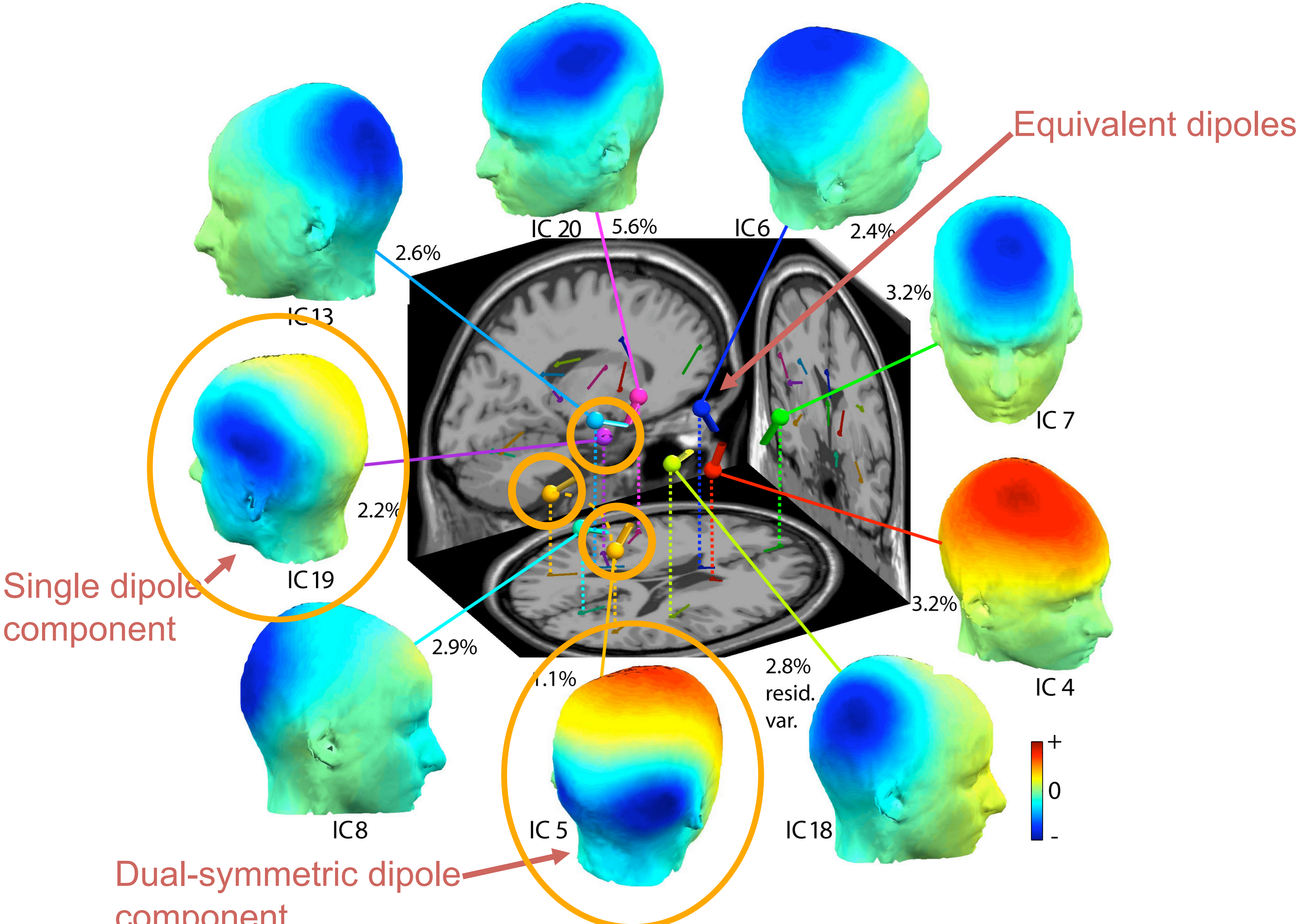
- **Inverse modeling**
  - Model assumption for volume conductor
  - Model assumption for source (I.e. dipole)
  - Additional assumptions on source
- **Single point-like sources**
- **Multiple point-like sources**
- **Distributed sources**
  - Different mathematical solutions
    - Dipole fitting (linear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

Independent Components



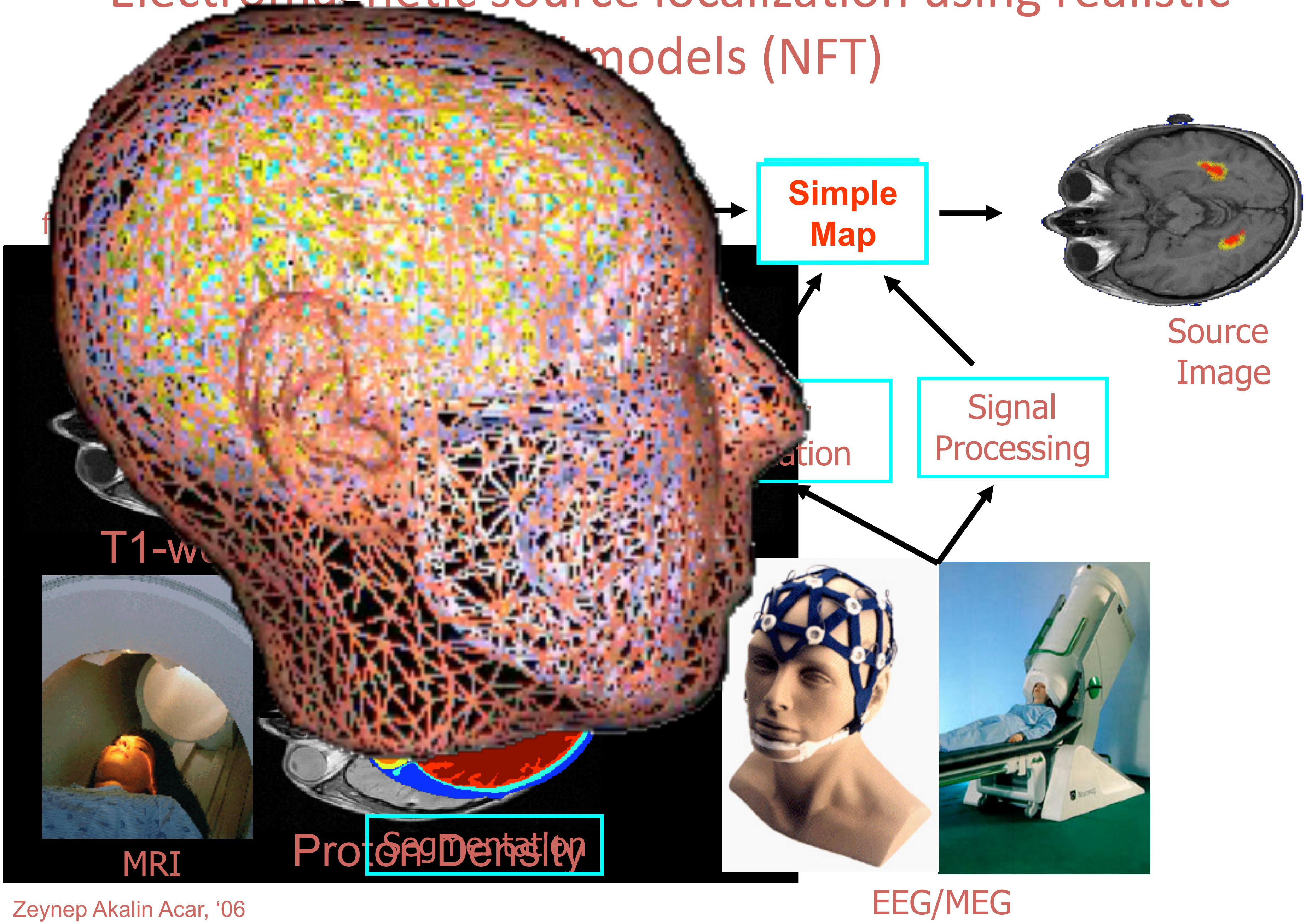
Onton & Makeig, submitted

Independent cortical components

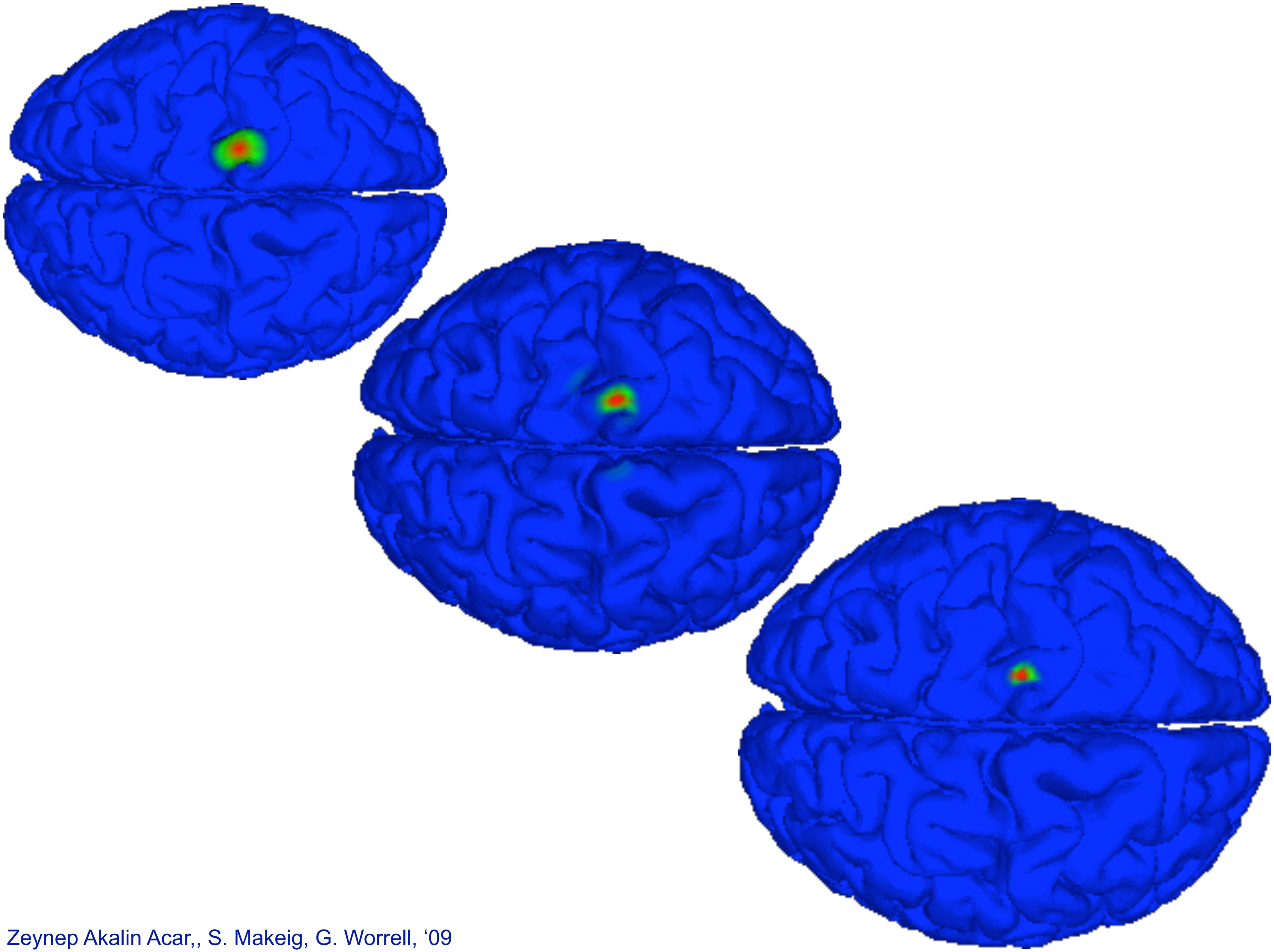


Julie Onton & S. Makeig (2006)

Electromagnetic source localization using realistic
models (NFT)

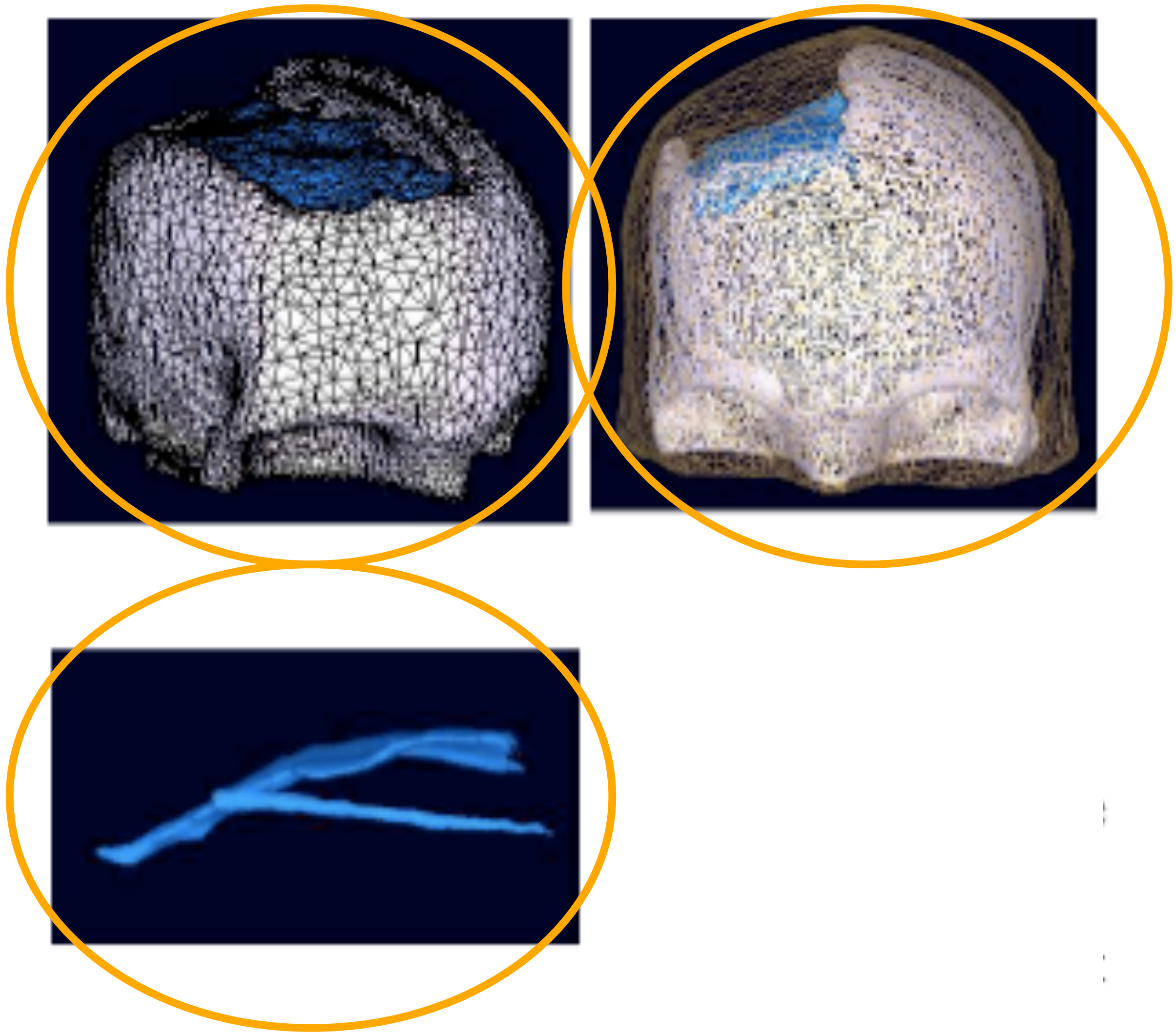


Zeynep Akalin Acar, '06



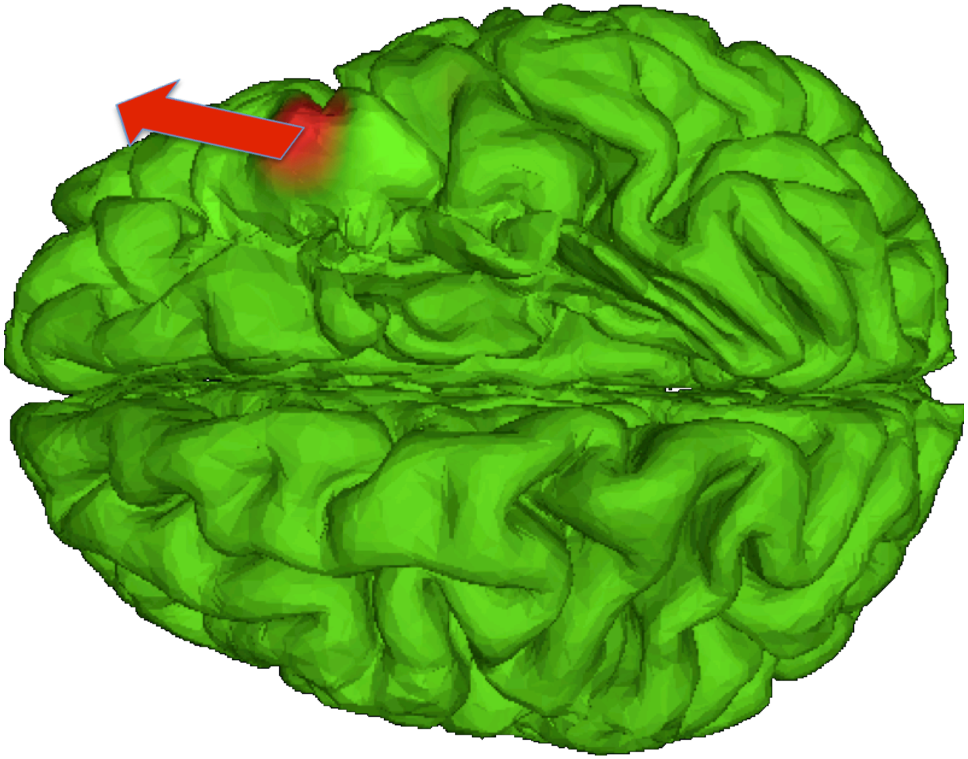
Zeynep Akalin Acar,, S. Makeig, G. Worrell, ‘09

Electromagnetic source localization using realistic head models – an intracranial monitoring model

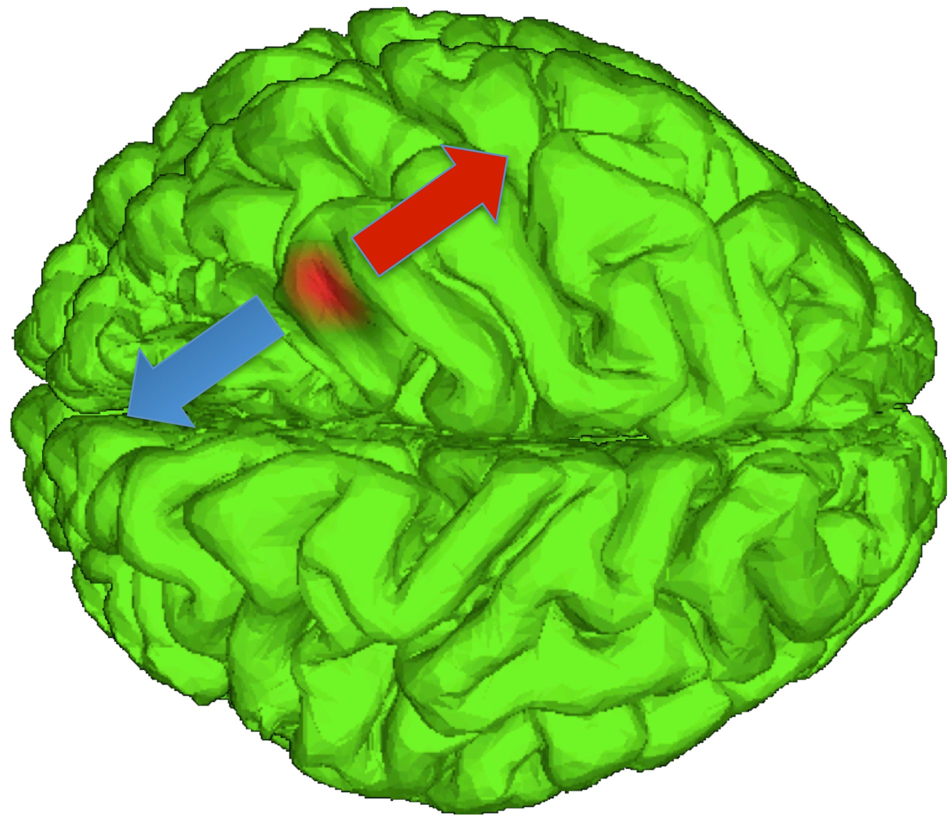


Zeynep Akalin Acar,, S. Makeig, G. Worrell, ‘09

gyral source

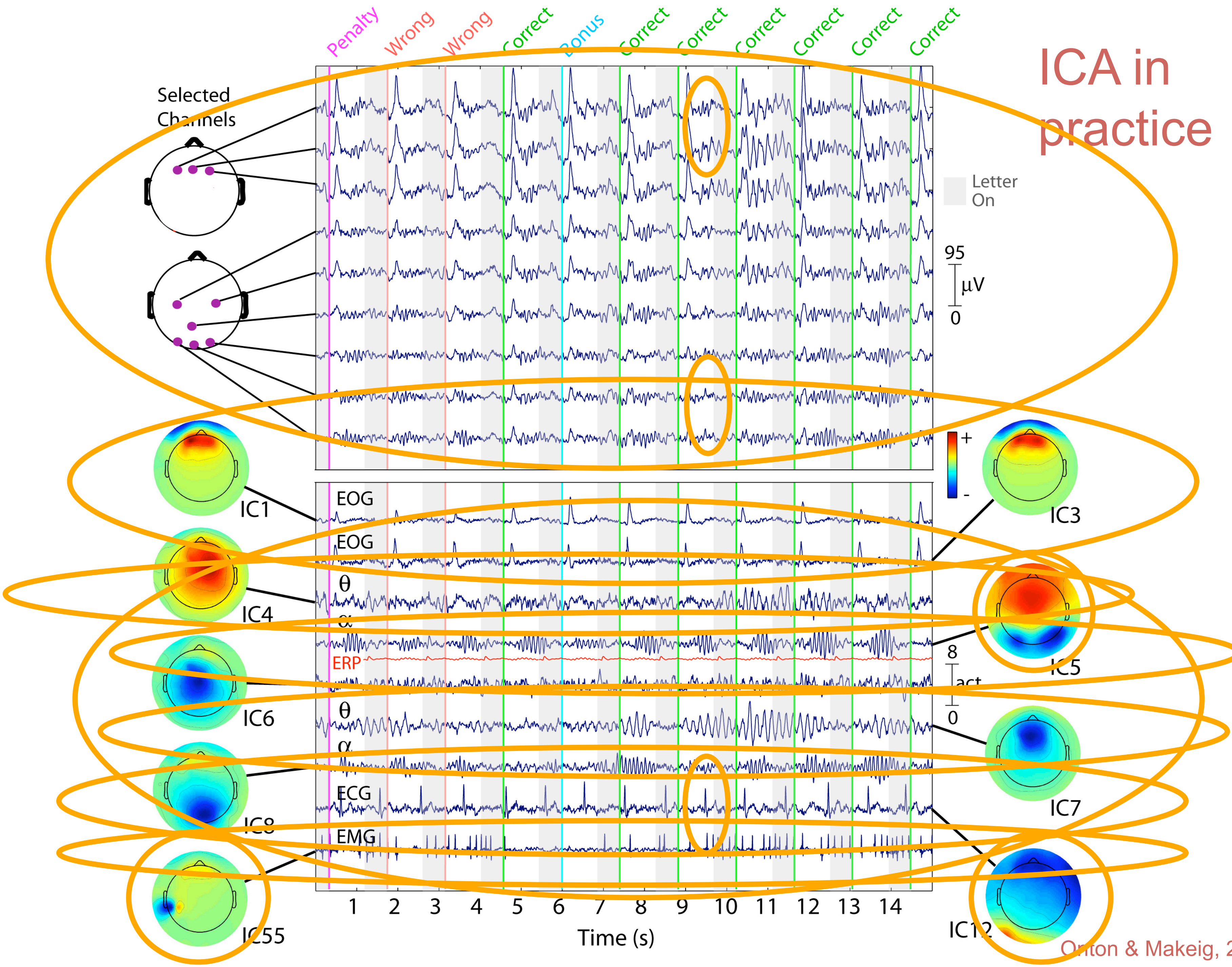


sulcal source

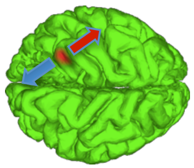


Zeynep Akalin Acar,, S. Makeig, G. Worrell, ‘09

ICA in practice

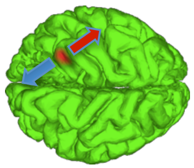


Onton & Makeig, 2006



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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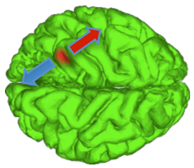

Why EEG?: extra information

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

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