Visual Medicine: Part Two – Advanced Topics in Visual Medicine

Diffusion Tensor Imaging

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DT-MRI

Measurement basics

Understanding Tensor Shape

Data Inspection with Glyphs

Fiber Tracking and Analysis

Future Work Ideas

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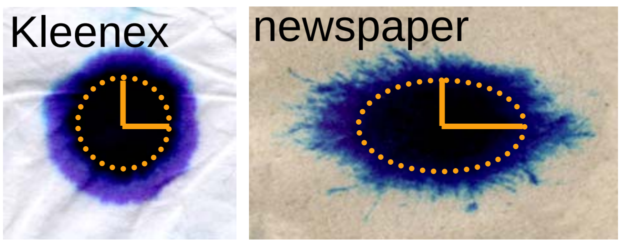
Diffusion-weighted MRI (DW-MRI)

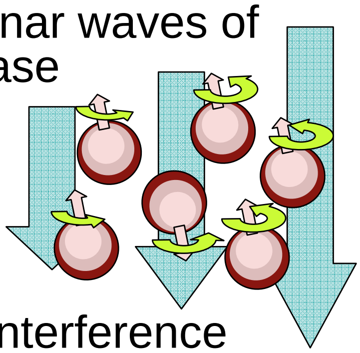
Brownian motion of one material through another

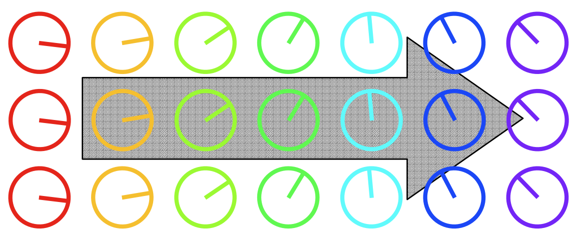
Anisotropy: diffusion rate depends on direction

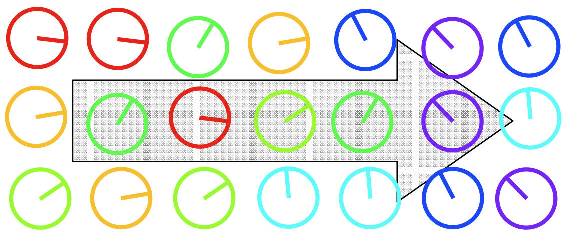
Magnetic gradients create spatial planar waves of proton phase

Destructive interference measures diffusion along gradient direction only





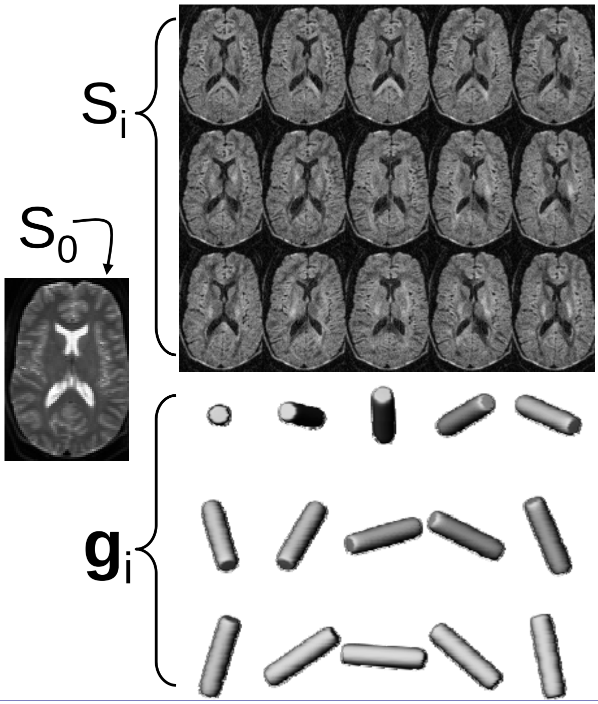


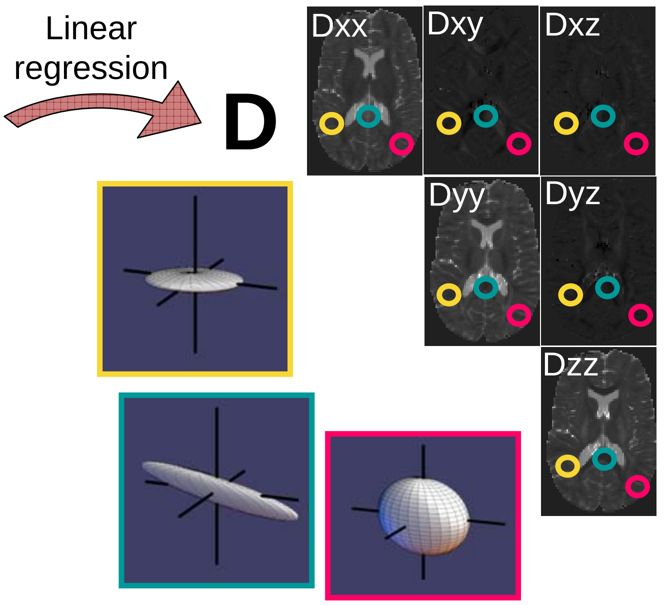


Multiple DWI → Tensor Estimate

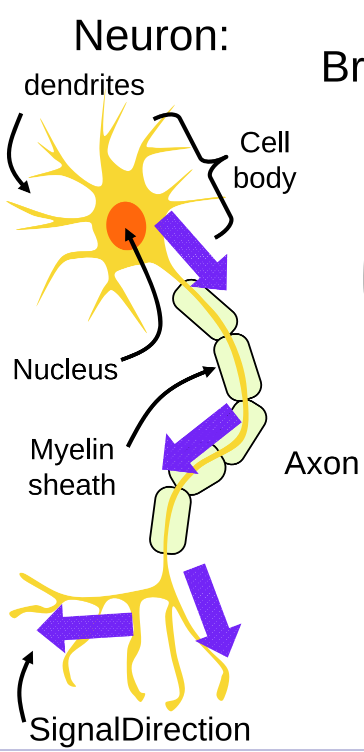
Single Tensor Model (Basser 1994)

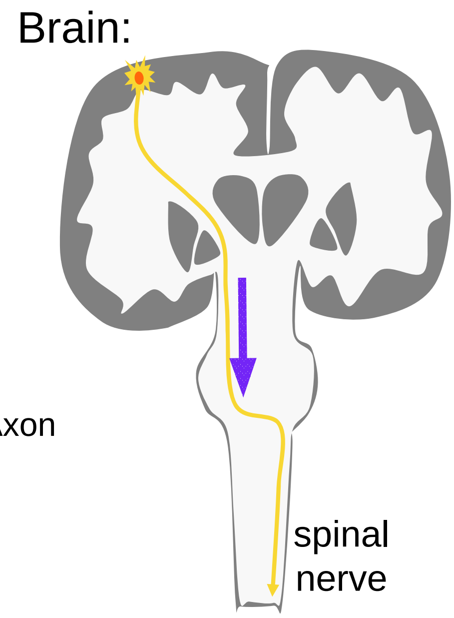
$$S_i(b, \mathbf{g}_i) = S_0 e^{-b\mathbf{g}_i^T \mathbf{D} \mathbf{g}_i}$$





Underlying Biology

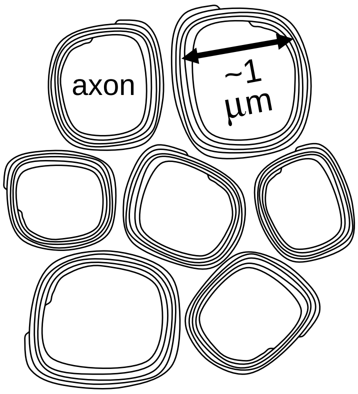




- Gray matter (cortex + nuclei): cell bodies
- White matter: axons
- Myelin sheath aids signal conduction
- Axon + sheath = nerve fibers
- Major white matter pathways aggregate many fibers into bundles

Biology of anisotropy in DW-MRI

Cross-section:



Microstructure of bundles directionally constrains water diffusion along fiber direction (LeBihan et al. 1985)

Intra- and extra-cellular diffusion

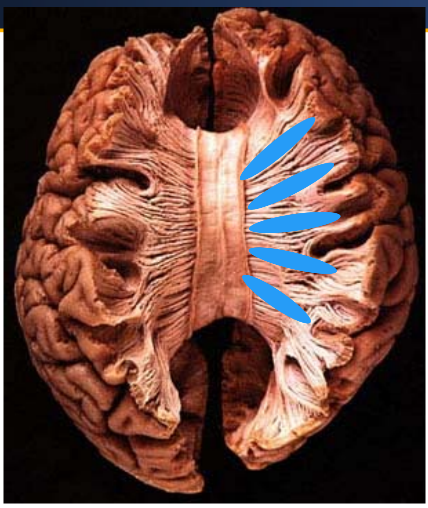
Diffusion lengths with the time-scale of MR measurement (TE ~= 100ms) on order of 10µm

Apparent diffusion coefficient: ADC

Voxels on the order of 1mm

⇒ Roughly two orders of magnitude away from measuring axons

Applications



Images from Virtual Hospital (www.vh.org)

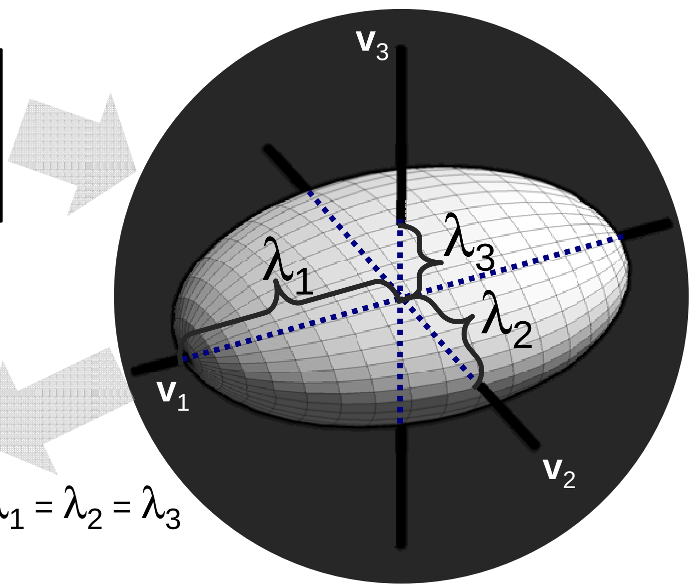
- Neuroanatomy
- Neurosurgery: tumor/tract relationship
- Stroke: detection
- Degenerative diseases: ALS, Multiple Sclerosis
- Psychiatric disorders: Schizophrenia

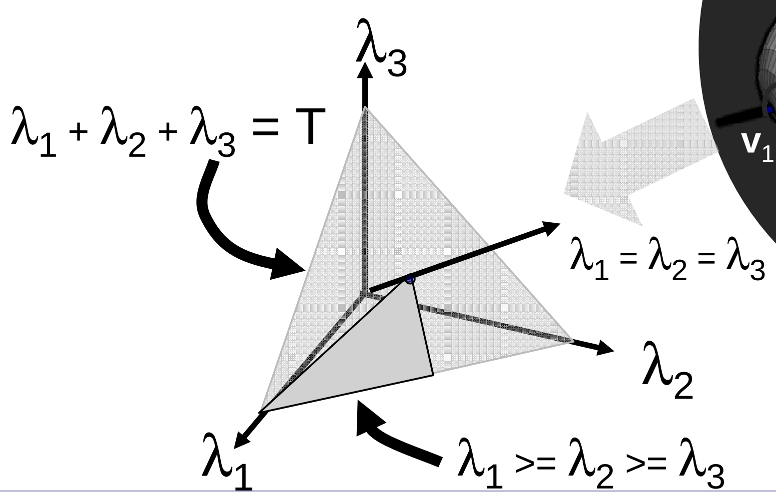
DT-MRI

- Measurement basics
- **Understanding Tensor Shape**
- Data Inspection with Glyphs
- Fiber Tracking and Analysis
- Future Work Ideas

Eigenvalues == Shape

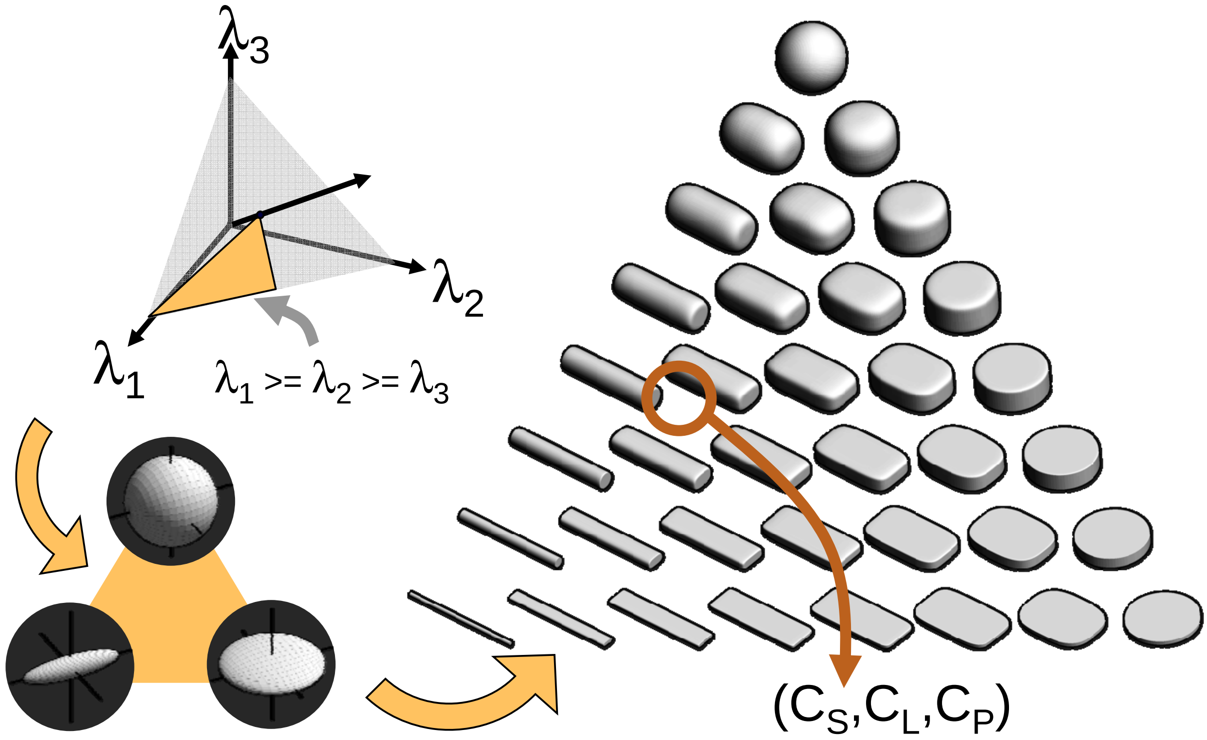
$$\mathbf{D} = \mathbf{R}\Lambda\mathbf{R}^{-1} = \begin{bmatrix} \mathbf{v}_1 & \mathbf{v}_2 & \mathbf{v}_3 \end{bmatrix} \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} \begin{bmatrix} \mathbf{v}_1 \\ \mathbf{v}_2 \\ \mathbf{v}_3 \end{bmatrix}$$





Tensor shape always has 3 degrees of freedom

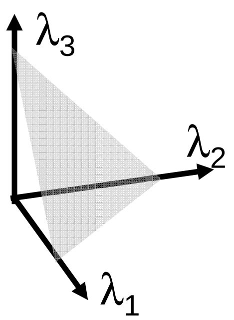
Barycentric shape space



Westin et al., 1997

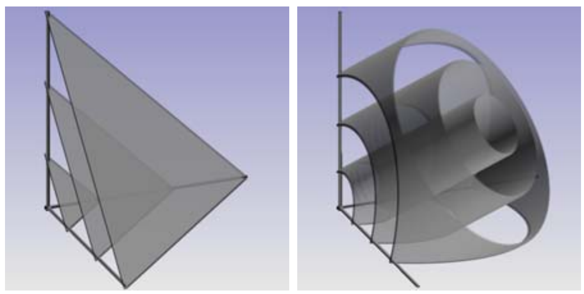
Tensor invariants as orthogonal shape parameterizations

Cylindrical or spherical coordinates
(Ennis+Kindlmann 2005)

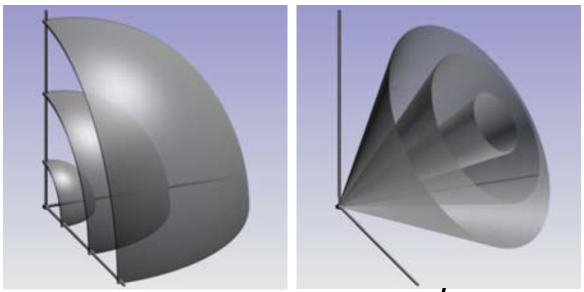


tr(**D**) = Dxx+Dyy+Dzz
|**D**| = sqrt(tr($\mathbf{D}^T\mathbf{D}$))

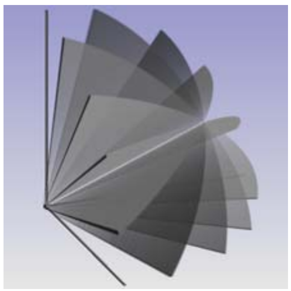
E = deviatoric(**D**)
= **D** - trace(**D**)***I**/3



tr(**D**) |**E**|



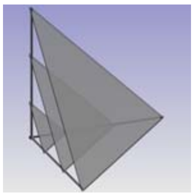
|**D**| |**E**|/|**D**|
= sqrt(2/3) FA



mode(**E**)
= det(**E**/|**E**|)
(Criscione '00)
Mode measures
Linear vs. planar
anisotropy

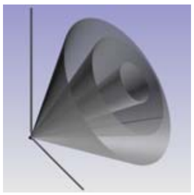
Biological Significance of Tensor Shape

Size: bulk mean diffusivity (“ADC”)



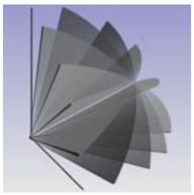
- ADC strictly speaking diffusivity along **one** direction
- tr(**D**) same across gray+white matter, high in CSF
- Indicator of acute ischemic stroke

Anisotropy (e.g. FA, RA): directional microstructure



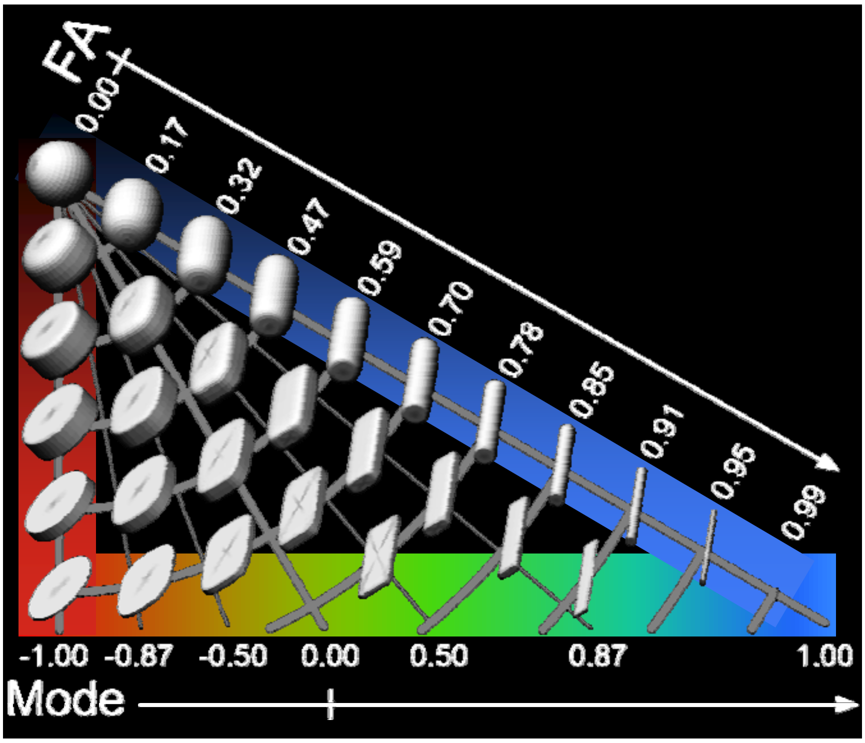
- High in white matter, low in gray matter and CSF
- Increases with myelination, decreases in some diseases

Mode: linear versus planar



- Partial voluming of adjacent orthogonal structures
- Fine-scale mixing (superior longitudinal fasciculus)
- Tensor fitting error increases with planarity (Tuch 2002)

Orthogonal vs. barycentric invariants



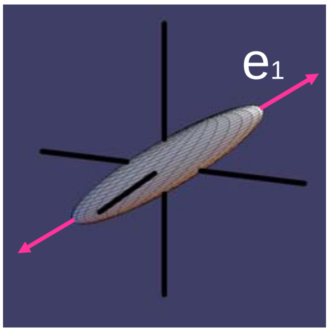
High FA $\Rightarrow$ linear
ONLY when FA > 1/sqrt(2)

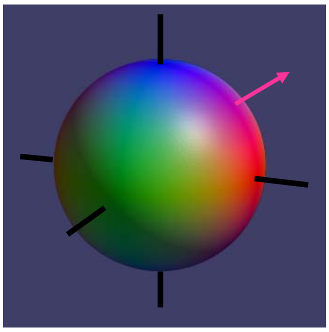
Need both FA and mode to characterize high linear anisotropy

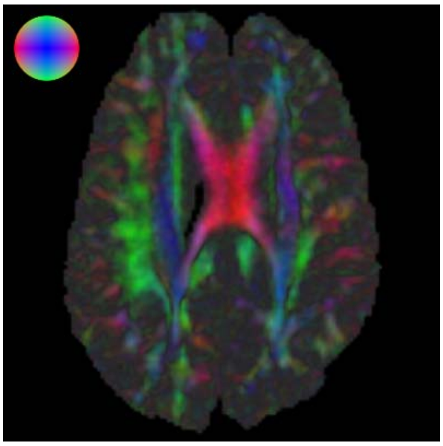
|**D**| constant

Significance of Tensor Orientation

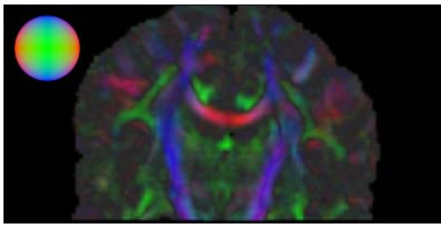
Principal eigenvector gives axon bundle direction



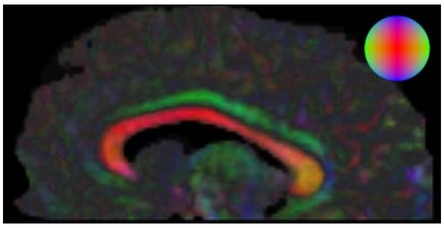




Axial



Coronal



Sagittal

R=$|\mathbf{e}_1 \cdot x|$
G=$|\mathbf{e}_1 \cdot y|$
B=$|\mathbf{e}_1 \cdot z|$

(Pierpaoli et al., 1997)

(demo of colormaps)

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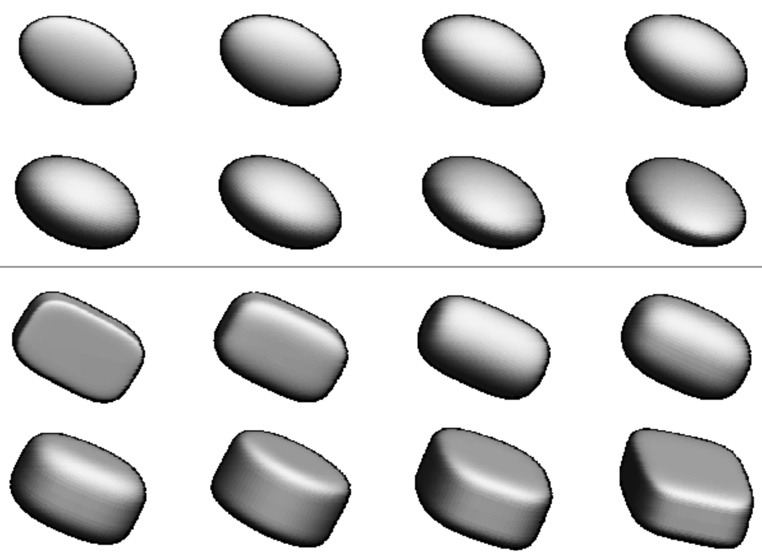
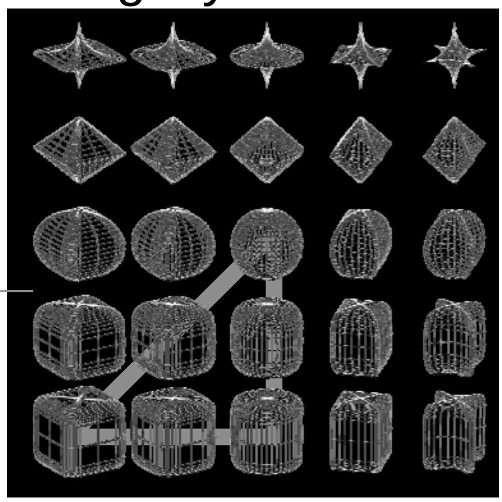
Glyphs for inspecting tensors

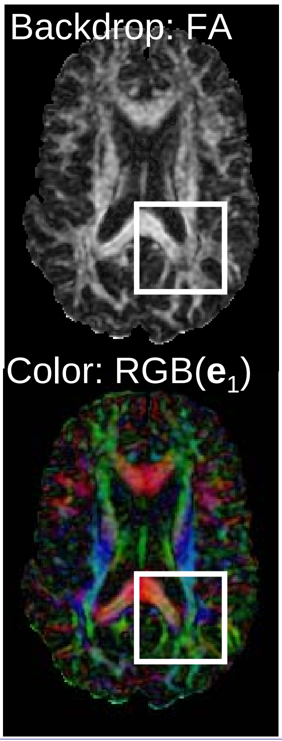
Superquadric tensor glyphs (Kindlmann 2004)

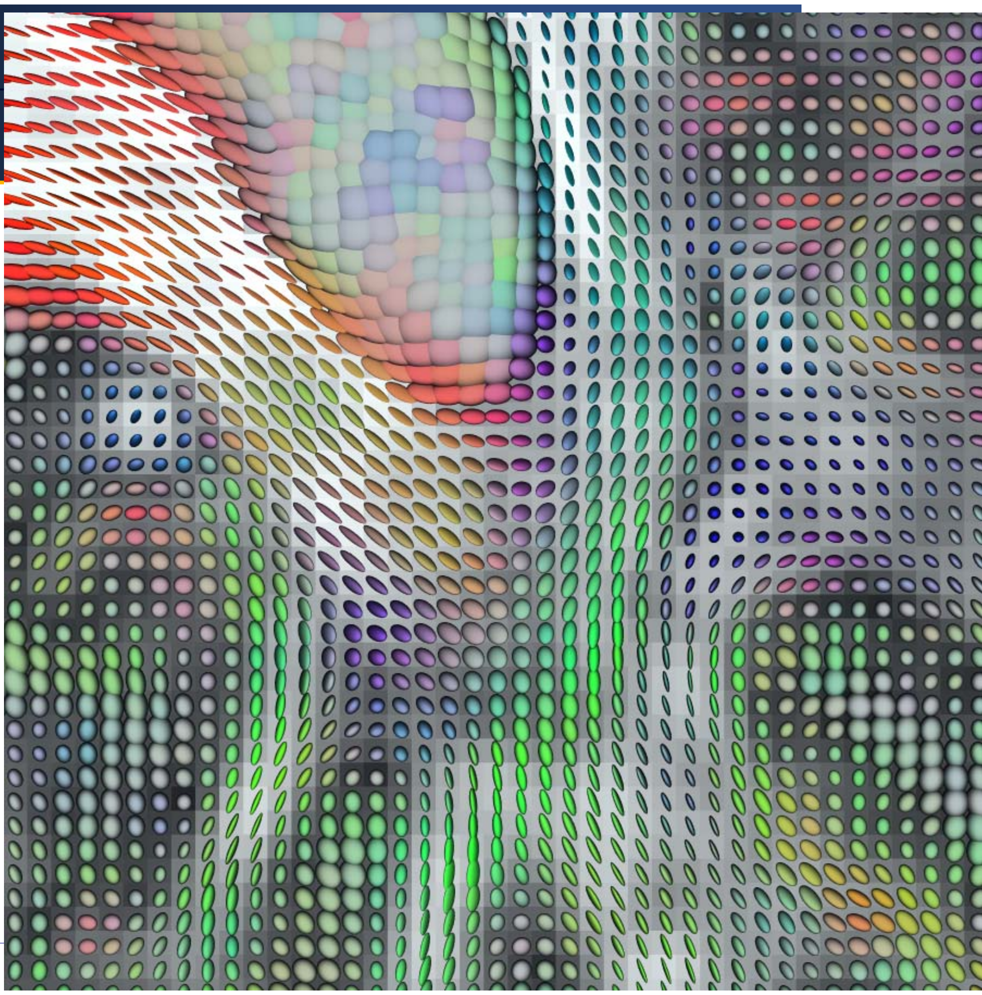
- Avoids visual ("bas-relief") ambiguity

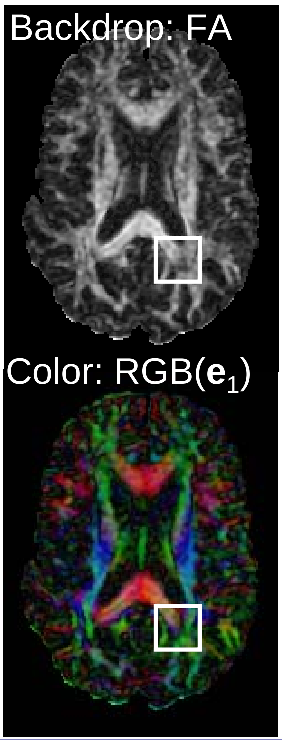




(Barr 1981)


Backdrop: FA
Color: RGB($\mathbf{e}_1$)




Backdrop: FA
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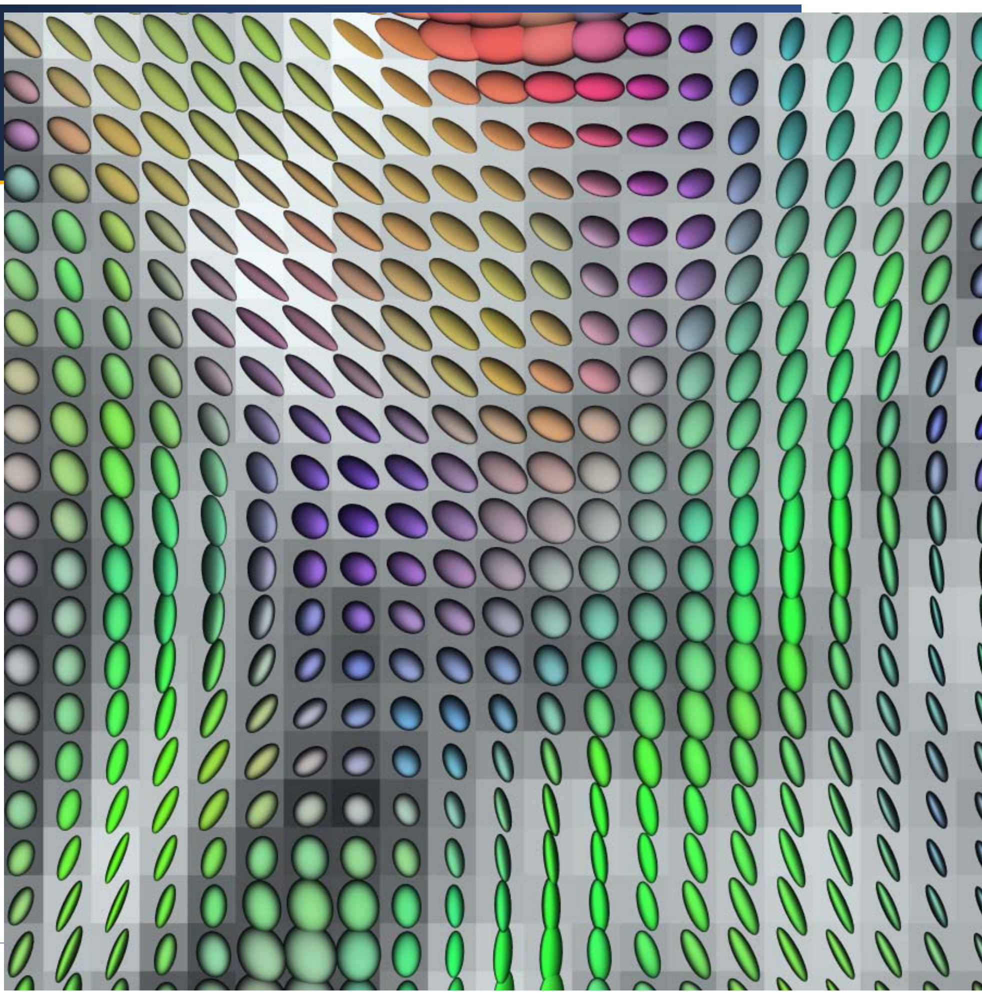
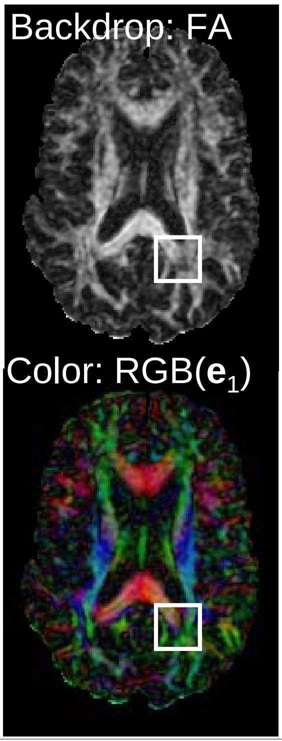
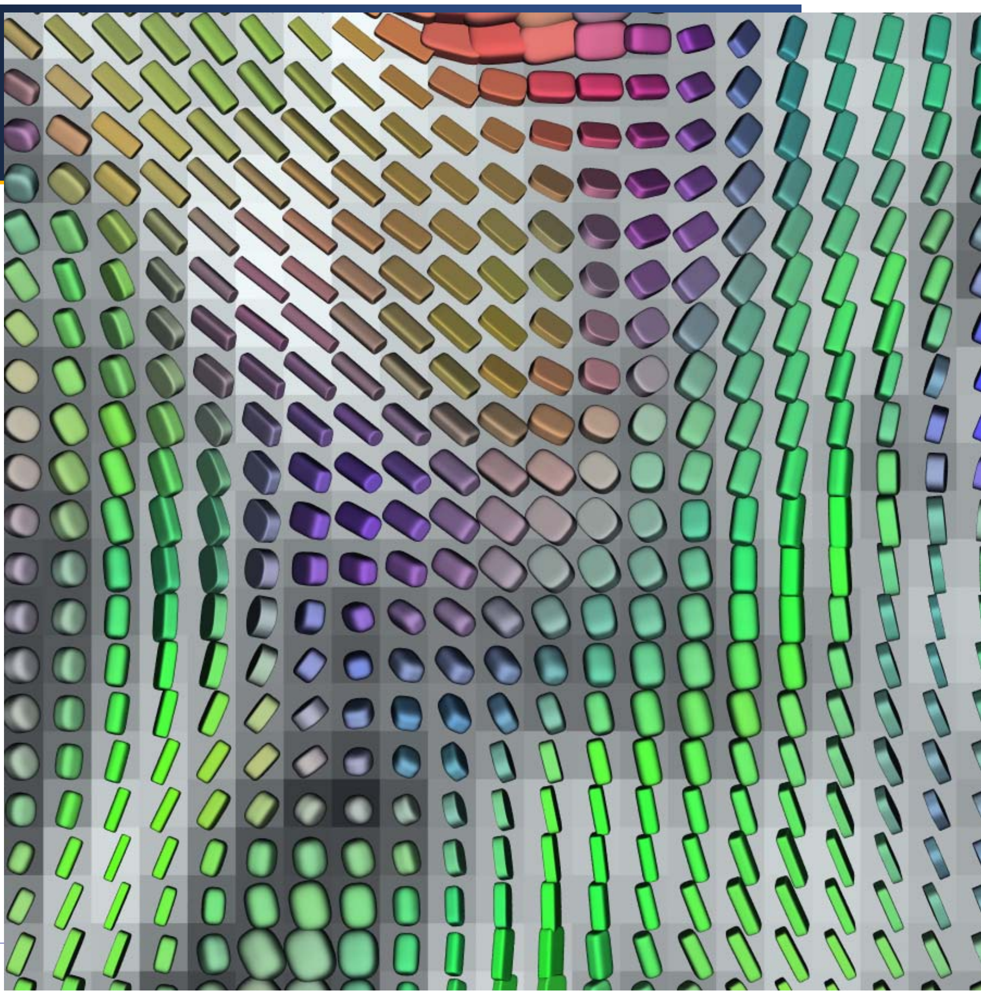


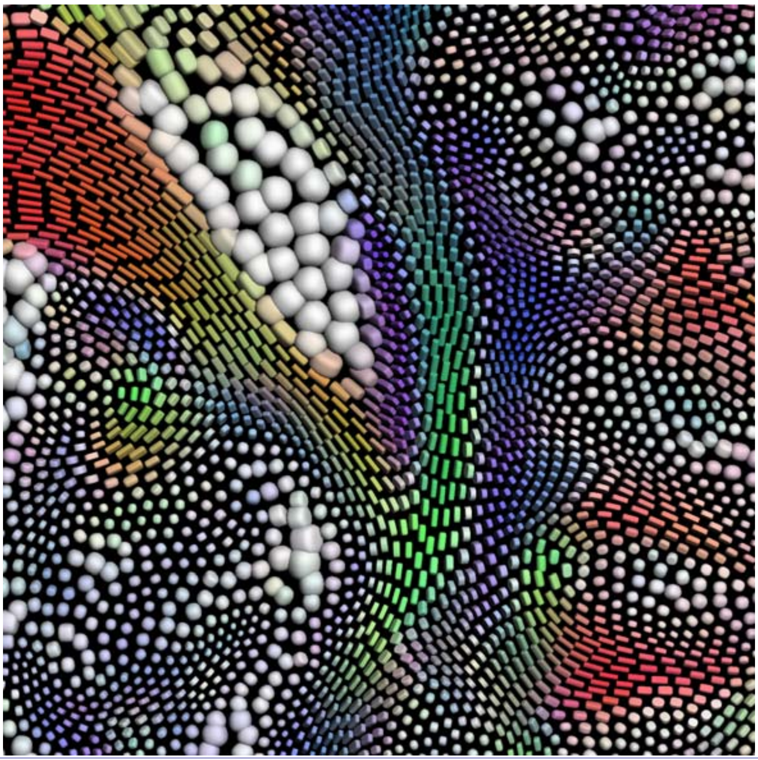




Particle systems for glyphs

- Use particle systems from graphics and and anisotropic mesh generation to place glyphs
- Avoids visual emphasis on regular grid of original data
- Initial evaluation in tumor studies

Kindlmann + Westin Vis ‘06



DT-MRI

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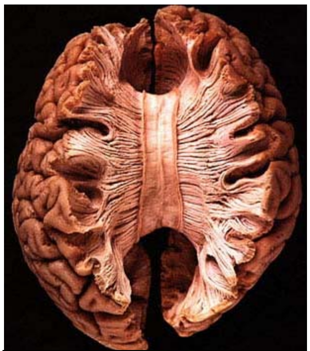
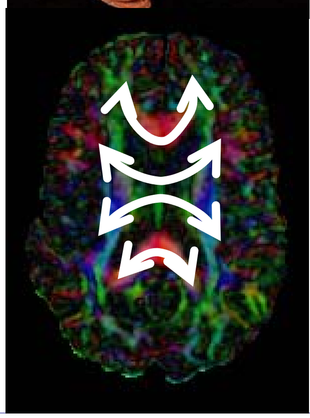
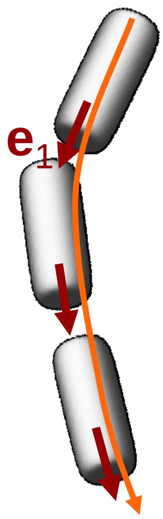
Fiber tractography (Basser 1999)

Tensorlines

- Path integration along principal eigenvector
- Hope: follow paths of individual axons!
  - Reality: 2-3 orders of magnitude too coarse
- Essentially hyperstreamlines (Delmarcelle 1993)





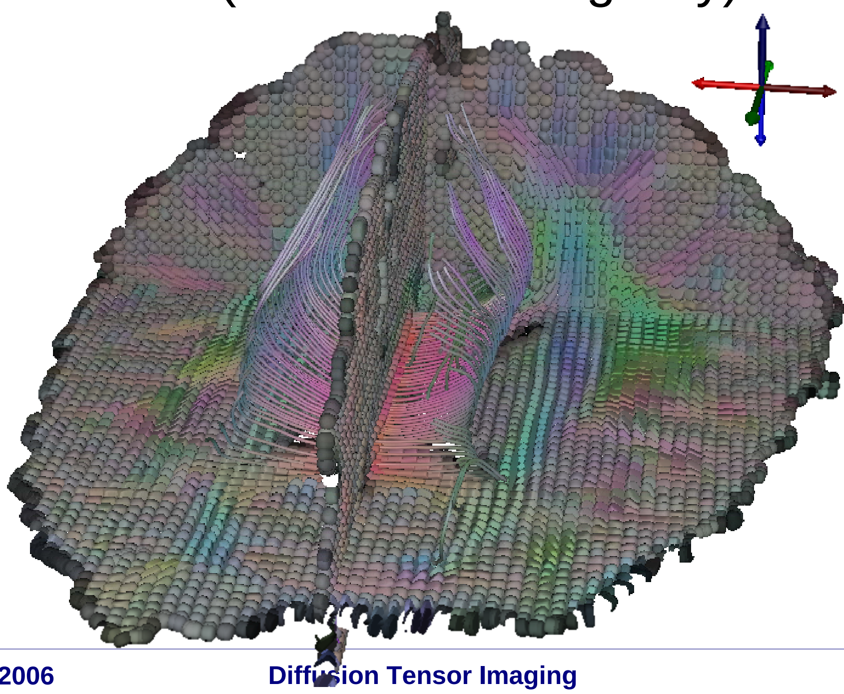


Fiber Tracking Issues

- Tensor Field Interpolation/Reconstruction
  - Interpolate in DWIs, tensor coefficients, something else?
  - Noise: smoothing as part of reconstruction (e.g. Zhukov 2002)
- Integration quality, step size
  - Eigensolve at every sample non-trivial
- Seedpoint selection
  - Once per voxel is arbitrary; want proper sampling
- Termination criteria
  - tr(**D**) too high or low
  - FA threshold: popular but not robust without mode (CL)
  - Length, # steps, curvature
- Parameter space, Reproducibility, Validation
- What to do at planar anisotropy: stop, coast?

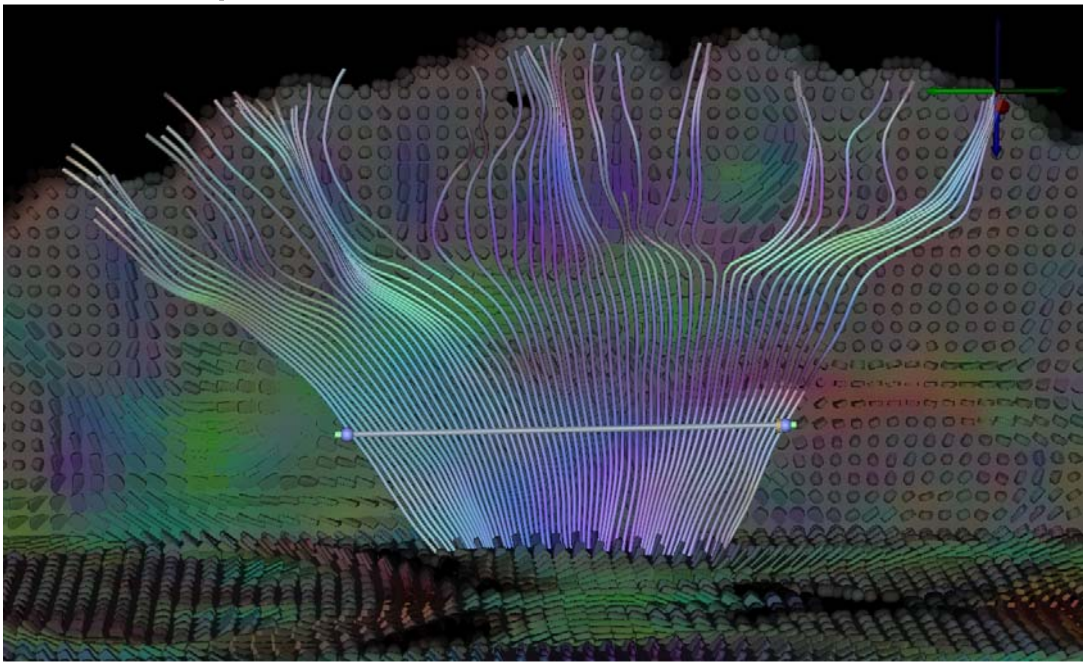
Fiber Tracking: Results

Corpus callosum (seeded mid-sagitally)

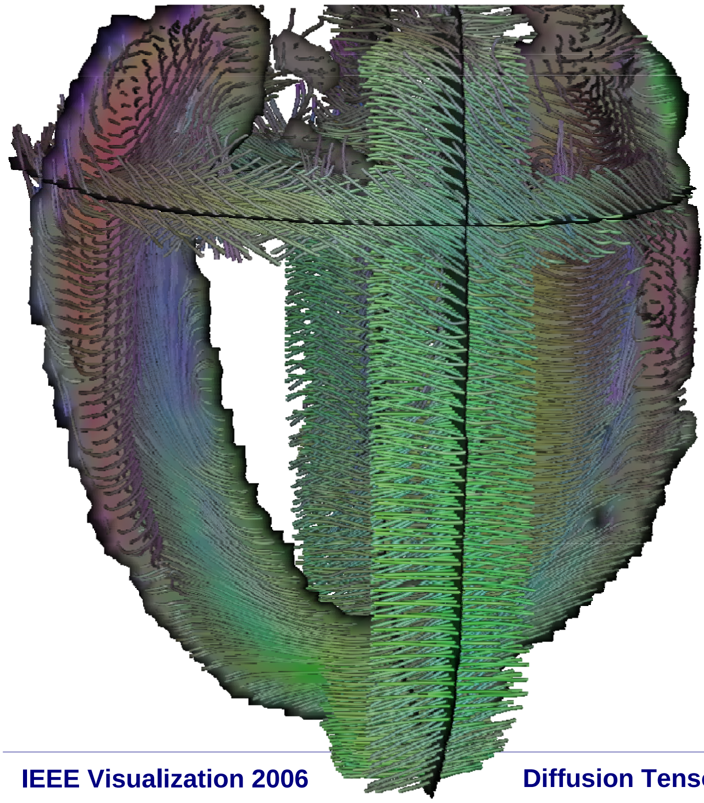


Fiber Tracking: Results

Internal Capsule → Corona Radiata



Fiber Tracking In Heart DT-MRI

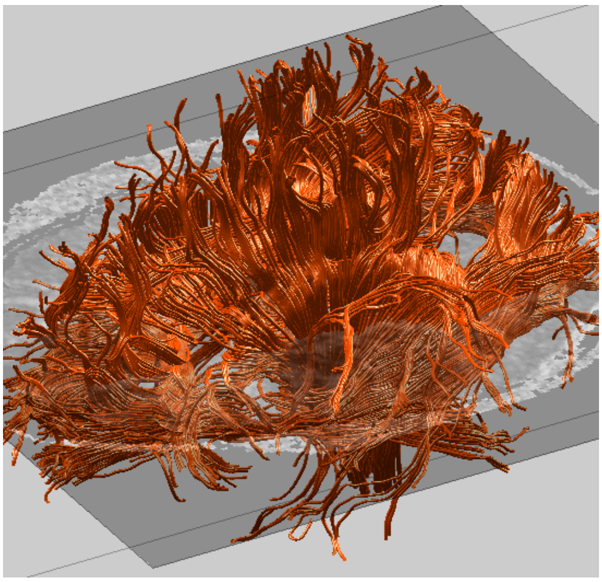


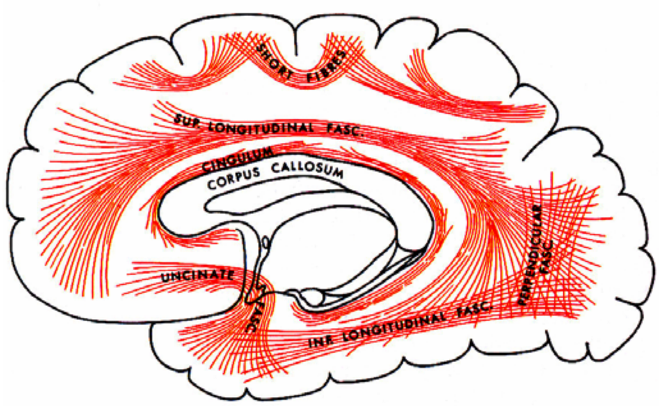
- Contractile muscle tissue (myofibers) induces anisotropy
- Histological validation (Hsu 1988)
- Transmural twist of myofibers

(demo glyphs +
fiber tracking)

Segmentation challenge

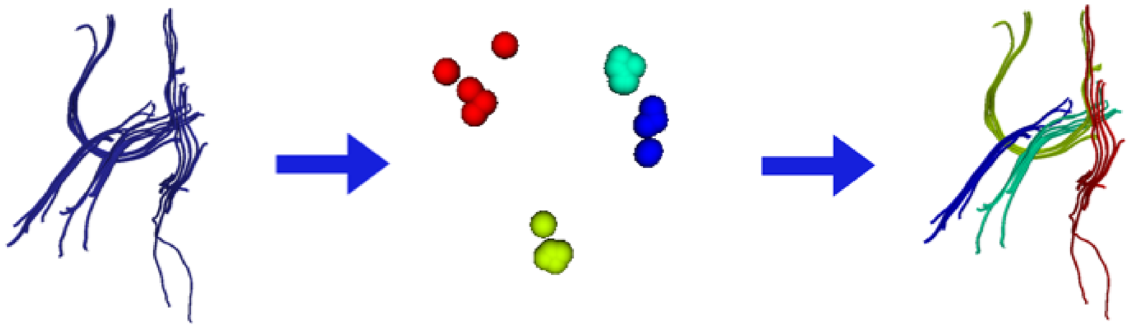
From DT-MRI tractography …





… to white matter tract models using **clustering**

Fiber Clustering



Traced fibers | High-dimensional feature space | Colored bundles

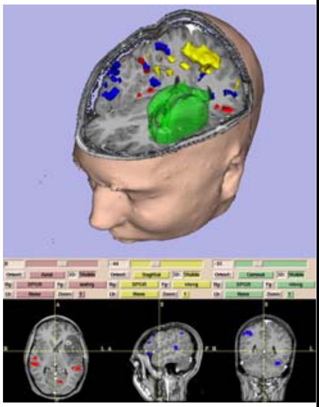
O'Donnell MICCAI 2005

A clustering algorithm takes a number of traced fibers (left), extracts features from these fibers (middle), and produces a segmentation based on the similarity of the fibers (right).

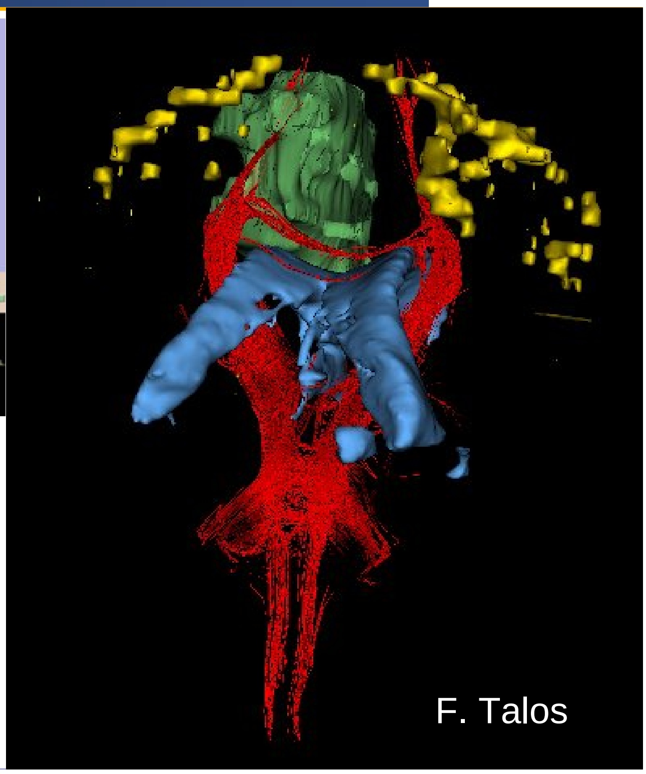
Neurosurgery: tumor study

- 3D Slicer

http://www.slicer.org



- Brain connectivity important question
- Relationship between tumor and surrounding white matter



F. Talos

DT-MRI

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Future Work Ideas

Interactive fiber generation and analysis

Uncertainty visualization

Bridge between tensor and high-angular DWI

Better use of GPUs

Volume Rendering?

Non-photorealistic rendering?