Exploration of the Brain's White Matter Structure through Visual Abstraction and Multi-Scale Local Fiber Tract Contraction

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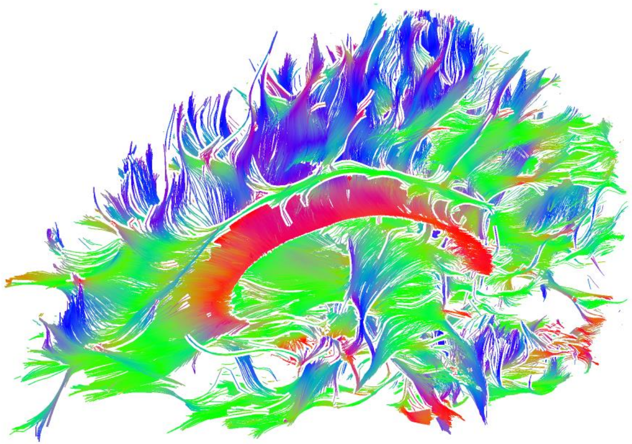
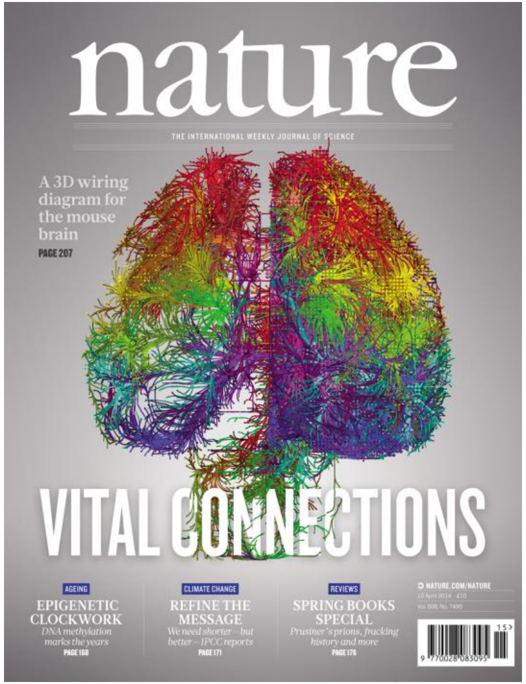
TNO

informatics mathematics Inria



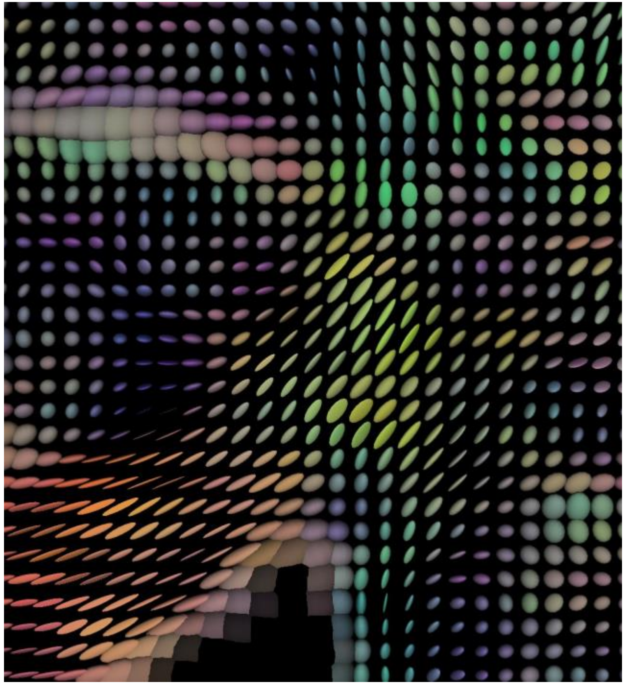
Analysis of the Brain’s Structure

long-distance connections of macaque brain regions
Science 339(6119), February 2013



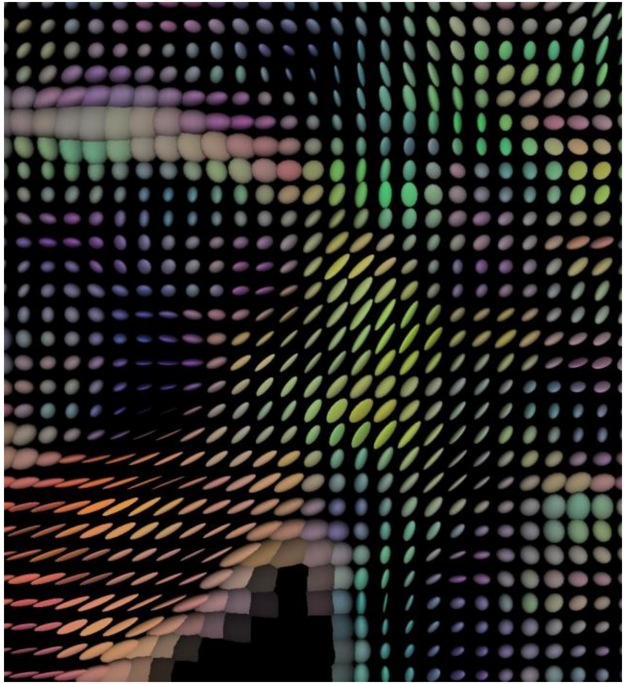
structure of a mouse brain
Nature 508(7495), April 2014

Related Work



representation of DTI as tensors using glyphs
[image: Thomas Schultz]

Related Work



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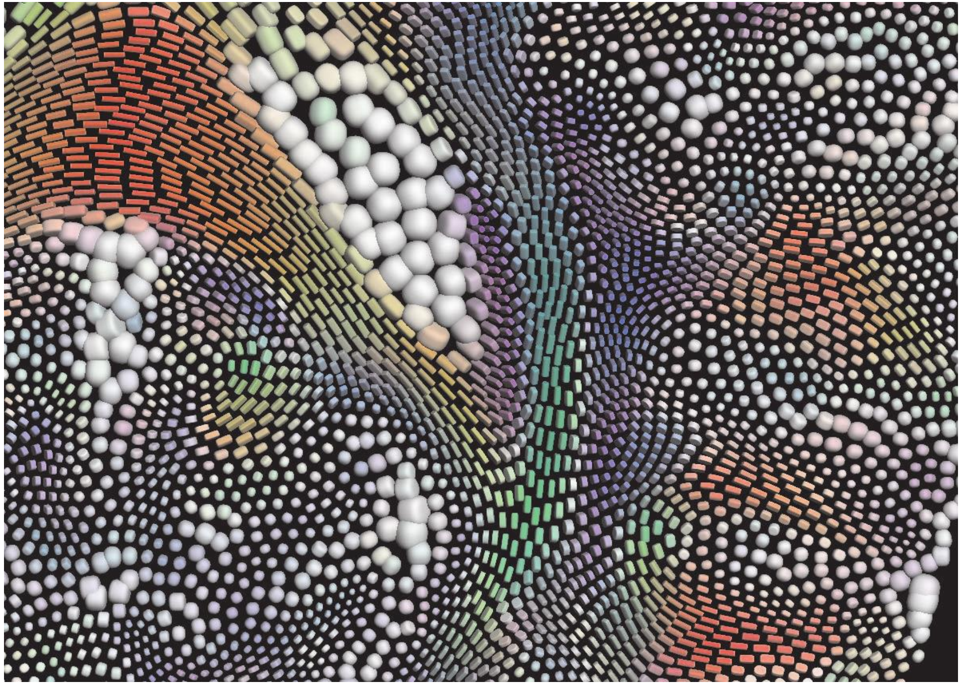
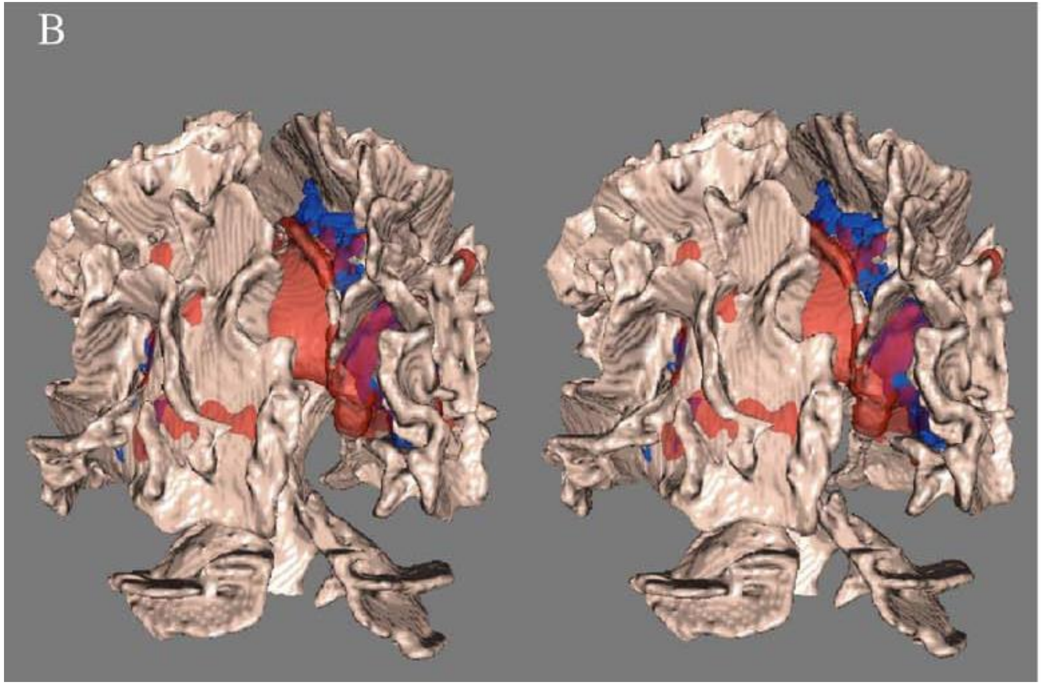


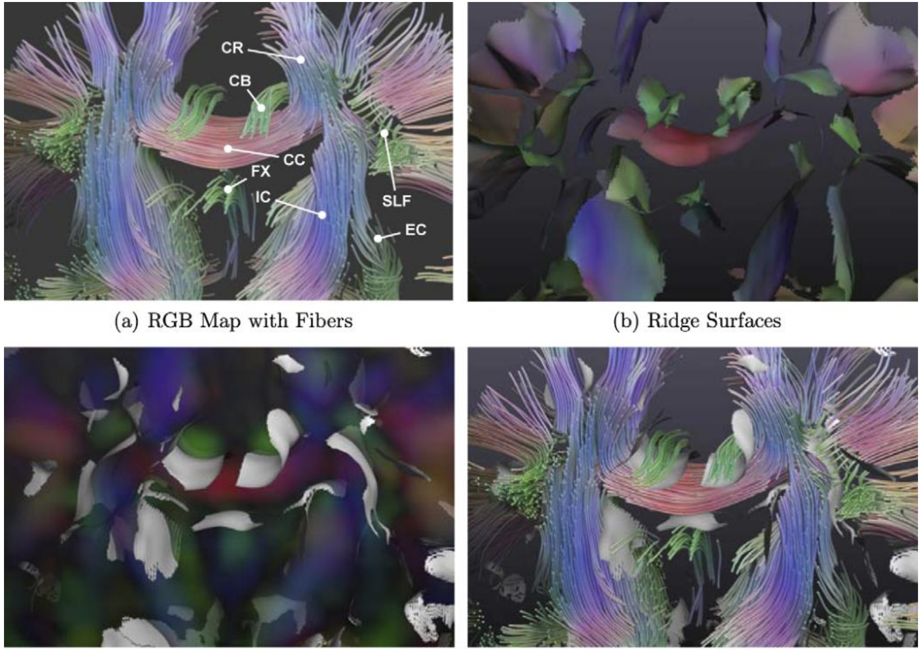
glyph packing
[Kindlmann and Westin, 2006]

Related Work



volumetric skeleton of mean FA volume
[Smith et al., 2006]

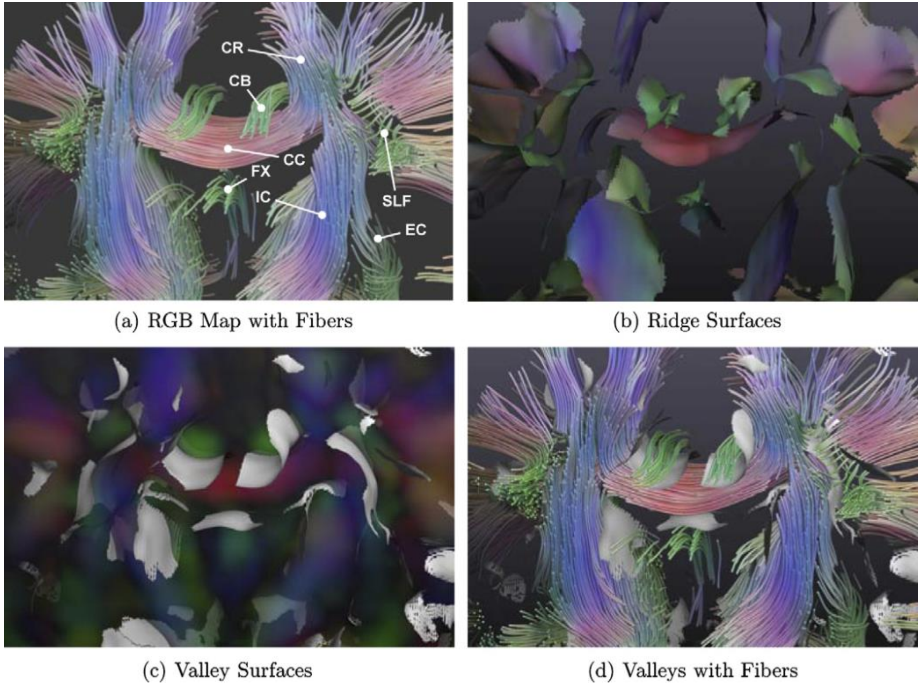
Related Work



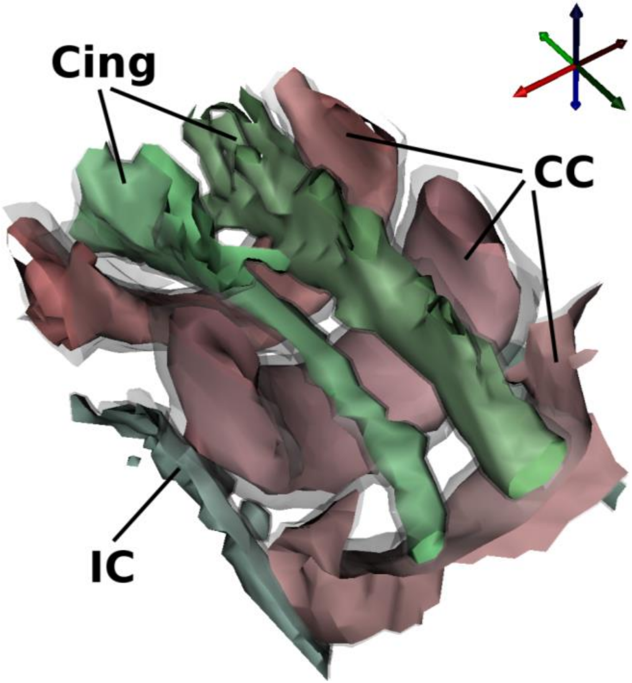
(a) RGB Map with Fibers
(b) Ridge Surfaces
(c) Valley Surfaces
(d) Valleys with Fibers

anisotropy crease surfaces
[Kindlmann et al., 2007]

Related Work

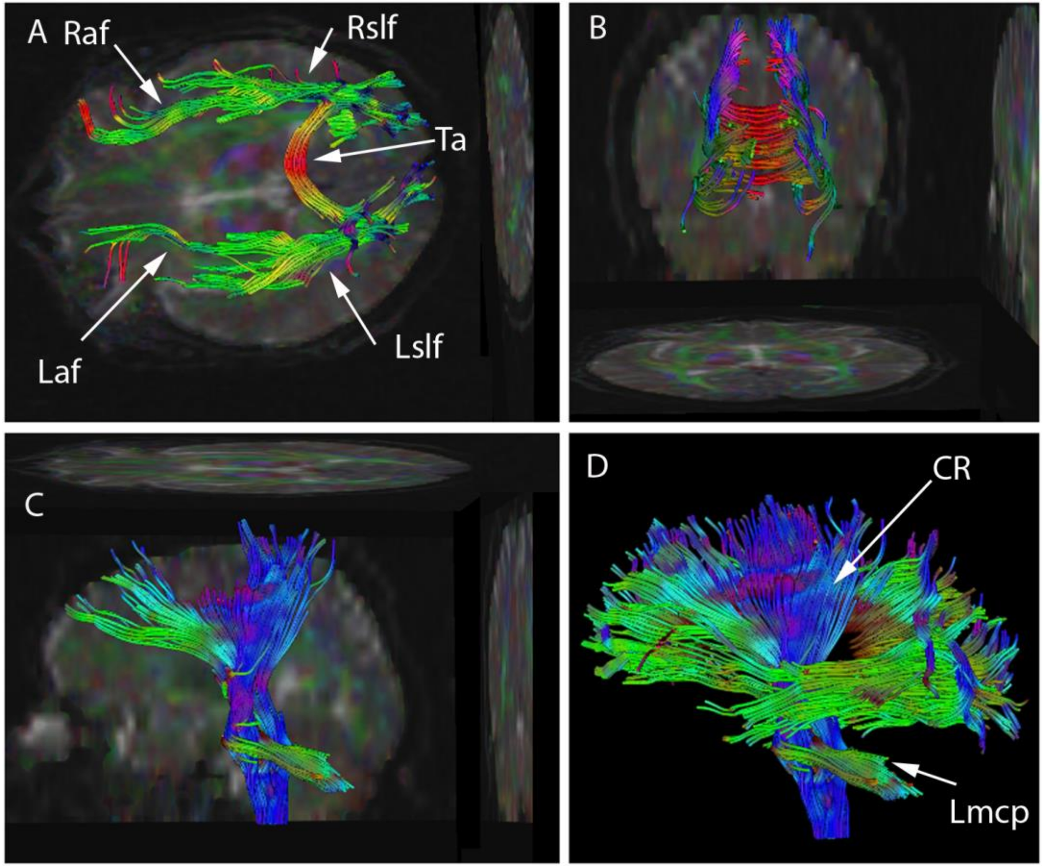


anisotropy crease surfaces
[Kindlmann et al., 2007]



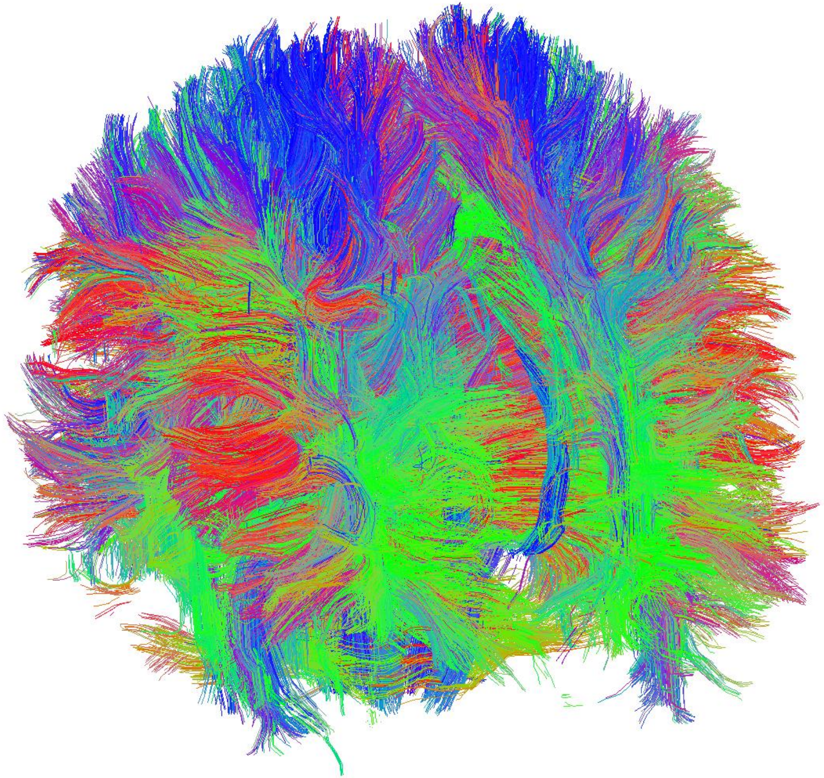
tensor field topology (probabilistic fiber tracking)
[Schultz et al., 2007]

DTI Tractography

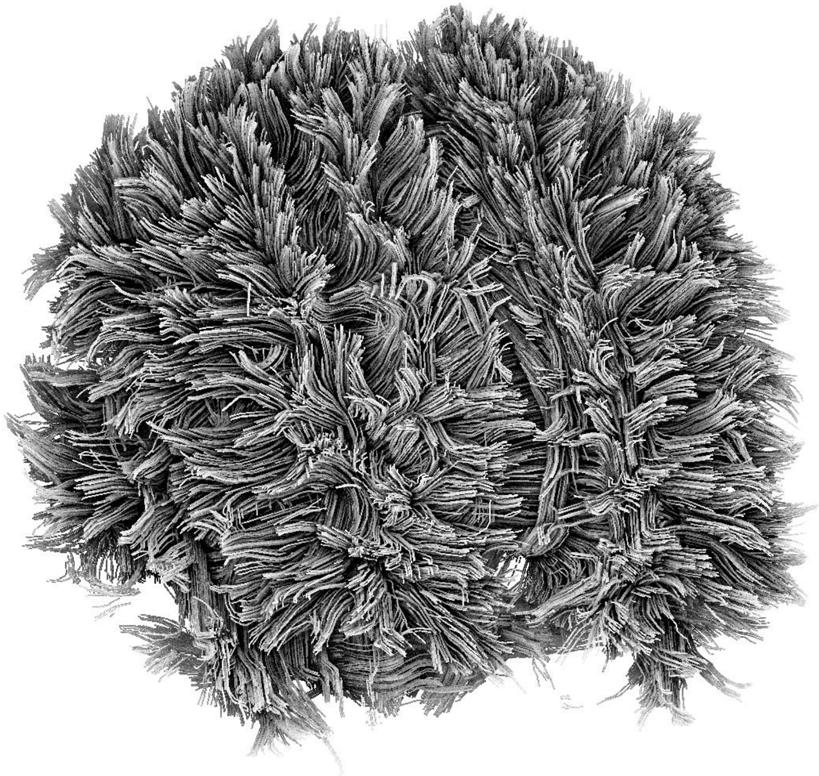


[image: Aaron G. Filler]

White Matter Fibertract Visualizations

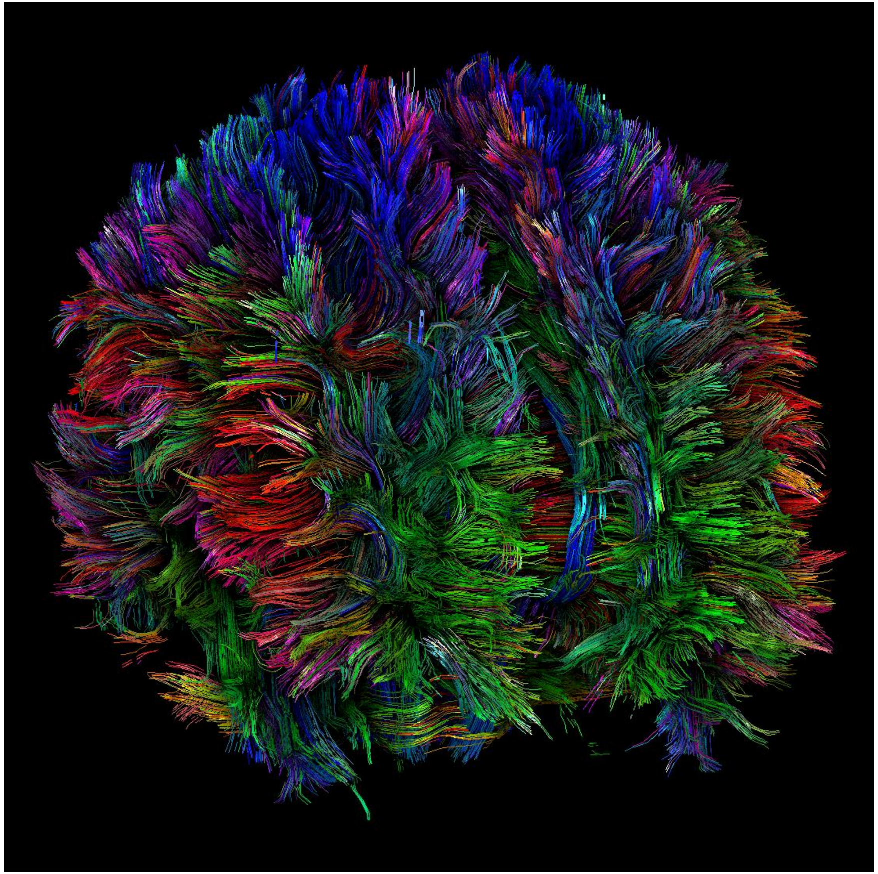


White Matter Fibertract Visualizations



[LineAO: Eichelbaum et al., 2013]

White Matter Fibertract Visualizations

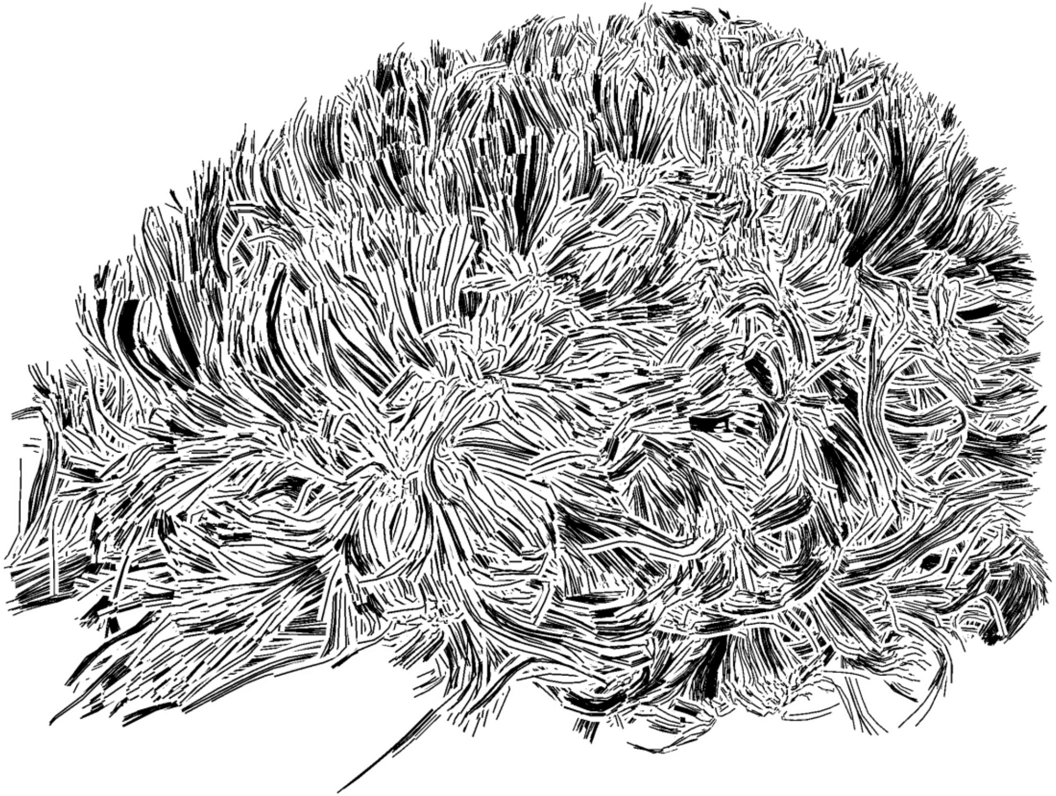


[LineAO: Eichelbaum et al., 2013]

White Matter Structure of the Whole Brain?

[Depth-Dependent Halos: Everts et al., 2009]

White Matter Structure of the Whole Brain?



[Depth-Dependent Halos: Everts et al., 2009]

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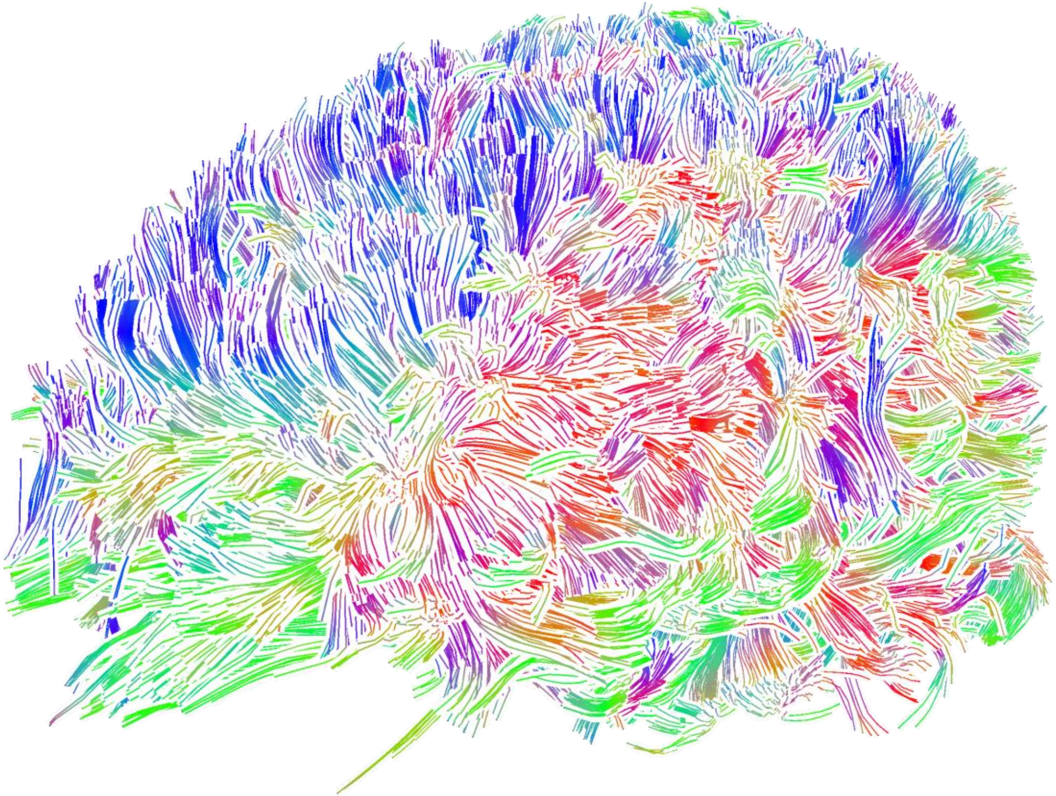


[Depth-Dependent Halos: Everts et al., 2009]

Goals

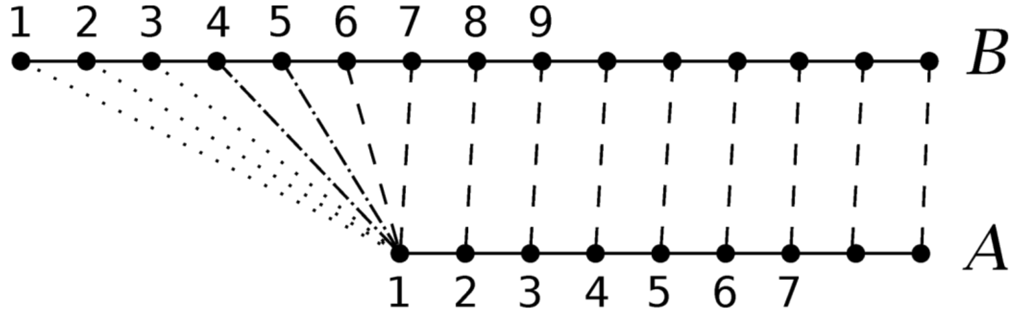
1. analyze brain connectivity at a higher level/scale
   $\rightarrow$ use of abstraction

2. method suited for analysis of full-brain tractograms

3. ability to control the scale of the abstraction

Abstraction Through Local Similarity Analysis

- dense & even tract sampling/re-tessellation (1mm)
- then tract-to-tract comparison



Abstraction Through Local Similarity Analysis

- dense & even tract sampling/re-tessellation (1mm)
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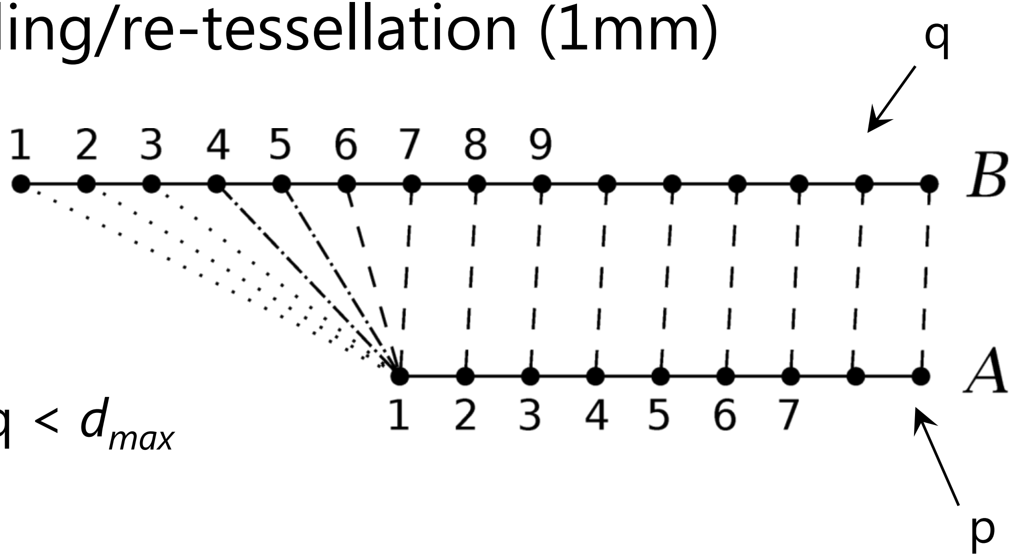
  three conditions

  1. distance between p and q < d_{max}



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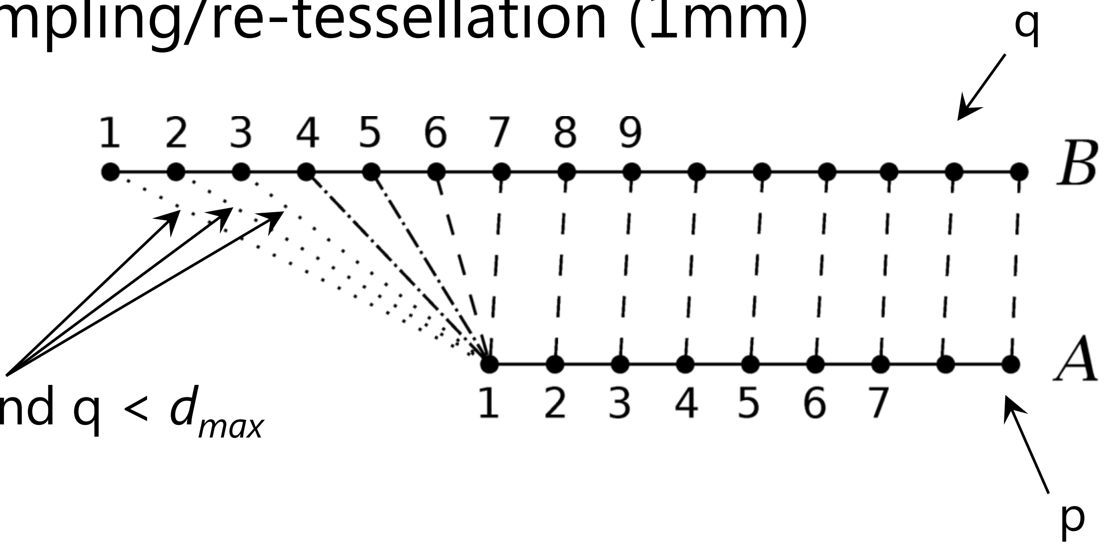

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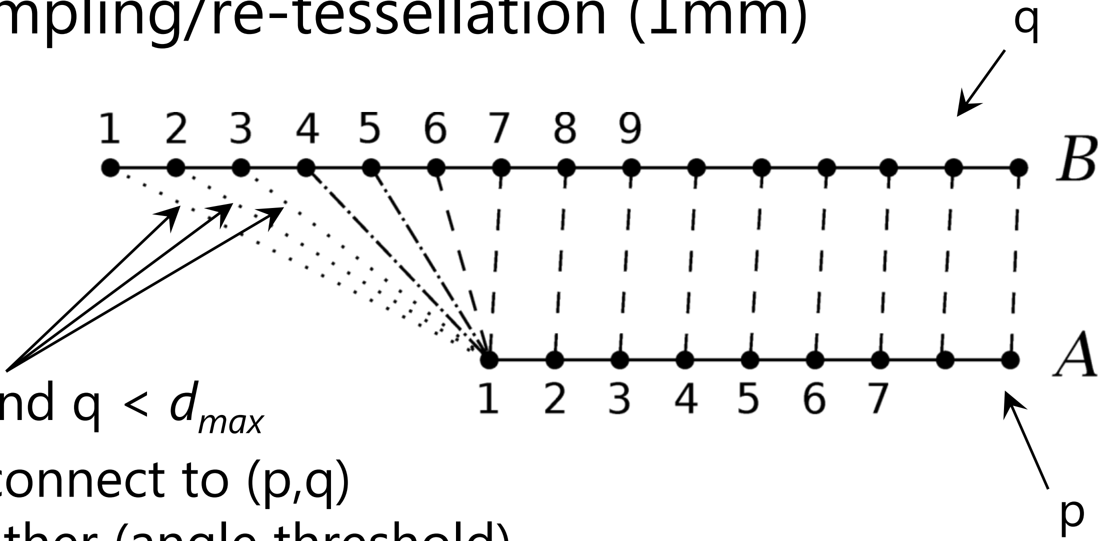
  1. distance between p and q < d_{max}
  2. edges in A and B that connect to (p,q) are roughly || to each other (angle threshold)



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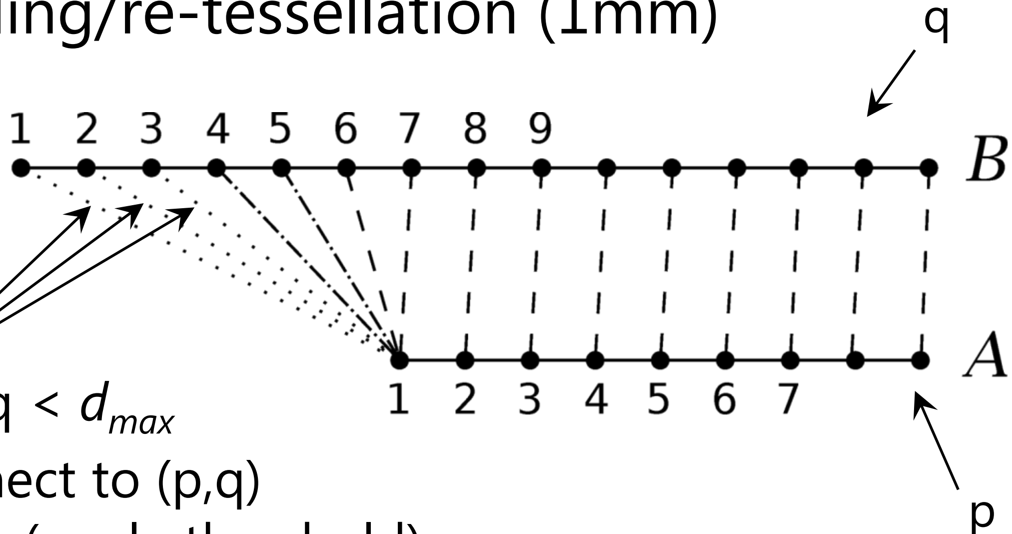

three conditions

1. distance between p and q < d_{max}
2. edges in A and B that connect to (p,q) are roughly || to each other (angle threshold)
3. the nearest-neighbor relation of p and q is approximately mutual, i.e., the nearest neighbor of q in A is at most 1 index away from p, and vice versa

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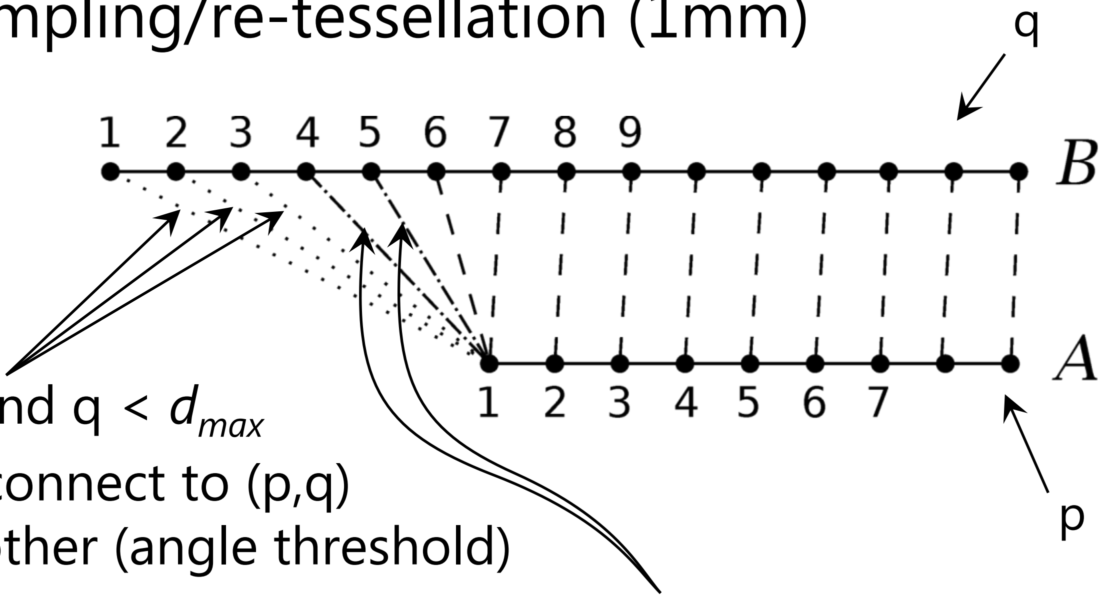

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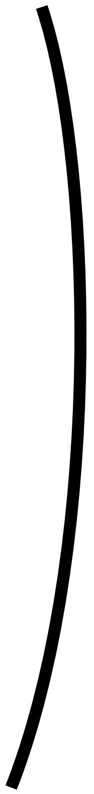
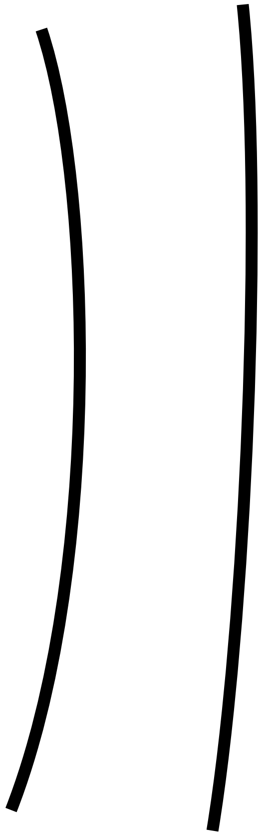
Similarity Graph



Similarity Graph



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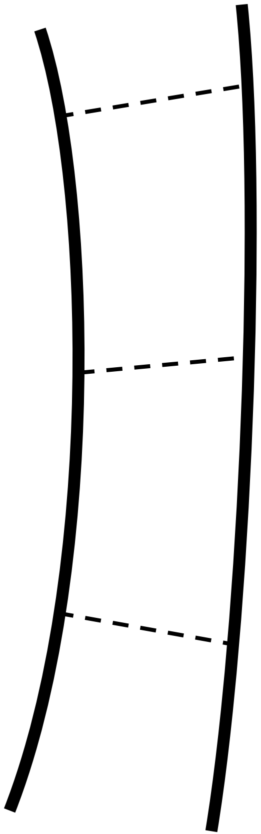

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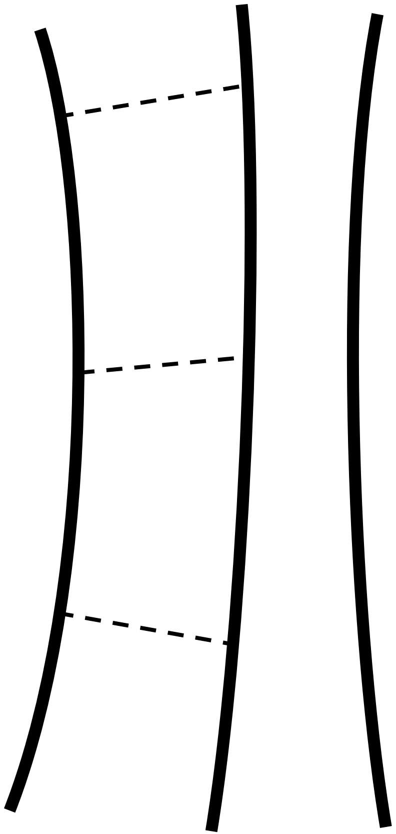

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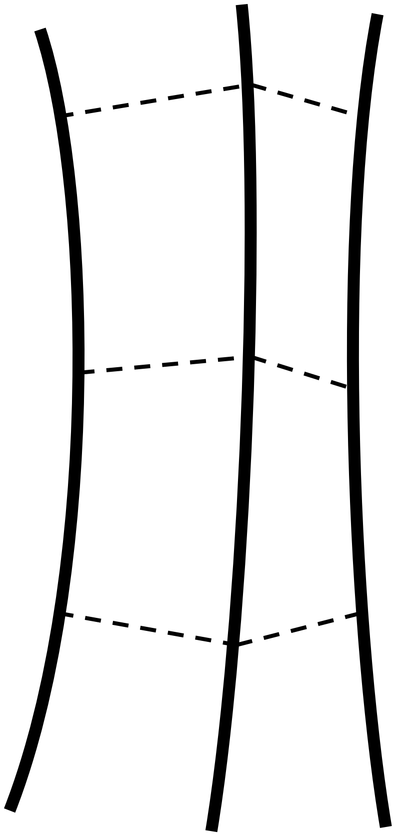

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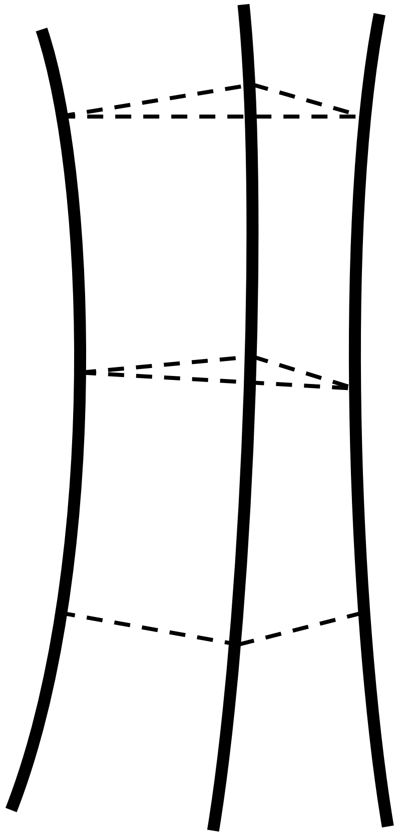

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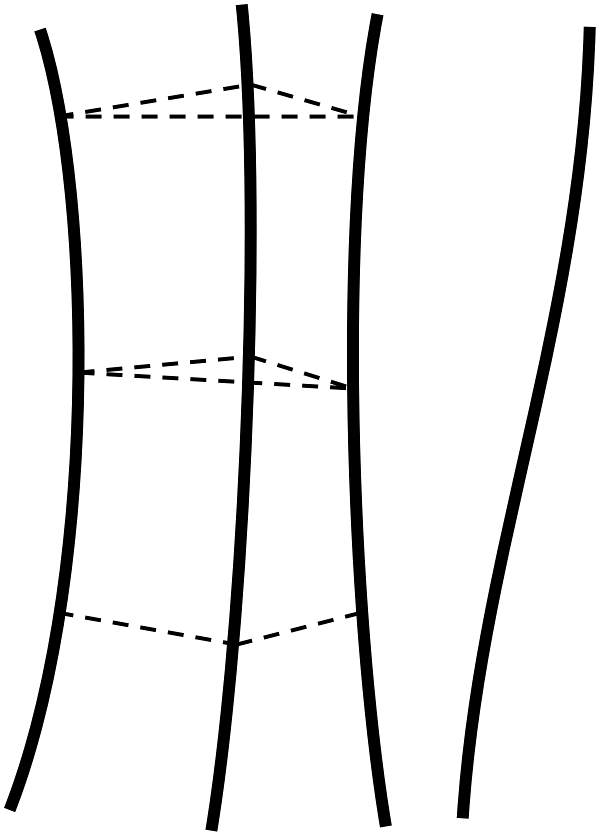

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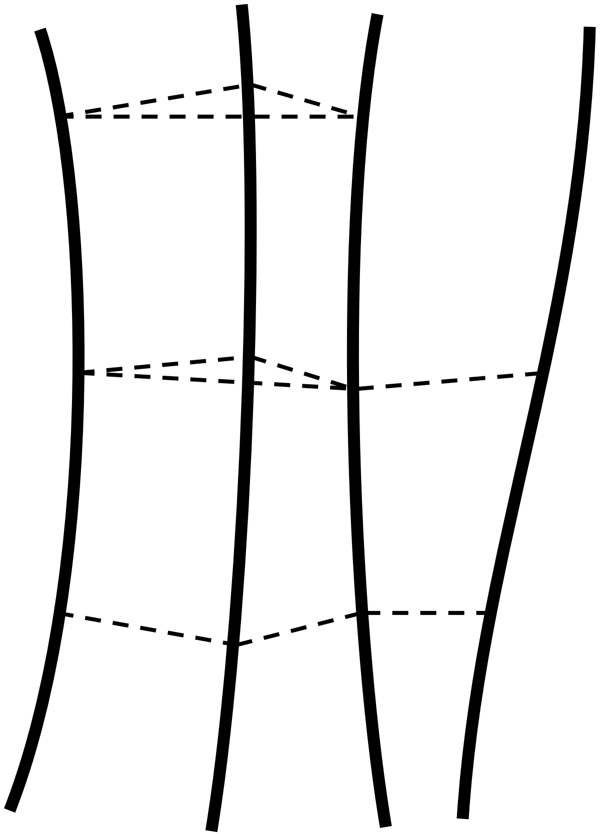

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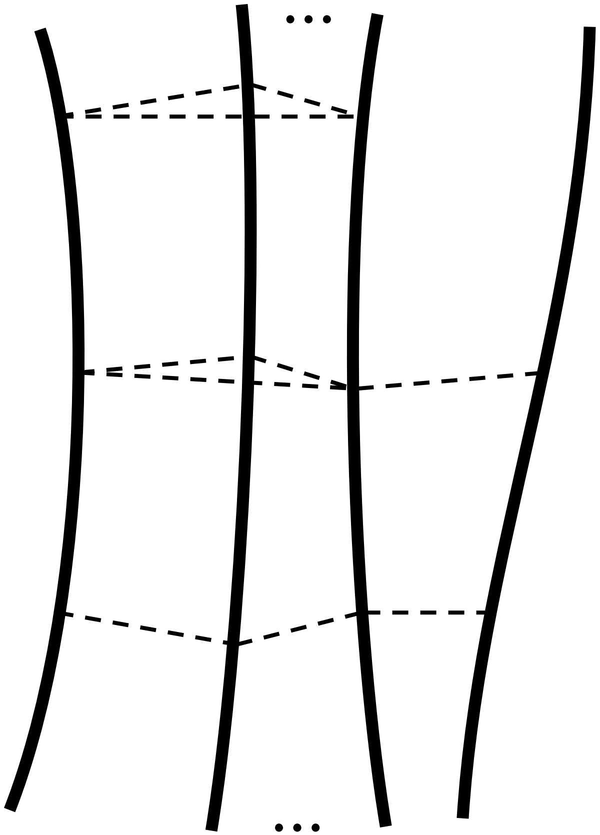

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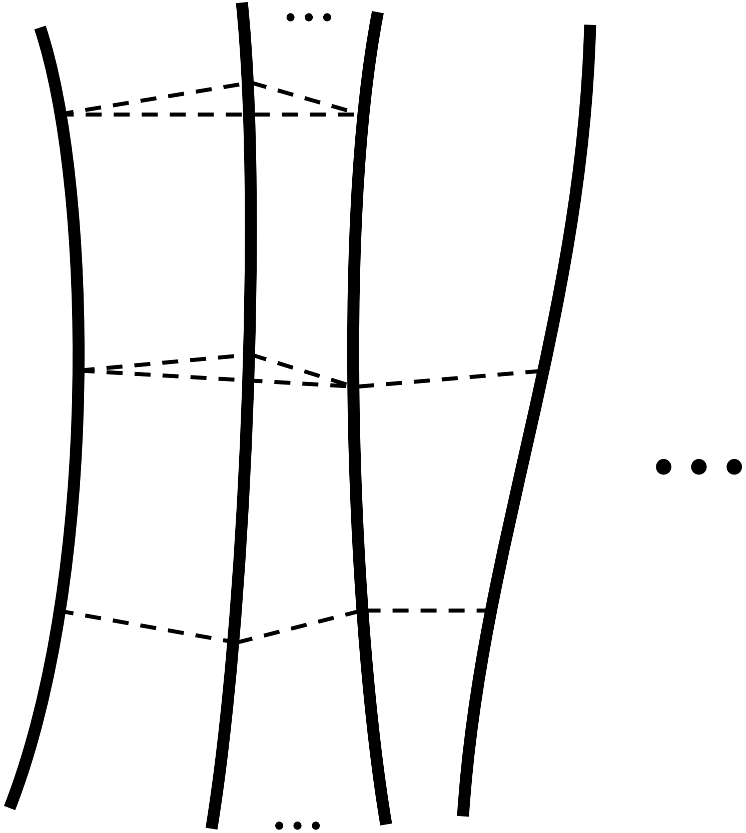

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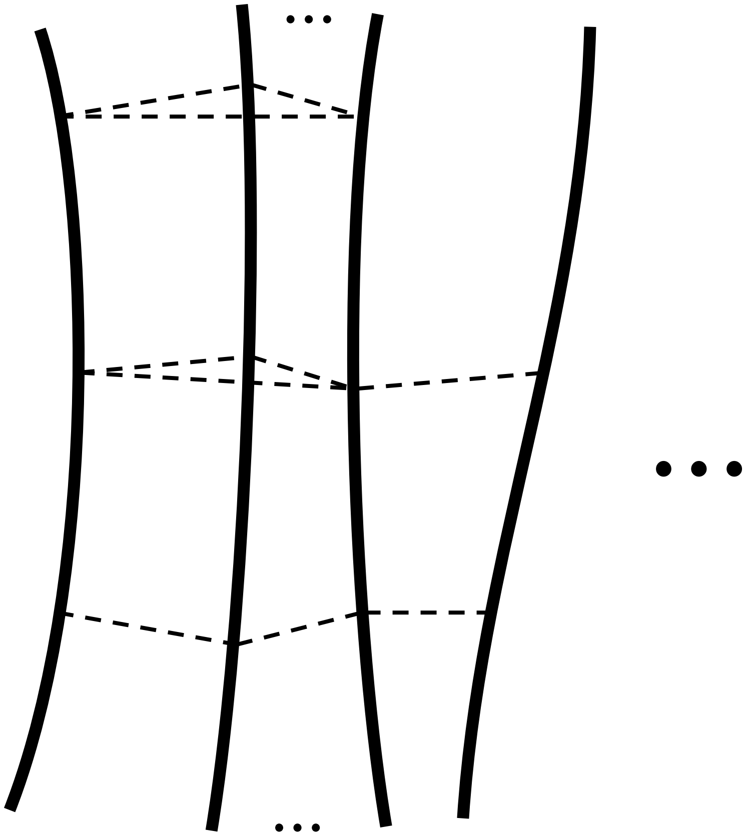
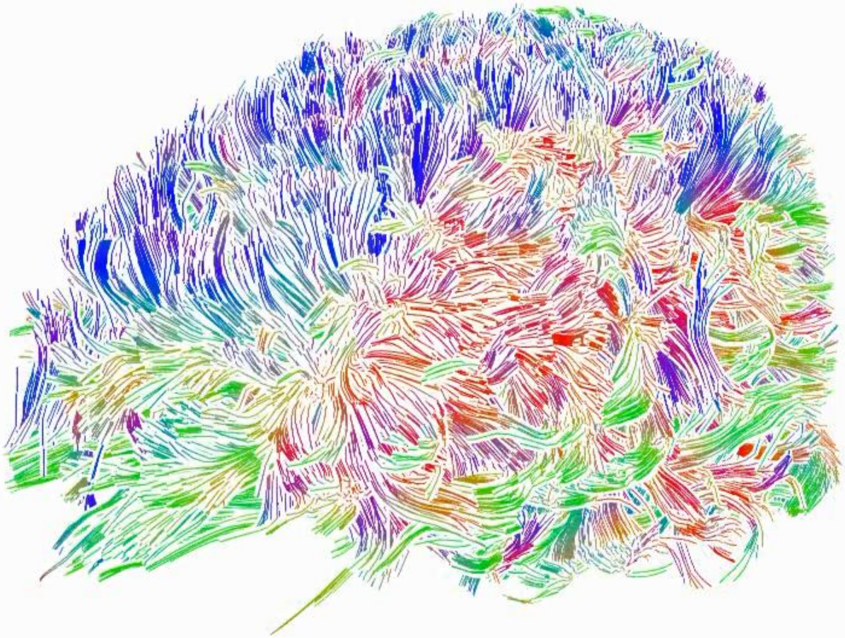


one similarity graph for
each d_{max} level

Contraction based on Similarity/Proximity



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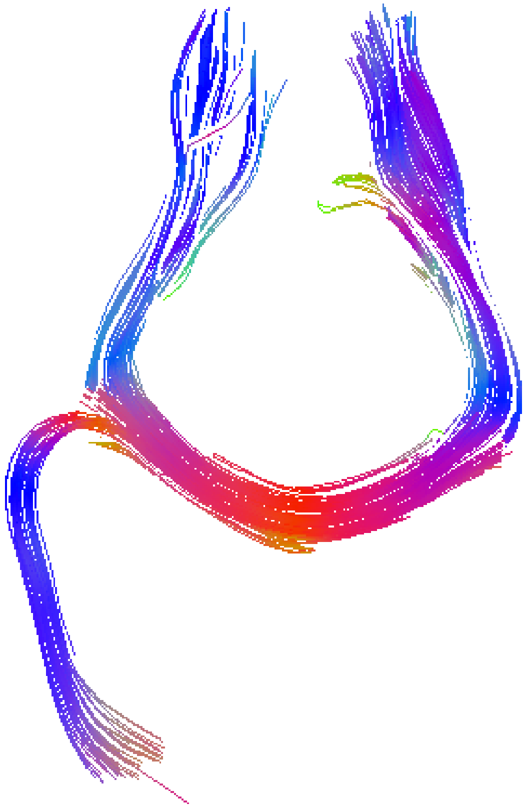

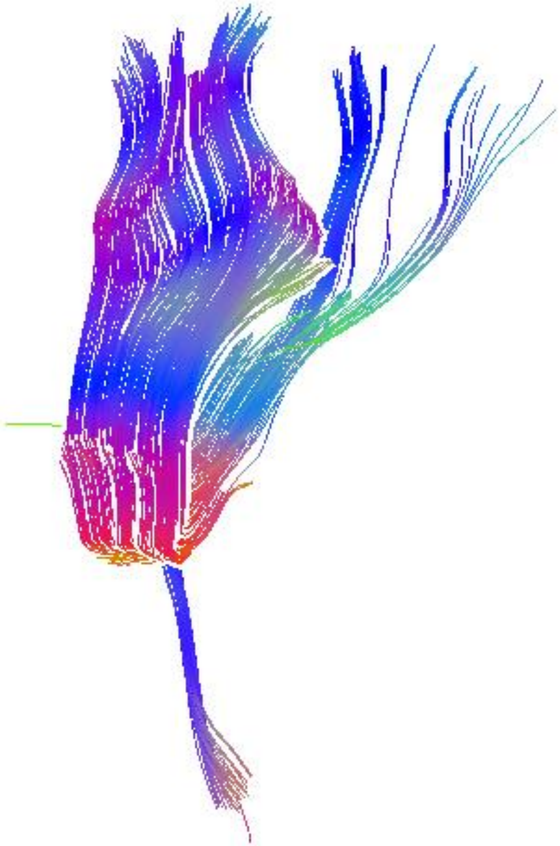

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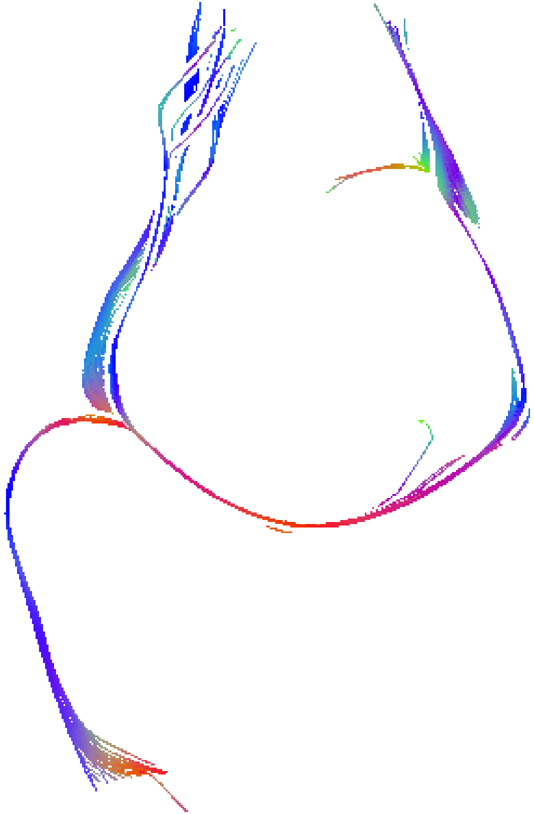
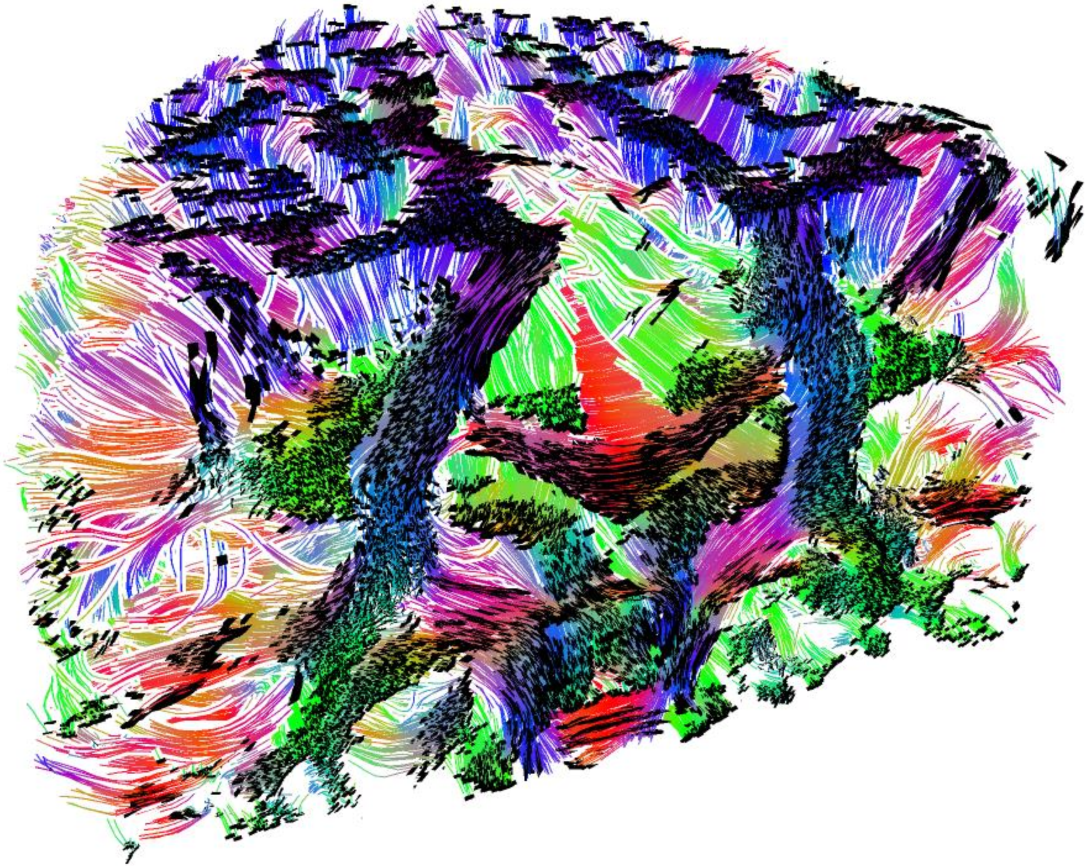


Visual Evidence for Brain’s sheet-like Structure



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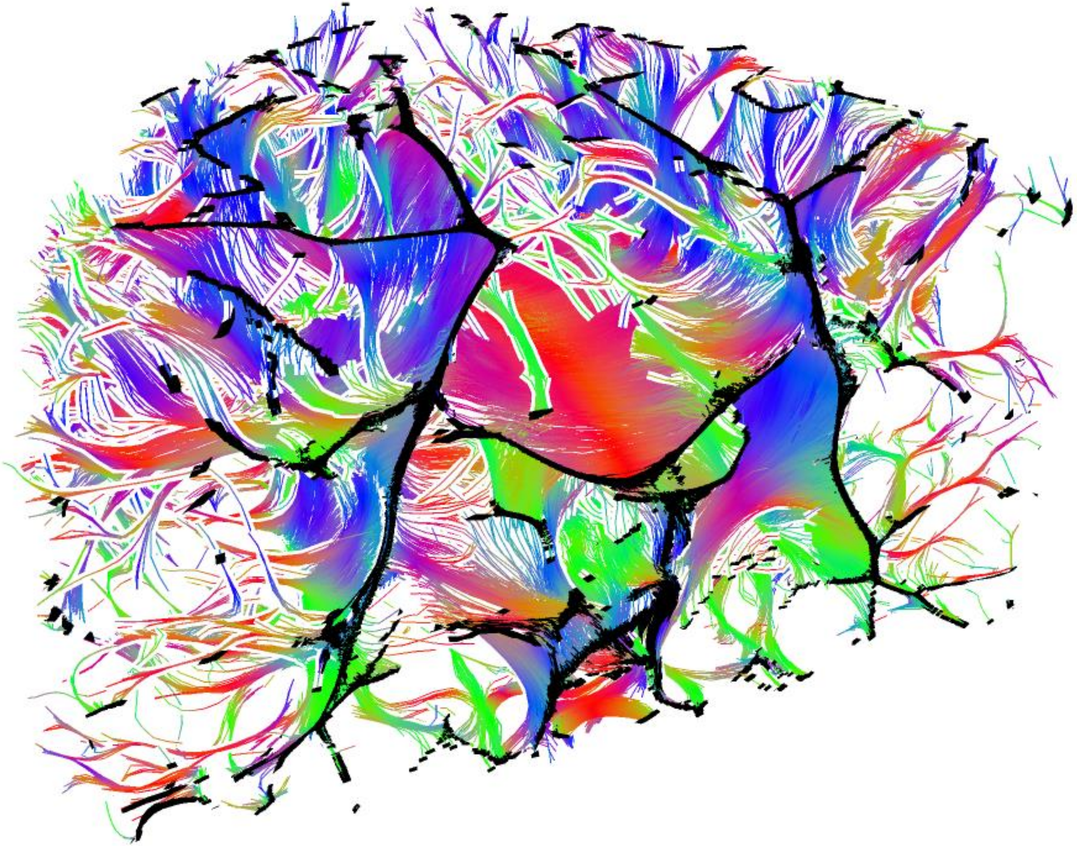
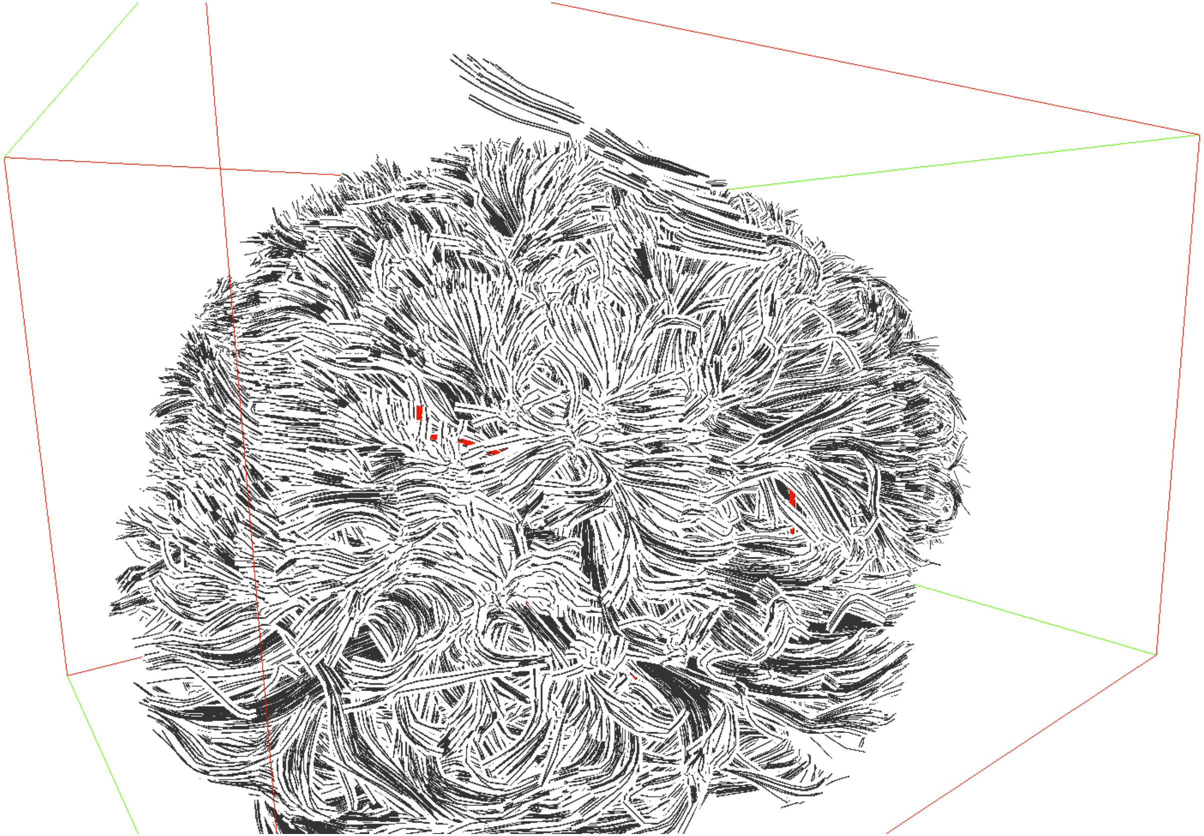


Creation of Volumetric Voids



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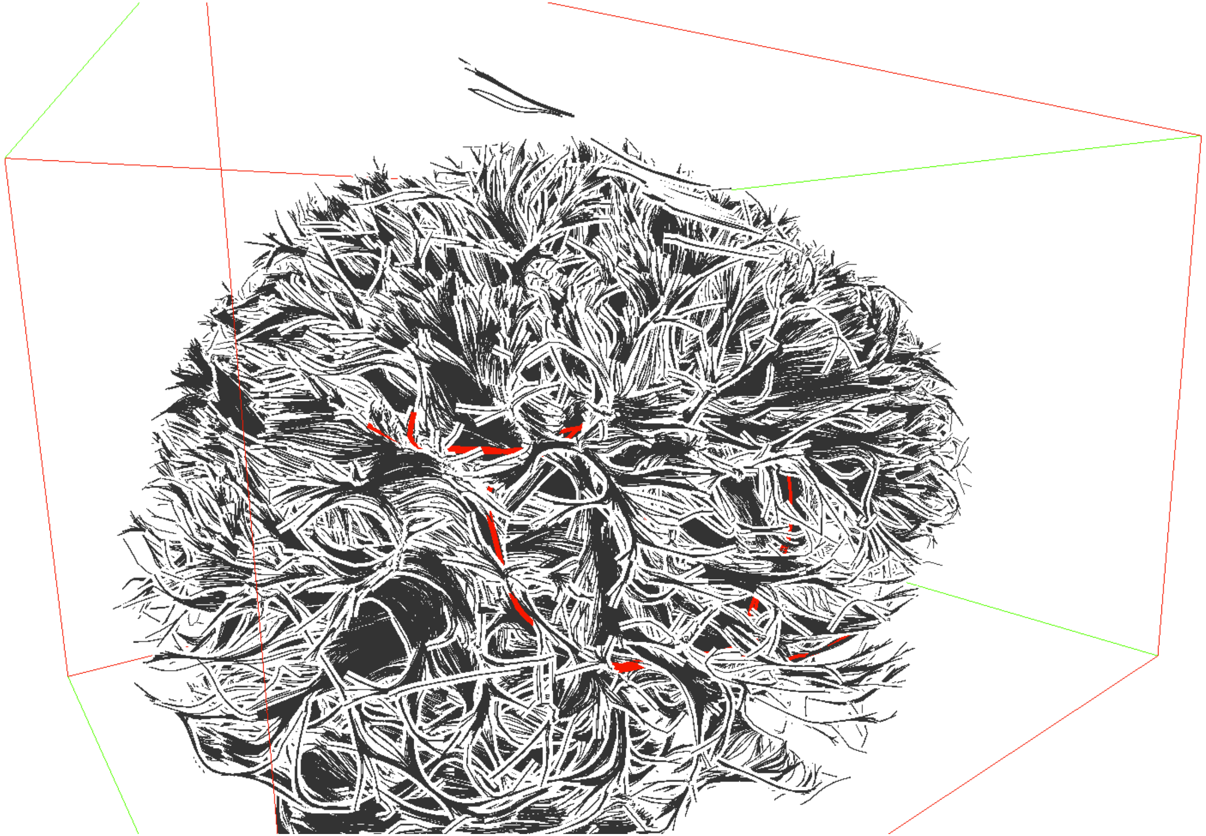
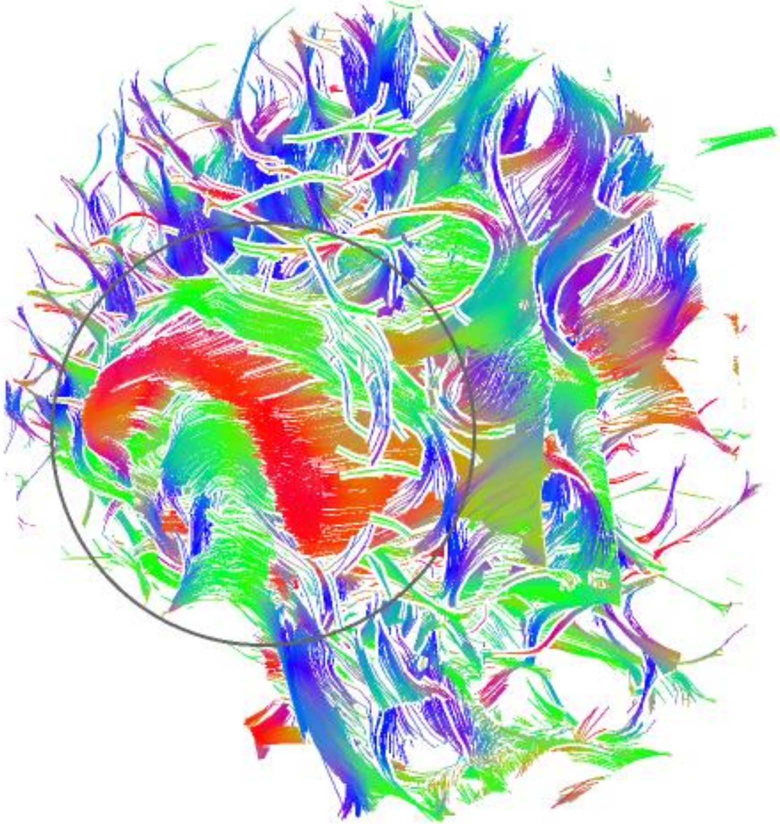


Interactive Exploration: Lenses



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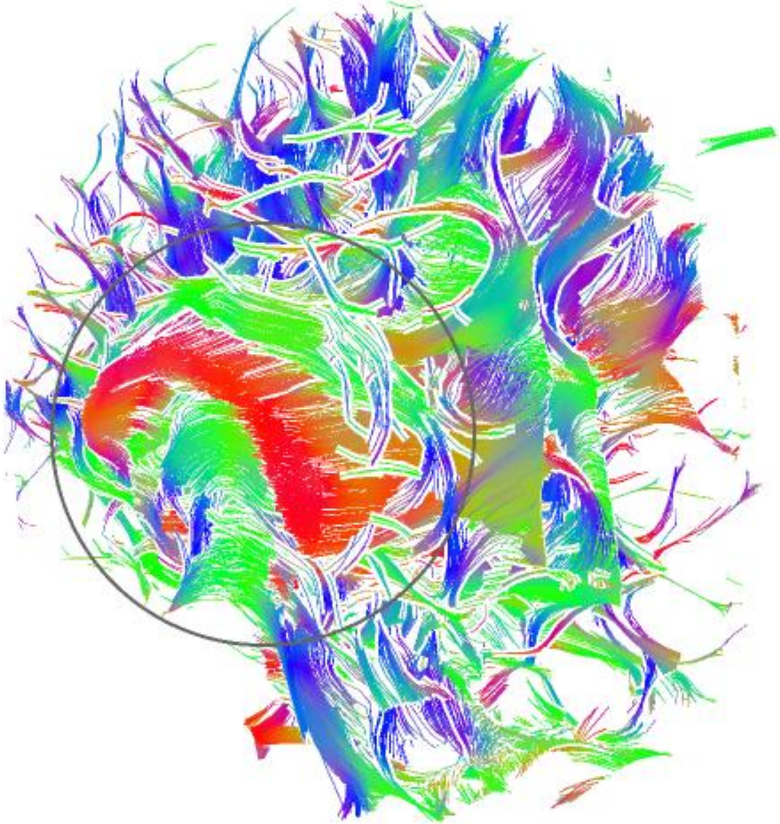
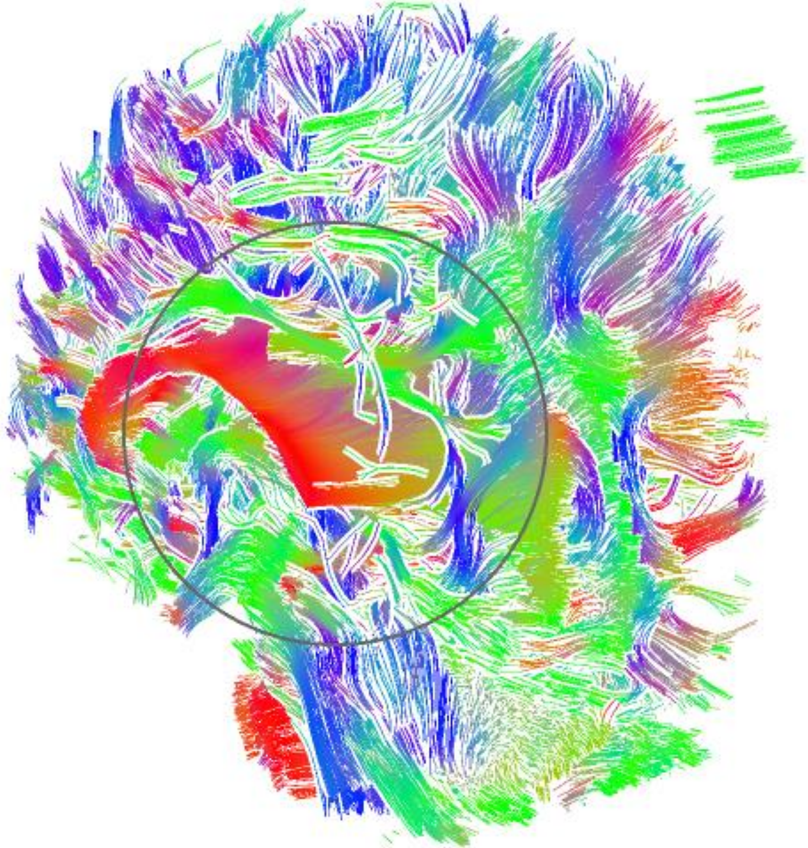
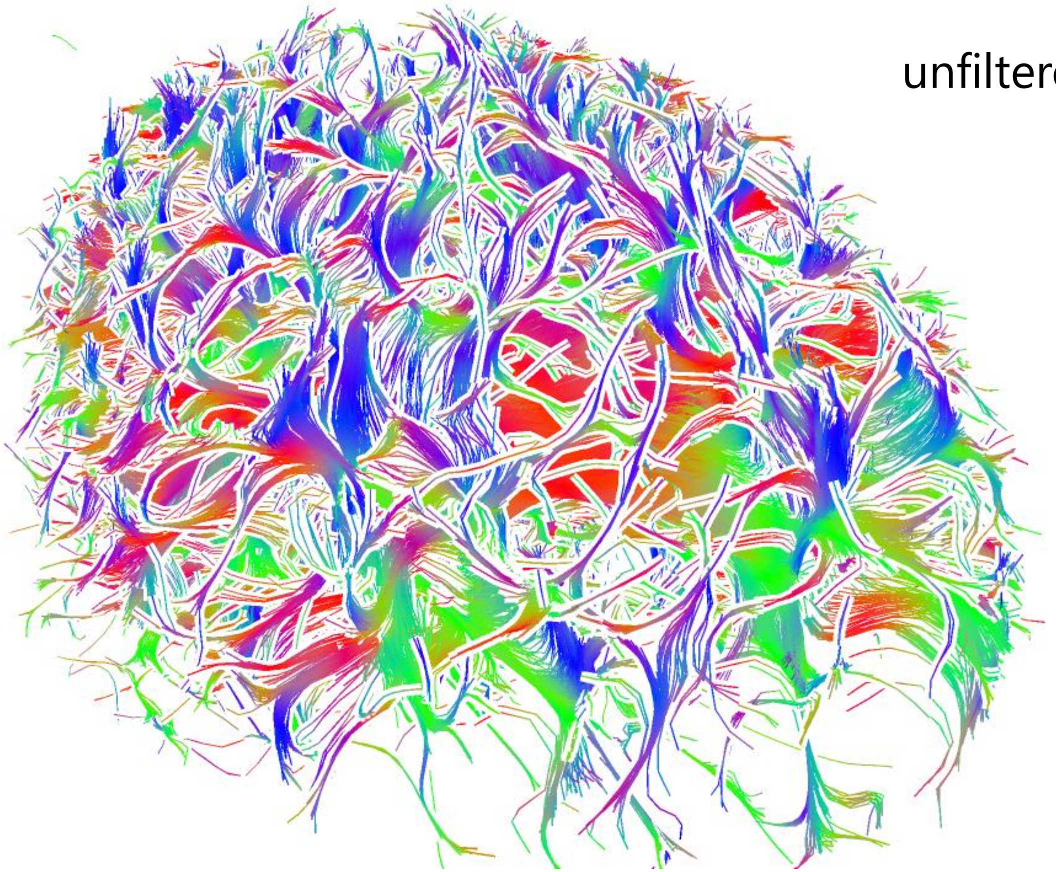


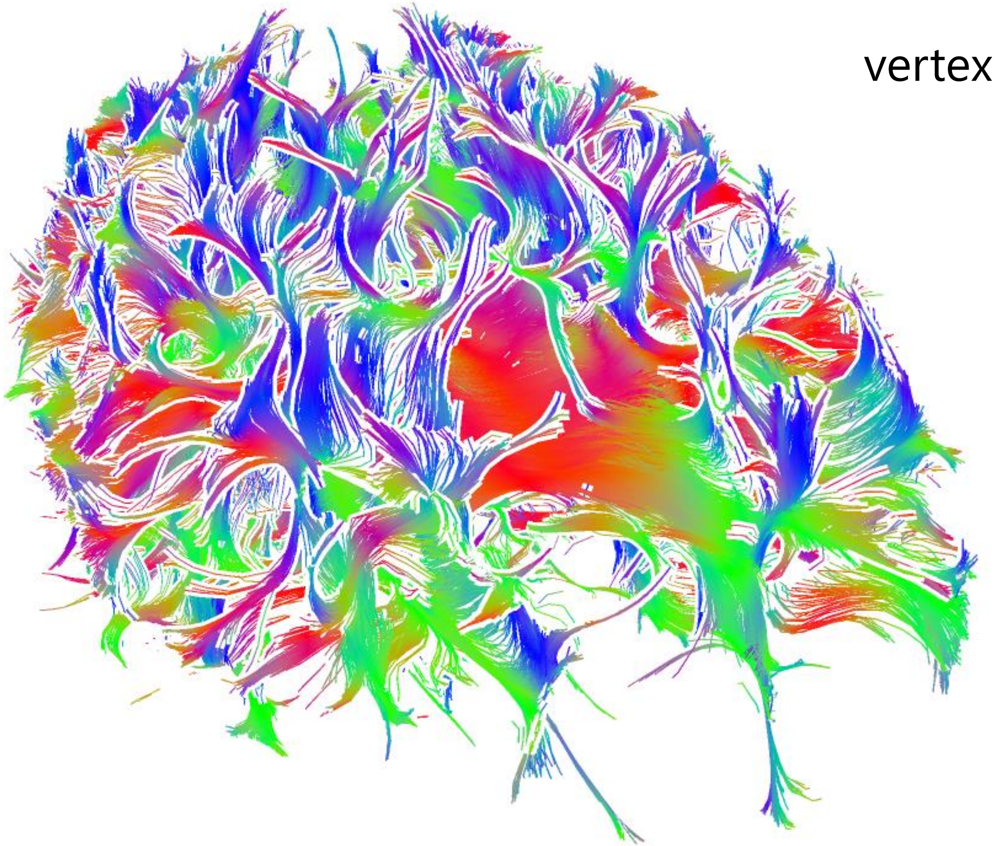


Filtering for Vertex Degree in Similarity Graph



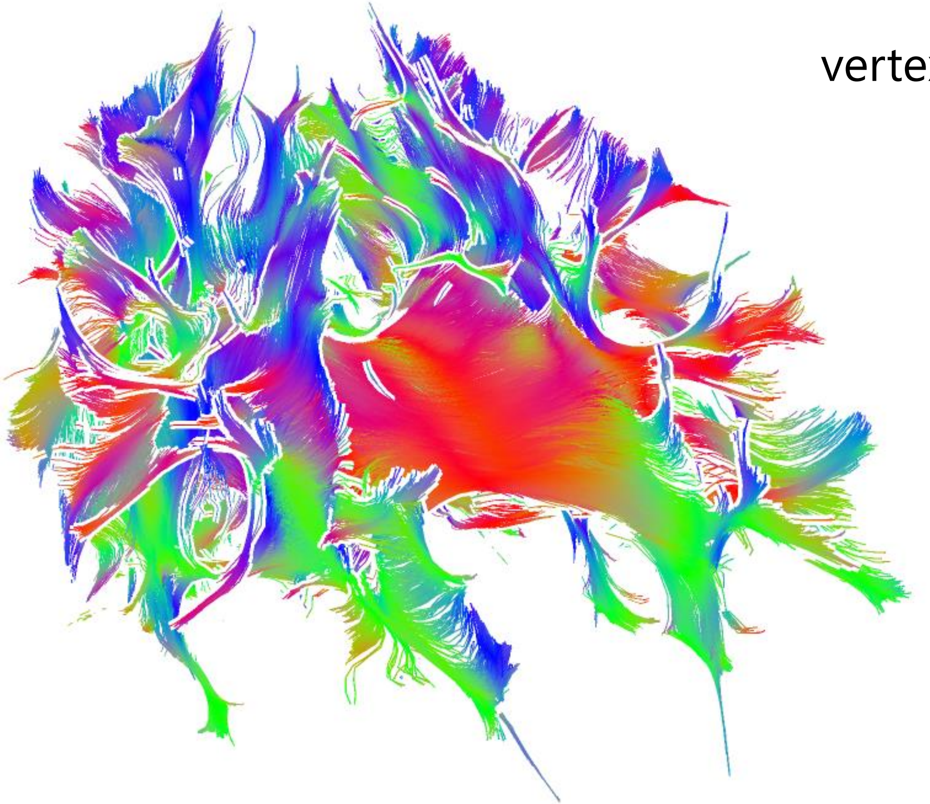
unfiltered (average vertex degree ≈ 200)

Filtering for Vertex Degree in Similarity Graph



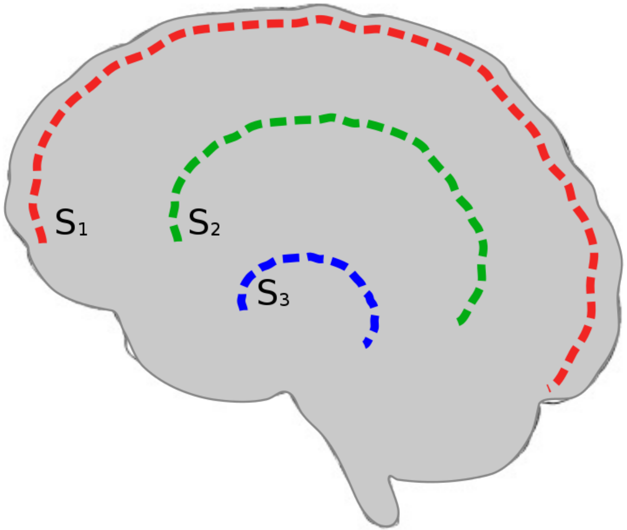
vertex degree ≥ 160

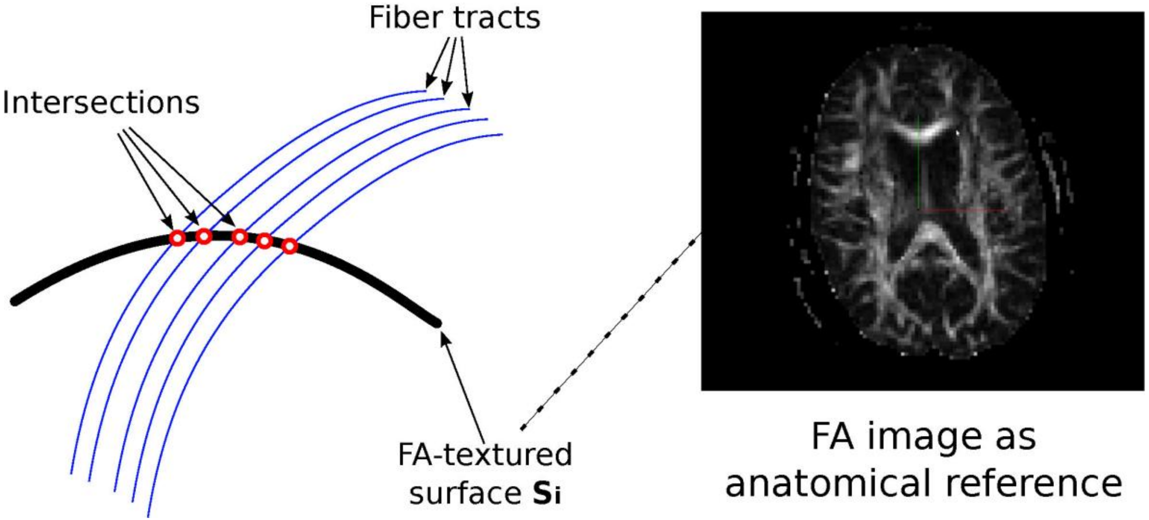
Filtering for Vertex Degree in Similarity Graph



vertex degree ≥ 560

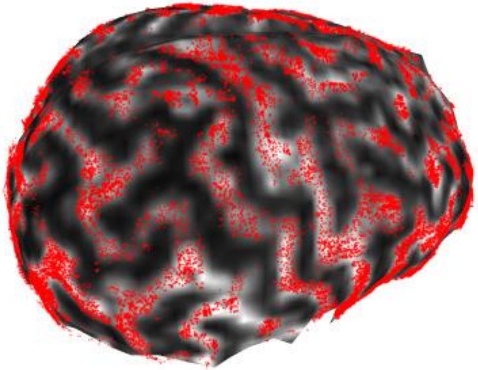
Visual Analysis of Abstraction Accuracy





Visual Analysis of Abstraction Accuracy

d_{max} = 0mm



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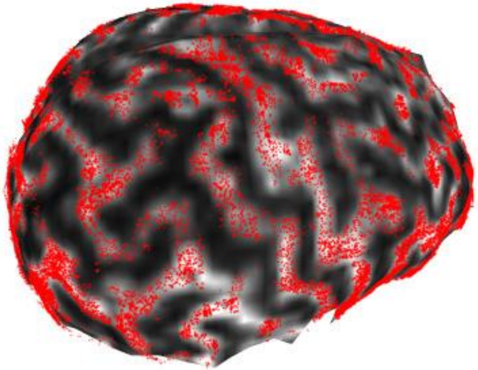

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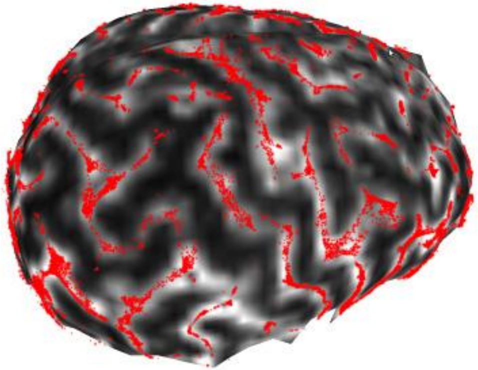

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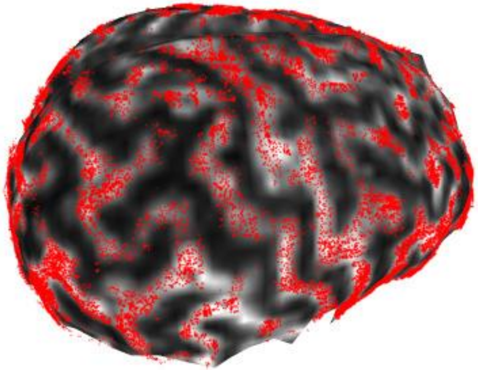

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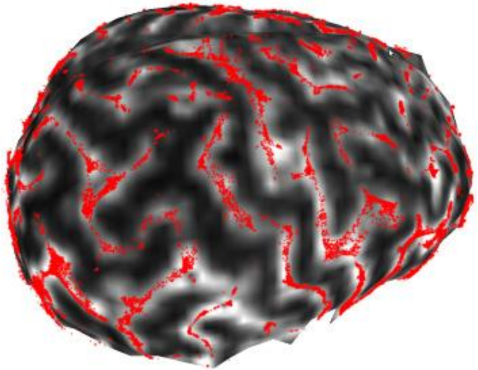
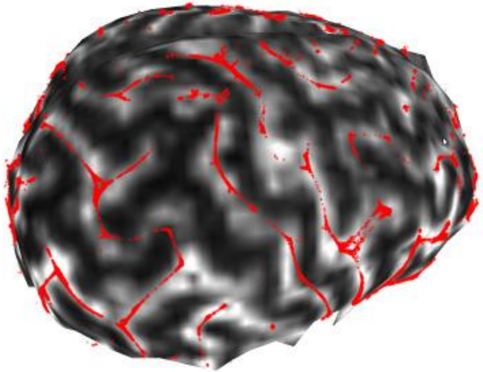


d_{max} = 3mm



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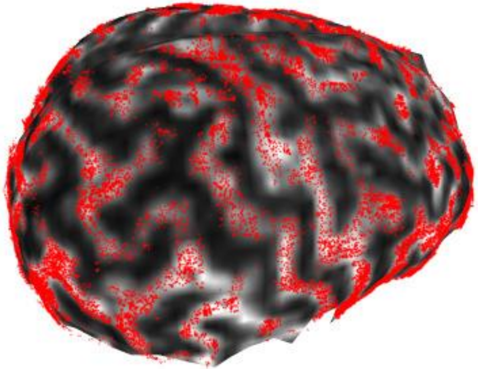
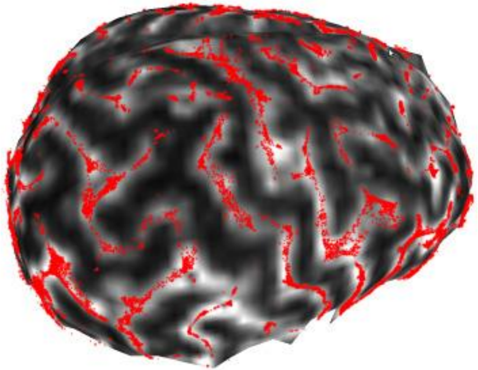
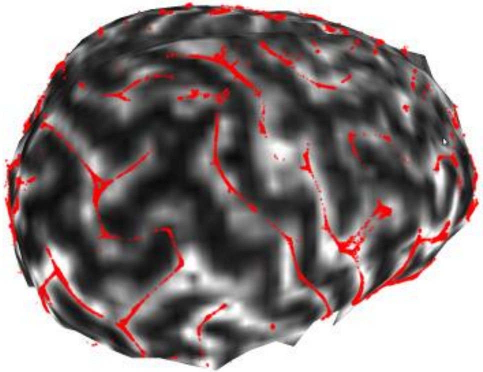


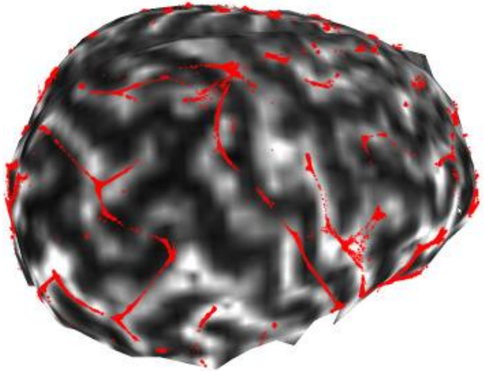
d_{max} = 1mm



d_{max} = 3mm

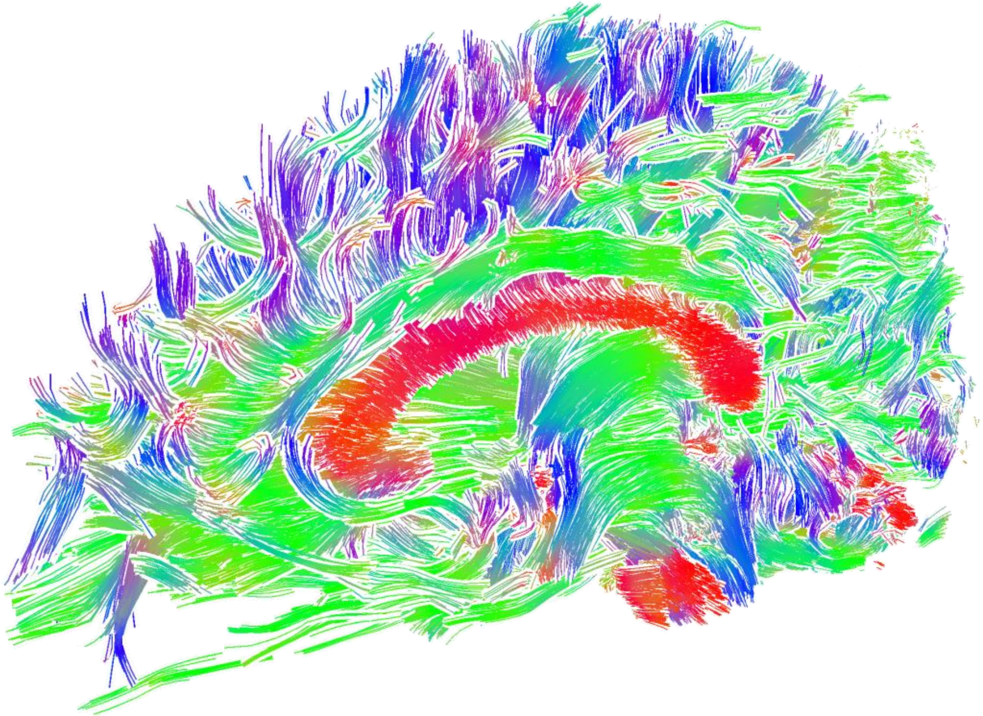


d_{max} = 7mm



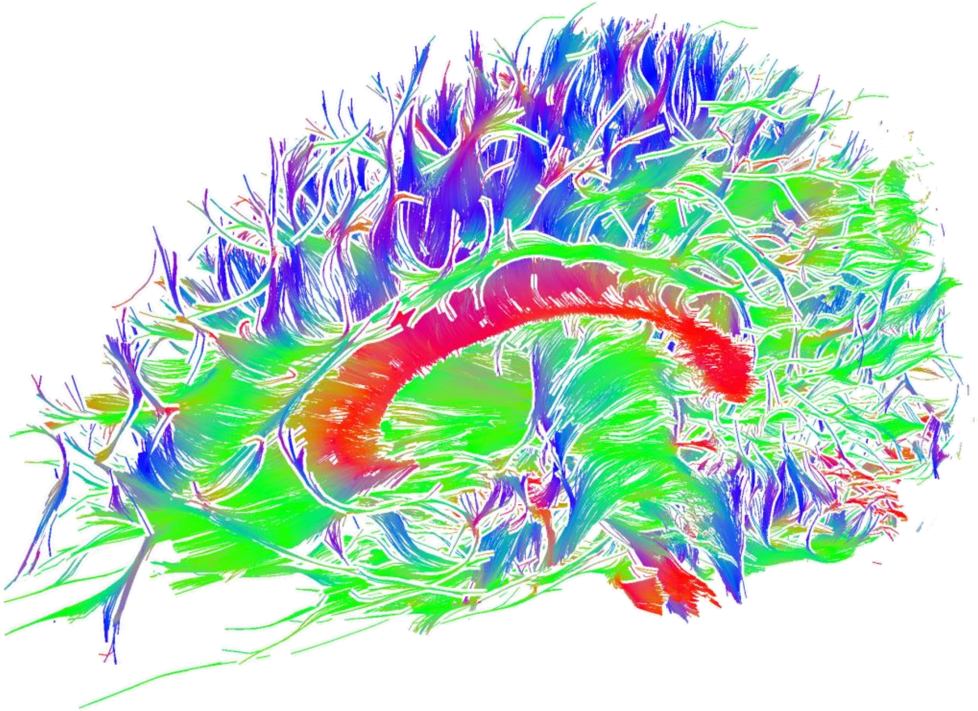
Implications for the Use of Contraction

d_{max} = 0mm



Implications for the Use of Contraction

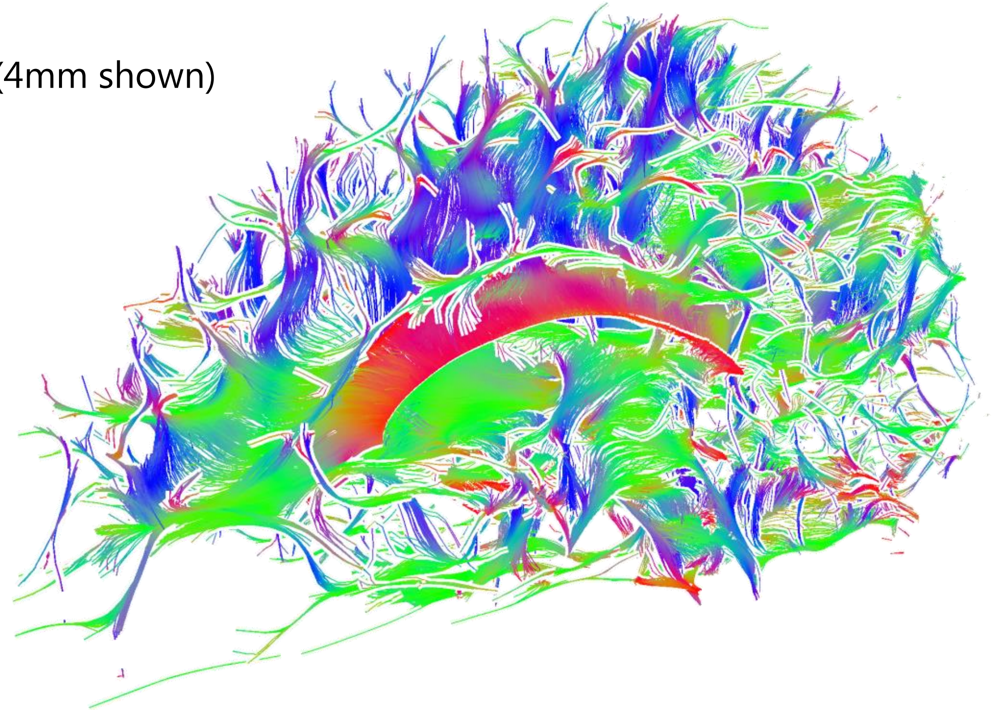
d_{max} = 2mm



anatomically correct, but only limited abstraction

Implications for the Use of Contraction

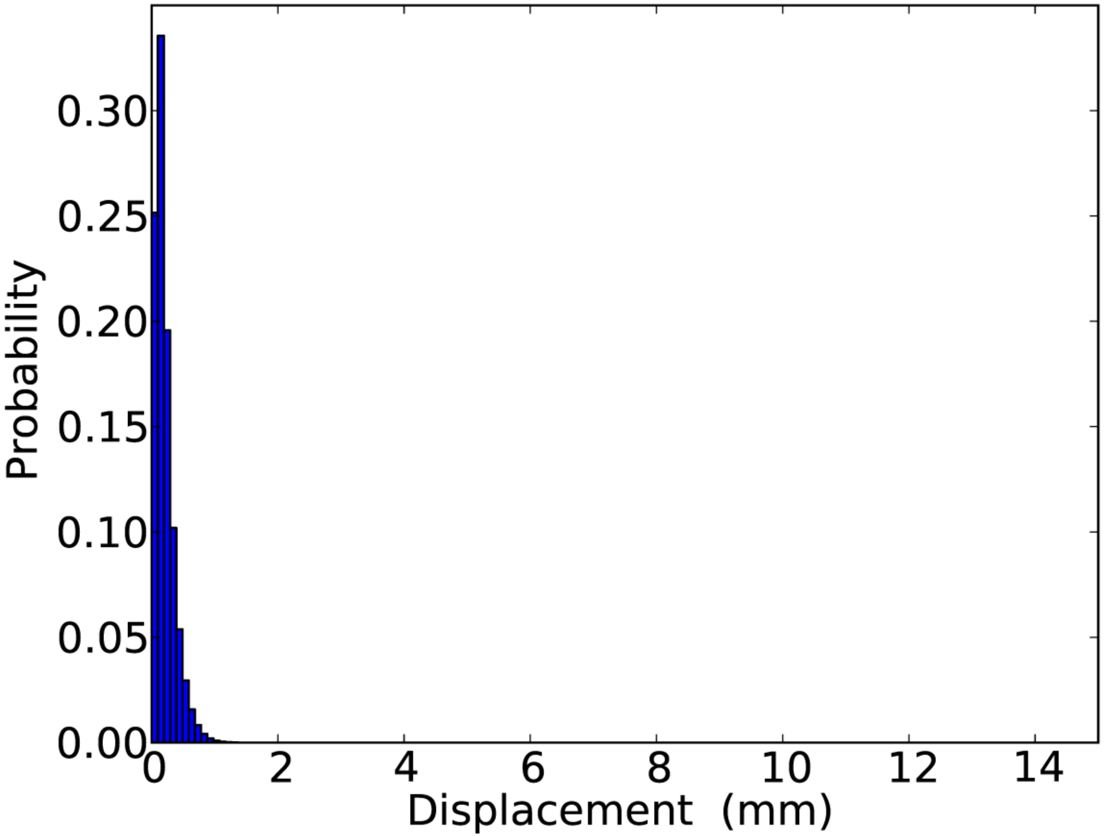
d_{max} > 2mm (4mm shown)



can be anatomically incorrect, but more abstraction, higher-level view

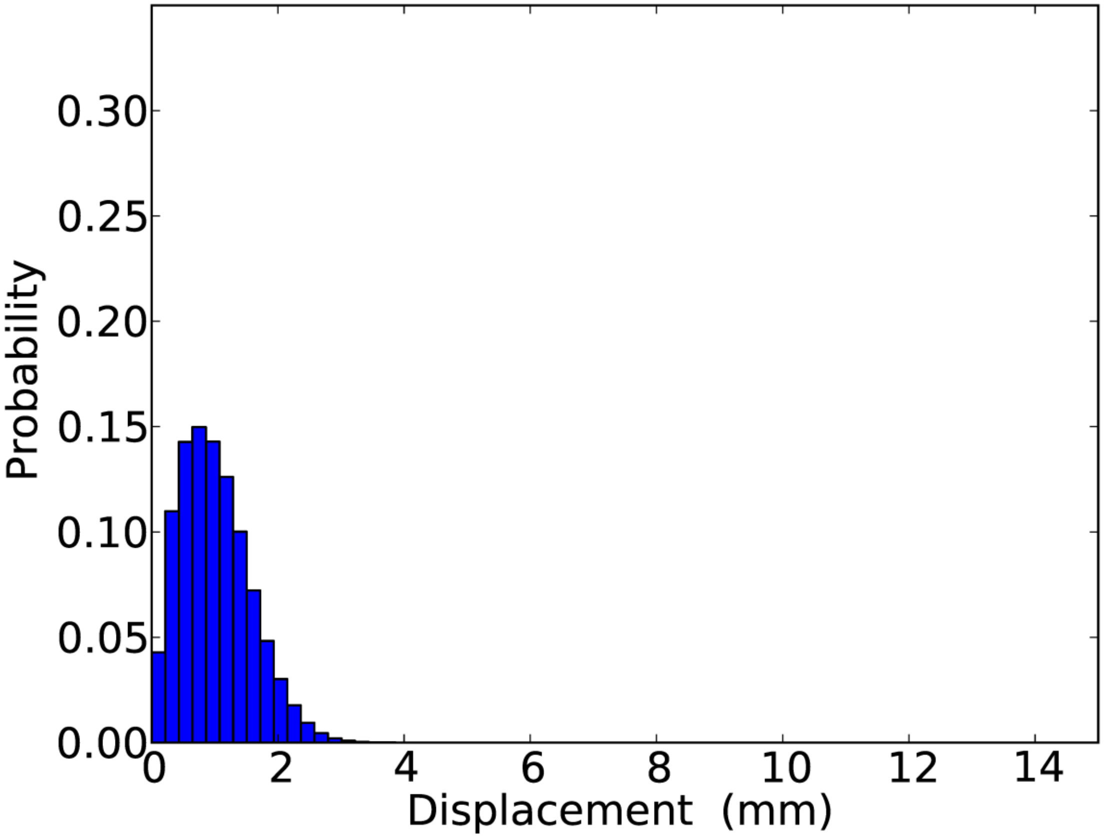
Numeric Analysis of Abstraction Accuracy

d_{max} = 1mm



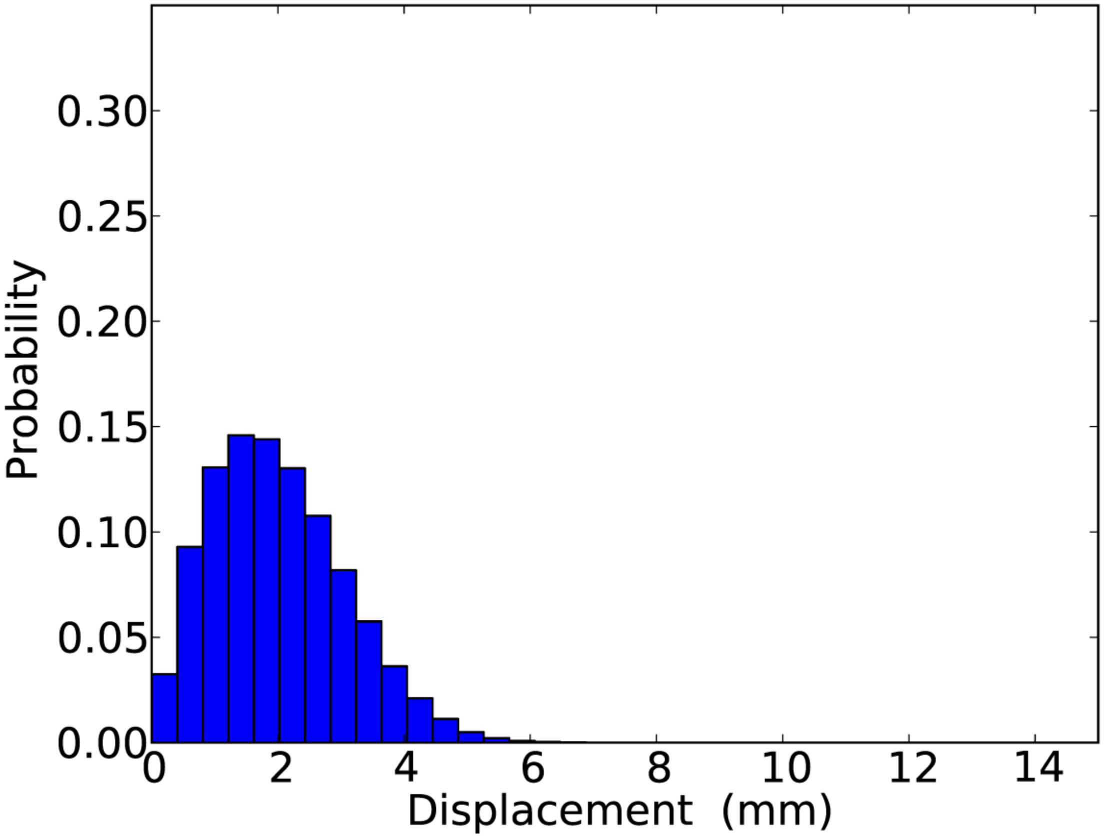
Numeric Analysis of Abstraction Accuracy

d_{max} = 2mm



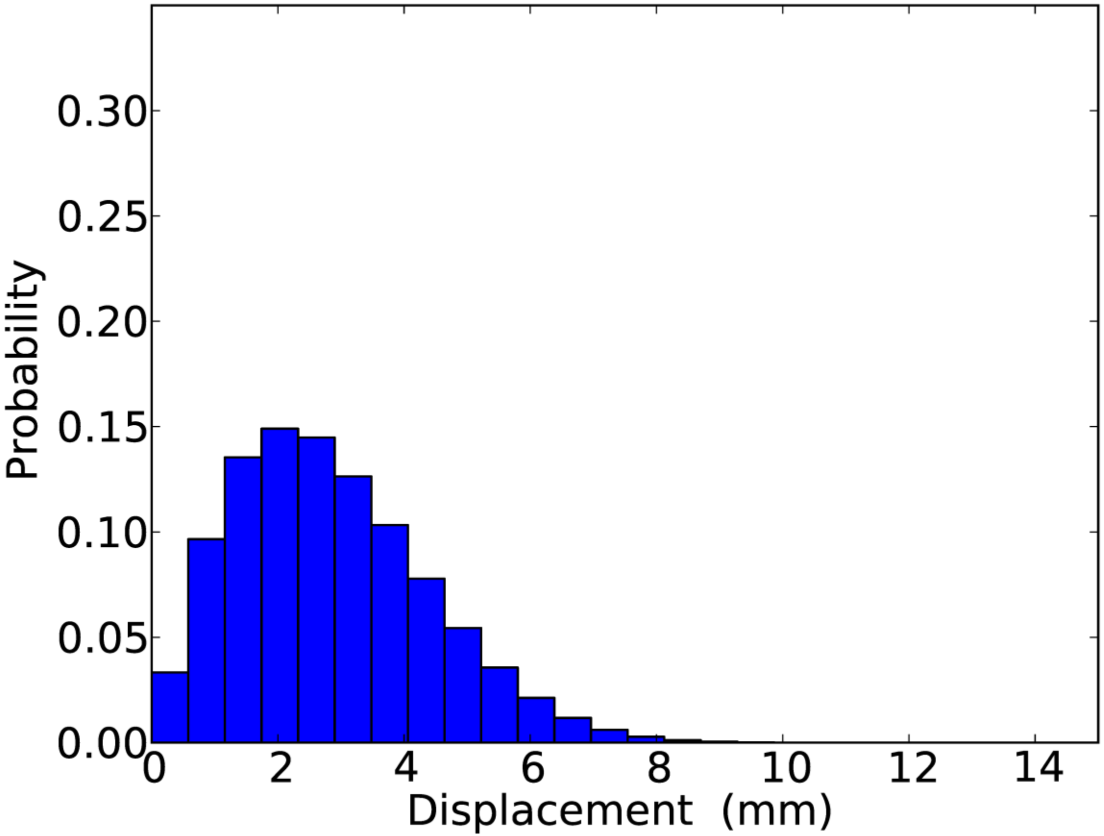
Numeric Analysis of Abstraction Accuracy

d_{max} = 3mm



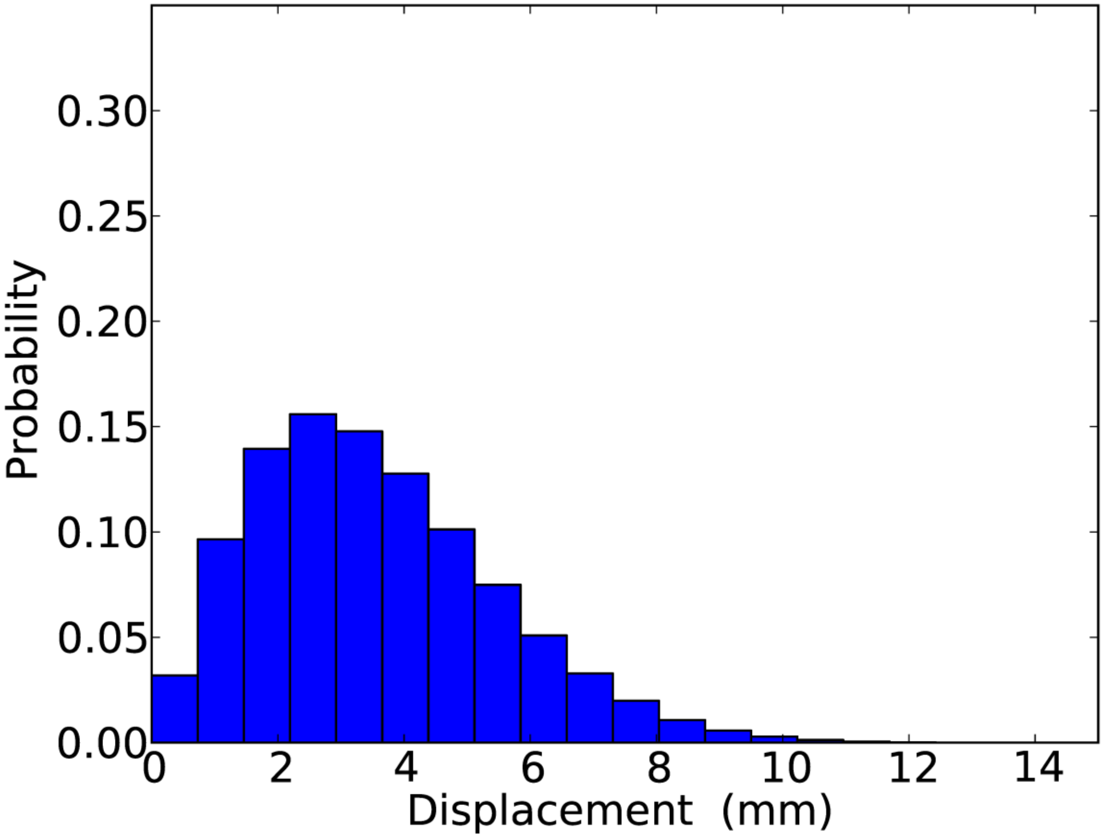
Numeric Analysis of Abstraction Accuracy

d_{max} = 4mm



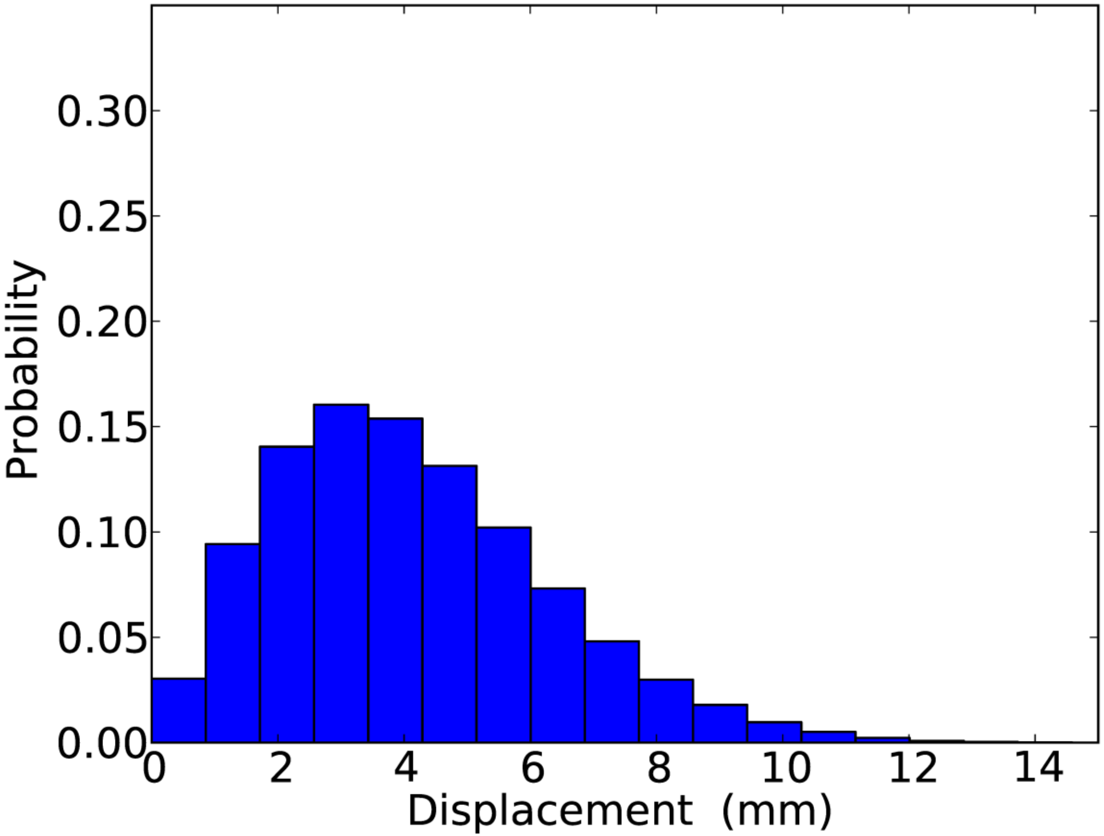
Numeric Analysis of Abstraction Accuracy

d_{max} = 5mm



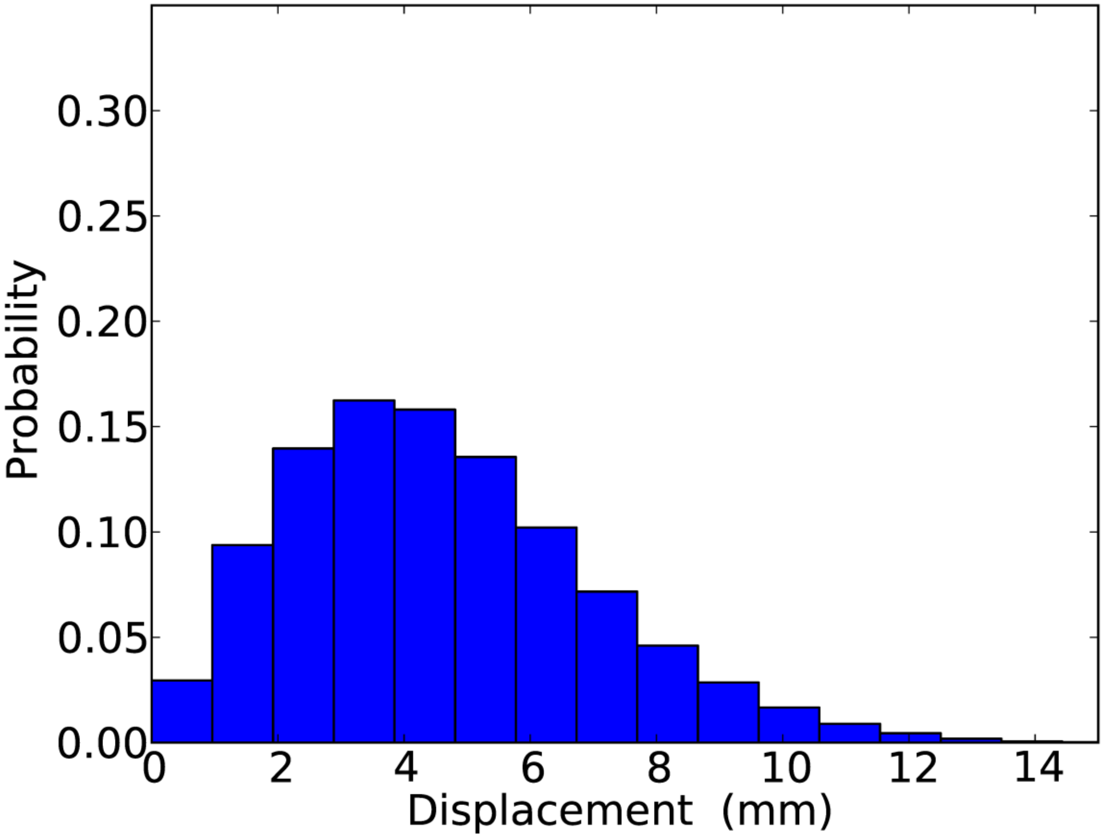
Numeric Analysis of Abstraction Accuracy

d_{max} = 6mm



Numeric Analysis of Abstraction Accuracy

d_{max} = 7mm

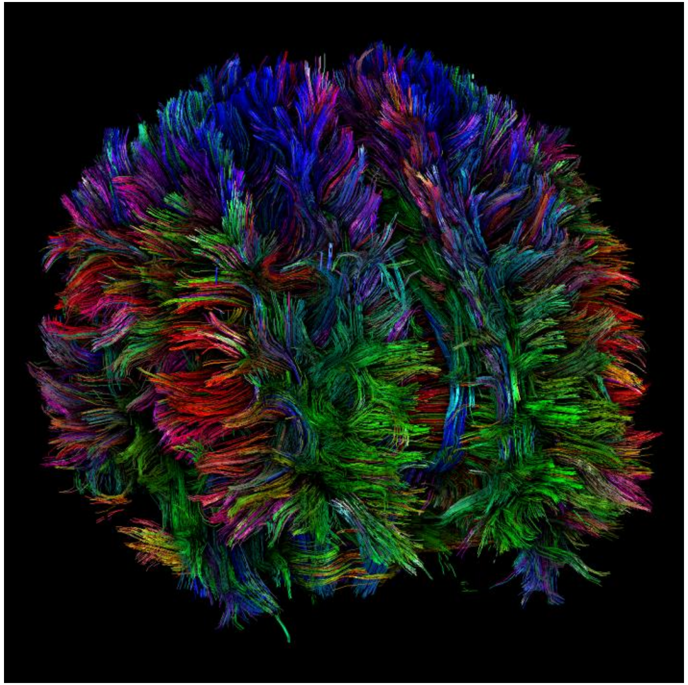


Focus Group Feedback from Experts

- neuroscience researcher
  (male, age 40, 19 years experience)
- neuroscience engineer
  (female, age 28, 4 years experience)
- neuroscience engineer
  (male, age 32, 7 years experience)
- research intern
- work with connectivity data several times daily to several times yearly
- 90 minute focus group session, video-recorded

Focus Group Feedback from Experts

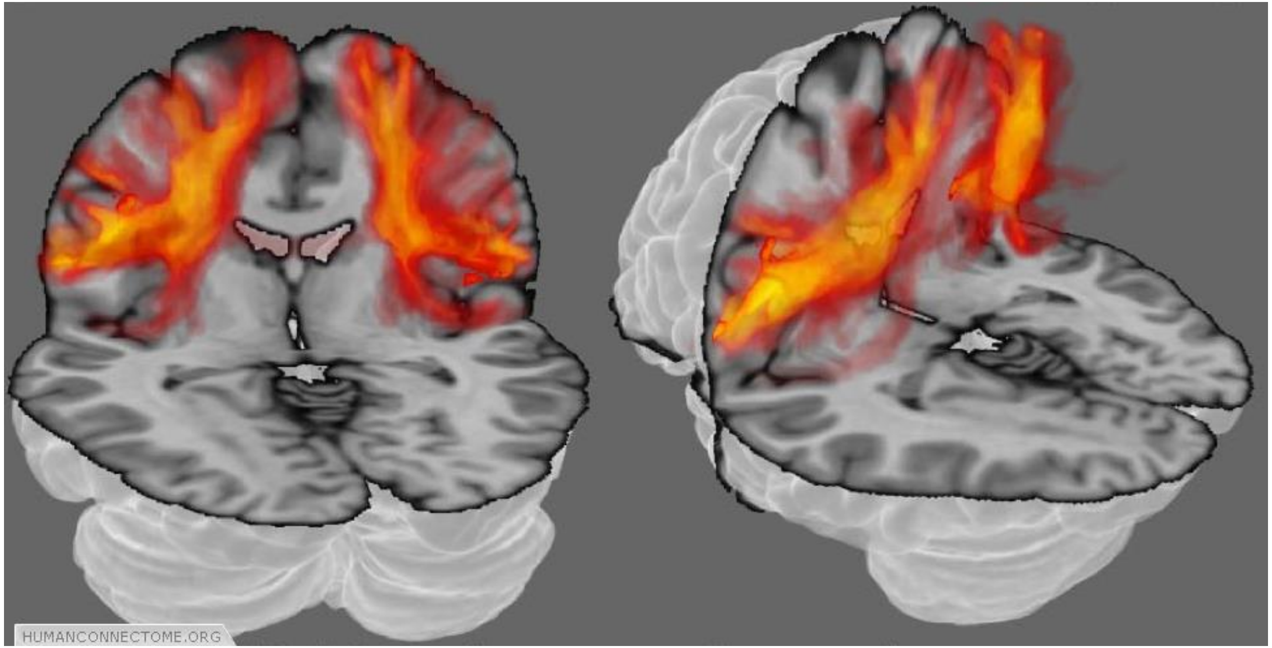
- full-brain tractography useful, good as unbiased overview
- R: “It’s often the first step.” E2: “This is less biased than putting your seeds somewhere and then doing tracking.”
- starting point of a detailed analysis



[LineAO: Eichelbaum et al., 2013]

Focus Group Feedback from Experts

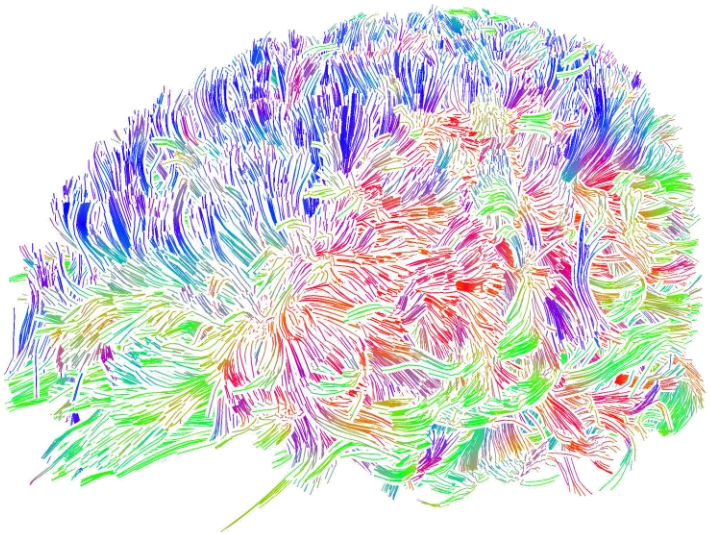
- contraction useful for better analysis, in particular for probabilistic tractography

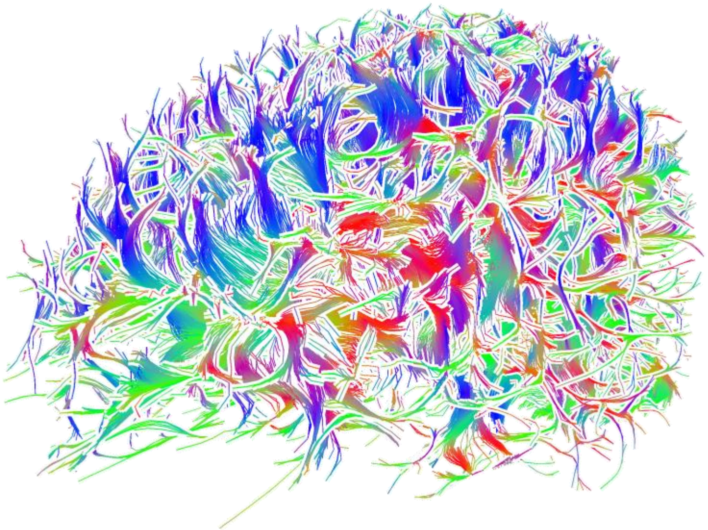


[humanconnectome.org]

Focus Group Feedback from Experts

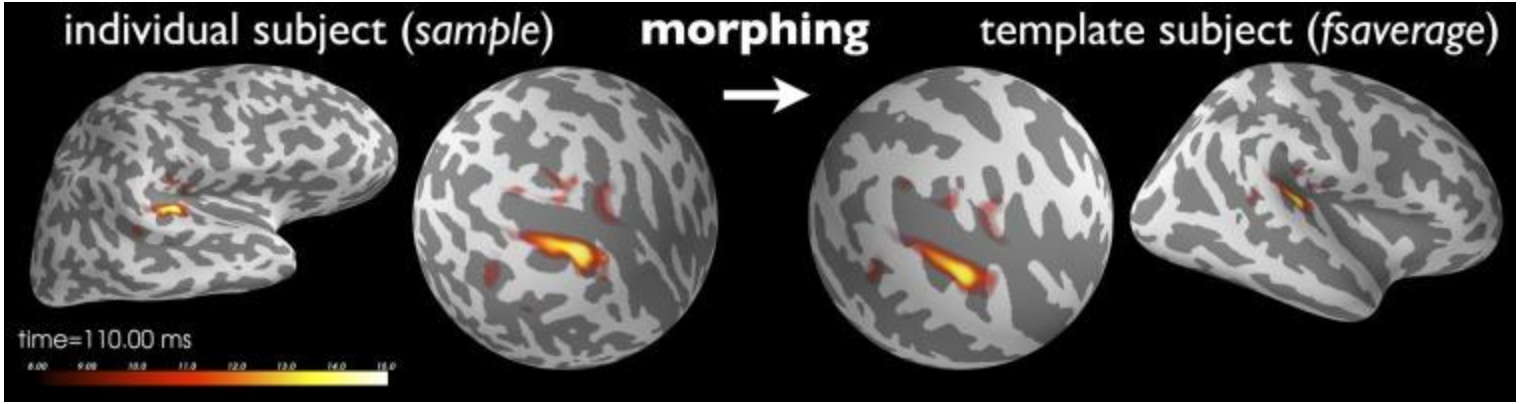
- main benefit: removal of noise; ability to check for error
  E1: “We don’t see spaghetti, we see bundles.” (☺)





Focus Group Feedback from Experts

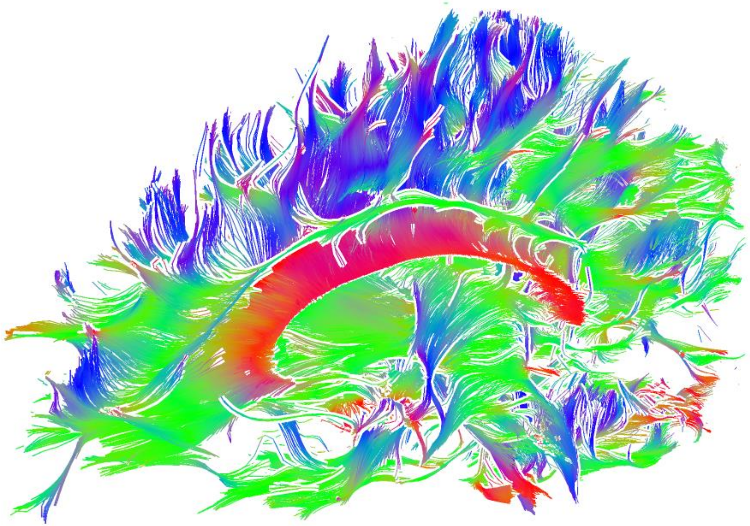
- use for registration of different patients' datasets
- no problem if anatomically incorrect due to high d_{max}
- similar to registration to "average brain" (e.g., FreeSurfer)



[Gramfort et al., 2013]

Focus Group Feedback from Experts

- exciting possibility: tract selection in abstracted views



Focus Group Feedback from Experts

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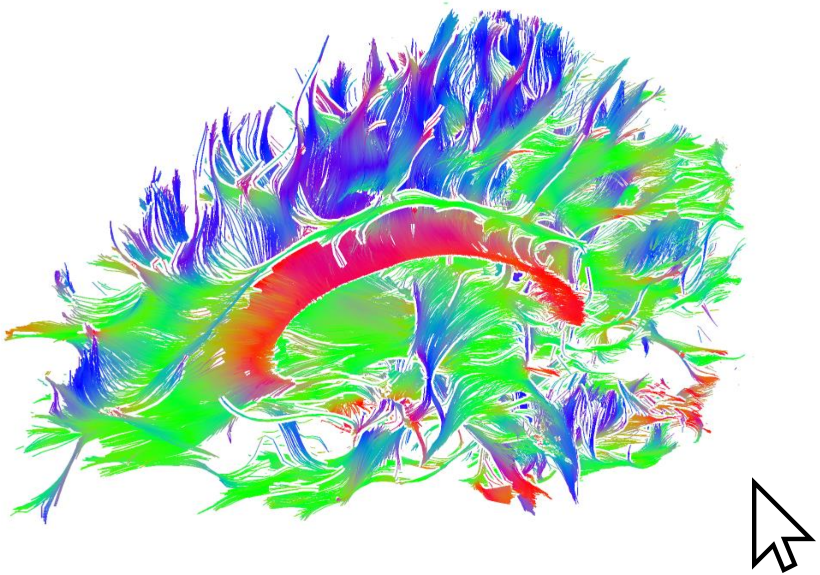

Focus Group Feedback from Experts

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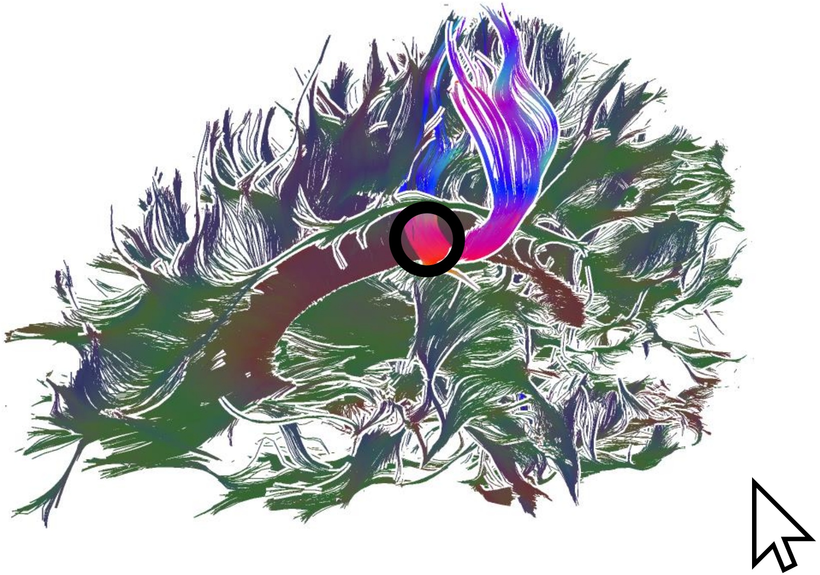
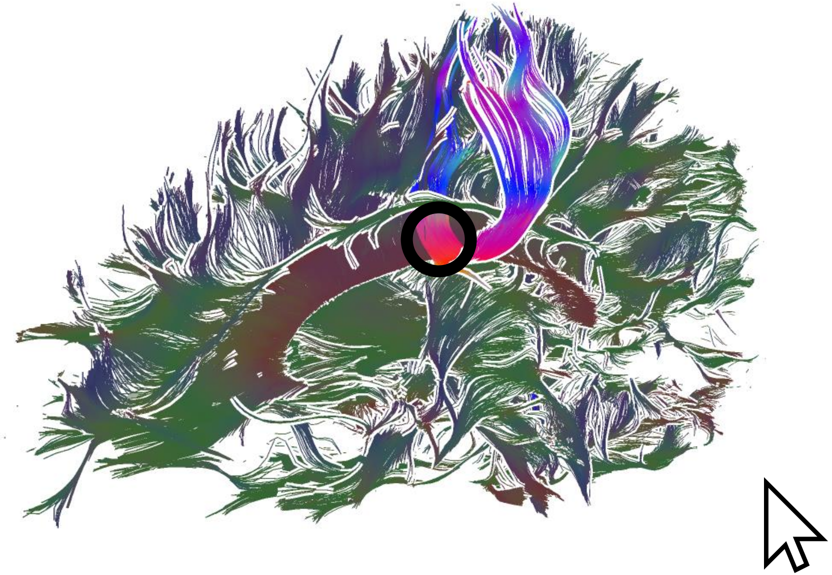
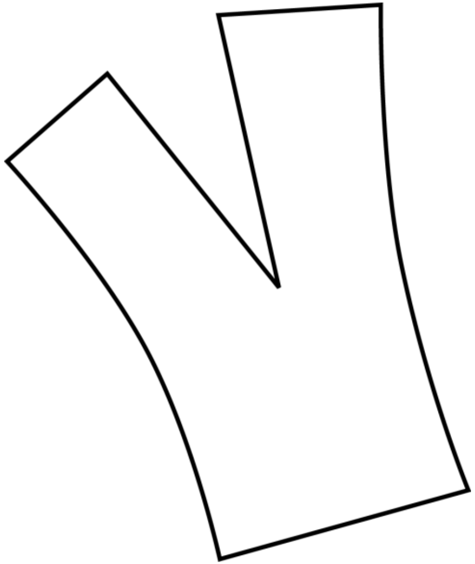


Focus Group Feedback from Experts

- exciting possibility: tract selection in abstracted views

  future: automatic bundle segmentation from abstraction
  analytic sheet representation with splitting bundles





Focus Group Feedback from Experts

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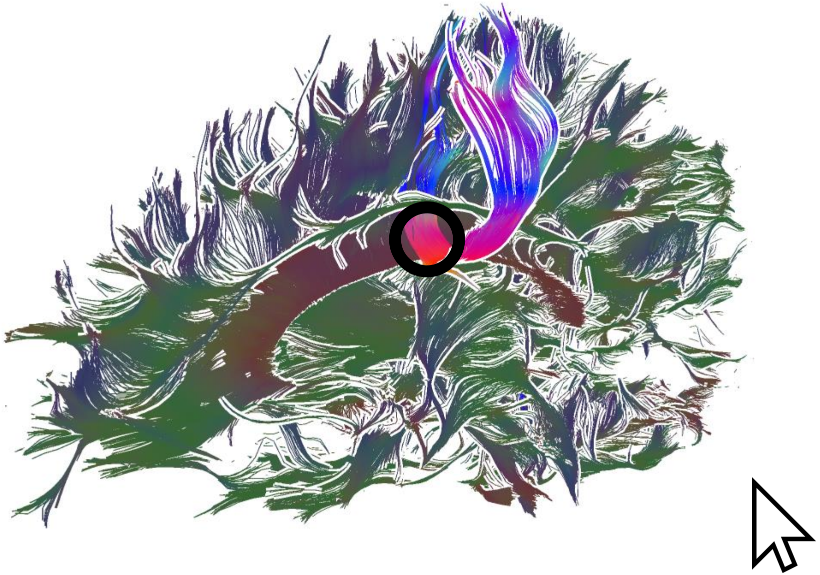

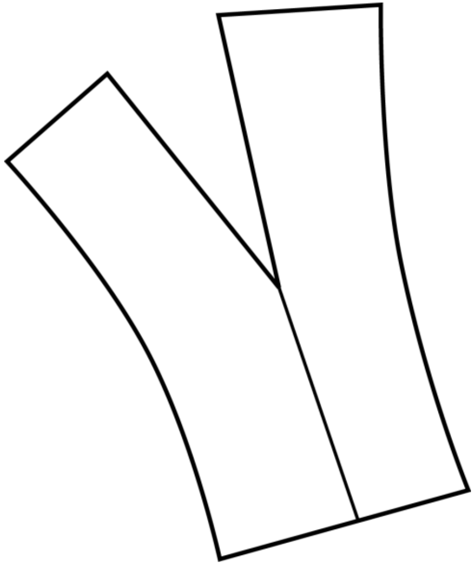

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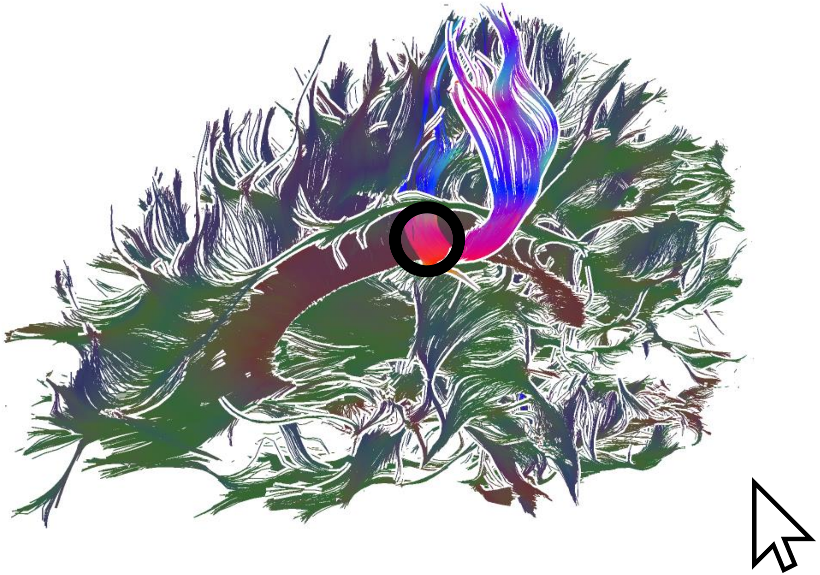
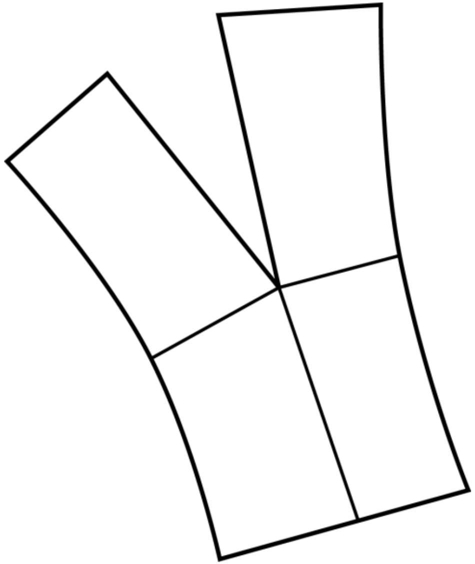
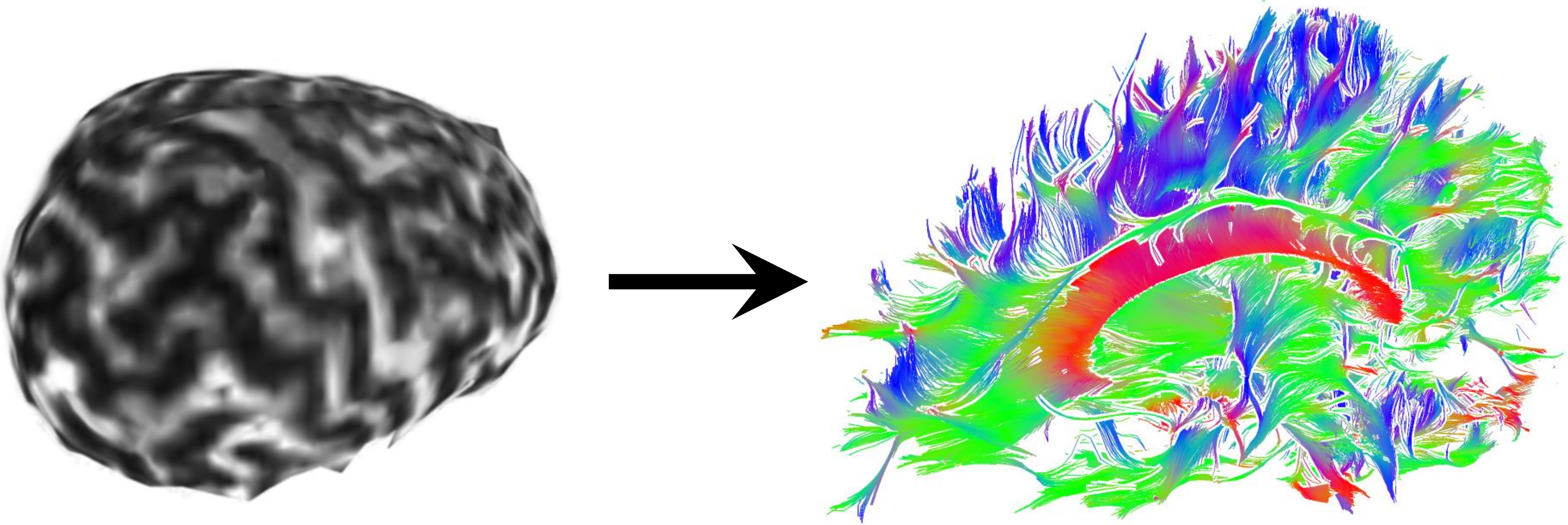




Focus Group Feedback from Experts

- future: use FA field for guiding contraction

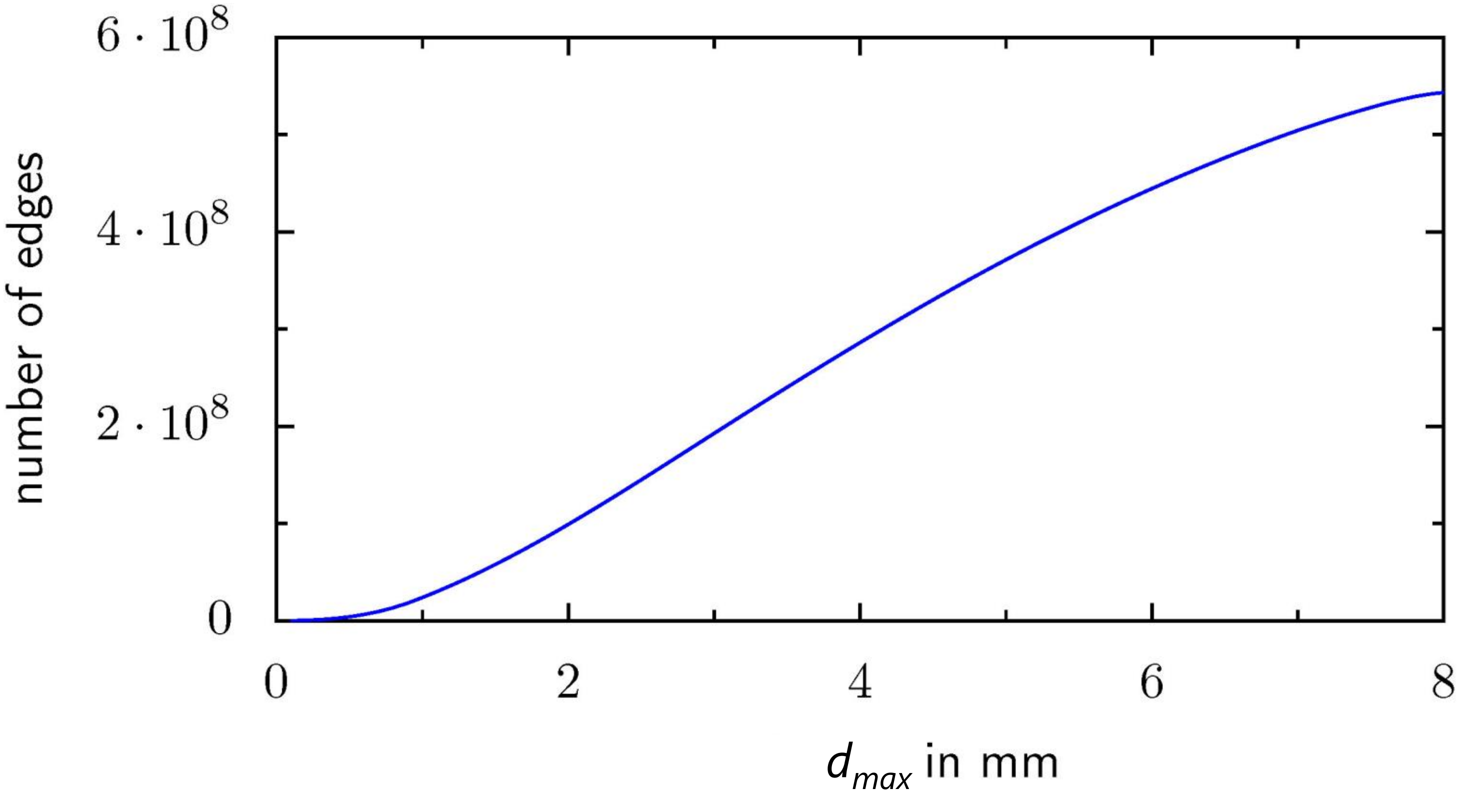


- could also be useful for local deep-brain analysis

Performance and Limitations

- exploration interactive frame rates (GPU-supported)
- naïve computational complexity:
  $O(N^2 M^2)$;   N: # tracts; M: mean # of vertices per tract
- improvements: (a) grid search, (b) storing angle comparisons, (c) linear sweep algorithm to process two tracts in parallel
- practical computation times of the similarity graph:
  - 4× Intel® Xeon® X7350, 4 cores @ 2.93GHz each, 128GiB RAM
  - 77,389 tracts, total of 1,944,570 vertices, d_{max} = 1mm
  - naïve: 76min; improved: 15min (using 4 threads)

Analysis of the Similarity Graph



two likely effects:

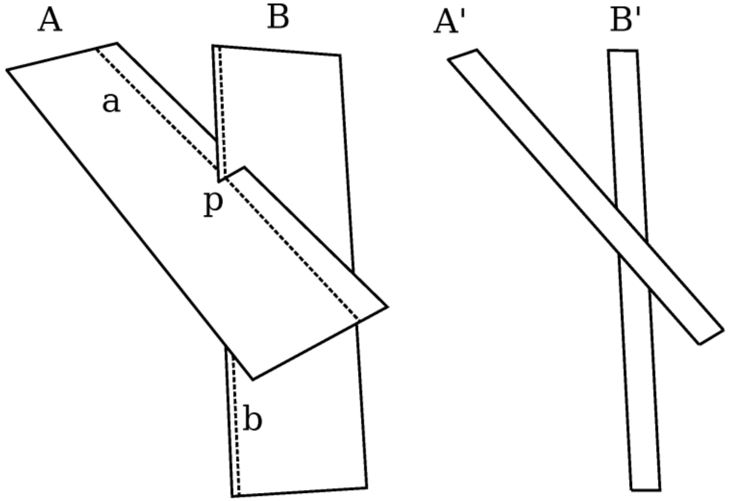
- # edges grows quadratically with d_{max}
- as d_{max} grows, fewer tracts are parallel to each other
- opposite effect

Performance and Limitations

- individual computation manageable, but:
- iterative computation of several levels in the order of hours
- would be much worse for probabilistic tractography

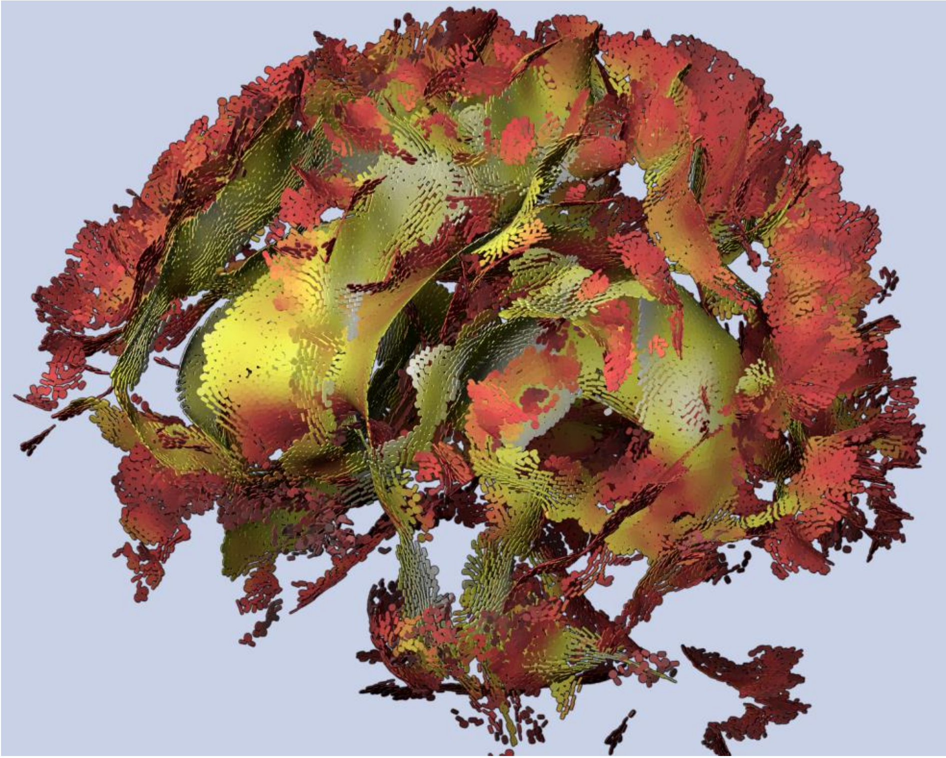
Performance and Limitations

- individual computation manageable, but:
- iterative computation of several levels in the order of hours
- would be much worse for probabilistic tractography
- possible topological changes:



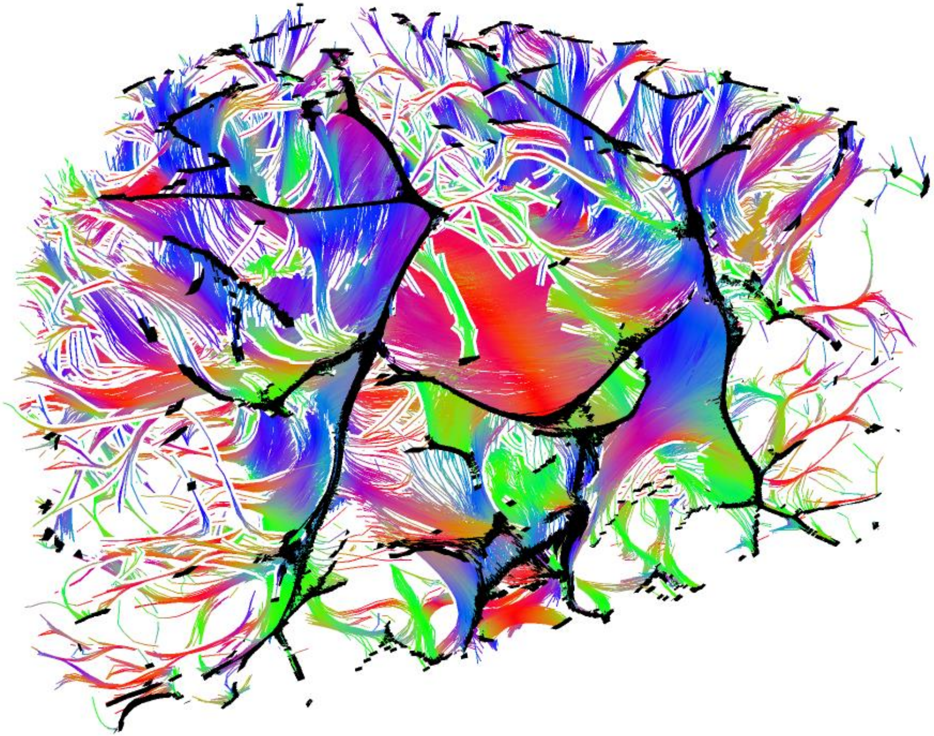
Connection to Related Analyses of Scale

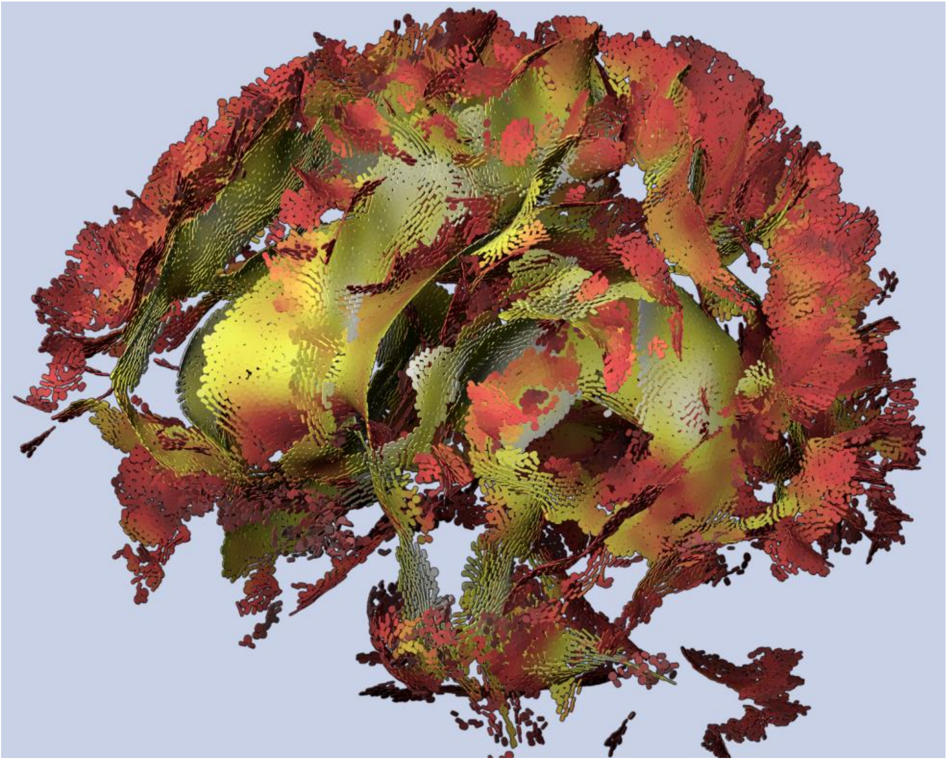
- Kindlmann et al., VIS 2009: Sampling and Visualizing Creases with Scale-Space Particles
  - faithful analysis of features in space
  - similar sheet features
  - could be used to evaluate our approach



[Kindlmann et al., 2009]

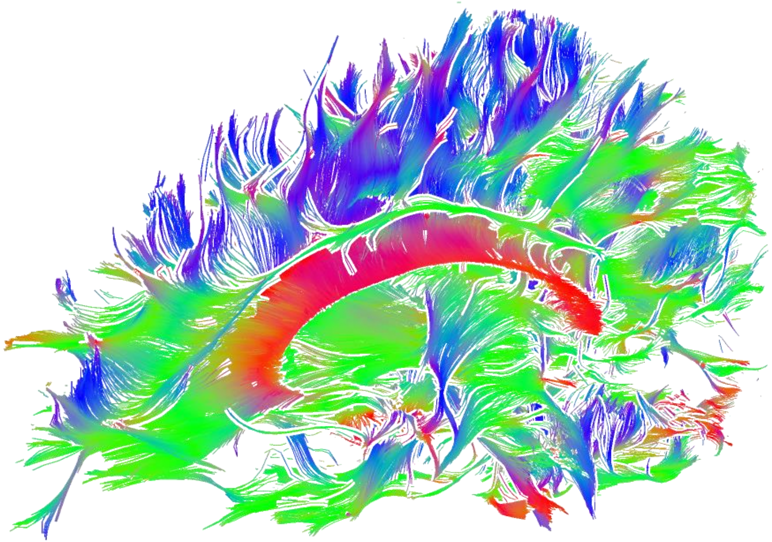
Connection to Related Analyses of Scale





[Kindlmann et al., 2009]

Thanks



http://tobias.isenberg.cc/VideosAndDemos/Everts2015EBW