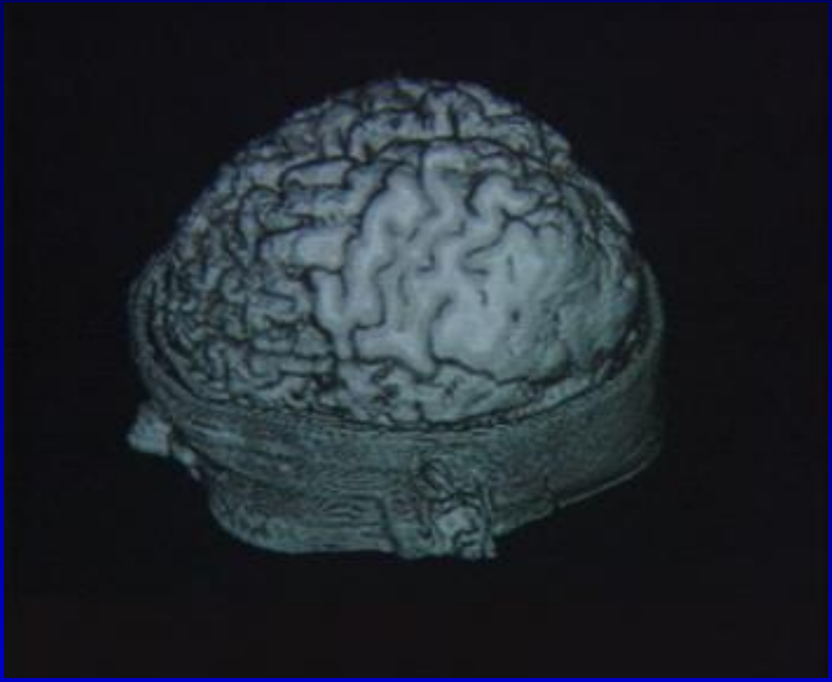
Magnetic Field Tomography (MFT): theory and applications with examples from the visual system

Andreas A. Ioannides
Laboratory for Human Brain Dynamics
Nicosia,
Cyprus

Outline



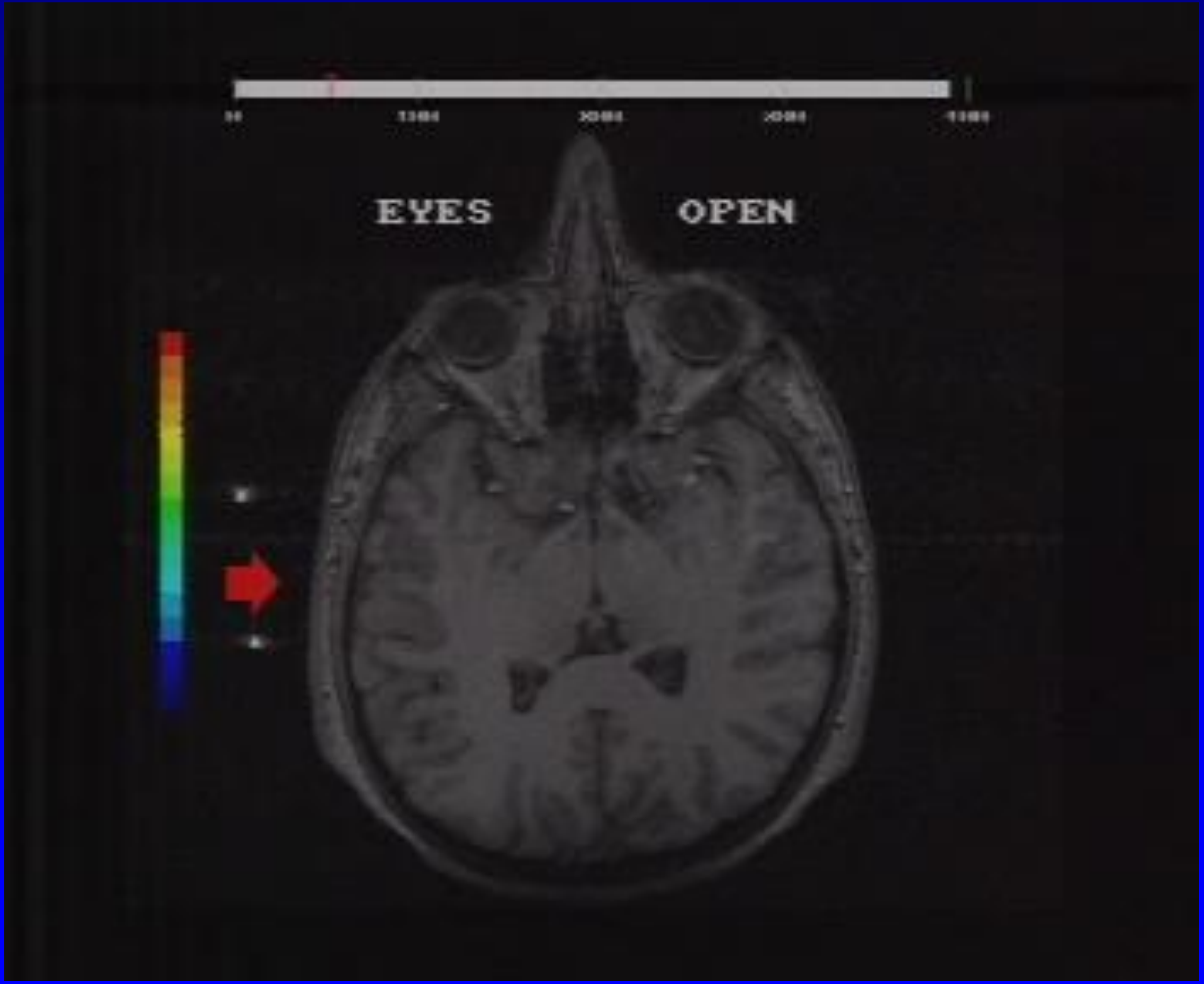
- Introduction and definitions
- Theoretical points
  - mathematical foundation
  - basic ideas in cartoon
- Examples with computer generated data
- MFT brain activations with visual stimuli
  - retinotopy, object recognition and emotions
- Post MFT analysis
  - statistics and activations (pixel and ROIs)
  - regional connectivity

Magnetoencephalography (MEG)

- MEG deals with the detection and interpretation of the minute magnetic field generated by the brain. The signal is detected by very sophisticated and expensive hardware, and it is generated by
  - external noise sources (not of interest)
  - subject (sources from the brain or body)
    - » some of which we are interested in
    - » others which are of no interest

MFT's goal and domain of applications

- Introduced in 1989 and used since for numerous studies with MEG data
- The goal of MFT is to extract from the MEG signal the activity <u>in real time throughout the brain</u>.



Singh KD, Ioannides AA, Gray N, Kober H, Pongratz H, Daun A, Grummich P, & Vieth J (1992)

MFT's goal and domain of applications

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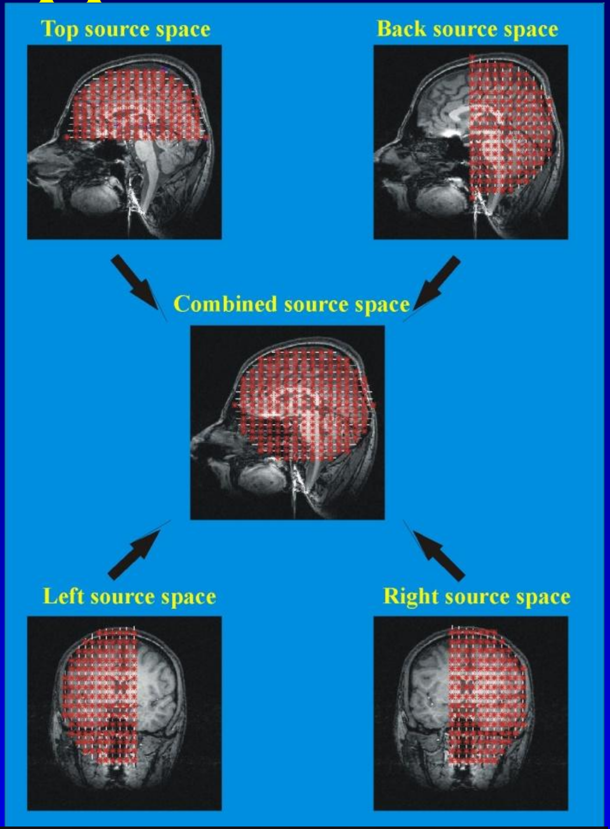
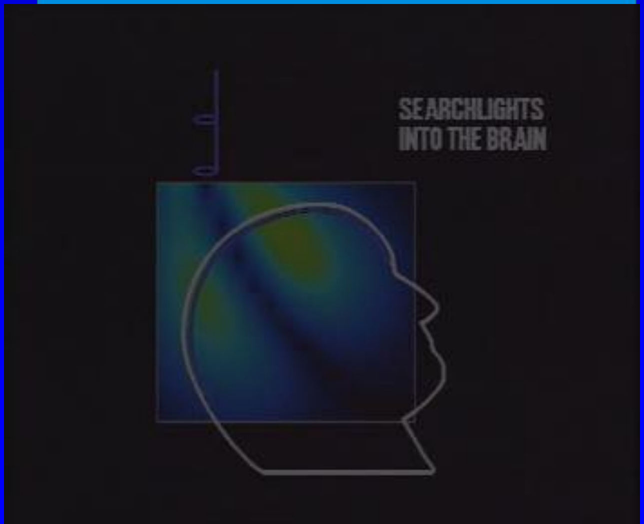
- The goal of MFT is to extract from the MEG signal the activity <u>in real time</u> <u>throughout the brain</u>.
- separate computations are made for each piece of data (timeslice)
- SS for left, right, top and back of the head
- The output provides
  - ms by ms tomography of activity (only magnetically non-silent part)
  - complete coverage:
    - » brain
    - » cerebellum
    - » brainstem.





To introduce MFT we need to consider how sources and data are related

The data condition

How the the signal is generated is well understood (physics):

The measurements

The sources

$$d_m = \int_Q \Phi_m(\mathrm{r}) \bullet \mathrm{j}(\mathrm{r}) d\mathrm{r}$$

SSP: the source space

Lead fields or sensitivity profiles: depend on sensor details and conductivity profile (the physics)

Notations for a spherical conductor

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi F^2}\left[F\mathbf{Q}\times\mathbf{r}_0 - (\mathbf{Q}\times\mathbf{r}_0 \bullet \mathbf{r})\nabla F\right]$$

$$F = a\left(ra + r^2 - \mathbf{r}_0 \bullet \mathbf{r}\right),\ \mathbf{a} = \mathbf{r} - \mathbf{r}_0$$

$$\mathbf{e}_m \bullet \mathbf{B}(\mathbf{r}_m) = \mathbf{Q} \bullet \Phi_m(\mathbf{r}_0)$$

$$\Phi_m(\mathbf{r}_0) = \mathbf{r}_0 \times \mathbf{L}_m$$

$$\mathbf{L}_m = \frac{1}{F}\left[\mathbf{e}_m - \left(\mathbf{e}_m \bullet \nabla \ln(F)\right)\mathbf{r}_m\right]$$

$$\mathbf{j}(\mathbf{r}_0) = \mathbf{r}_0 \times \left(\sum_m A_m \mathbf{L}_m\right)$$

Let, $\mathbf{E} = \sum_m A_m \mathbf{e}_m$ and

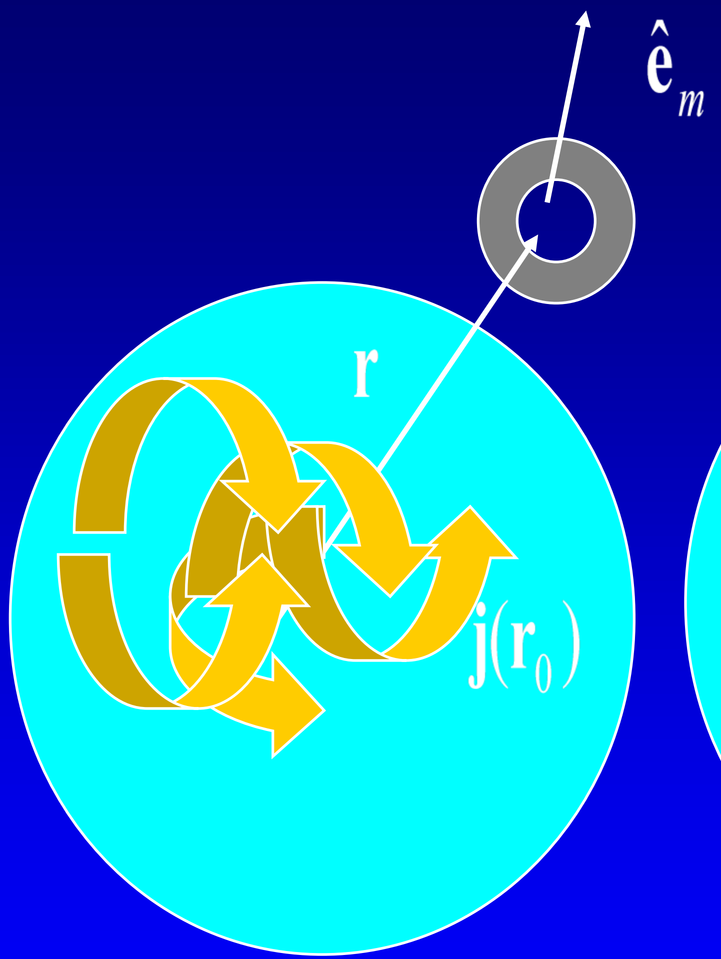
$$\mathbf{F} = \sum_m A_m \left(\mathbf{e}_m \bullet \nabla \ln(F)\right)\mathbf{r}_m$$

then, $\mathbf{j}(\mathbf{r}_0) = \mathbf{r}_0 \times (\mathbf{E} - \mathbf{F})$

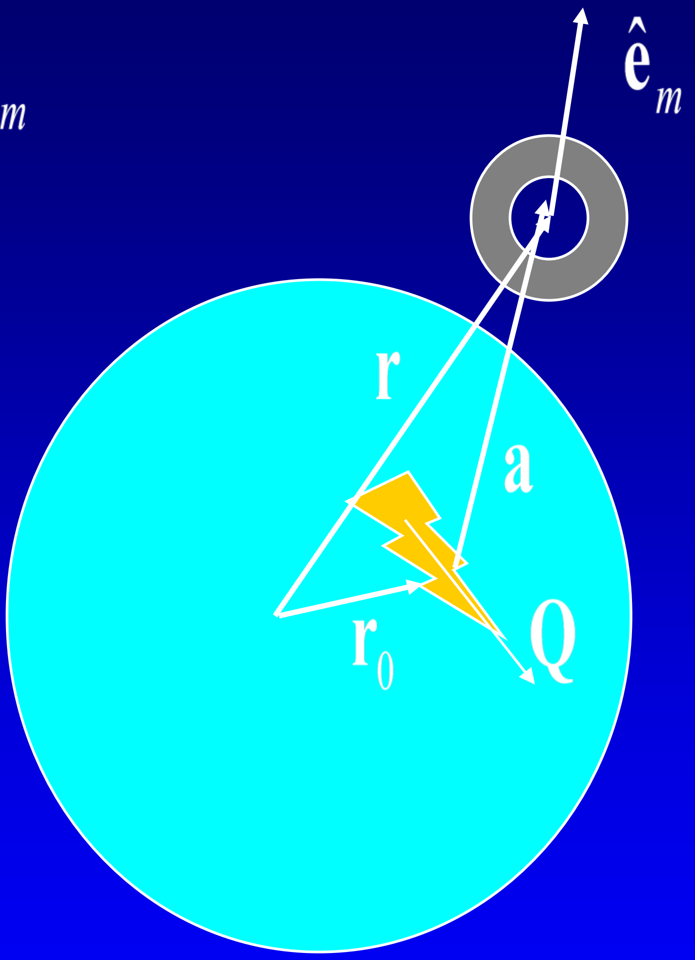
$\therefore$ $\mathbf{j}(\mathbf{r}_0)$ has exactly 2 DF

Take home message:

The forward problem is well defined and unique in theory (but difficult to capture exactly, in all its details, in practice)



Distributed activity
Current density



Focal activity
Equivalent current dipole

The data condition makes a basic and simple statement

- MEG data are produced by sources which add up linearly and depend through well understood physical laws on:
  - the geometric configuration and arrangement of sensors
  - the properties of the conducting medium
  - the location and orientation of the unknown current density

The data condition is not enough!

The mathematical properties of the data condition are such that Exact noise free measurements and perfect lead fields

$$d_m = \int_Q \mathbf{\Phi}_m(\mathbf{r}) \bullet \mathbf{j}(\mathbf{r})\,d\mathbf{r}$$

Can not define the sources uniquely

Intuition and art

Since everything is given, we can only play with constraints on the on the general form of the unknown (non-silent) current density J. The most general form we can write is:

$$\mathrm{j}(\mathrm{r}) = \sum_{\mathrm{m}} A_m w(\mathrm{r}, \mathrm{j}(\mathrm{r}))\Phi_m(\mathrm{r})$$

Art = choice of w(r,j) with respects for physics & biology.

MFT's philosophy:

• constraints must be limited to what we can be sure about and kept to the minimum necessary to solve the problem.

• Solutions should be influenced more by the data rather than the constraints

Dangerous intuition
(wrong hunches?)

It is easy to hide many assumptions by writing down the most innocuous looking ansatz. Here are two examples:

$$\mathrm{j}(\mathrm{r}) = \sum_{\mathrm{m}} \mathbf{Q}_m\, \delta(\mathrm{r} - \mathrm{r}_m)$$

(Multiple) Current dipole model

$$\mathrm{j}(\mathrm{r}) = \sum_{\mathrm{m}} A_m \Phi_m(\mathrm{r})$$

Minimum norm

In terms the degrees of freedom of **j(r)** the above make assumptions about the form of **j(r)** which are very strong and severely restrict the possible solutions. If these constraints are true they are invaluable, but if they are incorrect they simply destroy the data.

The linear model (minimum norm)

$$\mathrm{j}(\mathrm{r}) = \sum_{\mathrm{m}} A_m \Phi_m(\mathrm{r})\, w(\mathrm{r}, \mathrm{j}(\mathrm{r}))$$

$$w(\mathrm{r}, \mathrm{j}(\mathrm{r})) = w(\mathrm{r})$$ The linear ansatz

$$w(\mathrm{r}) = \text{constant}$$ The minimum norm ansatz

The model is linear because substitution of the ansatz into the data condition yields:

$$d_m = \sum_{\mathrm{n}} \mathrm{A}_{\mathrm{n}} L_{mn}, \text{ with}$$

$$L_{mn} = \int_{\mathrm{Q}} dr\, w(\mathrm{r}) \left(\Phi_m(\mathrm{r}) \bullet \Phi_n(\mathrm{r})\right)$$

Advantages and disadvantages of linear models

- Advantages:
  – Simple to describe
  – Easy to code
  – Very fast to use (because of linearity)
- Disadvantages
  – Properties of the lead fields dictate the solutions
  – Biology is trapped in arbitrary choices (where the sensors are placed)
  – The role of the data is minimized

Generalized &Standard MFT

$$\hat{j}(r) = \sum_{m} A_m \Phi_m(r)\, w'(r, j(r))$$

$$w'(r, j(r)) = \sum_{p} \left| j(r) \right|^{p} w_p(r) \qquad \text{General MFT}$$

$$w'(r, j(r)) = w_0(r) \qquad \text{Standard MFT}$$

$p = -1 \Rightarrow$ Minimum norm (linear model)

$p = 0 \Rightarrow$ Standard MFT

$p = 1 \Rightarrow$ (modified) FOCUSS

Standard MFT

$$\hat{j}(r) = \sum_{m} A_m \Phi_m(r)\, w_0(r)$$

- It has the right number of degreed of freedom (2)
- It was derived first by heuristic arguments and by selection through detailed testing with computer generated data
- minimal assumptions about the unknown current density
  - * only direction expressed as a linear sum of the lead fields
  - * actual current density modulus is determined at each point in the source space by the data itself

Standard MFT

Given the a priori probability weight, w, the strength of the source distribution can be obtained from the unit vector condition at each source point, leading to the following infinite set of equations:

$$1 = \left| \sum_{\mathrm{m}} \left[\left(\mathbf{L}\left(\left\| \mathbf{j} \right\| \right) \right)^{-1} d \right]_m \Phi_m(\mathbf{r})\, w_0(\mathbf{r}) \right|$$

The a priori probability weight, w, can be obtained from the same set of equations from computer generated data at fixed points in the source space.

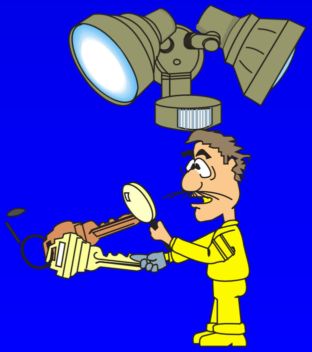
Step by step application of standard MFT

- **Forward problem:**
  - Source space definition(s)
  - Computation of lead fields

- **Training (fixing all free parameters)**
  - Definition of a priori probability weight
  - Definition of regularization parameter

- **Source estimation through a one step iteration**
  - Compute solutions independently for each timeslice
  - Identify ROIs and their activations

- **Post-MFT analysis**
  - Statistics
  - Connectivity



Advantages and disadvantages of standard MFT (I)

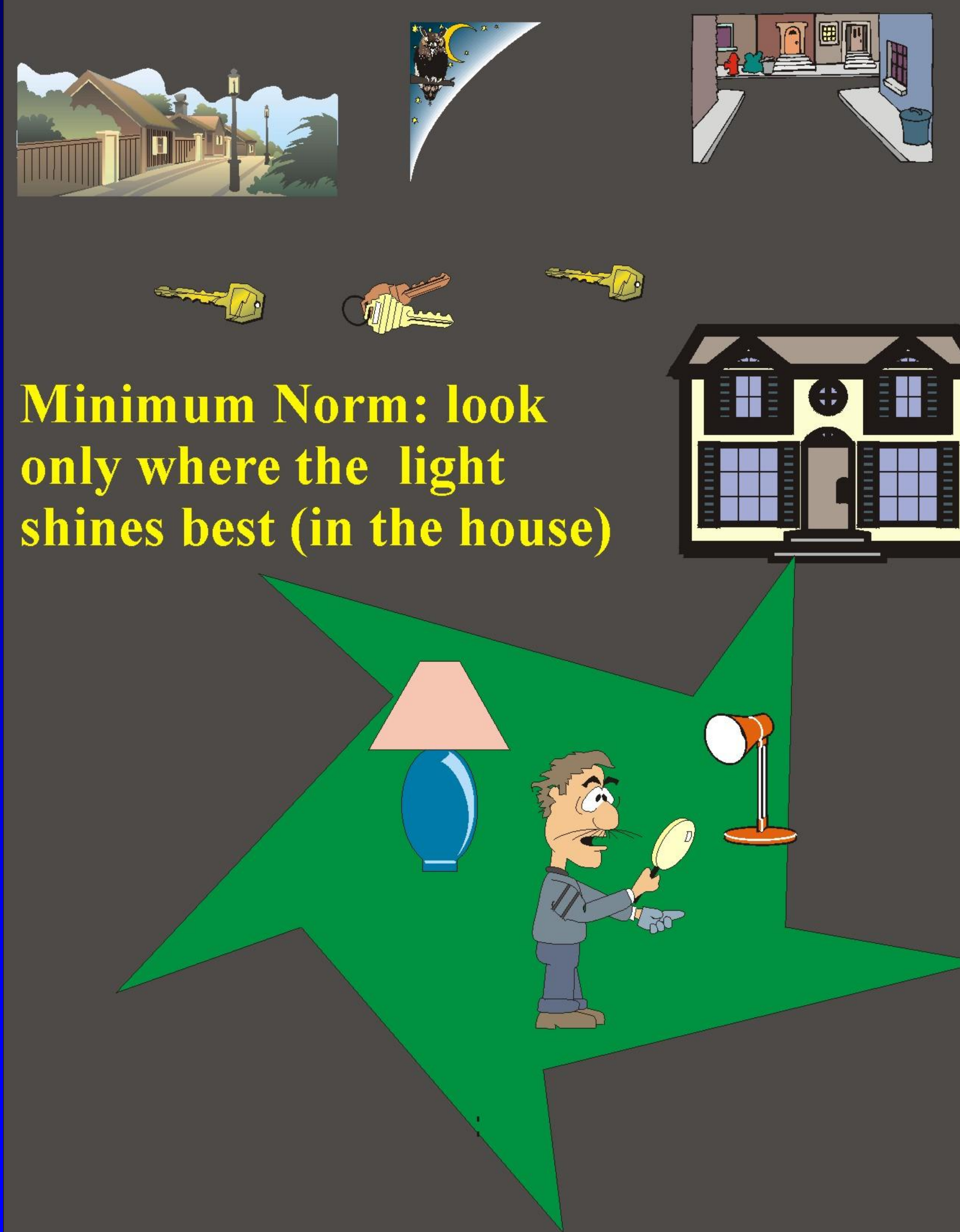
- **Advantages:**
  - Constraints correctly define the local properties of the solutions (only local direction of current density)
  - The strength of the source at each point is determined by the data condition
  - The a priori probability weight is derived from the formalism
  - additional constraints can be easily added
- **Disadvantages**
  - Non-linear (but here lies its power too)
  - Computationally intensive and resource hungry

A story of an inverse problem

There is no unique solution for it, but a possible solution can be provided by at least three methods:

- ECD
- Minimum Norm
- MFT

The Minimum norm



The search is restricted to the candidate area closest to the sensors

The ECD model

Flash quickly the flashlight in all directions and rush after the direction that seems to give the brighter reflection

(multiple)ECD: flash the flashlight and rush after one (or more) reflection(s)

MFT

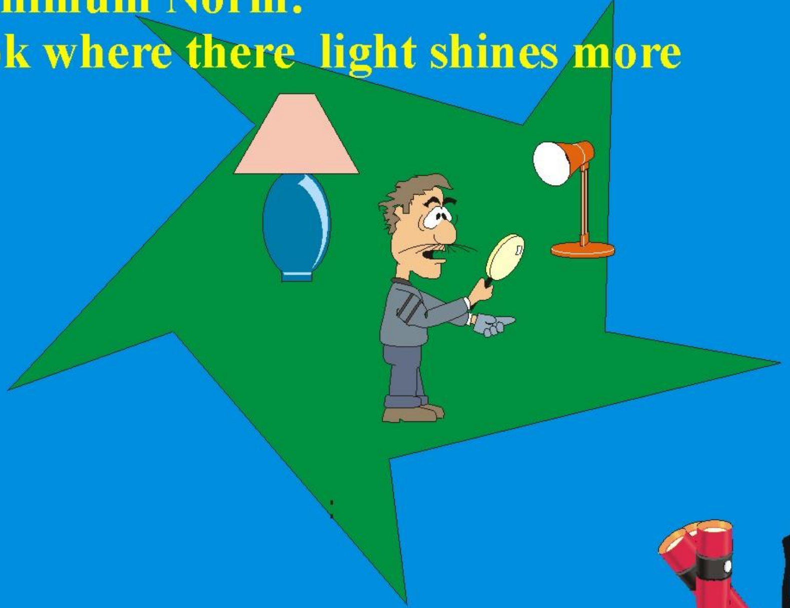
The method is laborious. It incorporates as much a priori information as available, but it makes no unnecessary assumptions about either where, how many and what is to be found

MFT: map earlier route (source-space), find best way to cover it (training), scan likely places (zeroth iterate) , look thorougly with emphasis on most likely places

Comparison of methods

Minimum norm is unlikely to be of much use (except if the keys were lost in the house), ECD is fast and quick but not very likely to give the right solution. MFT is cumbersome but the best bet to produce a solution, and one which can be elaborated further

Minimum Norm:
look where there light shines more



(multiple)ECD: flash the flashlight and rush after one (or more) reflection(s)

MFT: map earlier route (source-space), find best way to cover it (training), scan likely places (zeroth iterate) , look thorougly with emphasis on most likely places

Advantages and disadvantages of MFT

- No previous assumption is needed about source number or configuration. Very focal or distributed arrangements of generators can be recovered.
- Sources of interest can be identified in the presence of competing signals from other sources and hence in very noisy signal
- Slow as well as instantaneous activity can be reconstructed: a truly real time capability