Structural Brain Connectivity Analysis on HCP Dataset

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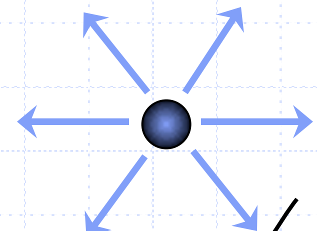
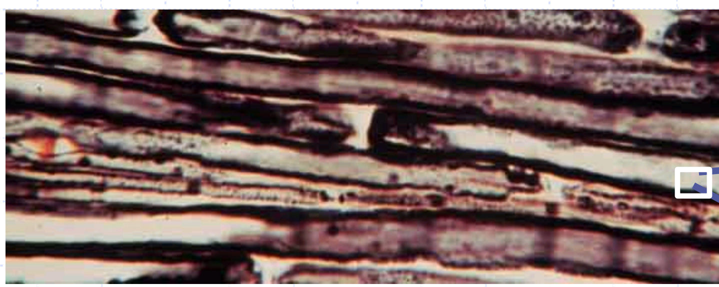
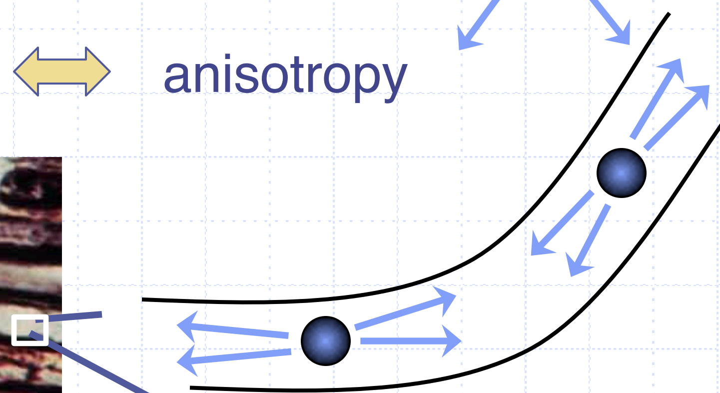
Diffusion in Brain Tissue

- Water molecules in different brain tissues have different diffusion properties.
  - Gray matter: Diffusion is unrestricted ⟺ isotropy
  - White matter: Diffusion is restricted ⟺ anisotropy







  - More diffusion along axon fibers

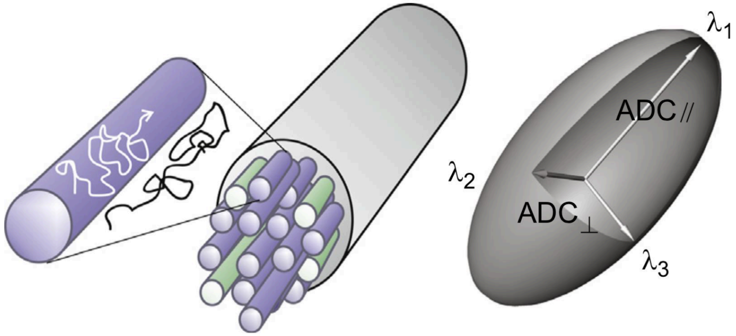
- Diffusion MRI measures the water diffusion movement inside brain

Representation of the Diffusion Directions

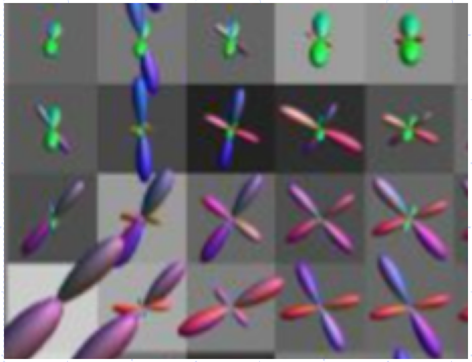
- At each voxel, we want to know:
  - What is the orientation of the diffusion?
  - What is the magnitude of diffusion?

- Two popular representations:
  - Diffusion tensor image (DTI)

$$D = \begin{pmatrix} d_{1,1} & d_{2,1} & d_{3,1} \\ d_{2,1} & d_{2,2} & d_{3,2} \\ d_{3,1} & d_{3,2} & d_{3,3} \end{pmatrix}$$

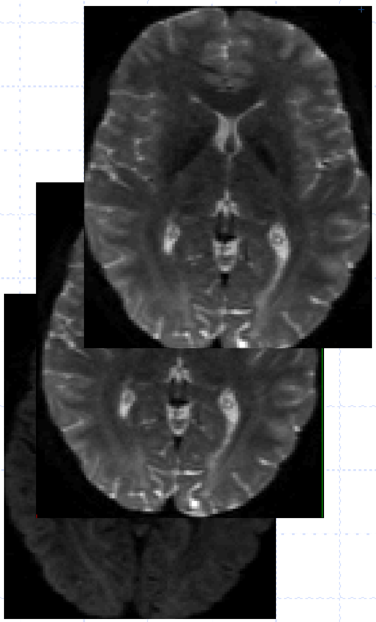


  - High angular resolution diffusion imaging (HARDI)
    - Orientation distribution function [Tuch’04]
    - Diffusion spectrum [Wedeen’05]
    - Ball-and-stick [Behren’s 03]
    - …

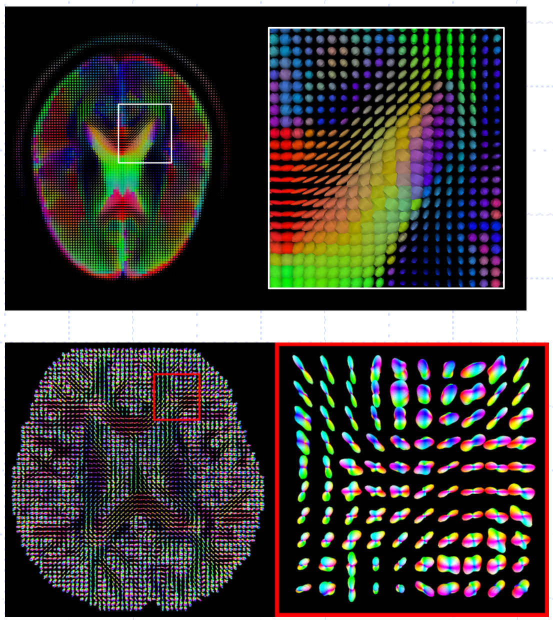


Diffusion MRI to Connectome

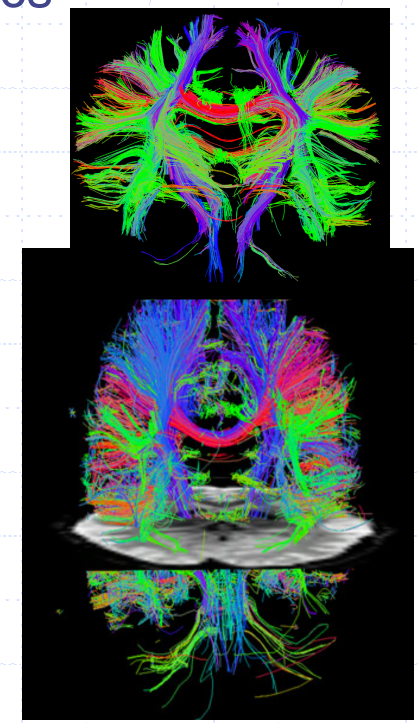
- From dMRI to structural connectomics



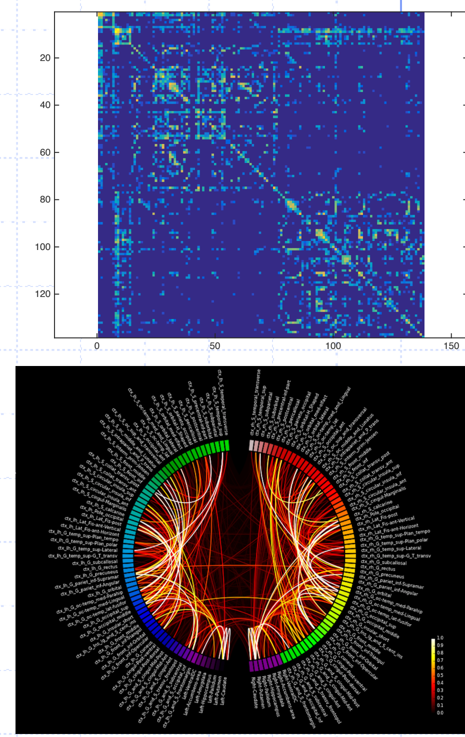
dMRI



diffusion directions



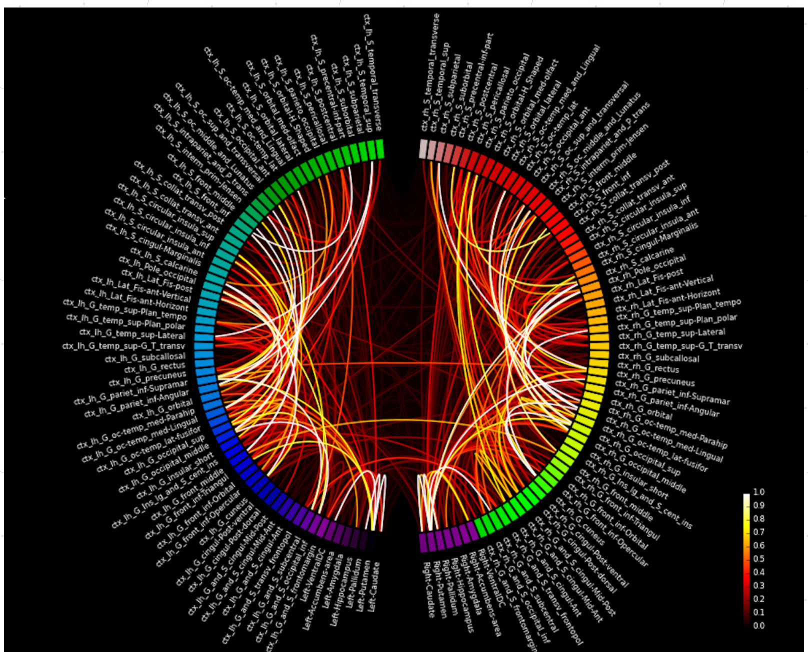
streamlines



connectivity matrix

Diffusion MRI to Connectome

- From raw data to structural connectomics
- From connectomics to brain network analysis



- Inheritance analysis
- Brain network analysis
- Prediction of phenotypes
- …

Introduction of Human Connectome Project

- May, 2009 : Request for Applications from NIH Blueprint
- Sept. 2010 : NIH awarded HCP grants to two consortia
    - Washington U, U of Minn, Oxford U,…
    - MGH and UCLA,…
- Goal of HCP: Characterize human brain connectivity and function
    - Scan ~1,200 healthy adults , ages 22-35, including
        - Twins and their non-twin siblings: MZ twins and DZ twins
- Dec. 2015: 900 subjects dataset release (Latest release)

Data Acquisition

(1) Imaging Data:

- 4 modalities, 1200 subjects, 1 customized 3T scanner (WashU)
  - Structural MRI (T1-weighted, T2-weighted)
  - Resting-state fMRI (rfMRI)
  - Task fMRI (tfMRI)
  - Diffusion MRI (dMRI)

- Improved scanners, pulse sequences: producing high quality data

Data Acquisition

(1) Imaging Data:

(2) MEG/EEG Data:

Data Acquisition

(1) Imaging Data:

(2) MEG/EEG Data:

(3) Behavioral Data:

- Measures that have the potential to covary with brain connectivity and function:
  - NIH Toolbox ; Penn Neuropsychological Battery

- Diverse phonotypes

  Cognition; Emotional health; Motor skills; Sensory; Personality; Fluid intelligence; Family environmental factors

- Demographic, physical data
- Psychiatric status, substance use

Data Acquisition

(1) Imaging Data:

(2) MEG/EEG Data:

(3) Behavioral Data:

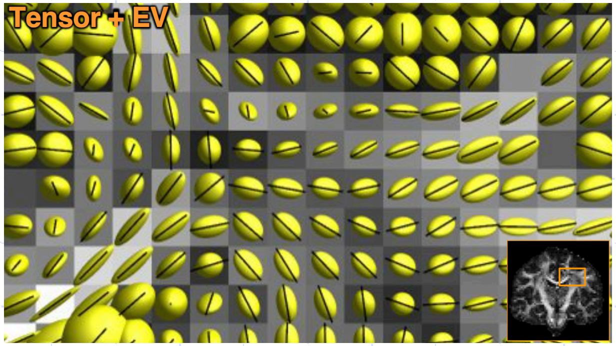
(4) Genetic Data:

Connectome Extraction

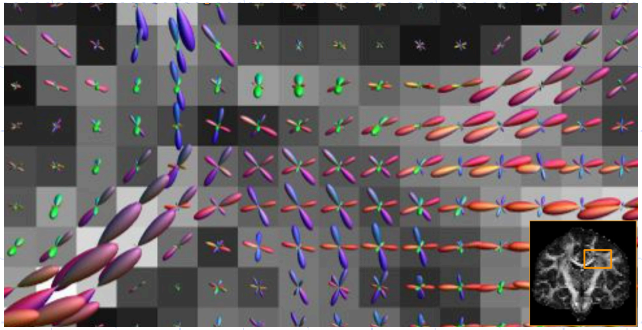
➢ We are interested in extracting the connectome from dMRI in HCP dataset.

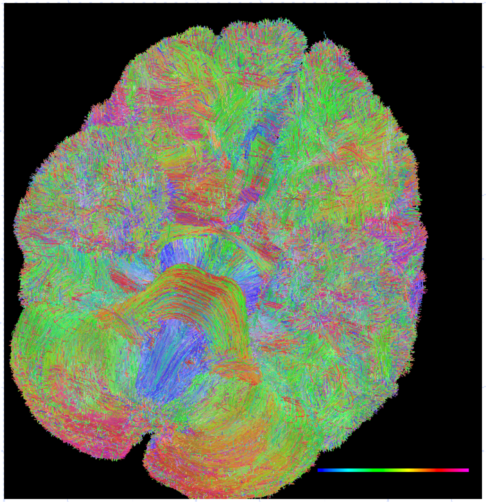
- Step1. Construct HARDI:
  better than DTI, can handle fiber crossing

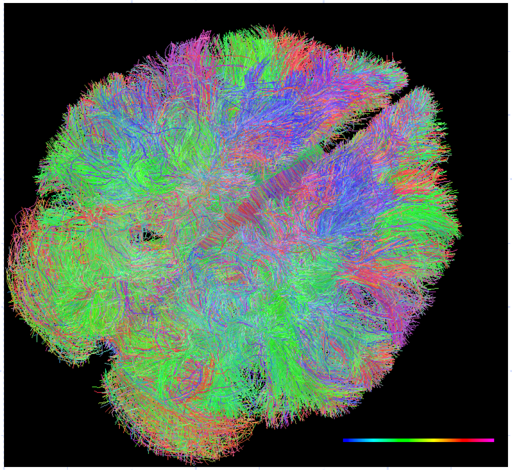
DTI:



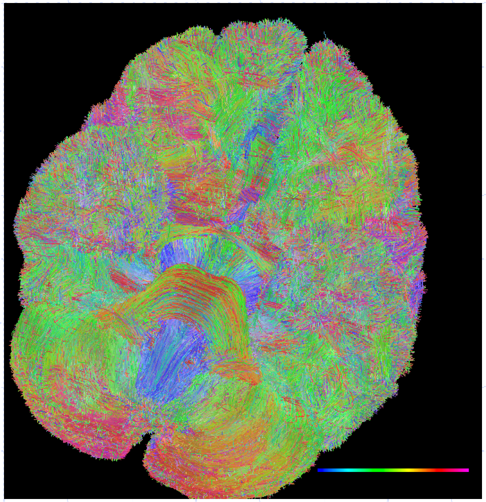
HARDI:

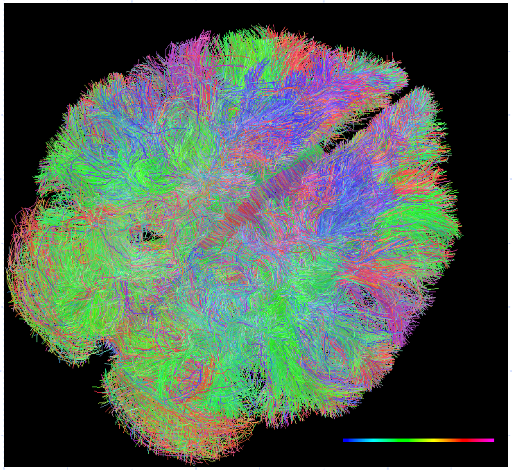






Connectome Extraction





➢ We are interested in extracting the connectome from dMRI in HCP dataset.

- Step1. Construct HARDI:
  better than DTI, can handle fiber crossing

- Step 2. Fiber tracking:
  - Masking
  - Seeding
  - Streamline growing

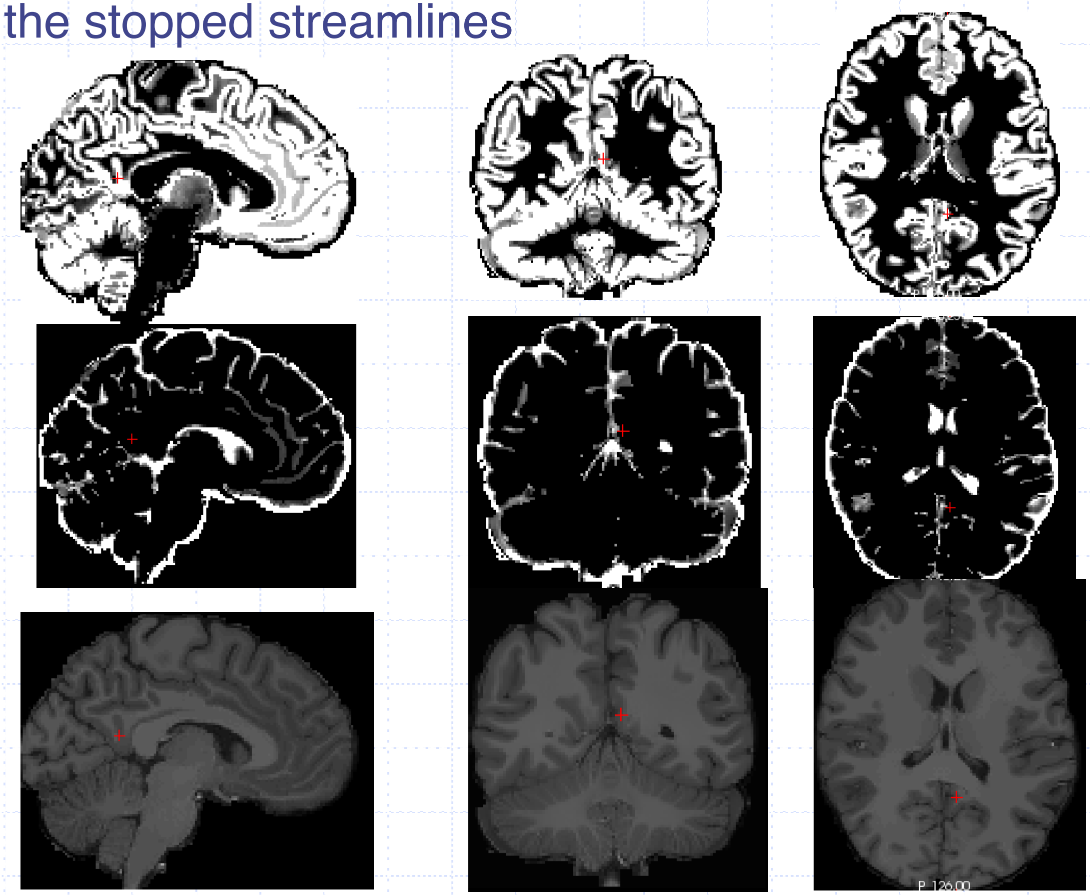
Masking and Seeding

- Masking is used to
  - decide the propagation of a streamline
  - include the stopped streamlines

Included mask:

Excluded mask:

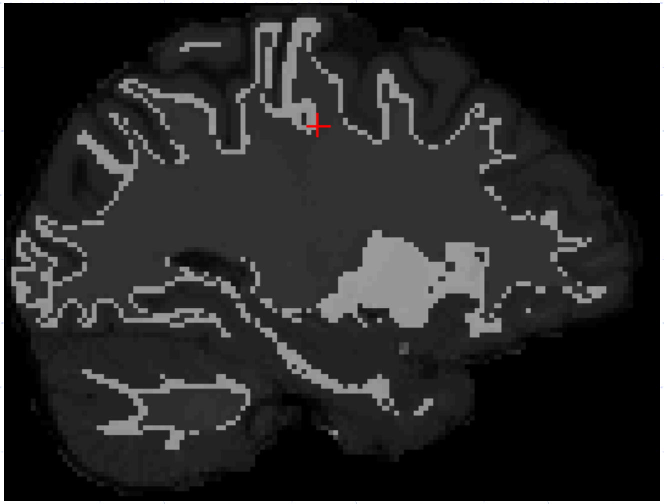
T1 brain:

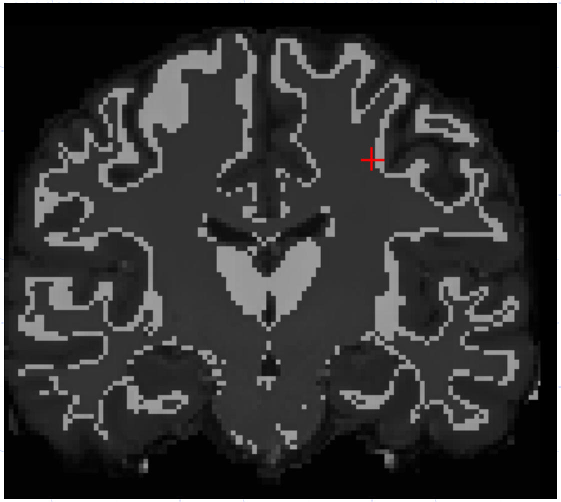


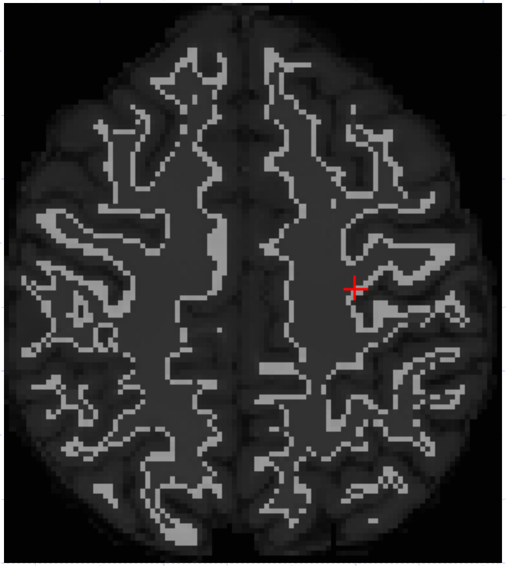
Masking and Seeding

- Seeding is used to
  - reduce the bias of streamlines

Seeding mask (the interface between GM and WM):





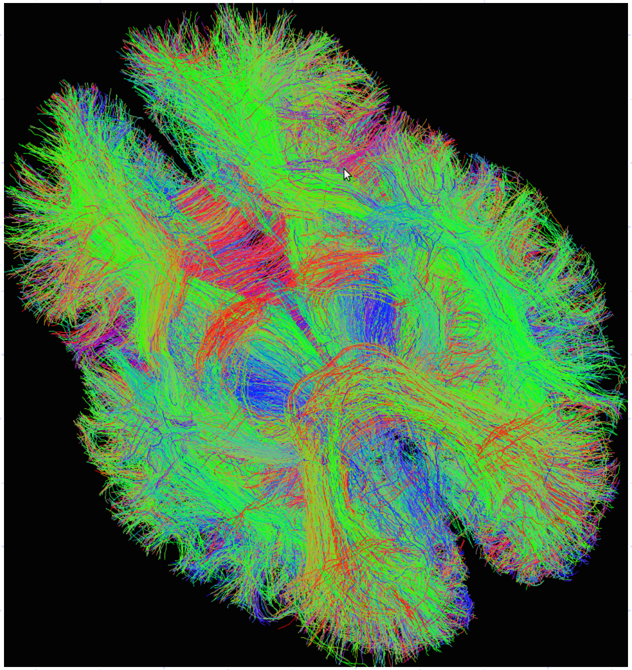


Streamline Growing

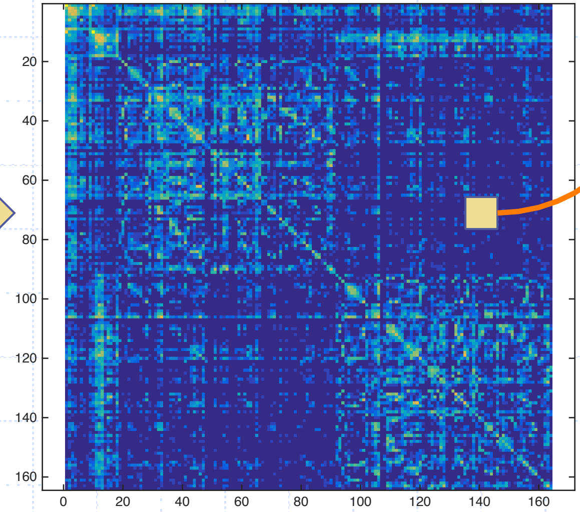
- Streamlines growing
  (1) probabilistic
  (2) deterministic
  (3) ……

Low Dimensional Representations

- Whole brain tractography is complicated
- A low dimensional representation is necessary for statistical inference



Connectivity Matrix



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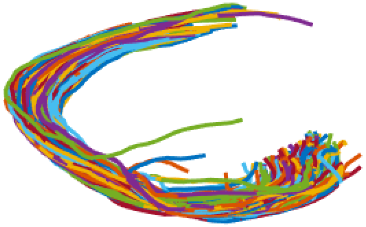


Connectivity Matrix

- Connectivity matrix is a summarization of the brain connections
- Given streamlines:

  Step 1. Brain parcellation – *freesurfer / other software*

  - Use Destrieux atlas in FreeSurfer: ~ 170 ROIs

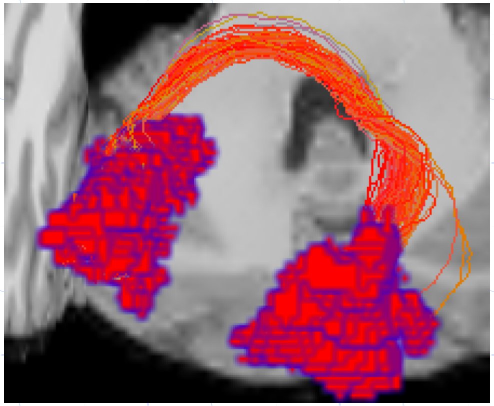
Connectivity Matrix

- Connectivity matrix is a summarization of the brain connections
- Given streamlines:

  Step 1. Brain parcellation – *freesurfer / other software*

  Step 2. Find the fibers connecting each pair of regions

CM(41,160) =



In order to include more streamlines:

- ROI dilation
- Streamline ending points expansion

Problems with the Connectivity Matrix

- The connectivity matrix contains millions of fibers
  - saving, loading, and analyzing are difficult
    - Compression is needed

- Summarize the connectivity matrix
    - Extract robust measure(s) of connectivity strength

Compression of Connectivity Matrix

- Examples of fibers in CM(1,160) for different subjects
  1 - left-lateral-ventricle *160 - ctx-rh-S-parieto-occipital*

- Observations:

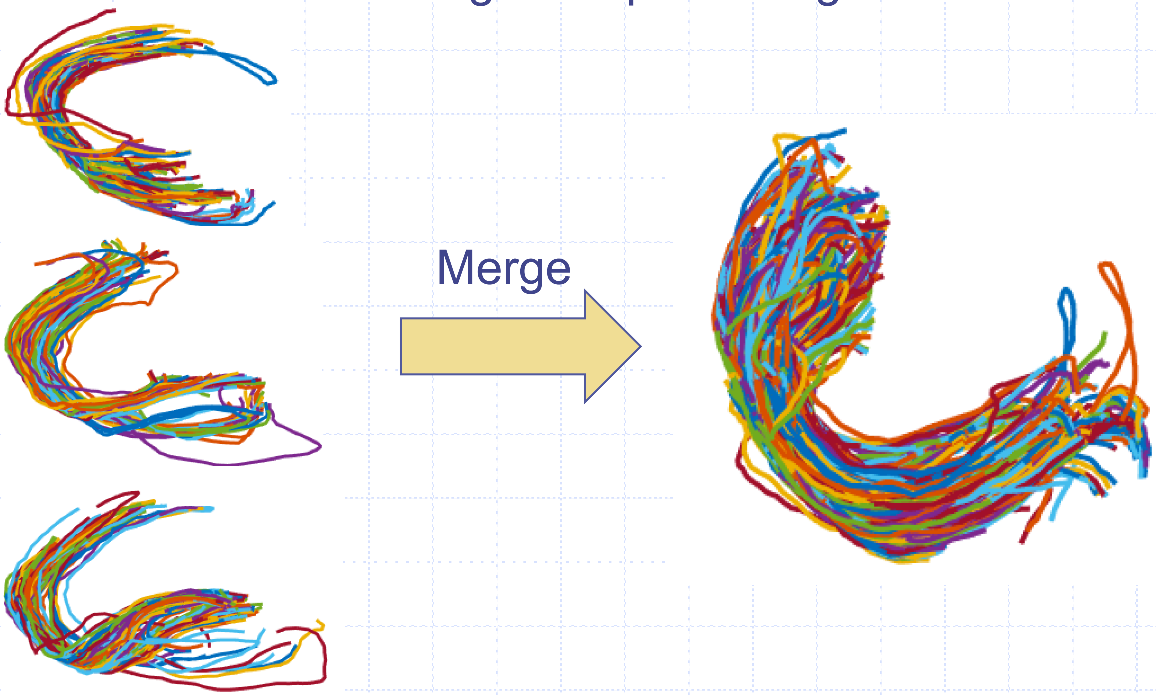
  - They have similar shapes after removing the translation, rotation, scaling and re-paramterization.

Compression of Connectivity Matrix

- Compression happens at efficiently representing the shapes of fibers
- Learn basis functions to represent the fibers connecting a pair of regions

Step 1. Generate atlas for fibers connecting each pair of regions

Randomly select healthy subjects:



Compression of Connectivity Matrix

- Compression happens at efficiently representing the shapes of fibers
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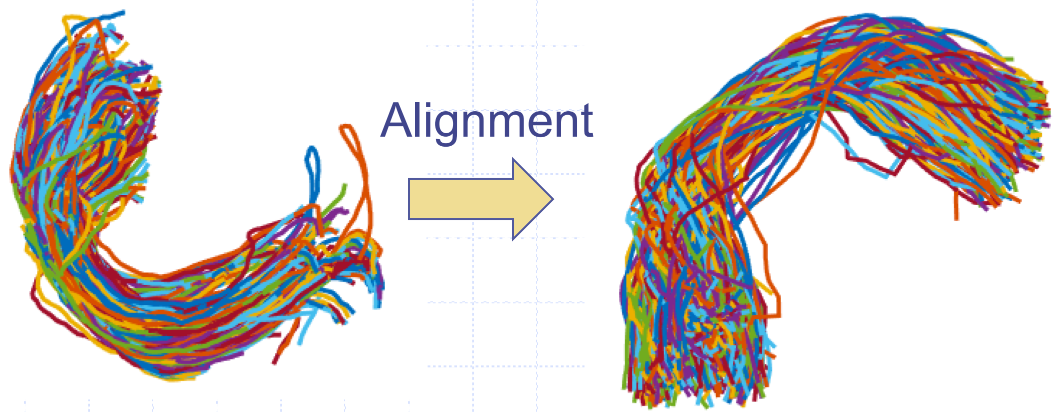
Step 1. Generate atlas for fibers connecting each pair of regions

Step 2. Alignment using the Elastic Shapes Analysis framework (Srivastava et al. 2012)

- rotation
- translation
- scaling
- re-parameterization



Compression of Connectivity Matrix

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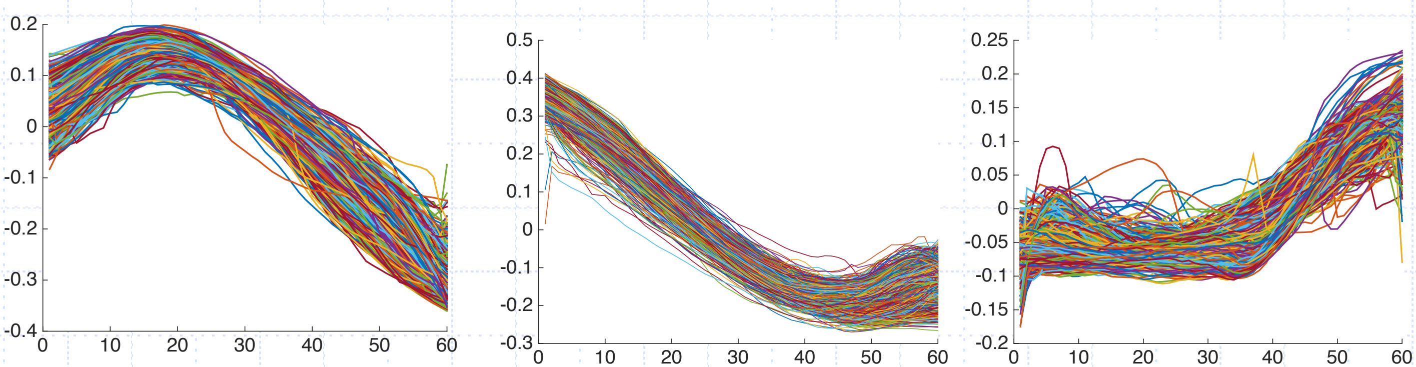
Step 1. Generate atlas for fibers connecting each pair of regions

Step 2. Alignment using the Elastic Shapes Analysis framework (Srivastava et al. 2012)

Step 3. Use fPCA to learn basis functions for each component



$j = 1$ $\quad j = 2$ $\quad j = 3$

$$\mu_j$$
$$\{\phi_{i,j}\}$$

Compression of Connectivity Matrix

- Compression happens at efficiently representing the shapes of fibers
- Learn basis functions to represent the fibers connecting a pair of regions
- Encoding: given a new fiber f

Step 1. Align f to the mean fiber in the atlas

$$\underset{O \in SO(3), C \in \mathbb{R}^3}{\operatorname{argmin}} \|O * (f - C) - \mu\|$$

$$g = \boxed{O} * (f - \boxed{C})$$

Step 2. Represent the aligned fiber using basis functions

$$\hat{g}_j = \mu_j + \sum_{i=1}^{M} \boxed{c_{j,i}} \phi_{j,i}$$

Parameters to save

Compression of Connectivity Matrix

- Compression happens at efficiently representing the shapes of fibers
- Learn basis functions to represent the fibers connecting a pair of regions
- Encoding
- Decoding: reconstruct f

$$\hat{f} = O' * \hat{g} + C$$

Compression of Connectivity Matrix

- Compression happens at efficiently representing the shapes of fibers
- Learn basis functions to represent the fibers connecting a pair of regions
- Encoding
- Decoding
- Compression Ratio: ~ 90-98%

$$\rho = 100 * (1 - \frac{N_c}{N_r})$$

N_c # parameters after compression

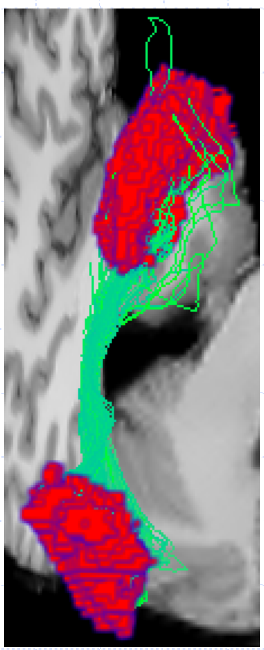
N_r # parameters before compression

Robust Coupling Strength Measures

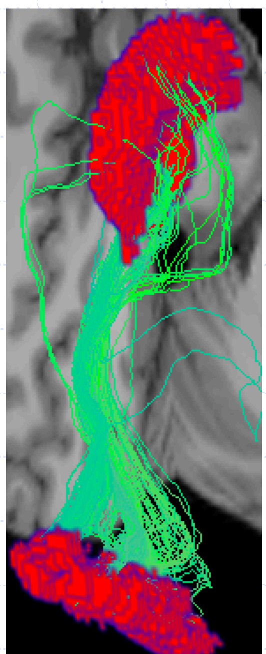
1. What is a good measure of the connectivity strength between two ROIs?

Right-Putamen (16) ctx_rh_G_occipital_sup(115)

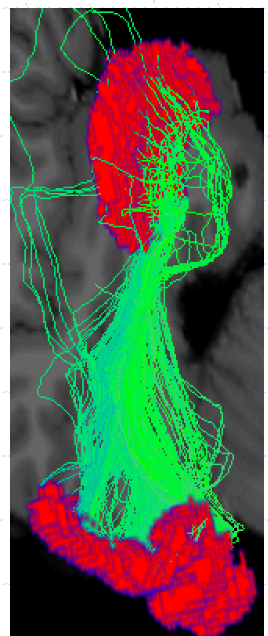
ID: 104820
$| CM(16,115) | = 483$



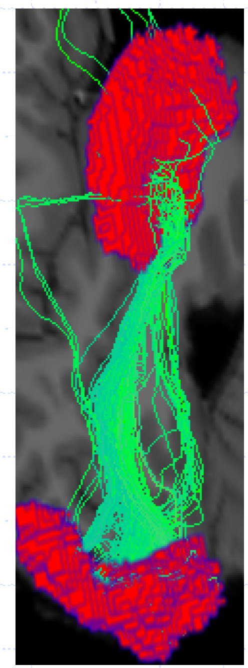
ID: 101006
$| CM(16,115) | = 758$



ID: 102311
$| CM(16,115) | = 614$



ID: 145836
$| CM(16,115) | = 429$

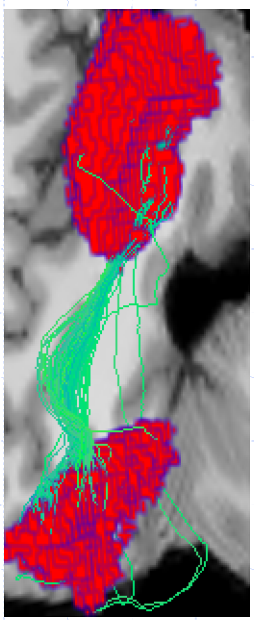


Robust Coupling Strength Measures

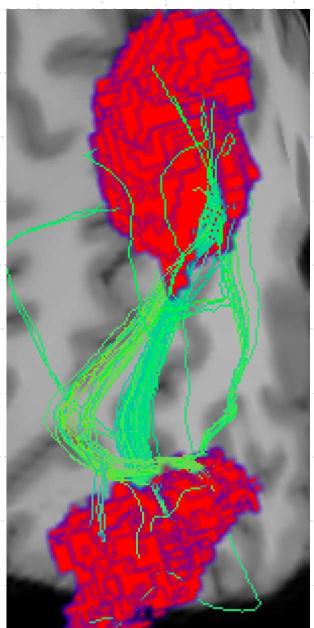
1. What is a good measure of the connectivity strength between two ROIs?

Right-Putamen (16) ctx_rh_S_parieto_occipital(160)

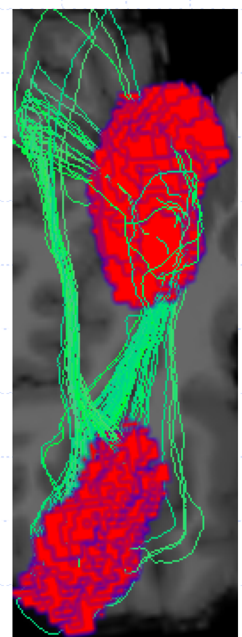
ID: 104820
$| CM(16,115) | = 89$



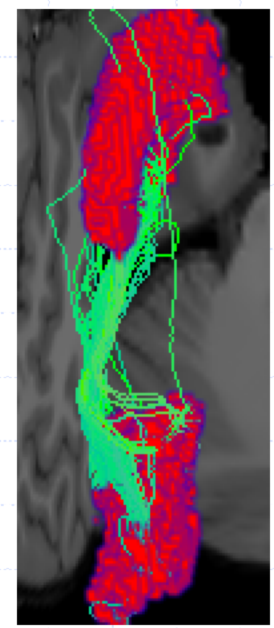
ID: 101006
$| CM(16,115) | = 226$



ID: 102311
$| CM(16,160) | = 76$



ID: 145836
$| CM(16,160) | = 249$



Robust Coupling Strength Measures

1. What is a good measure of the connectivity strength between two ROIs?

- Current people use only counts
- Should include:
  - Diffusion properties: FA values, AFD values along fibers
  - Geometry properties: Shapes, Loops, Clusters
  - Nodes information: Volume of nodes, Connected surface areas

  ...

- Working on extracting them now.
- Question: how to verify the measures?

Thank You