MRC Cognition and Brain Sciences Unit

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MEG forward modelling

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MEG UK 2013 pre-conference workshop

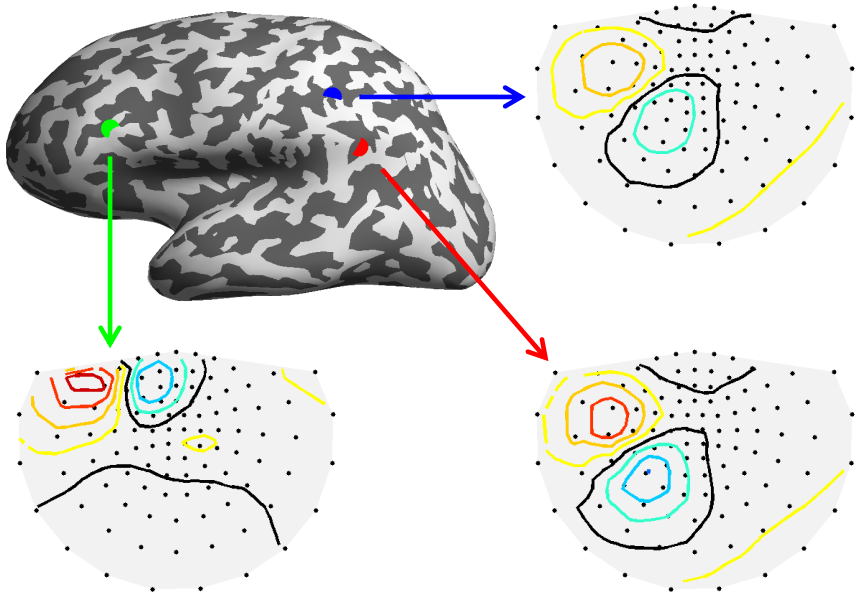
Intro Forward modelling?

What?

- Generally: compute physical field generated by known sources
- Here: compute MEG signal generated by neural activity.

Why?

- To understand the origins of MEG signal
- To design/optimize sensor setups
- To be used in source estimation.

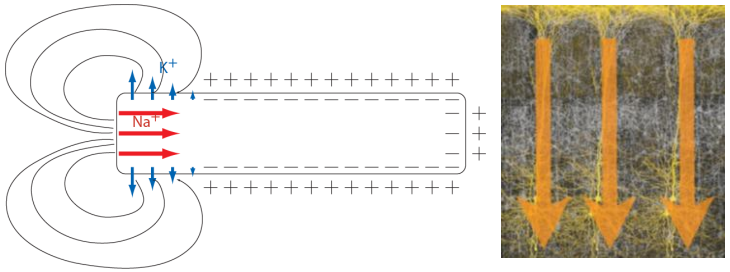


Intro Forward modelling?

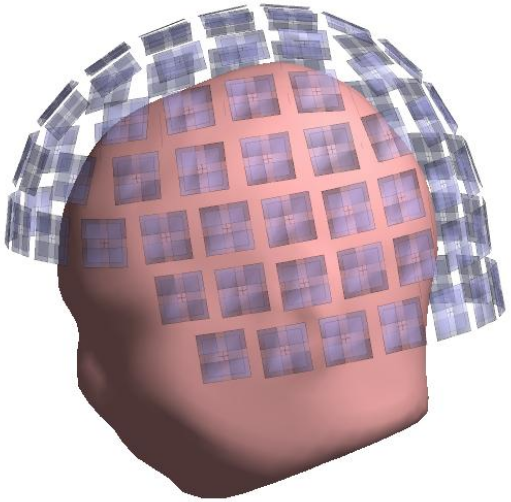
1. Physics

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi} \int_{V'} \frac{[\vec{J}(\vec{r}\,') + \vec{J}_{\mathrm{v}}(\vec{r}\,')] \times (\vec{r} - \vec{r}\,')}{|\vec{r} - \vec{r}\,'|^3} dV'$$

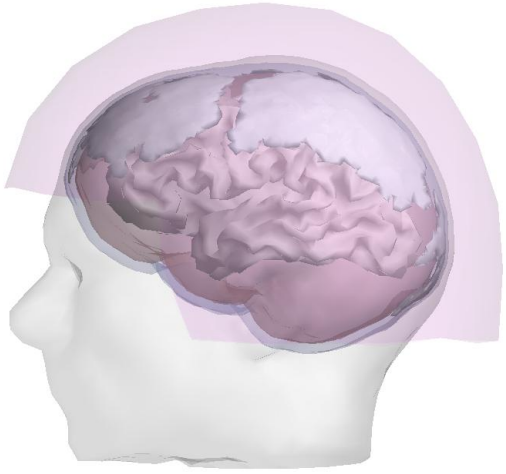
2. Source model



3. Sensor model

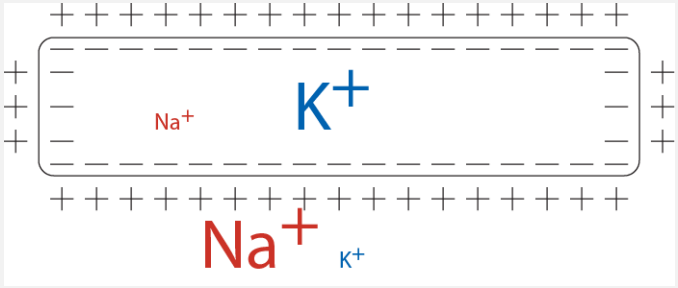


4. Conductivity model

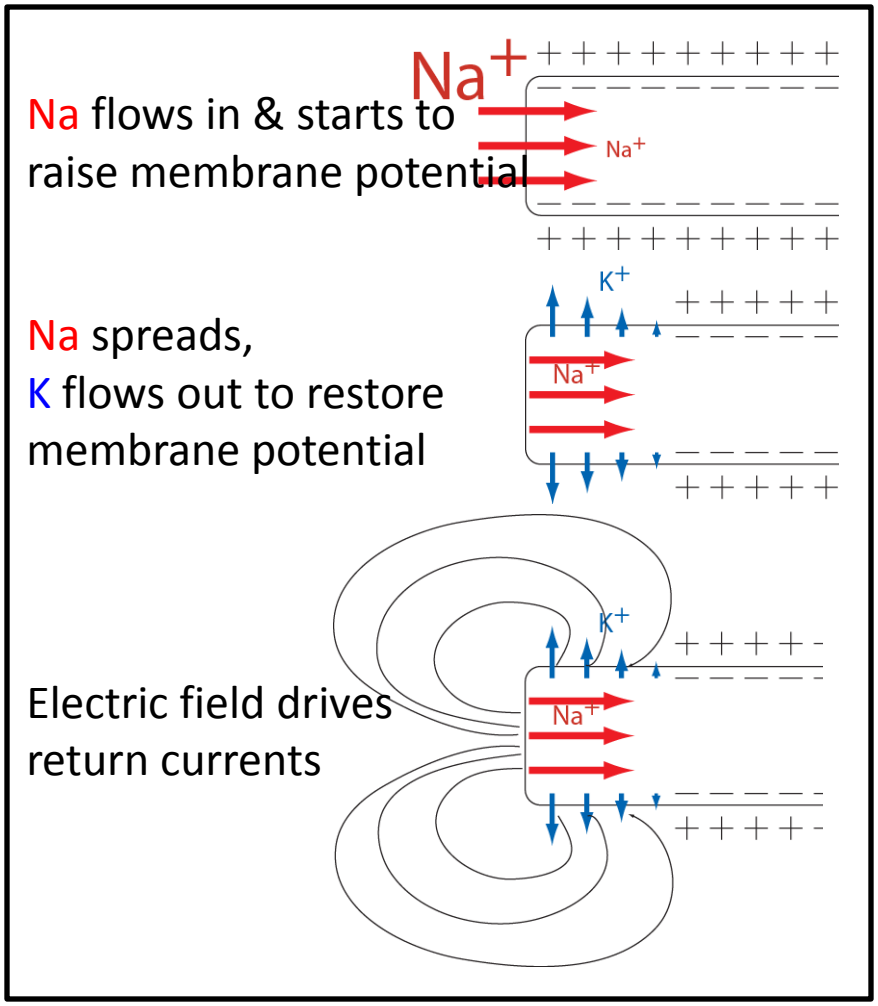


1 Physics simplified

Excitable cell, resting:



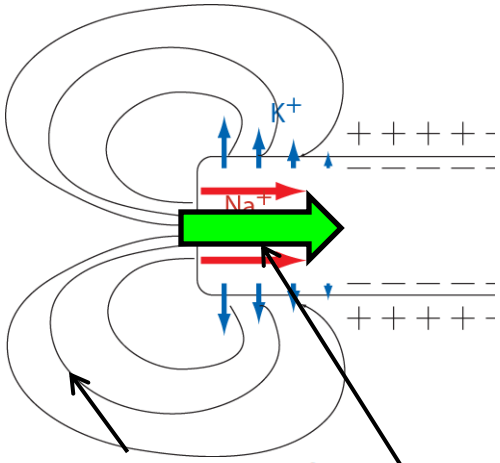
- Concentration gradient
- Ion channels: Na closed, K open
  - Polarised membrane/ membrane potential
- No currents or fields.



All currents generate magnetic field:

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi} \int_{V'} \frac{\vec{J}(\vec{r}\,') \times (\vec{r} - \vec{r}\,')}{|\vec{r} - \vec{r}\,'|^3} dV'$$

1 & 2 Source model and equations



volume current $\vec{J}_{\mathrm{v}}$

primary current $\vec{J}_{\mathrm{p}}$

Macroscopic source model

- Assume tissue continuum
  - No intra- and extracellular space
  - No cellular membrane, membrane currents
  - No intra/extra-cellular currents
- Source activity: primary current
- Total current $\vec{J}$:
  primary current $\vec{J}_{\mathrm{p}}$ + volume current $\vec{J}_{\mathrm{v}}$

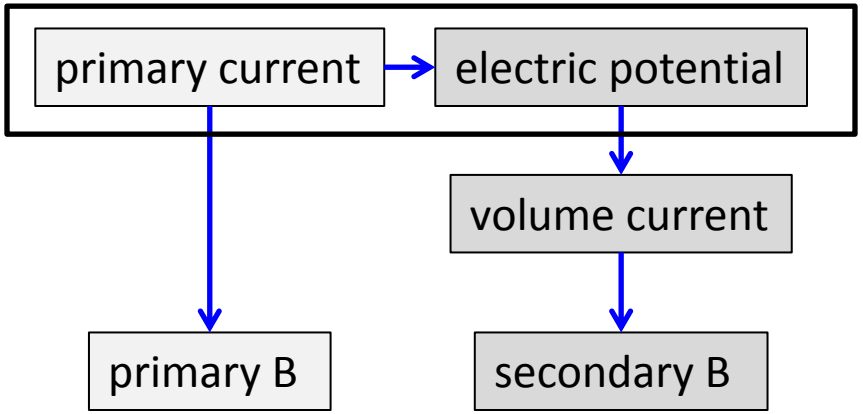
$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi}\int_{V'}\frac{\vec{J}(\vec{r}\,')\times(\vec{r}-\vec{r}\,')}{|\vec{r}-\vec{r}\,'|^3}dV'$$

$$\vec{J} = \vec{J}_{\mathrm{p}} + \vec{J}_{\mathrm{v}}$$

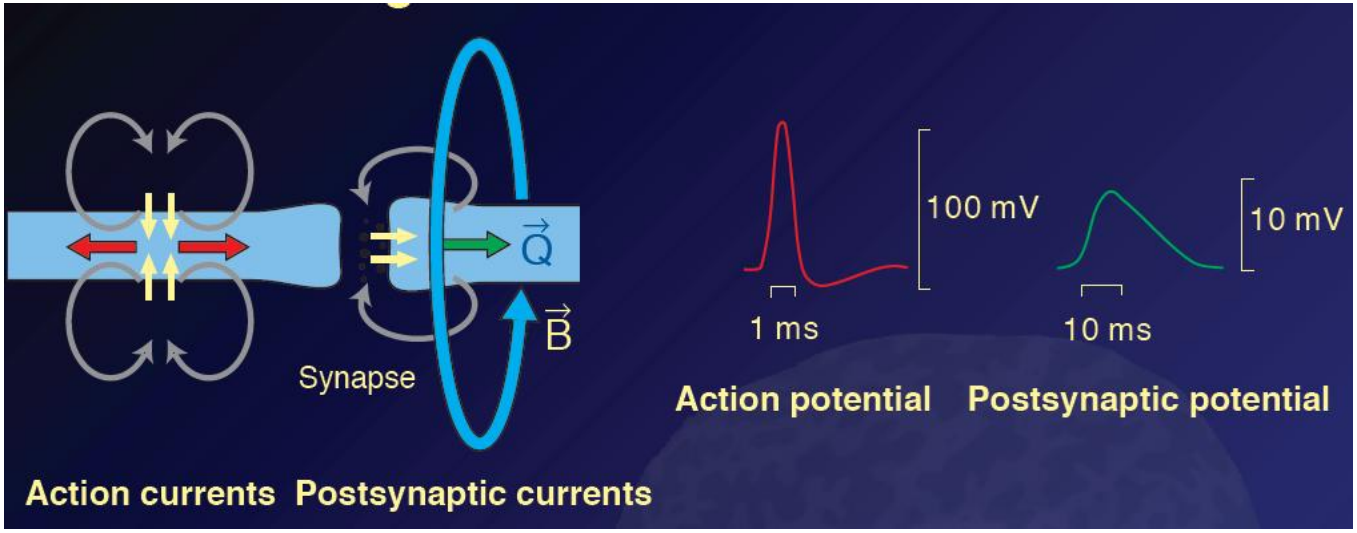
$$\vec{J}_{\mathrm{v}} = -\sigma\nabla\phi, \quad \nabla\cdot(\sigma\nabla\phi) = \nabla\cdot\vec{J}_{\mathrm{p}}$$

ϕ electric potential
σ conductivity

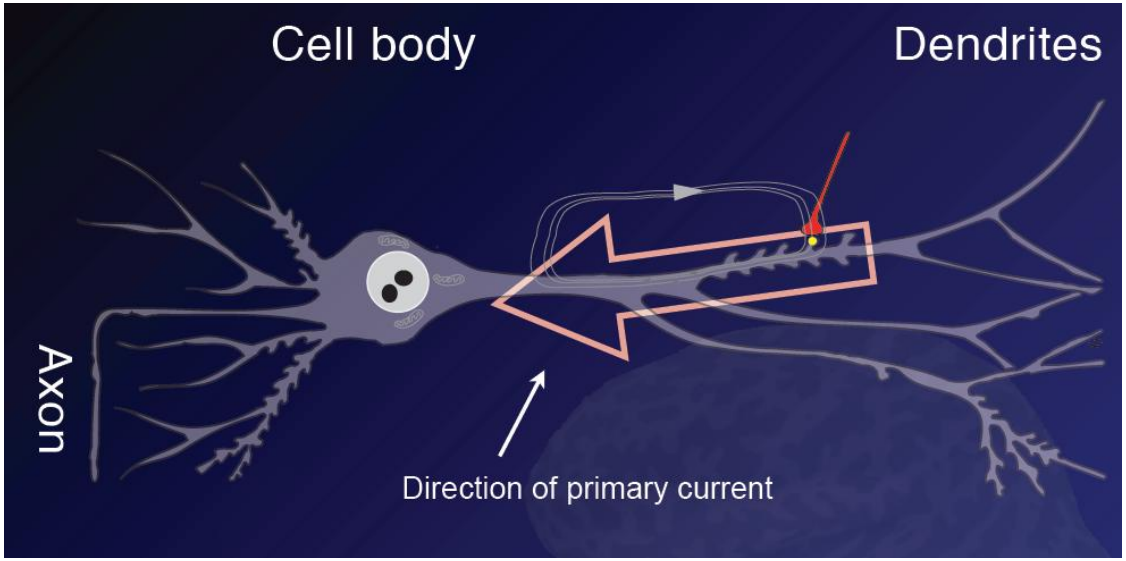
Volume conductor model



2 Neural sources

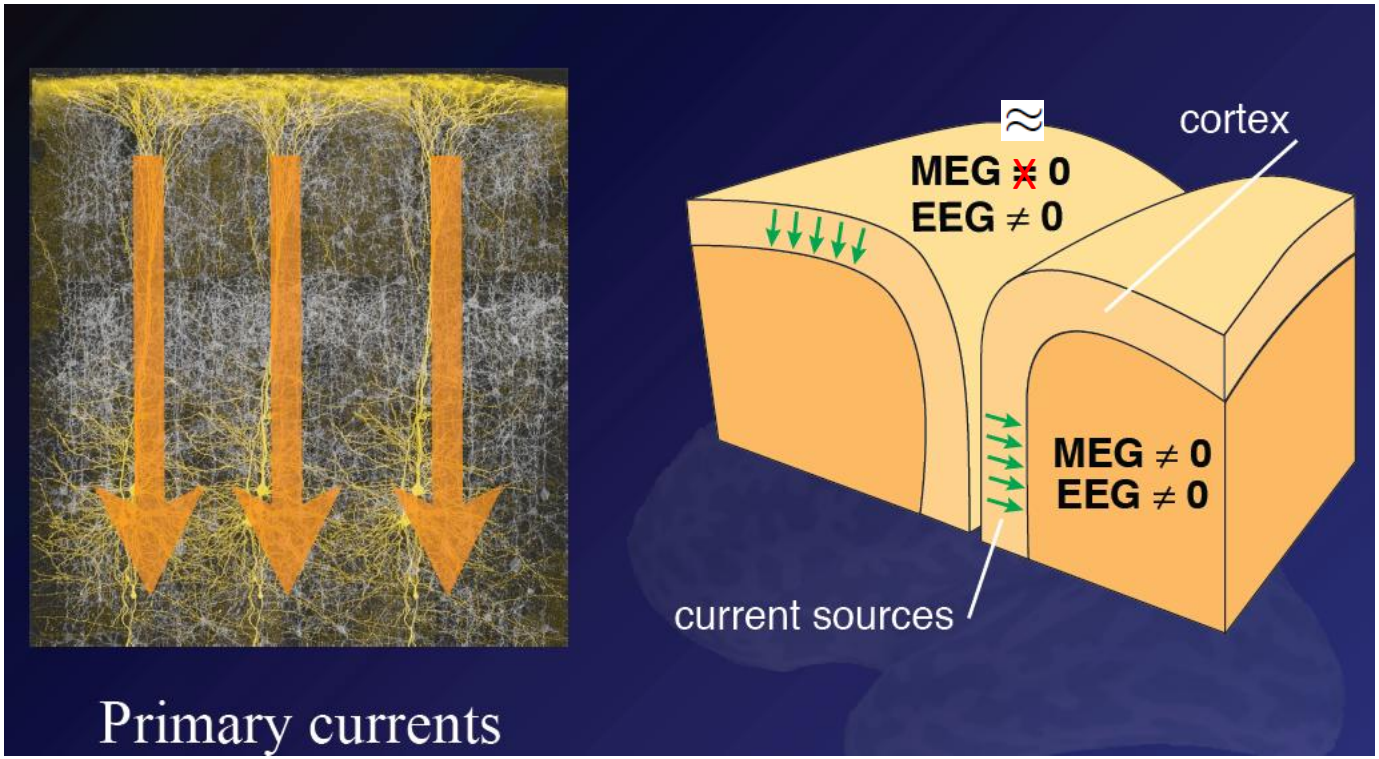


- Postsynaptic currents: dipole, attenuates ~ $1/r^2$
- Action currents: de- ja repolarisation close to each other → quadrupolar field, attenuates ~ $1/r^3$
- Action currents can be measured only in tissue.



Pics: Matti Hämäläinen

2 Cortical sources



Pic: Matti Hämäläinen

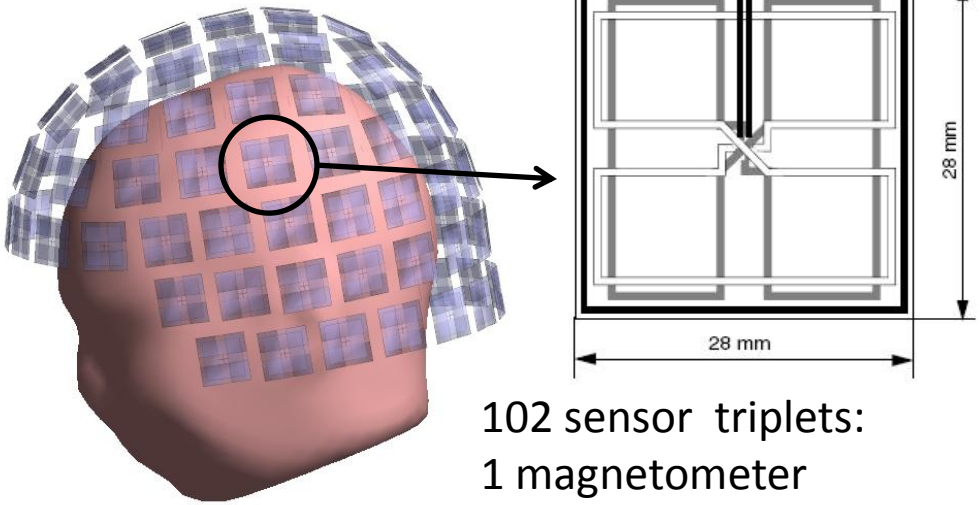
- EEG and MEG have the same neural source: primary current density in cortex
- Cellular source: postsynaptic currents in pyramidal neurons
- Sources are (anatomically) oriented normal to cortical surface
- A small patch of cortex, ~1cm^2, thousands of activated neurons: dipole
- Distributed source: primary current discretized into dipoles (N typically 5000-10000)

3 Sensor model

Sensor types

- Magnetometer: B_z
- Planar gradiometer: $\Delta B_z/\Delta x$, $\Delta B_z/\Delta y$
- Axial gradiometer: $\Delta B_z/\Delta z$
- Sensor size ~ 2 cm.

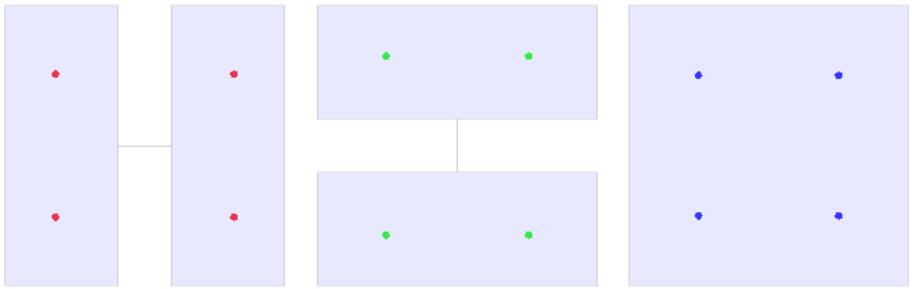
Elekta 306 setup



102 sensor triplets:
1 magnetometer
2 planar gradiometers

Sensor model: numerical integral

- Each sensor: set of points (1 to 8).
- For each point, compute B_z
- Weighted sum over points.



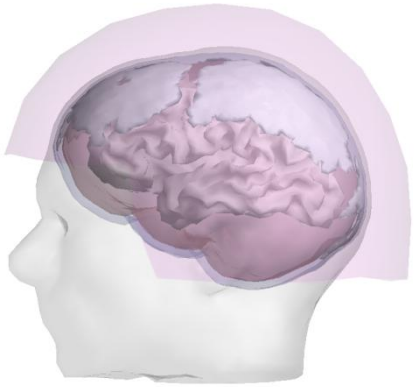
GM1 GM2 MM

4 Volume conductor model

- Both EEG and MEG are generated by both primary currents and volume currents

$$\vec{B}(\vec{r}) = \frac{\mu_0}{4\pi}\int_{V'}\frac{[\vec{J}_{\mathrm{p}}(\vec{r}\,') - \sigma(\vec{r}\,')\nabla\phi V(\vec{r}\,')]\times(\vec{r}-\vec{r}\,')}{|\vec{r}-\vec{r}\,'|^3}dV'$$

$$\nabla\cdot(\sigma\nabla\phi) = \nabla\cdot\vec{J}_{\mathrm{p}}$$



- To solve the volume currents, conductivity distribution in the head needs to be modelled: volume conductor model.
  - Numerical field computation or analytical series expansions.

Misunderstandings or strange statements:

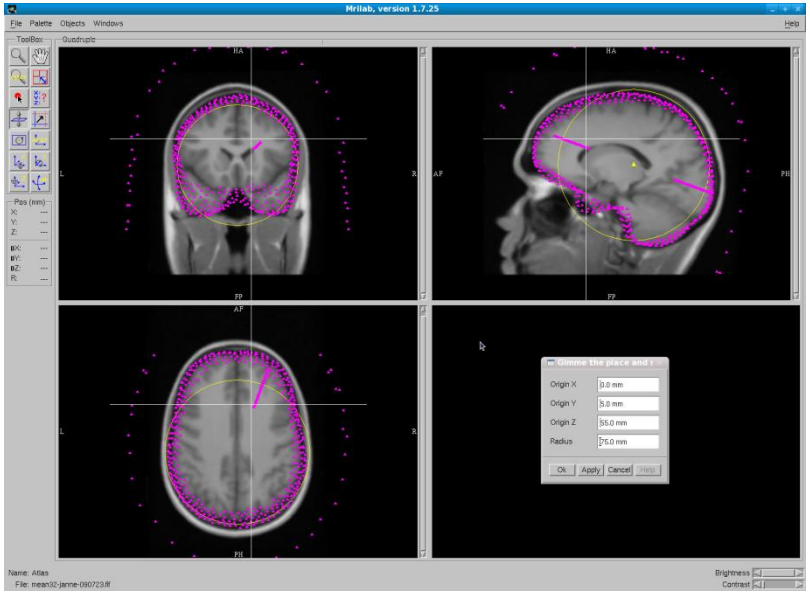
”The conductivity profile of head does not distort MEG signals”

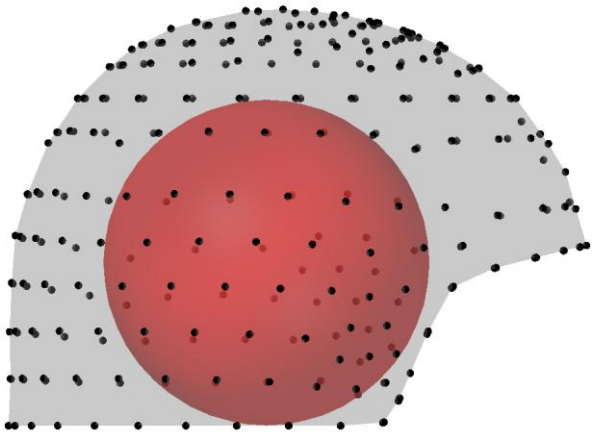
”Volume currents have no effect on MEG”

”The conductivity profile of head has more effect on EEG than on MEG”.

4 MEG volume conductor models

- Spherical models
  - Local spheres model
  - Perturbed sphere
- 1-shell realistic model
- 3-shell realistic model





Spherical model

- Radial sources produce no field
- Radial conductivity-profile has no effect on field
- Radial field of a tangential source same as in vacuum
- One free parameter: origin
- Fitted globally or locally to inner skull

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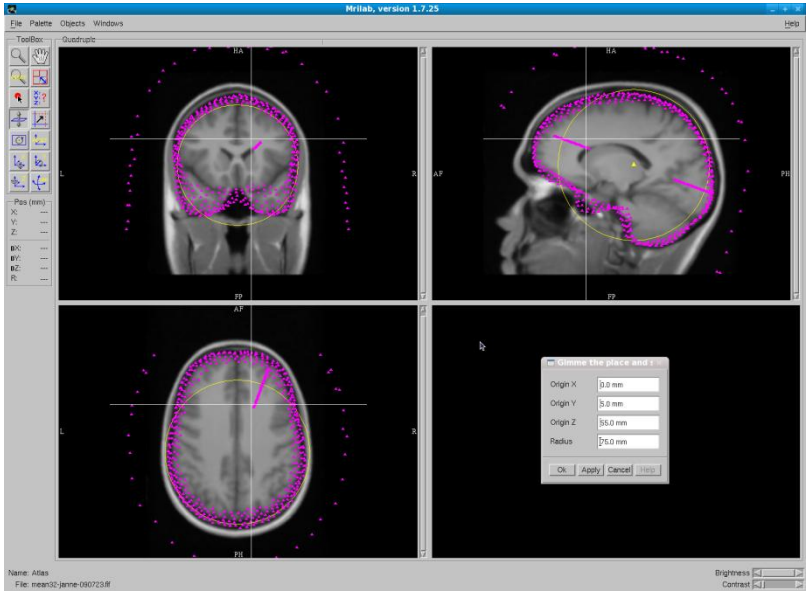

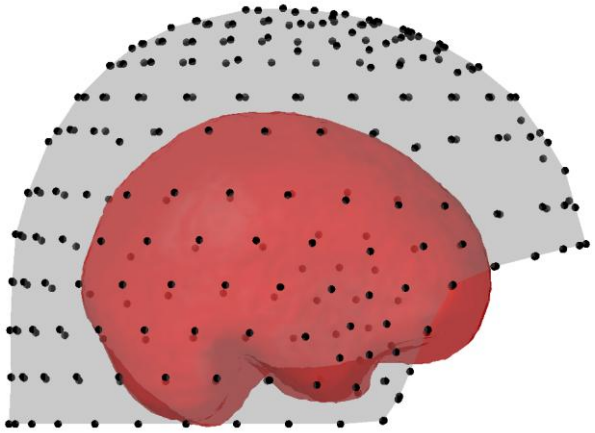

1-shell model

- Most of the currents inside the skull
- Omit currents in skull and scalp
- Reasoning: head almost spherical, skull almost insulator

4 MEG volume conductor models

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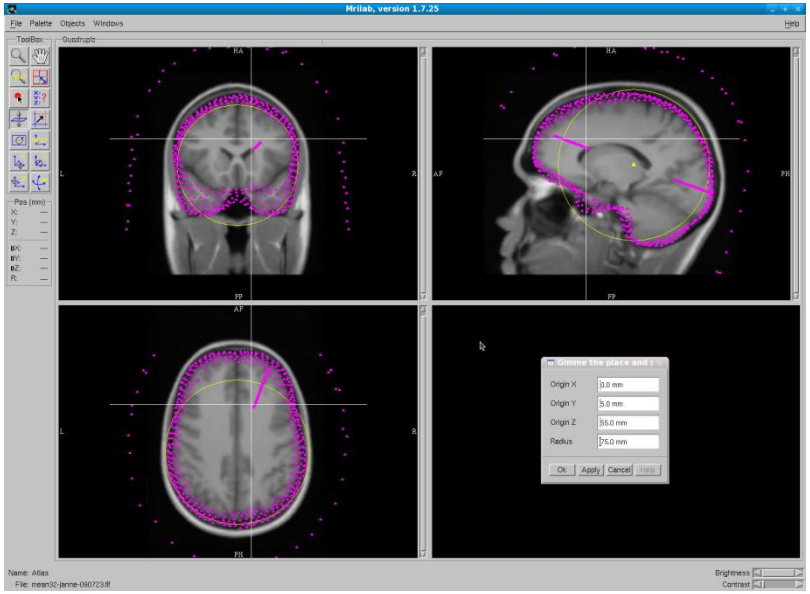
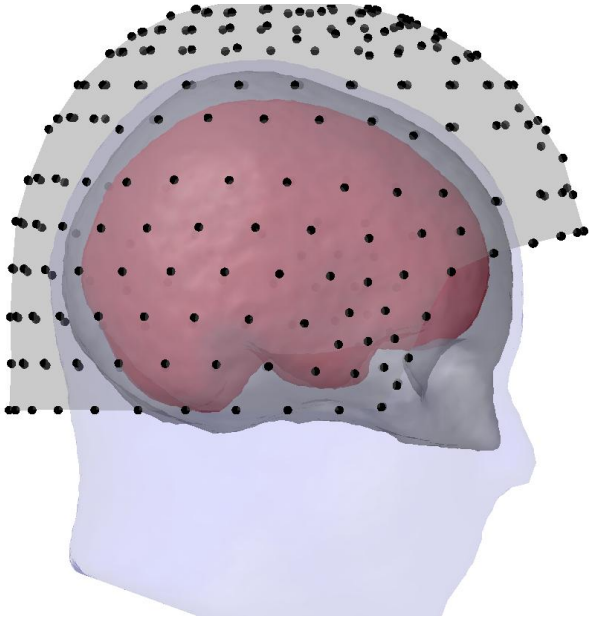
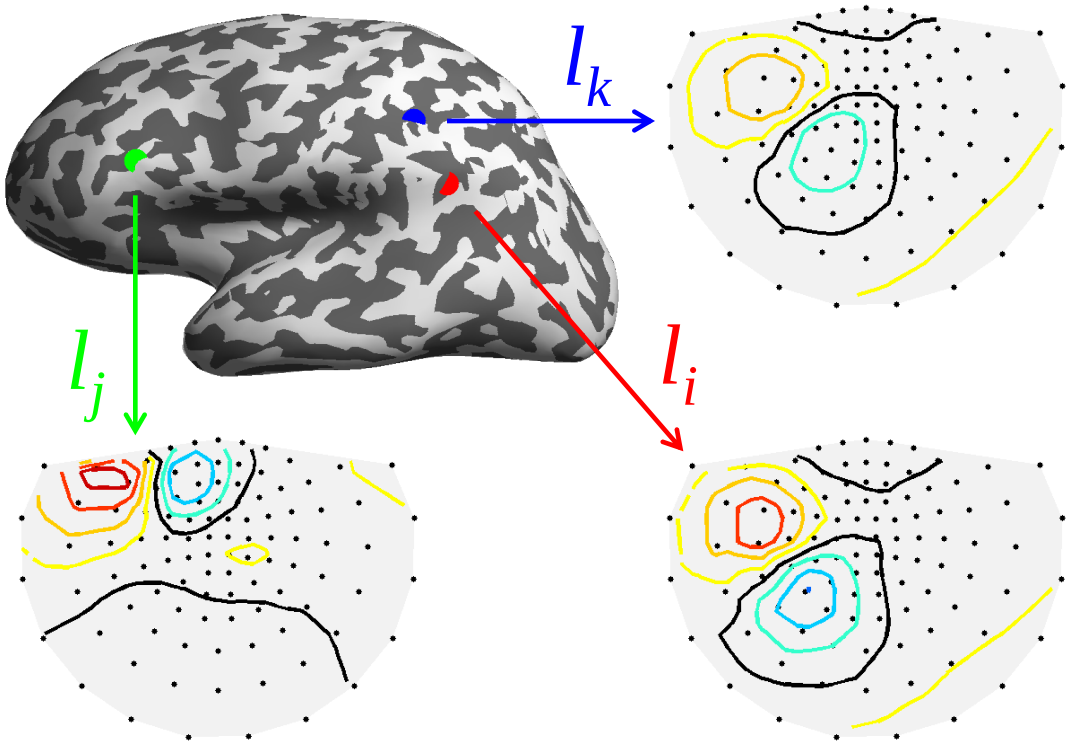




3-shell model

- Most accurate easy-to-generate model
- Inner skull, outer skull, scalp
- Sources of error:
  - Poor MRI contrast for skull
  - CSF, fiber anisotrophy, air cavities omitted
  - Inaccurate numerical solution due to crude meshing or poor solver

The result Lead fields



Lead vector $\boldsymbol{l_i}$:
signal produced in all sensors by a unit-strength oriented source in $\boldsymbol{r_i}$

- Lead-field matrix: $\boldsymbol{L}=[\boldsymbol{l_i} \ \ldots \ \boldsymbol{l_N}]$
- Linear measurement model: $\boldsymbol{m}=\boldsymbol{Ls}+\boldsymbol{n}$

Summary Forward modelling

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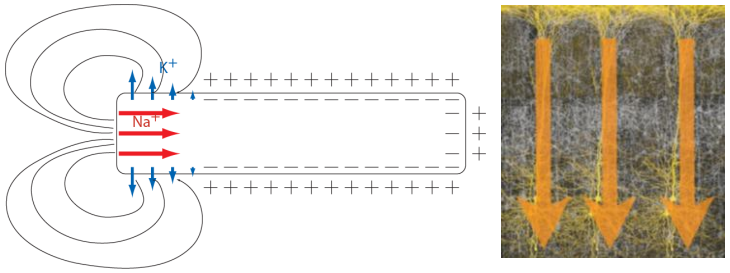

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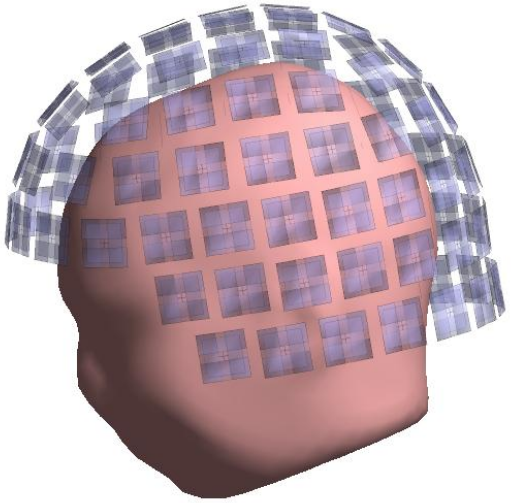

4. Conductivity model