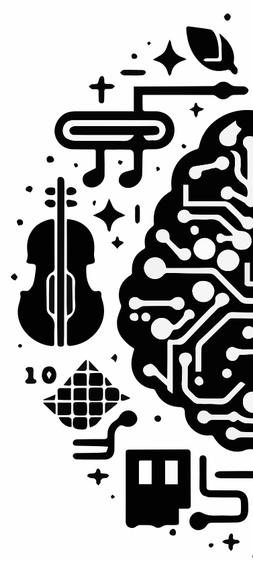
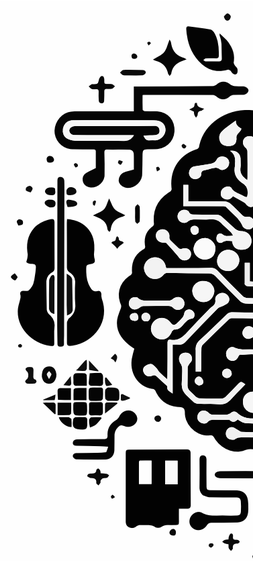


Practical Introduction to Structural and Diffusion MRI

Adam W. Anderson

Biomedical Engineering and VUIIS

github.com/brainhack-vandy/traintrack



Why measure brain structure and connectivity?

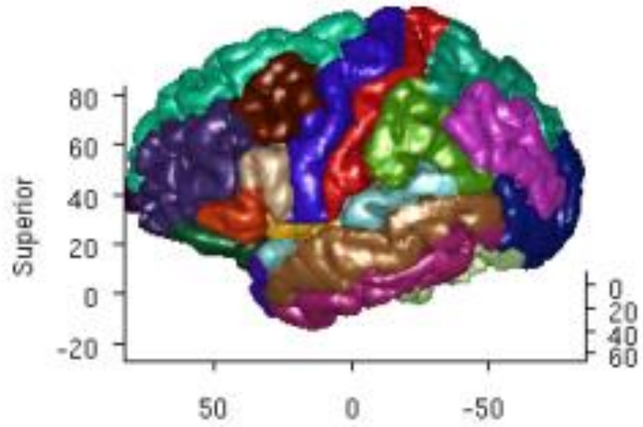
- Brain structure, connectivity, and function are intimately related
- Examples
  - Injury can reduce local tissue volume and information processing
  - Disrupted connections between brain regions can affect brain function
  - Neuroplasticity and learning can drive structural tissue changes
- Key aspects of brain structure and connectivity are measurable noninvasively using MRI
  - T1-weighted imaging for anatomy
  - Diffusion imaging for tissue microstructure/connectivity
- Image analysis packages accelerate hypothesis testing
  - Structure: FreeSurfer
  - Connectivity: MRtrix, DSI Studio

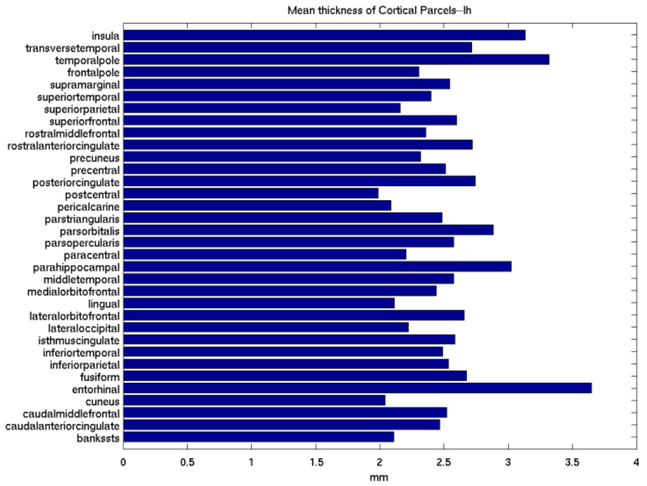
I. Structural analysis

- Goal: quantify the size or shape of brain structures
  - Find boundaries of the structure
  - Determine size/shape
- Requires good image quality
  - Contrast-to-noise ratio (CNR)
  - Resolution
  - Low distortion
  - Low artifacts

Example: cortical parcellation

- Automatically define cortical regions
- Measure parcel area, thickness, and volume
- Relies on segmenting the cortex from white matter and CSF/skull
- Performed by FreeSurfer, among other packages

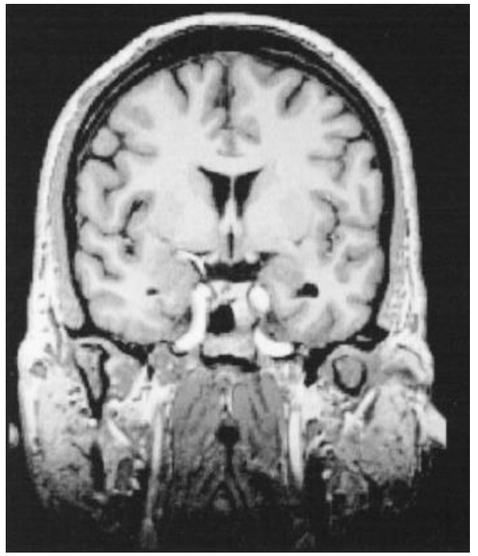




github.com/brainhack-vandy/traintrack

Computational steps

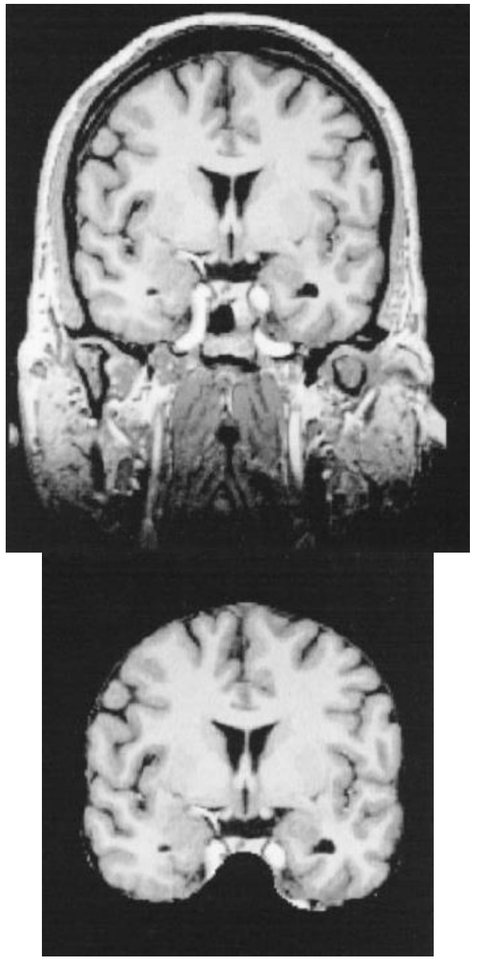
- Suppose we want to measure the thickness of the cortex (i.e., gray matter)
- How can we deal with
  - Spatially-dependent sensitivity?
  - Image warping?
  - Folded surface of the brain?
  - Identifying parcels?



Dale et al (1999)

Computational steps

- Remove intensity variations across image to simplify segmentation
- Remove the skull and extracranial tissues from image (“skull-stripping”)
- Gray matter/white matter/CSF segmentation
- Separate hemispheres from each other and subcortical structures (assume spherical topology)
- Tessellate gray and white matter surfaces



Dale et al (1999)

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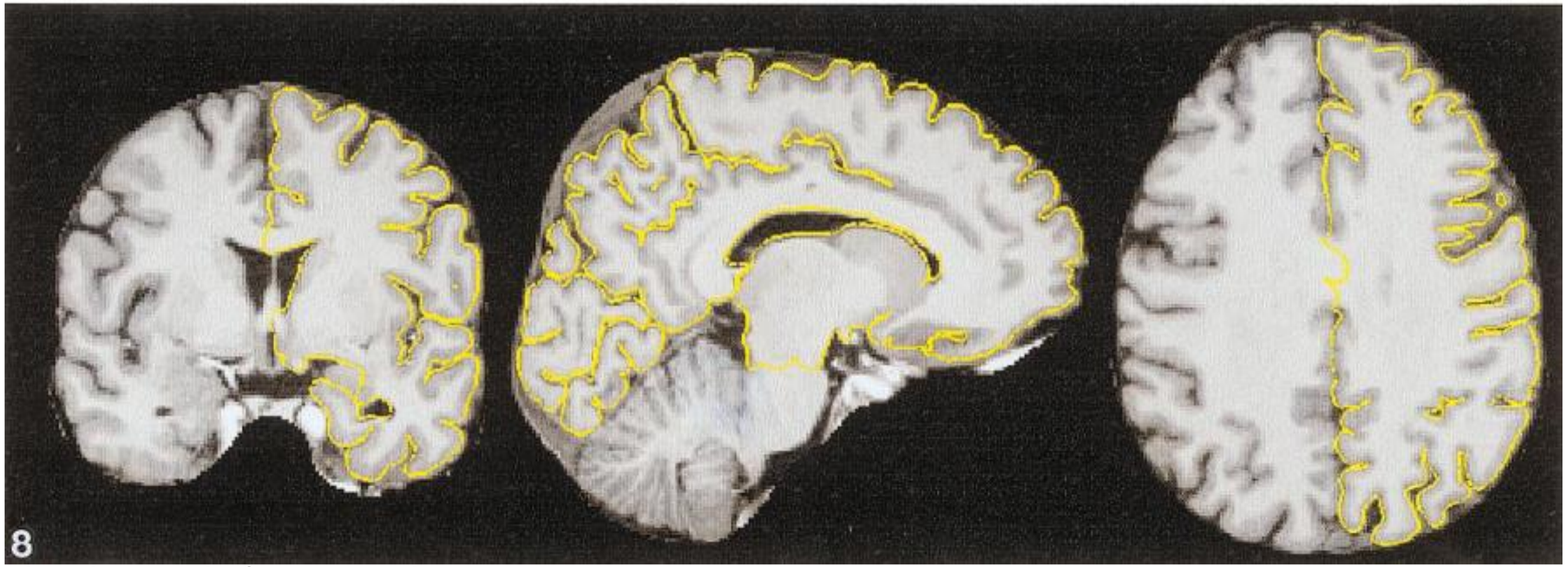

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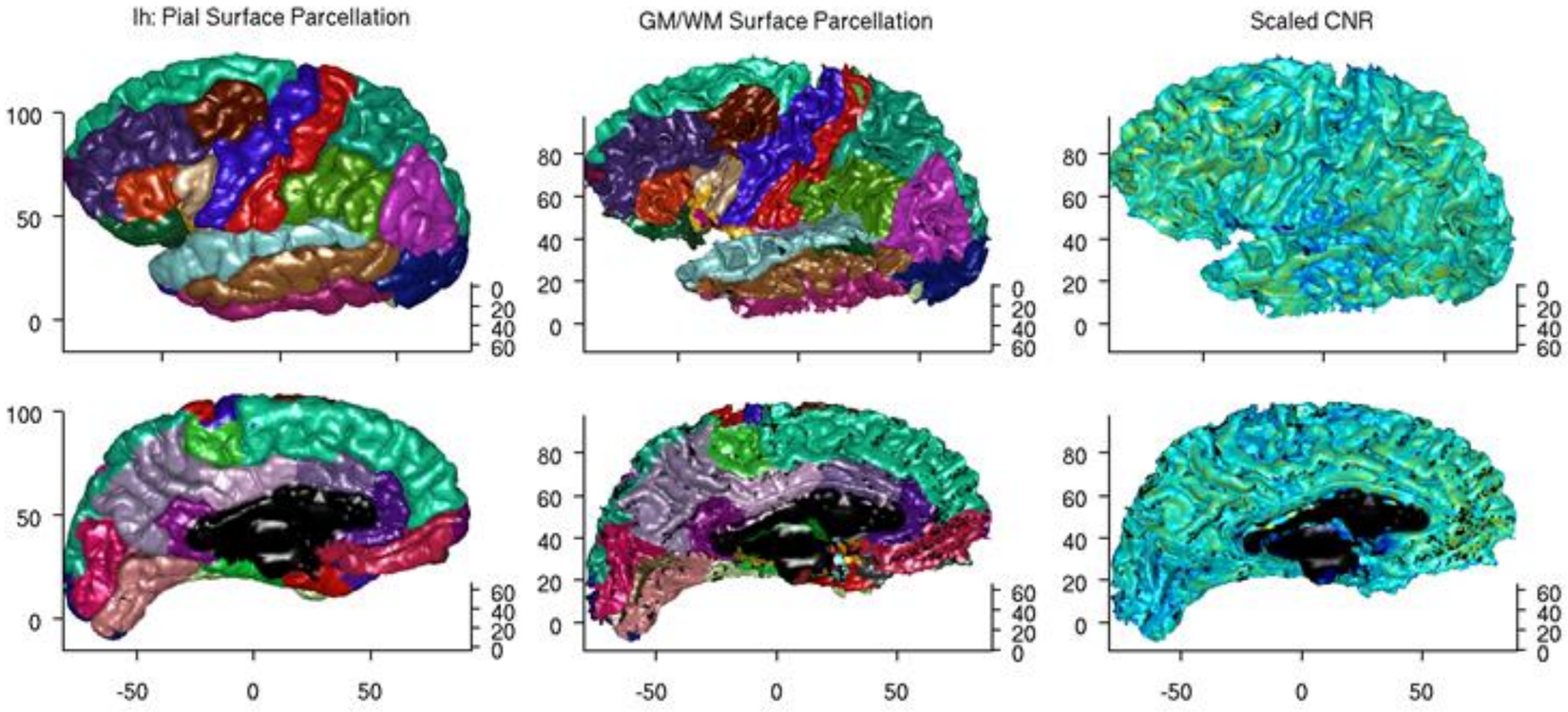
Dale et al (1999)

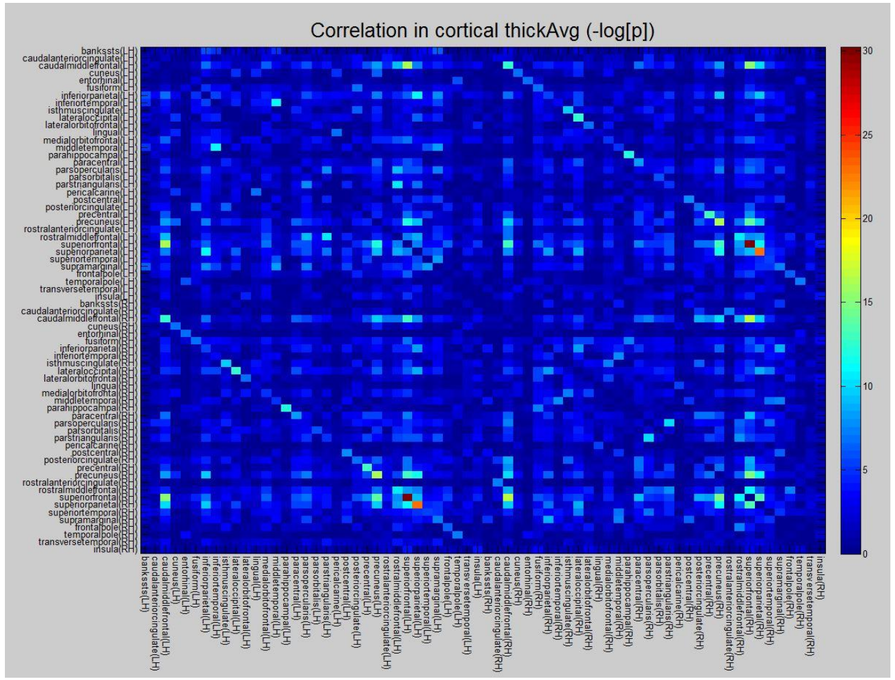
Classify points on cortical surface

- The surface is modeled as a deformable surface
  - Balance smoothness with intensity-matching
- Labels are added using a reference atlas



Quantify cortical properties by parcel

- Measure thickness of cortex in each region
- Many uses:
  - Test for changes over time (by parcel)
  - Assess group differences (by parcel)
  - Correlate thickness variations between parcels in a large group



Large values in the correlation matrix indicate cortical regions that tend to vary together

Evidence that the regions are involved in the same networks

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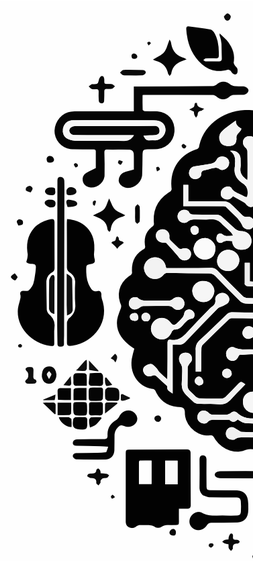
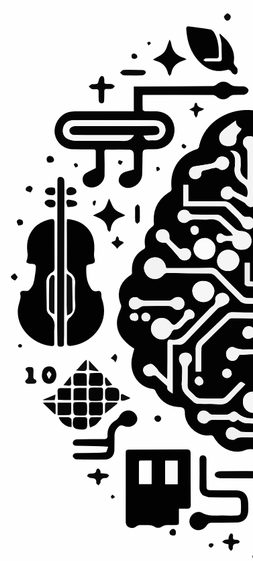
Practical issues



- FreeSurfer performs these steps automatically using a simple call:

  recon-all –i <T1w file.nii> –subject <your subject name> -all

  (come back the next day…)
- For more information on FreeSurfer, see
  - Fischl B, *FreeSurfer*. NeuroImage 62, 774-781 (2012).
  - https://surfer.nmr.mgh.harvard.edu/fswiki/FreeSurferWiki
- Runs on
  - Linux
  - MacOS
  - Windows in a VM
- Best way to learn is to dive in…



II. Tissue microstructure from diffusion MRI

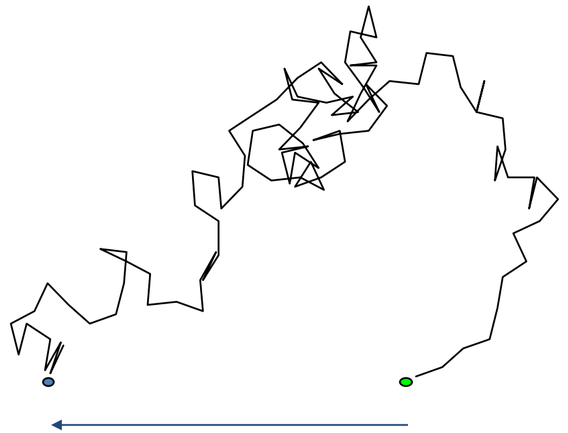
- Microscopic movement of tissue water reflects
  - Density of cell membranes in each direction in space
  - Axon fiber orientation
- Paths that follow the local axon orientation coincide with fiber pathways
- Fiber pathways reveal long-range connections in the brain
- Connections can be assembled into brain networks

Free diffusion of water

- Random thermal motion
- No preferred direction (isotropic)
- Modeled as a random walk
- Net displacement:
  $\langle r^2 \rangle = 2DT$
- D = 2.5 microns^2/msec

Diffusion

en.wikipedia.org



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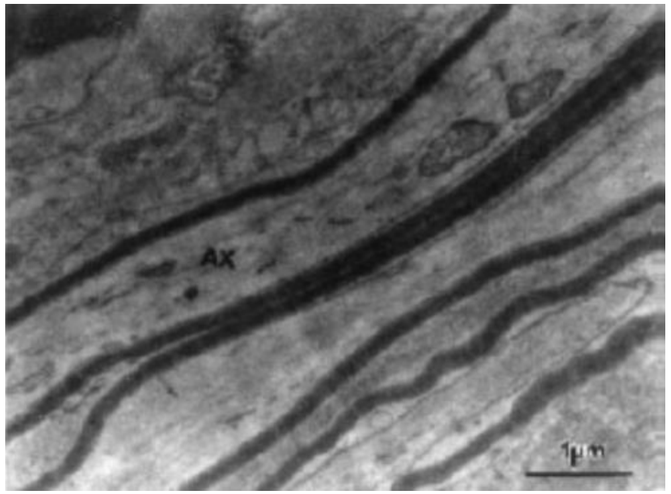
Water diffusion reflects tissue microstructure

- Diffusion of water in tissue
  - Constrained by cell membranes
  - Preferred direction of membranes -> preferred direction of water diffusion
- Largest displacements
  - Parallel to axons in brain
- Variation of displacements over orientations reflects
  - Membrane density
    - Membrane permeability
    - Fiber coherence (angular deviation)



Beaulieu, *NMR Biomed*, 2002

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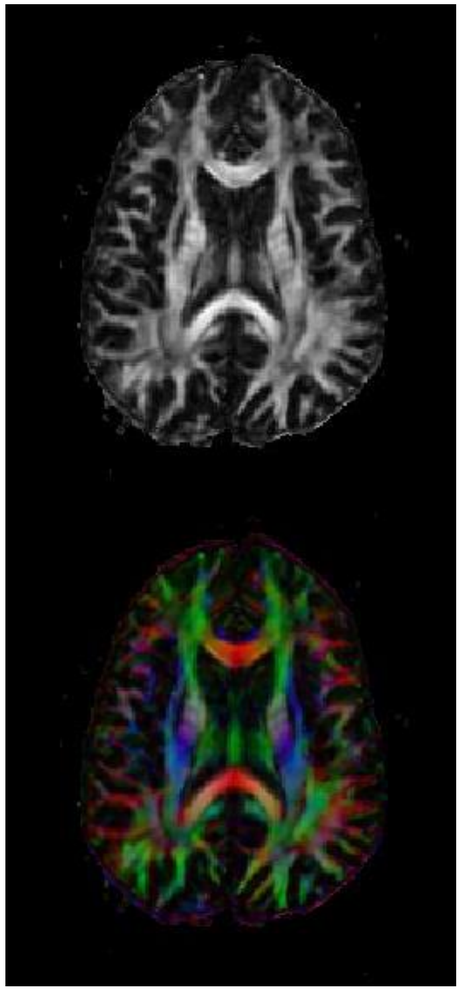
Diffusion Anisotropy reveals fiber bundle orientation

- Anisotropy maps
  - Bright in coherent white matter
  - Darker
    - Where fibers diverge
    - In gray matter
  - Fractional Anisotropy (FA): $0 \leq FA \leq 1$
- Orientation information
  - Color code FA by fiber direction
    - Red = Right/Left
    - Green = Anterior/Posterior
    - Blue = Superior/Inferior
- Reveals structure within white matter



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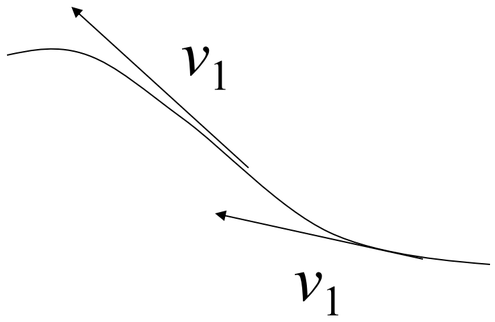
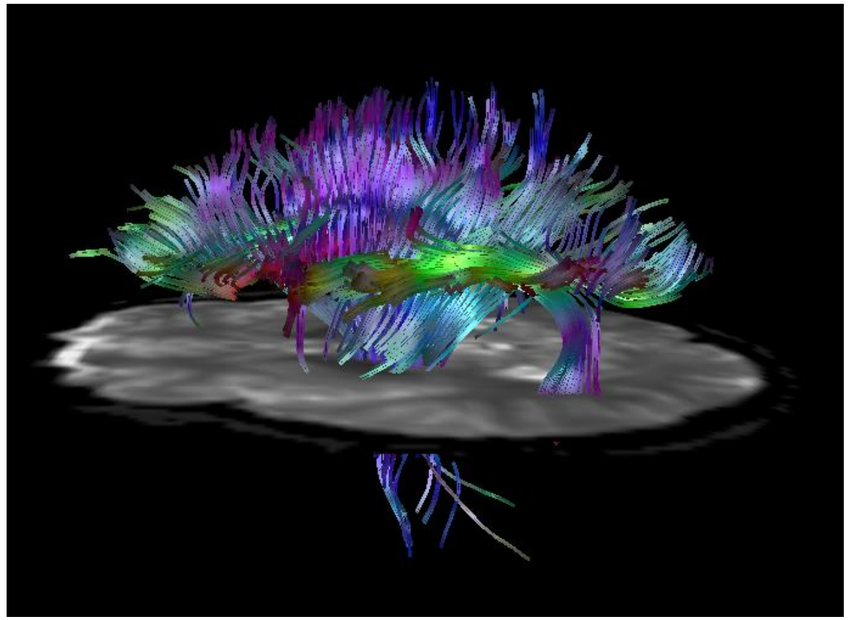
Fiber tracking

- Fiber paths calculated from fast diffusion direction





- Integrate starting from user-defined seed points

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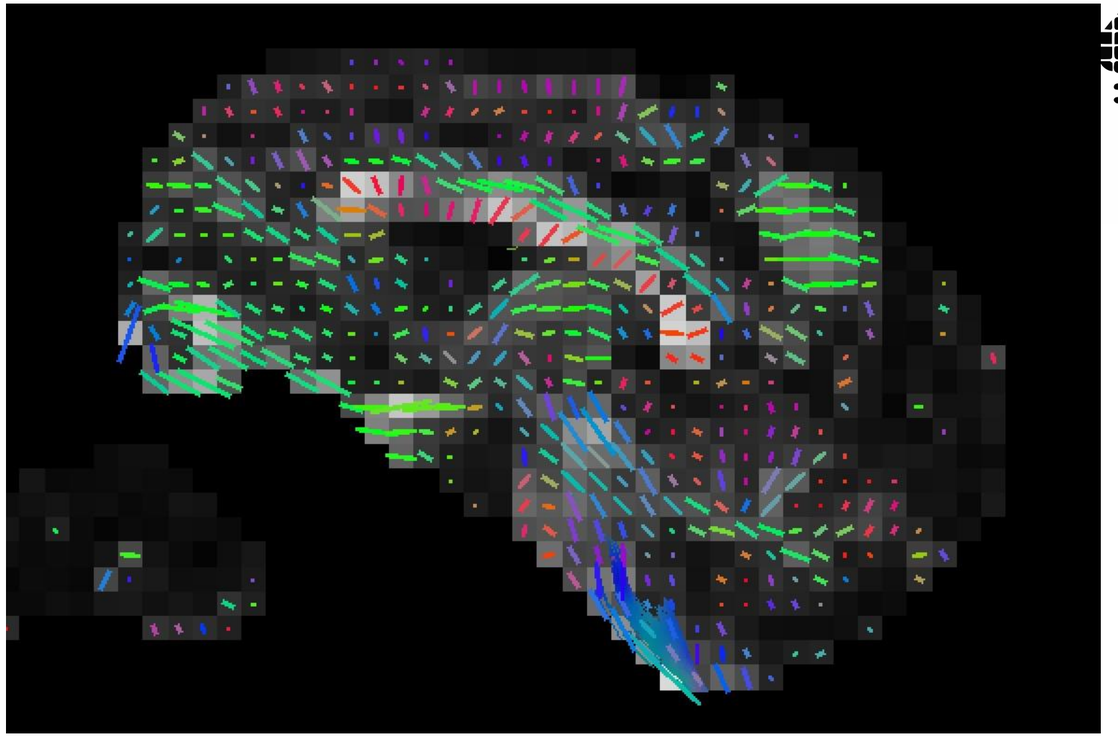
Steps in visualizing connectivity

- Read diffusion MR image files
- For each voxel,
  - Analyze signal as a function of diffusion measurement direction
  - Infer fiber direction, v
- Track fiber pathways through voxels
  - Using v as tangent to fiber (deterministic)
  - Allowing a range of possible tangents around v (probabilistic)



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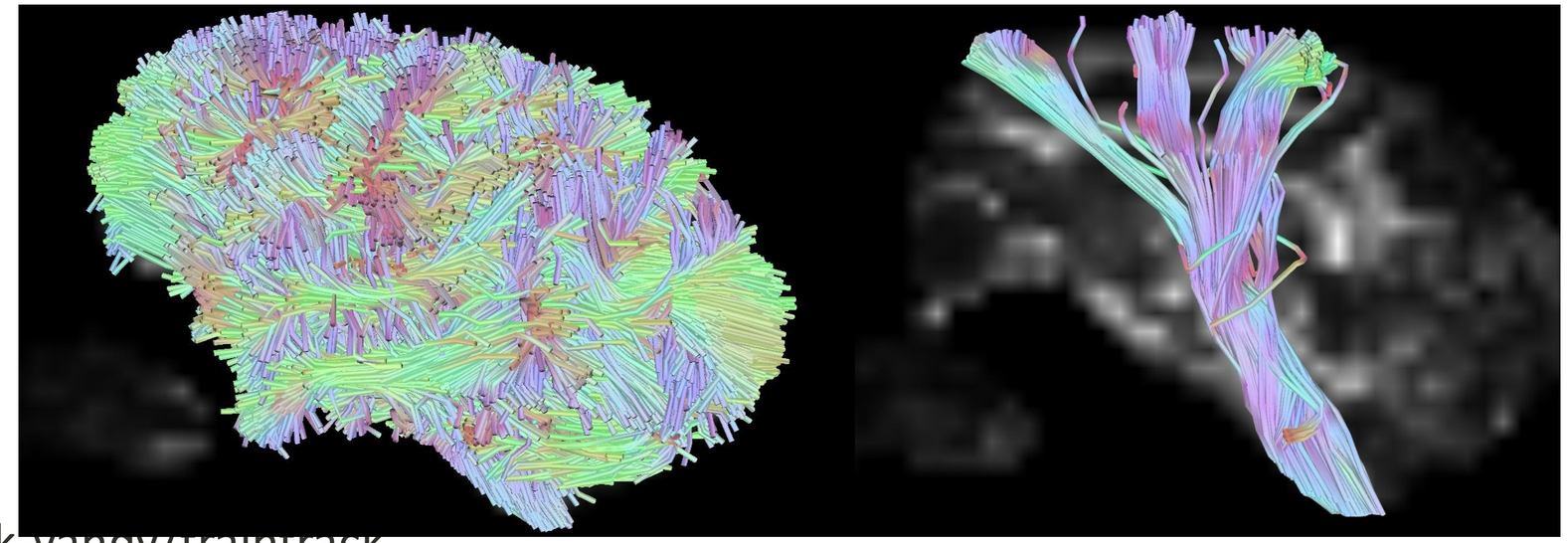
Characterizing pathways

- What DMRI can tell us
  - Where are the large white matter pathways?
  - What microstructural properties (e.g., FA, MD) do these fiber pathways have?
    - How are they affected by normal development, ageing, injury, disease, etc.?
- What DMRI cannot tell us (yet…)
  - How many axons are in a fiber (or how ‘strong’ is the connection)?
  - Where are all pathways in the brain?



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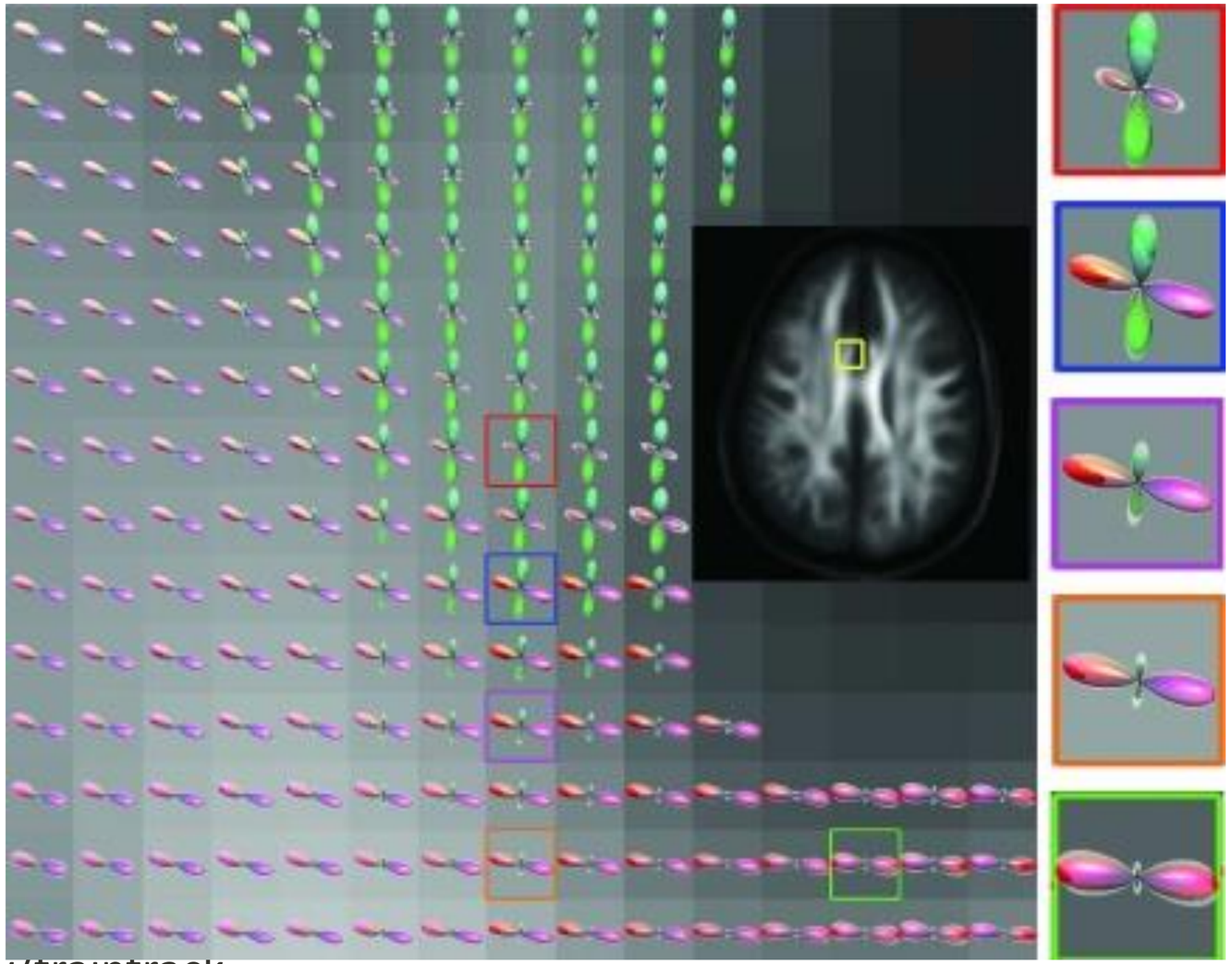
High Angular Resolution Diffusion Imaging (HARDI) can provide fiber orientation distributions



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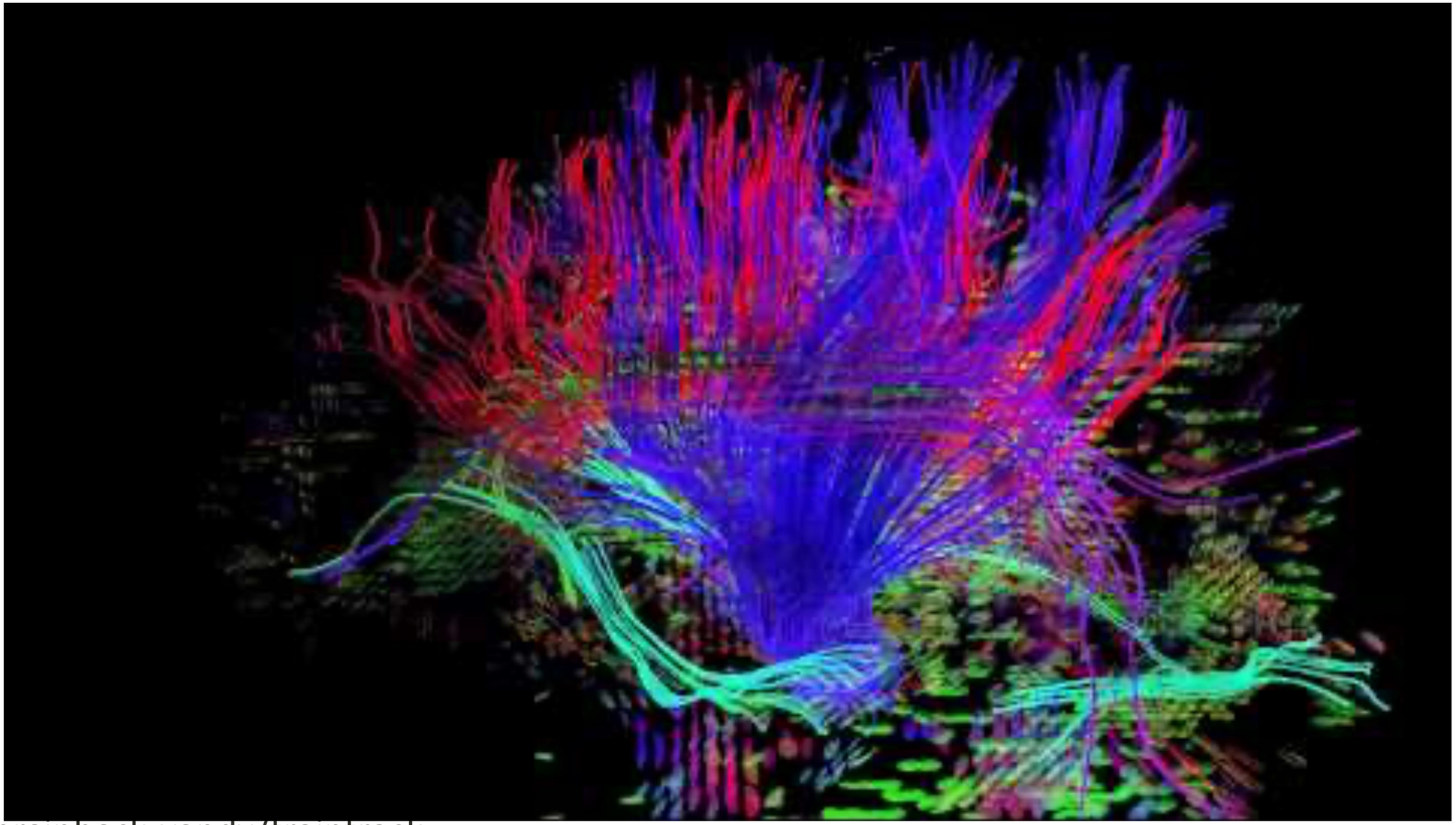
Multiple levels of analysis



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https://youtu.be/wy8KEUmyasA