Diffusion Modeling in BrainSuite

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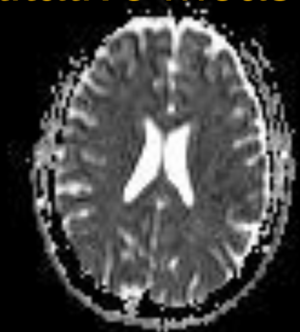
Motivation

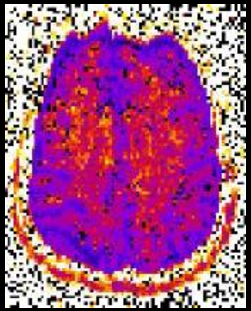
- Diffusion MRI provides unique insight into tissue microstructure
  - Quantitative measures



Apparent Diffusion Coefficient

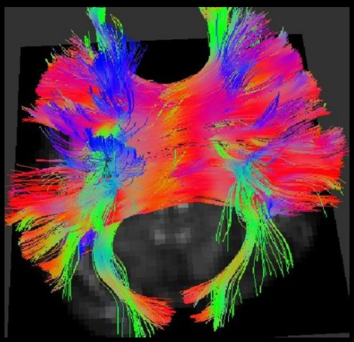
Fractional Anisotropy

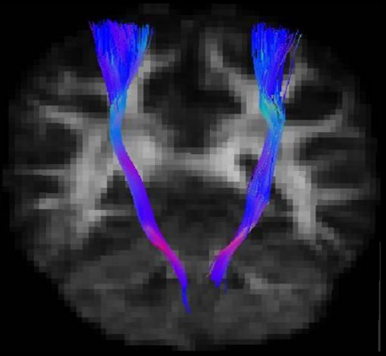
Anomalous Exponent

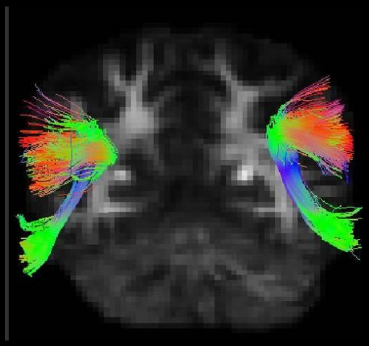


Kurtosis

  - Connectivity







Diffusion Imaging (in general)

1. Acquisition

- 6+ Directions
- HARDI
- Multi-Shell
- DSI
- …

2. Preprocessing

- Registration
- Distortion Correction
- Outlier Removal

3. Modeling

- DTI
- Multi-DTI
- ODF
  - FRT
  - FRACT
  - Nonlinear Methods
- DKI, CHARMED, …

4. Tracking

- Deterministic
- Probabilistic

5. Analysis

- Visualization
- Connectivity Analysis
- ROI Analysis

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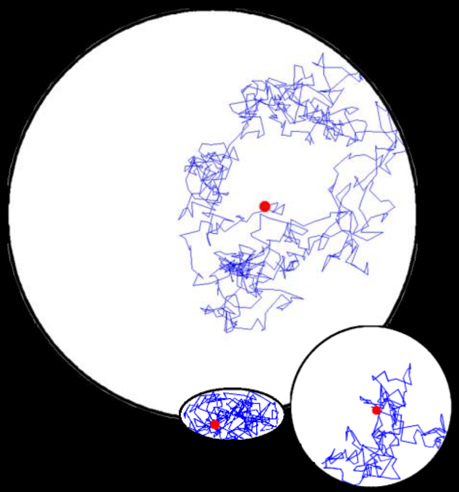
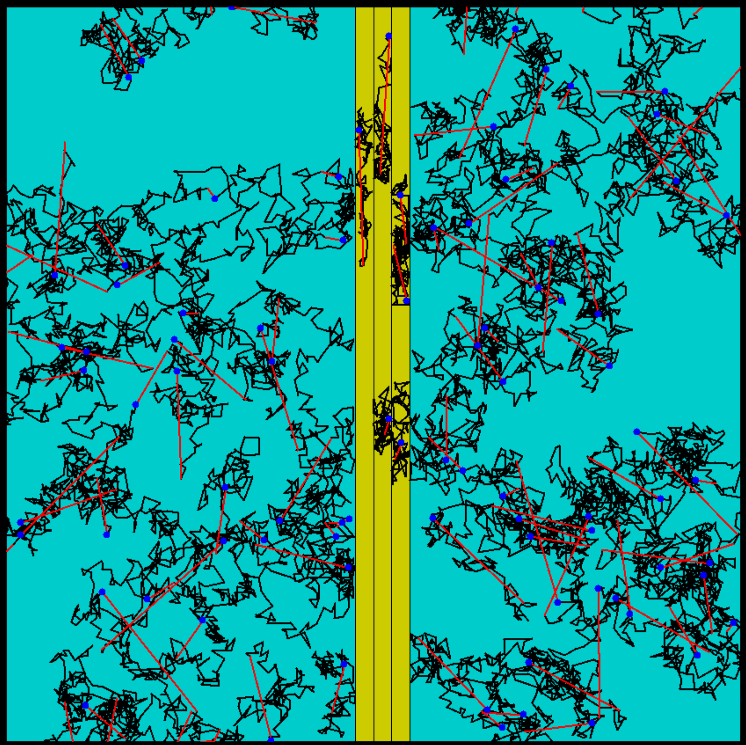
Data Sampling

- Diffusion data is sampled from a 6D space
  - 3D Spatial
    - Where in the brain am I located? (mm scale)
  - 3D Diffusion
    - Where do water molecules typically move? (µm scale)

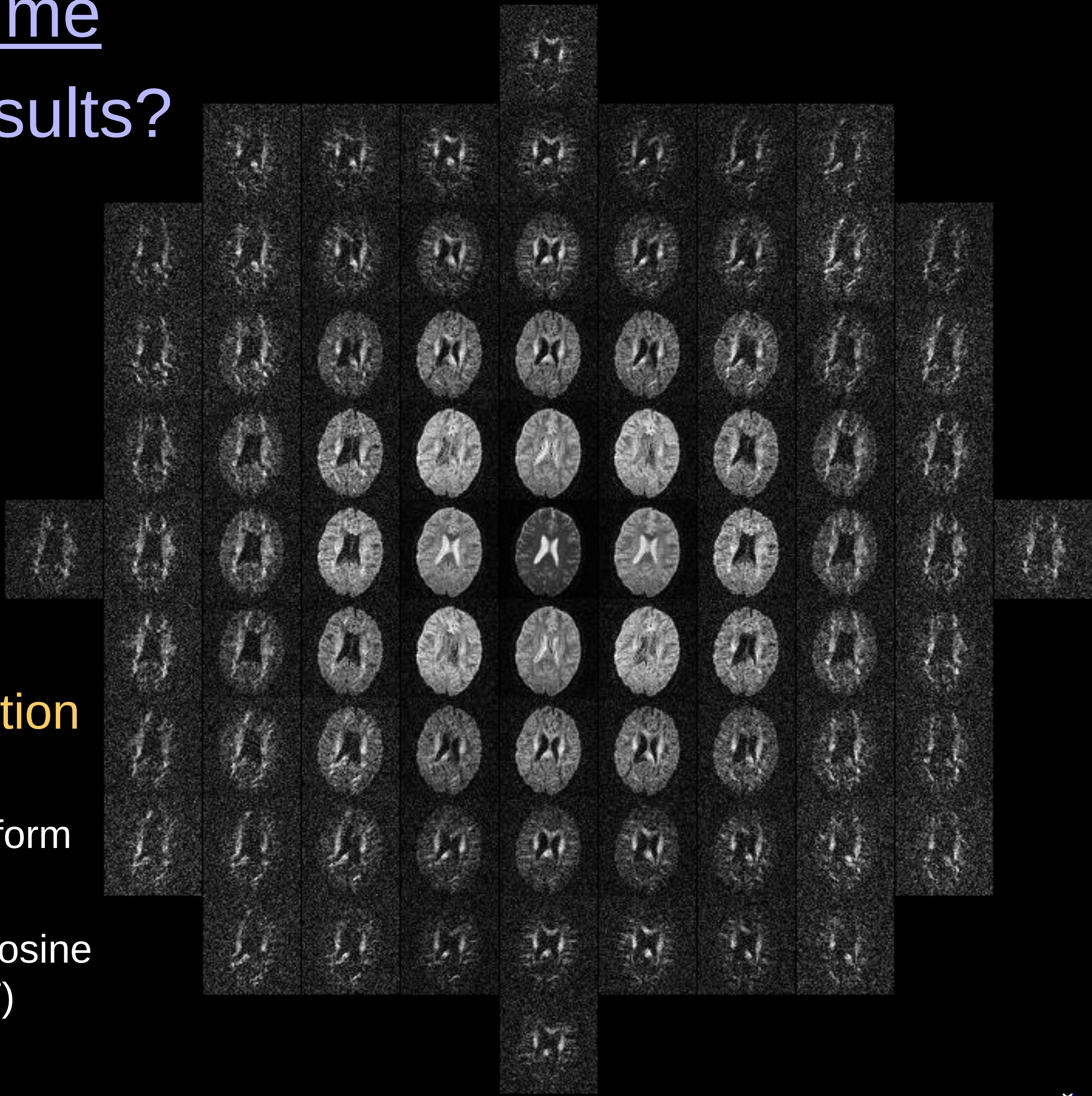




Diffusion Data is Complicated

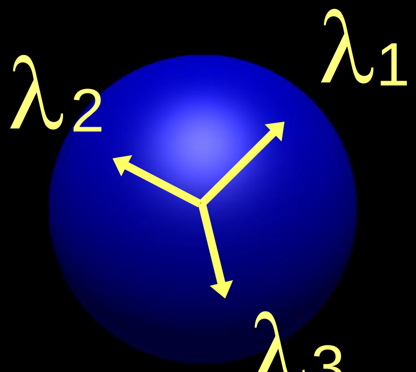
- Sampling in 6D = time
- How to interpret results?

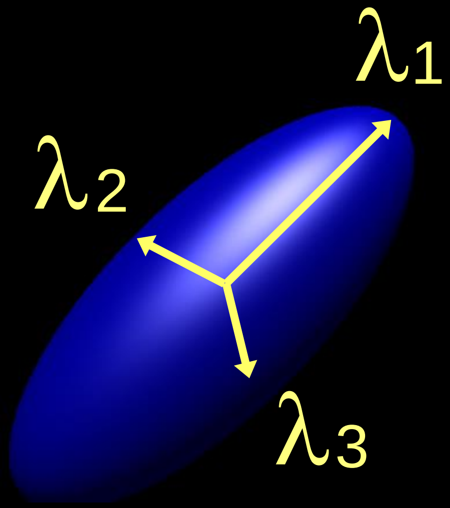
- Solution:
  - Models!
  - In BrainSuite:
    - Diffusion Tensor Imaging (DTI)
    - Orientation Distribution Functions (ODFs)
      - Funk Radon Transform (FRT)
      - Funk Radon and Cosine Transform (FRACT)



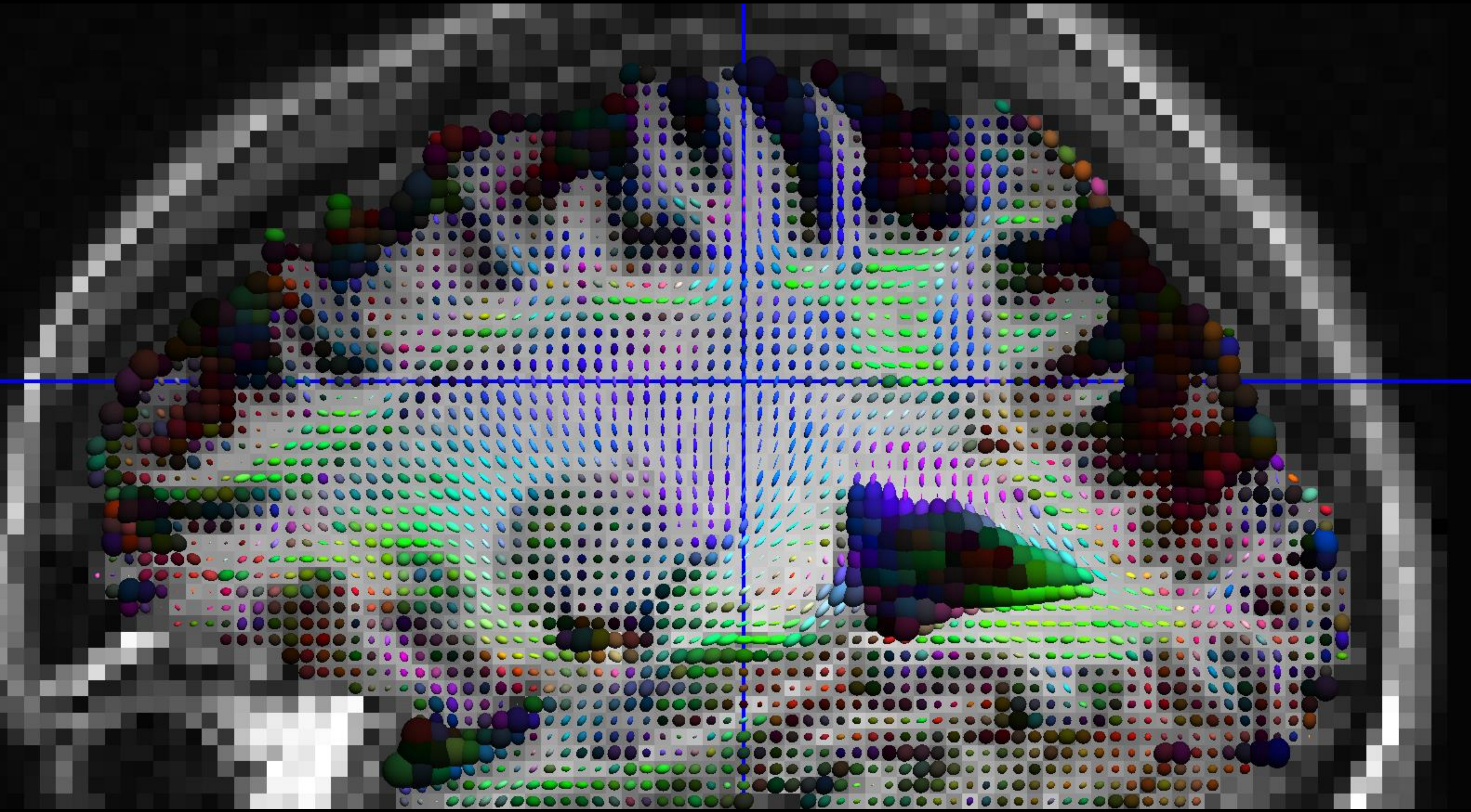
DTI

- Diffusion Tensor Imaging:
  - A simple model with 7 degrees of freedom
    - 3 orthogonal directions
    - 3 diffusivities along each direction
    - 1 baseline image intensity



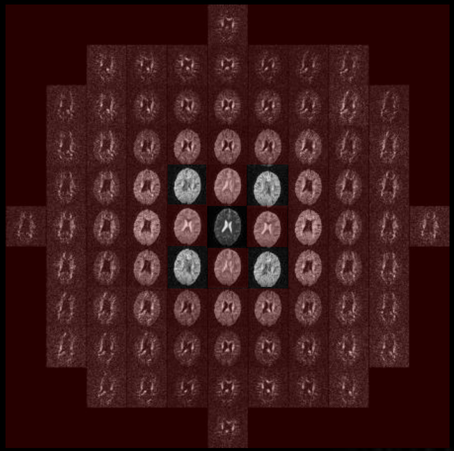


DTI in BrainSuite



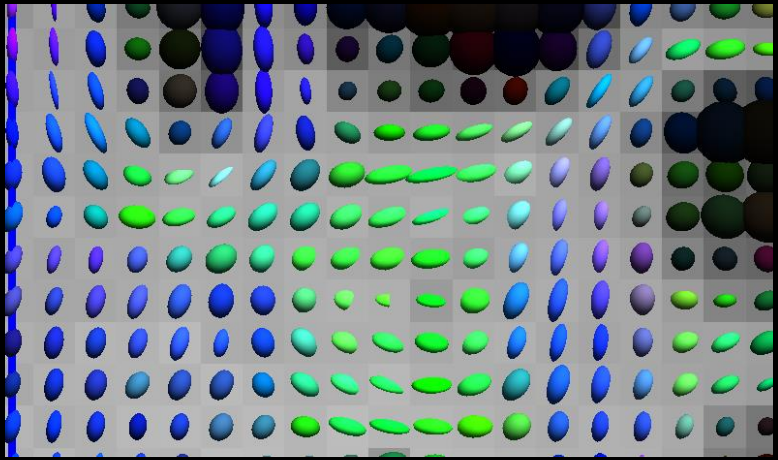
Benefits of DTI

- Only need to sample 7 images
  - In practice ~30 is preferred
  - Sampling is very flexible
- Quantitative information:
  - Mean Diffusivity
    - $(\lambda_1+\lambda_2+\lambda_3)/3$
  - Fractional Anisotropy
    - $\sqrt{\frac{3}{2}}\frac{\sqrt{(\lambda_1-\bar{\lambda})^2+(\lambda_2-\bar{\lambda})^2+(\lambda_3-\bar{\lambda})^2}}{\sqrt{\lambda_1^2+\lambda_2^2+\lambda_3^2}}$
- Tissue Orientation
  - Enables tracking

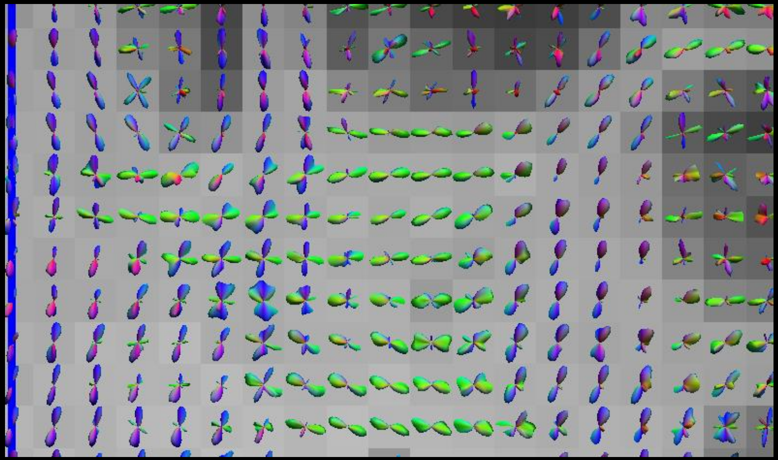


Limitations of DTI

- Model is almost never valid
  - (But it still provides good biomarkers for microstructure)
- Cannot model multiple orientations in a single voxel



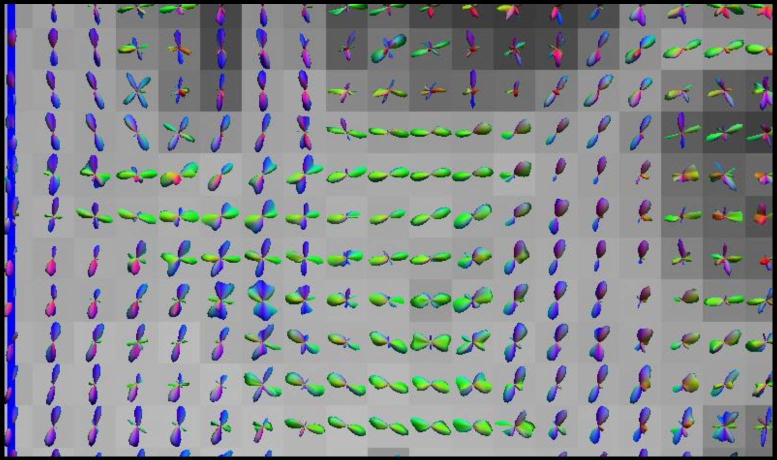
DTI



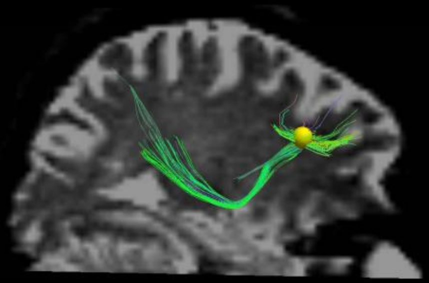
ODFs

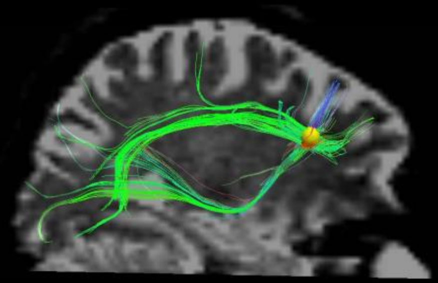
Orientation Distribution Functions

- Give the ability to model multiple orientations in a single voxel



- Enables better tracking in complicated regions with multiple fiber crossings


DTI

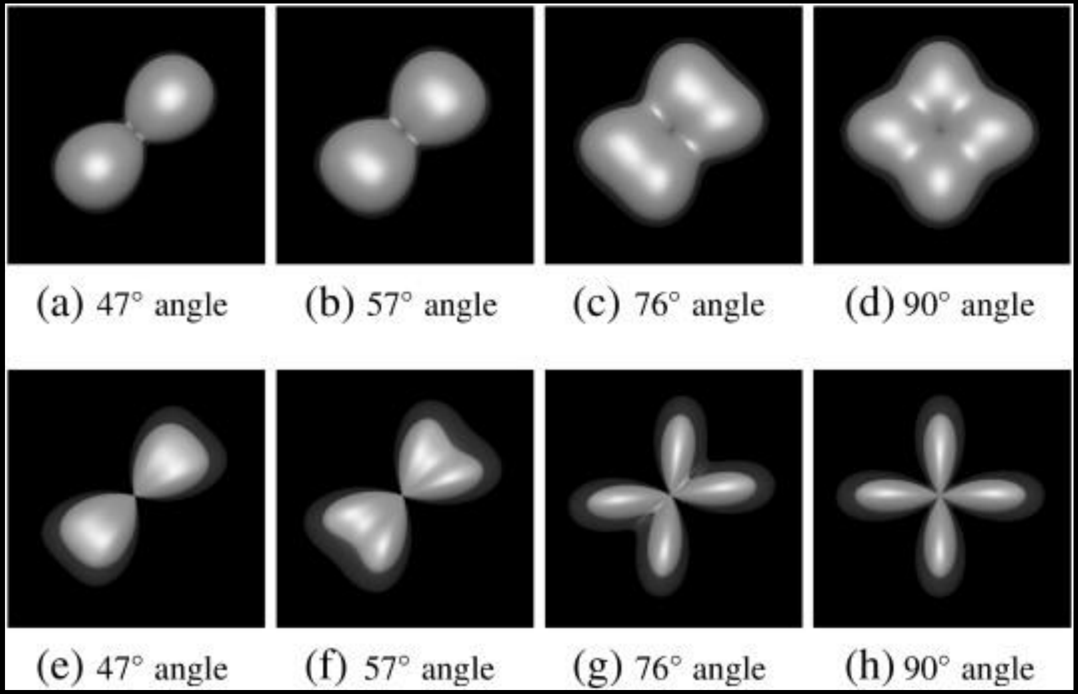

ODF

FRT vs. FRACT

- BrainSuite Provides two ODF methods:
  - Funk Radon Transform [1]
    - Most prevalent ODF method in other software
  - Funk Radon and Cosine Transform [2]
    - Higher angular resolution

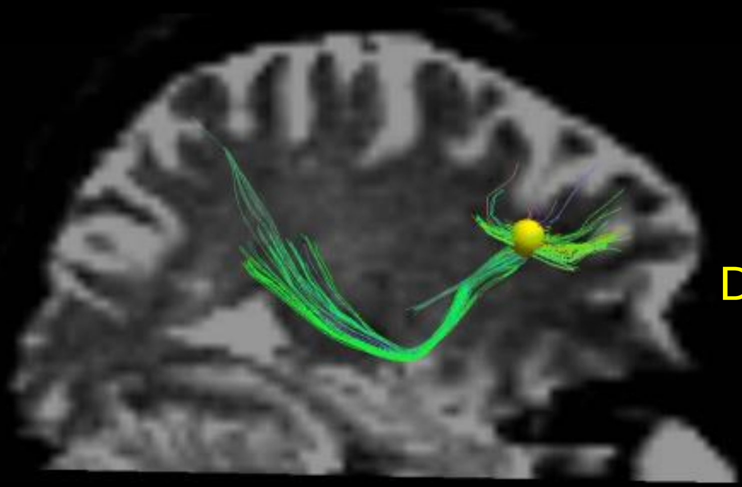
FRT

FRACT

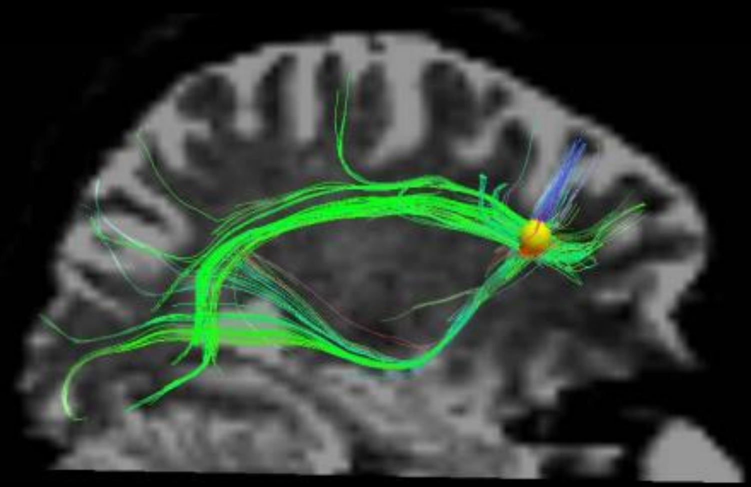


[1] Tuch, *Magn Reson Med* 52:1358-1372, 2004.
[2] Haldar and Leahy, *NeuroImage* 71:233-247, 2013.

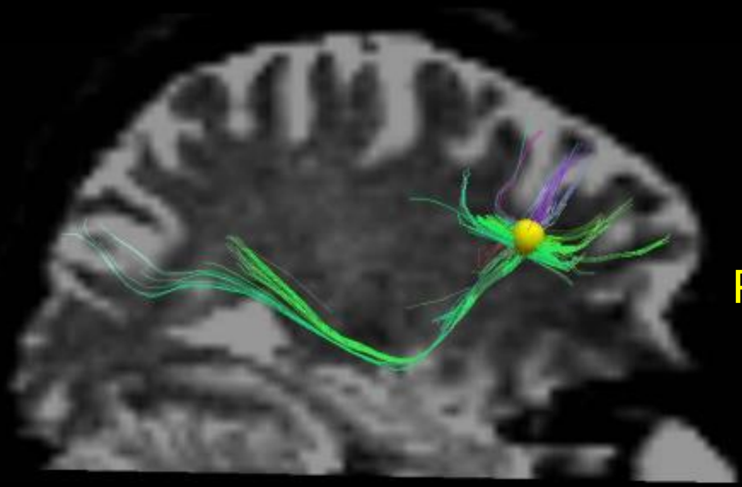
DTI vs FRT vs FRACT



DTI



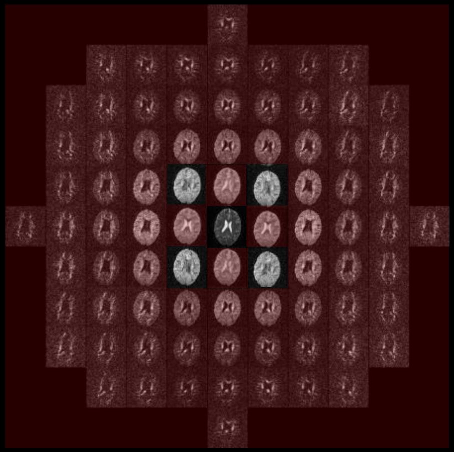
FRACT



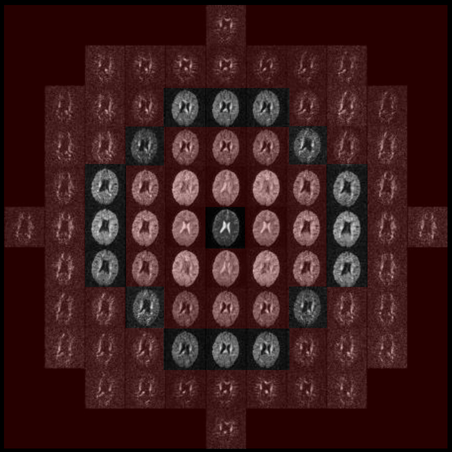
FRT

Limitations of FRT+FRACT

- Requires more data than DTI
  - 64+ directions recommended (often more is needed)
- Works only for data on the sphere
  - better with high b-value data
- More sensitive to noise than DTI

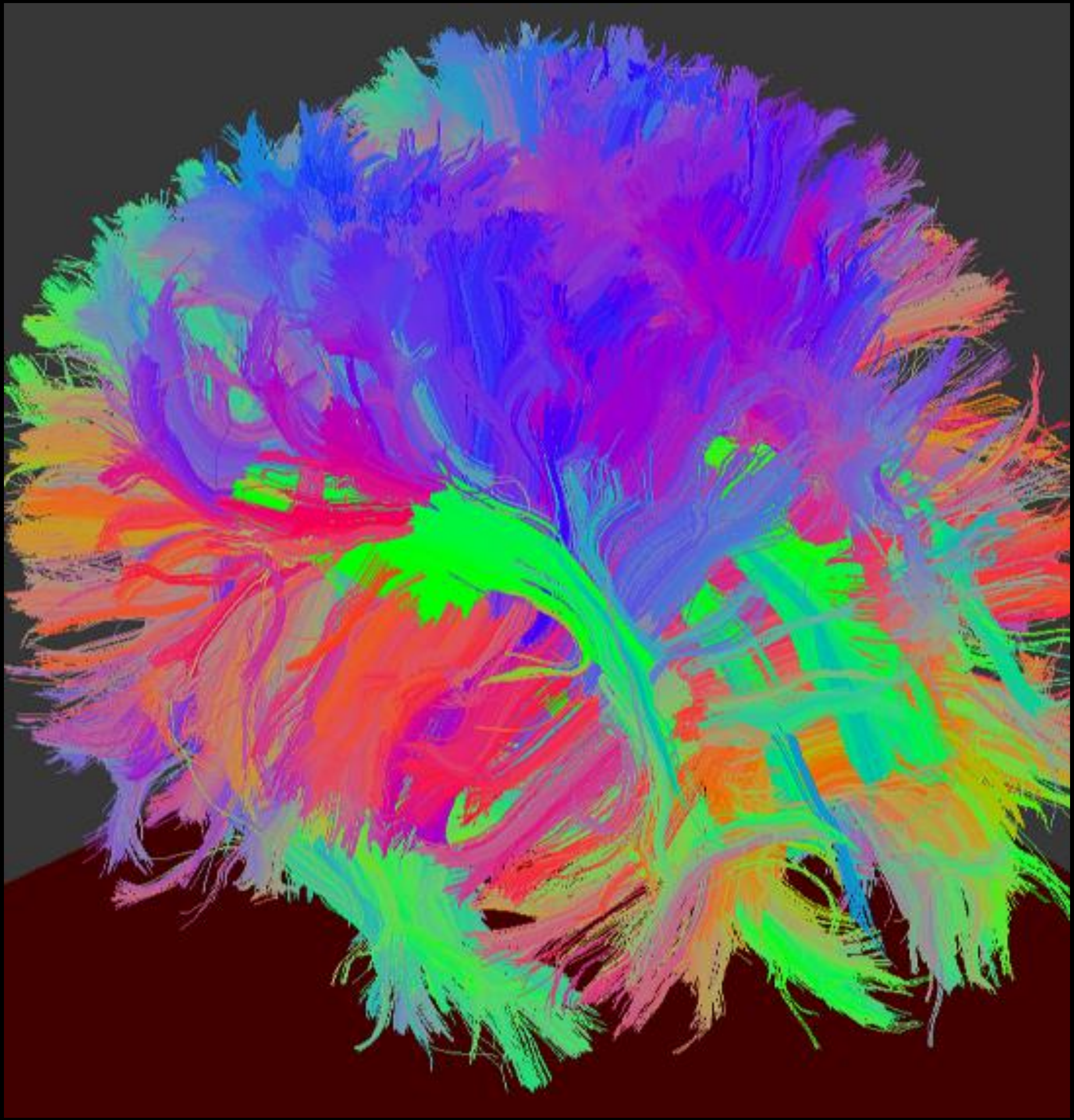


DTI



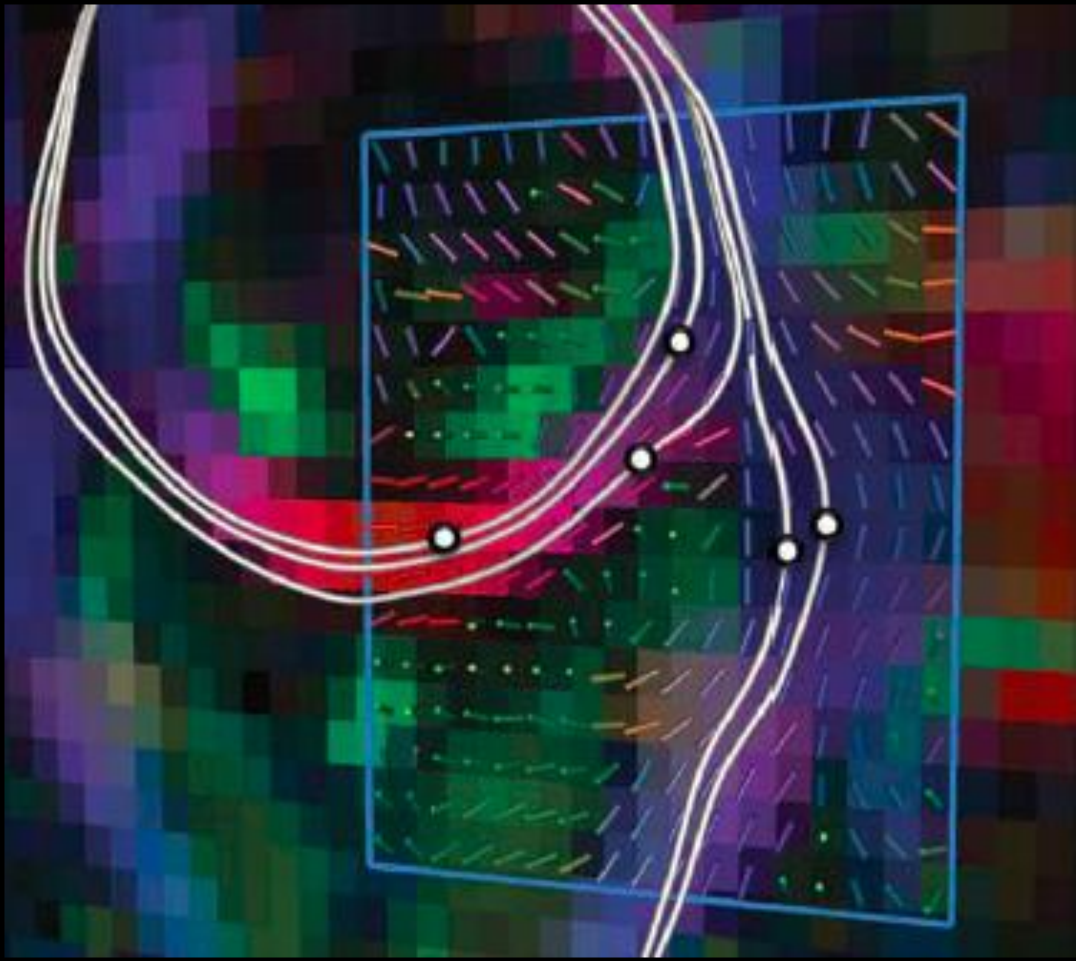
ODF

Tracking



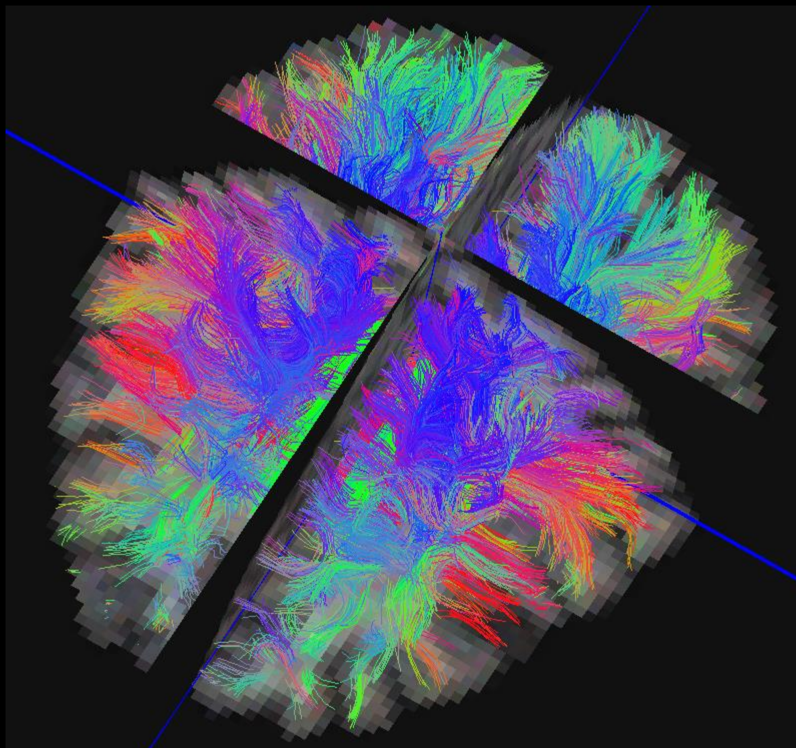
Deterministic Tractography

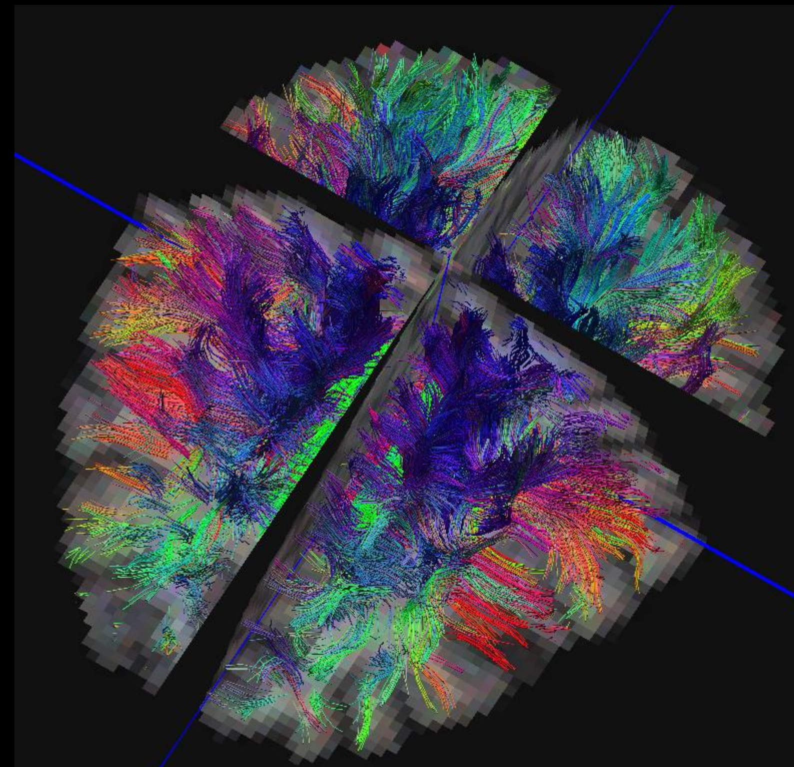
- Start at seed locations
- Follow major orientation
- Know when to stop

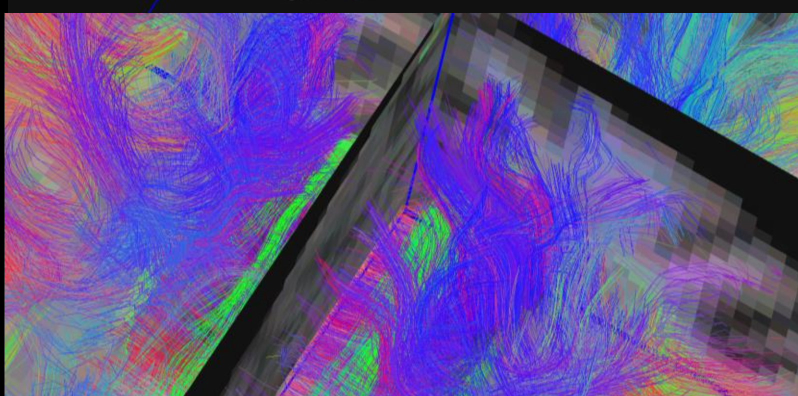


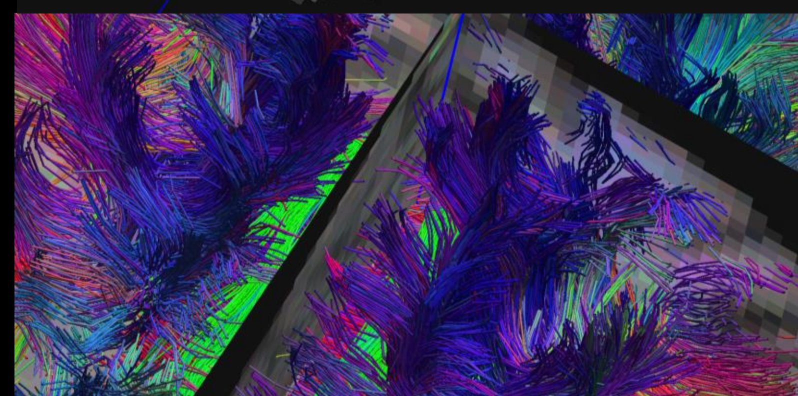
Tournier 2011

Render as Tubes

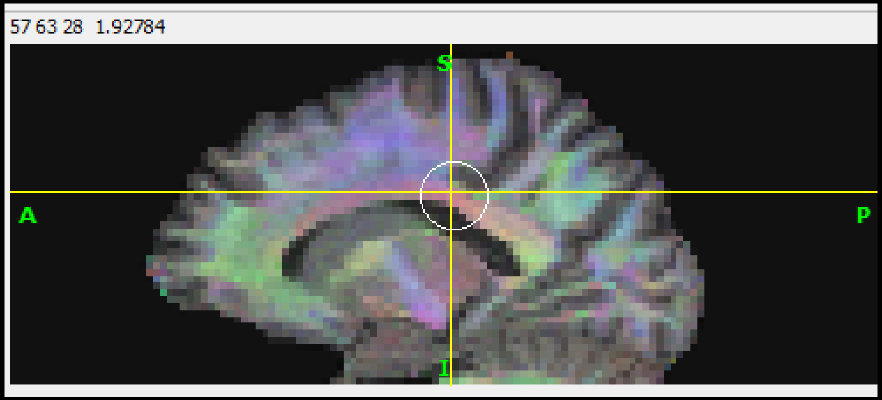


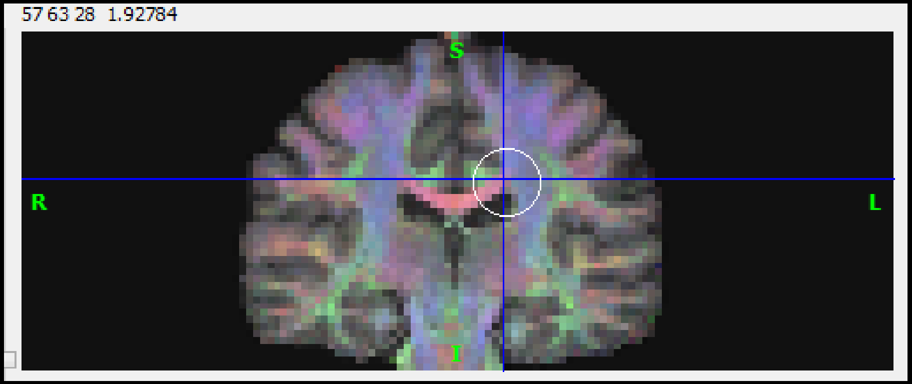


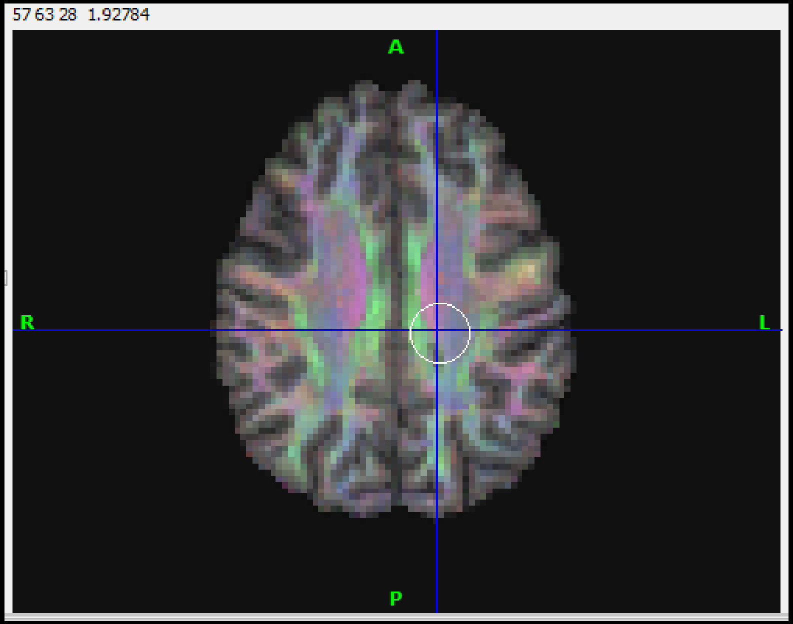


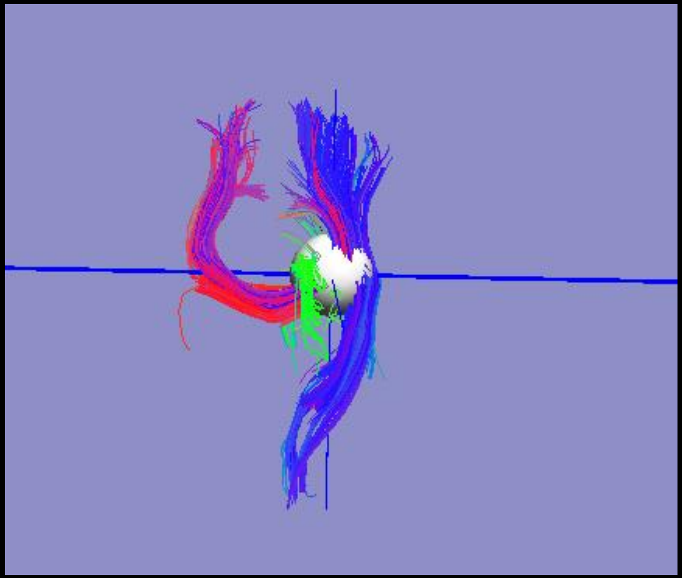


Sphere Filtering

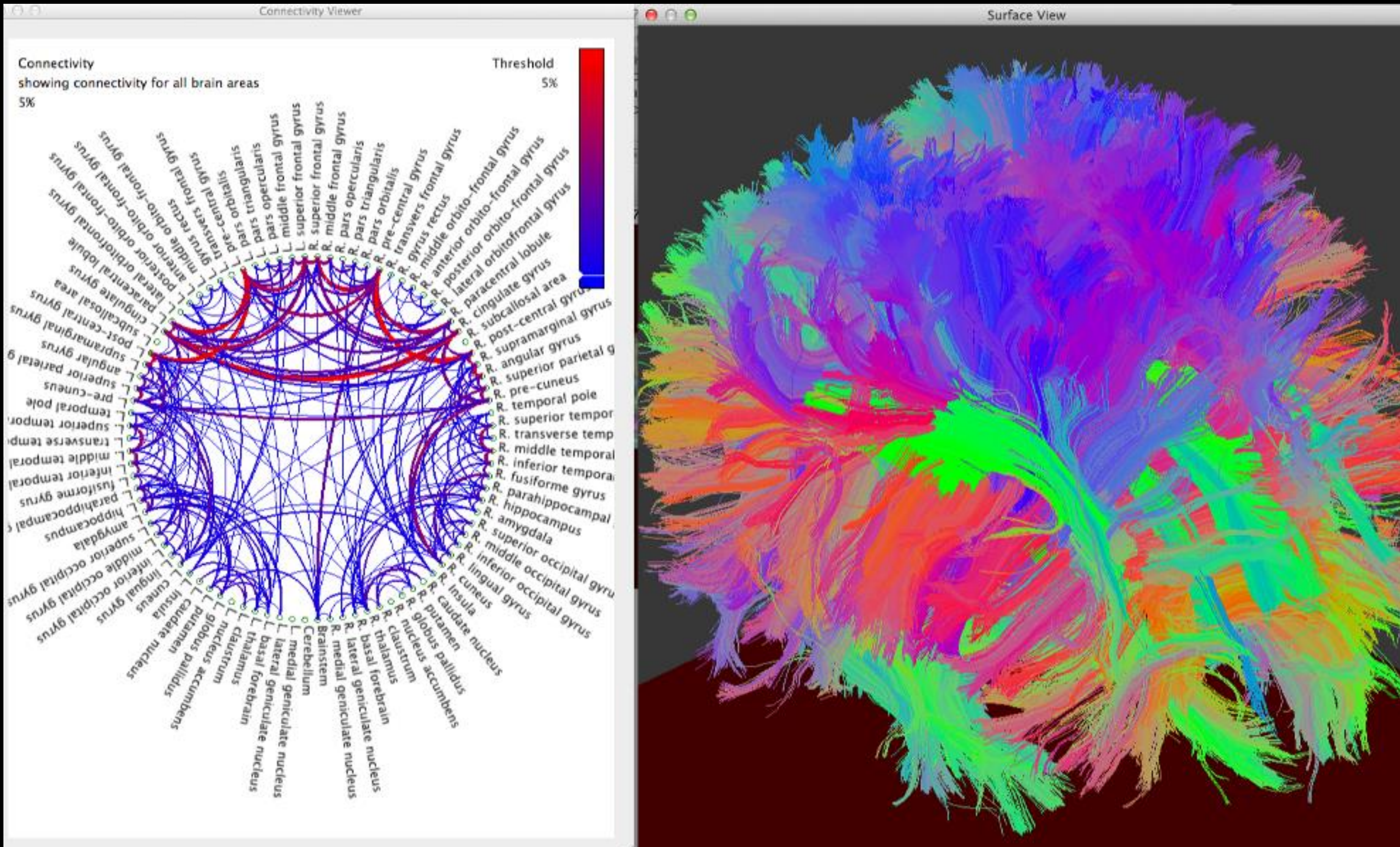






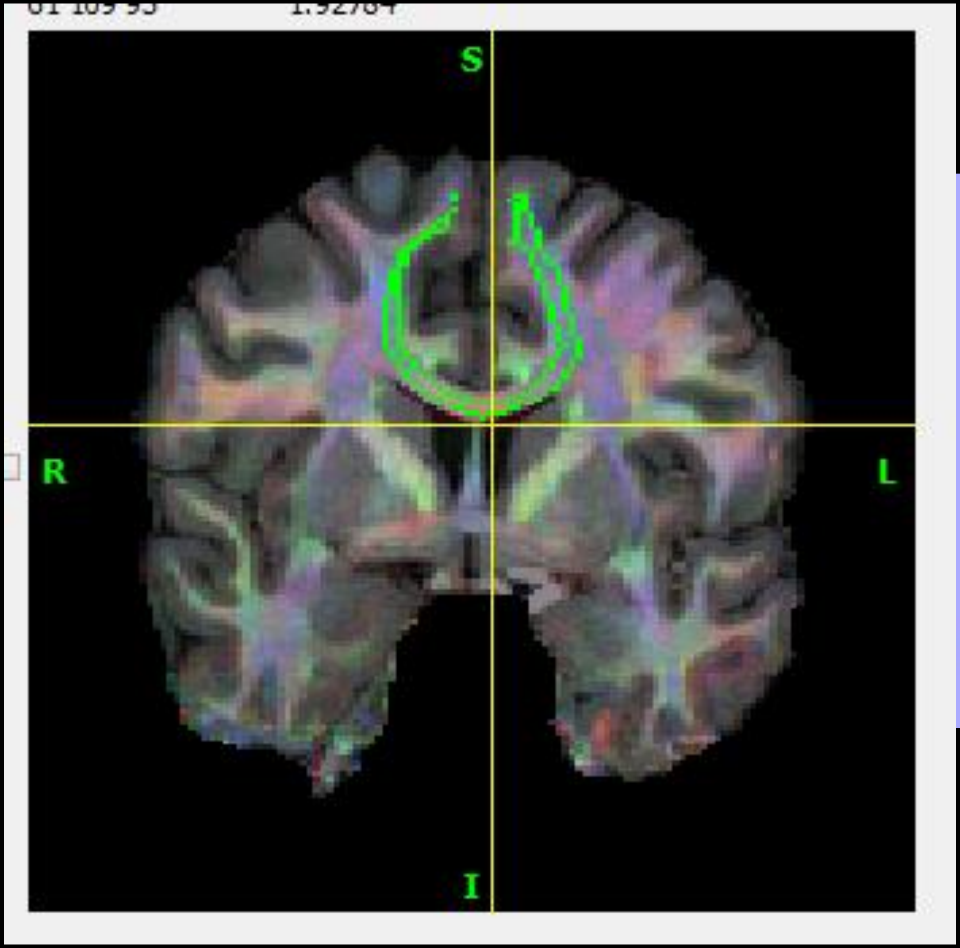


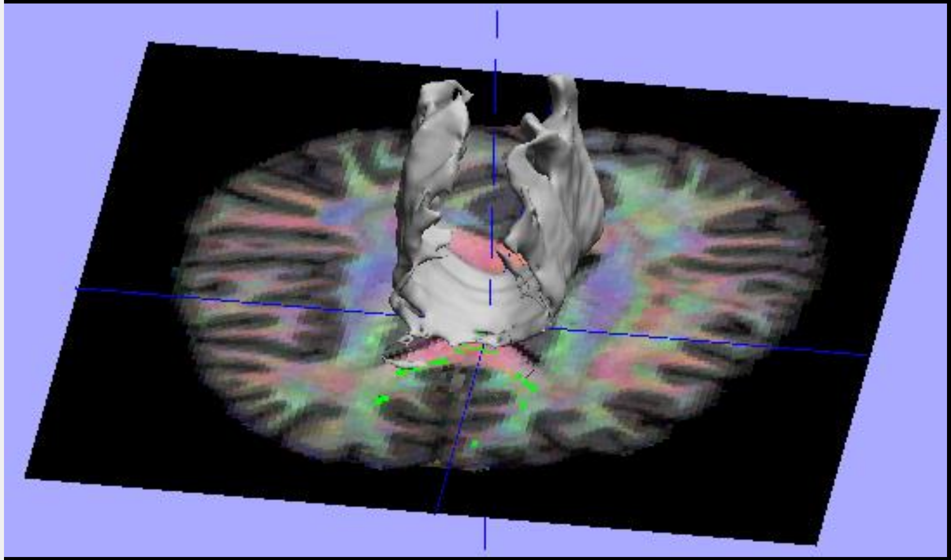
Connectivity



Track-Based ROI Tool

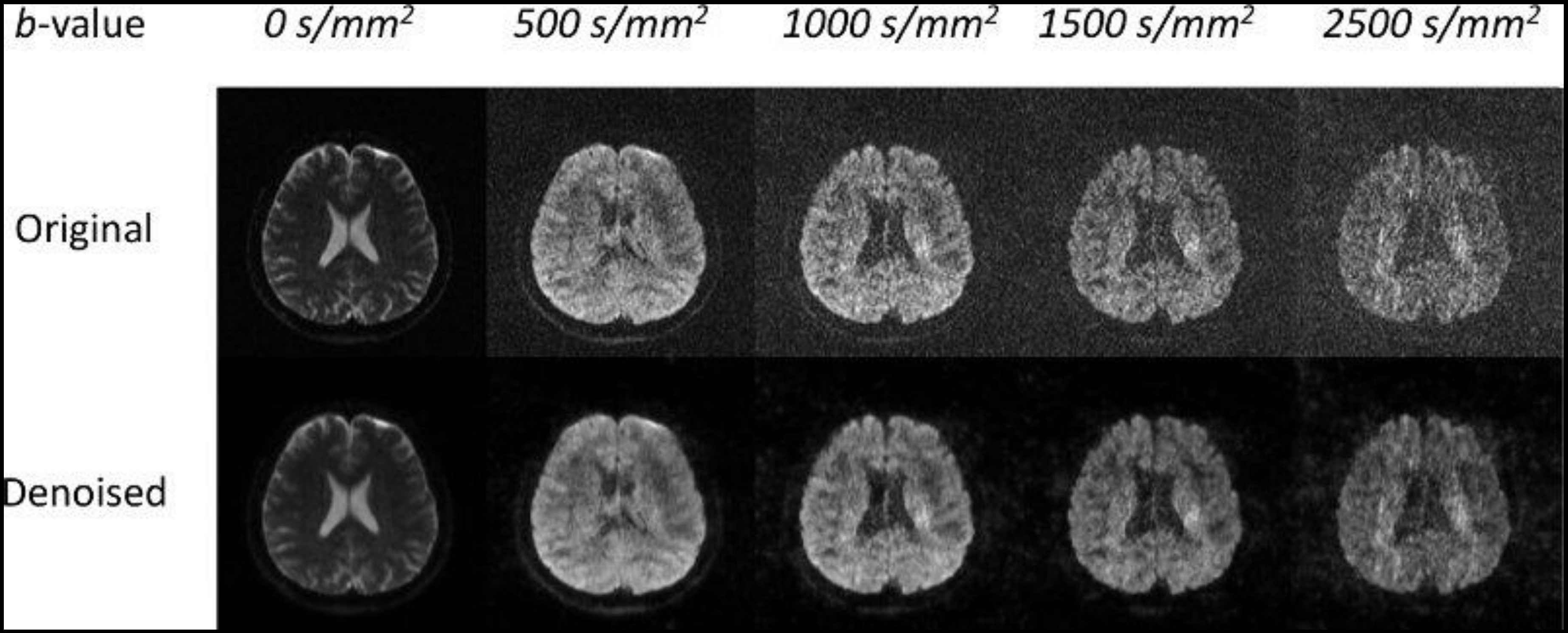
- Select voxels based on tracks





- http://brainsuite.org/processing/additional-tools/

Denoising



[1] Haldar, Wedeen, Nezamzadeh, Dai, Weiner, Schuff, Liang, *Magn Reson Med* 69:277-289, 2013.
[2] Varadarajan and Haldar, *IEEE ISBI*, 2013, pp. 708-711.

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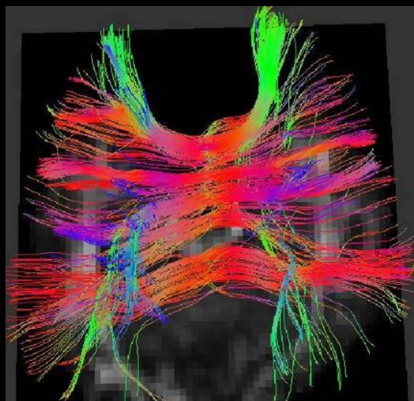
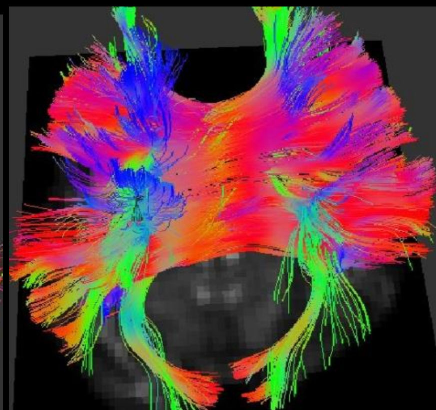
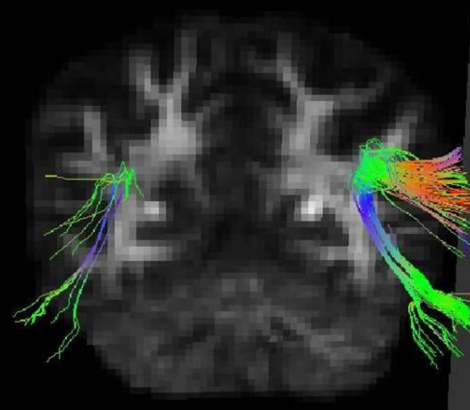

Conventional


Denoised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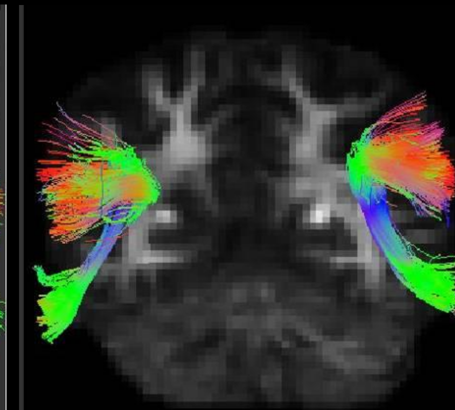
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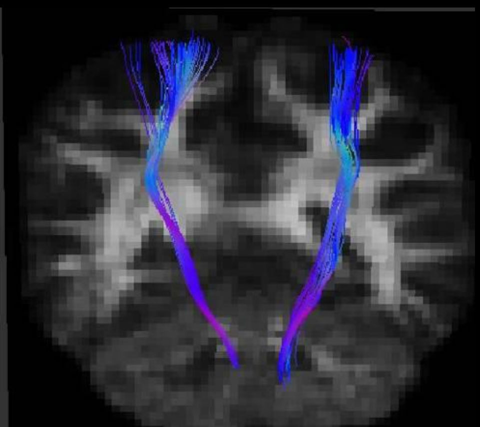
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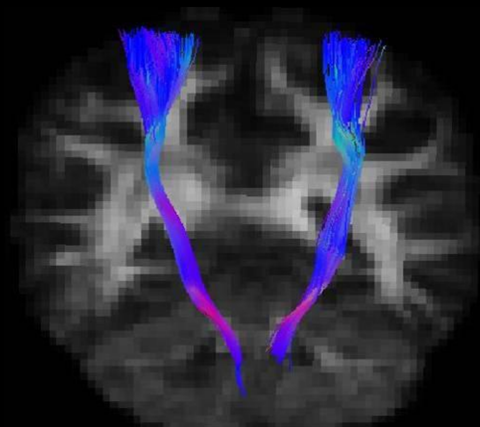
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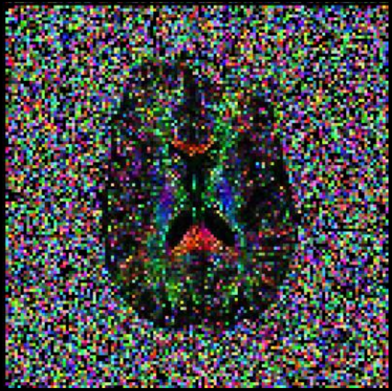
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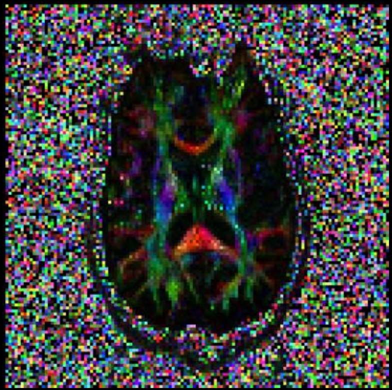
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Biases and Errors

- Diffusion is powerful!
- But make sure you know how to interpret the results!

Twenty-five Pitfalls in the Analysis of Diffusion MRI Data[†]

NMR Biomed. 2010; **23**: 803–820

Derek K. Jones[a*] and Mara Cercignani[b]

Challenges and limitations of quantifying brain connectivity *in vivo* with diffusion MRI

Derek K Jones

Imaging Med. (2010) **2**(3), 341–355

White matter integrity, fiber count, and other fallacies: The do's and don'ts of diffusion MRI

NeuroImage 73 (2013) 239–254

Derek K. Jones[a,b,*], Thomas R. Knösche[c], Robert Turner[c]