Diffusion MRI

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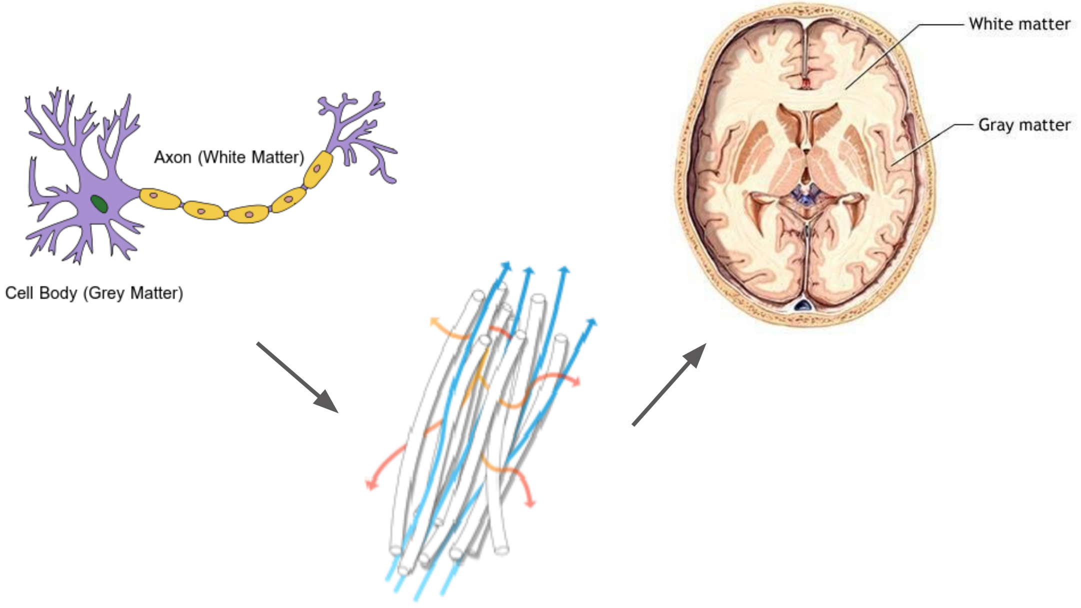
Brain Topology

- The brain is principally composed of a type of cells called ***neurons*.**
- A neuron is composed of a cellular body called ***soma*** and a tail called ***axon*** that is physical link between the neurons.
- The axons are usually group in bundles called ***fibers*.**
- In the brain the *soma* are positioned in the cortex and are generally called ***gray matter*** (GM), while the *fibers* are positioned in the central regions and are called ***white matter*** (WM).



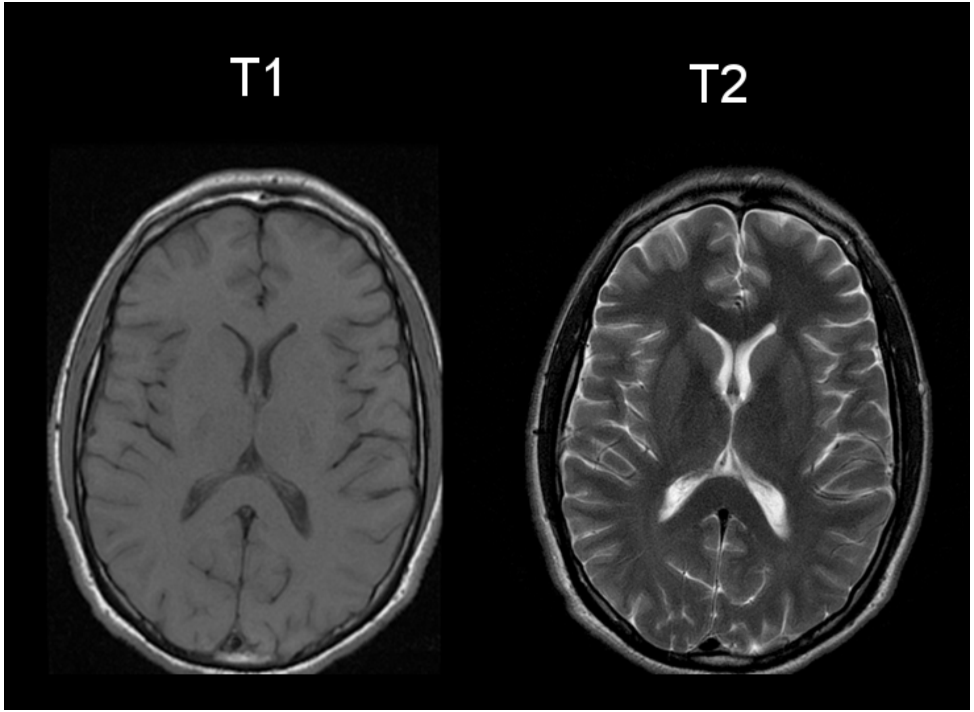
Axons bundles

Magnetic Resonance Imaging

- **Standard MRI** is the principal non-invasive imaging technique used for clinical purposes.

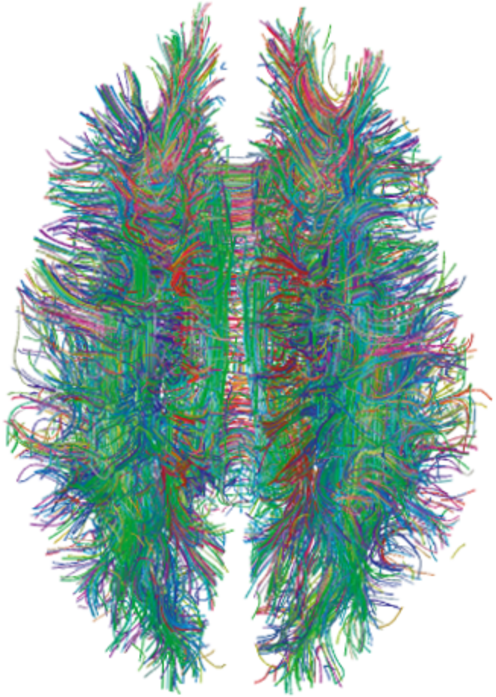
- Using standard MRI techniques is possible to distinguish between GM, WM and CSF but not the **complex structure** of the White Matter fibers bundles.

- To overcome this limitation, using an additional pulse is possible to obtain a different type of images called **Diffusion Weighted MRI**.



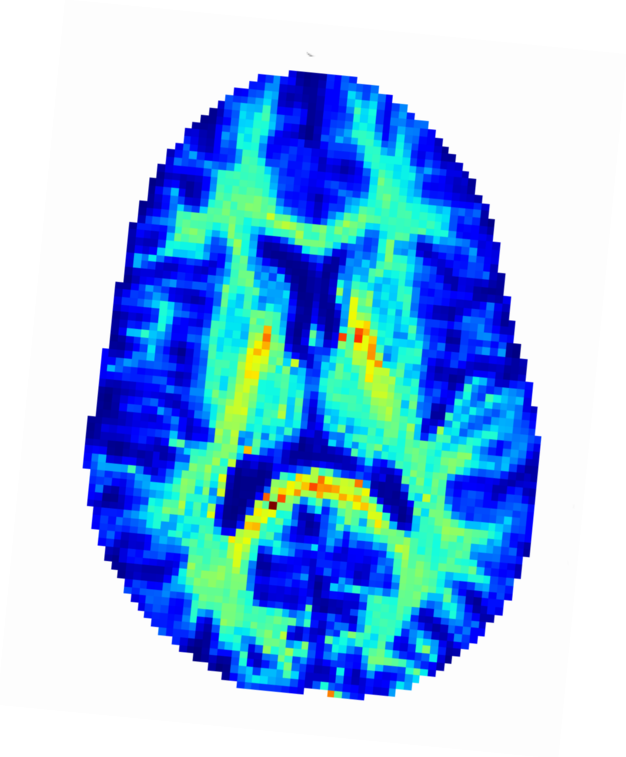
Diffusion Weighted MRI

- Diffusion MRI was born to observe the **diffusion of water molecules** in soft tissues.
- The diffusion signal can be modelled using some mathematical algorithms called **reconstruction techniques.**
- From the reconstructed signal is possible to calculate numerous measures to characterize the tissue and to calculate the **orientation of the fibers** tract in the voxel.
- From the single voxel orientation profile is possible to reconstruct the brain fibers tracts topology, this operation is called **tractography**.



Objectives

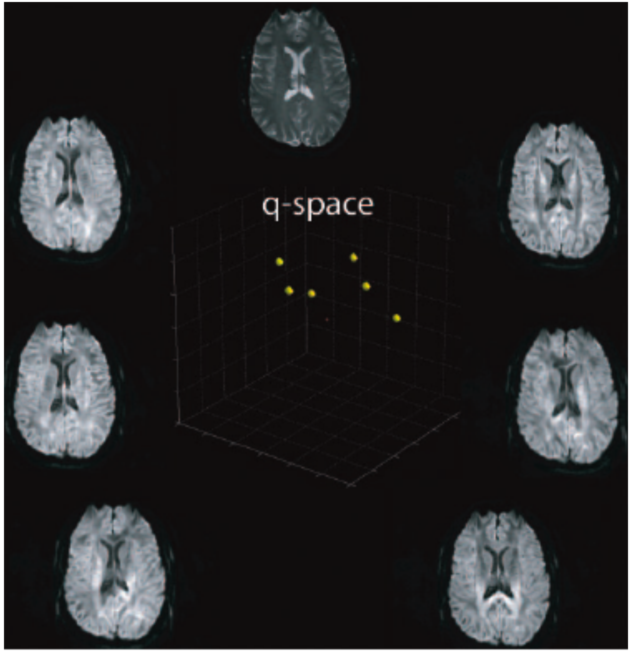
- Find the **optimal** reconstruction technique for Diffusion MRI data
- Definition of a standard criterion for validation
    - Synthetic data
- Identification of **new scalar indices** as numerical biomarkers of the **structural properties** of brain tissues
    - Anatomically and biophysically plausible besides being objectively measurable
    - Supporting and improving cortical connectivity modeling
- Uses of this indices features
    - Tissues characterization by pattern recognition
    - Patient vs Control classification



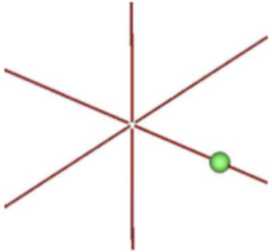
Diffusion signal

- Invented by Stejskal and Tanner (**1965**)
- It exploits an additional sequence of pulses: Pulse Gradient Spin Echo (PSGE) to measure the **attenuation** of the signal due to the diffusion of water in the soft tissues
- Changing the gradient direction (***u***) and strength (*b-value*) it is possible to obtain different volumes called **DWI**, each one representing the attenuation of the diffusion in the chosen direction
- The *b-value* depends on the duration of the pulse $\boldsymbol{\tau}$ and the **pulse frequency** *q*:

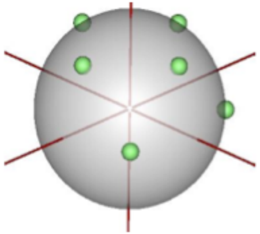
$$b = 4\pi^2 q^2 \tau \ (s/mm^2)$$



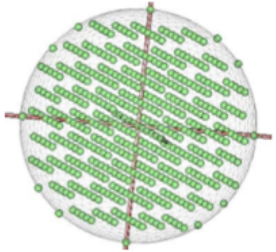
Sampling topologies



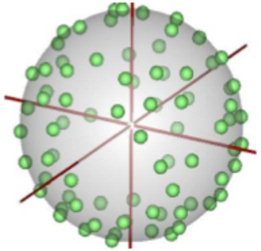
Pulsed Gradient Spin Echo
Stejskal & Tanner, 1965



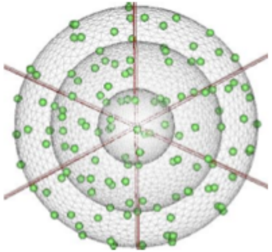
Diffusion tensor imaging
Basser, 1994



Diffusion spectrum imaging
Van Wedeen, 2000



Single-Shell High Angular
Resolution Diffusion Imaging
2000-2008



Multiple-Shell, sparse
Hybrid Diffusion Imaging
2008-now

From diffusion signal to water molecules pdf

- The signal attenuation *E(**q**)* is related to Ensemble Average Propagator (EAP) by a Fourier relationship:

  $$P(\mathbf{r}) = \int_{\mathbf{q} \in \Re^3} E(\mathbf{q}) exp(+2\pi i \mathbf{q} \cdot \mathbf{r}) d\mathbf{q}$$

  r: distance traveled by molecules in the unit time
  q: reciprocal vector

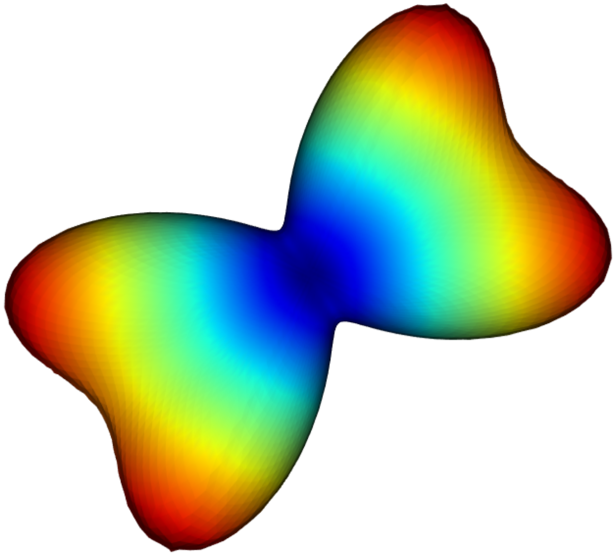
- The EAP represents the probability of a net displacement **r** in the unit time

Orientation Distribution Function

- From the **EAP** is possible to recover the probability of diffusion in each direction ***u*** called Orientation Distribution Function (ODF)

- The **ODF** is the radial integral of the EAP weighted by the square of the radius:

$$ODF(\mathbf{u}) = \int_0^\infty P(r\mathbf{u})r^2 dr$$



Diffusion Tensor Imaging

- Standard diffusion imaging technique used by the clinicians for brain **surgical planning**
- First Diffusion Imaging technique invented by Basser in 1994
- DTI models the signal attenuation in each voxel as multivariate Gaussian function
- Each Gaussian is parametrized as 3x3 symmetric matrix ***D*** called the ***diffusion tensor***

$$E(\mathbf{q}) = exp(-4\pi^2 \tau \mathbf{q}^T \mathbf{D} \mathbf{q})$$

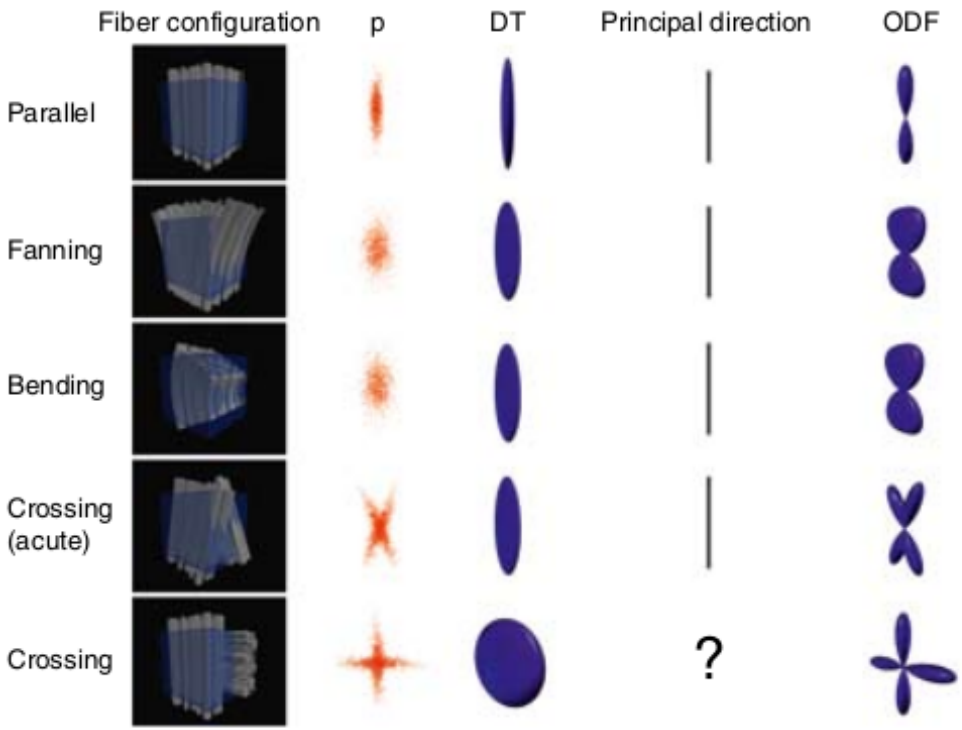
$$P(\mathbf{r}) = \frac{1}{\sqrt{(4\pi\tau)^3 |\mathbf{D}|}} exp\left(\frac{-\mathbf{r}^T \mathbf{D}^{-1} \mathbf{r}}{4\tau} \right)$$

Eigen decomposition of the DT

Ellipsoidal visualization of the DT

Diffusion Tensor Imaging

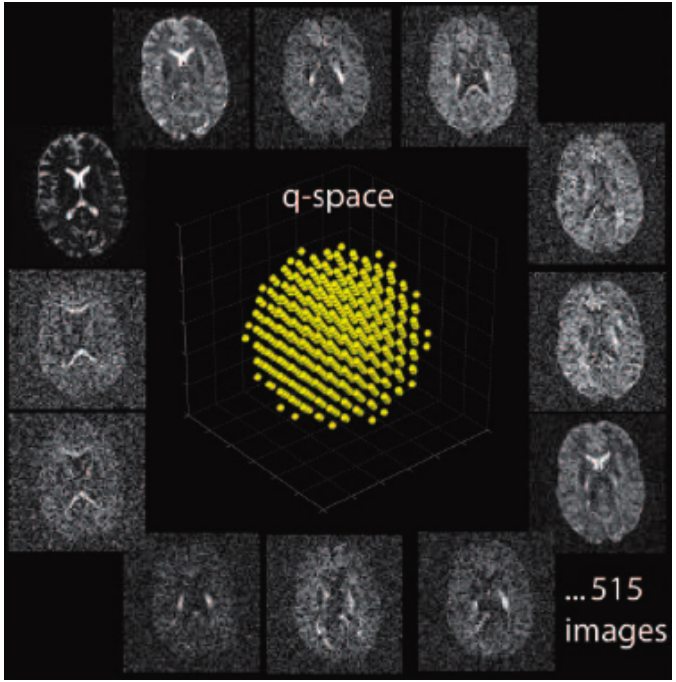
- **Advantages**
  - Fast acquisitions (30 gradients)
  - Efficient reconstruction
- **Drawback**: since the EAP is modeled as a single tensor, DTI is not able to resolve complex **fibers architectures** like fannings and **crossings**



Diffusion Spectrum Imaging

- *Diffusion Spectrum Imaging* (DSI, Wedeen 2000)
- In DSI the *q-space* is sampled using a *Cartesian grid scheme*, then the inverse 3D Discrete Fourier Transform is directly applied to the signal to obtain the **EAP**

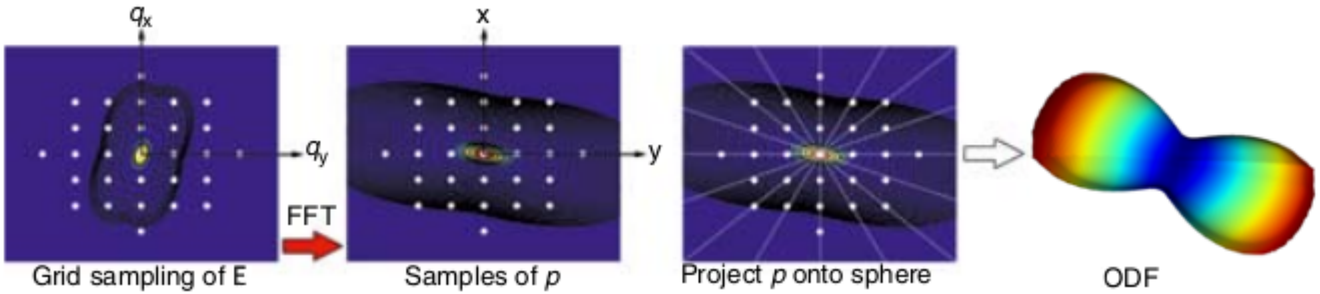
- **Advantages**
  - **Model free** representation of the propagator
  - Ability to solve **crossing of fibers** down to 30°
- **Drawbacks**
  - Long **acquisition time**
  - Use of the high *b-values*
  - **Discrete model: artefacts** introduced by the sampling (aliasing, low resolution)



DSI: discrete model

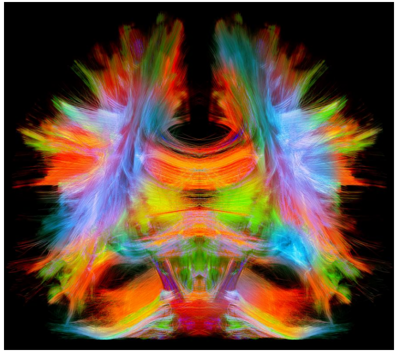
$$P[r_x, r_y, r_z] = FFT(E[q_x, q_y, q_z])$$

$$ODF[\theta, \varphi] = \sum_{r=0}^{r_{max}} P[\theta, \varphi, r] \cdot r^2$$

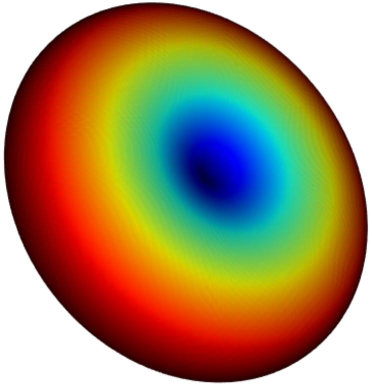


Thank you!

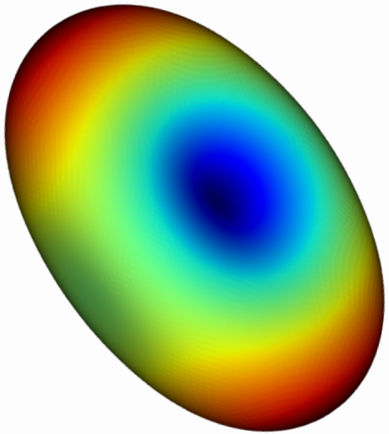
Any question?



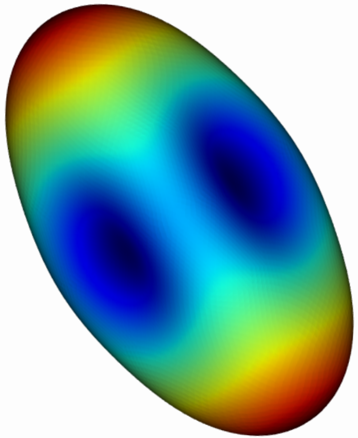
EXTRA: Signal attenuation on a sphere



Single fiber



60° crossing



90° crossing