Forward and inverse modelling of EEG and MEG

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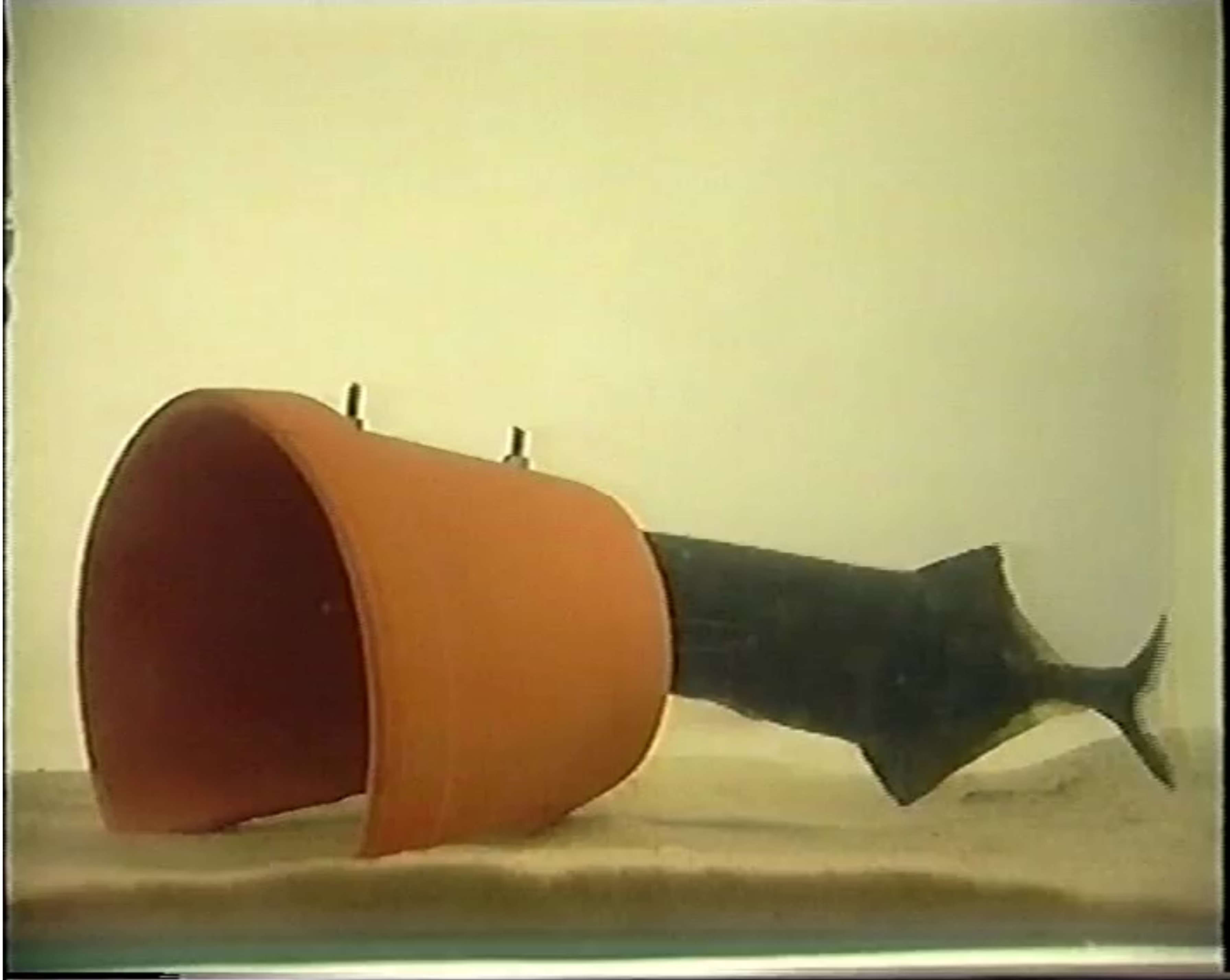

Overview

- Motivation and background
- Forward modeling
  - Source model
  - Volume conductor model
- Inverse modeling - general
  - Single and multiple dipole fitting
  - Distributed source models
  - Beamforming methods
- Inverse modeling - independent components
- Summary

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Motivation and background

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Motivation 1

Strong points of EEG and MEG

- Temporal resolution (~1 ms)
- Characterize individual components of ERP
- Oscillatory activity
- Disentangle dynamics of cortical networks

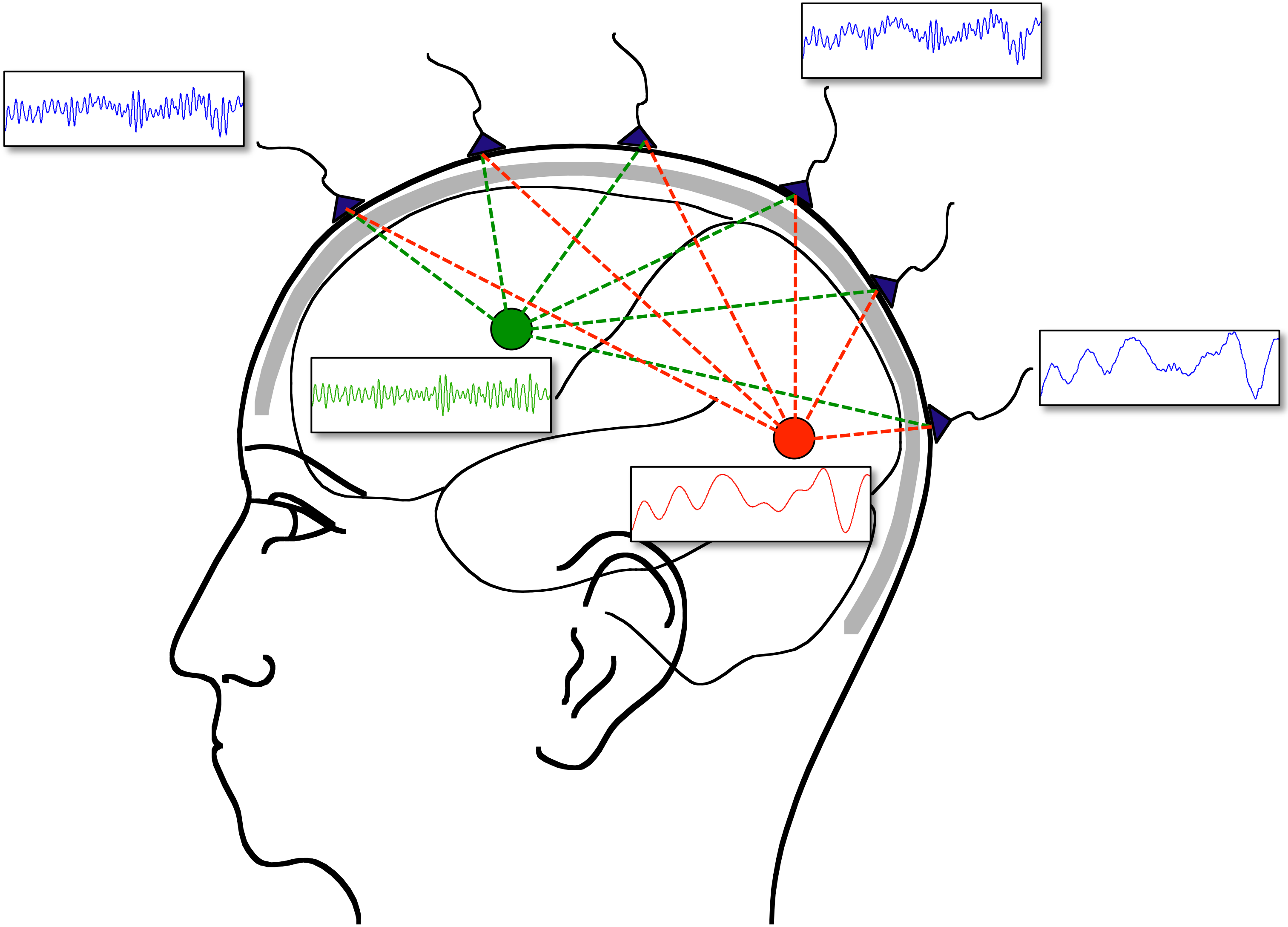
Weak points of EEG and MEG

- Measurement on outside of brain
- Overlap of components
- Low spatial resolution

Motivation 2

- If you find a ERP/ERF component, you want to characterize it in physiological terms
  - Time or frequency are the “natural” characteristics
  - “Location” requires interpretation of the scalp topography
- Forward and inverse modeling helps to interpret the topography
- Forward and inverse modeling helps to disentangle overlapping source timeseries

Superposition of source activity



Superposition of source activity

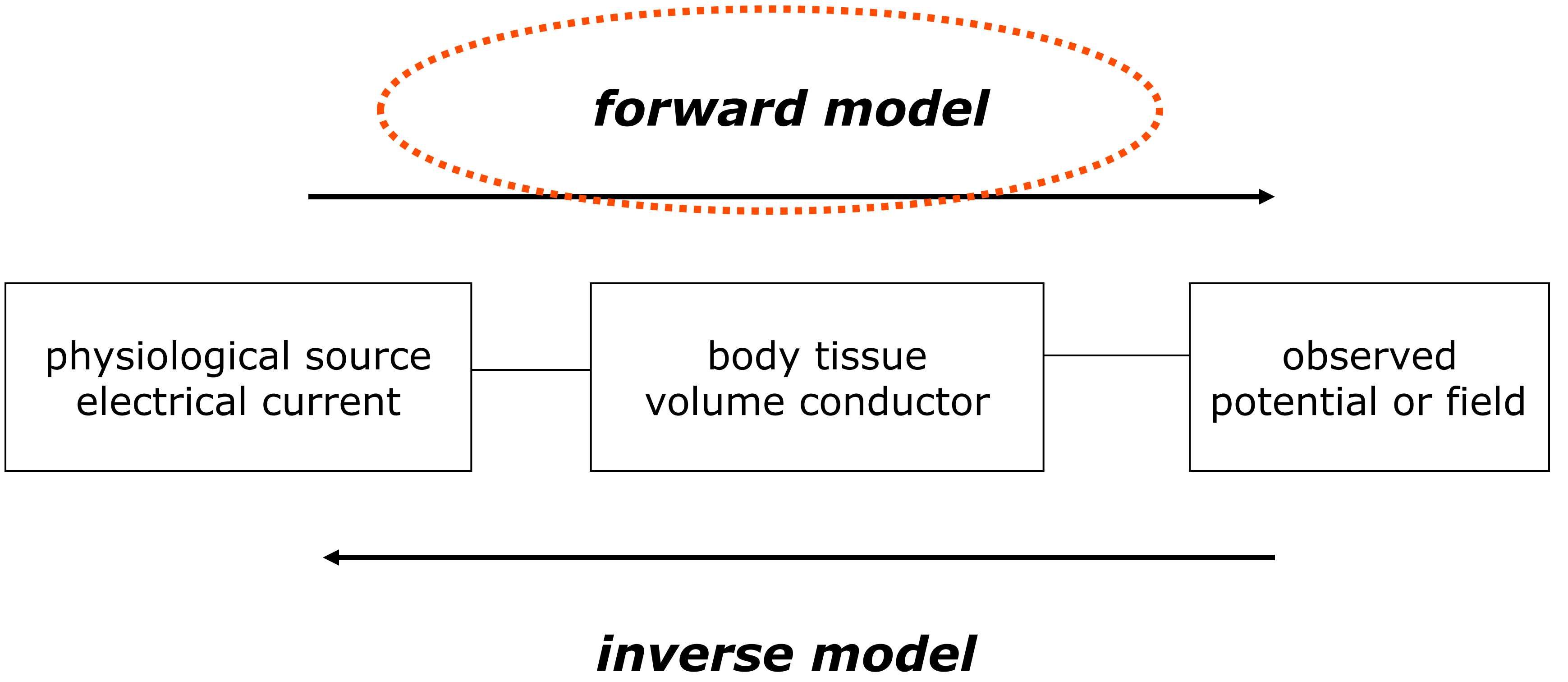
Varying "visibility" of each source to each channel

Timecourse of each source contributes to each channel

The contribution of each source depends on its "visibility"

Activity on each channel is a superposition of all source activity

Biophysical source modelling: overview



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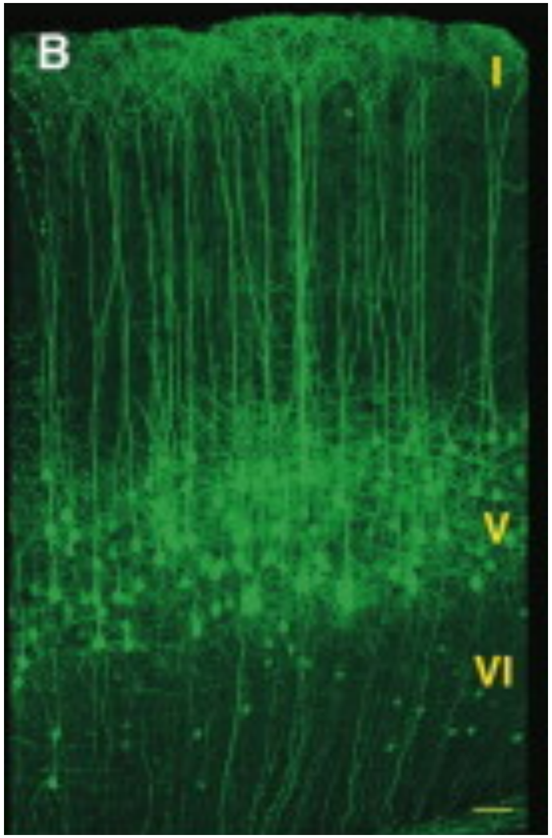
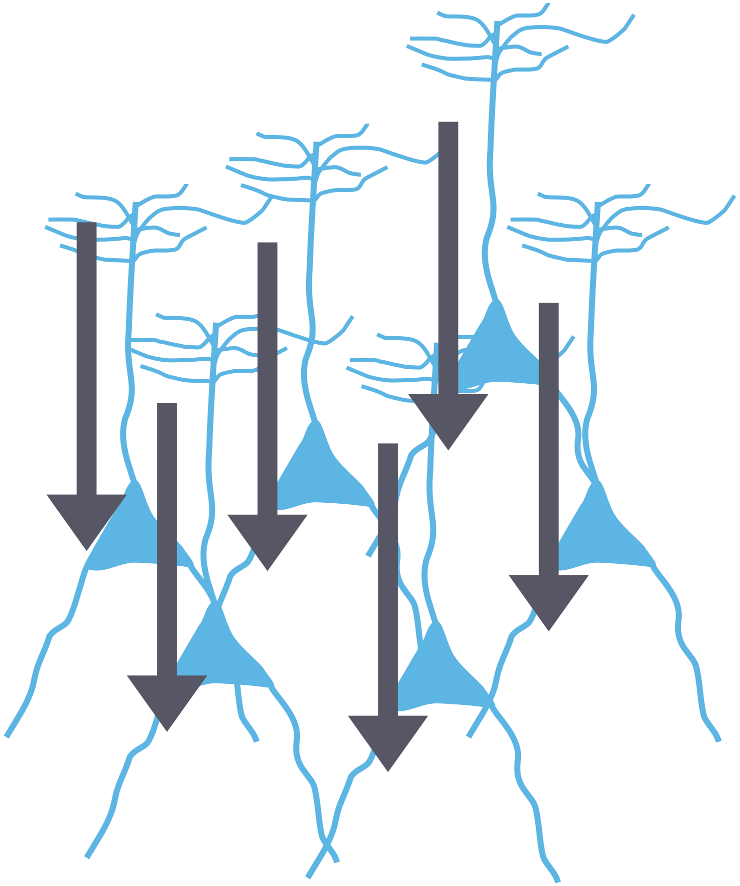
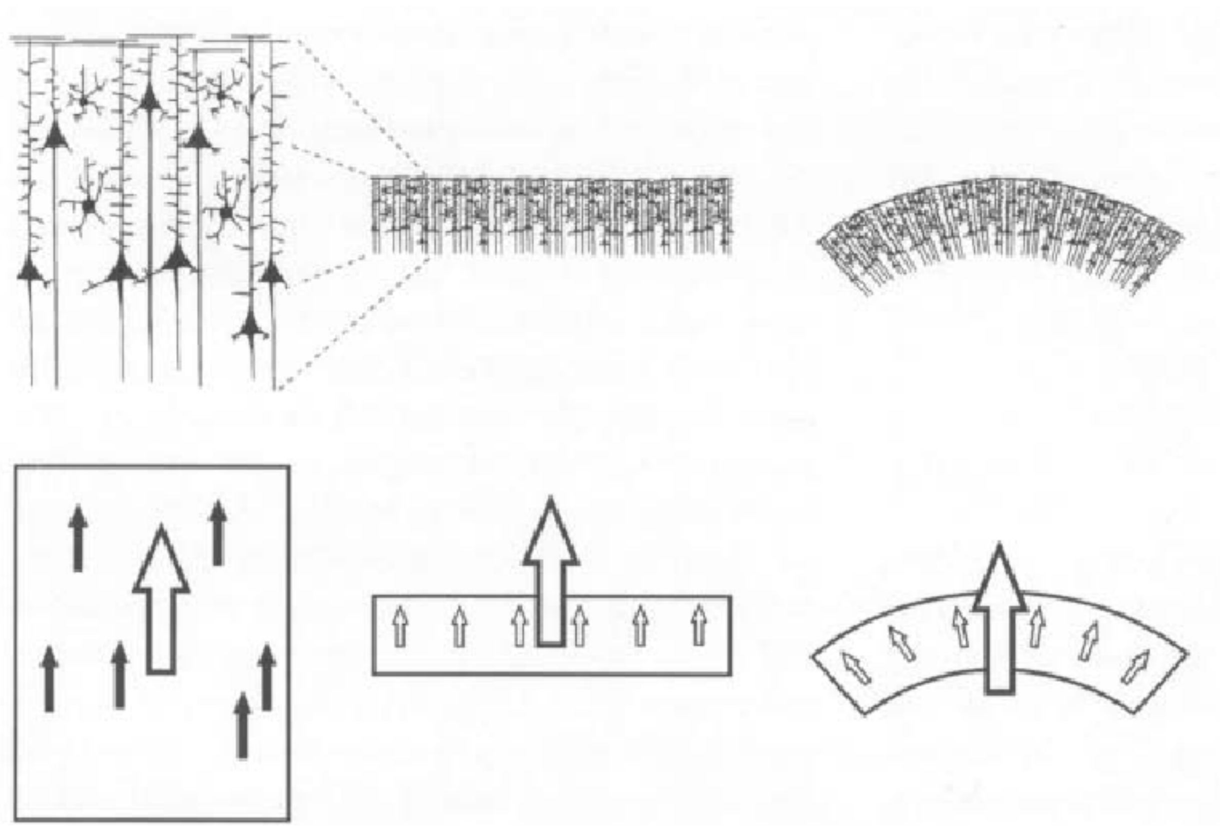
What produces the electric current





Equivalent current dipoles



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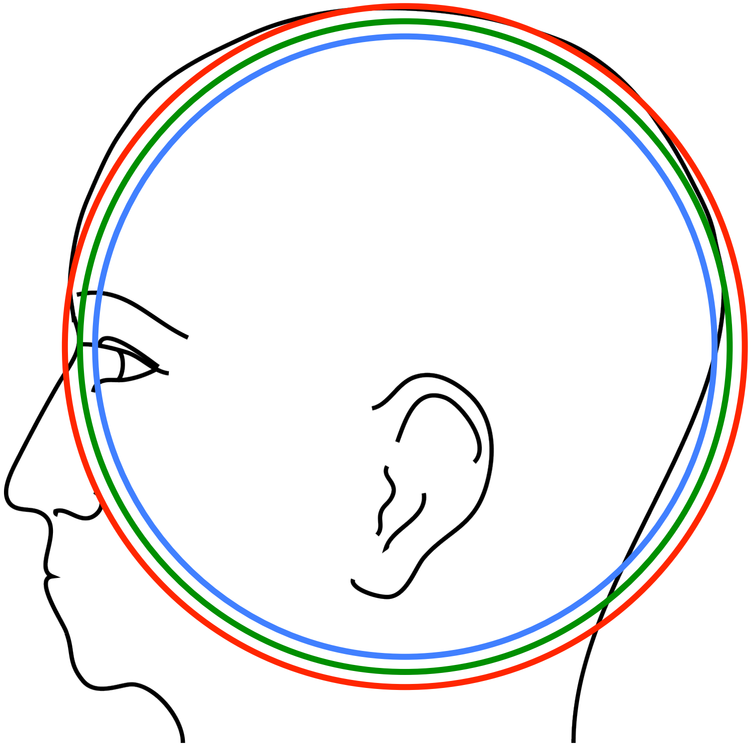
Volume conductor

described electrical properties of tissue

describes geometrical model of the head

describes **how** the currents flow, not where they originate from

same volume conductor for EEG as for MEG, but also tDCS, tACS, TMS, …



Volume conductor

Computational methods for volume conduction problem that allow for realistic geometries

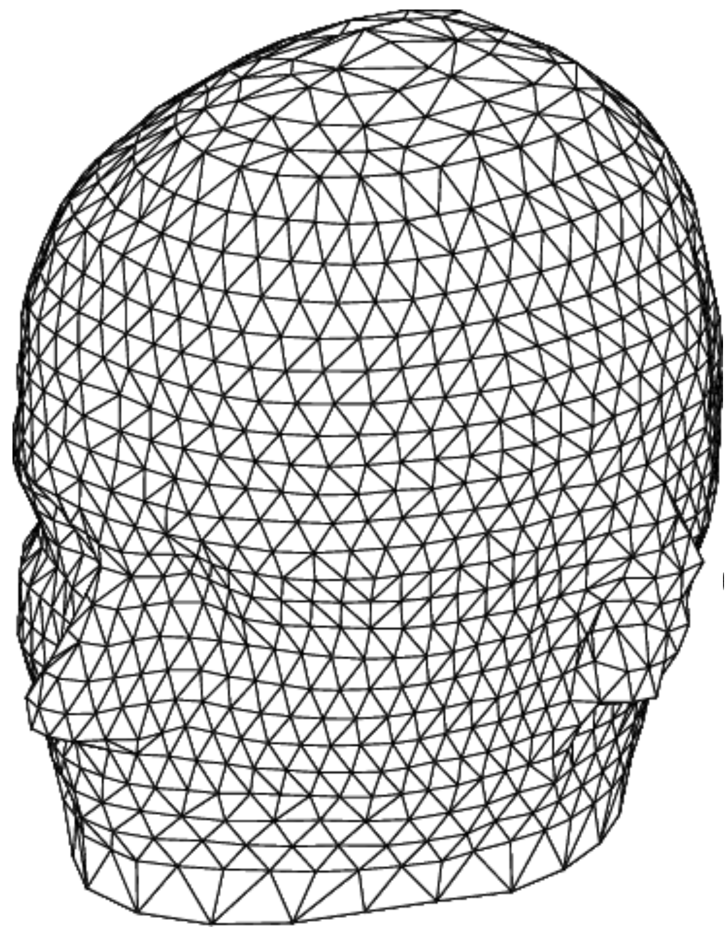
BEM	*Boundary Element Method*
FEM	*Finite Element Method*
FDM	*Finite Difference Method*

Volume conductor: Boundary Element Method

Each compartment is
- homogenous
- isotropic

Important tissues
- skin
- skull
- brain
- (CSF)

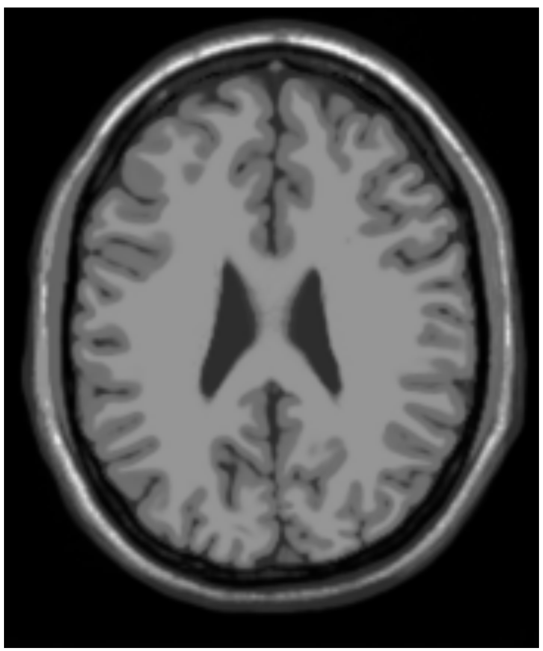
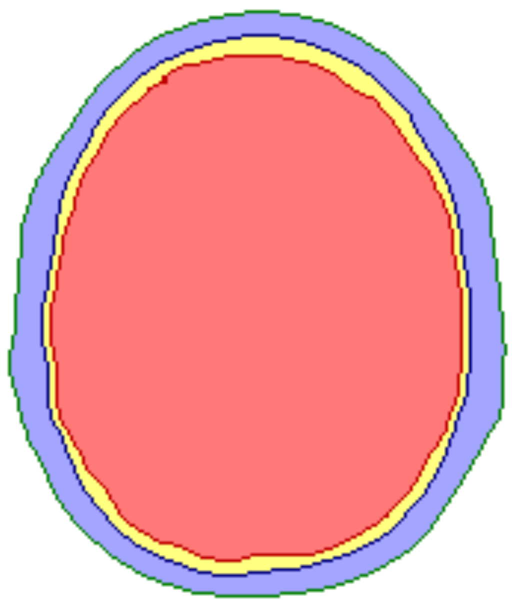
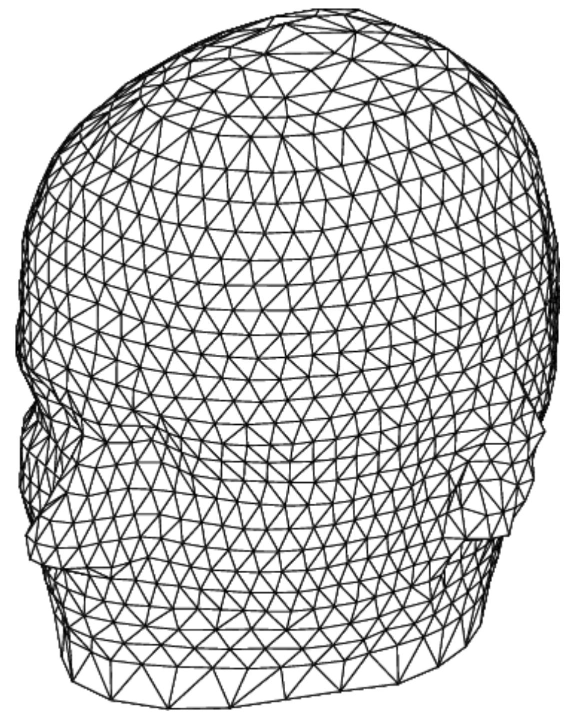
Triangulated surfaces describe boundaries



Volume conductor: Boundary Element Method

Construction of geometry

- segmentation in different tissue types
- extract surface description
- downsample to reasonable number of triangles

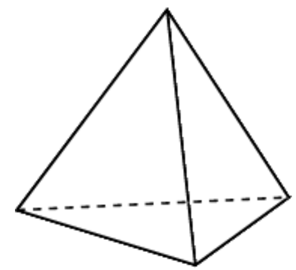




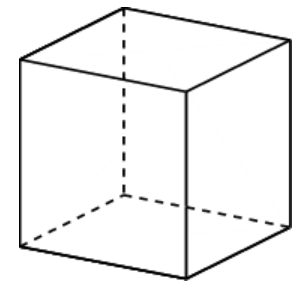
Volume conductor: Boundary Element Method

- Construction of geometry
  - segmentation in different tissue types
  - extract surface description
  - downsample to reasonable number of triangles
- Computation of model
  - independent of source model
  - only one lengthy computation
  - fast during application to real data
- Can (almost) be arbitrary complex

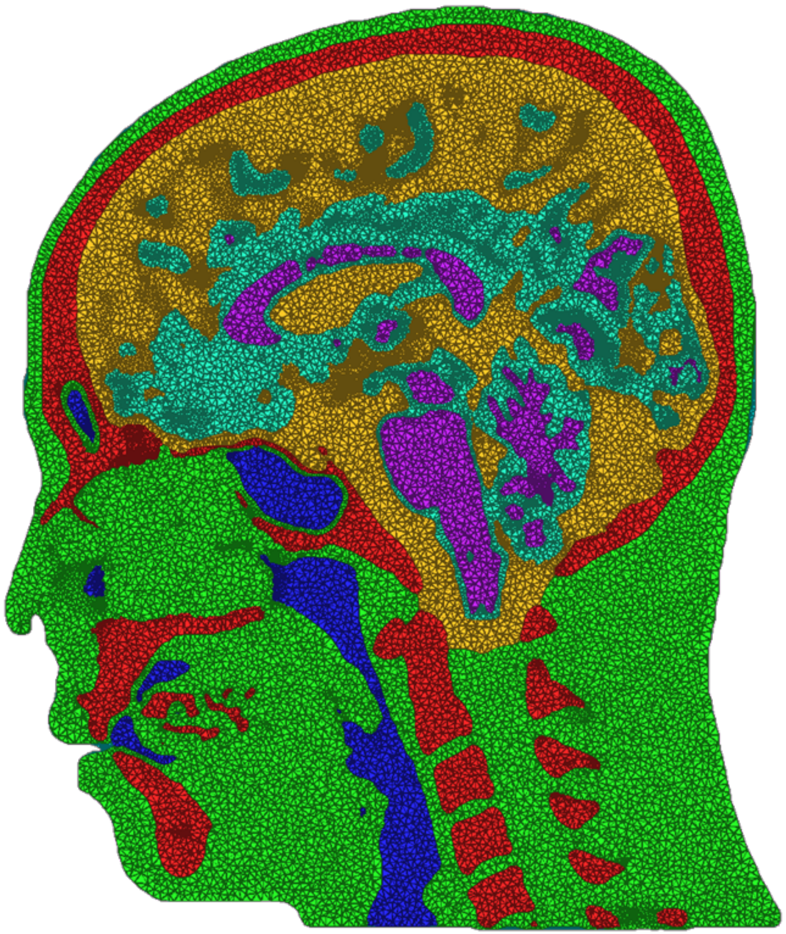
Volume conductor: Finite Element Method

Tesselation of 3D volume in tetraeders or hexaheders

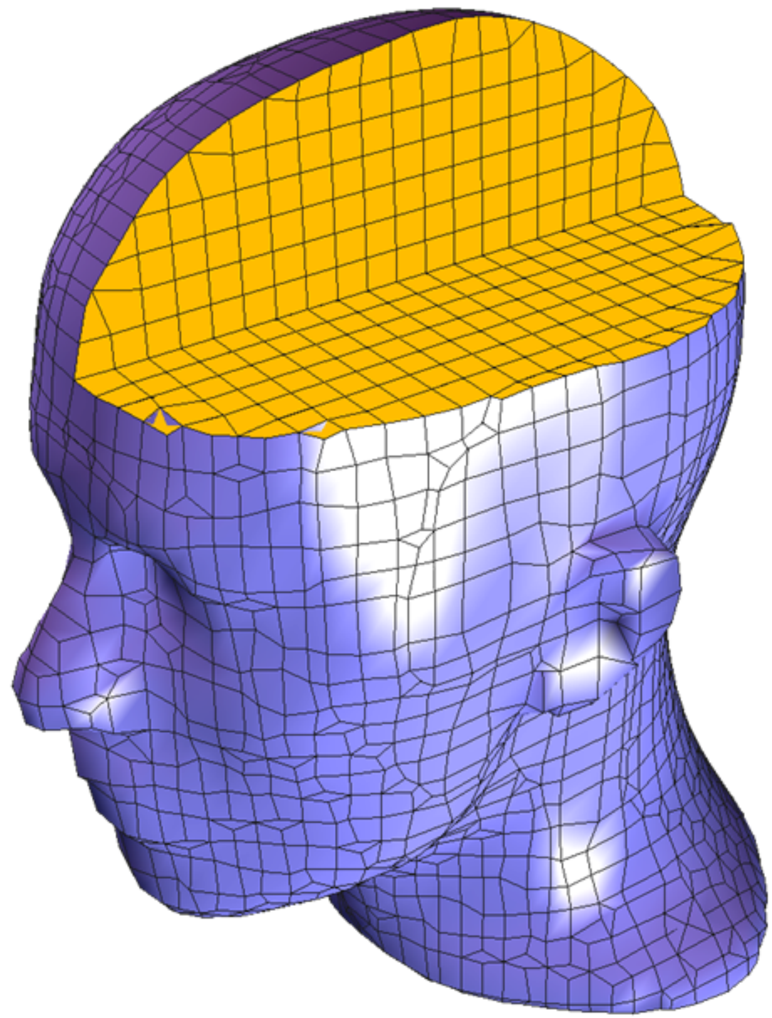




Volume conductor: Finite Element Method



tetraeders

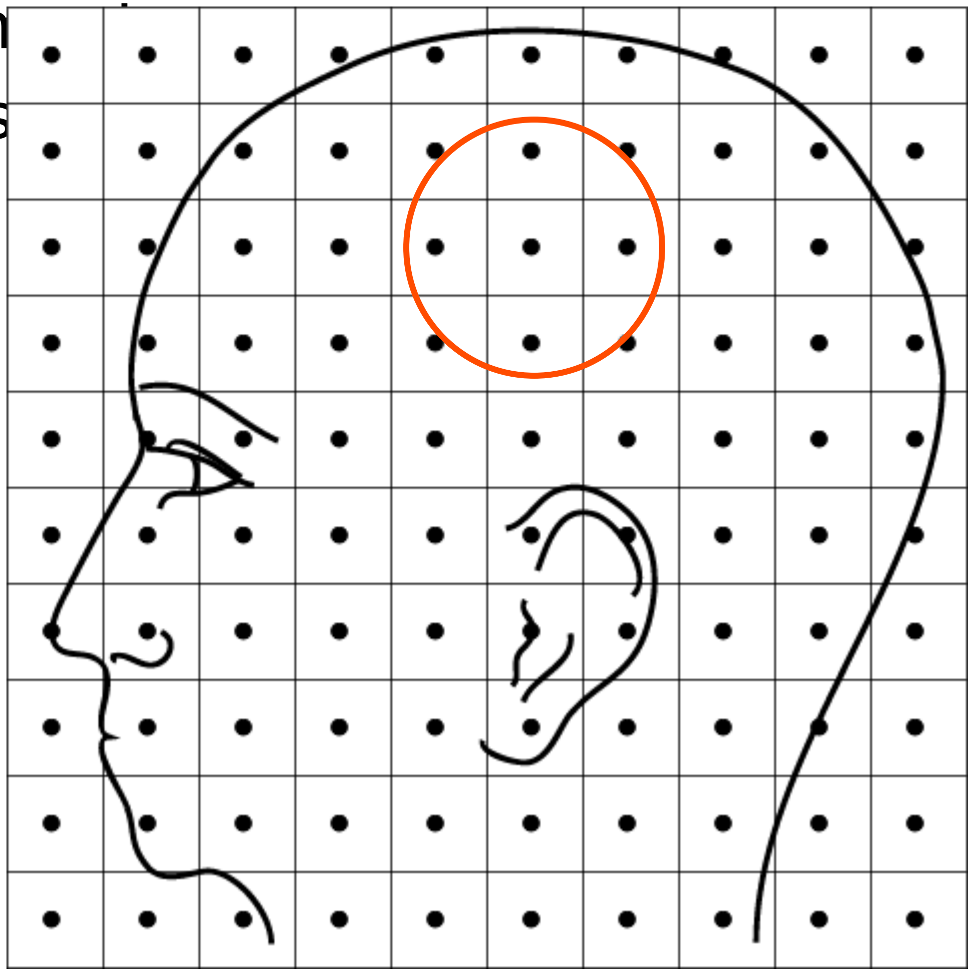


hexaheders

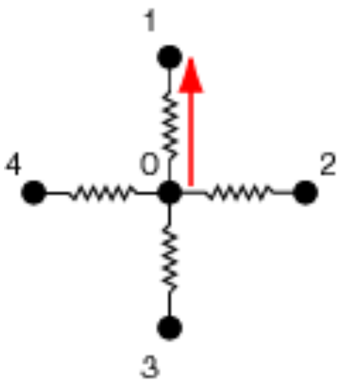
Volume conductor: Finite Difference Method

Easy to con

Not very us



Volume conductor: Finite Difference Method



$$I_1 + I_2 + I_3 + I_4 = 0$$
$$V = I*R$$
$\Rightarrow$

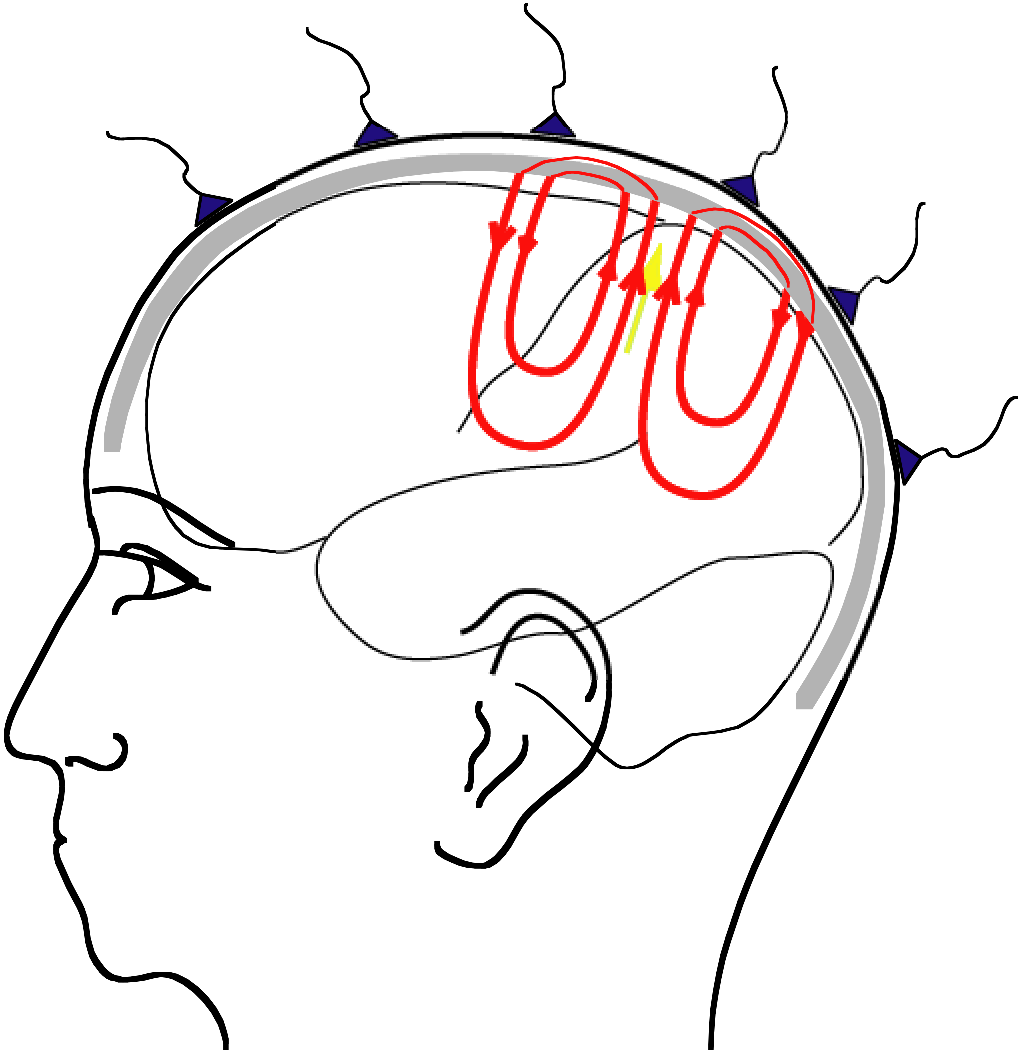
$$\Delta V_1/R_1 + \Delta V_2\,/R_2 + \Delta V_3\,/R_3 + \Delta V_4\,/R_4 = 0$$
$\Rightarrow$

$$(V_1\text{-}V_0)/R_1 + (V_2\text{-}V_0)/R_2 + (V_3\text{-}V_0)/R_3 + (V_4\text{-}V_0)/R_4 = 0$$

Volume conductor: Finite Difference Method

- Unknown potential Vi at each node
- Linear equation for each node
  - approx. 100x100x100 = 1.000.000 linear equations
  - just as many unknown potentials
- Inject some current +I and –I at two of the nodes
- Solve for unknown potential

EEG volume conduction



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 the skull and skin as accurately as possible

MEG volume conduction

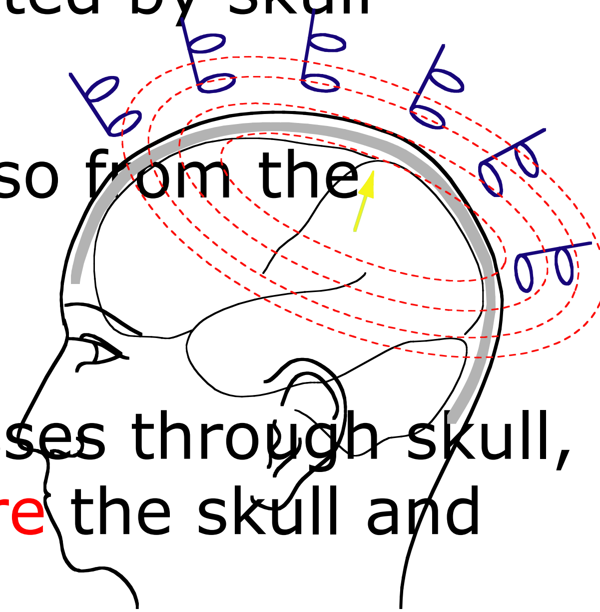
MEG measures magnetic field over the scalp

M istorted by skull

M ut also from the

O passes through skull,

gnore the skull and



Practical differences between EEG and MEG

fixed sensor positions in MEG
flexible cap in EEG

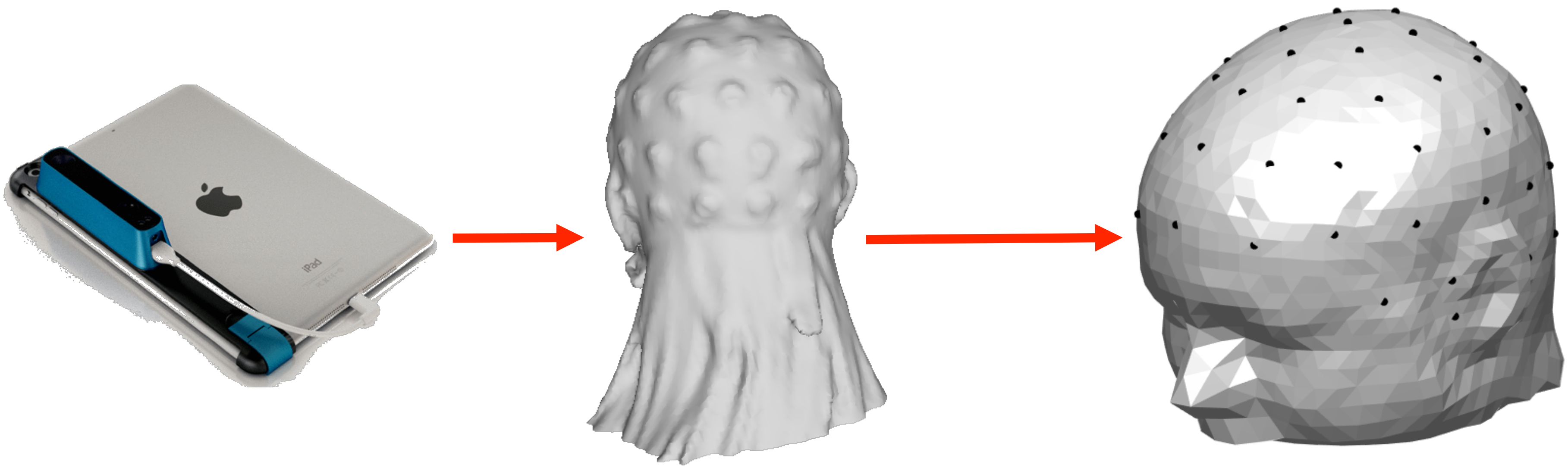
MEG requires head size to be known in analysis
- using individual anatomical MRI
- position of sensors is accurately known

EEG requires the electrode positions to be known in analysis

Obtaining geometrical data

3D scanning instead of MRI

3D scanning - pipeline for EEG modelling



Surface scan

Individualised template

Forward modeling – practical considerations

Most accurate source estimate using individual headmodels and electrode positions

Decent accurate source estimate with template headmodel and individual electrode positions

Reasonably accurate source estimate with template BEM headmodel and template electrodes

Least accurate source estimate with spherical model and template electrodes

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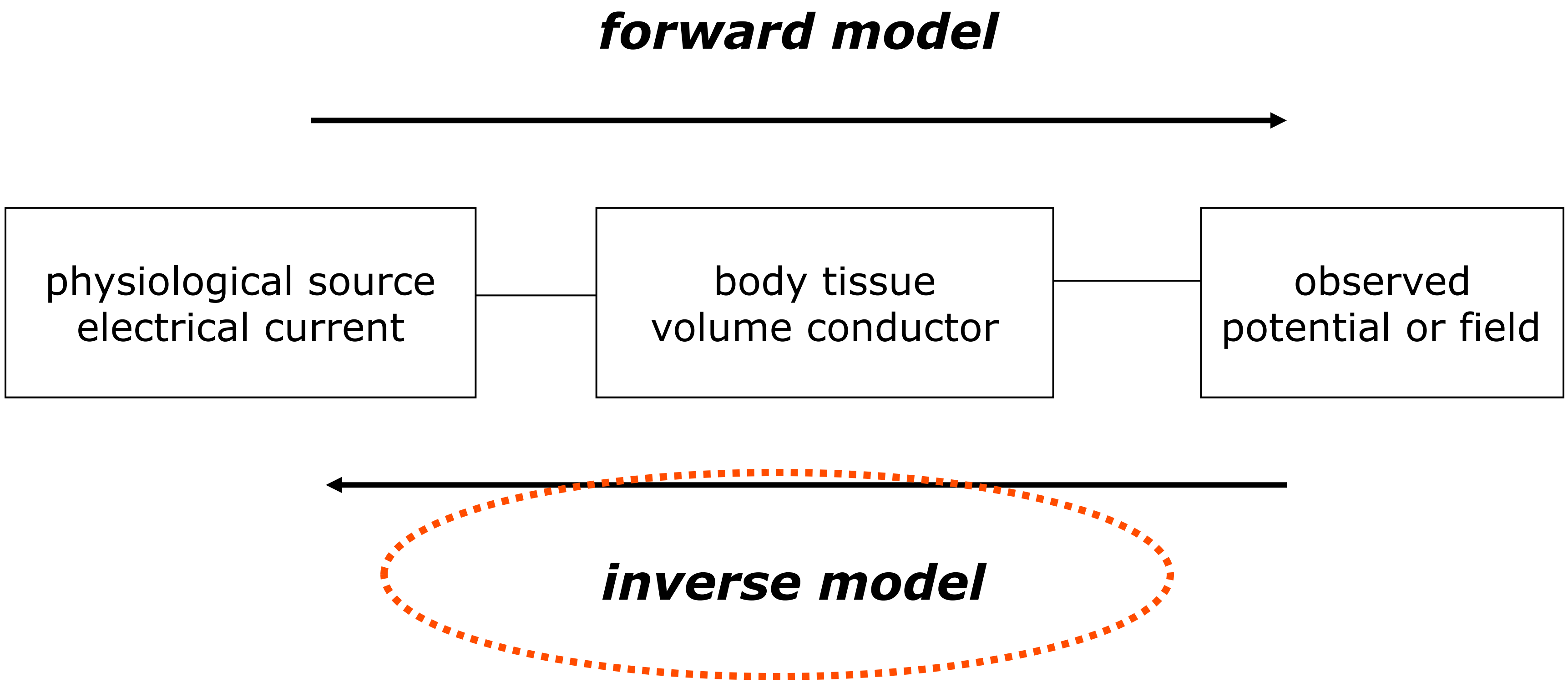
Biophysical source modelling: overview



Inverse methods

Single and multiple dipole models

Minimize error between model and measured potential/field

Distributed source models

Perfect fit of model to the measured potential/field

Additional constraint on source smoothness, power or amplitude

Spatial filtering

Scan the whole brain with a single dipole and compute the filter output at every location

Beamforming (e.g. LCMV, SAM, DICS)

Multiple Signal Classification (MUSIC)

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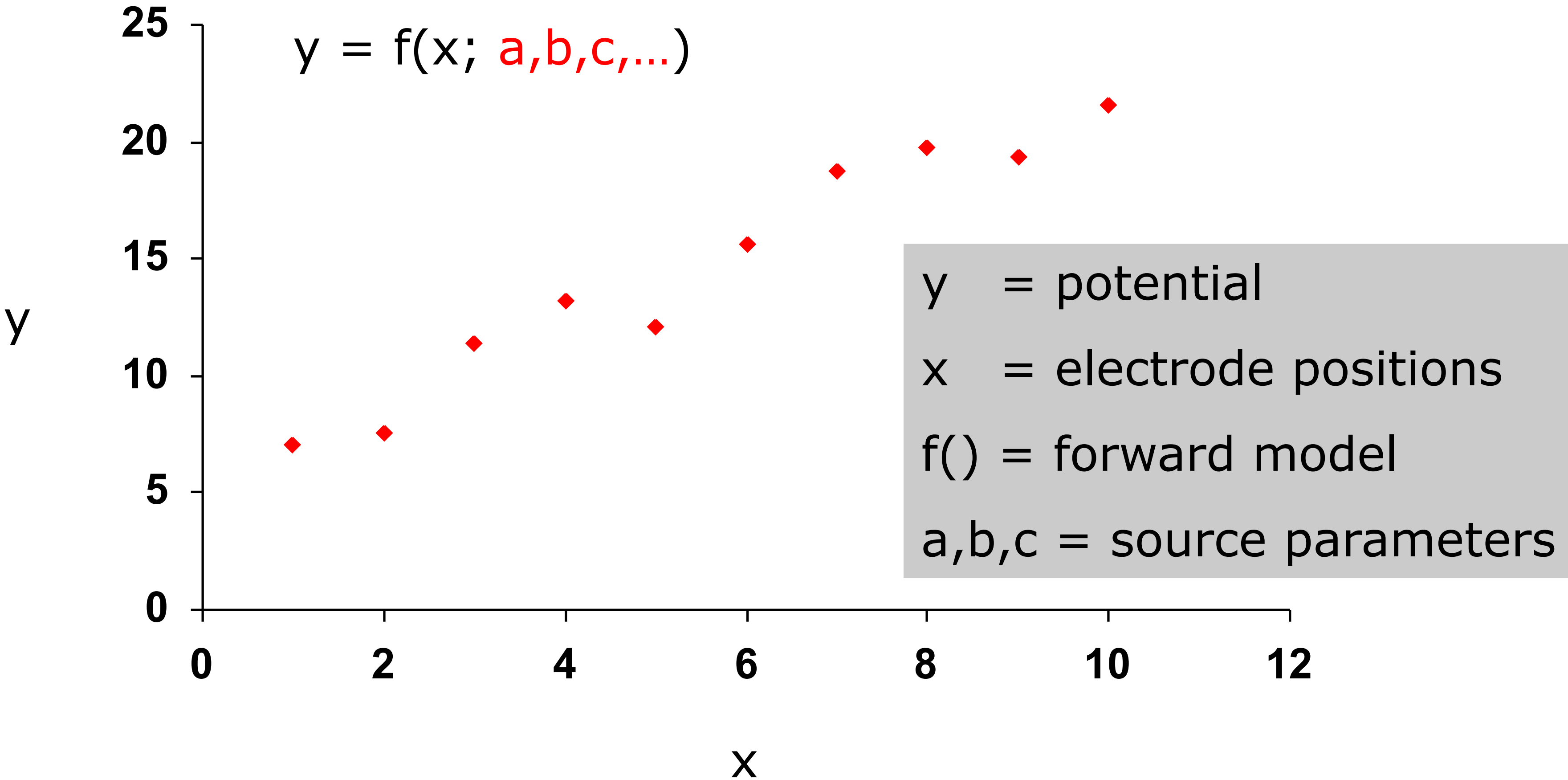
Single or multiple dipole models - Parameter estimation



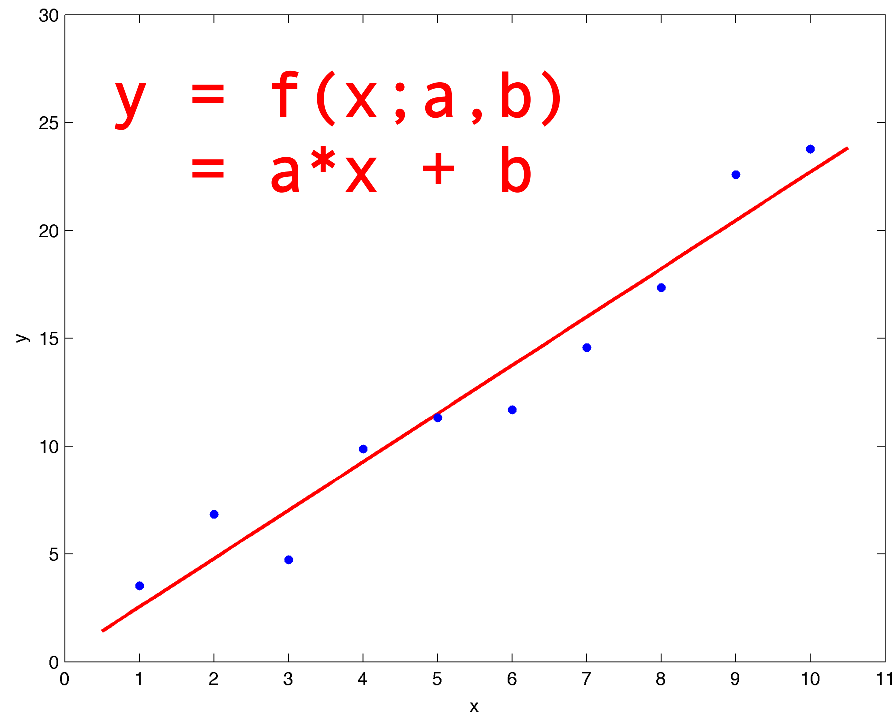
Parameter estimation: dipole parameters

source model with few parameters

- position
- orientation
- strength

compute the model data

minimize difference between actual and model data



Non-linear parameters: grid search

One dimension, e.g. location along medial-lateral

100 possible locations

Two dimensions, e.g. med-lat + inf-sup

100x100=10.000

Three dimensions

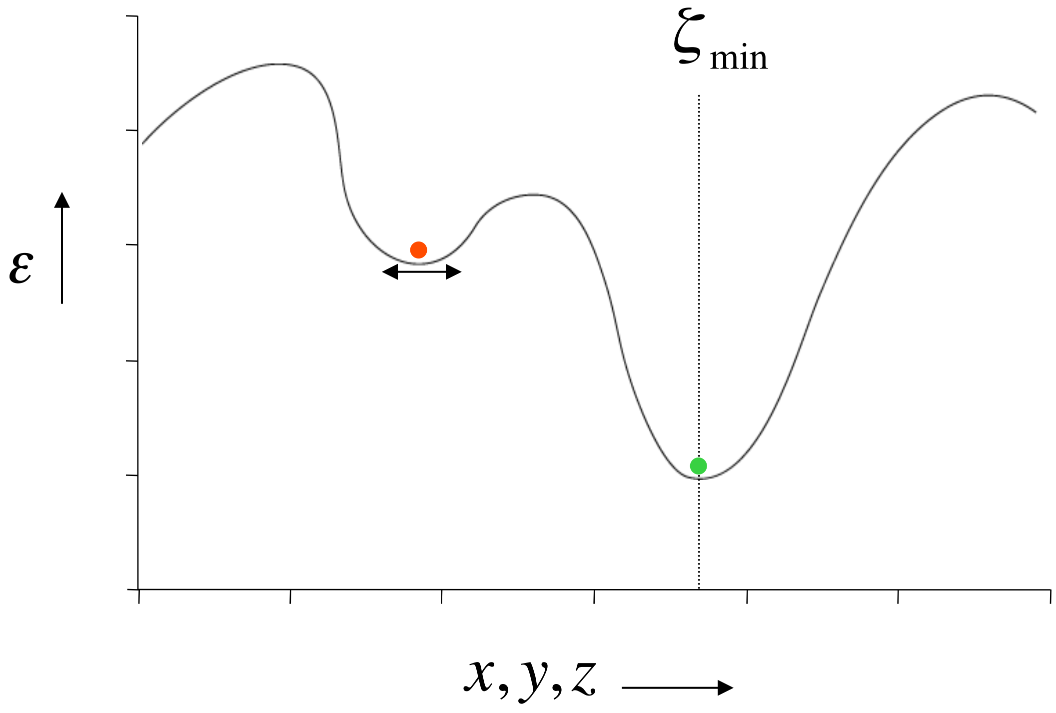
100x100x100 = 1.000.000 = 10^6

Two dipoles, each with three dimensions

100x100x100x100x100x100 = 10^{12}

Optimization of non-linear parameters

$$\varepsilon rror(x,y,z) = \sum_{i=1}^{N} \left(Y_i(x,y,z) - V_i\right)^2 \Rightarrow \min_{x,y,z}\left(\varepsilon rror(x,y,z)\right)$$



Single or multiple dipole models - Strategies

Single dipole:

scan the whole brain, followed by iterative optimization

Two dipoles:

scan with symmetric pair, use that as starting point for iterative optimization

More dipoles:

sequential dipole fitting

Sequential dipole fitting for ERPs

- Assume that activity starts "small"
  - explain earliest ERP component with single equivalent current dipole
- Assume later activity to be more widespread
  - add ECDs to explain later ERP components
  - estimate position of new dipoles
  - re-estimate the activity of all dipoles

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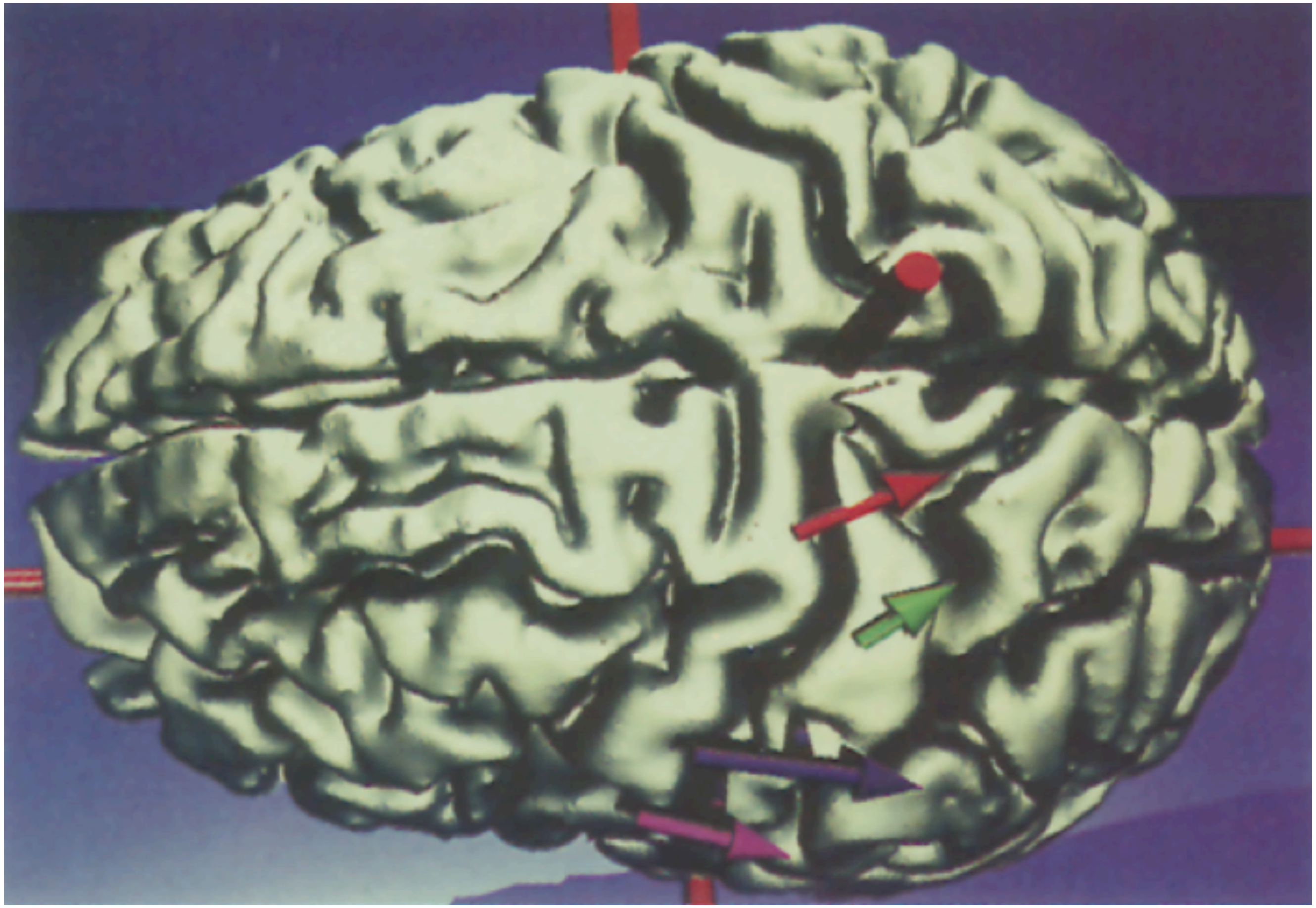
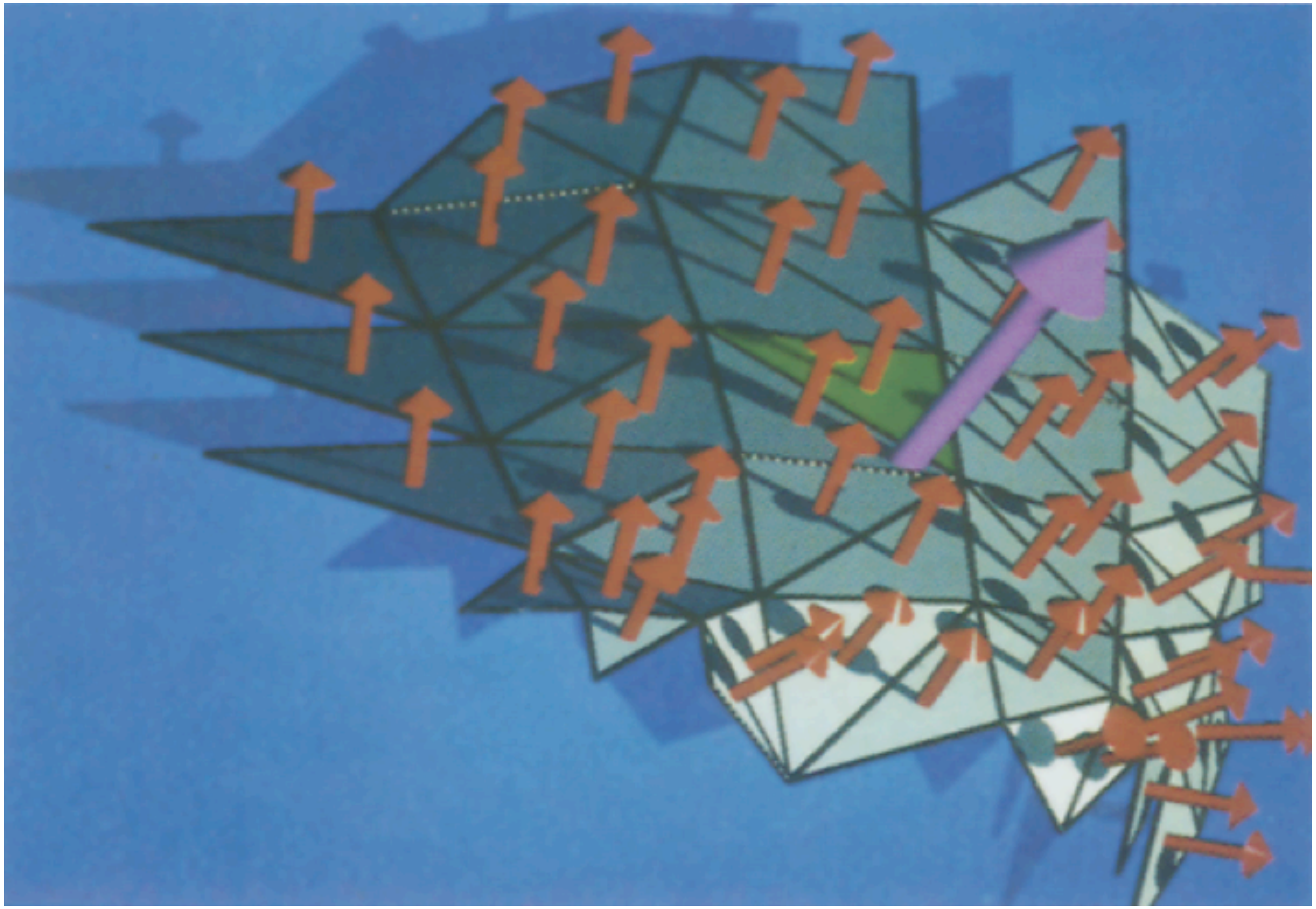
Distributed source model

- Position of the source is not estimated as such
  - Pre-defined grid (3D volume or on cortical sheet)
- Strength is estimated
  - In principle easy to solve, however…
  - More “unknowns” (parameters) than “knowns” (measurements)
  - Infinite number of solutions can explain the data perfectly
  - Additional constraints required

Distributed source model



Distributed source model

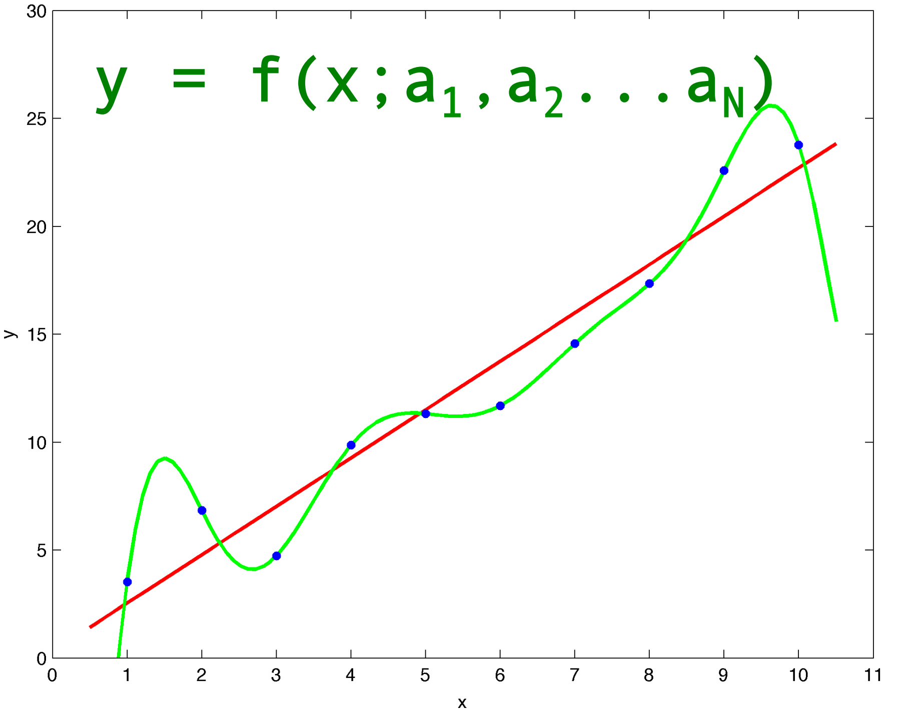


Distributed source model: linear estimation

distributed source model with **many dipoles** throughout the whole brain

estimate the strength of all dipoles

data and noise can be perfectly explained



Distributed source model: regularization

$$V = G \cdot q + Noise$$

$$\min_q \{\| V - G \cdot q \|^2\} = 0 \;\; !!$$

Regularized linear estimation:

$$\rightarrow \min_q \{\underbrace{\| V - G \cdot q \|^2}_{\text{mismatch with data}} + \lambda \cdot \underbrace{\| D \cdot q \|^2}_{\text{mismatch with prior assumptions}}\}$$

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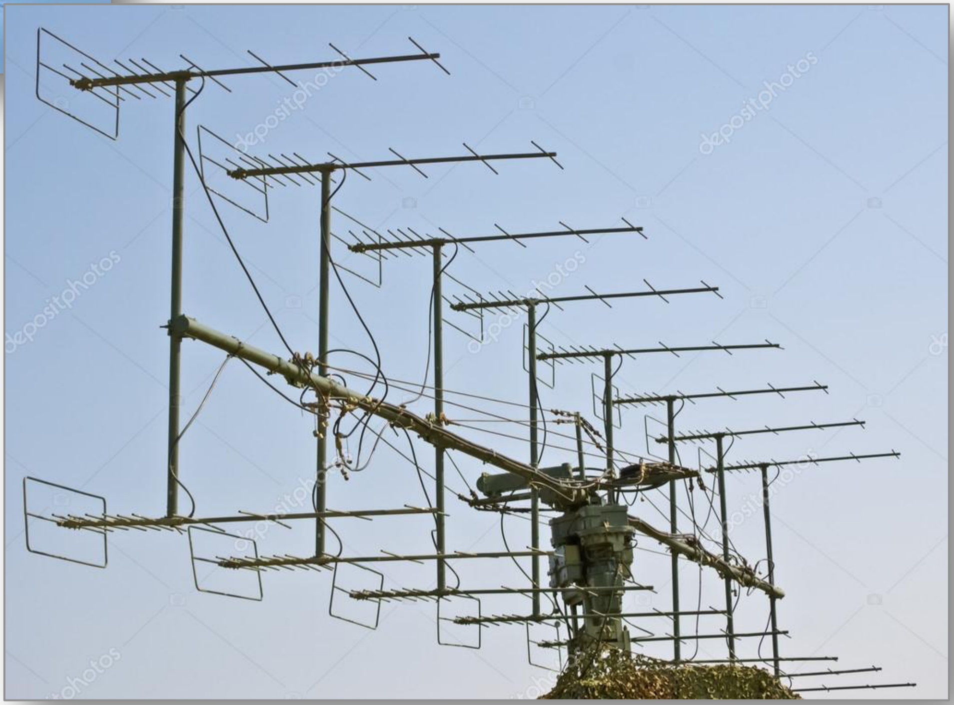
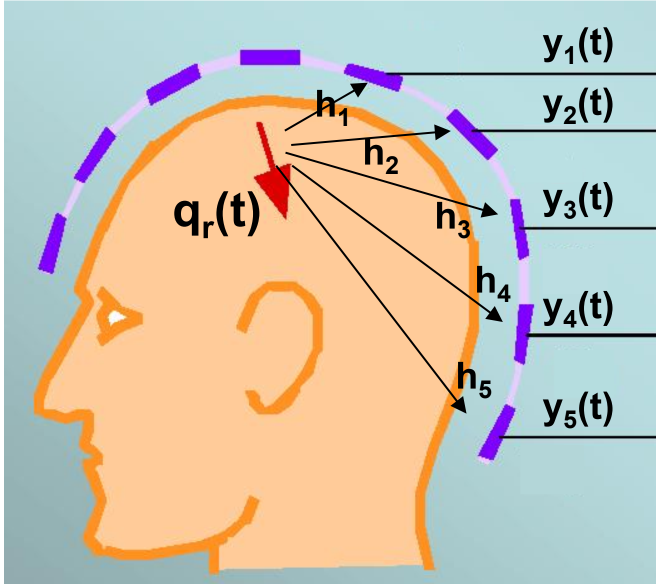
Scanning with a beamformer filter

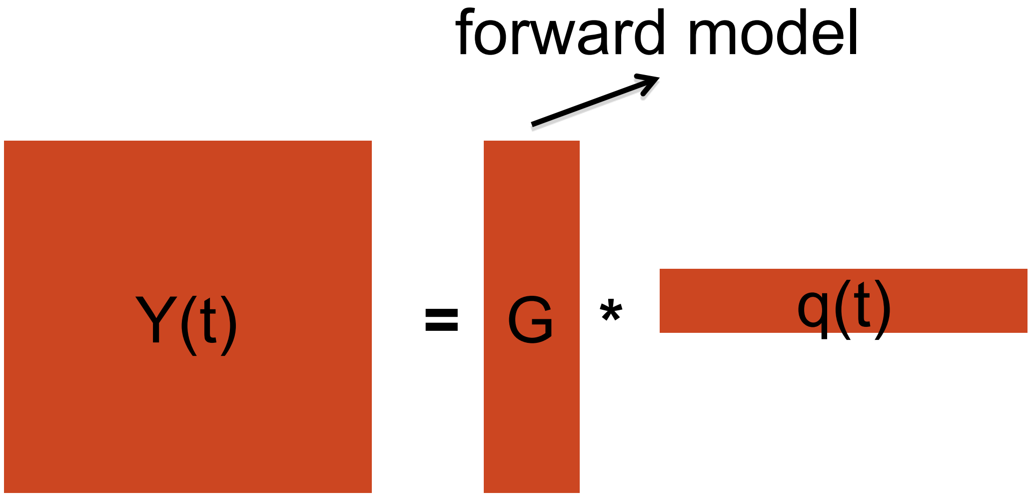


Spatial filtering with beamforming

- Position of the source is not estimated as such
- Manipulate filter properties, not source properties
  - No explicit assumptions about source constraints (implicit: single dipole)
  - Assumption that sources that contribute to the data should be uncorrelated

Beamformer ingredients: forward model





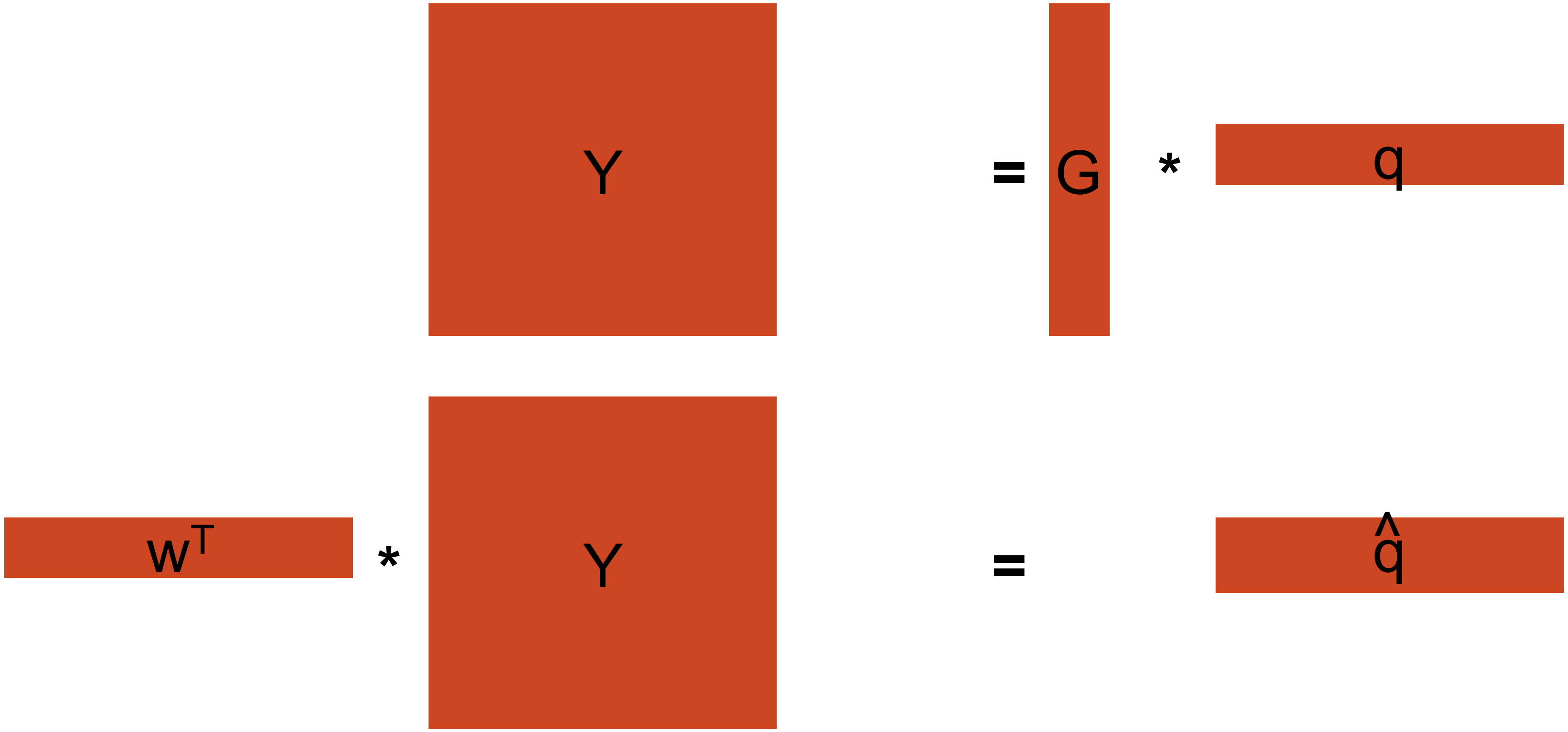
Beamformer: the question revisited

What is the activity of a source **q**, at a location **r**, given the data **Y**?

We know how to get from source to data: $\boldsymbol{Y = G * q}$

We want to go from data to source: $\boldsymbol{w^T * Y = \hat{q}}$

$\mathbf{w^T}$ is called a spatial filter



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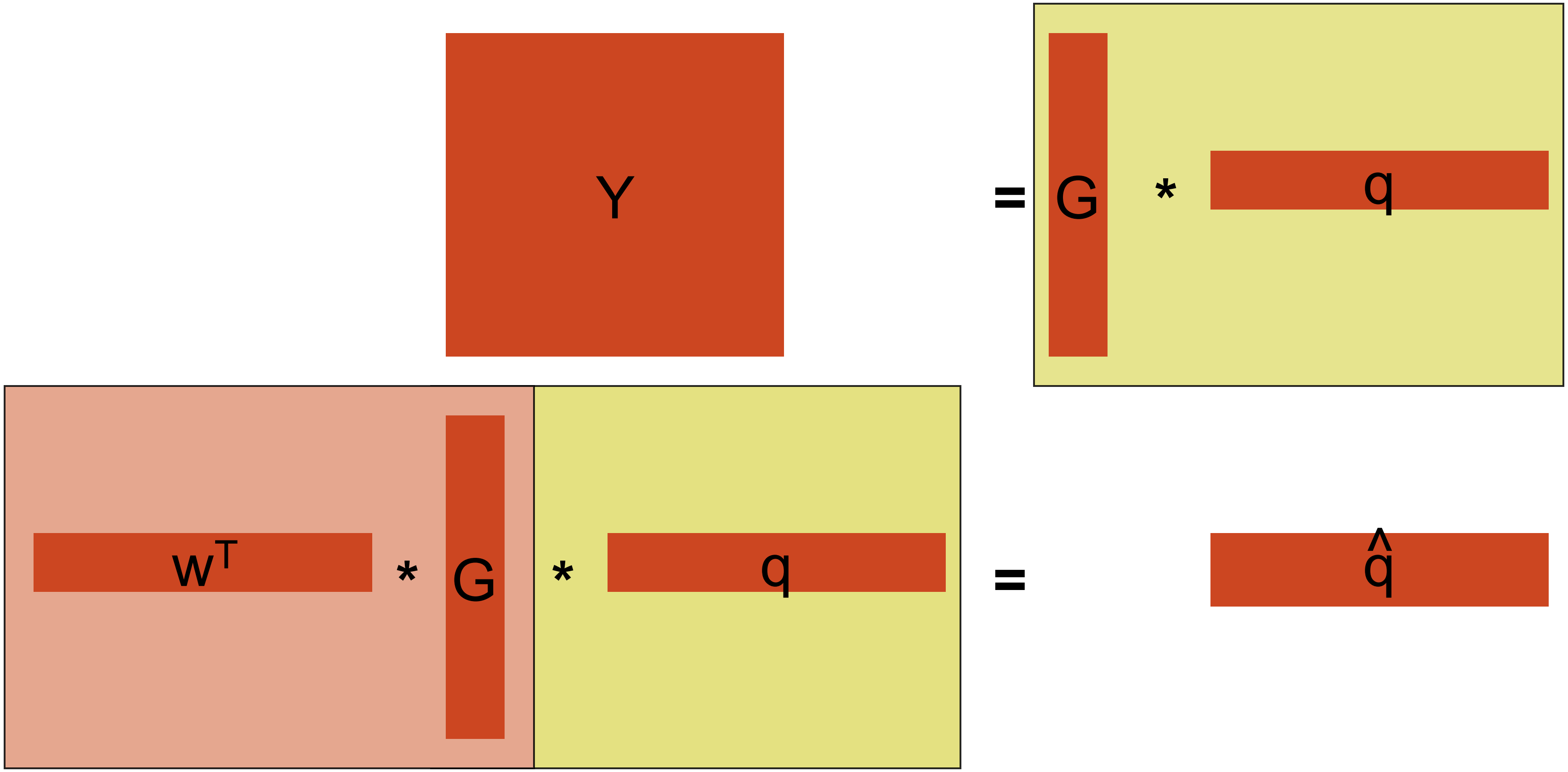
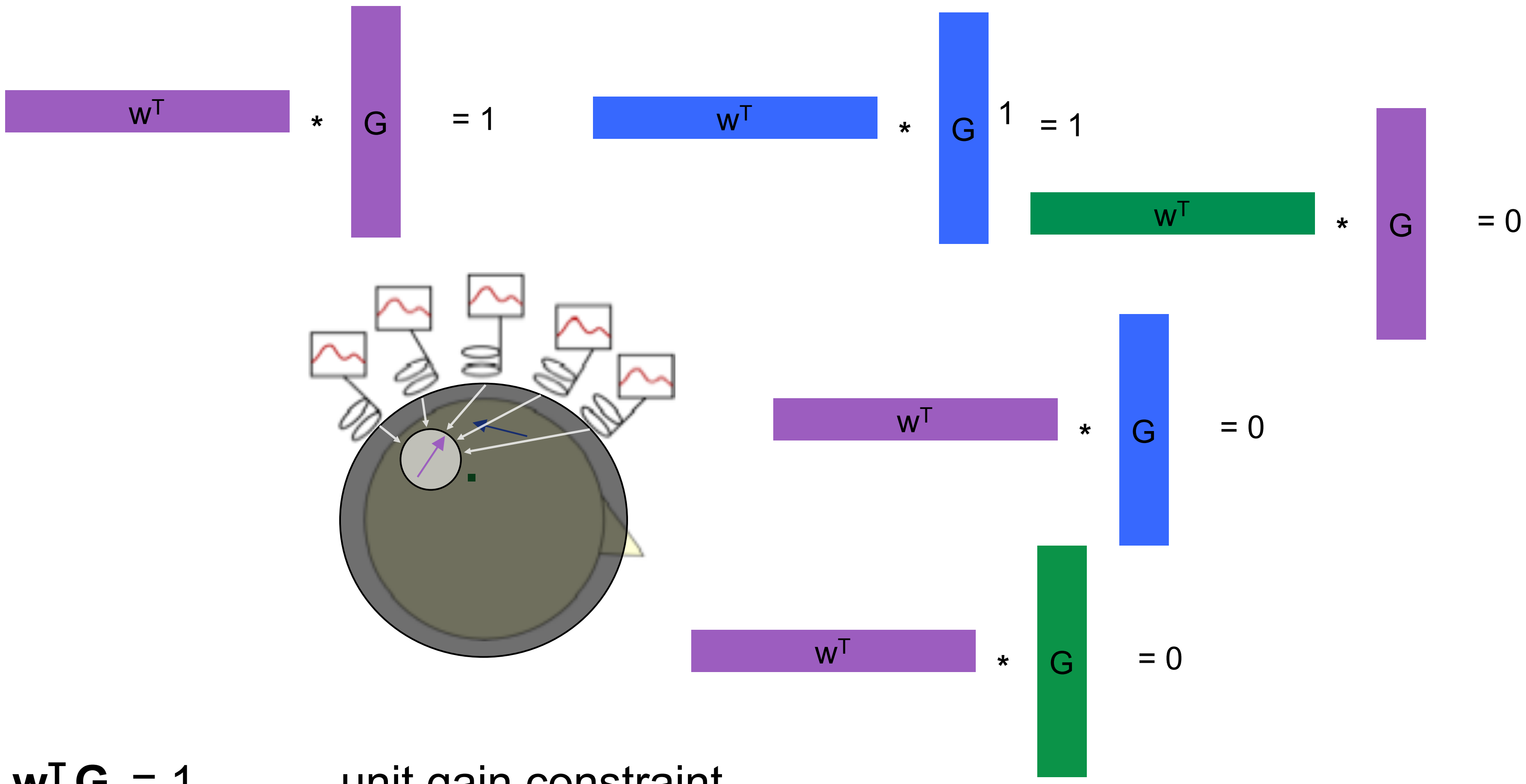
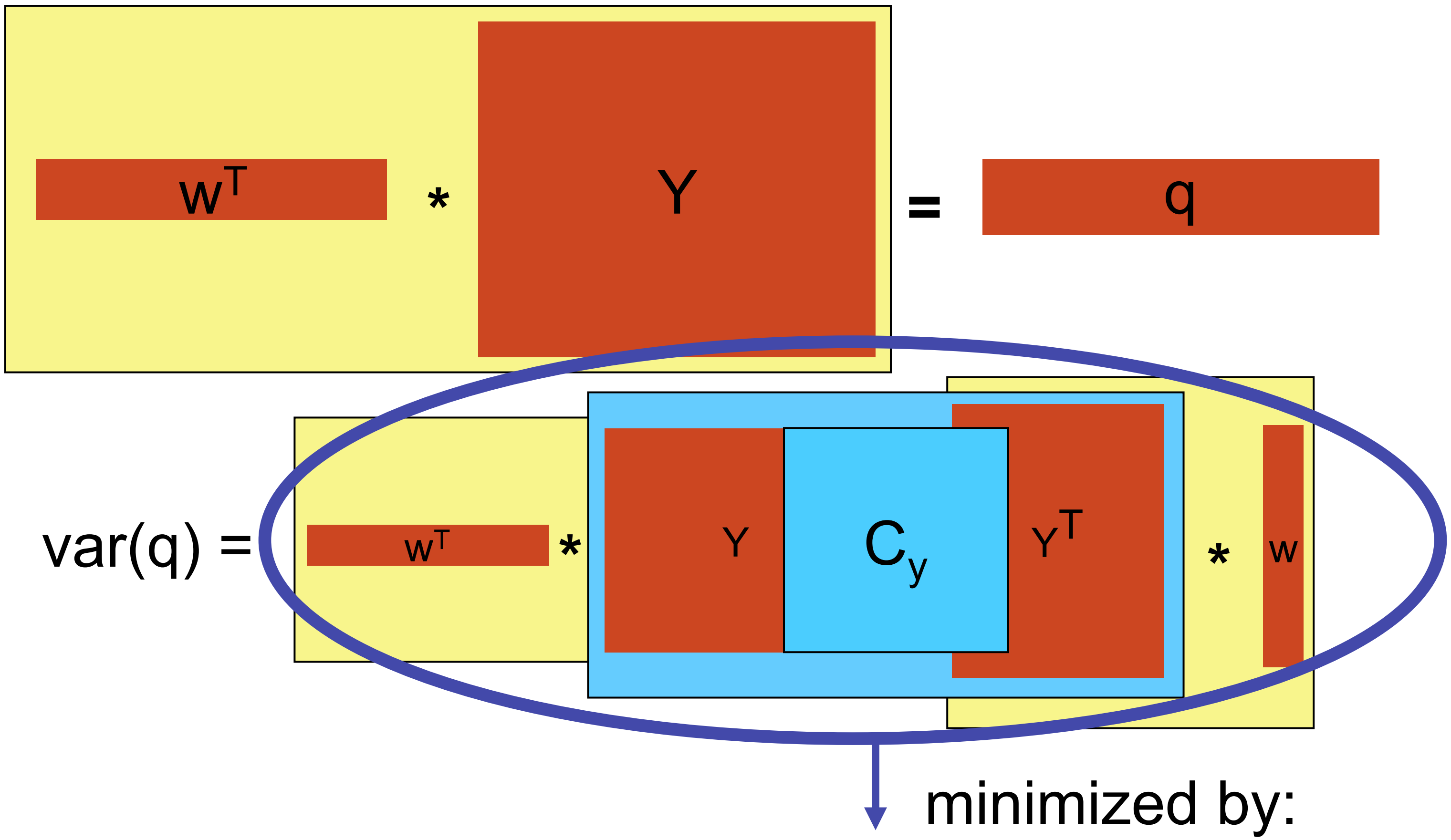


What would we like a spatial filter to do?



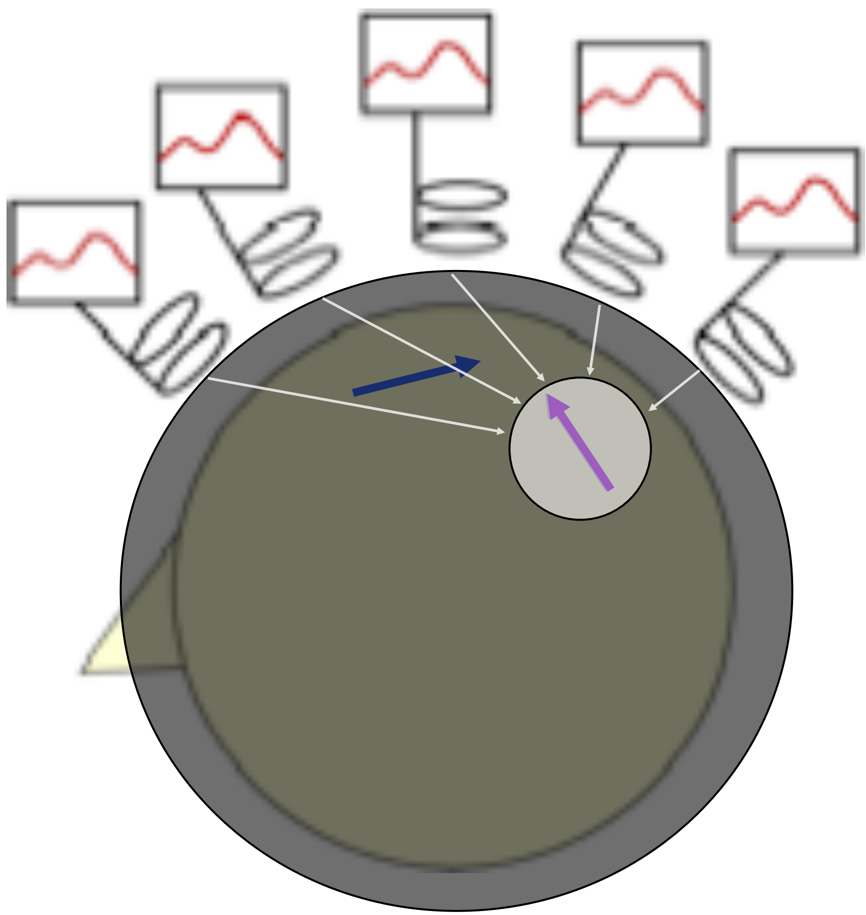
$\mathbf{w^T{}_i G_i} = 1$	unit gain constraint
$\mathbf{w^T{}_i G_k} = 0$	cannot generally be fulfilled, hence we minimize the *variance* of the filter output

Adaptive spatial filter: minimum variance constraint



$$\mathbf{w^T = [G^T C_y^{-1} G]^{-1} G^T C_y^{-1}}$$

Spatial filtering with beamforming



$$w^T * G = 1$$

$$w^T * G = 1$$

$$w^T * G = 0$$

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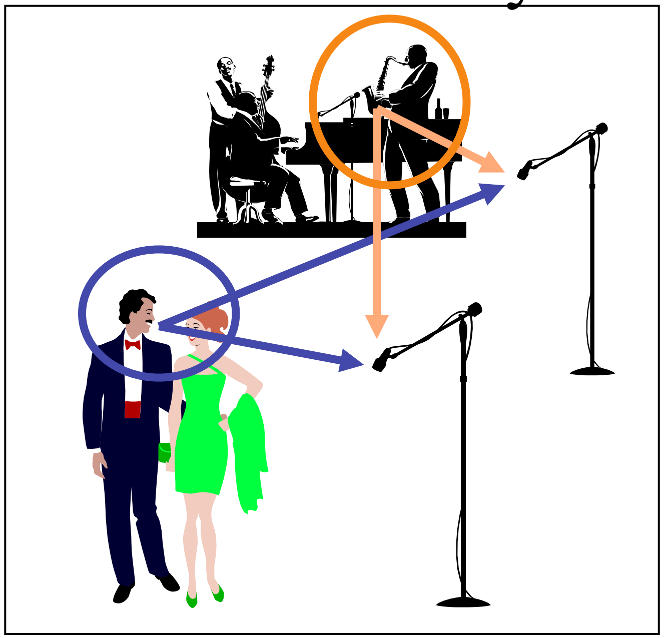
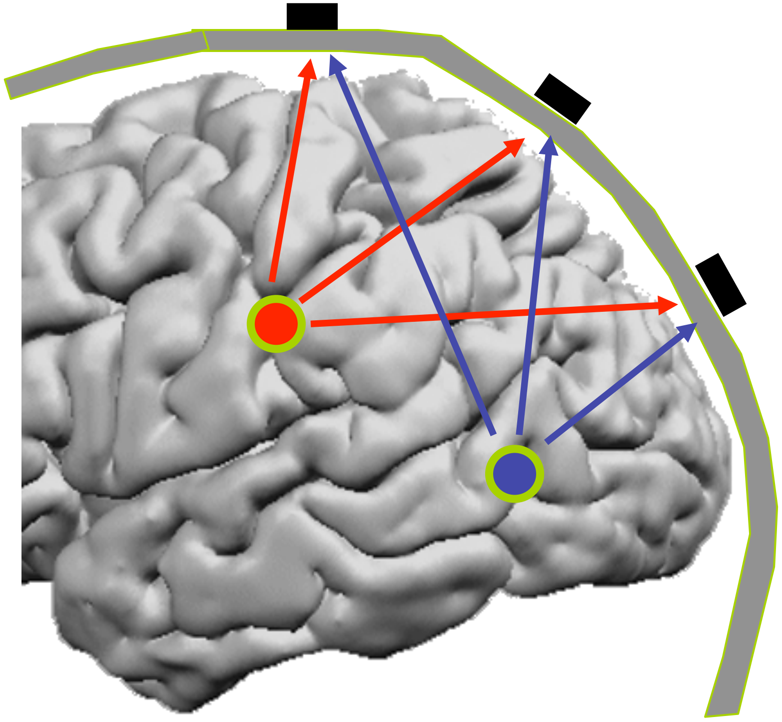
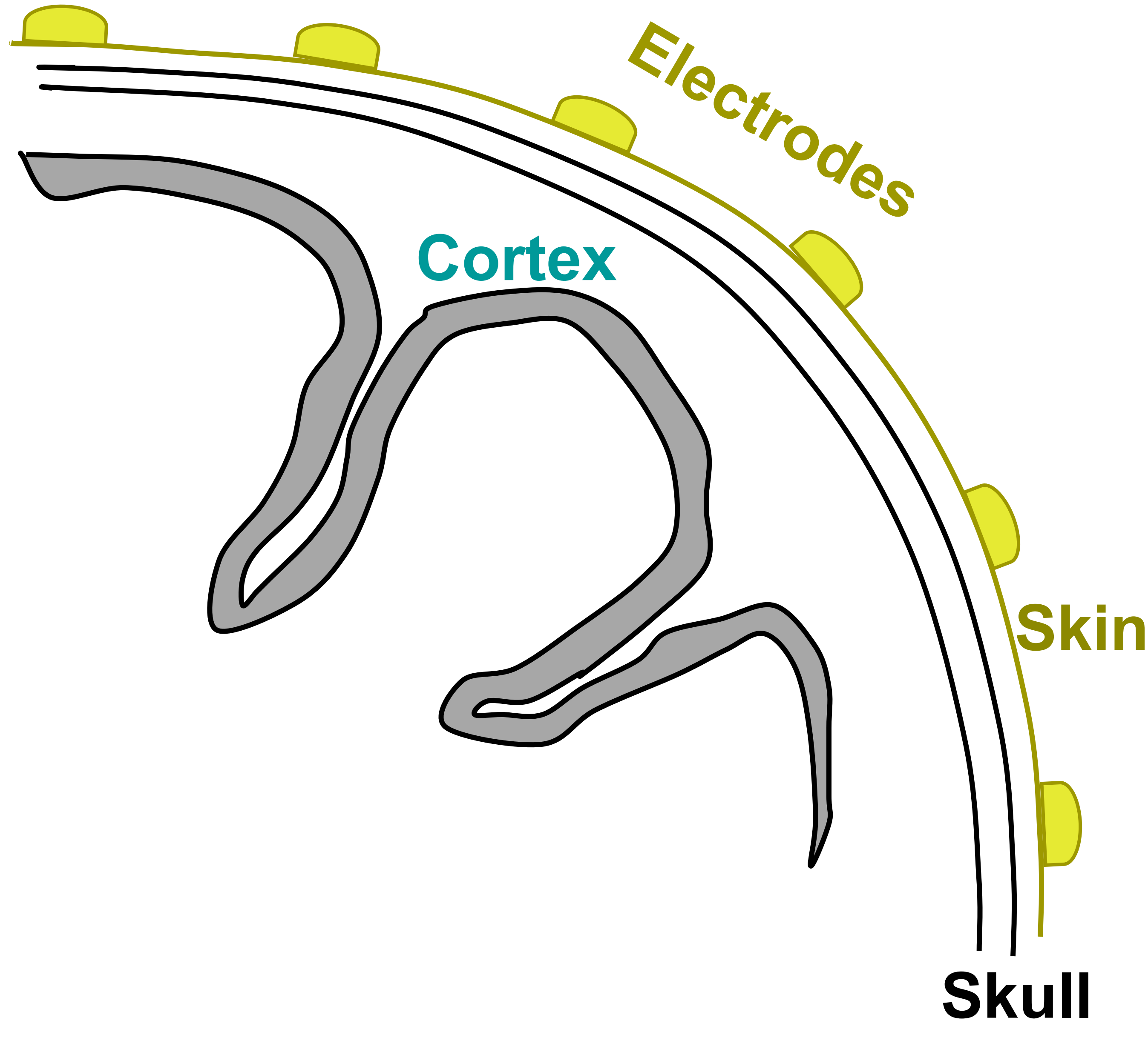
Independent component analysis

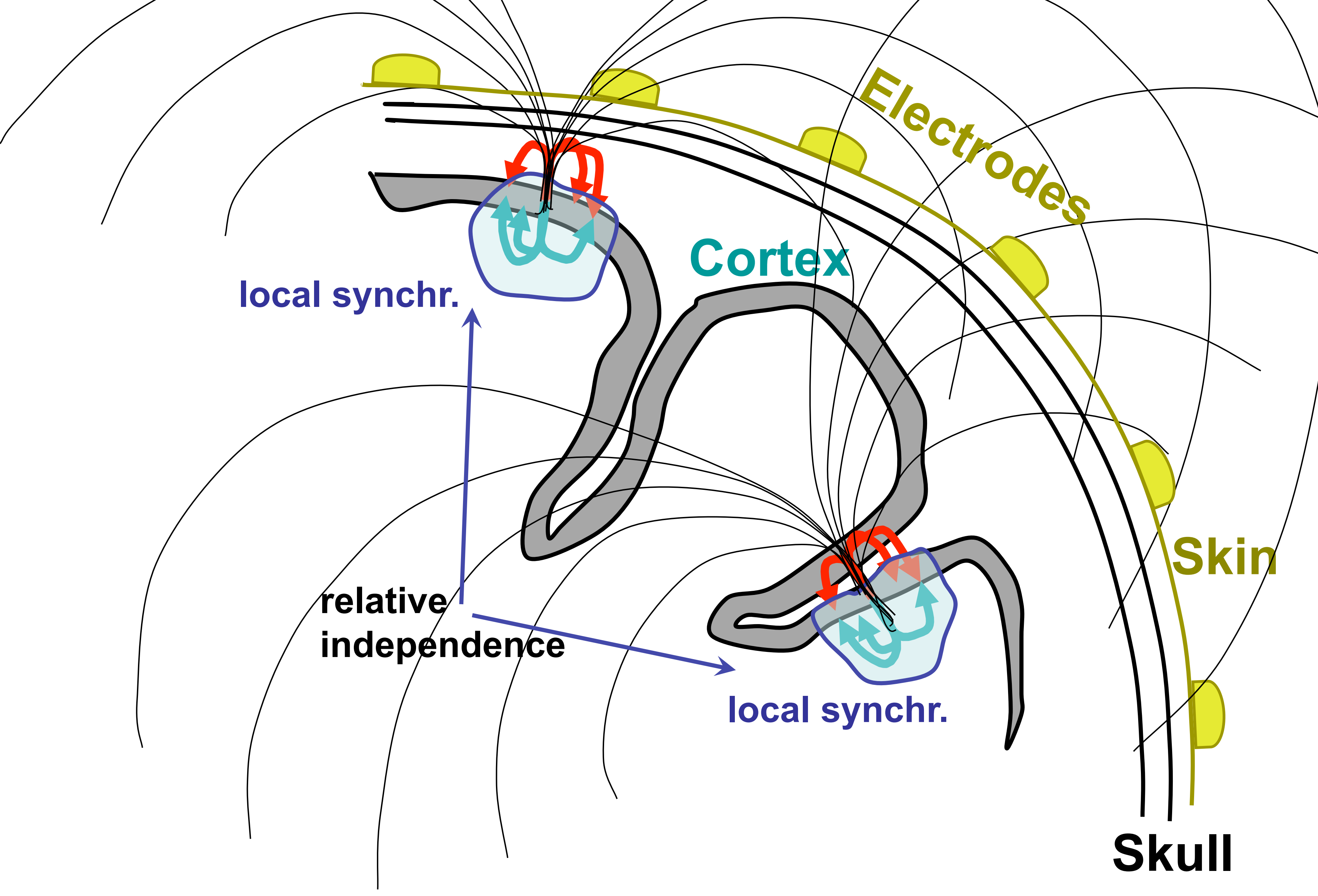
Cocktail Party

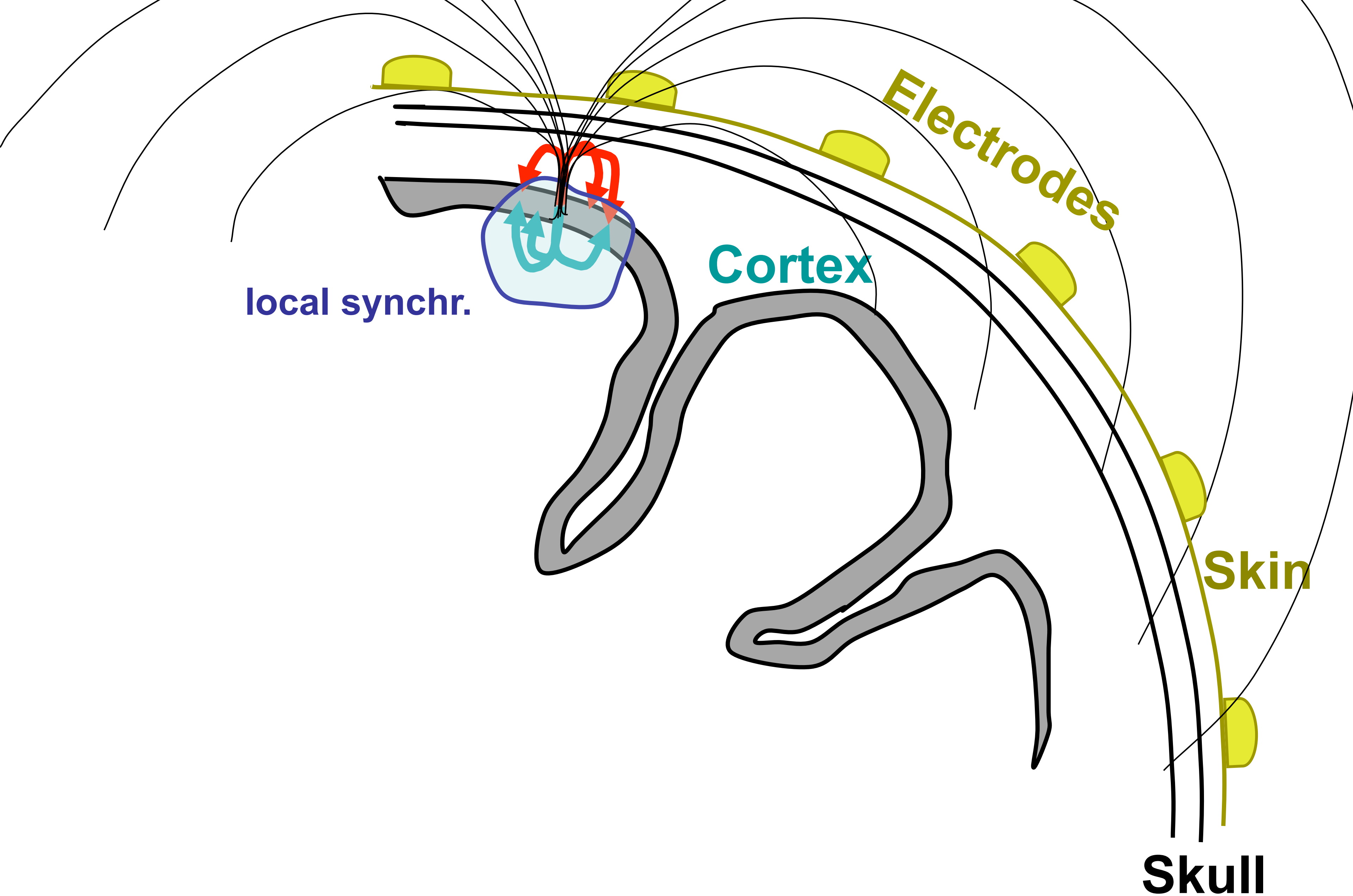


Mixture of Brain source activity




Electrodes
Cortex
Skin
Skull


Electrodes
Cortex
local synchr.
Skin
relative
independence
local synchr.
Skull


Electrodes
Cortex
local synchr.
Skin
Skull

Source modelling of independent components

ICA takes care of unmixing of timeseries

Source analysis to take care of the location

Assumption: components correspond to compact spatial patches (or bilateral patches)

Use simple dipole models to model the spatial component topographies

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Forward modelling

- Required for the interpretation of scalp topographies
- Different methods with varying accuracy

Inverse modelling

- Estimate 1) location and 2) timecourse

Assumptions on source locations

- Single or multiple point-like source
- Distributed source

Assumptions on source timecourse

- Uncorrelated (and dipolar)
- Independent

Summary 2

- Independent component analysis
  - separates topography and timecourse
- Inverse methods to interpret topography
  - Single or multiple point-like source
  - Distributed source