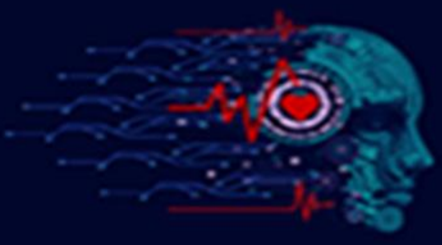
The First (TvAI) Skyroom
International Virtual Congress on the practical Application of Artificial Intelligence in Medical Sciences
Date & Time: 1–5 February 2025 (09:00 Am - 12:00)



تاریخ و زمان برگزاری: ۱۳ تا ۱۷ بهمن ۱۴۰۳ (۱۲:۰۰ - ۰۹:۰۰ صبح)
اولین کنگره بین المللی مجازی
کاربرد هوش مصنوعی
در علوم پزشکی

AI-Powered Tractography: Unveiling the Pathways of the Brain from Diffusion MRI

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Assistant professor of Biomedical
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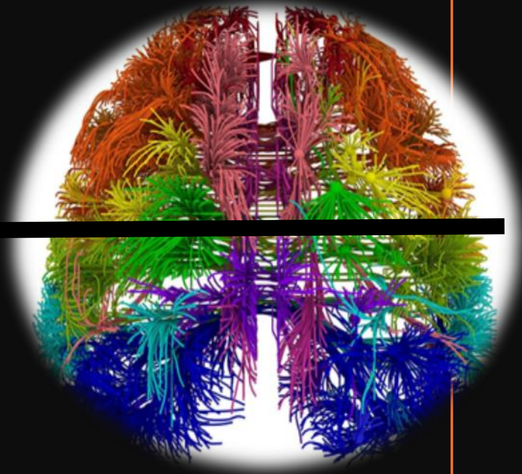
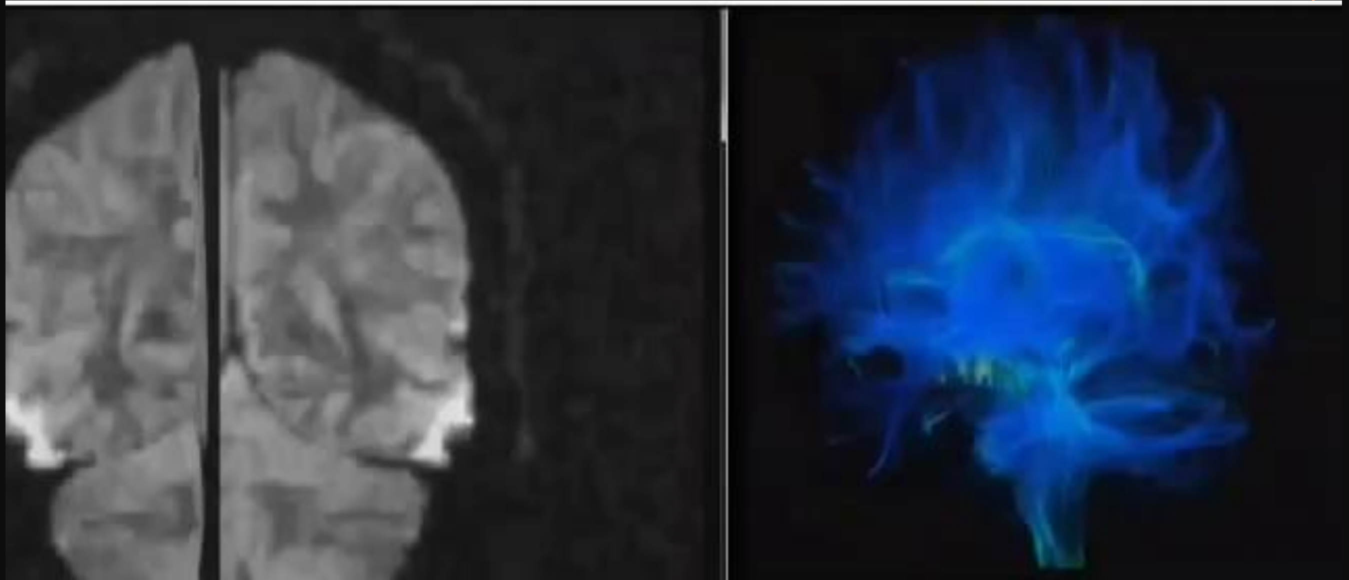
university of medical science

"Nothing better defines the function of a neuron than its connections"
Marsel Mesulam (2006)

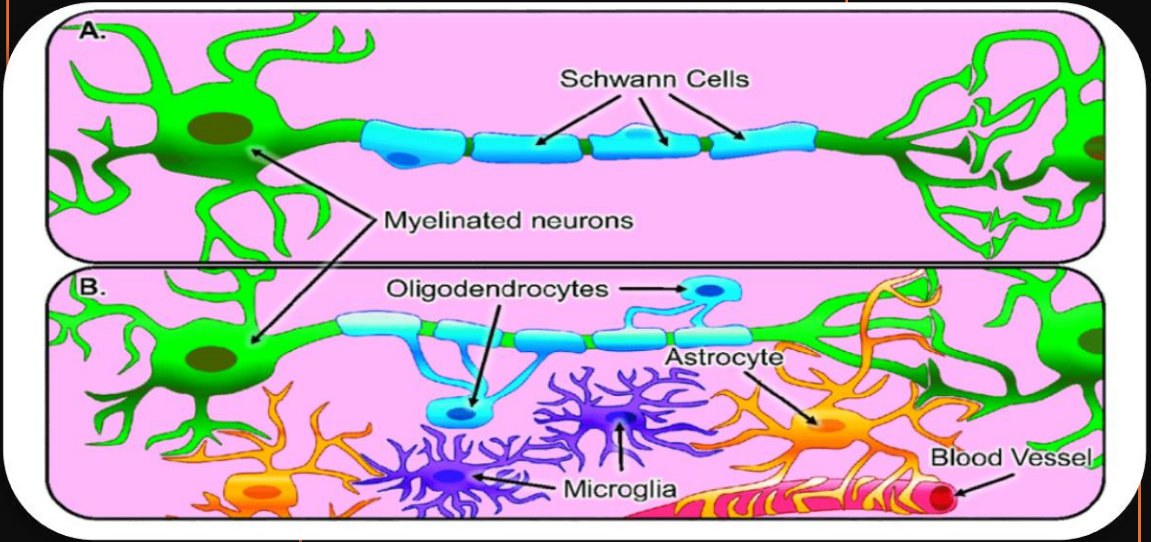


- **To better understand the brain, we need to understand its structure and connections, which fundamentally involve white matter**

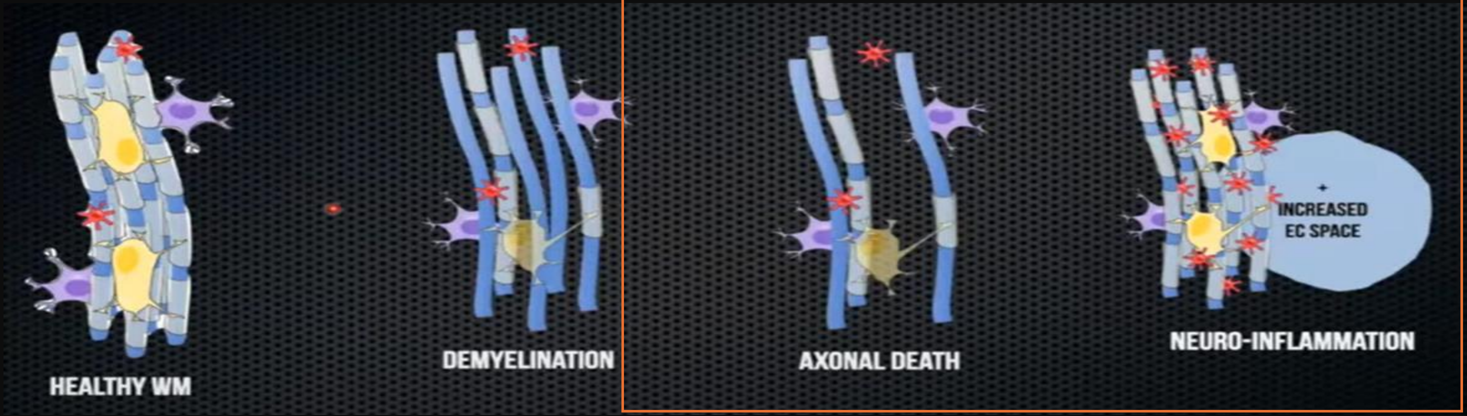


Microstructure of White Matter

- White matter is **very unique Biologically** and Anatomically
- The dream is to have **biomarkers** or **quantitative measures** that can detect whether a bundle of axons is healthy, with healthy myelin and a supportive environment, or if there are **anomalies**:
- **Demyelination**
- **Axonal loss**
- **Axons swelling**
- **Neuroinflammation**

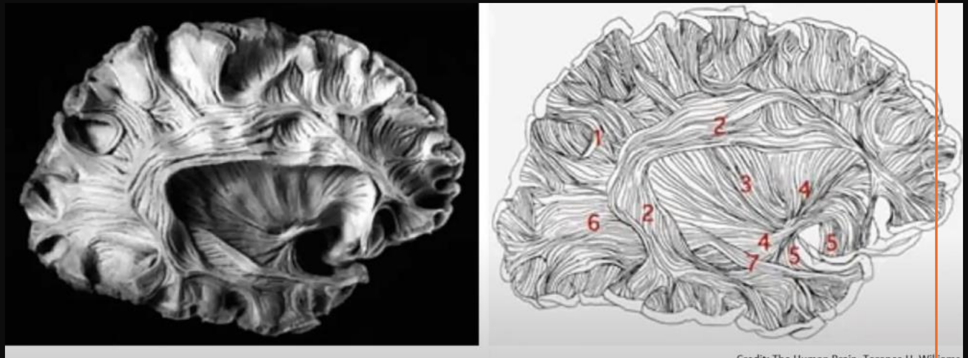


- *Figure adapted from 'Electrospun Fiber Scaffolds for Engineering Glial Cell Behavior to Promote Neural Regeneration*

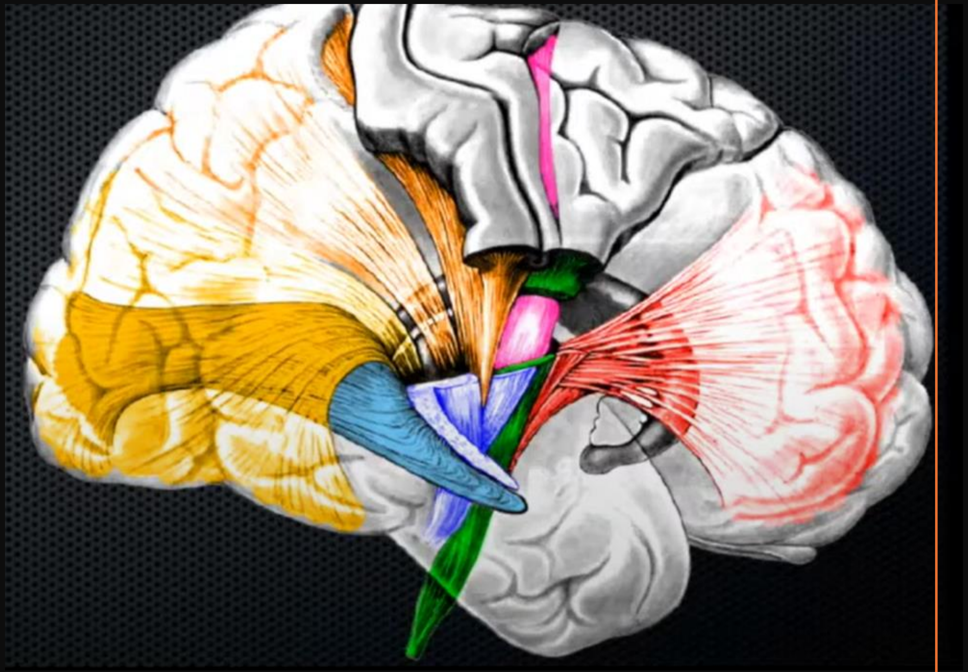


Macrostructure of White Matter

- White matter also has a **macrostructural organization**: axons organize themselves in **families** or **bundles** (fascicles)



Credit: The Human Brain, Terence H. Williams



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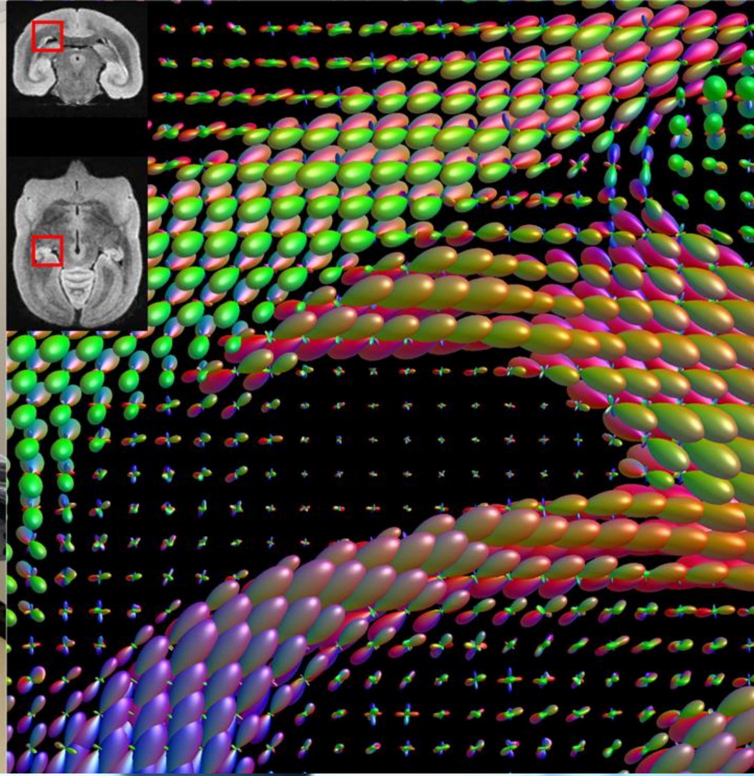
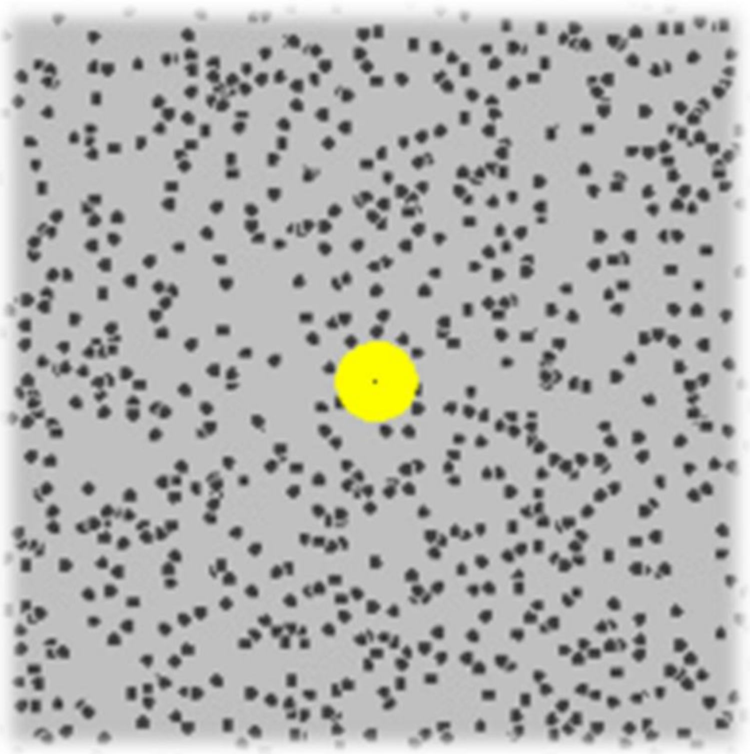


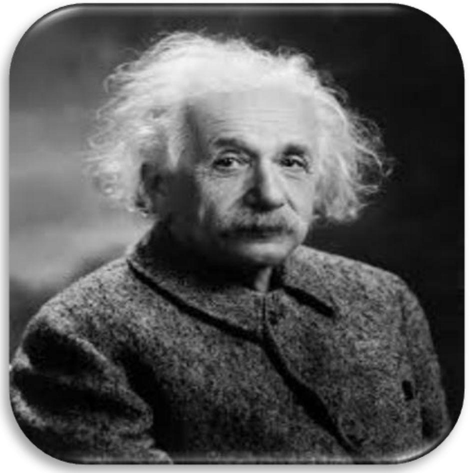
Why Diffusion

How do we **quantitatively** assess this complexity?

Diffusion is Essentially a R**andom** W**alk**



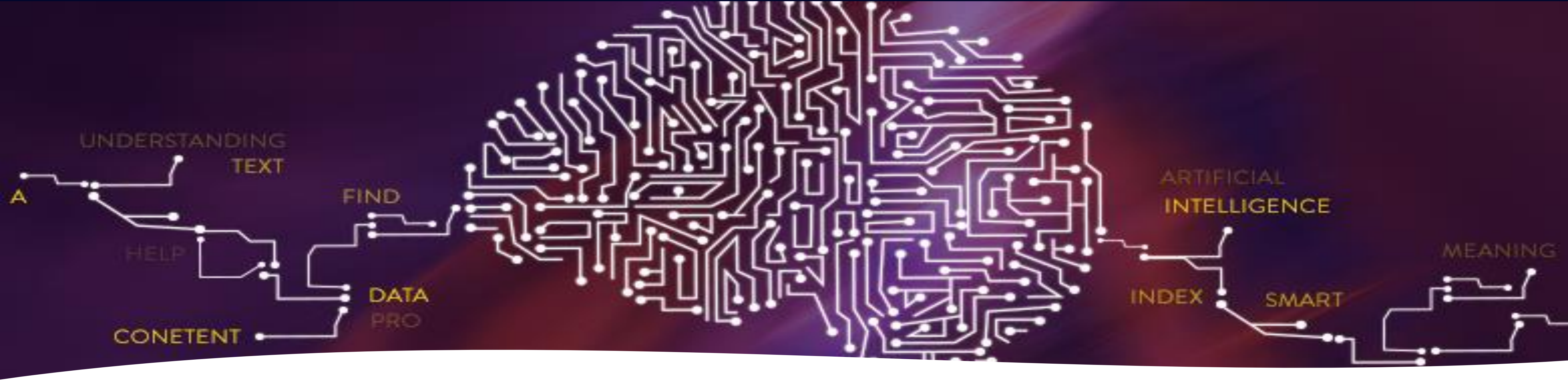
Robert Brown,1827
Brownian motion



Albert Einstein,1905
Derived the Diffusion Equation

Google Maps Analogy

Curtesy of G. Zhang & D Alexander (UC London)]



Challenges That Necessitate Machines

- **Number of Neurons**
- **Total Length of Axons**
- **Number of Synapses**
- **High Dimensionality of data**
- **Need for Precision**
- **Visualization and Interpretation**

The main idea is the Apparent Diffusion Coefficient (ADC)

Denis Le Bihan
1985

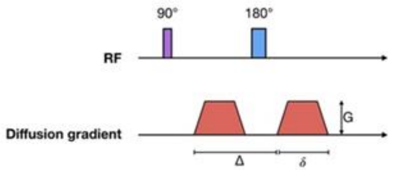
Le Bihan D, **1985**
- ✓ *b* factor
- ✓ *ADC* concept

A key paper by **Denis Le Bihan** introduced **Diffusion-Weighted Imaging (DWI)** in the French Academy of Science

By acquiring enough data, we can find a **normal ADC** for brain tissue; any **tumor, stroke, or other abnormality** causes ADC to deviate from that norm.

b value

$$b = \gamma^2 G^2 \delta^2 (\Delta - \frac{\delta}{3})$$



γ = gyromagnetic ratio
G = magnitude of the two balanced DW gradient pulses
δ = width of the two balanced DW gradient pulses
Δ = time between the two balanced DW gradient pulses

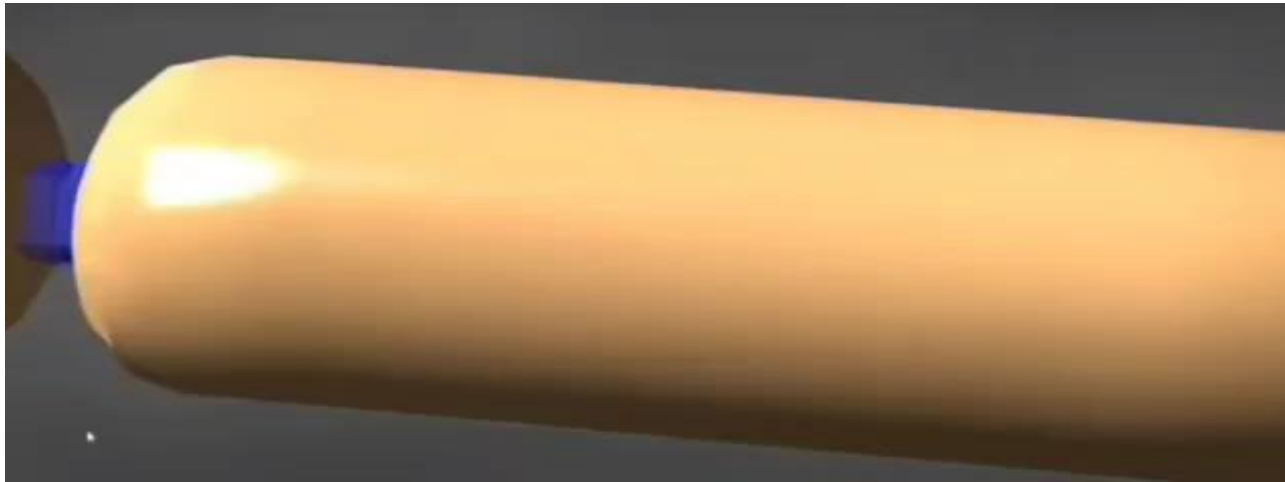
Relationship between signal of b = 0, DWI and ADC

$$S_{DWI} = S_{b=0} \times e^{(-b \times D)}$$

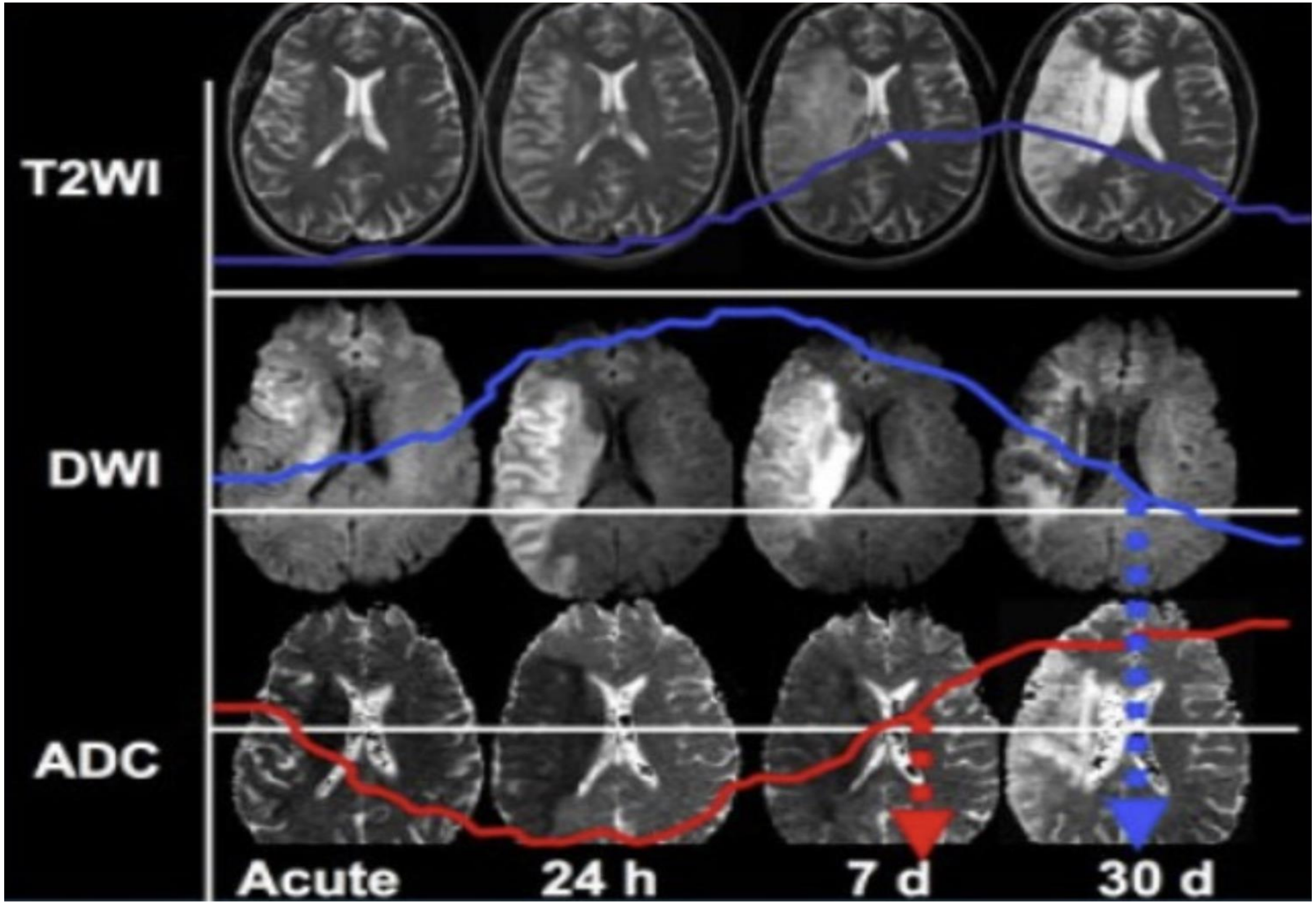
equivalent to...

$$D = -\frac{1}{b} \times \ln\left(\frac{S_{DWI}}{S_{b=0}}\right)$$

S_{DWI} = signal intensity of isotropic DWI
$S_{b=0}$ = signal intensity of b = 0
b = b value
D = apparent diffusion coefficient (ADC)

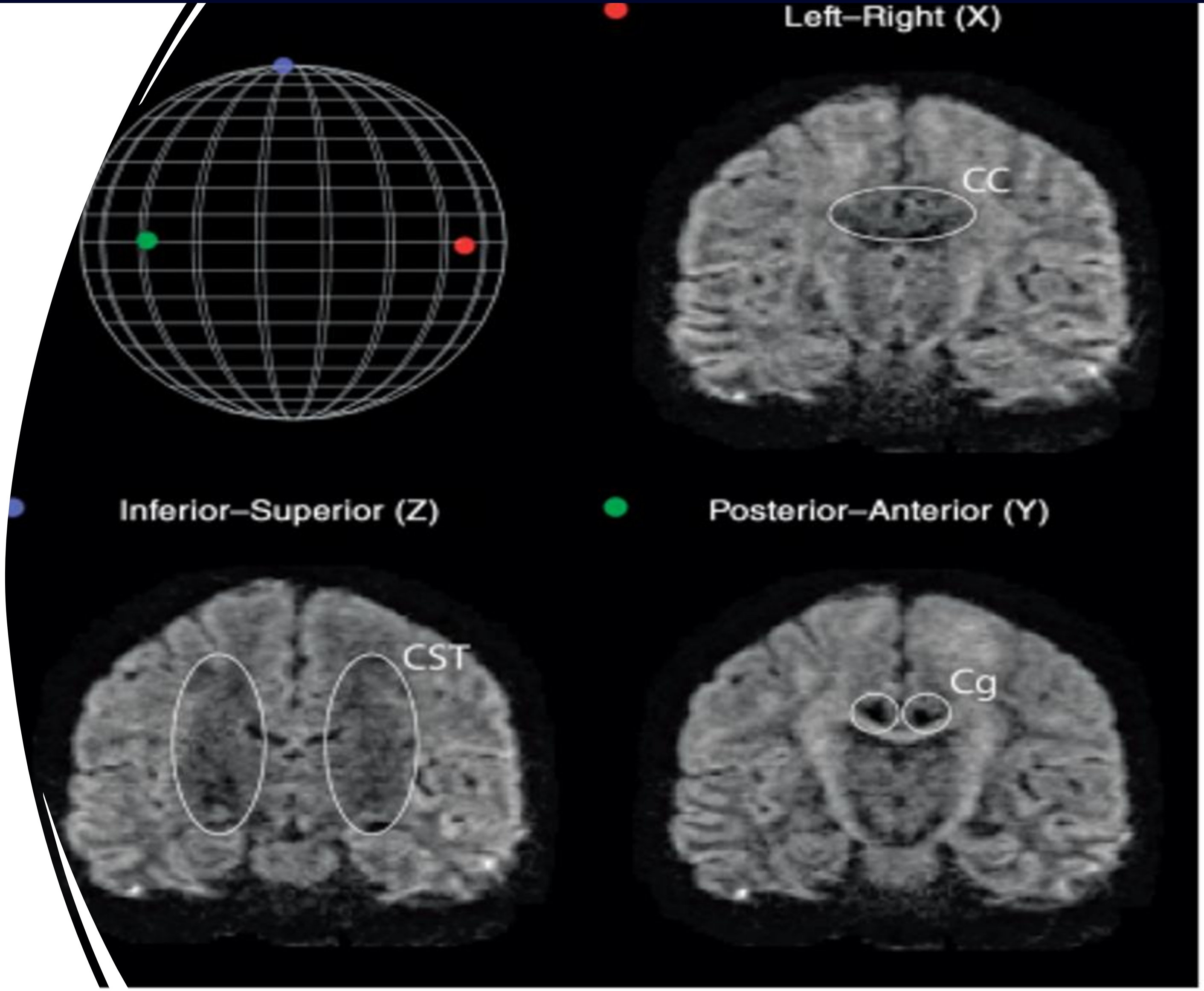


Stroke Imaging



Beyond ADC: Orientation and White Matter Organization

- Diffusion along X, Y, and Z directions. The signal in the left/right oriented corpus callosum is lowest when measured along X, while the signal in the inferior/superior oriented corticospinal tract is lowest when measured along Z.

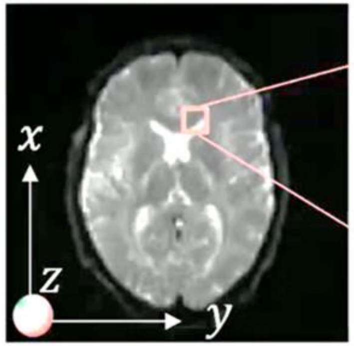


Diffusion Tensor Imaging (DTI)

- Diffusion Tensor Imaging (DTI) models diffusion in each voxel using a 3*3 tensor:

$$\boldsymbol{D} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{bmatrix}$$

Diffusion Tensor



Peter Basser,1994

– Ellipsoid representation

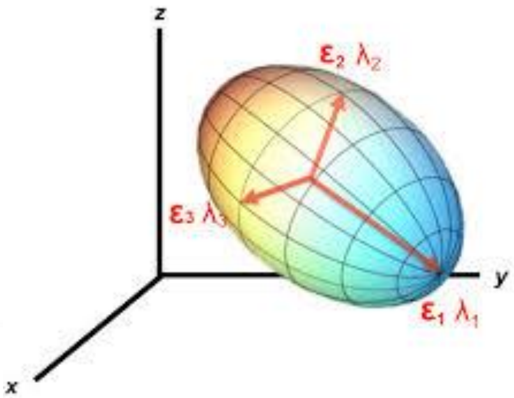
$$S(\mathbf{b}) = S_0 e^{-b\,\mathbf{g}^T \mathbf{D} \mathbf{g}},$$

$$\mathbf{g} = [g_x, g_y, g_z]^T$$

– AD, RD and MD can be more generally computed from eigen-value decomposition

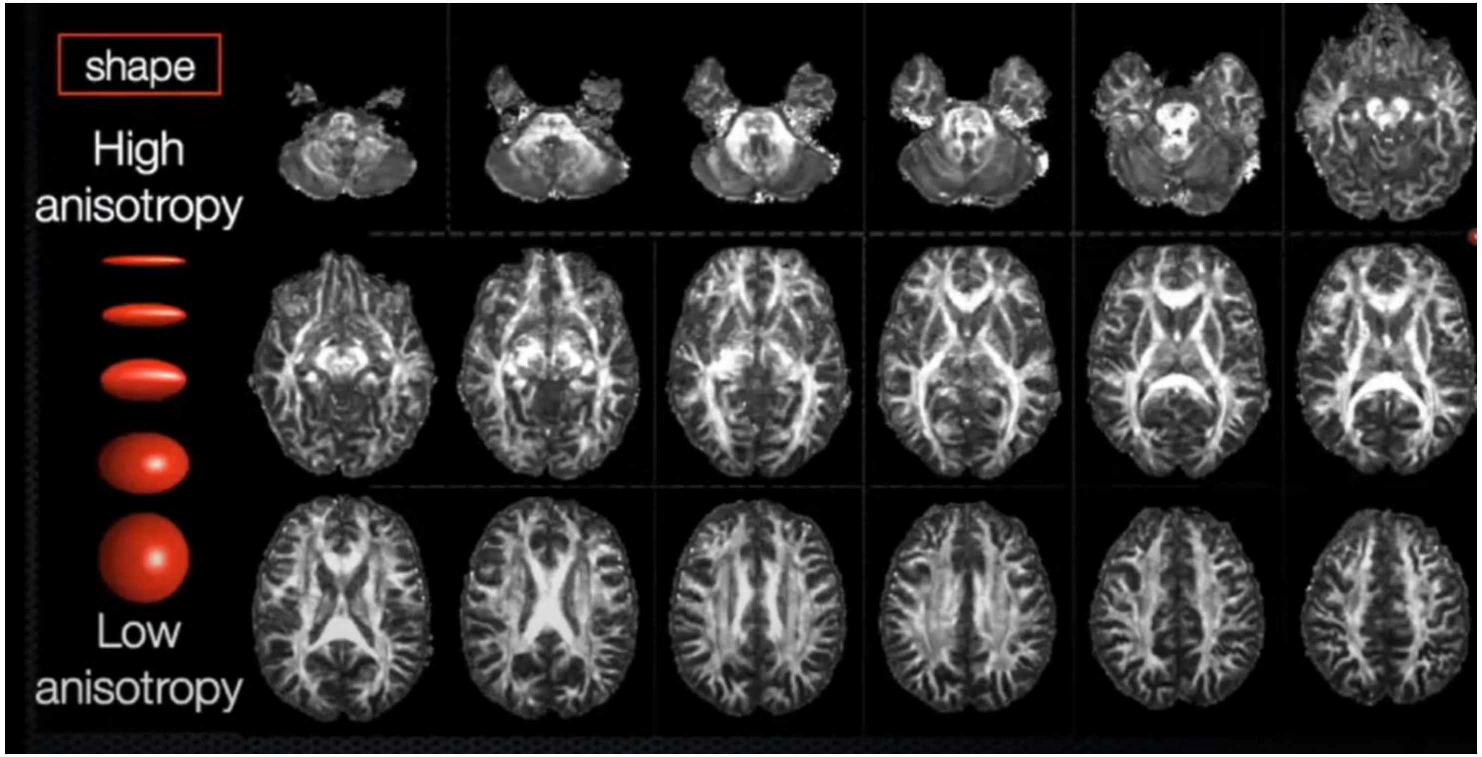
$$\begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{bmatrix} = [\boldsymbol{v}_1 \quad \boldsymbol{v}_2 \quad \boldsymbol{v}_3] \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} \begin{bmatrix} \boldsymbol{v}_1 \\ \boldsymbol{v}_2 \\ \boldsymbol{v}_3 \end{bmatrix}$$

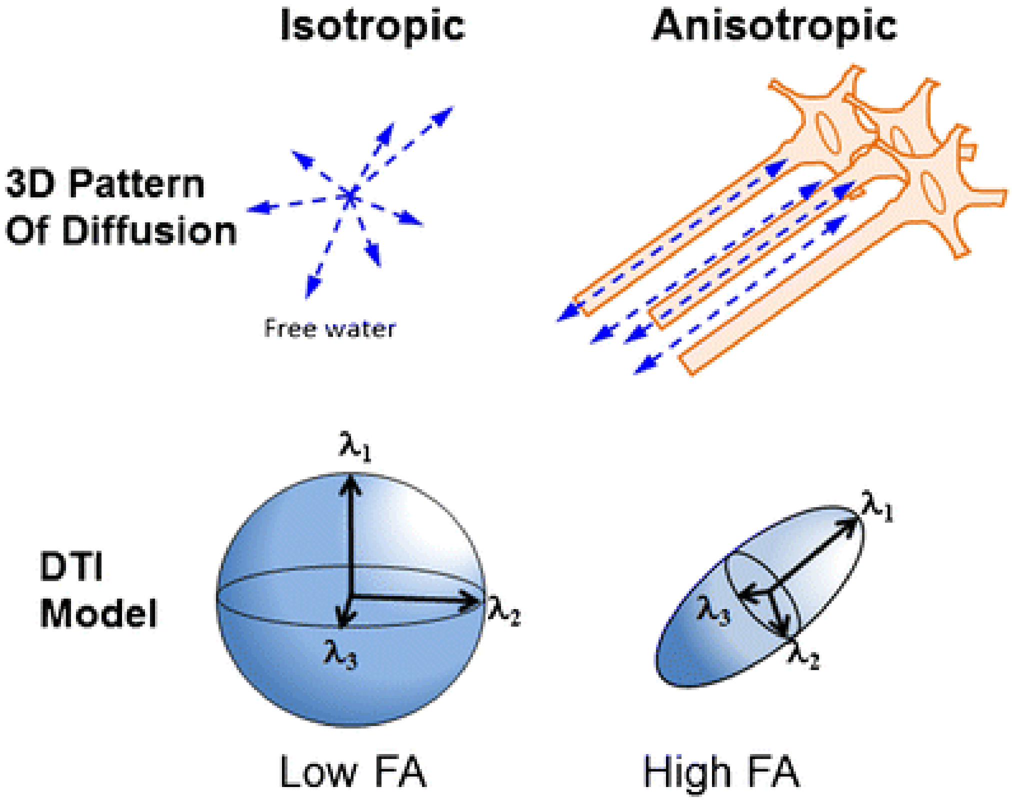
$$AD = \lambda_1 \qquad RD = (\lambda_2 + \lambda_3)/2 \qquad MD = (\lambda_1 + \lambda_2 + \lambda_3)/3$$



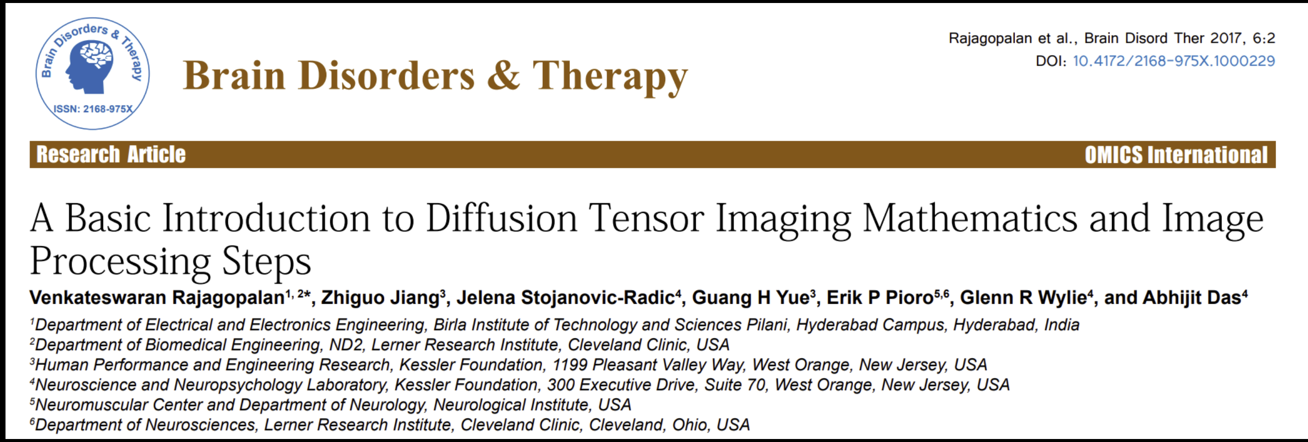
$$FA = \sqrt{\frac{3}{2}} \cdot \frac{\sqrt{(\lambda_1 - \mathrm{MD})^2 + (\lambda_2 - \mathrm{MD})^2 + (\lambda_3 - \mathrm{MD})^2}}{\sqrt{\lambda_1^2 + \lambda_2^2 + \lambda_3^2}}$$

Fractional Anisotropy (FA)





Limits of DTI



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A Basic Introduction to Diffusion Tensor Imaging Mathematics and Image Processing Steps

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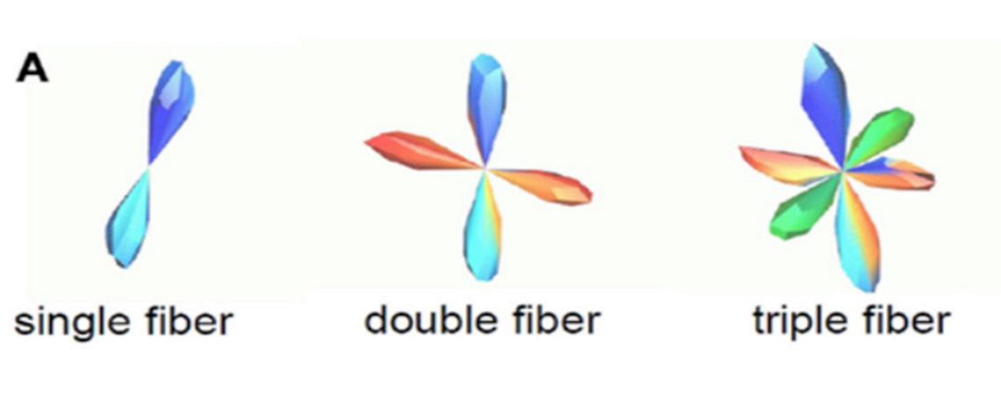
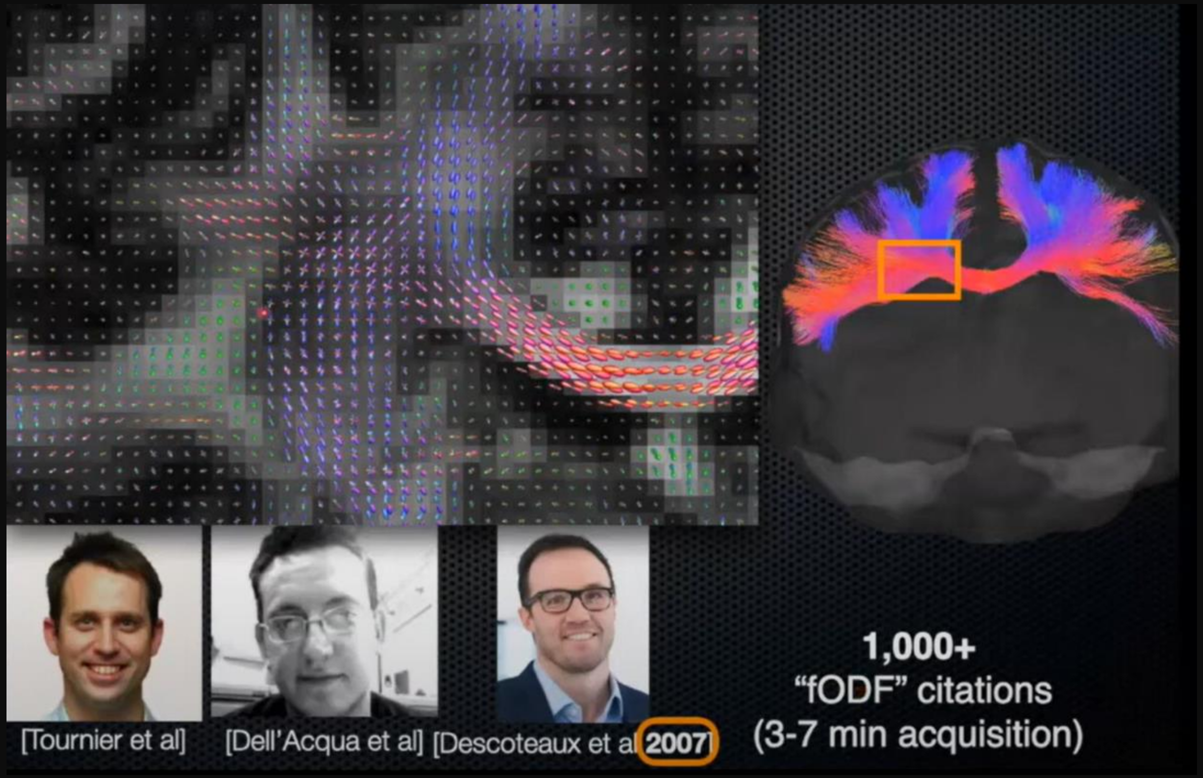
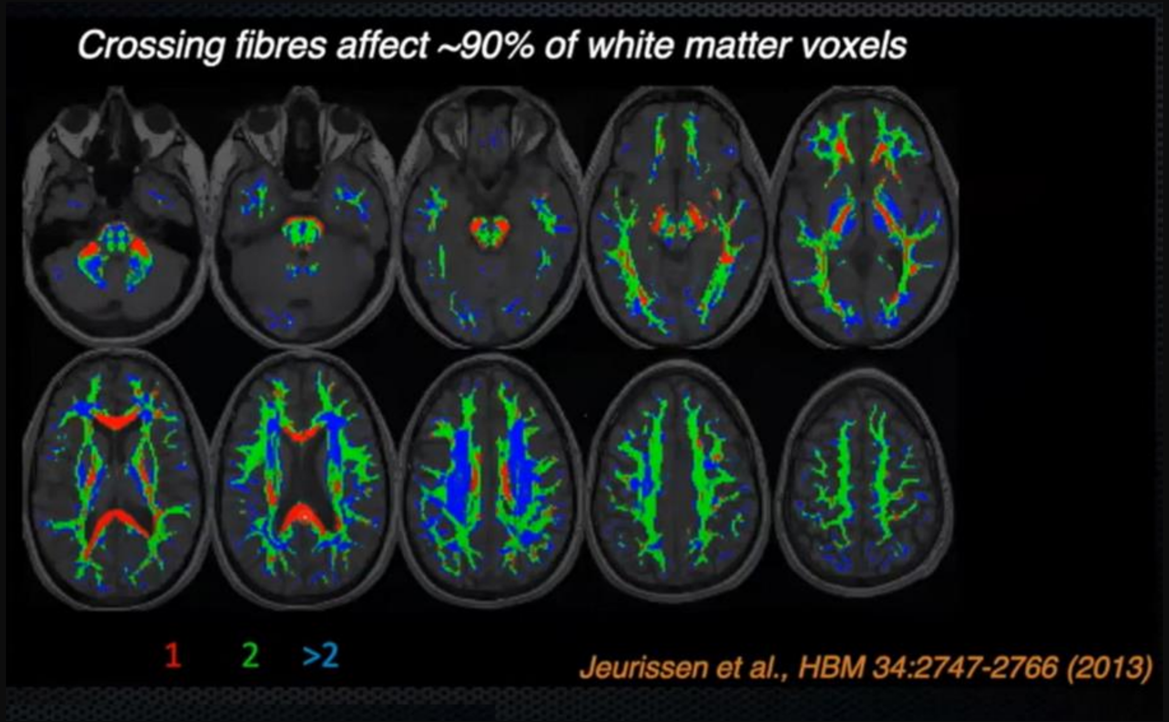
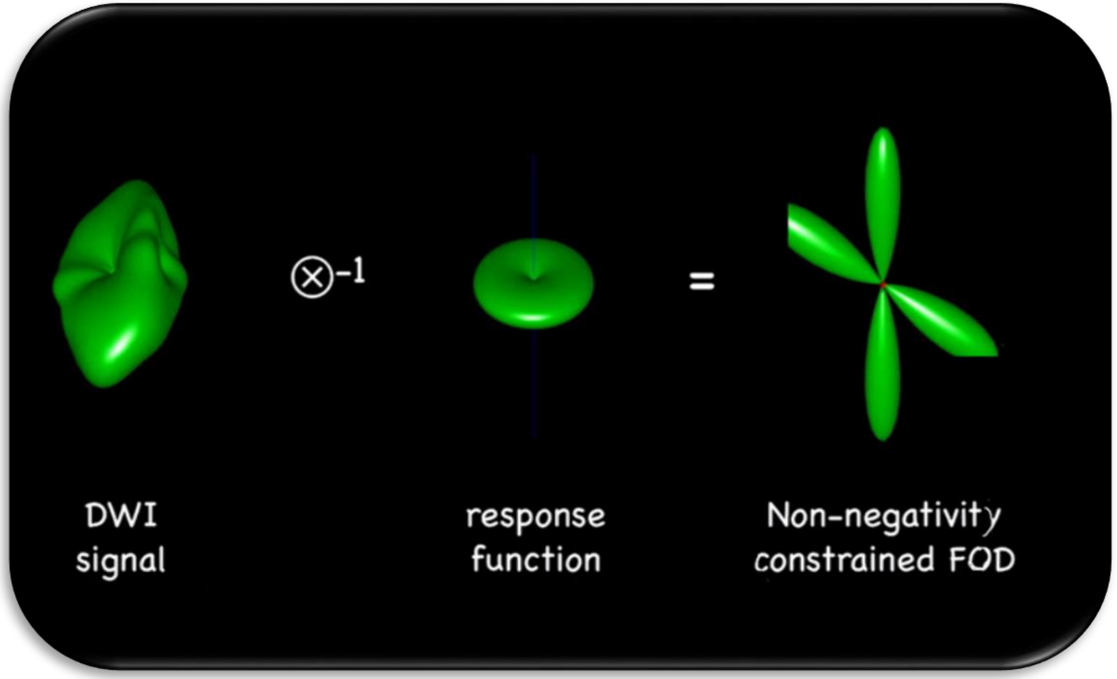


Crossing fibers everywhere





Constrained Spherical Deconvolution (CSD)



Mathematical Model:

$$S(\mathbf{q}) = \int_{\Omega} E(\mathbf{q}, \mathbf{r}) F(\mathbf{r}) d\mathbf{r},$$

where:

- $S(\mathbf{q})$: Measured diffusion signal.
- $E(\mathbf{q}, \mathbf{r})$: Single-fiber response function (kernel).
- $F(\mathbf{r})$: Fiber Orientation Distribution (FOD).

Model the Problem: The FOD is estimated by solving the optimization problem:

$$\mathbf{F} = \arg\min_{\mathbf{F}} \|\mathbf{S} - \mathbf{E}\mathbf{F}\|^2 + \lambda R(\mathbf{F}),$$

subject to:

$$F(\mathbf{r}) \geq 0 \quad \forall \mathbf{r}.$$

Instead of solving the optimization problem iteratively, the network approximates:

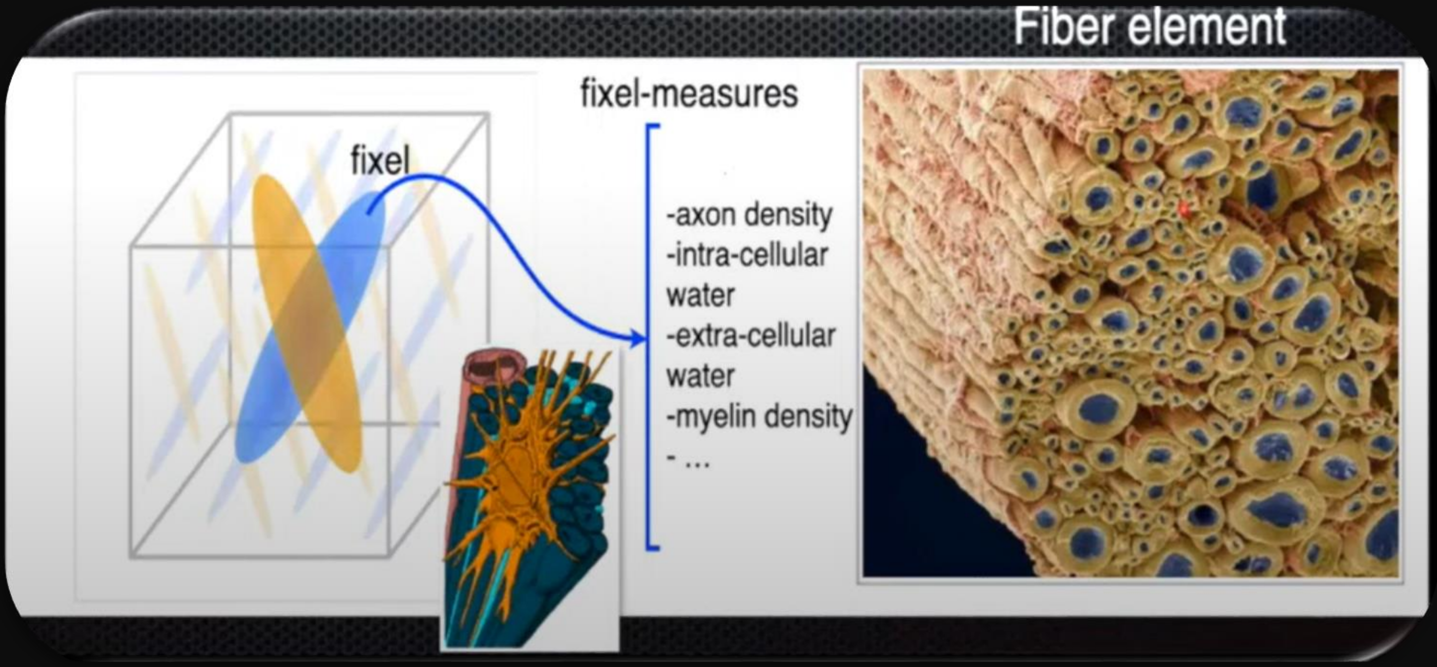
$$\mathbf{F} \approx f_{\text{NN}}(\mathbf{S}),$$

where f_{NN} is parameterized by neural network weights Θ learned by minimizing:

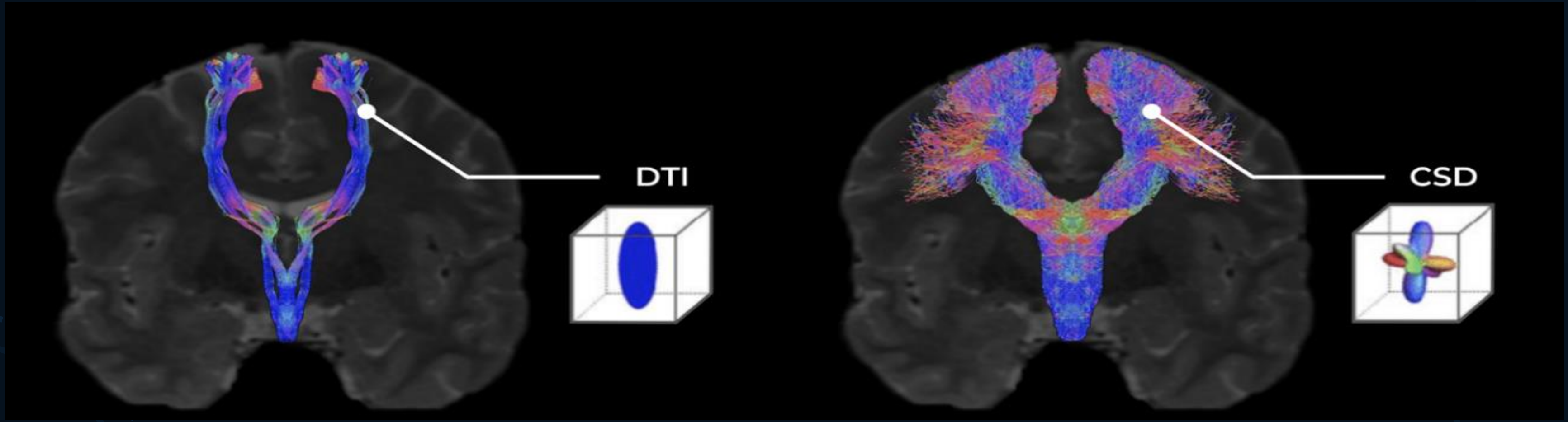
$$\mathcal{L}(\Theta) = \|\mathbf{F}_{\text{true}} - f_{\text{NN}}(\mathbf{S}; \Theta)\|^2 + \lambda R(f_{\text{NN}}(\mathbf{S}; \Theta)).$$

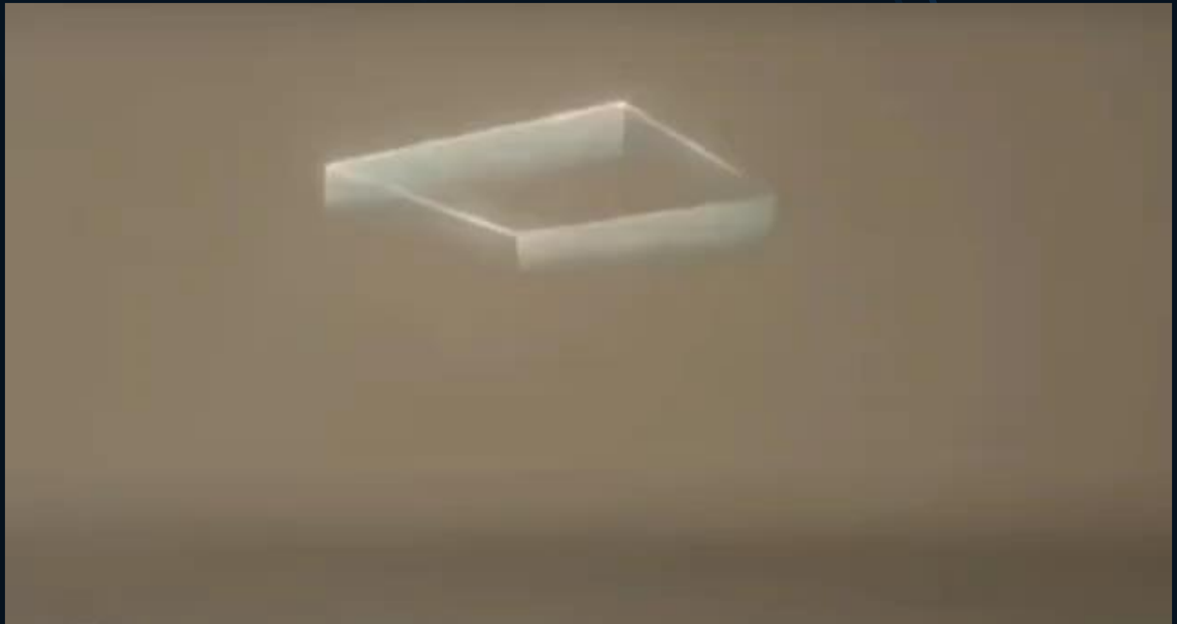
Fixel-Based Analysis (FBA)

- Pixel=picture element (2D)
- Voxel=Volume element (3D)
- Fixel=fiber element (5D)



Tractography



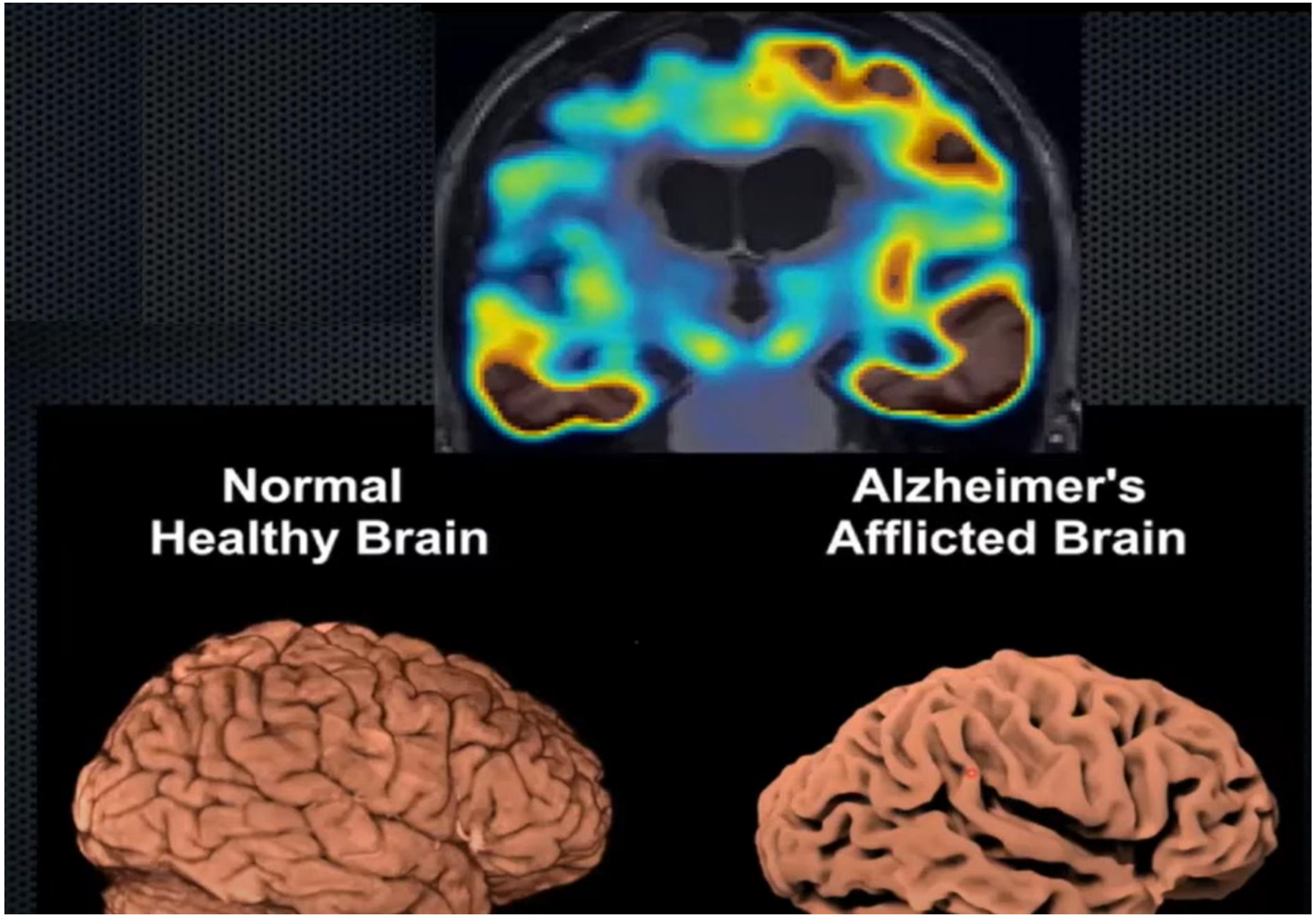


- **Tractography'** is a brain imaging technique that broadly describes the mapping of the location and direction of white matter bundles and their constituent fibers within the human brain

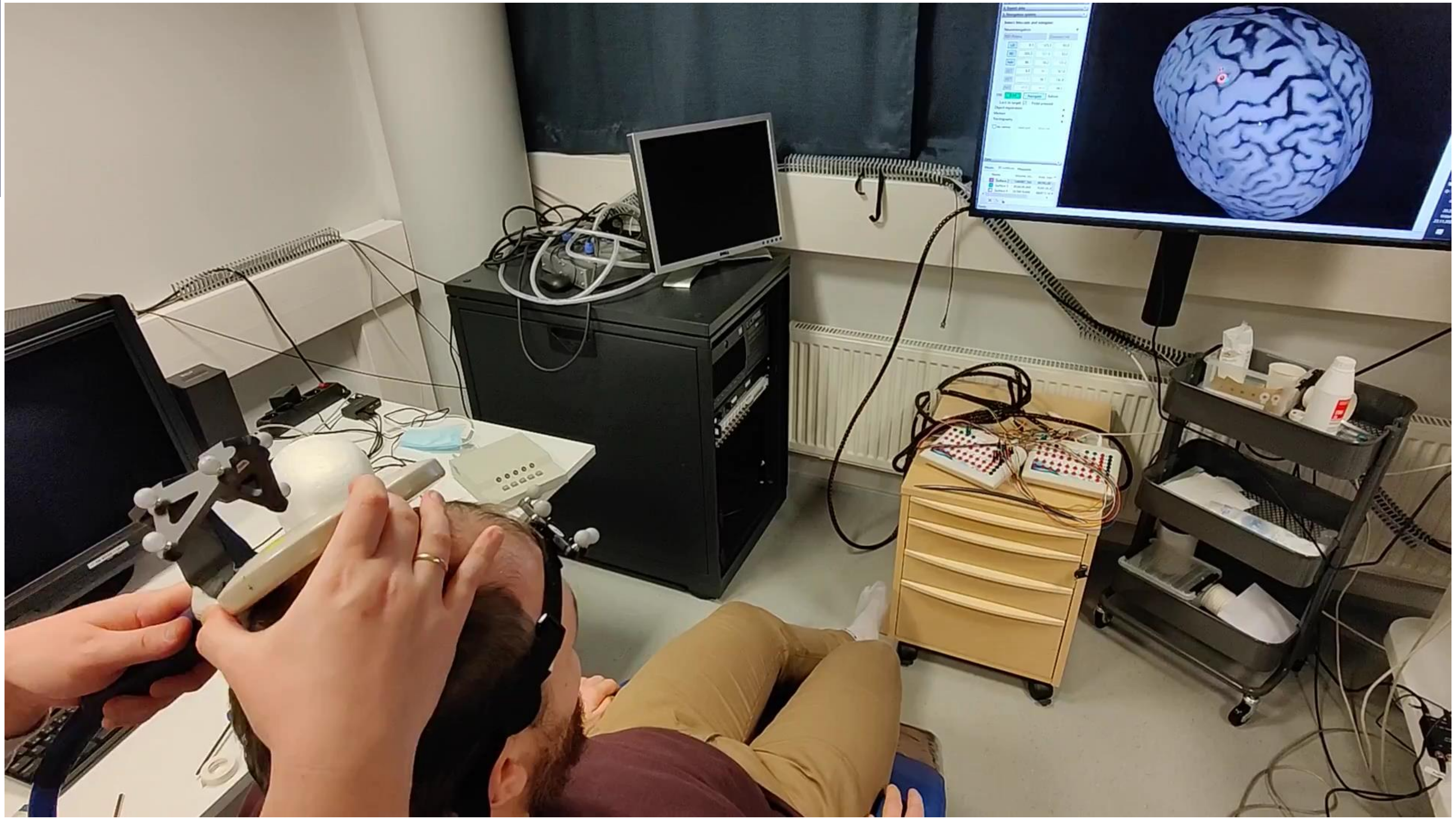
$$xi + 1 = xi + \Delta s \cdot di$$

Segmentation and Tractometry

Application of Tractography in Alzheimer’s Disease(AD)



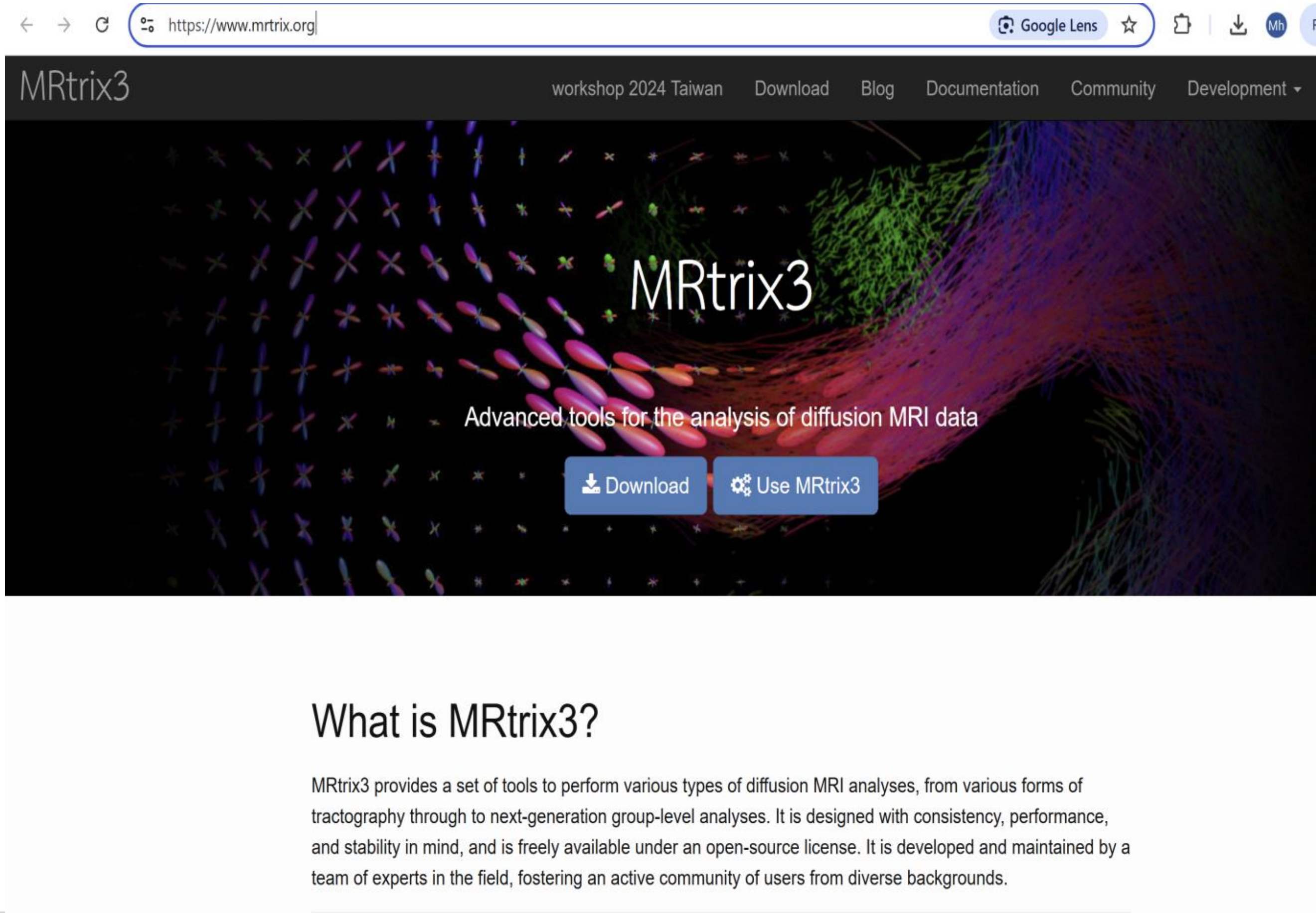
Combining TMS and Tractography



DIPY

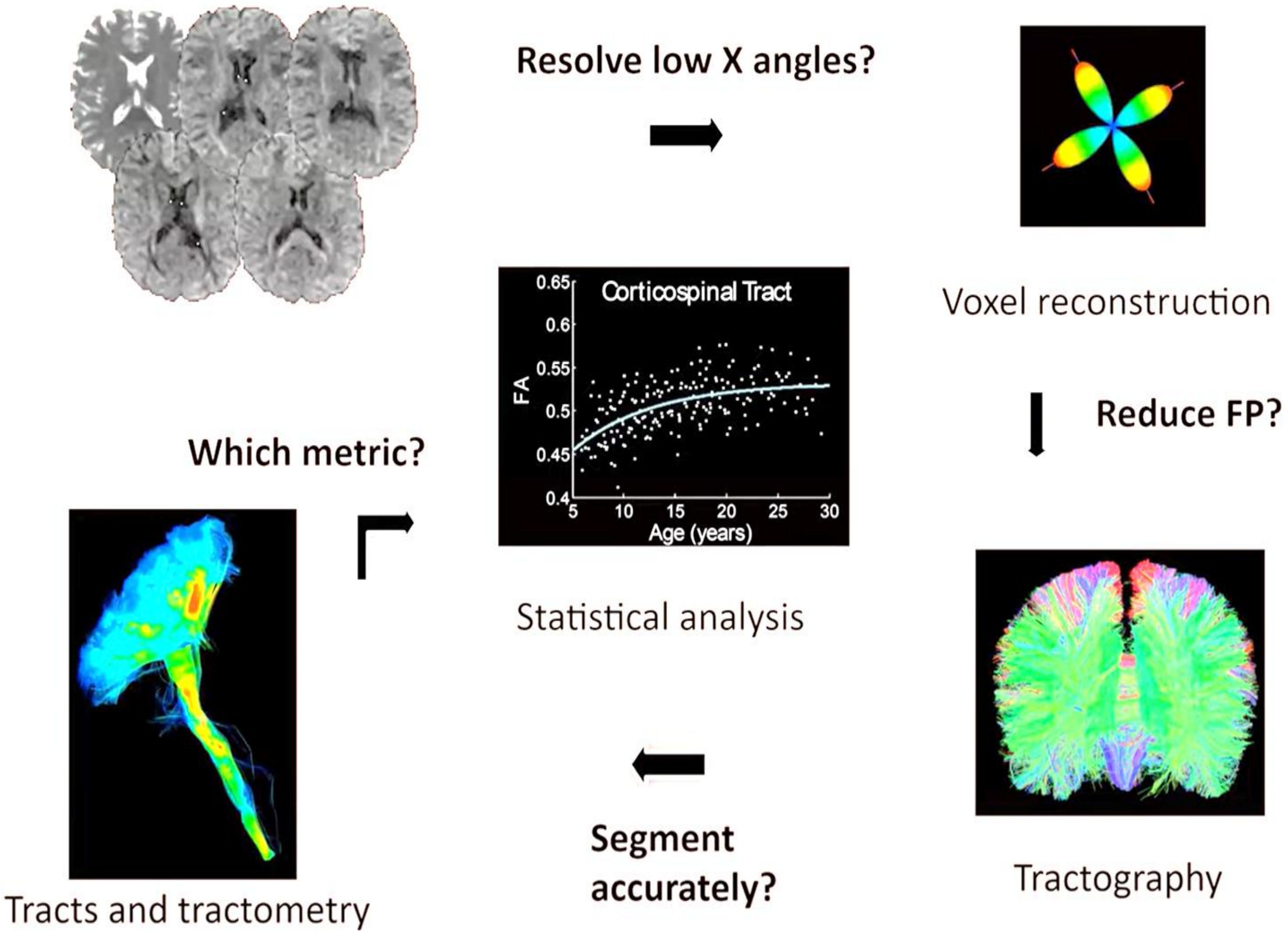
MRtrix3

- Open-source Python software designed for computational anatomy.
- Primarily focuses on diffusion MRI but also offers general medical imaging algorithms like denoising and registration.
- DIPY and MRtrix3 are global initiatives that foster collaboration among researchers across laboratories and countries
- Aims to share cutting-edge code and expertise, accelerating progress in medical imaging research.



Use Case	Best Tool
High-performance tractography pipelines	MRtrix3
Interactive GUI for diffusion MRI analysis	MRtrix3 (`mrview`)
Flexible scripting and integration	DIPY
Teaching diffusion MRI principles	DIPY
Python-based workflows or pipelines	DIPY
Multi-modal connectomics	MRtrix3
Large-scale, multi-shell data	MRtrix3

Ongoing Research



Thank you for your attention ☺

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