Machine Learning for Neuroimaging and Neuroscience

AGH University of Science and Technology

Lesson 2

Structural Connectivity

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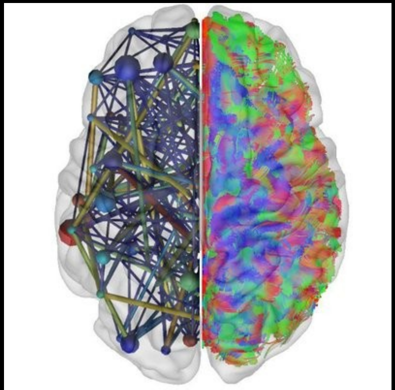
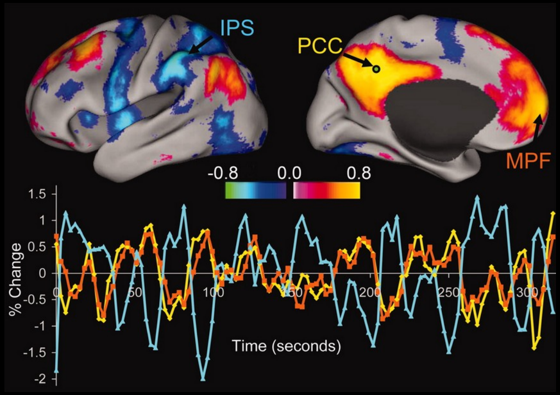
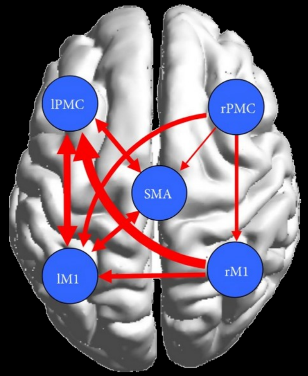
Structural, functional & effective connectivity





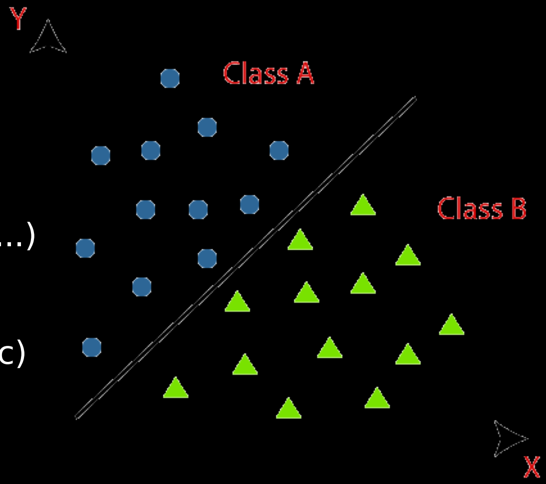


Structural/anatomical connectivity
= presence of axonal connections / white matter tracks (eg, DWI, AAV tracers)

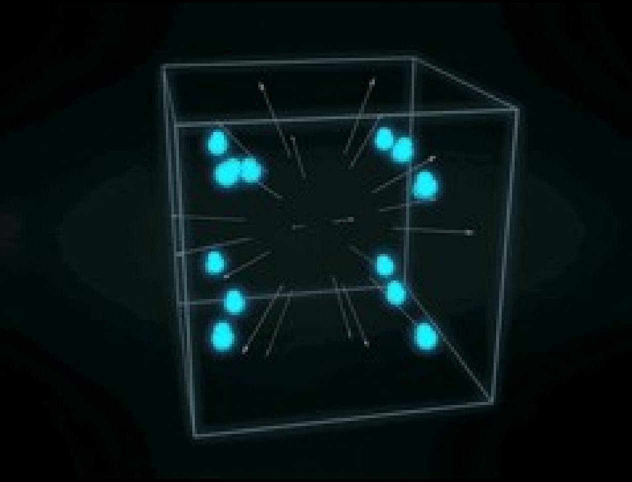
Functional connectivity
= statistical dependencies between regional time series (eg, Pearson correlation, ICA,...)

Effective connectivity
= causal (directed) influences between neuronal populations (eg, DCM, Granger C., etc)

Nobody cares about **Morphological connectivity** □ ...



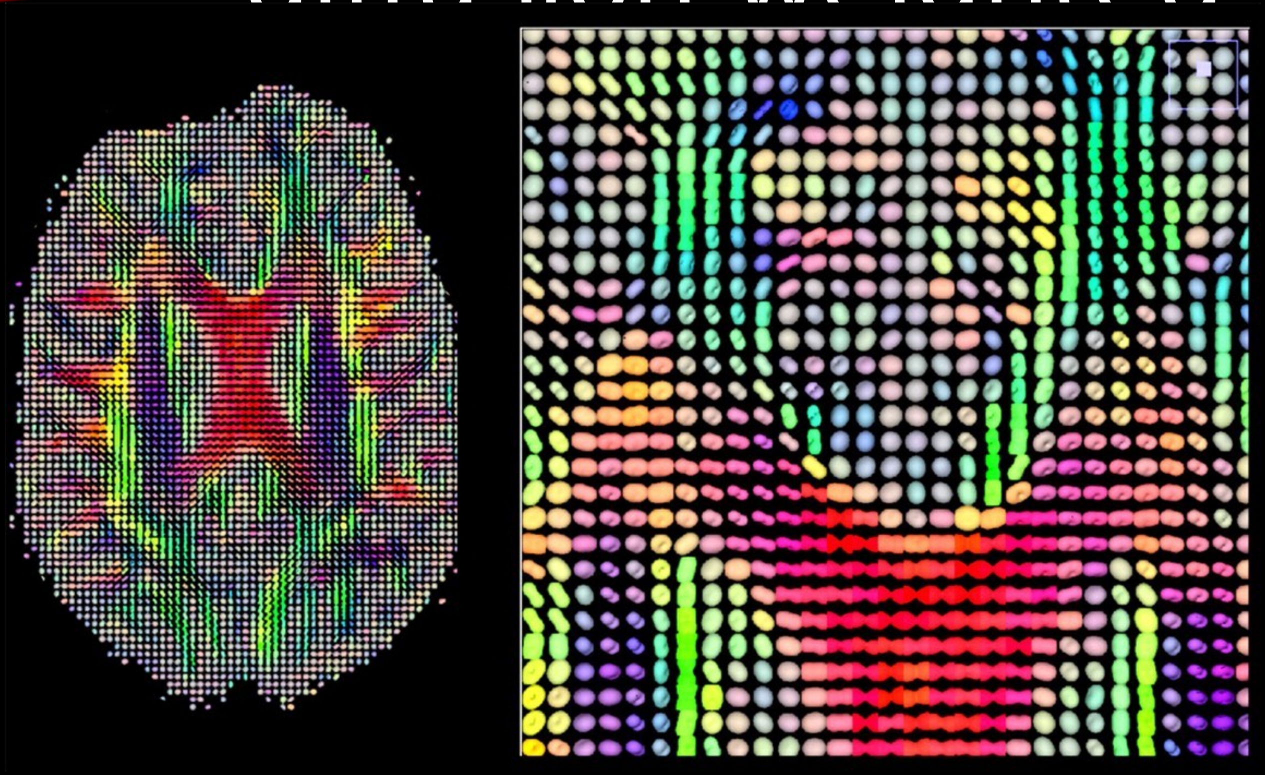
Plenty of water in the brain



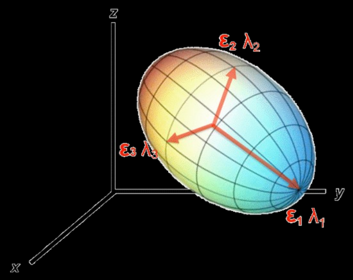
Credit: MaxPlanck Society

Structural Connectivity

diffusion weighted images



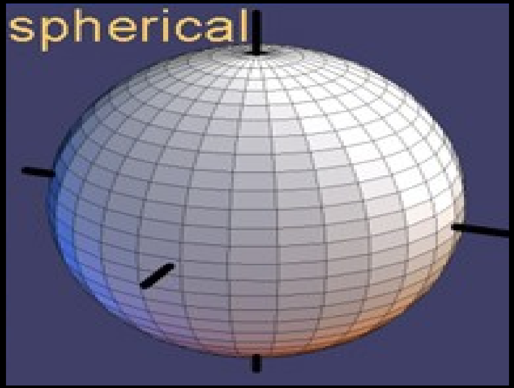
$$\bar{D} = \begin{vmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{vmatrix}$$



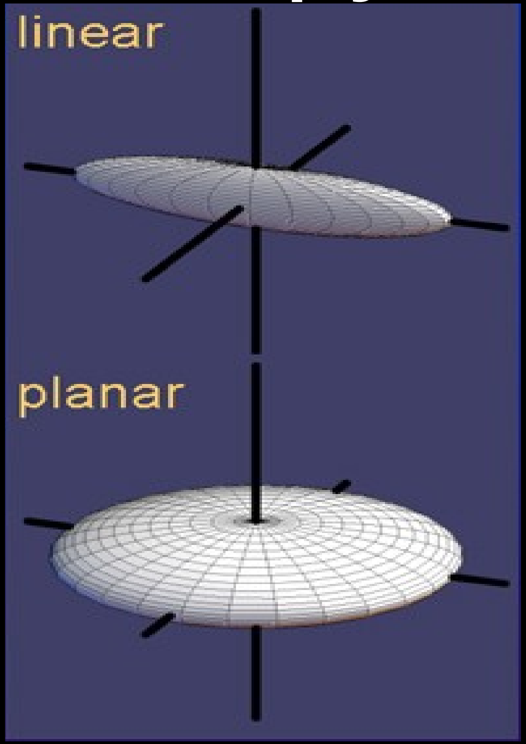
$$FA = \sqrt{\frac{(\lambda_1-\lambda_2)^2+(\lambda_2-\lambda_3)^2+(\lambda_1-\lambda_3)^2}{2({\lambda_1}^2+{\lambda_2}^2+{\lambda_3}^2)}}$$

(Alger 2012 J.Neurocience)

Models of 3D Isotropy



Isotropic



Anisotropic

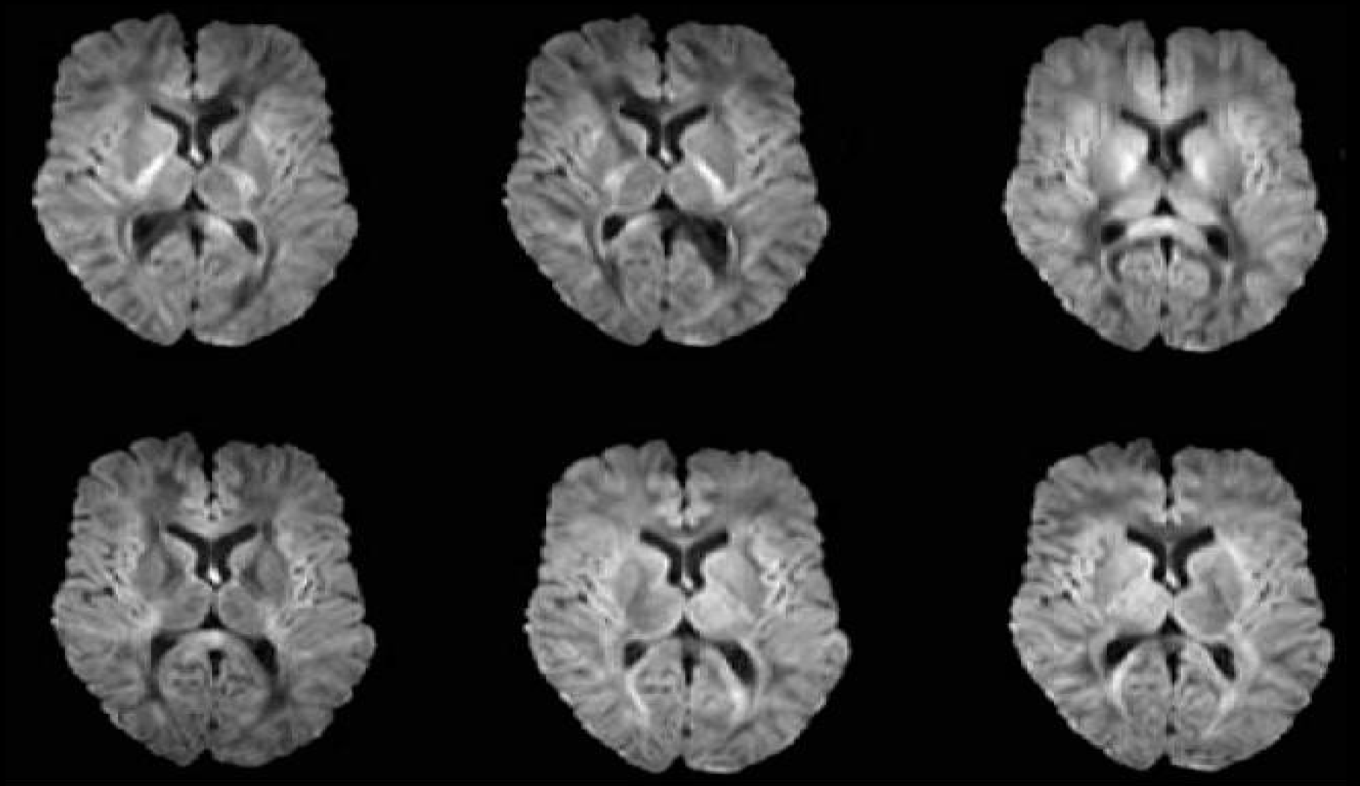
DTI Sequence

- Repeat the DWI sequence with gradients applied in a number of different directions
- From the contribution of all the different directions we can calculate the direction of diffusion as well as the relative rate (ADC)
- Areas with restricted diffusion will have a directional bias which is used to determine the direction of diffusion

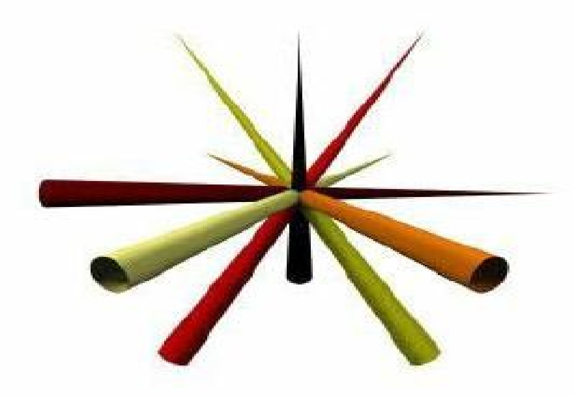
Raw Diffusion Images
6 directions

- Diffusion sensitive gradients applied in six directions all with b=1000

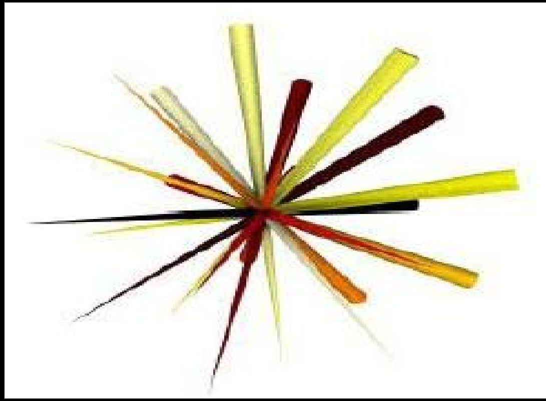
- Dark areas represent areas with a higher degree of restricted diffusion



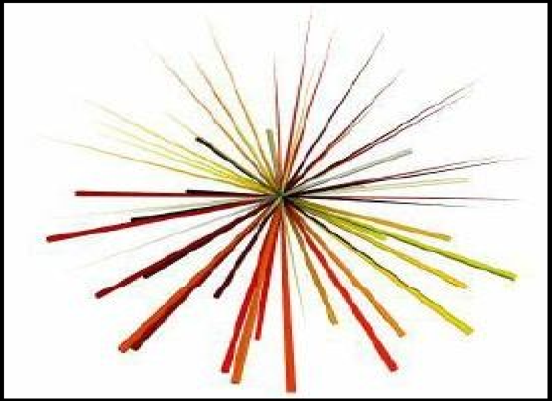
Different Gradient Directions



6 Directions



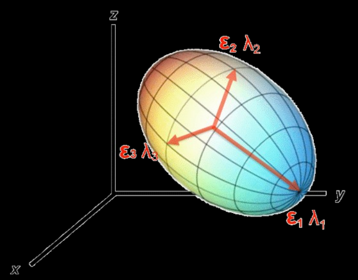
12 Directions



30 Directions

Diffusion Tensor

$$\mathbf{D} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{xy} & D_{yy} & D_{yz} \\ D_{xz} & D_{yz} & D_{zz} \end{bmatrix}$$

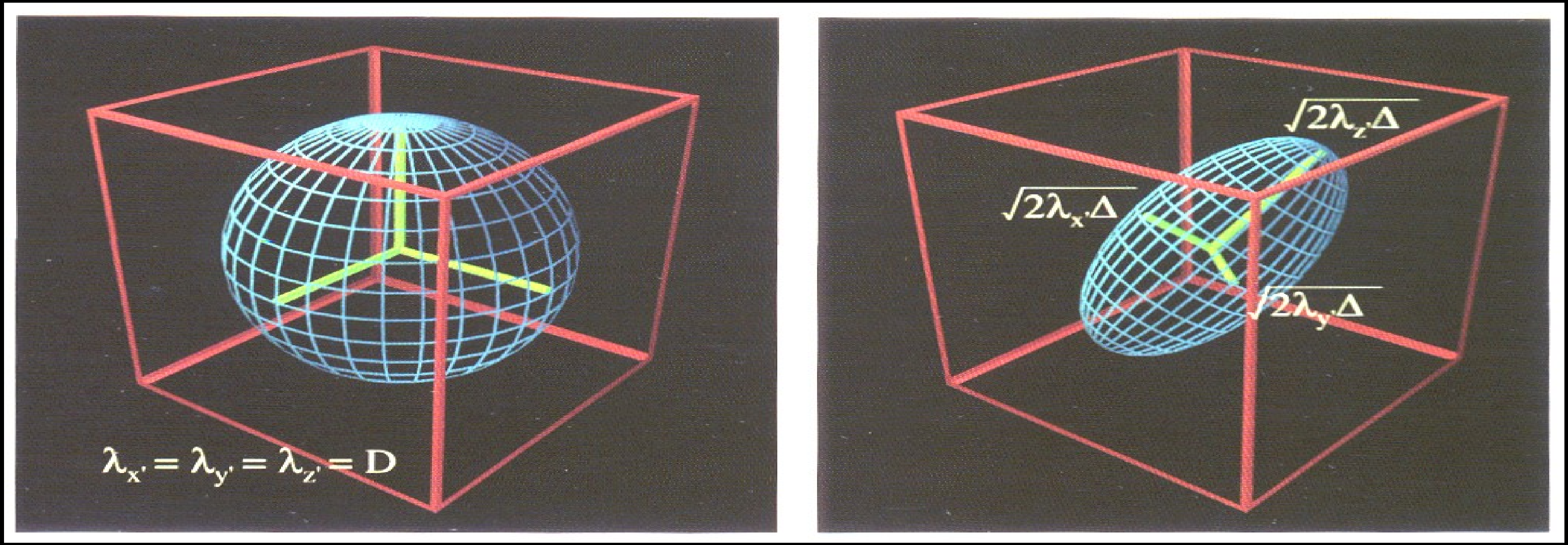


- Diffusion properties described with a 3 X 3 symmetric tensor matrix
- Diagonal elements of D (Dxx , Dyy , Dzz) are the ADC values along x, y and z axes respectively
- Off-diagonal elements (Dxy , Dxz , Dyz) represent the correlation between molecular displacements in orthogonal directions

DTI Calculation

- Eigenvalues of the diffusion tensor (λ_x, λ_y, and λ_z) provides length of the ellipsoid in the three principal directions of diffusivity
- Eigenvectors provide information about the direction of diffusion
- The eigenvector corresponding to the largest eigenvalue is used as the main direction of diffusion
- Maps are constructed of various measures of anisotropy from the eigenvalues and eigenvectors

Tensor Model of Isotropy

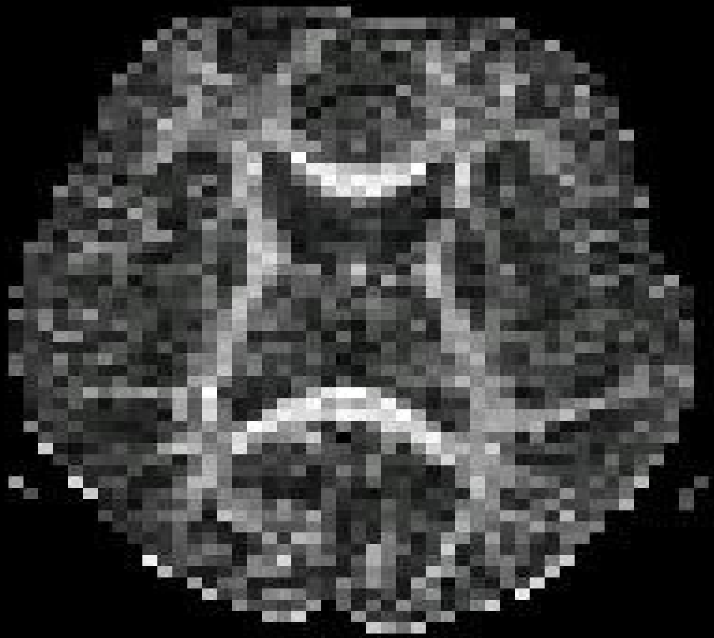


Isotropic **Anisotropic**

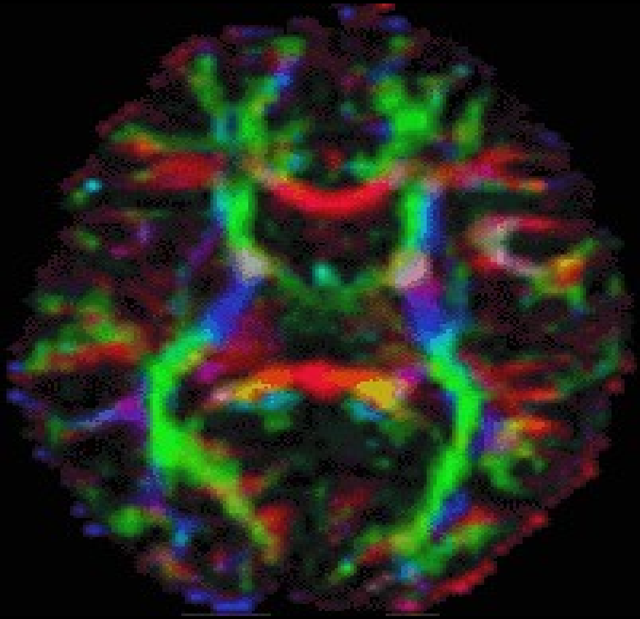
Fractional Anisotropy (FA)

- Measure of degree of anisotropy regardless of direction
- Brighter areas correspond to areas with higher degree of anisotropic diffusion
- Ranges from 0 – 1 where FA=1 corresponds to completely anisotropic

$$FA = \sqrt{\frac{(\lambda_x - \lambda_y)^2 + (\lambda_x - \lambda_z)^2 + (\lambda_y - \lambda_z)^2}{2(\lambda_x^2 + \lambda_y^2 + \lambda_z^2)}}$$



Visualization of Direction of Diffusion (general convention)

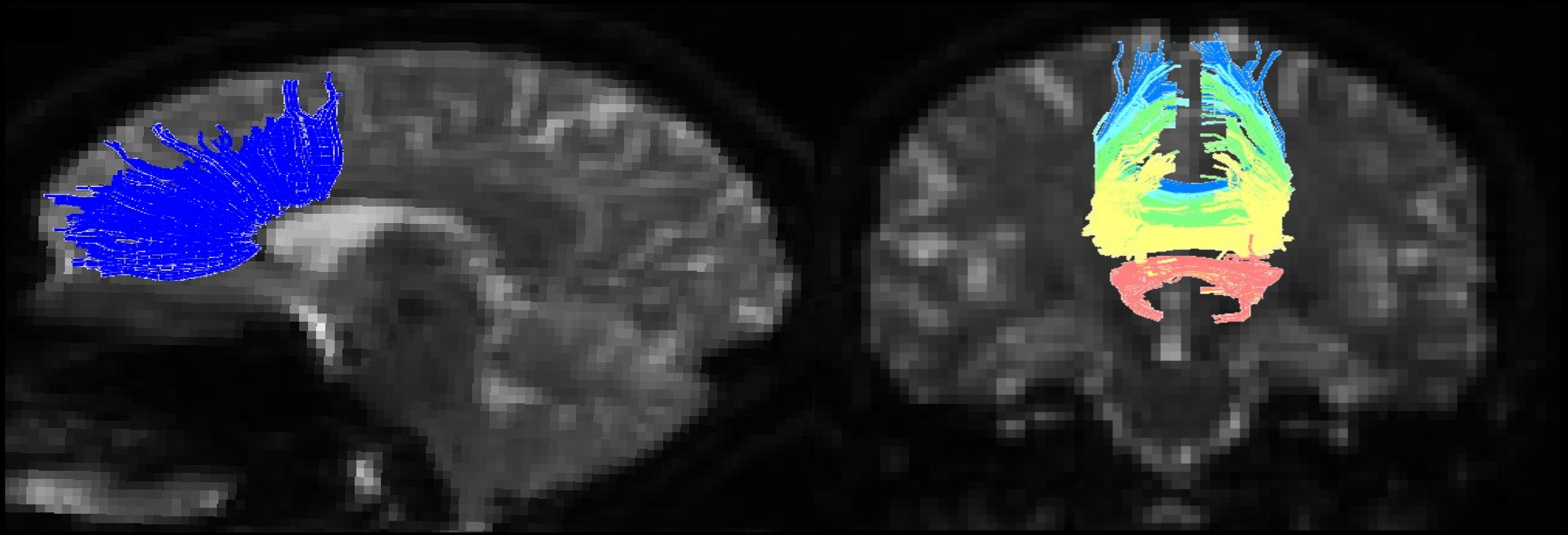


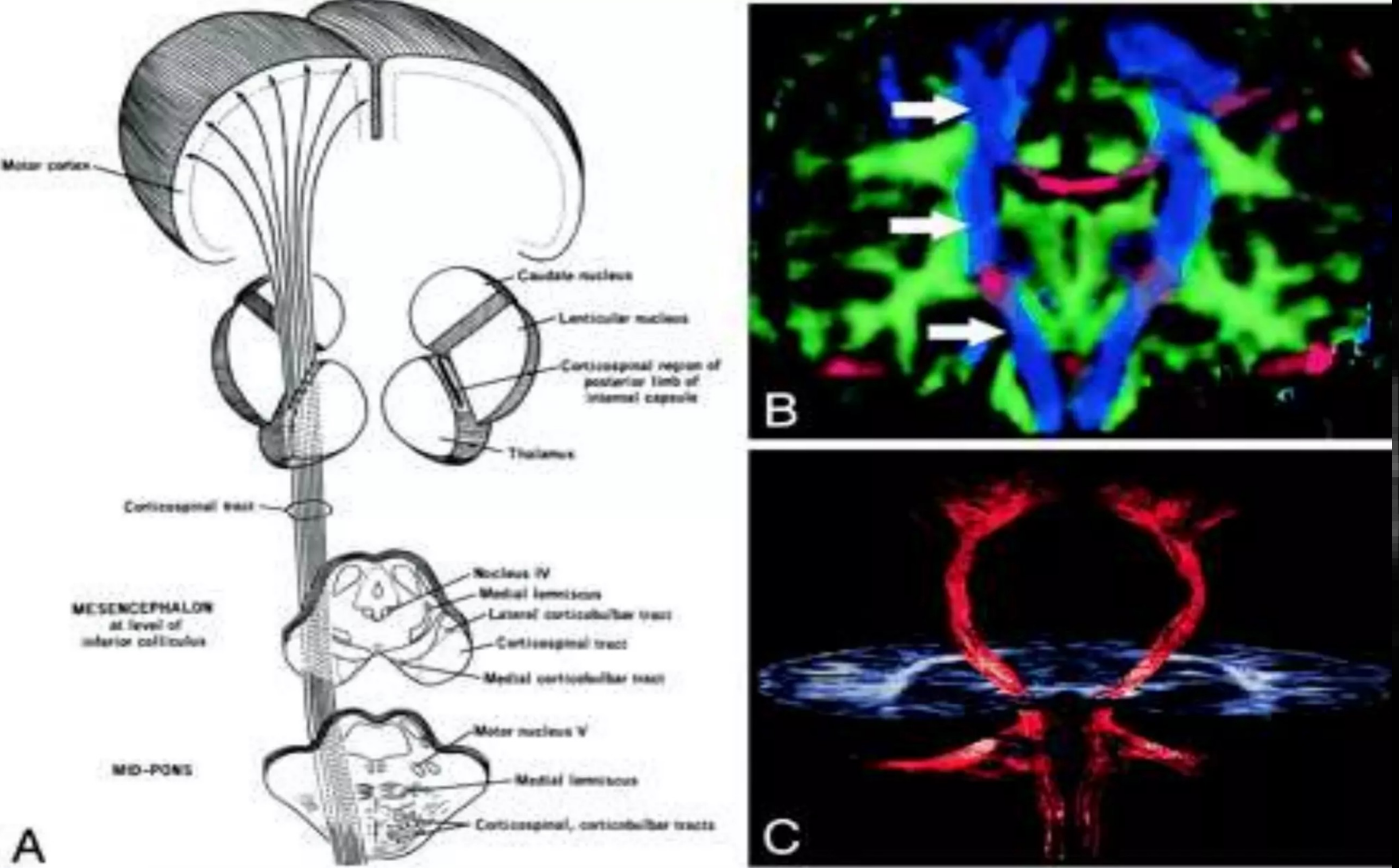
Red = Left-Right

Green = Anterior-Posterior

Blue = Superior-Inferior

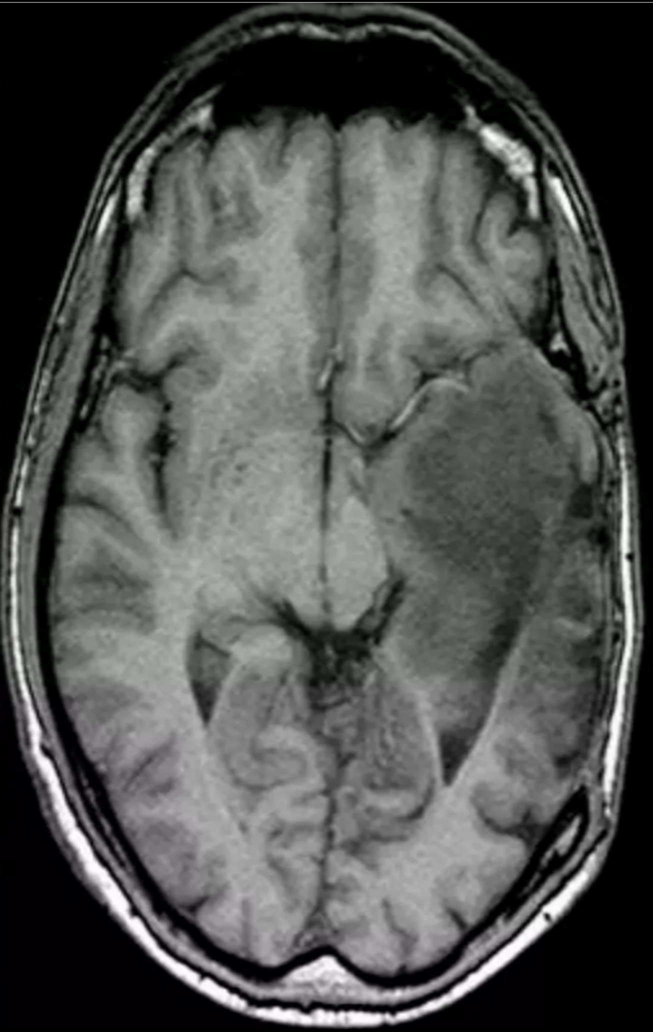
Structural Connectivity: Corpus Callosum Tracts

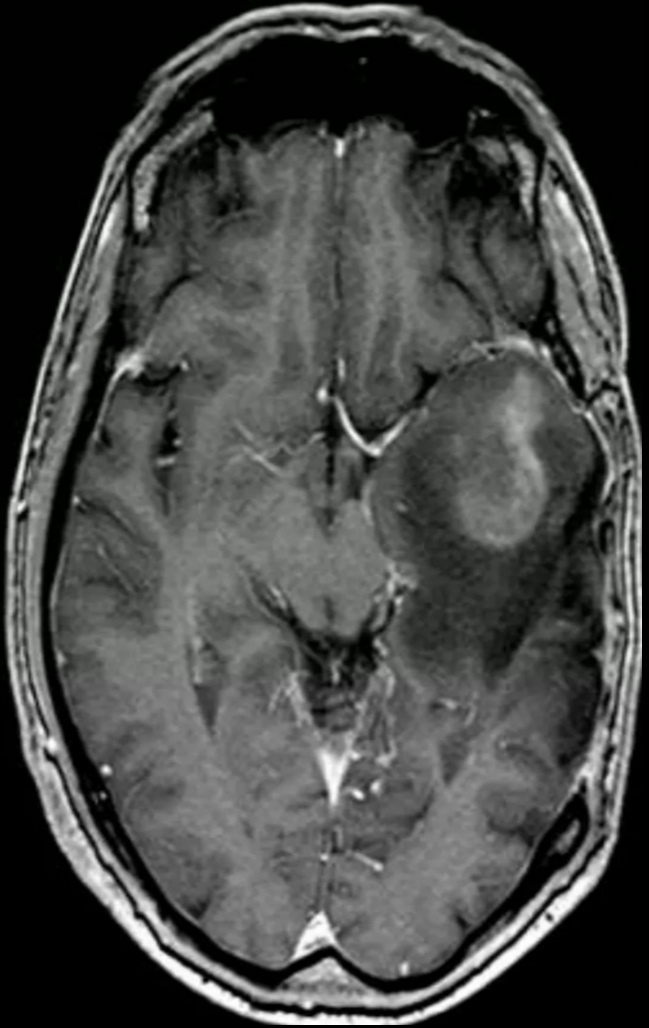


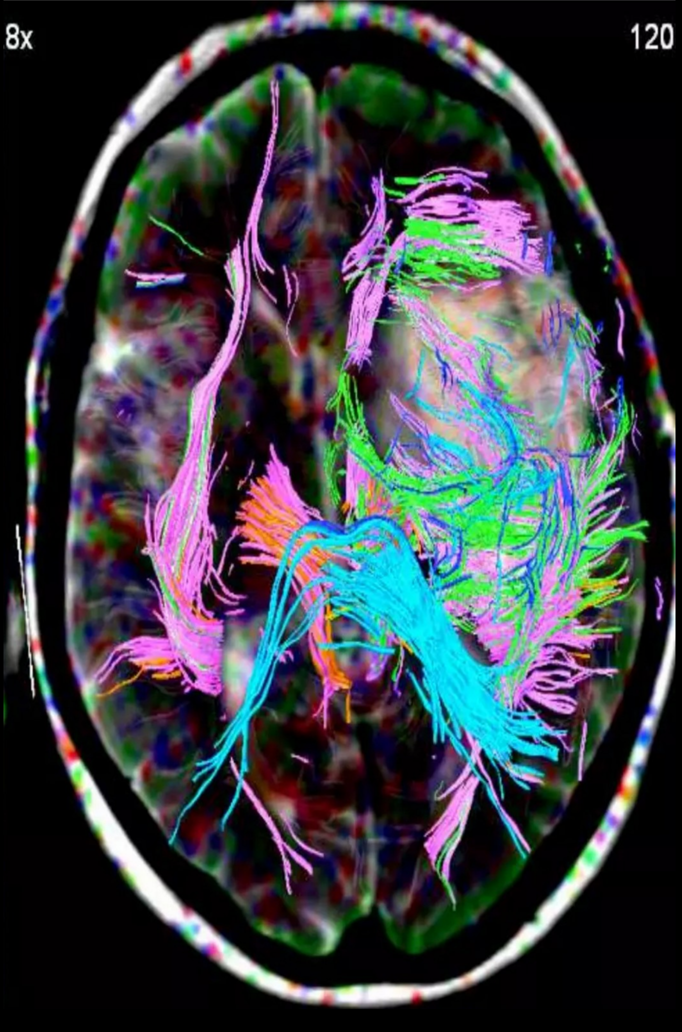


Motor cortex
Caudate nucleus
Lenticular nucleus
Corticospinal region of posterior limb of internal capsule
Thalamus
Corticospinal tract
Nucleus IV
Medial lemniscus
MESENCEPHALON at level of inferior colliculus
Lateral corticobulbar tract
Corticospinal tract
Medial corticobulbar tract
Motor nucleus V
MID-PONS
Medial lemniscus
Corticospinal, corticobulbar tracts
A
B
C

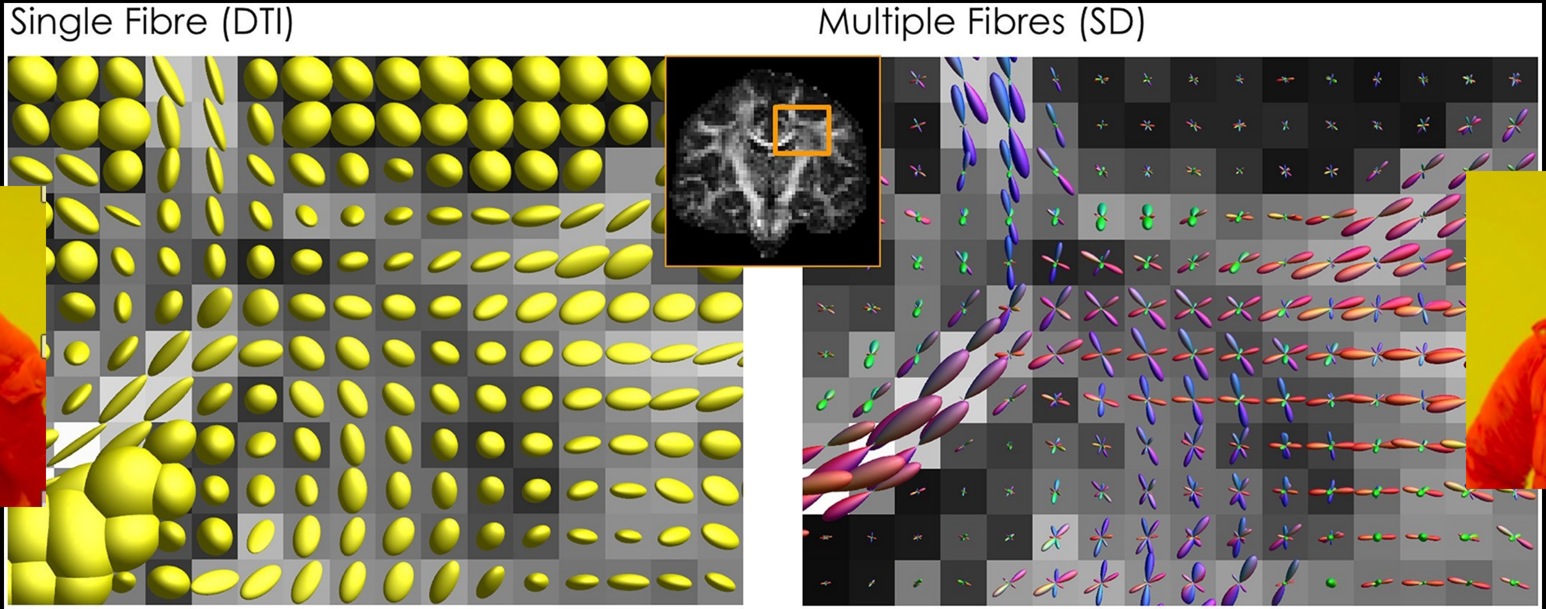
Structural Connectivity with brain tumor





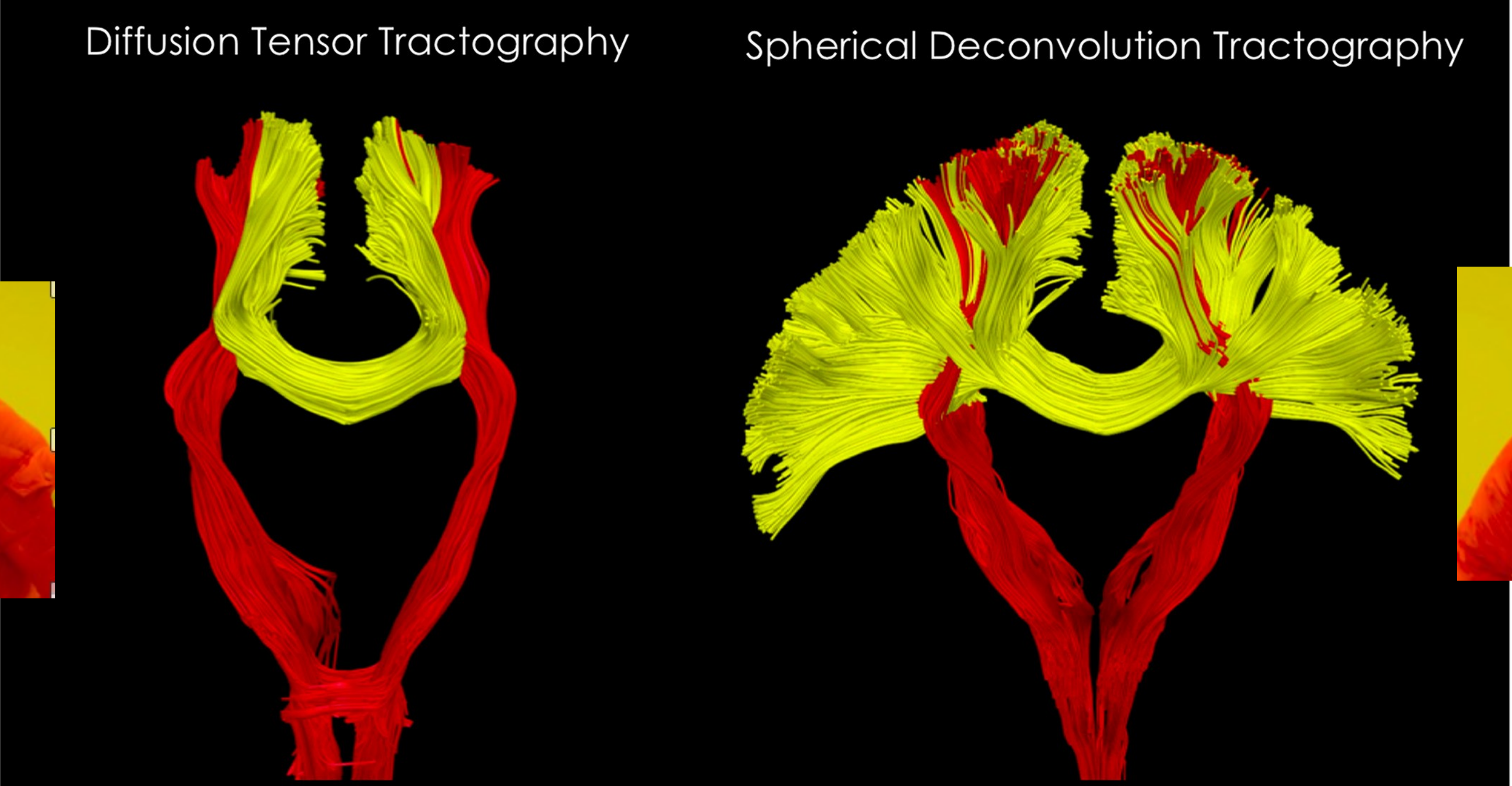


MODELS MATTER



(Dell'acqua & Tournier NRM in Biomedicine 2018)

MODELS MATTER



(Dell’acqua & Tournier NRM in Biomedicine 2018)

Break

Constrained spherical deconvolution-based (CSD)

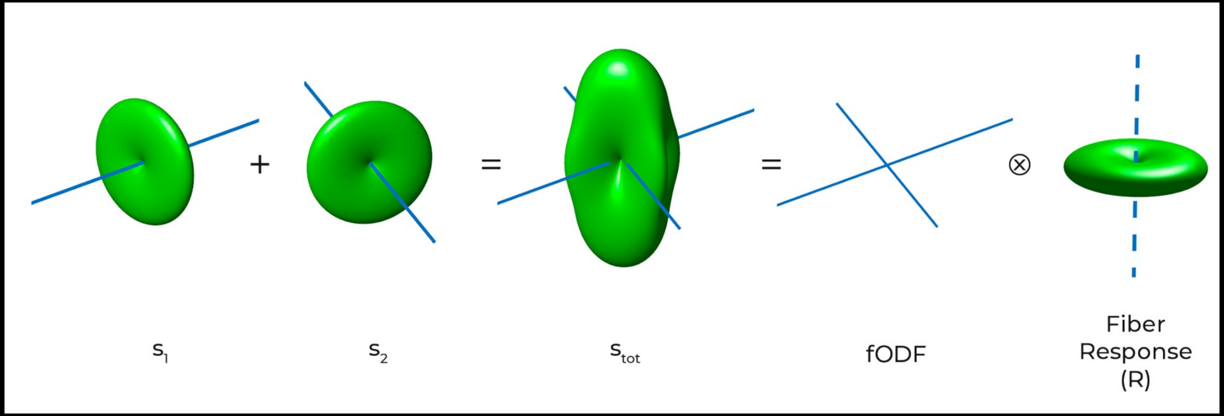
An alternative model to DTI which accommodates the issue of ‘crossing fibers’ is the fiber orientation distribution (fODF)

With CSD we assume that the DWI signal is a convolution of the true fiber orientation distribution and the response function of the imaging system

CSD calculates multiple tensors in heterogeneous regions and is thus able to support crossing fibers and areas of multiple fiber orientations.

Spherical Harmonics: CSD typically uses spherical harmonics to represent the fODF, which can capture multiple fiber orientations within a single voxel accurately.

CSD



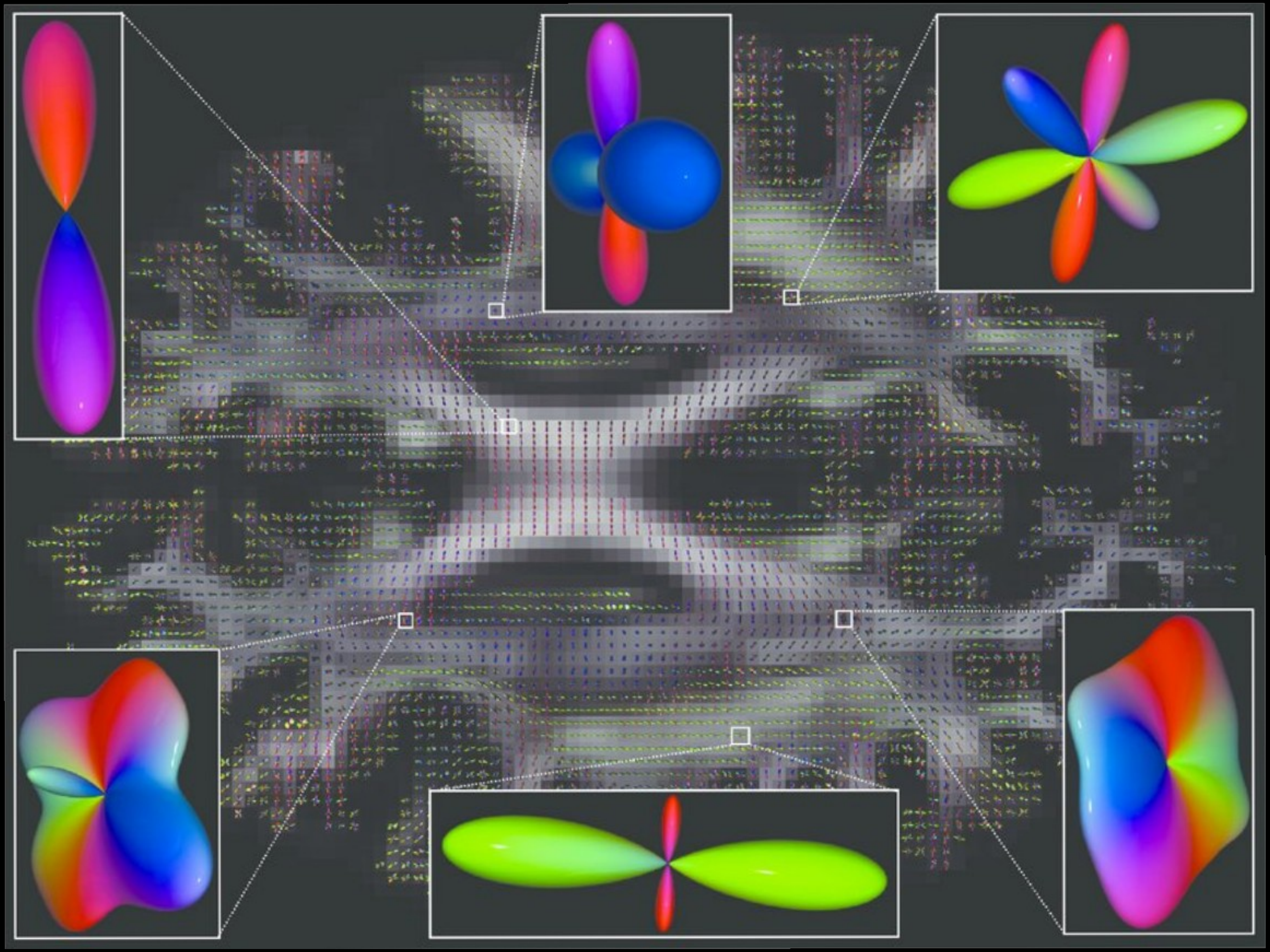
$$Y_\ell^m(\theta,\varphi) = N e^{im\varphi} P_\ell^m(\cos\theta)$$

The CSD model then estimates the fiber orientation distribution (fODF) by assuming that the diffusion weighted signal captured can be adequately described by the fiber response function(the diffusion weighted signal in each voxel is a summative combination of the fiber response from the multiple fibers in each voxel).

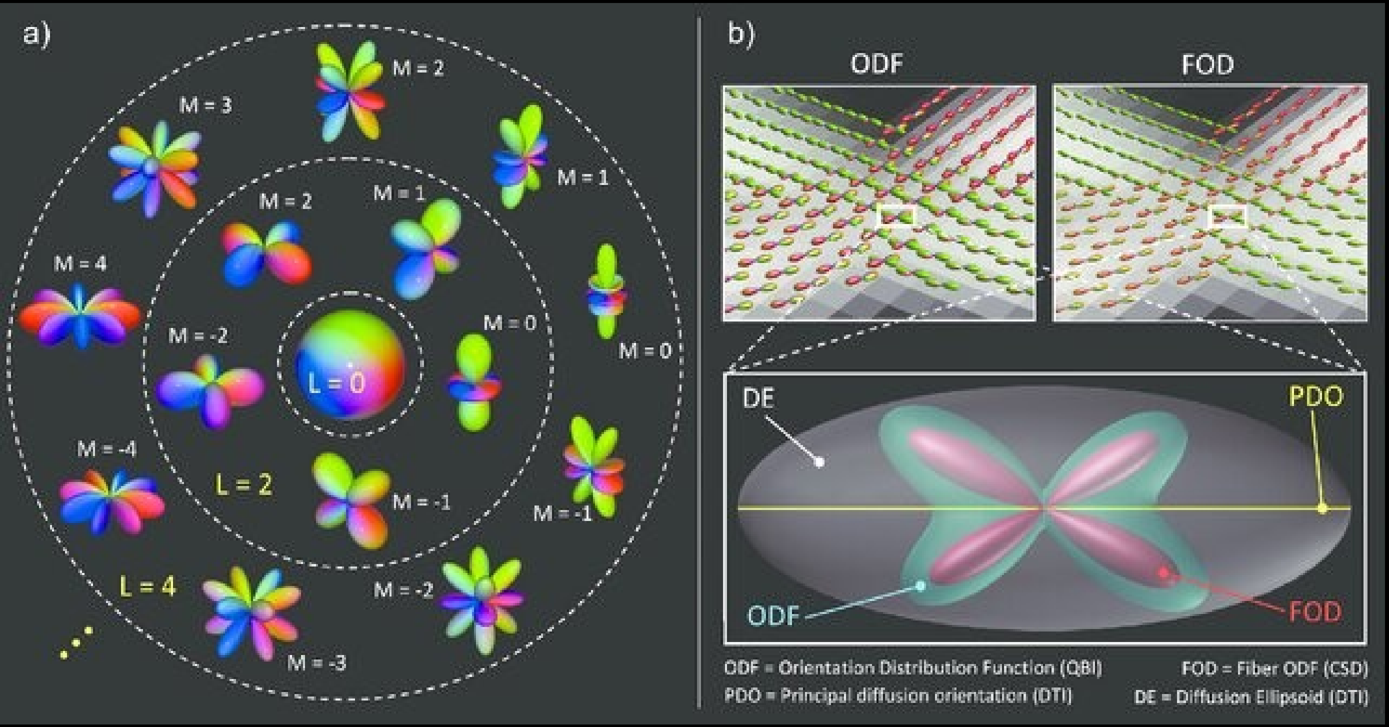
We represent fODF in a spherical harmonic basis.

One of the innovations of CSD is therefore to penalize negative amplitudes through a soft regularizer in the least-squares fit of the coefficients of the fODF to the diffusion weighted signal.

This soft regularizer penalises negative amplitudes in the fODF coefficients which does not guarantee a non-negative solution but prefers one.



Spherical harmonics



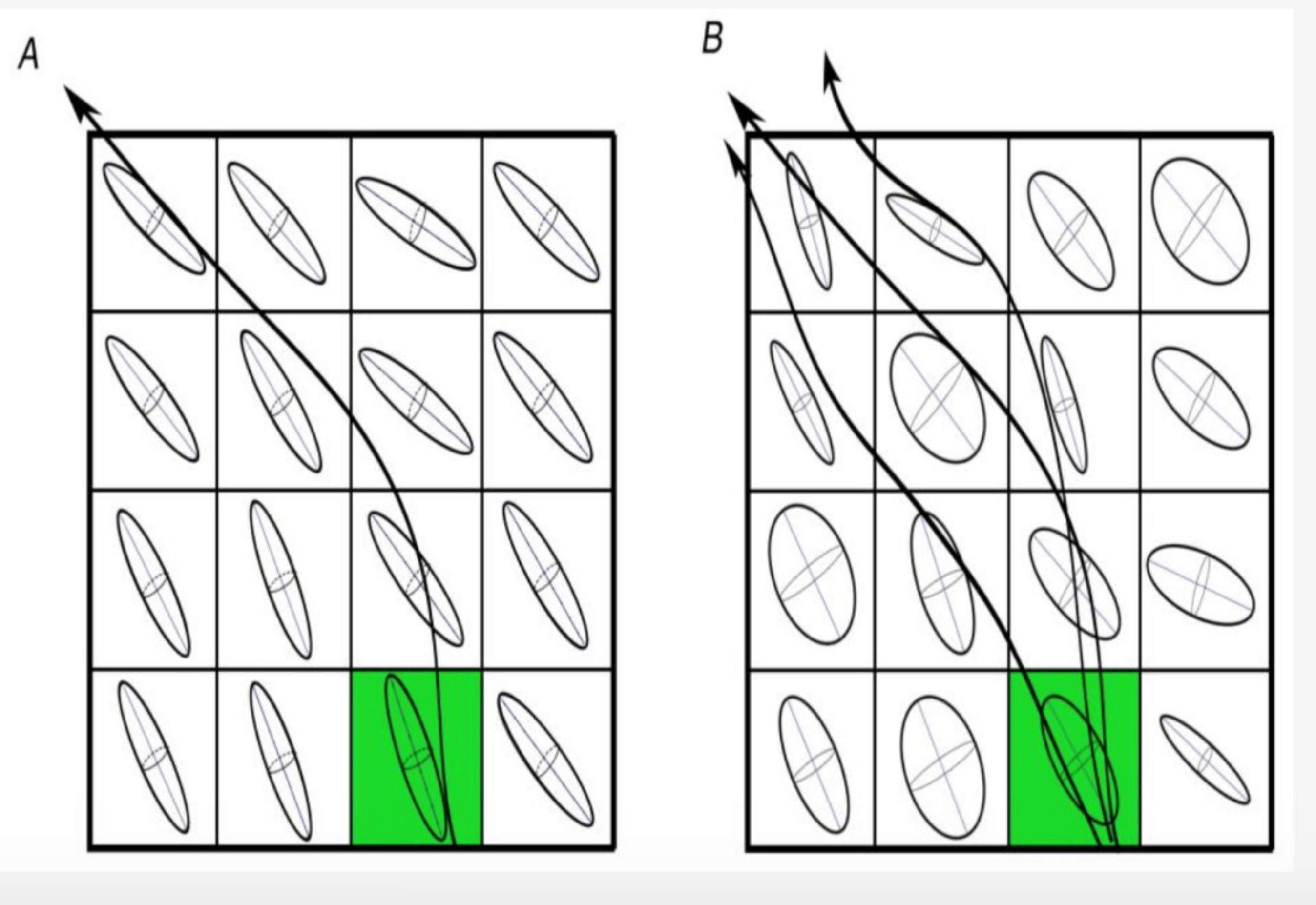
$$Y_\ell^m(\theta, \varphi)$$

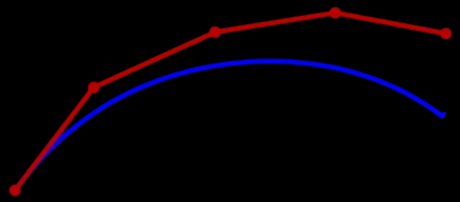
"l" (lowercase L) is called the **azimuthal quantum number** and represents the orbital angular momentum. It determines the shape of the spherical harmonics. The allowed values for "l" are non-negative integers (0, 1, 2, 3, ...). The larger the value of "l," the more complex and intricate the shape of the spherical harmonics becomes.

"m" is called the **magnetic quantum number** and represents the projection of the orbital angular momentum along a specific axis. "m" can take values ranging from -l to +l, including zero. Each value of "m" corresponds to a different orientation or angular distribution of the spherical harmonic. For a given value of "l," there are 2l+1 possible values of "m." The orientation of the spherical harmonic depends on the specific value of "m" within the allowed range.

The general expression for spherical harmonics, denoted as $Y_{lm}(\theta, \varphi)$, is a function of two angles, θ (theta) and φ (phi), which represent the polar and azimuthal angles, respectively. The values of "l" and "m" determine which spherical harmonic function you are referring to, and they play a crucial role in characterizing the angular part of a wavefunction or a spherical system.

Deterministic vs Probabilistic



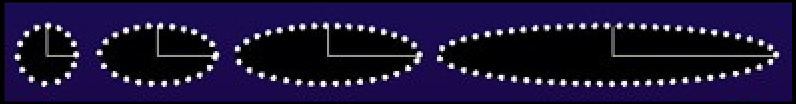


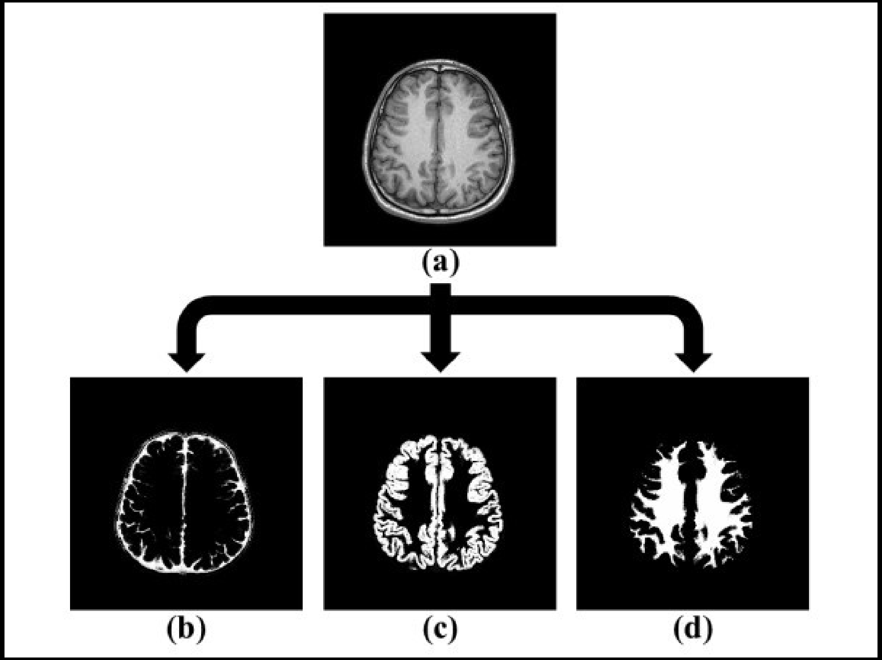
$$y_{n+1} = y_n + hf(t_n, y_n).$$

The Euler method is a first-order method, which means that the local error (error per step) is proportional to the square of the step size,

Stopping criteria

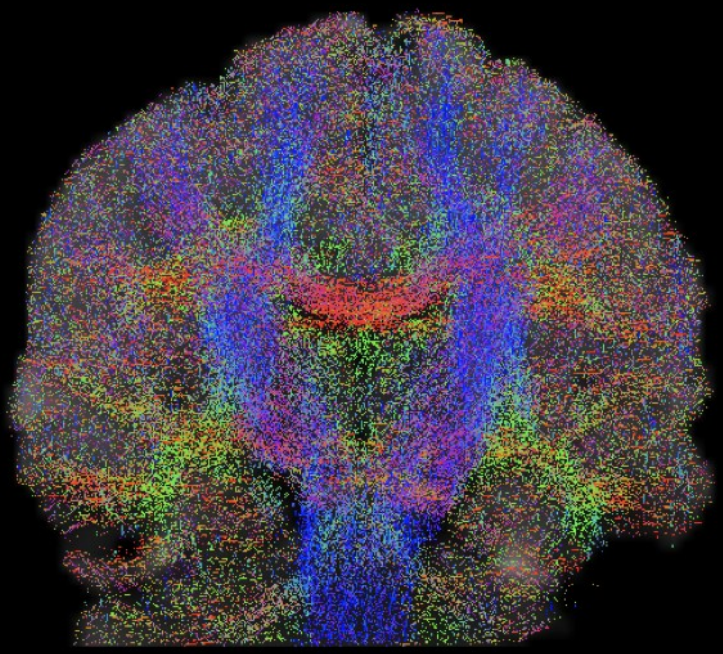
-Fractional anisotropy
-Anatomically constrained tractography
-A combination Of both

Isotropic  Anisotropic

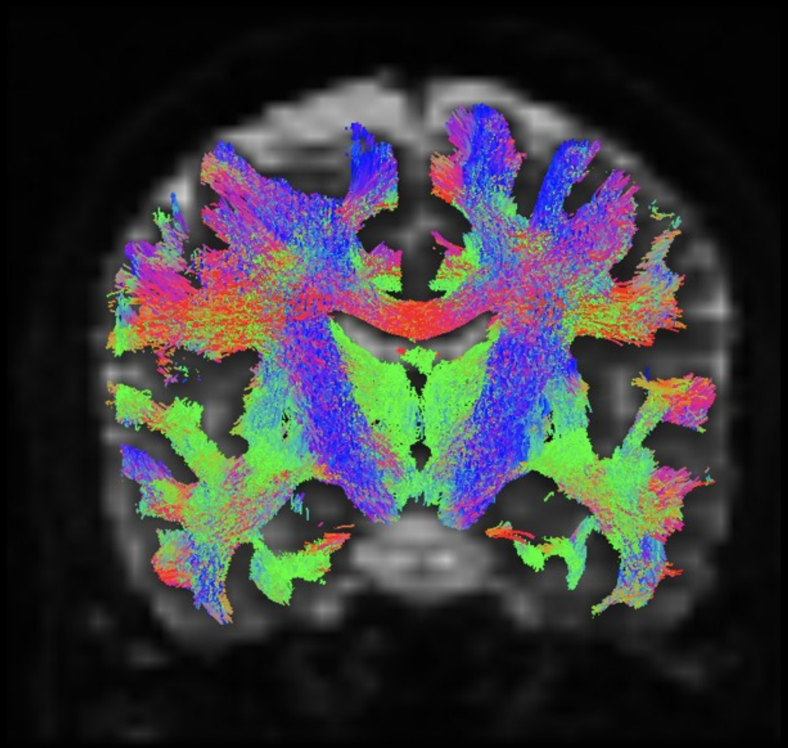


Stopping criteria

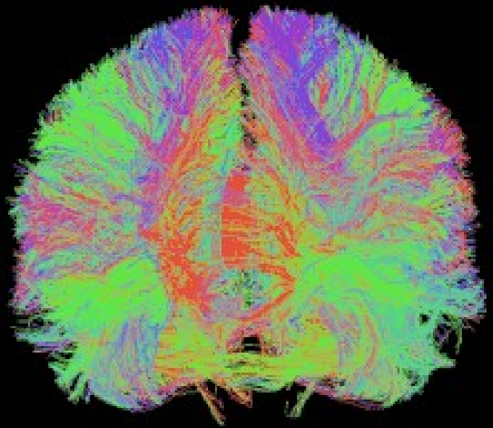
Without ACT

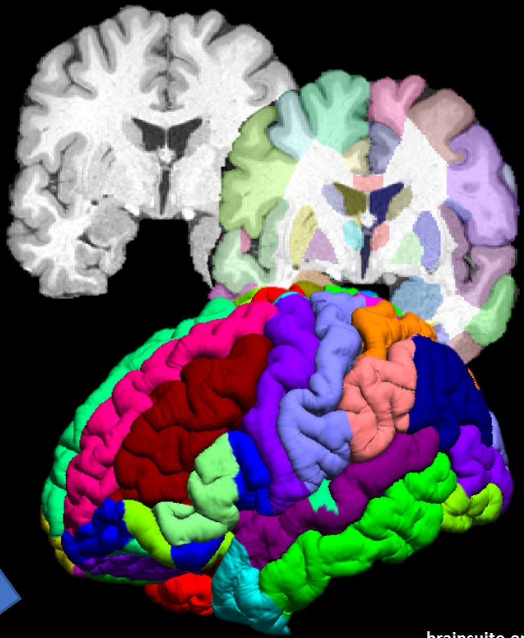


With ACT

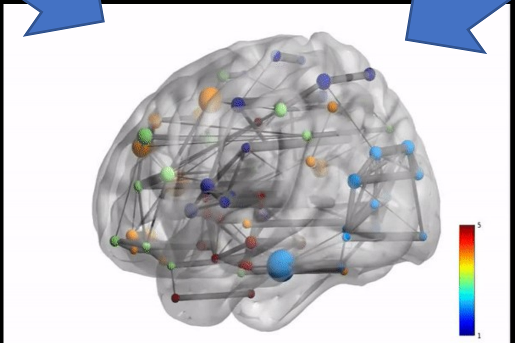


Structural Connectivity

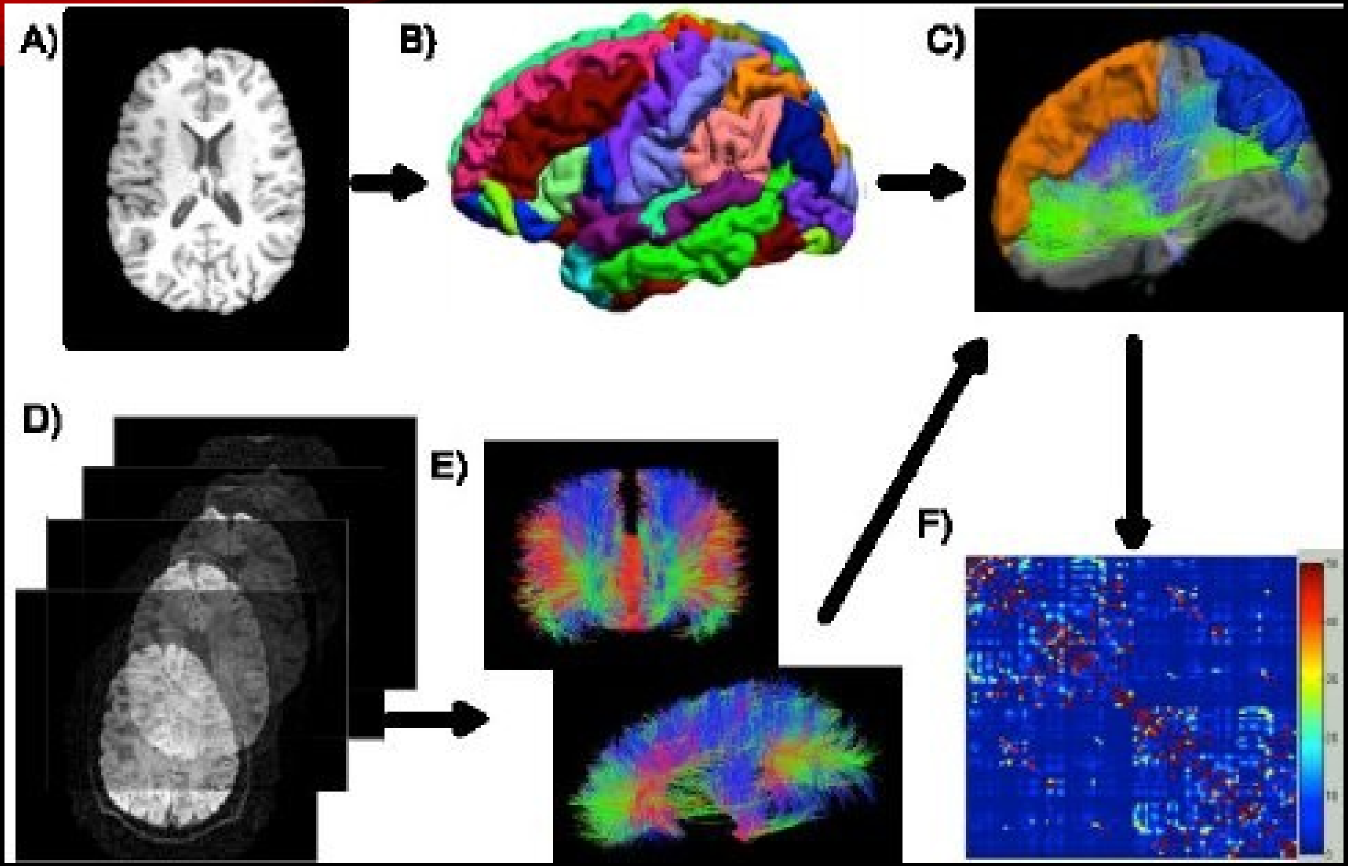




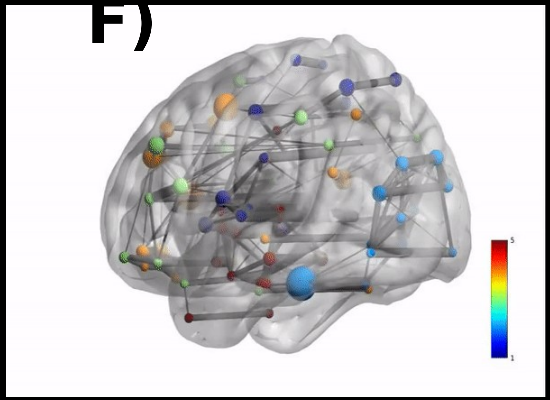
brainsuite.org

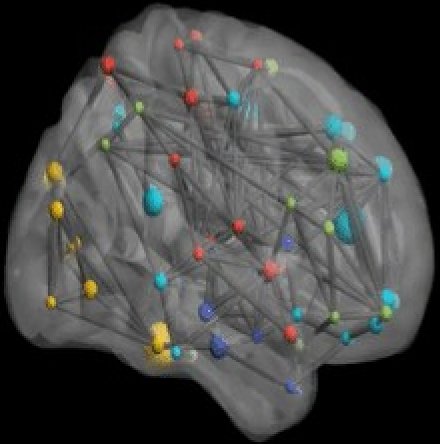


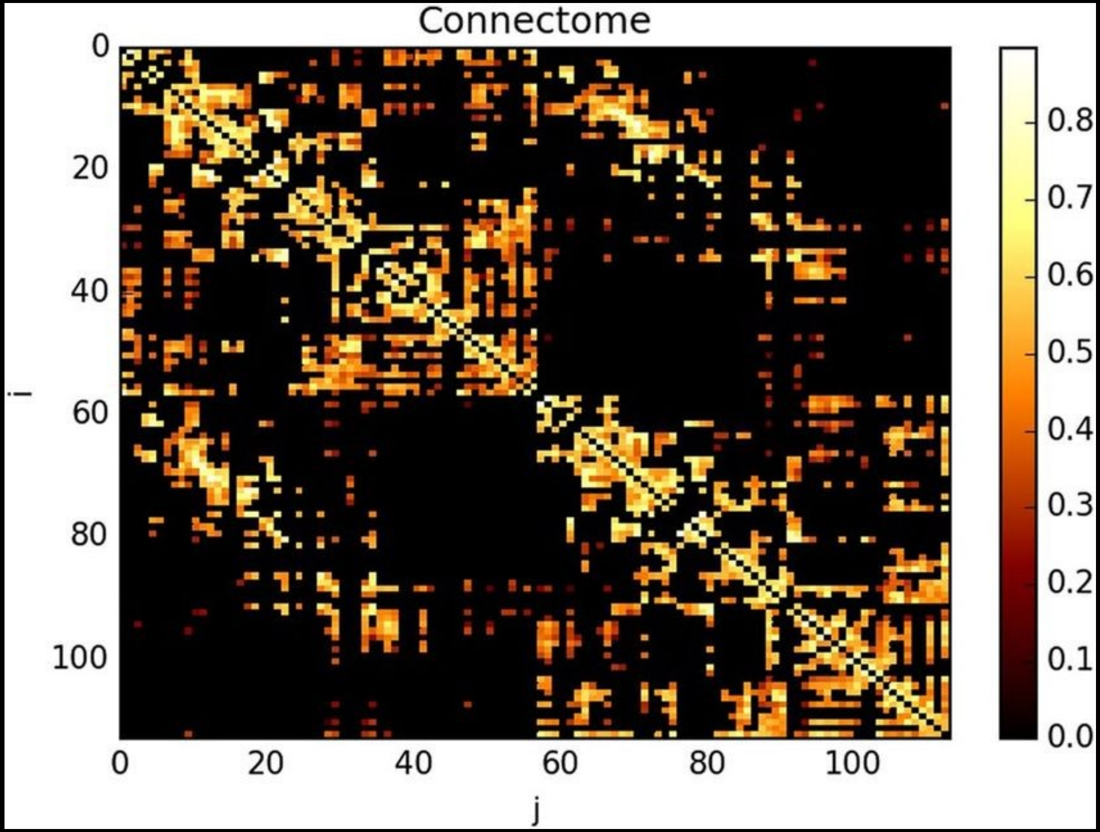
Brain Connectivity



Computationally
The brain network
Is more
represented
As “connectivity
matrix”






Connectome
0
20
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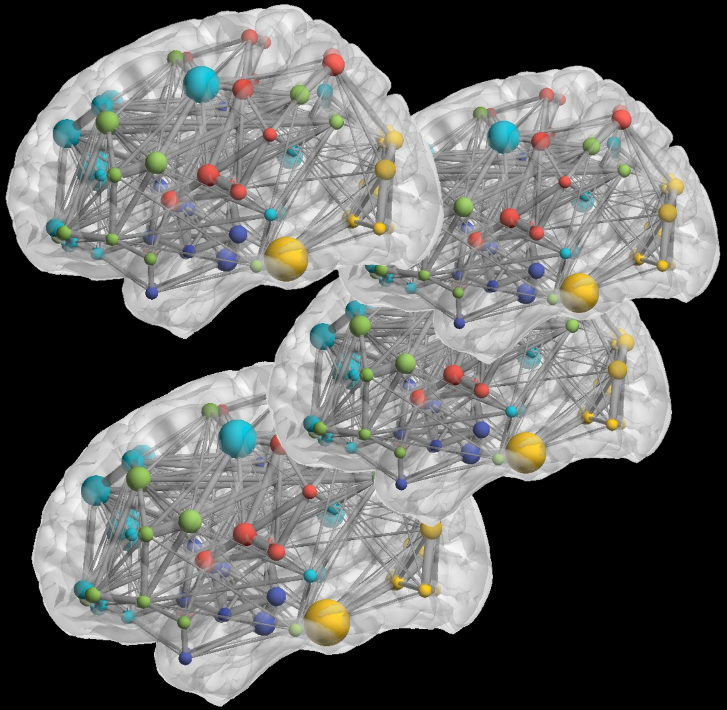
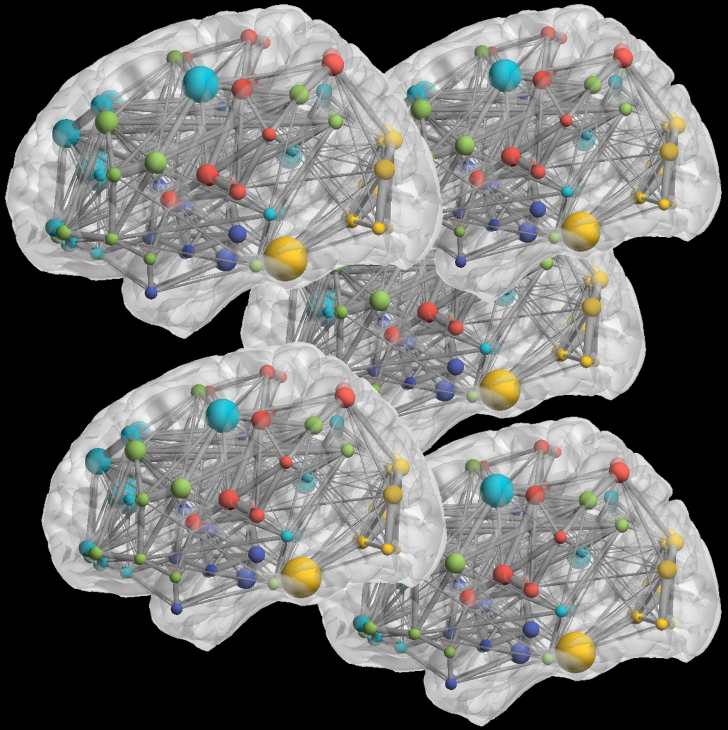
60
80
100
i
j
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0.0

Alzheimer, Schizophrenia,... **Matched healthy control**

Healthy vs Alzheimer





Questions?