Invariance and diffusion MRI

Application of ML to MRI, electrophysiology and brain computer interfaces

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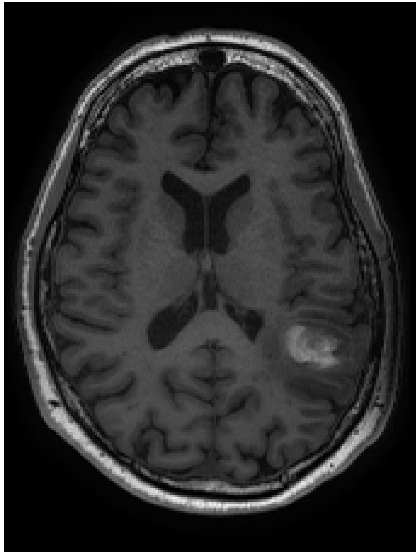
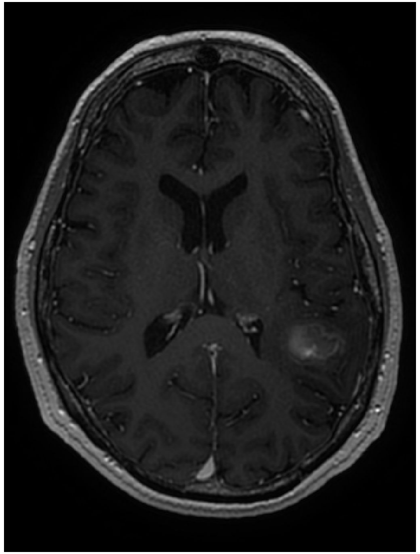
Reminder: MRI Contrasts

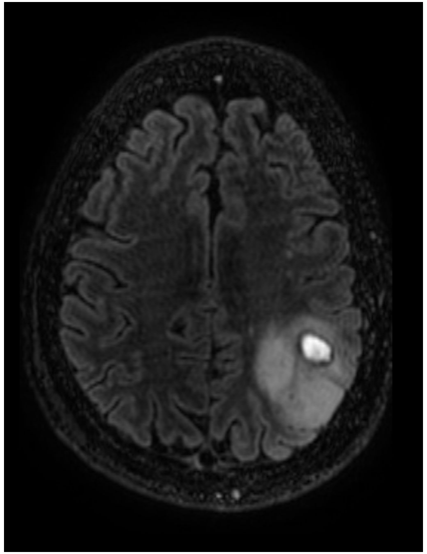
T1w



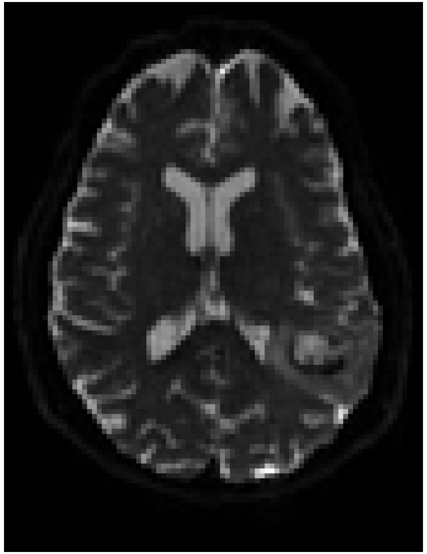
T1w Gadolinium



FLAIR



T2w



Different contrasts can be treated like color channels in RGB images

MRI Open Datasets

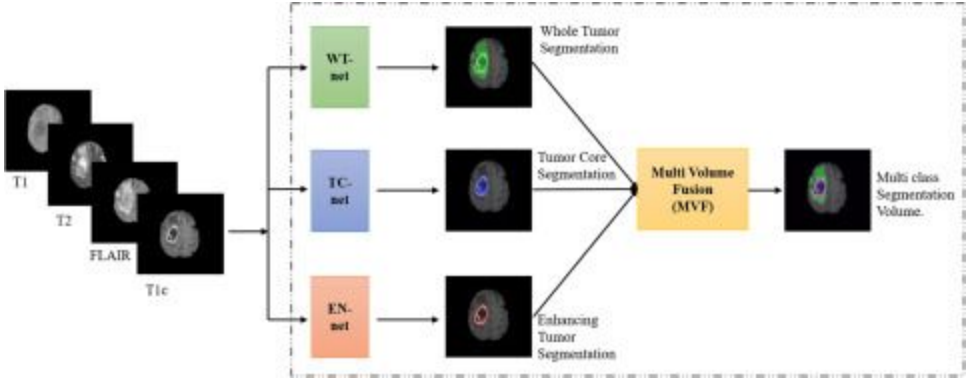
- Human Connectome Project: Young Adults https://www.humanconnectome.org/study/hcp-young-adult
- Alzheimer's Disease Neuroimaging Initiative: https://adni.loni.usc.edu/
- Multimodal Brain Tumor Segmentation: https://www.med.upenn.edu/cbica/brats2020/data.html
- Large scale: https://www.ukbiobank.ac.uk/
- General: https://openneuro.org/

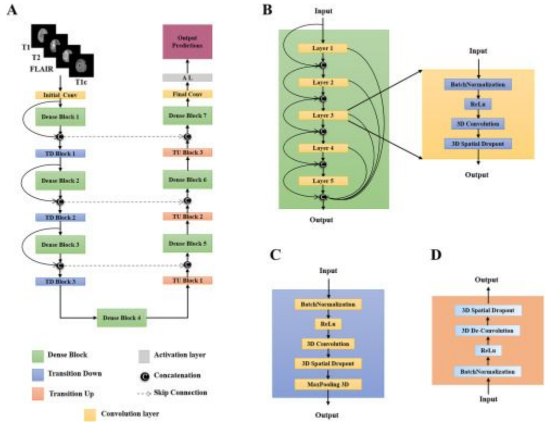
Uses the BIDS format: https://bids.neuroimaging.io/

Challenge: Most datasets are small (< 1000 participants)

Reading - Discussion

A Fully Automated Deep Learning Network for Brain Tumor Segmentation





The network is large for so little data … how did they manage?

Reading - Discussion

“Data augmentation steps included horizontal flipping, vertical flipping, random rotation, and translational rotation.”

What is the underlying hypothesis?

Invariance vs Equivariance

Invariance: if the targets for a transformed input are unaffected.

$$f(g(I)) = f(I)$$

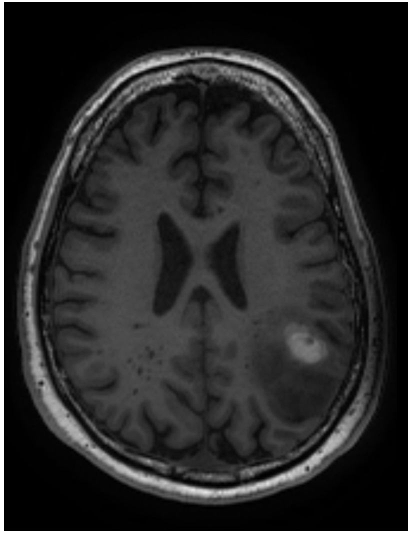
Equivariance: if the targets for a transformed input are transformed in the same way as the input.

$$f(g(I)) = g'(f(I))$$

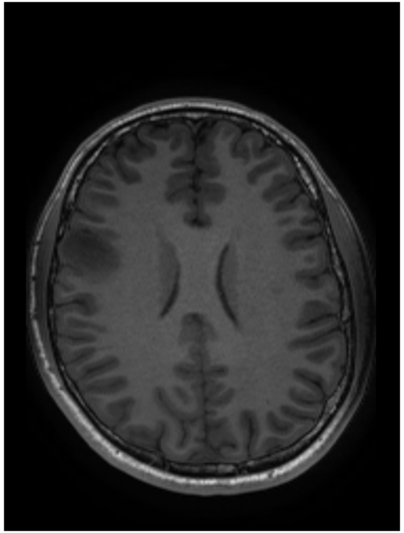
Invariance and equivariance

Translation invariance

Tumor



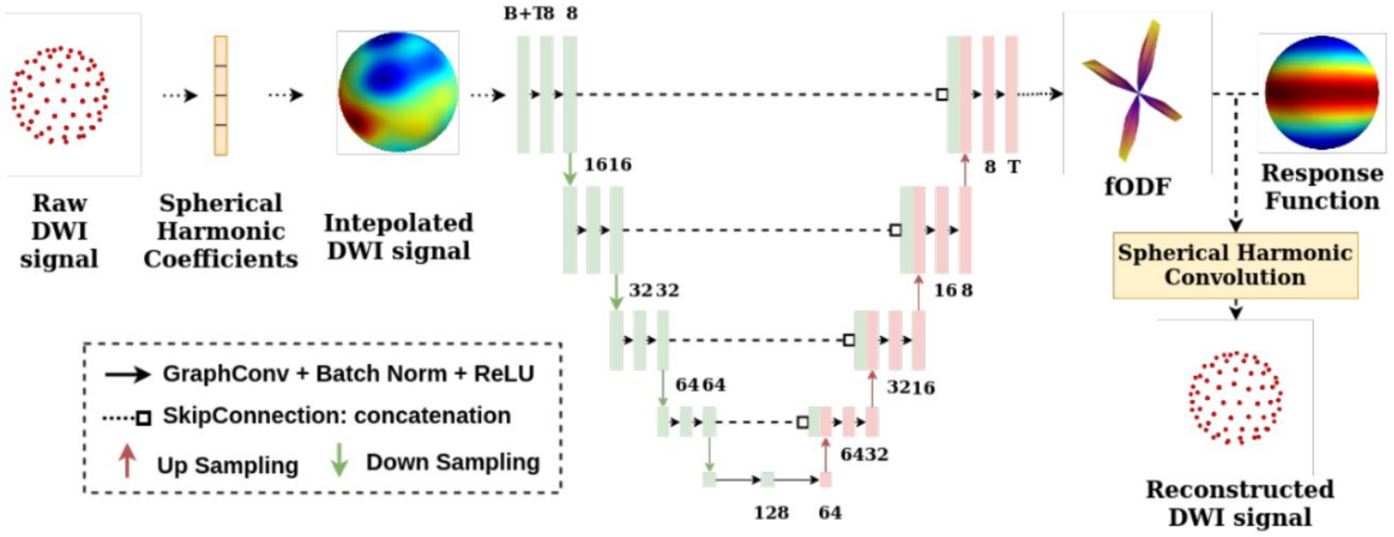
Tumor



The decision must not depend on the location (x, y, z coordinates) of the pathology.

$$f(I(x-t)) = f(I(x))$$

Invariance and equivariance



Sedlar et al. A Spherical Convolutional Neural Network for White Matter Structure Imaging via dMRI, MICCAI 2021.

Elaldi et al. Equivariant Spherical Deconvolution: Learning Sparse Orientation Distribution Functions from Spherical Data. arXiv, 2021.

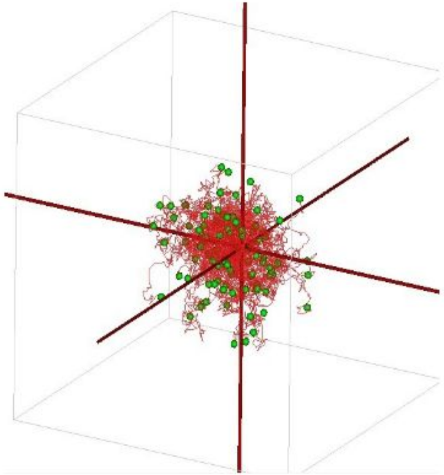
Invariance in ML

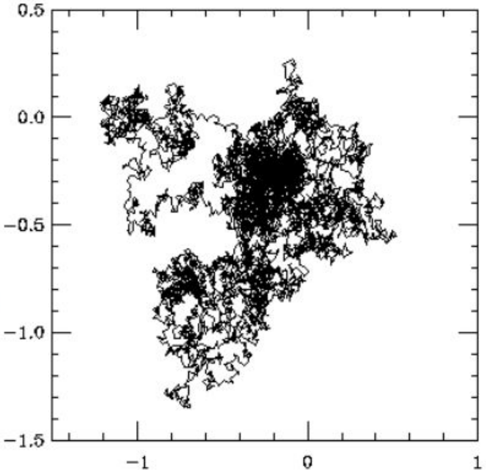
3 ways to consider invariance:

1. Data augmentation
    a. Misra et al. Self-supervised learning of pretext-invariant representations. In CVPR, 2020.
    b. Bangalore et al. A fully automated deep learning network for brain tumor segmentation. Tomography. 2020.
2. Invariant feature extraction
    a. Zucchelli et al. Investigating the effect of dMRI signal representation on fully-connected neural networks brain tissue microstructure estimation. ISBI, 2021.
3. Invariance by model construction
    a. CNNs are almost equivariant to translation (why?)
    b. Horace Pan et al. Permutation equivariant layers for higher order interactions. Proceedings of The 25th International Conference on Artificial Intelligence and Statistics, PMLR, 2022.

Invariance example - Diffusion MRI

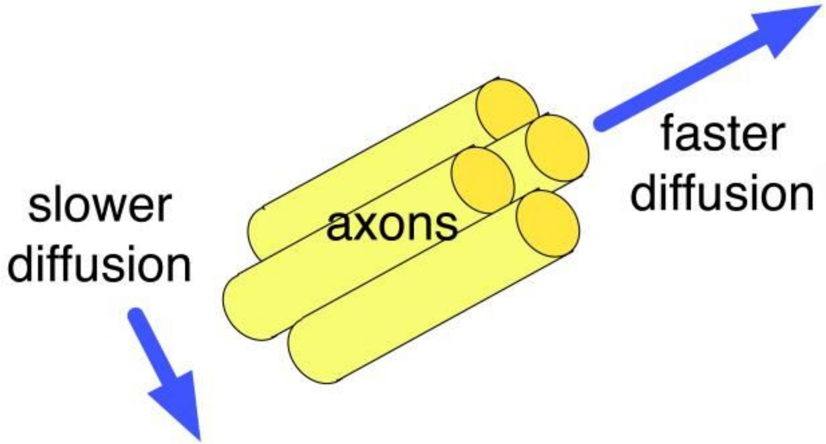
Sensitive to the displacement of water molecules

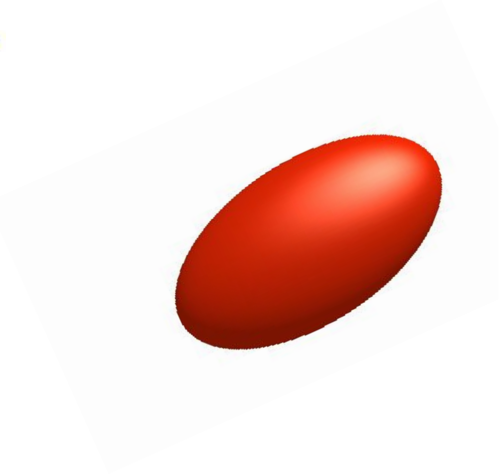




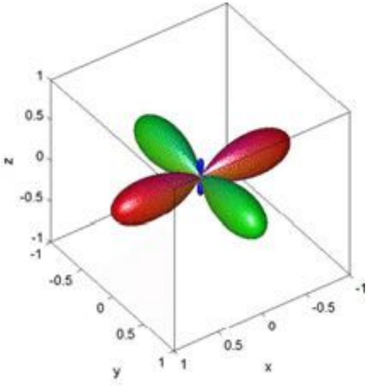
Diffusion MRI

Axons hinder the displacement of water molecules





Tensor

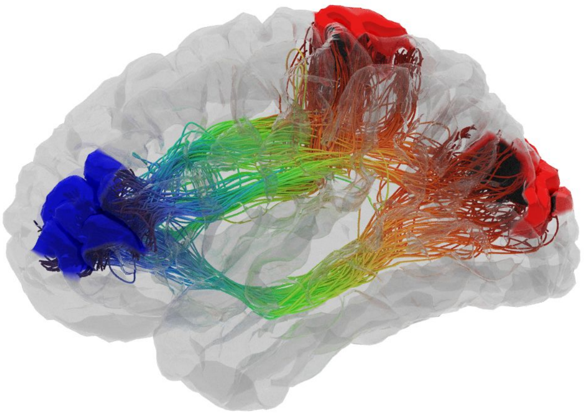


fODF

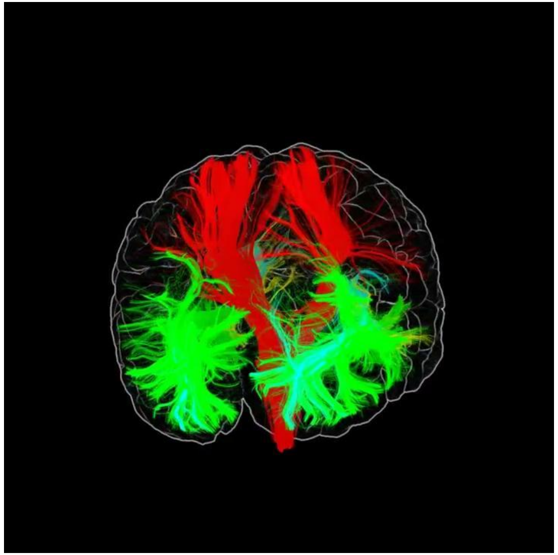
O'Donnell LJ, Westin CF. An introduction to diffusion tensor image analysis. Neurosurg Clin N Am. 2011

Diffusion MRI Tractography

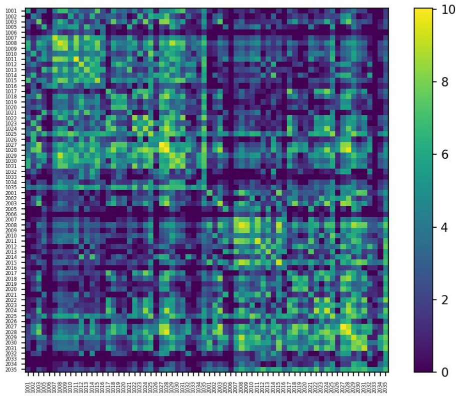
From local to global connectivity



Streamlines



Tractograms

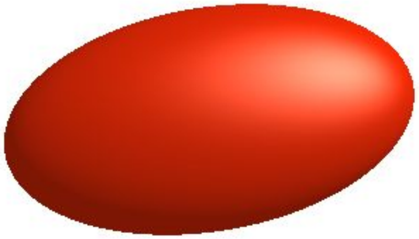


Connectivity matrix

Diffusion tensor (DTI)

A model for the dMRI signal

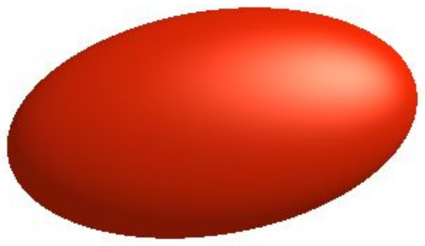
$S(\boldsymbol{x}, \boldsymbol{q})$



Diffusion tensor (DTI)

A model for the dMRI signal

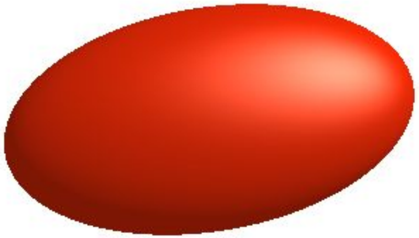
$$S(\boldsymbol{x}, \boldsymbol{q}) = S(\boldsymbol{x}, b, \boldsymbol{g})$$



Diffusion tensor (DTI)

A model for the dMRI signal

$$S(\boldsymbol{x}, \boldsymbol{q}) = S(\boldsymbol{x}, b, \boldsymbol{g}) = S_0(\boldsymbol{x}) \exp\left(-b\boldsymbol{g}^T \boldsymbol{D}\boldsymbol{g}\right)$$



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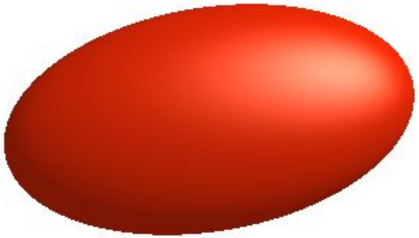

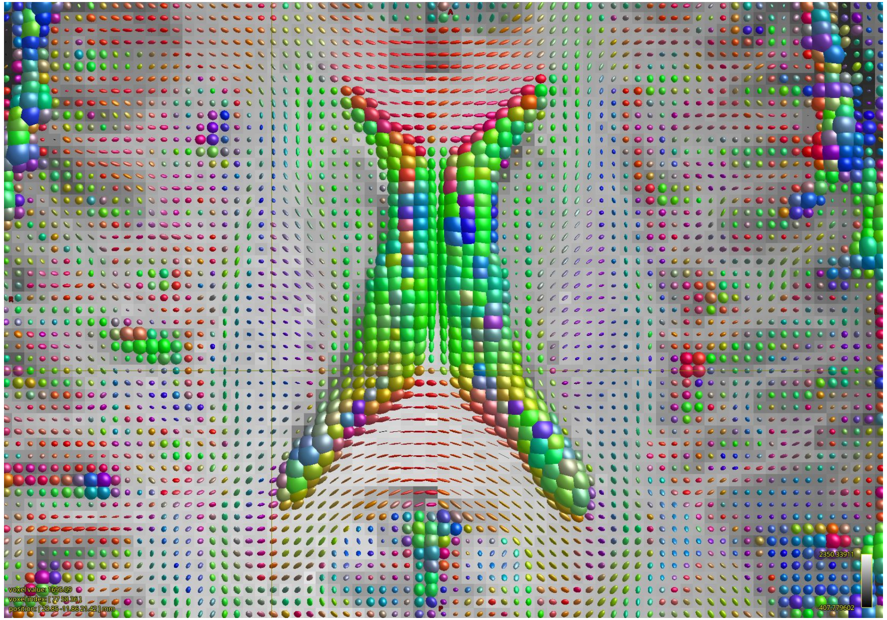

Tensor metrics

Rotation invariants derived from the tensor

$$\boldsymbol{D} = \begin{bmatrix} d_{xx} & d_{xy} & d_{xz} \\ d_{yx} & d_{yy} & d_{yz} \\ d_{zx} & d_{zy} & d_{zz} \end{bmatrix} = V \Lambda V^T = V \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix} V^T$$

Tensor metrics

Rotation invariants derived from the tensor

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$$\mathrm{FA} = \sqrt{\frac{3}{2}} \sqrt{\frac{(\lambda_1 - \hat{\lambda})^2 + (\lambda_2 - \hat{\lambda})^2 + (\lambda_3 - \hat{\lambda})^2}{\lambda_1^2 + \lambda_2^2 + \lambda_3^2}}$$

$$\mathrm{MD} = \mathrm{ADC} = \frac{\lambda_1 + \lambda_2 + \lambda_3}{3}$$

Tensor metrics in sport-related TBI

- Karl A Zimmerman, Etienne Laverse, Ravjeet Samra, Maria Yanez Lopez, Amy E Jolly, Niall J Bourke, Neil S N Graham, Maneesh C Patel, John Hardy, Simon Kemp, Huw R Morris, David J Sharp, White matter abnormalities in active elite adult rugby players, Brain Communications, Volume 3, Issue 3, 2021, https://doi.org/10.1093/braincomms/fcab133

- Hellewell SC, Nguyen VPB, Jayasena RN, Welton T, Grieve SM. Characteristic patterns of white matter tract injury in sport-related concussion: An image based meta-analysis. Neuroimage Clin. 2020;26:102253. doi: 10.1016/j.nicl.2020.102253

- Koerte IK, Wiegand TLT, Bonke EM, Kochsiek J, Shenton ME. Diffusion Imaging of Sport-related Repetitive Head Impacts-A Systematic Review. Neuropsychol Rev. 2023 Mar;33(1):122-143. doi: 10.1007/s11065-022-09566-z\

- Thomas AW, Watts R, Filippi CG, Nickerson JP, Andrews T, Lieberman G, Naylor MR, Eppstein MJ, Freeman K. Dynamic changes in diffusion measures improve sensitivity in identifying patients with mild traumatic brain injury. PLoS One. 2017 Jun 12;12(6):e0178360. doi: 10.1371/journal.pone.0178360

Computing diffusion tensors

1. Install Mrtrix3 (many other options available)
   https://mrtrix.readthedocs.io/en/dev/installation/package_install.html
2. Download dMRI data (from course website: dwi.nii.gz, bvecs, bvals)
3. Run the following command in the terminal:
   dwi2tensor dwi.nii.gz tensors.nii.gz -fslgrad bvecs bvals
4. The create file “tensors.nii.gz” contains the tensors (they are also given on the course website).

Challenge: WM segmentation using DTI

- Data:
  - Diffusion tensors of 1 participant
  - WM binary label
  - Brain mask
- Task:
  - Build an architecture that predicts the WM label using the tensor **entries**
  - Build an architecture that predicts the WM label using the tensor **singular values**
  - (bonus) Build an architecture that predicts the WM label using the tensor entries using rotation data augmentation
- Evaluation:
  - % of correct WM labels (60% training, 20% testing, 20% validation)
  - Learning rate curves