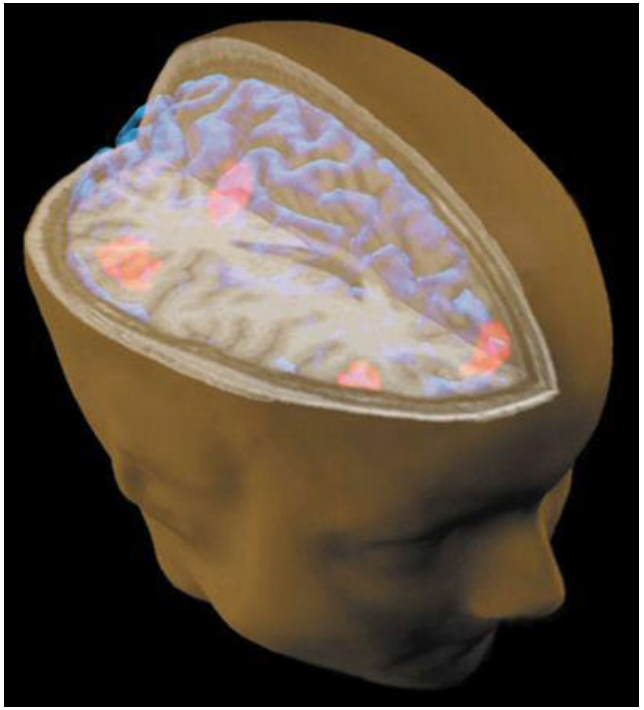
Introduction to Brain Mapping

With MRI

Vahid Malekian

Postdoctoral Associate,
School of Cognitive Sciences, IPM, Tehran.
Email: vmalekian@ipm.ir



Vahid Malekian

- **School of cognitive Science, Institute for Research in Fundamental Science Tehran, Iran**
- **Advanced Medical Imaging Research Lab, Department of Biomedical Engineering, Amirkabir University of Technology, Tehran, Iran**
- **Donders Center for Cognitive Neuroimaging, Nijmegen, Netherlands**
- **Email Address:** v.malekian@aut.ac.ir,vd.malekian@gmail.com.

Research Interests

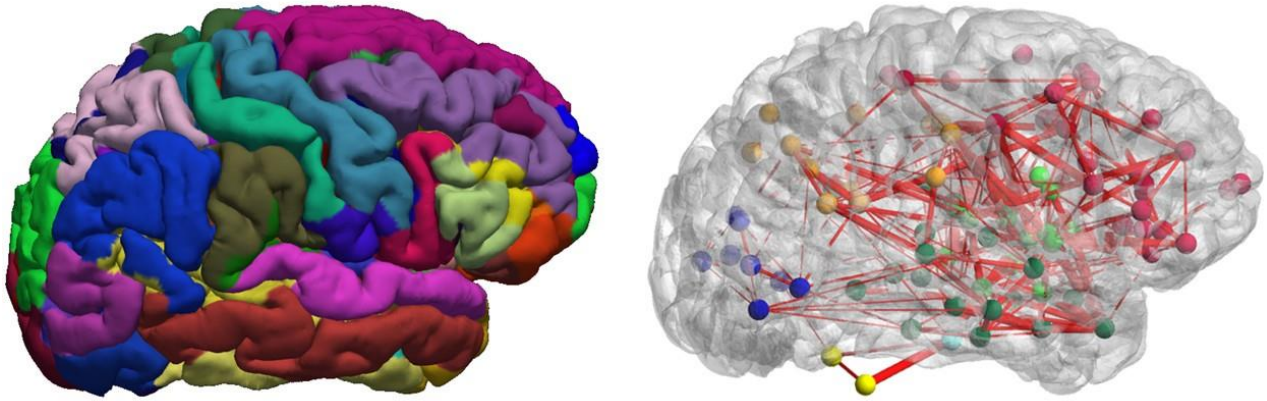
- **Functional Neuroimaging (fMRI)**
- **MRI Physics & Pulse Sequence Developments**
- **Medical Signal & Image Processing**
- **Pattern Recognition & Neural Networks**

Outline

- MR Physics
- Structural MRI
- Functional MRI (BOLD)
- Diffusion Imaging (DWI & DTI)
- Perfusion Imaging (ASL)

MRI for Brain Mapping?

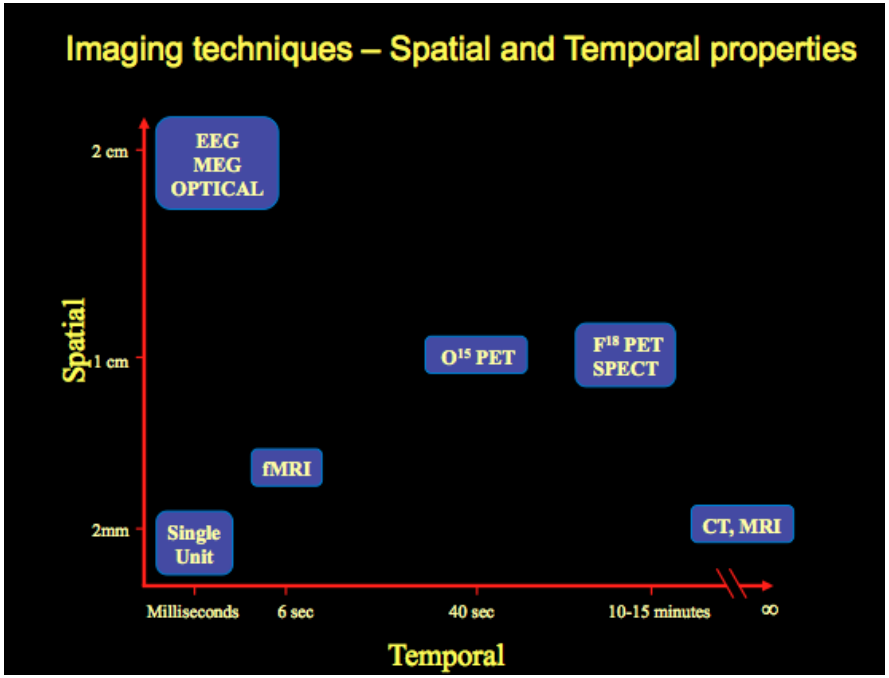
- MRI delineates the structural and functional alterations determined by disease conditions.
- Modern MRI technologies are of great interest due to MRI's potential to characterize the signature of each neurodegenerative process and help both the diagnostic aspect and the monitoring of disease development.



(a) (b)

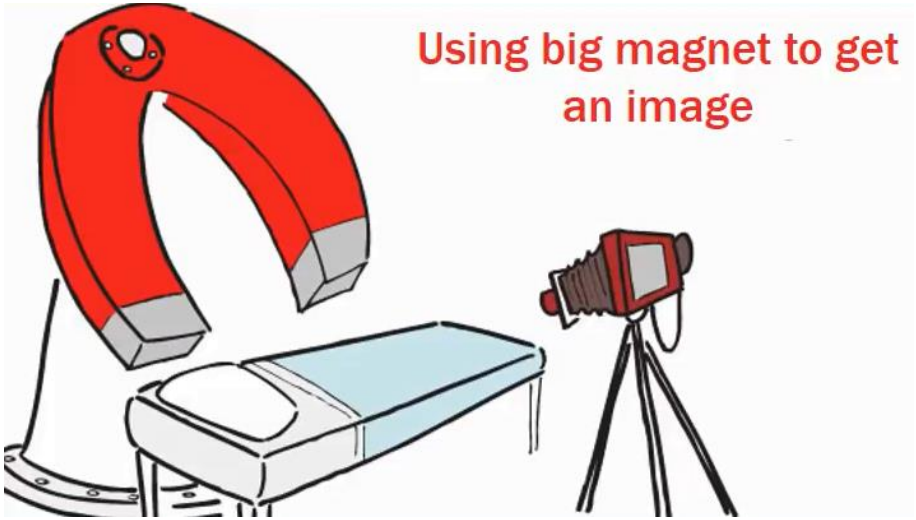
MRI Advantages

- Advantages
  - Non-invasive, no radiation
  - Spatial resolution
  - Multi-contrast
  - Relatively easy for researchers to use
- Limitations
  - Expensive!
  - Metal free!
  - Time resolution (many have started to combine EEG or MEG w/fMRI)
  - Need expert!



What is MRI?

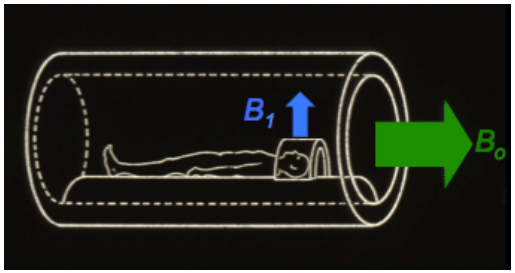
- B0 = constant, strong and homogenous magnetic field
- Always ON!



$$\vec{\mu} \longrightarrow \vec{M} \longrightarrow \vec{M}_{xy} \longrightarrow S(t) \longrightarrow S(\vec{k}) \longrightarrow I(\vec{x})$$

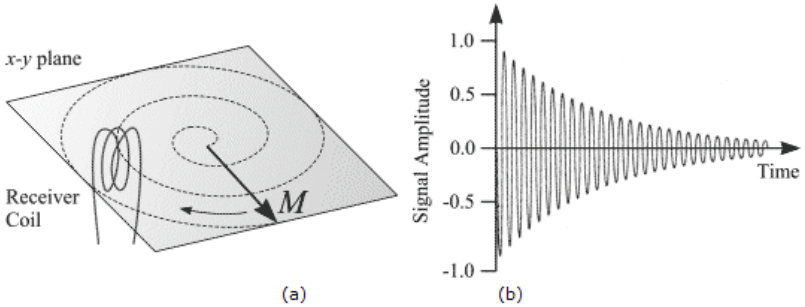
Magnetization

$$\vec{\mu} \longrightarrow \vec{M}$$



RF Excitations

$$\vec{M} \longrightarrow \vec{M}_{xy}$$

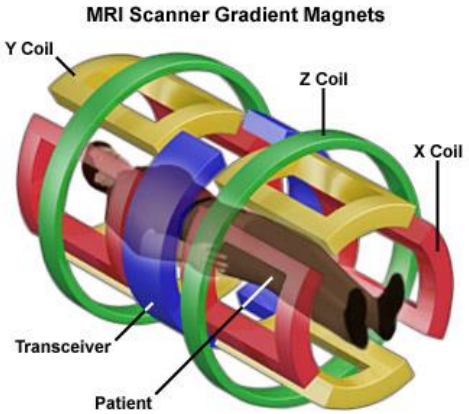


Signal Generation

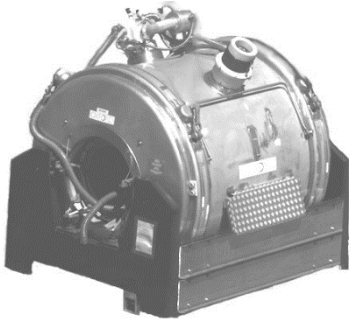
$$\vec{M}_{xy} \longrightarrow S(t)$$

Image Formation

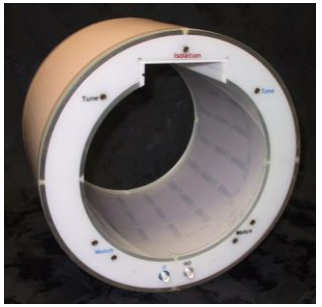
$$S(t) \longrightarrow S(\vec{k})$$



Magnet

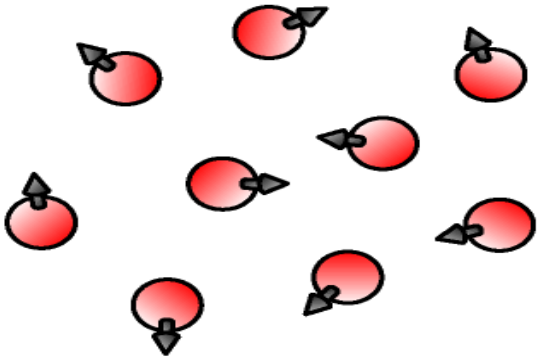


RF Coli

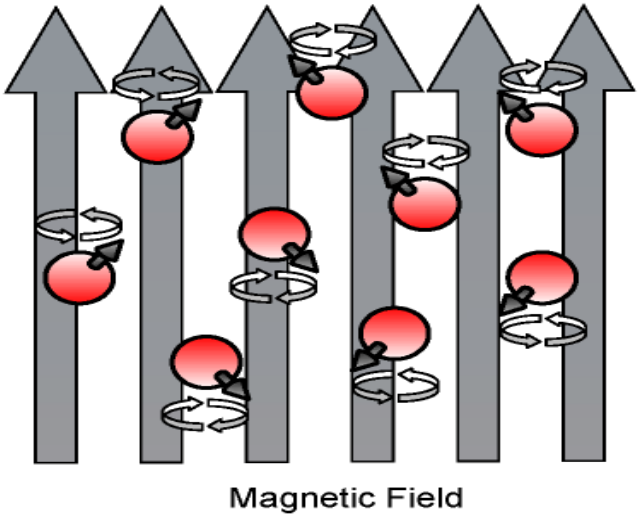


Gradient Coli

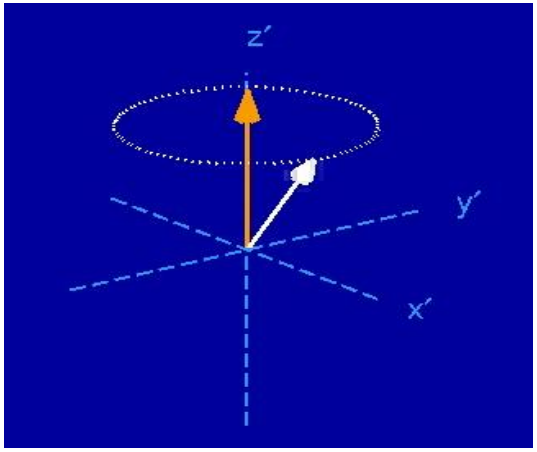
What happens in the scanner?



Equilibrium



Magnetization



RF Excitations

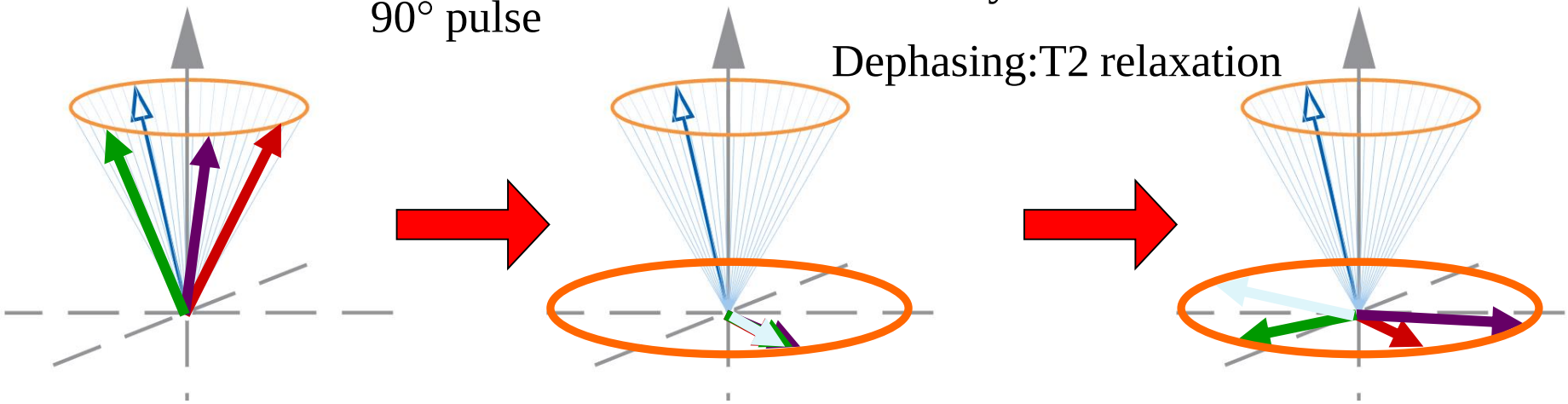
What is the relaxation?

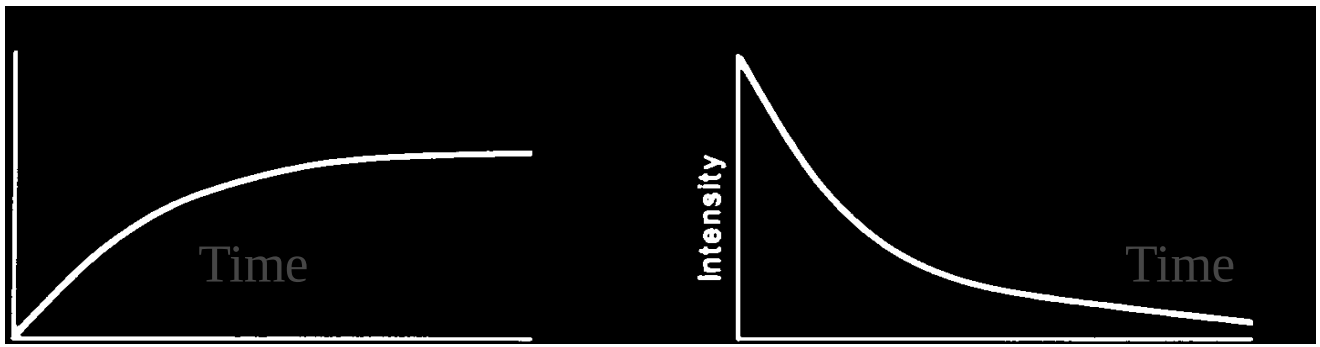
Dephasing in x-y plane = horizontal relaxation = spin-spin relaxation

90° pulse

Recovery: T1 relaxation

Dephasing:T2 relaxation

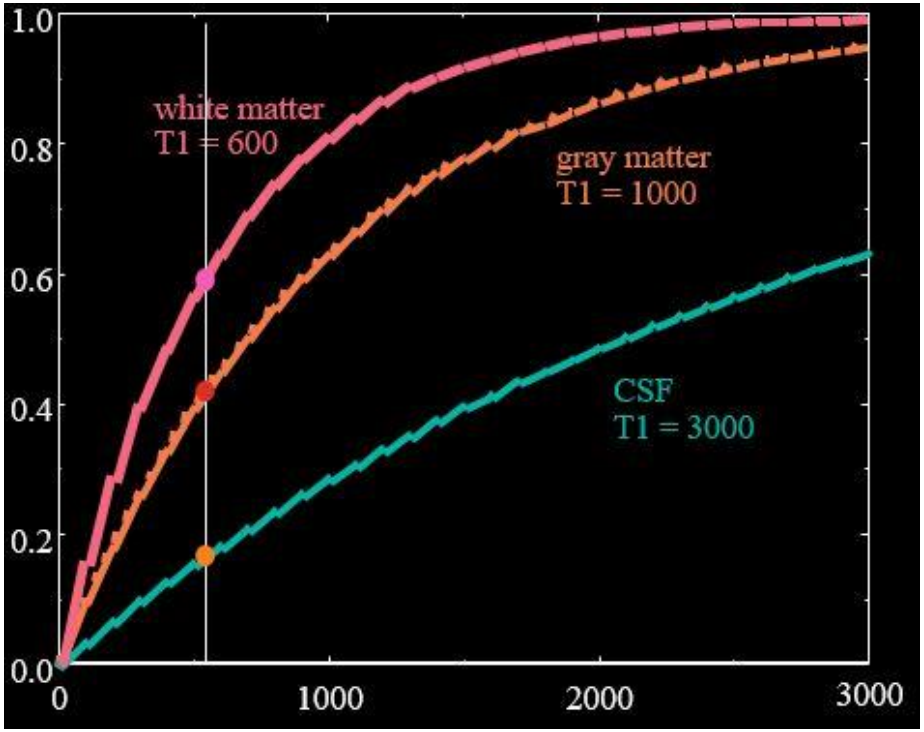


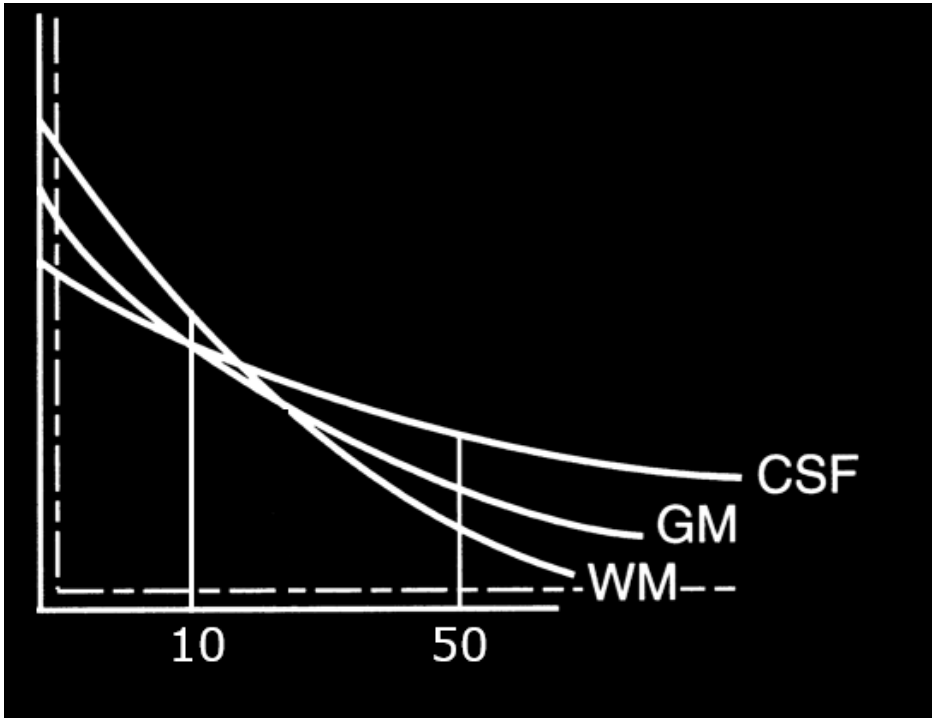


T1 Curve

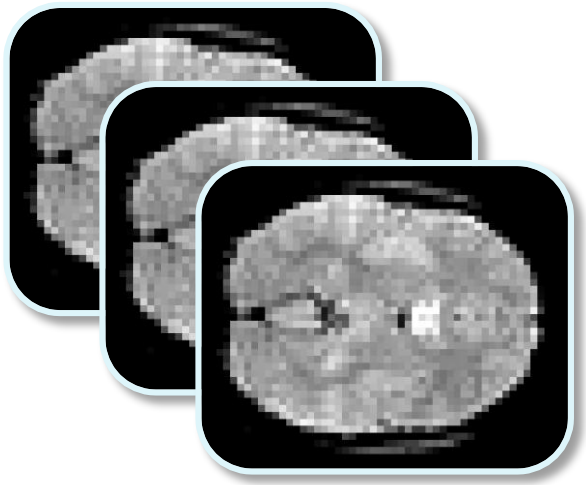
T2 Curve

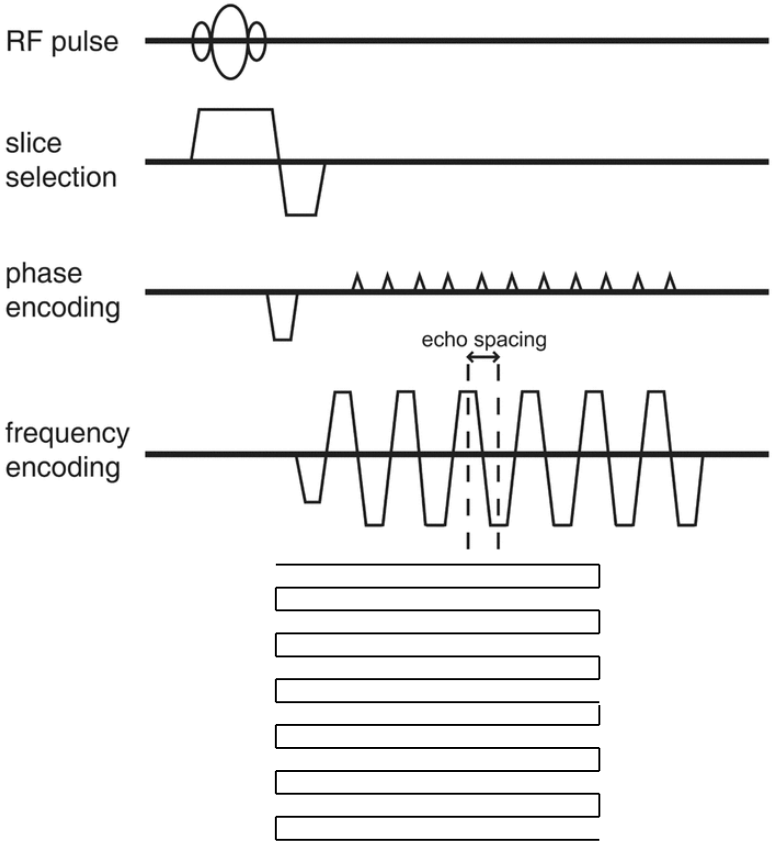
T1 & T2 Contrast





MRI & Pulse Sequence

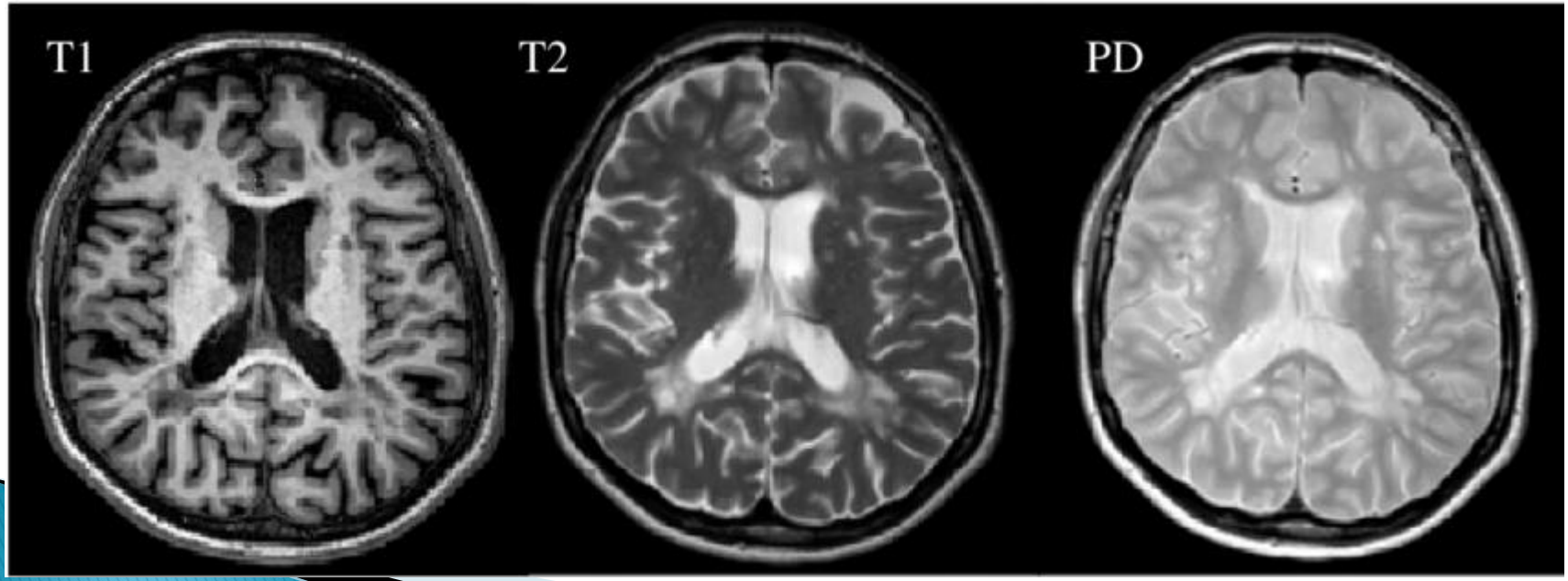




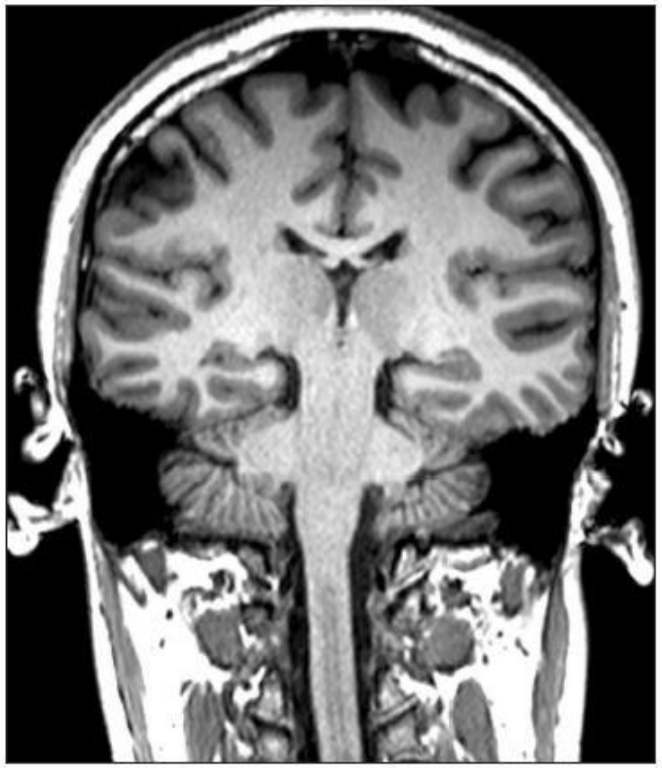
K space sampling

Structural Imaging: T1 T2 Weighted MRI

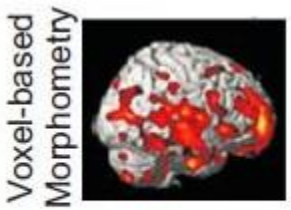
- T1-weighted: Structural imaging, Vascular Changes, …
- T2-weighted: Anatomical details (CSF spaces), most lesions, improve gray-white differentiation, …
- PD, T2*, combination of T1/T2, …

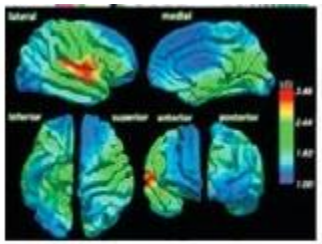


Structural MRI

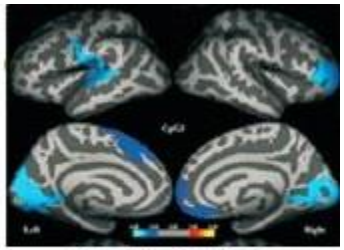


- Structural MRI provides a variety of information, including the integrity of grey and white matter, and both quantitative and qualitative shapes and size of substructures.
  - Cortical Volumetry
  - Voxel-based morphometry
  - Cortical thickness





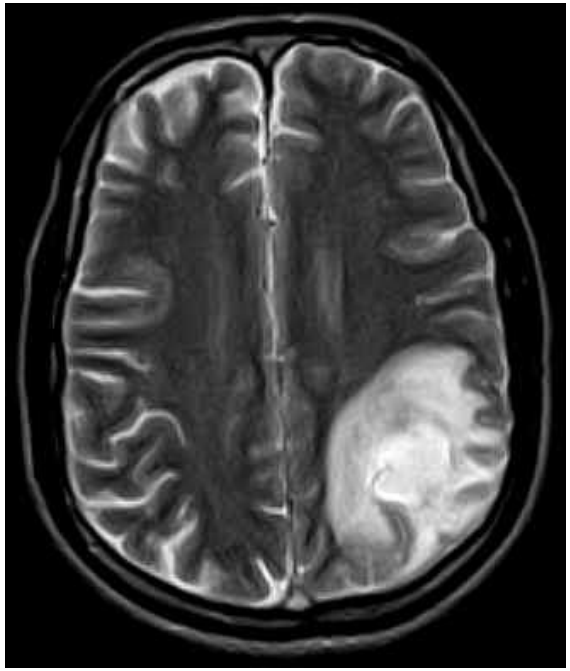
Local gyrification index



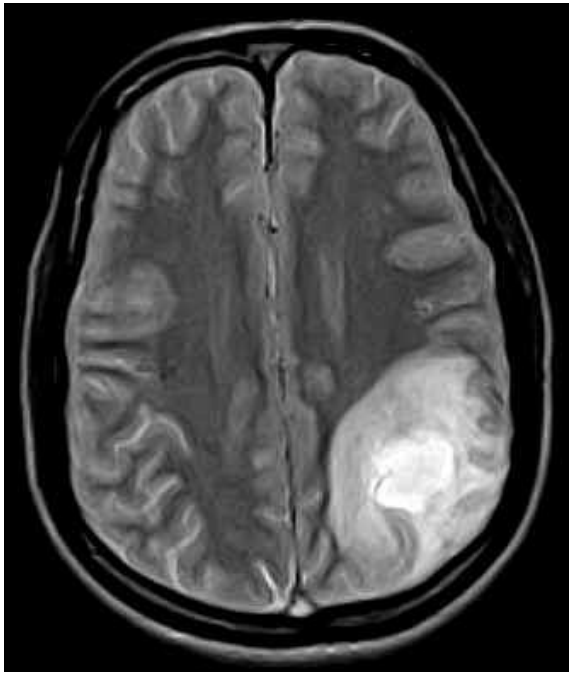
Cortical thickness analysis

Venous Infarct

T1-Weighted



T2-Weighted

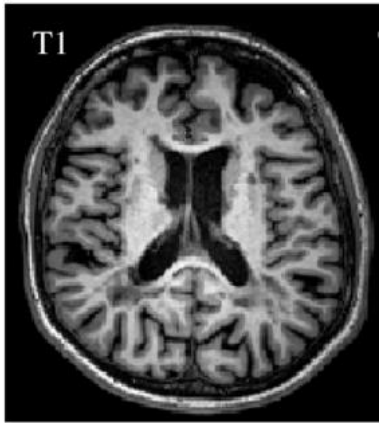


PD-Weighted

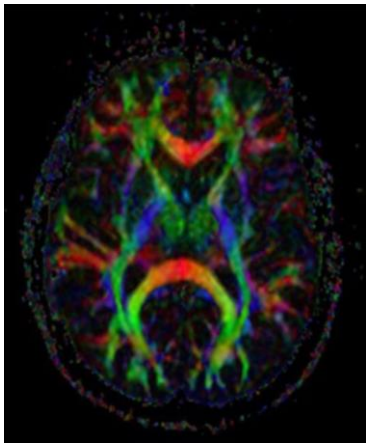
MRI
Brain Mapping

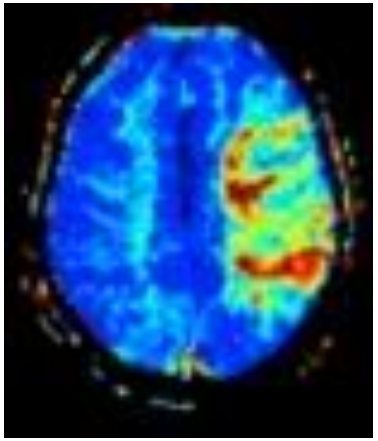
- Structural MRI
- Functional MRI
- Diffusion MRI
- Perfusion MRI

T1, T2 contrast

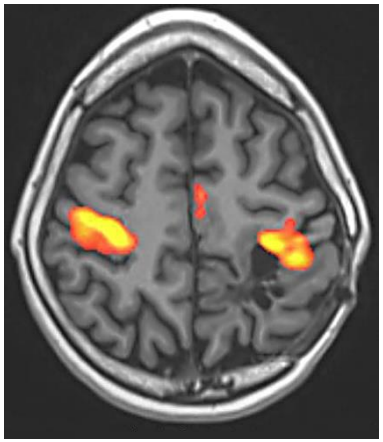


DWI & DTI





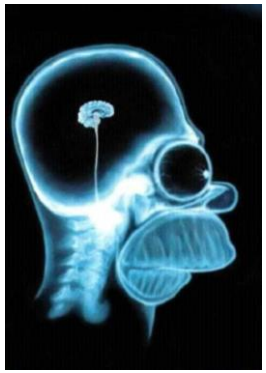
ASL

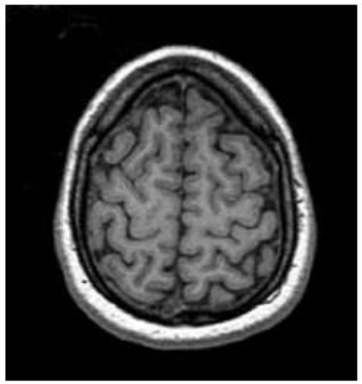


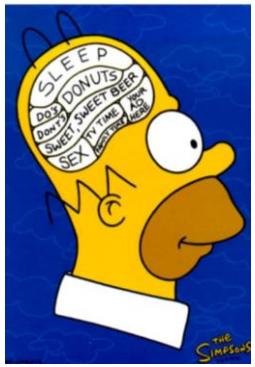
BOLD-fMRI

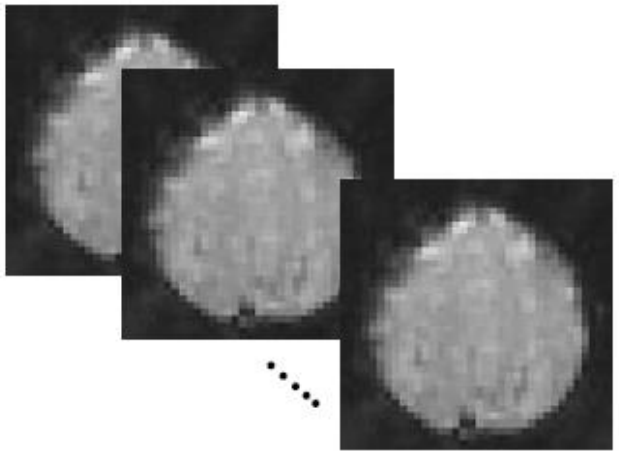
What is fMRI?

- sMRI studies brain anatomy.
  - High spatial resolution
  - Can distinguish different types of tissue
- fMRI studies brain function.
  - Functional images
  - Lower spatial resolution/ Higher temporal resolution









What is fMRI? Physiology and Physics

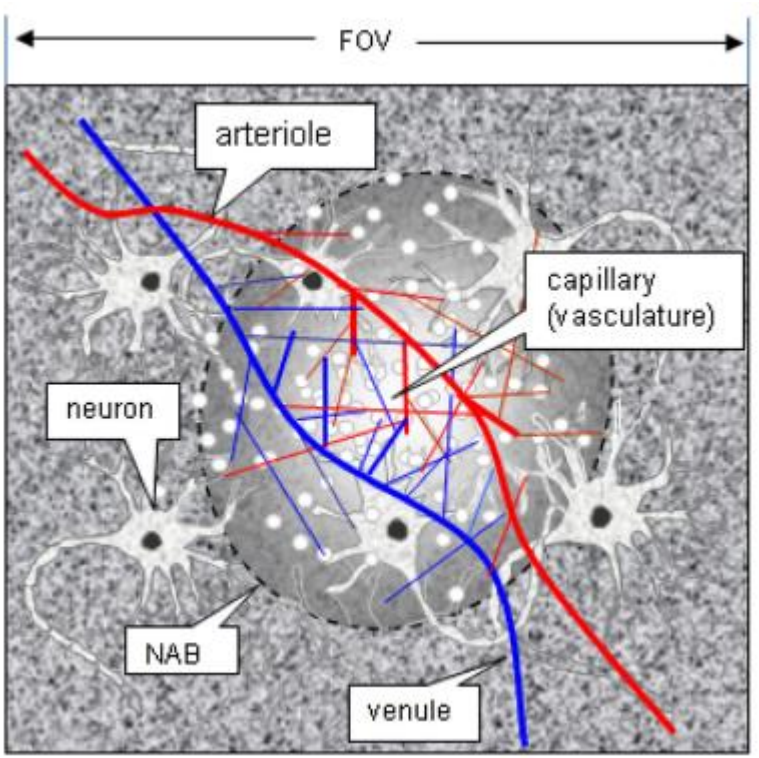
Neural Activity

PHYSIOLOGY

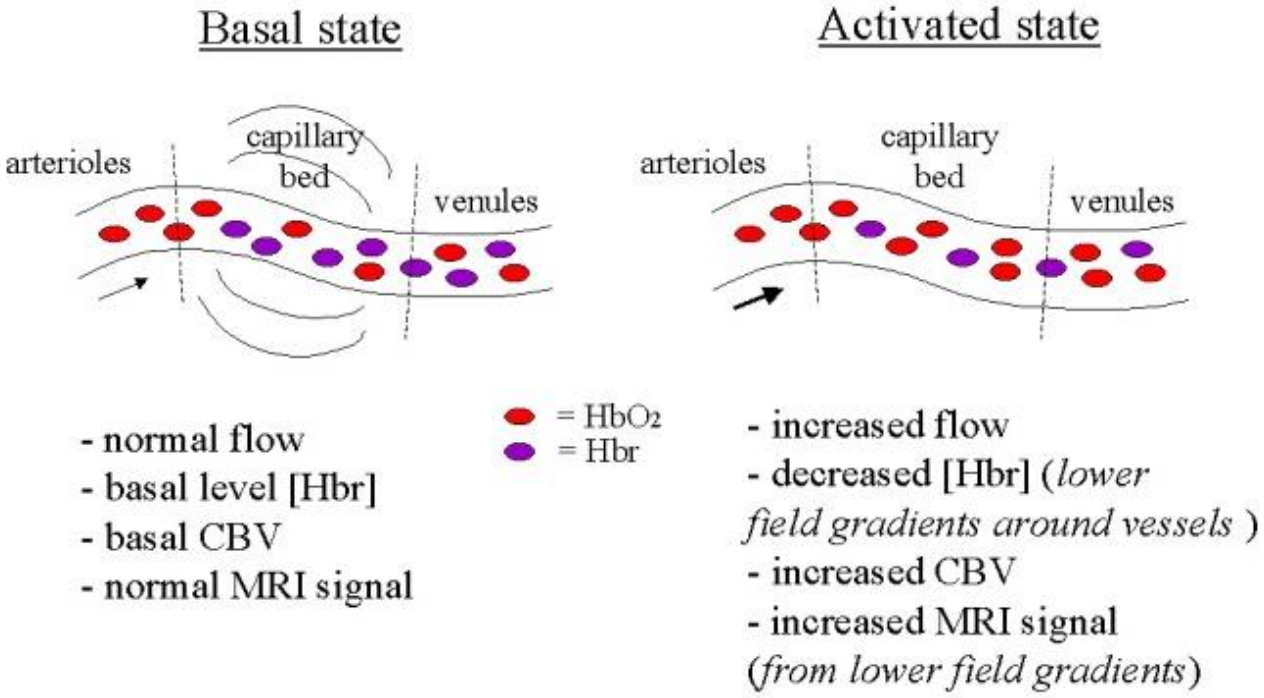
Hemodynamic Response

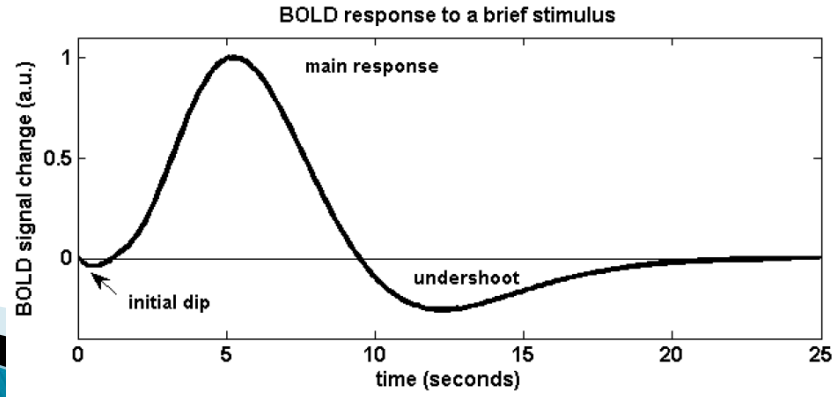
PHYSICS

MRI Contrast



BOLD Effect & HRF



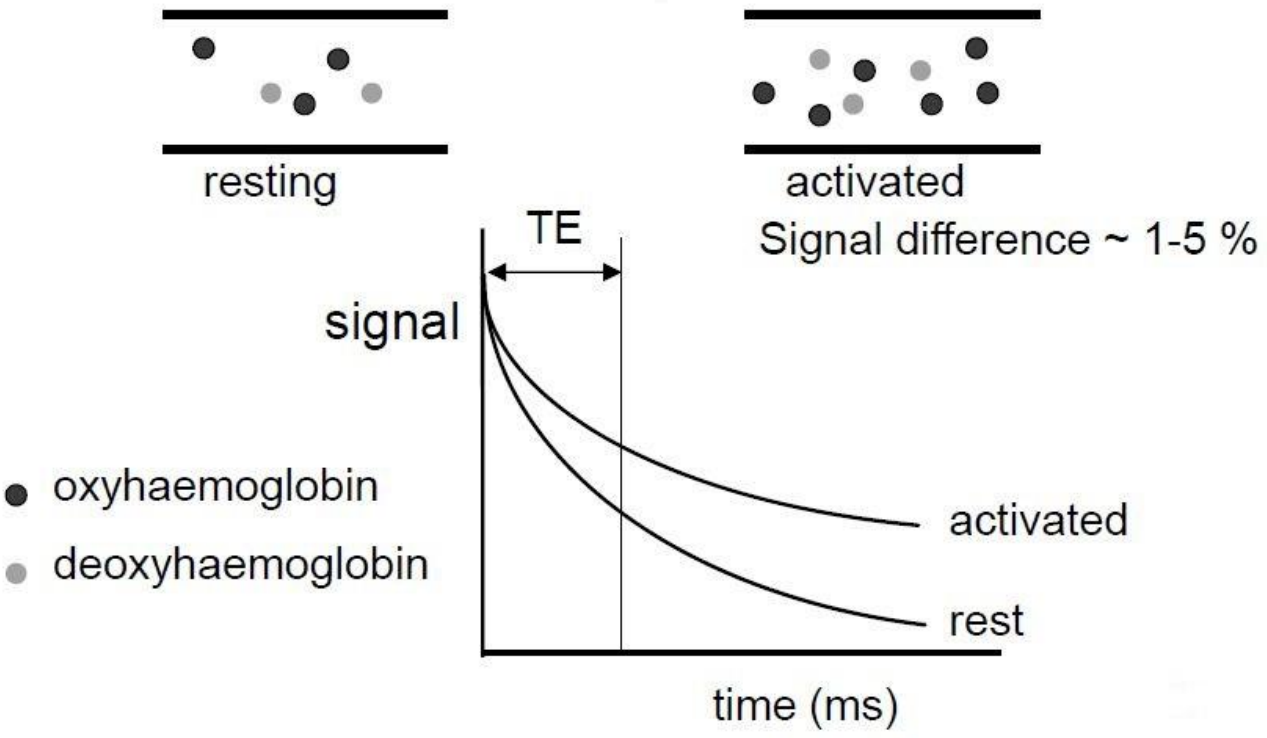


fMRI Contrast

field in-homogeneities

DeoxyHb paramagnetic

strong field inhomogeneities

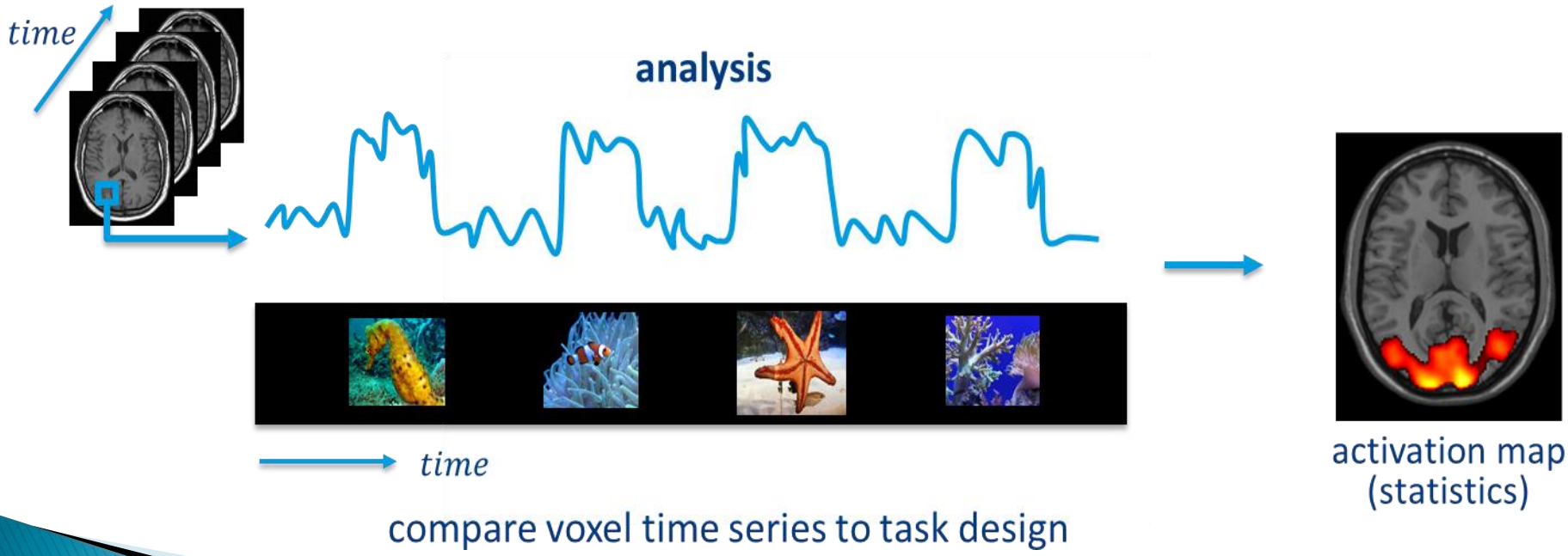


OxyHb diamagnetic

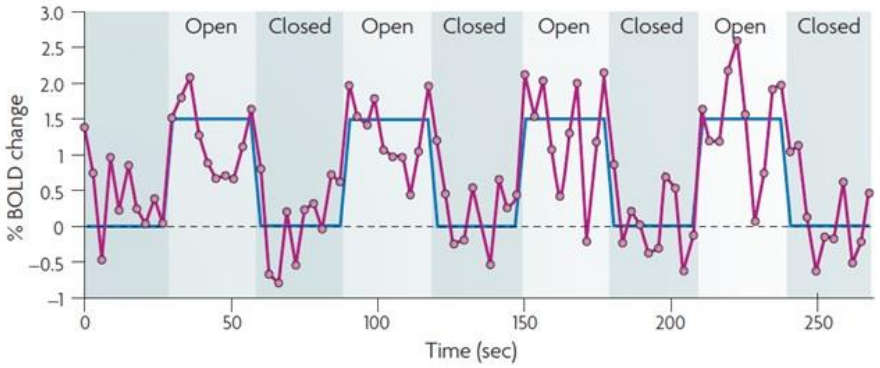
weak field inhomogeneities

fMRI Experiment

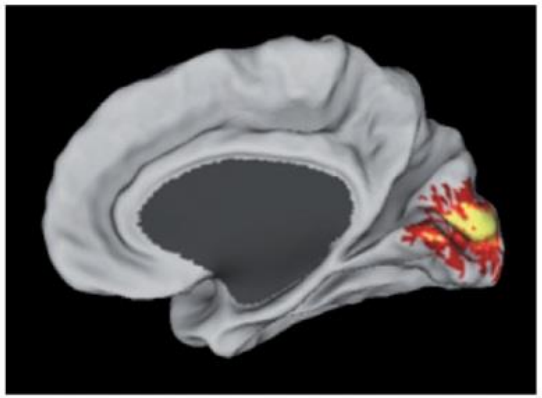
- An fMRI experiment consists of a sequence of individual MR images, where one can study oxygenation changes in the brain across time



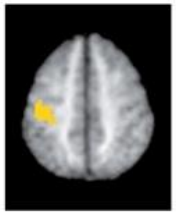
Traditional fMRI

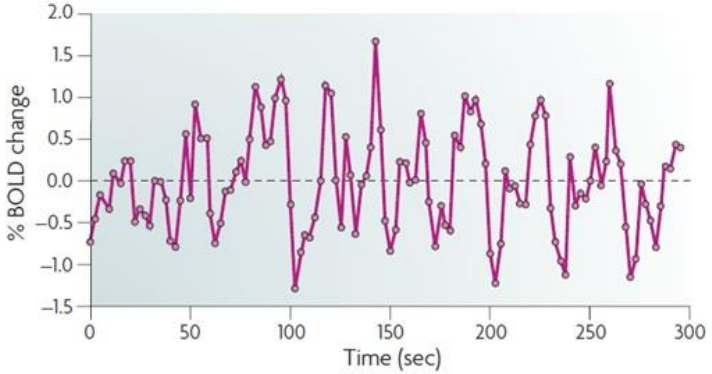


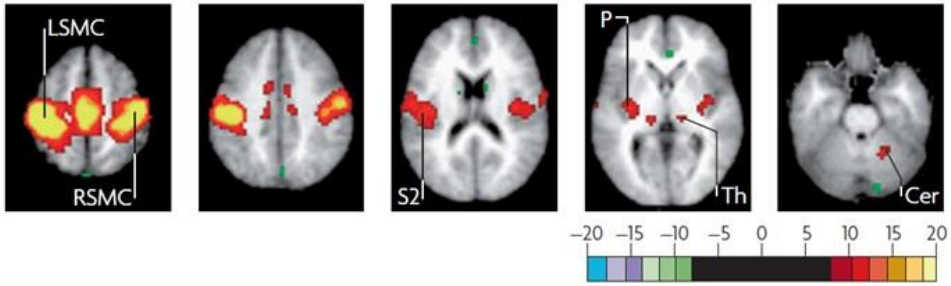
Open – Closed =



Resting fMRI

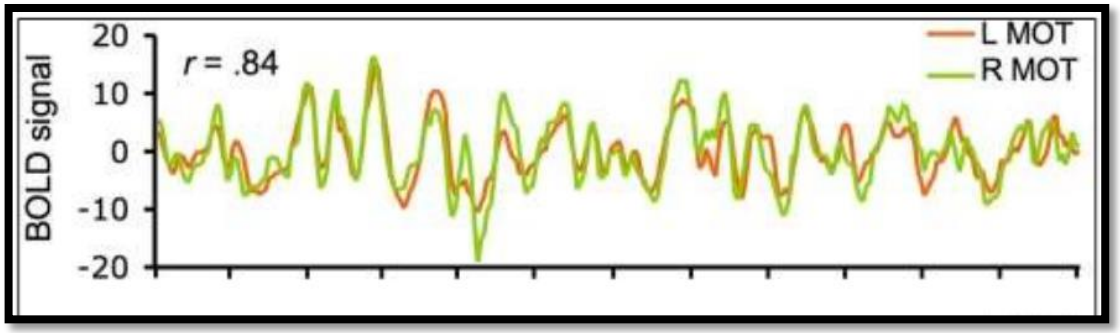






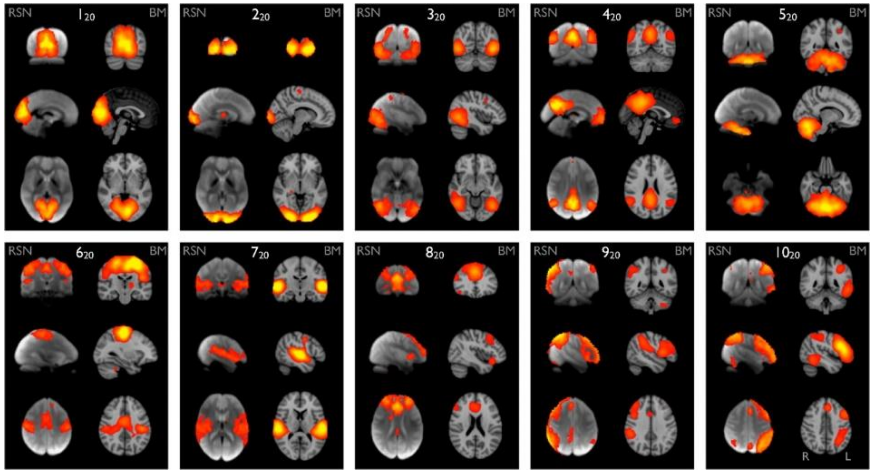
Fox, M. D. and Raichle, M. E. Spontaneous fluctuations in brain activity observed with functional magnetic resonance imaging. Nature Reviews Neuroscience 8(9), 700-711. 2007

Functional Connectivity: Spontaneous BOLD activity

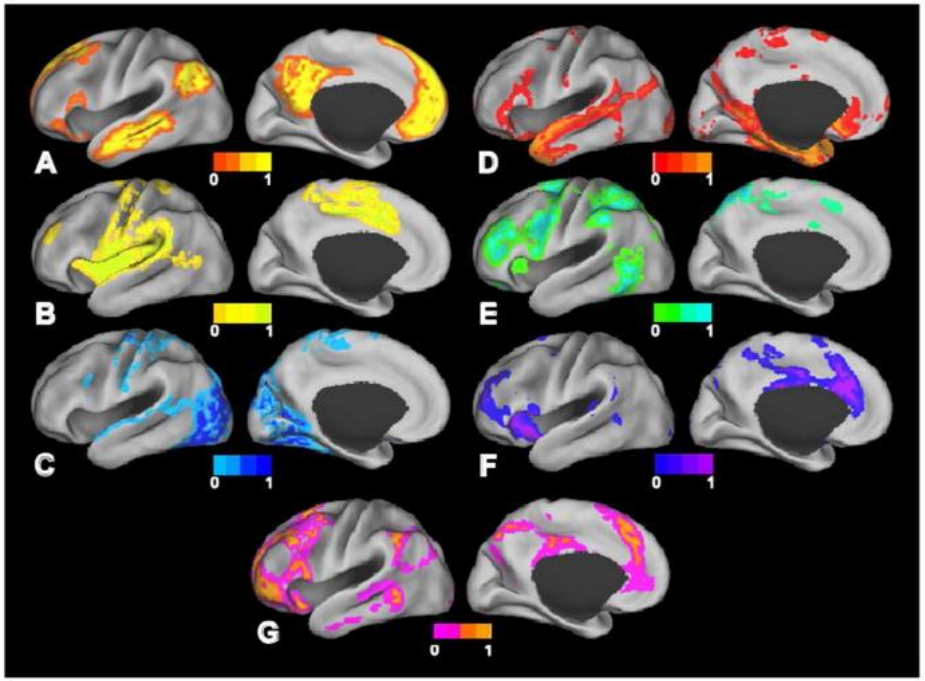


- Resting-state networks
  - correlation between spontaneous BOLD signals of brain regions known to be functionally related
- Neuroscientists are studying this spontaneous BOLD signal and its correlation between brain regions in order to learn about the intrinsic functional connectivity of the brain

Resting-state Networks



Smith's 10 RS-Networks

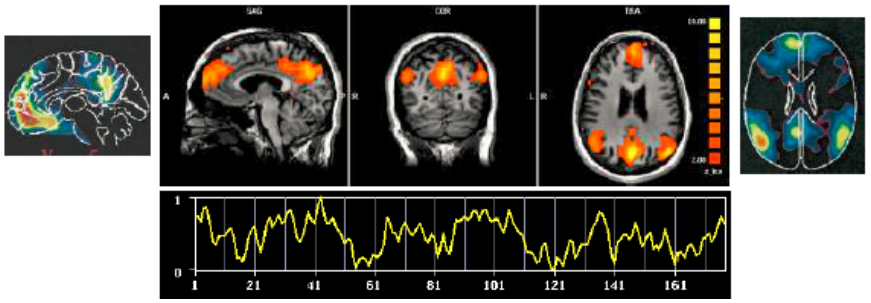


A) Default mode network, B) Somatomotor network, C) Visual network, D) Language network, E) Dorsal attention network, F) Ventral attention network, and G) Frontoparietal control network

DMN Network

Default mode network shows up in resting fMRI as areas with temporally correlated baseline activity, 0.01 Hz < frequency < 0.08 Hz

Two approaches: PCA/ICA and ROI

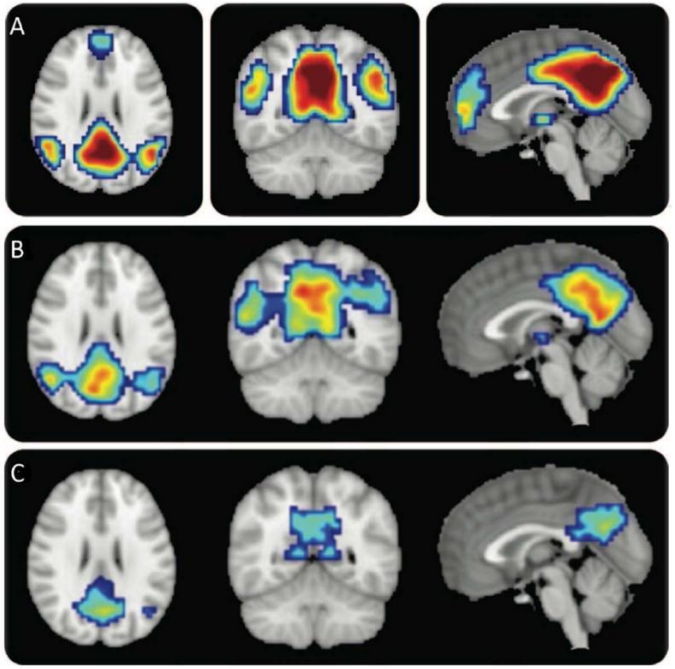


- For a longitudinal study, Goodness-of-fit to a DMN template based on the healthy controls was a significant predictor of future conversion to AD in subjects with MCI

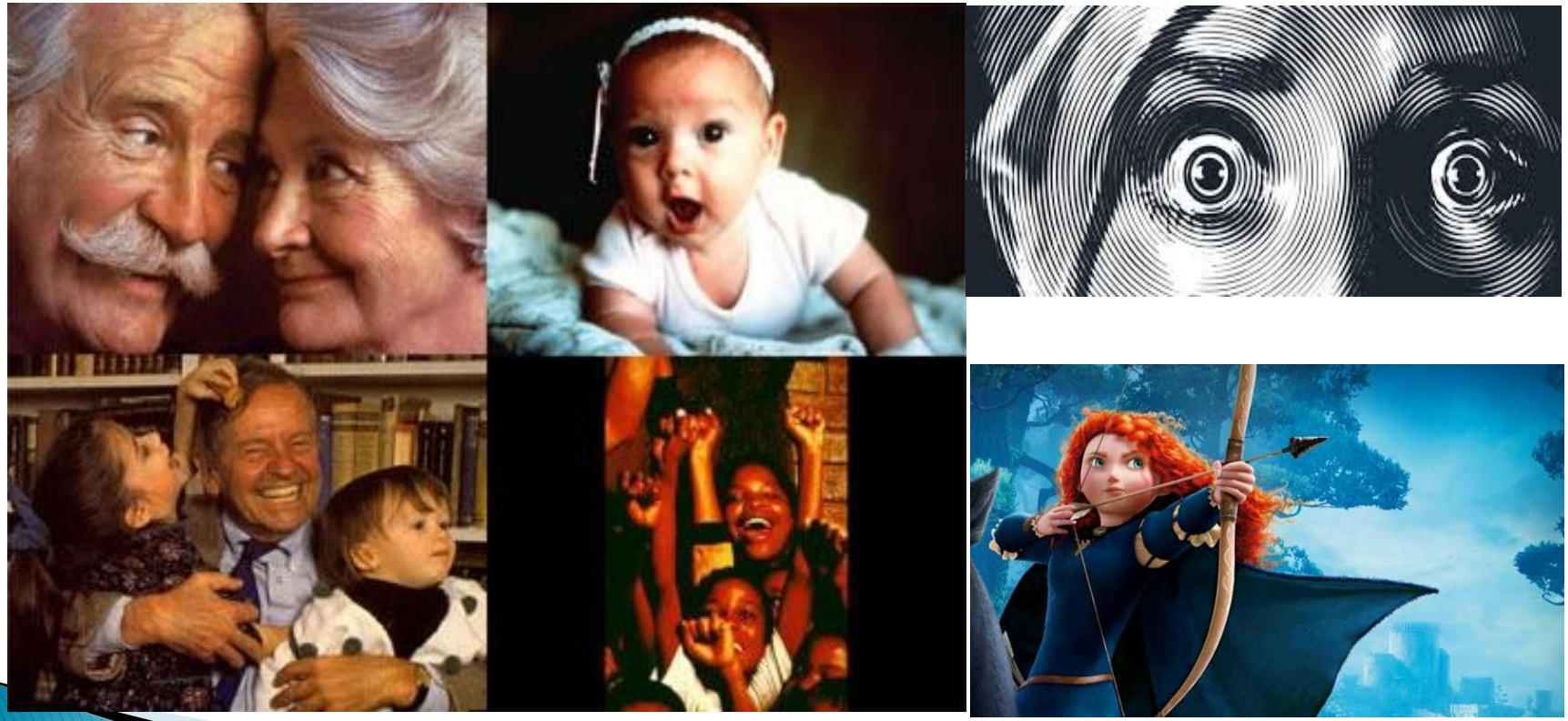
DMN Mask

MCI non-converters

MCI converters



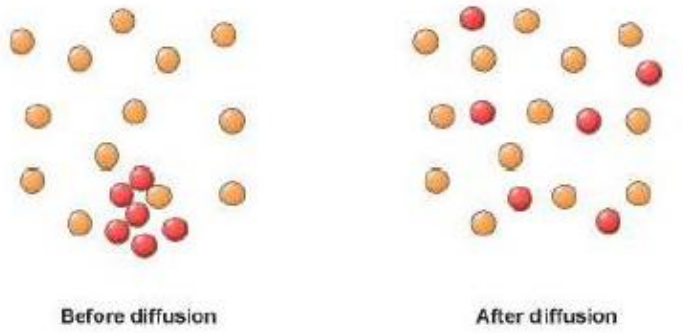
fMRI Investigation of Pro-Social Emotions

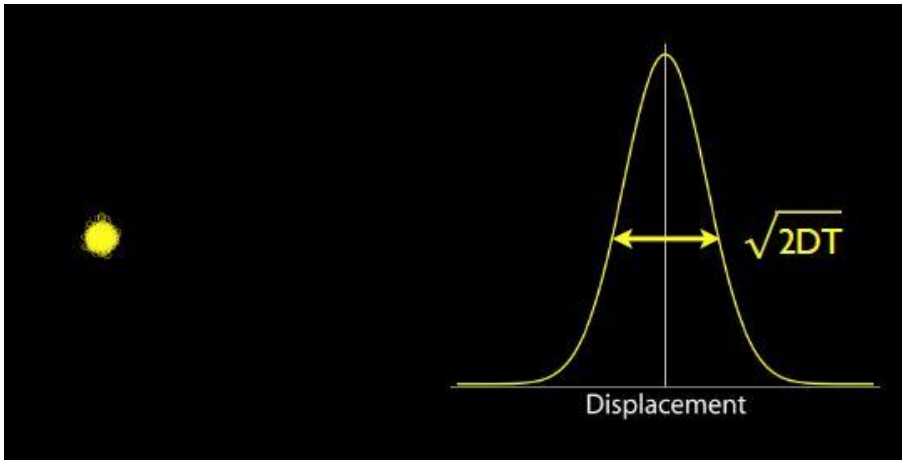


MR Diffusion Imaging

What is Diffusion?

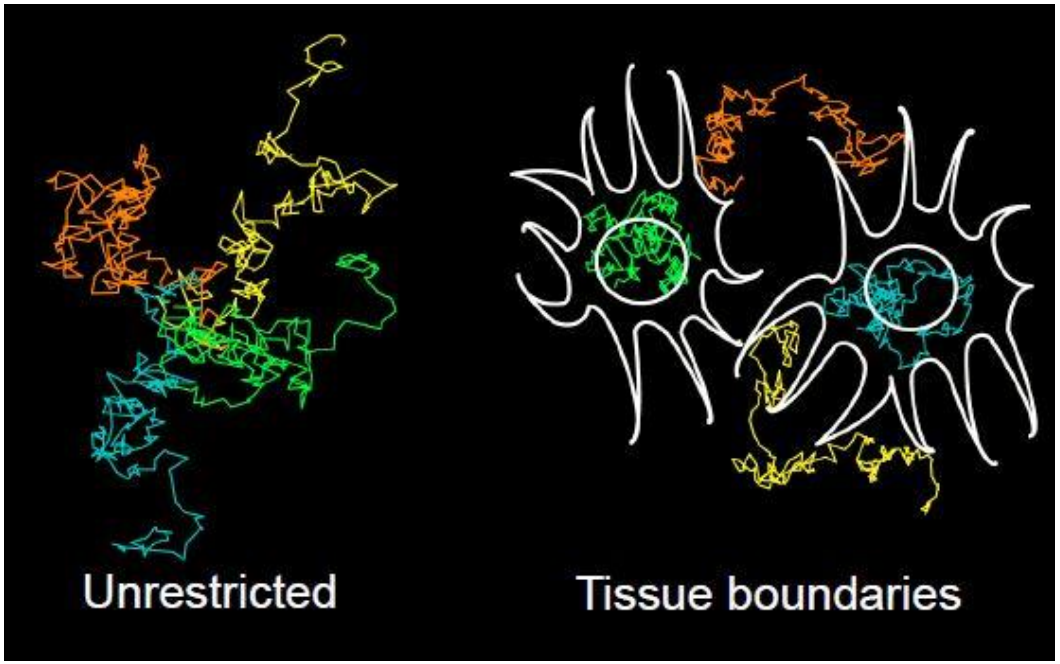
- Random motion of particles due to thermal energy
- water molecules collide and experience net displacement described by diffusion coefficient (D)
- Normally, diffusion is isotropic (equal in all directions)





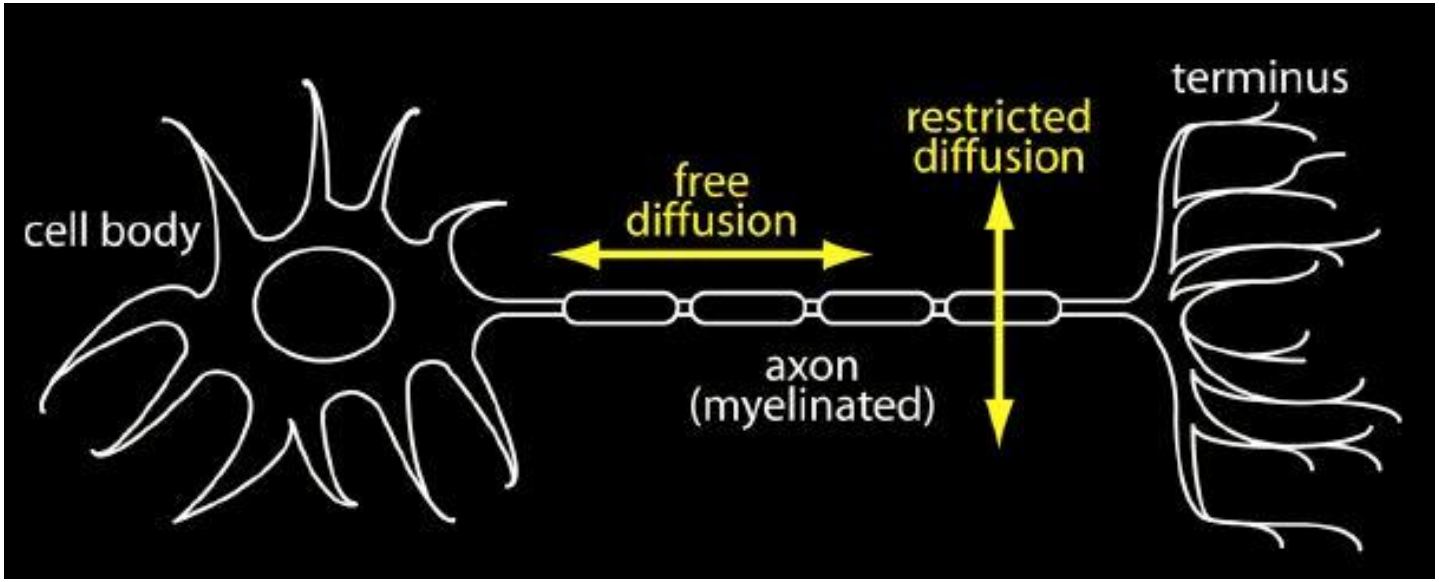
Why is diffusion interesting?

- Diffusion is restricted by tissue-boundaries, membranes...
- Diffusion is **EXTREMELY SENSITIVE** to differences and changes in **tissue microstructure**
  - Myelination/Demyelination
  - Axon damage/loss
  - Inflammation/Edema
  - Necrosis
- Marker for tissue structure (healthy and pathology)

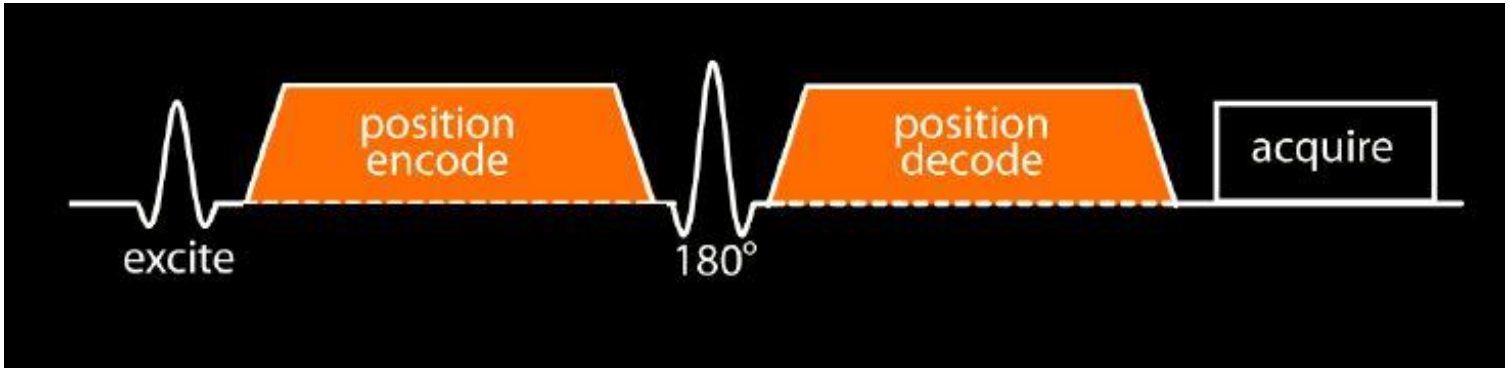


Diffusion anisotropy in white matter

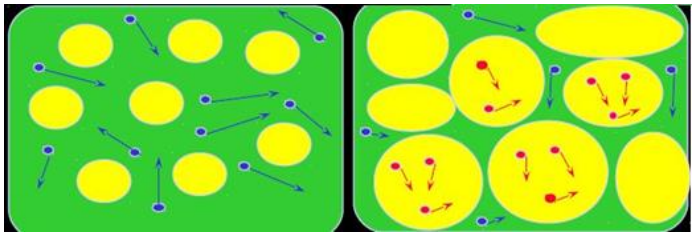
- Water can diffuse more freely along white-matter fibers than across them



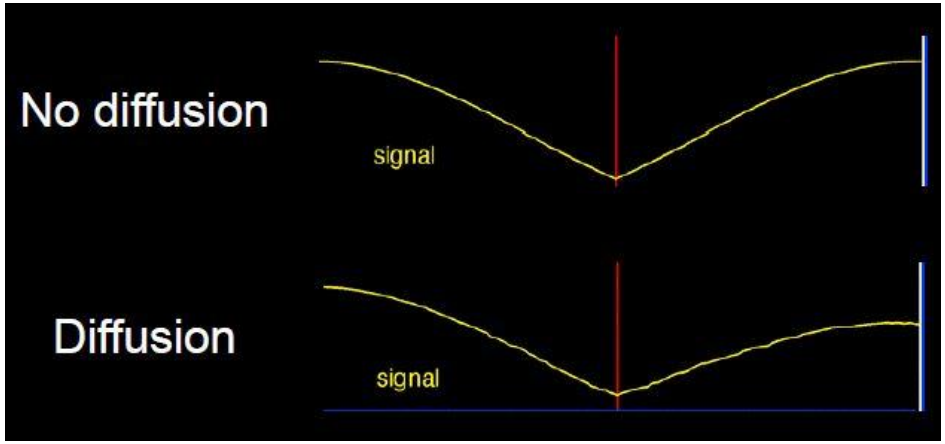
Contrast in DWI



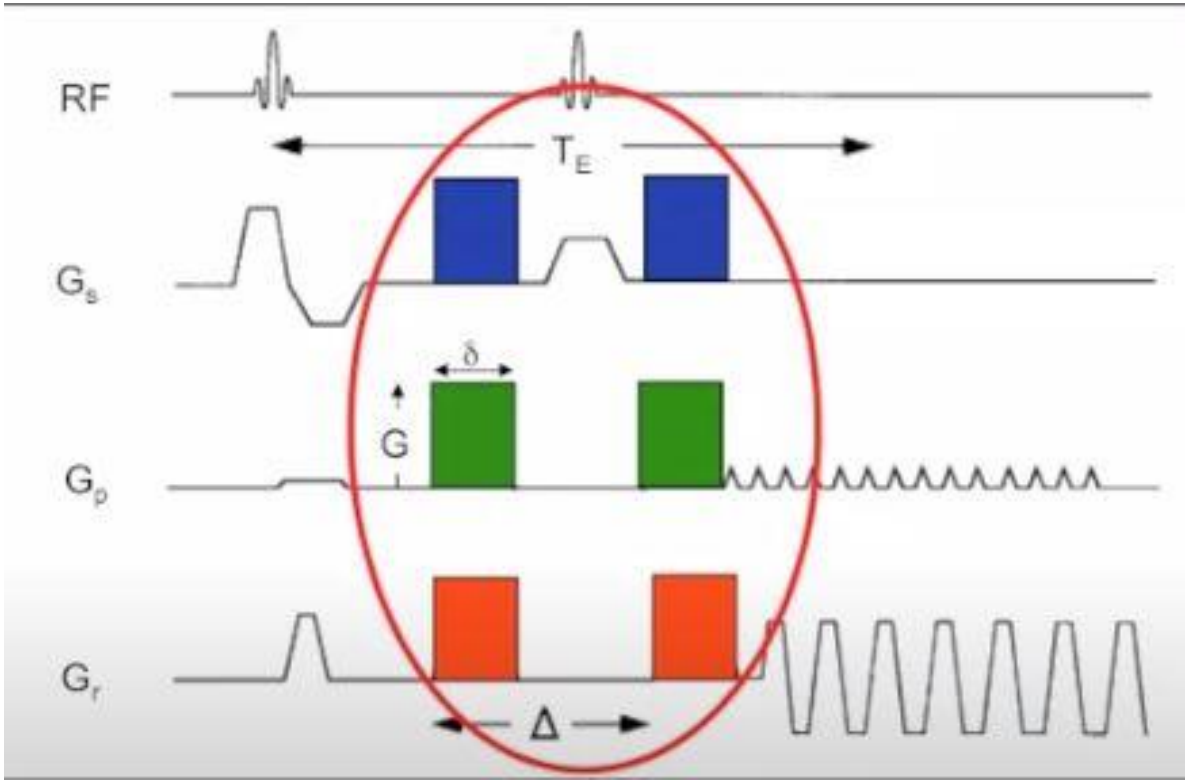
Diff No Diff



Freely Diffusing Water = Dark
Restricted Diffusion = Bright



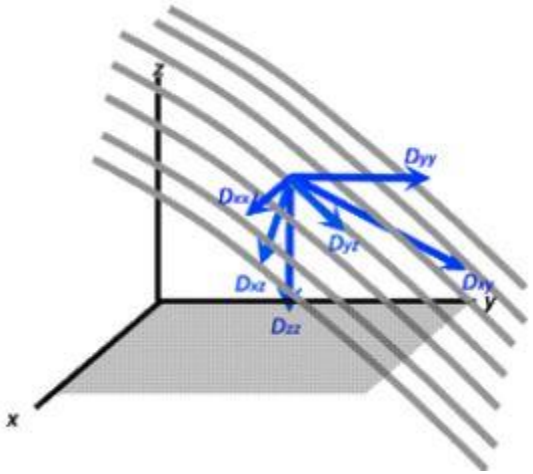
DWI Sequence

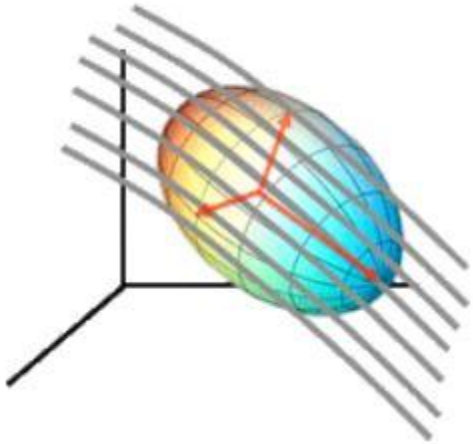


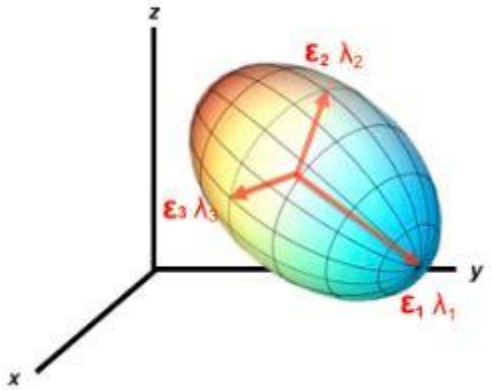
DWI vs DTI

- DWI can tell us about diffusion restriction but no information on the direction or magnitude of molecular movements.
- Diffusion tensor imaging (DTI) evaluates diffusion in multiple different directions (represented by vectors with magnitude & direction) to investigate micro-anatomical structure of brain.
- Each pixel of tissue is represented as a multidimensional diffusion vector mathematically that is known as a diffusion tensor.
- The diffusion tensor can be fully characterized by calculating its "eigenvalues"

Diffusion Tensor







$$\mathcal{D} = \begin{bmatrix} D_{xx} & D_{xy} & D_{xz} \\ D_{yx} & D_{yy} & D_{yz} \\ D_{zx} & D_{zy} & D_{zz} \end{bmatrix}$$

Eigen-Values

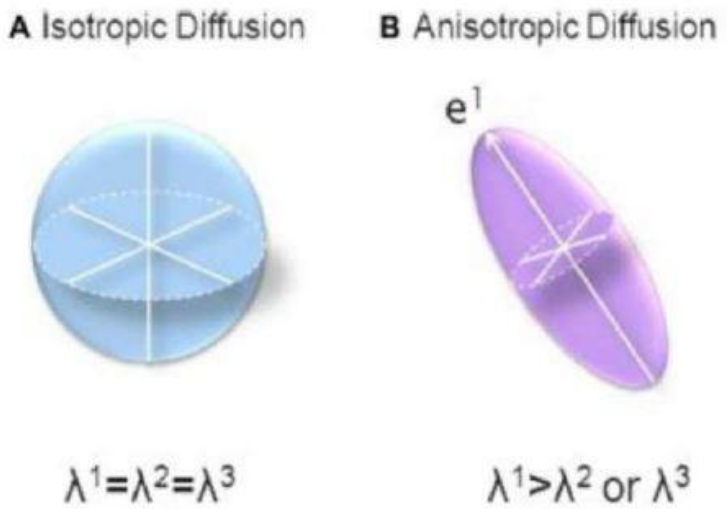
$$\Lambda = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \lambda_2 & 0 \\ 0 & 0 & \lambda_3 \end{bmatrix}$$

Diffusion Tensor

Diffusion along a group of fiber tracts. In the frame of reference (x-y-z) we measure diffusion coefficients in 6 unique directional combinations

Diffusion Tensor

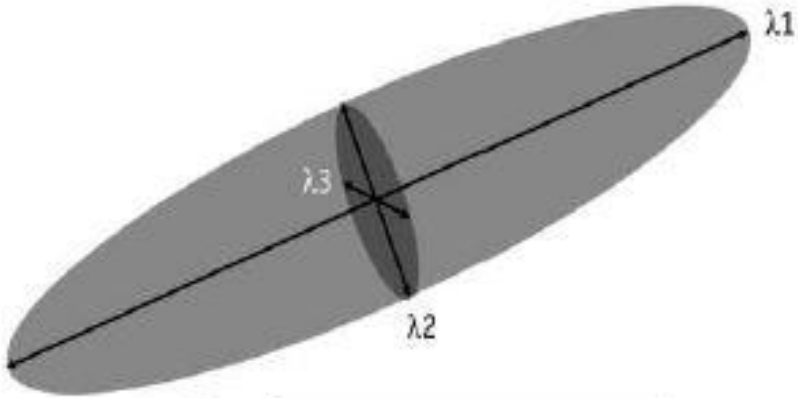
- In cerebrospinal fluid, the diffusion of protons is unrestricted in all directions, and therefore isotropic.
- In highly organized biological tissue, diffusion often is restricted in some directions or anisotropic. And represented by an elongated ellipsoid tensor



DTI

- From the eigenvalues, the mean diffusivity (MD), is calculated.
- Most commonly used measure for diffusion anisotropy is fractional anisotropy (FA), which is calculated from the eigenvalues and gives a normalized value to the tensor's degree of anisotropy (0 is completely isotropic and 1 is completely anisotropic).
- Average of the eigenvalues, it describes the overall size of the tensor and as such represents a invariant ADC measure.

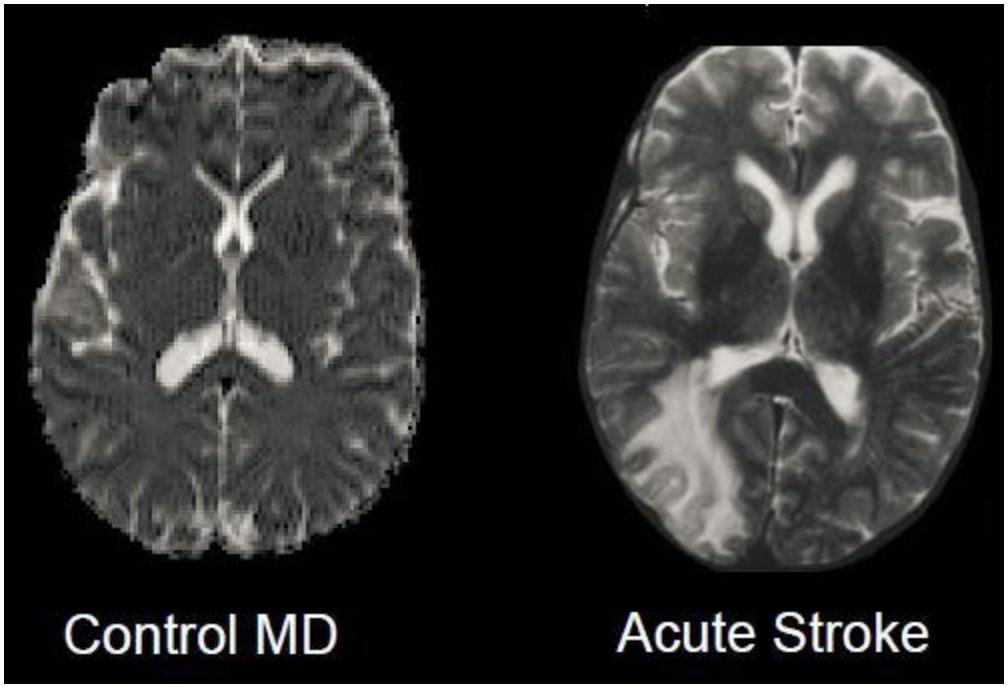
$$MD = \frac{\lambda_1 + \lambda_2 + \lambda_3}{3}$$



$$FA = \sqrt{\frac{1}{2}} \frac{\sqrt{(\lambda_1 - \lambda_2)^2 + (\lambda_2 - \lambda_3)^2 + (\lambda_3 - \lambda_1)^2}}{\sqrt{\lambda_1^2 + \lambda_2^2 + \lambda_3^2}}$$

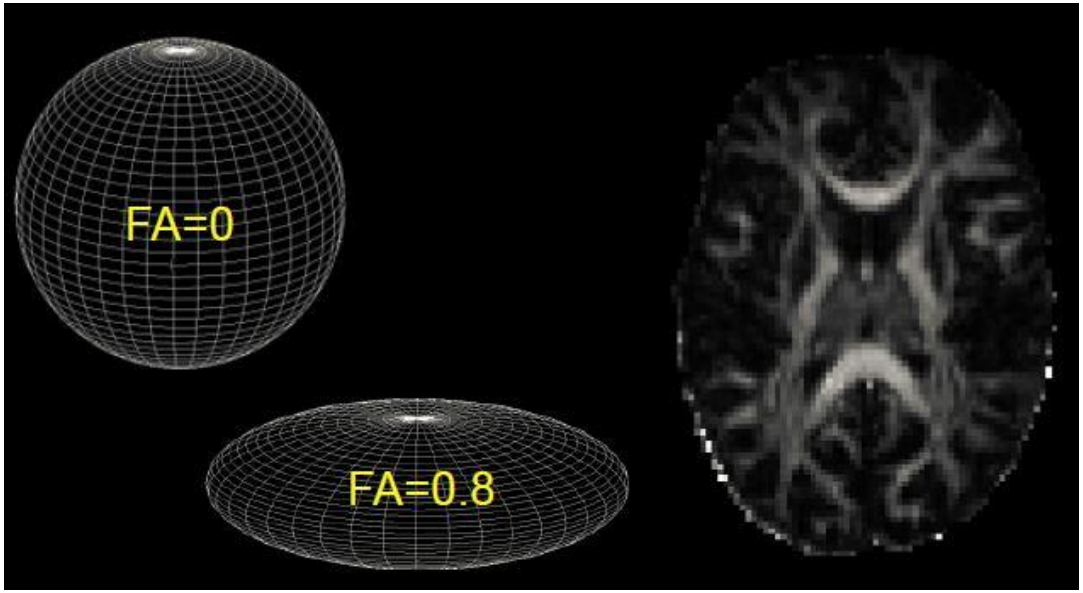
Mean diffusivity (MD)

- Mean diffusion coefficient across all directions
- Correlate of tissue integrity (white and gray matter)
- Example: MD is altered in acute and chronic stroke



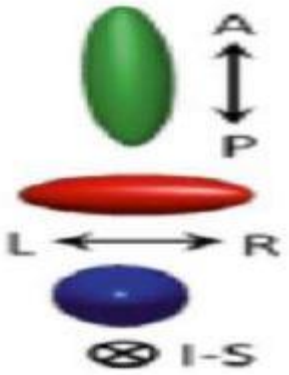
Fractional Anisotropy (FA)

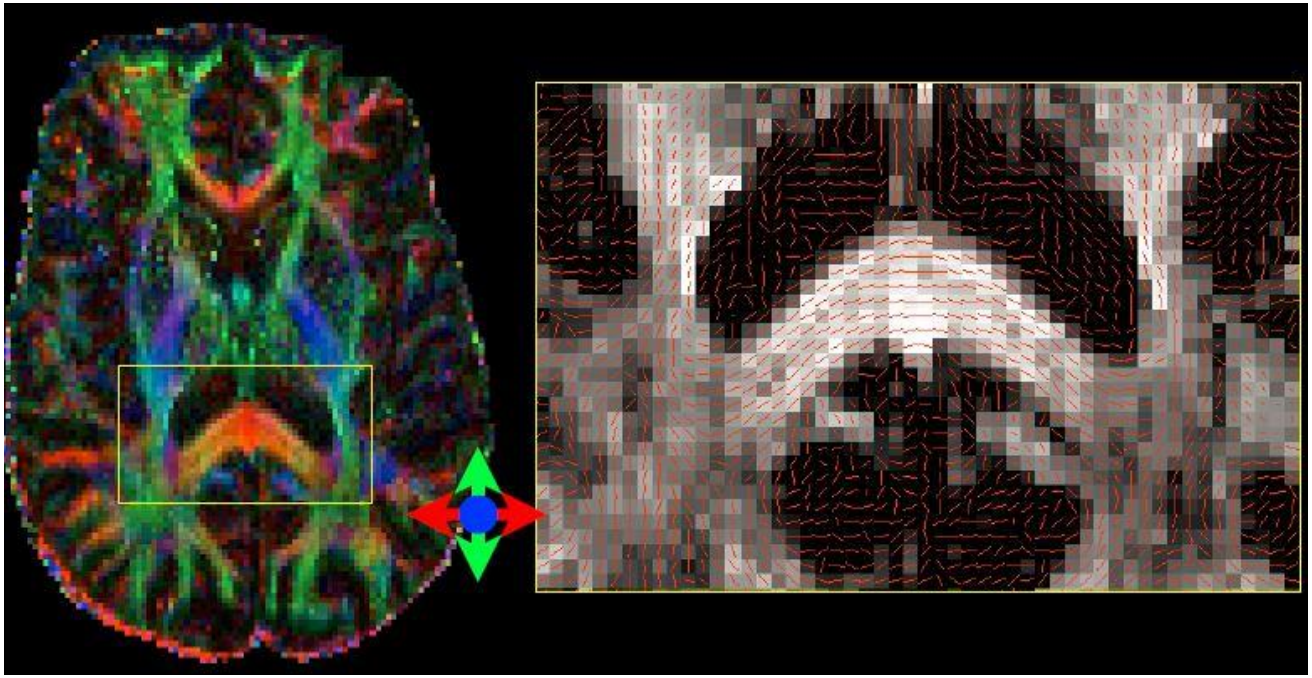
- How elongated is the ellipsoid?
  - Variance of diffusion coefficient across different directions.
- High in regions where diffusion is most directional
- Relates to integrity of white matter fiber bundles



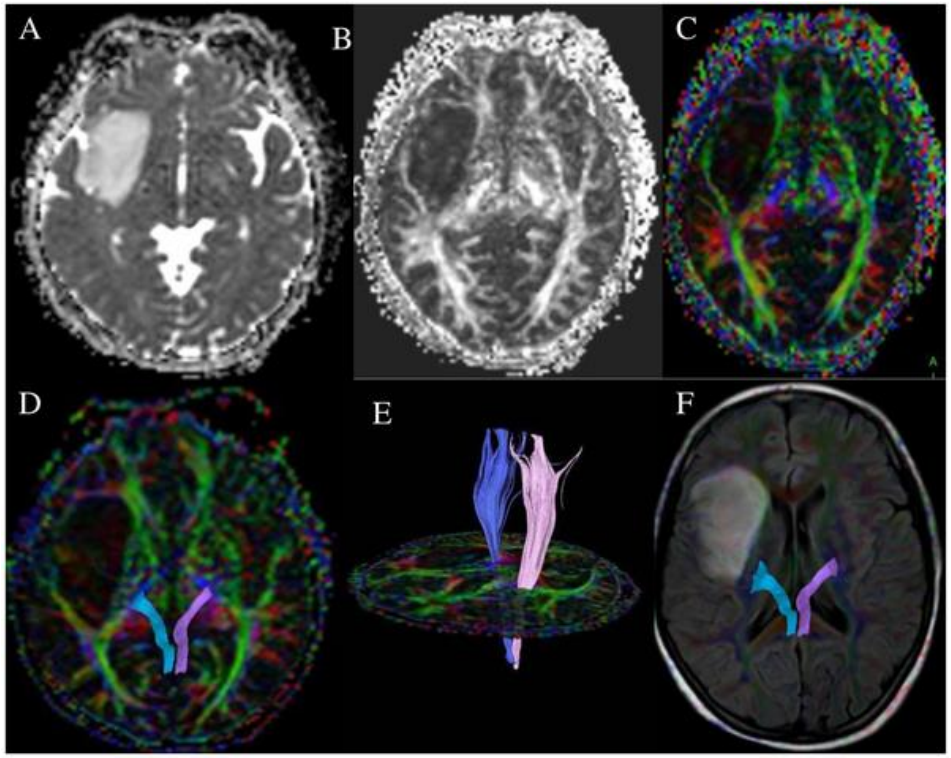
Principal diffusion direction (PDD)

- what direction is greatest diffusion along?
  - Direction along which greatest diffusion occurs.
- Relates to direction of fiber orientations.

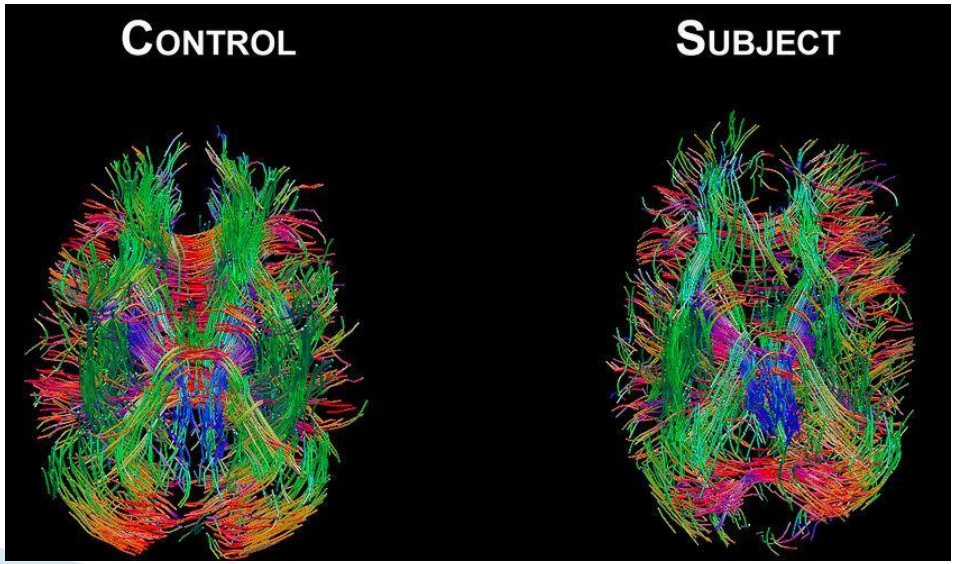




DTI Preoperative study



DTI Tractography of Injured brain vs Control



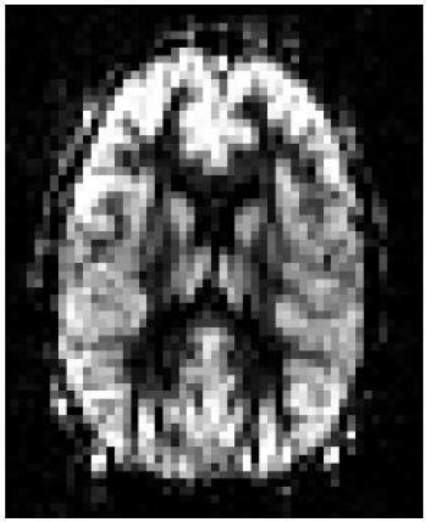
MR Perfusion Imaging

Perfusion

- Definition: Perfusion is the delivery of nutrients (such as oxygen) by the vascular system to the tissue.
- Perfusion, in physiological term, is traditional measured as a rate (1/T).
- It shows for example the total amount of blood delivery to the brain per unit of time divided by the weight of the brain (ml/min/100g).
- For the brain, the measure is called Cerebral blood flow (CBF)

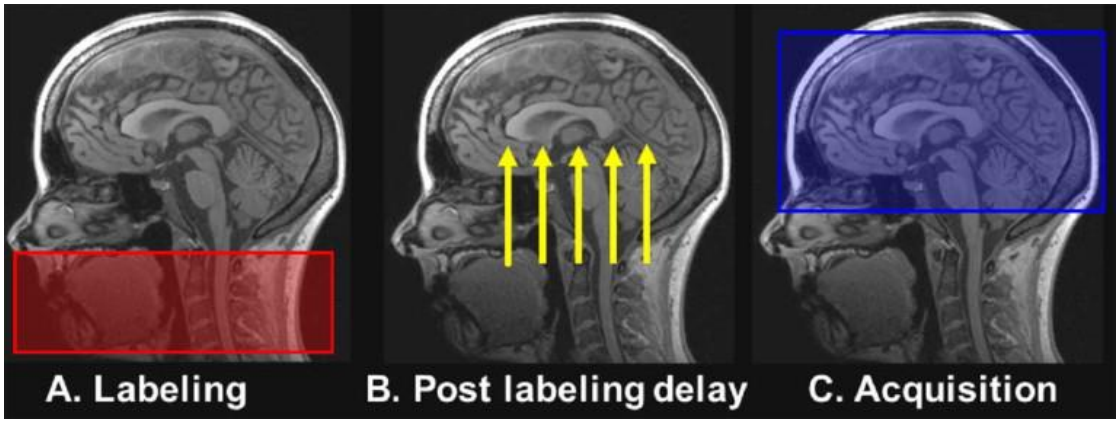
Why perfusion is interesting?

- All organs are critically dependent on blood supply.
- Default in blood supply results in ischemia or the lack of oxygenation to the organ
- Alternatively, a default in energy metabolism will be mirrored by lower perfusion.
- Perfusion is a measurement of delivery of blood to capillary bed
  - Related to nutrient delivery to cells.
  - Altered by task activity.
  - Changes in disease.
- To imaging the perfusion, we need a tracer!
  - ASL uses blood-water as a tracer.



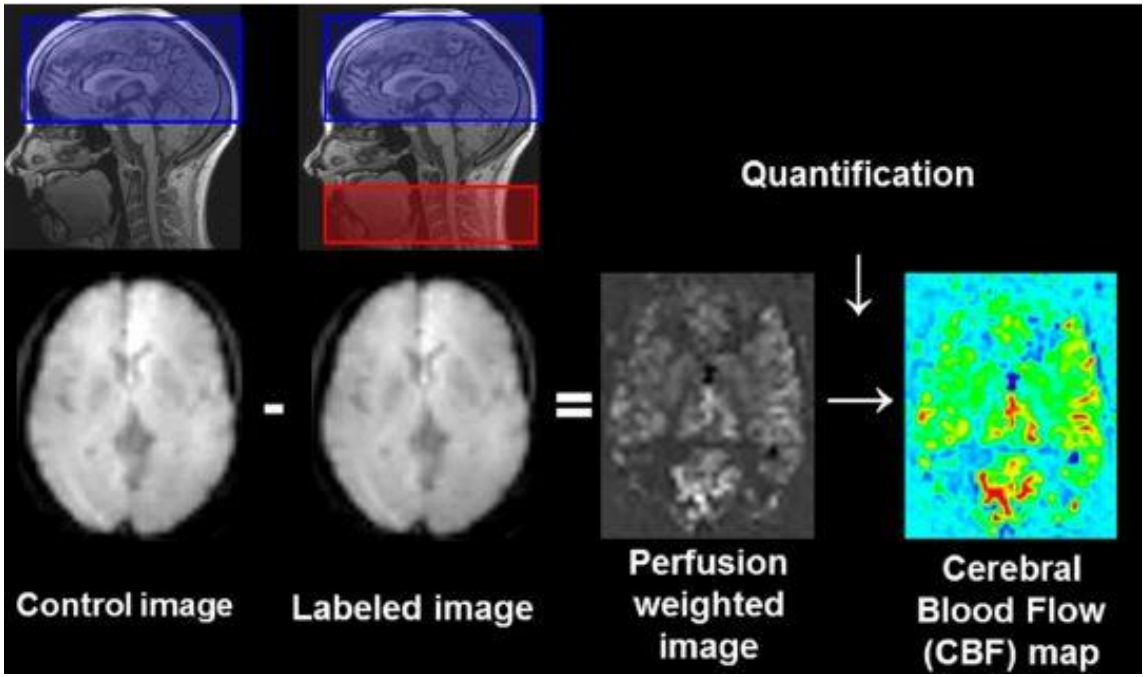
Arterial Spin Labeling (ASL)

- Arterial spin labelling (ASL) is an alternative technique of performing MR perfusion **without the use of contrast agent**.
- This technique utilizes arterial water as an internal diffusible tracer which is usually achieved by Magnetically labelling incoming blood
  - No injections or chemicals
  - No radiation
  - Absolute value



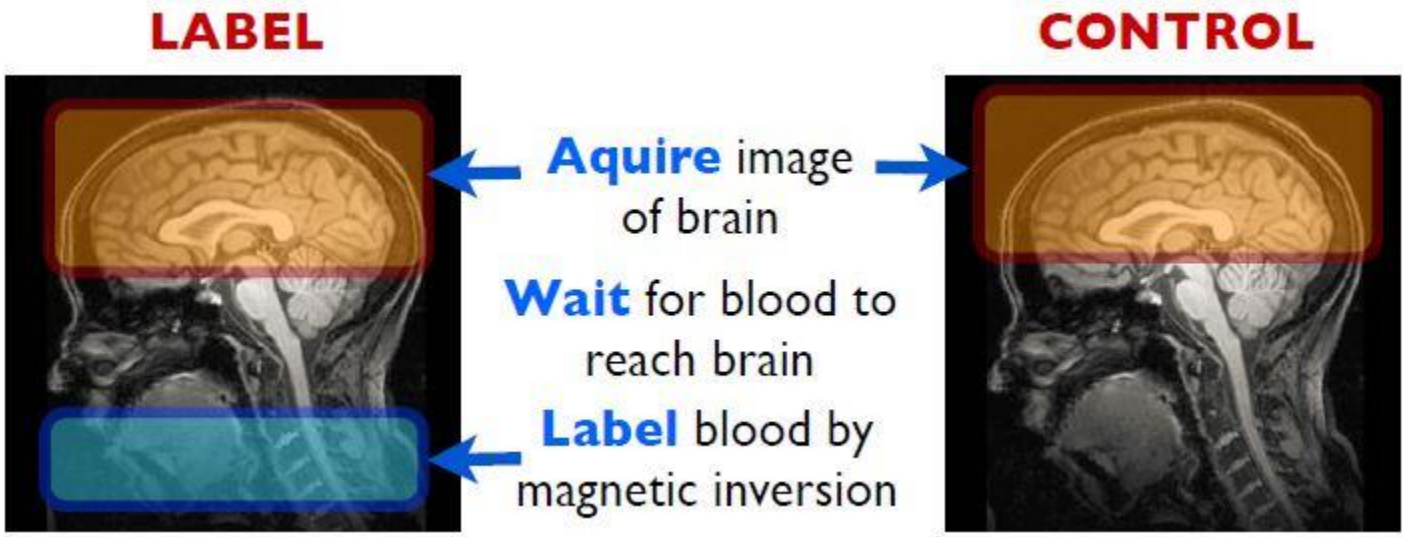
ASL Acquisition

- What should I do?
  ➞Label-control subtraction
- The Static tissue are identical in both images but the magnetization of inflowing blood is different because of "Labelling"
- The final subtracted image is thus *perfusion-weighted!*

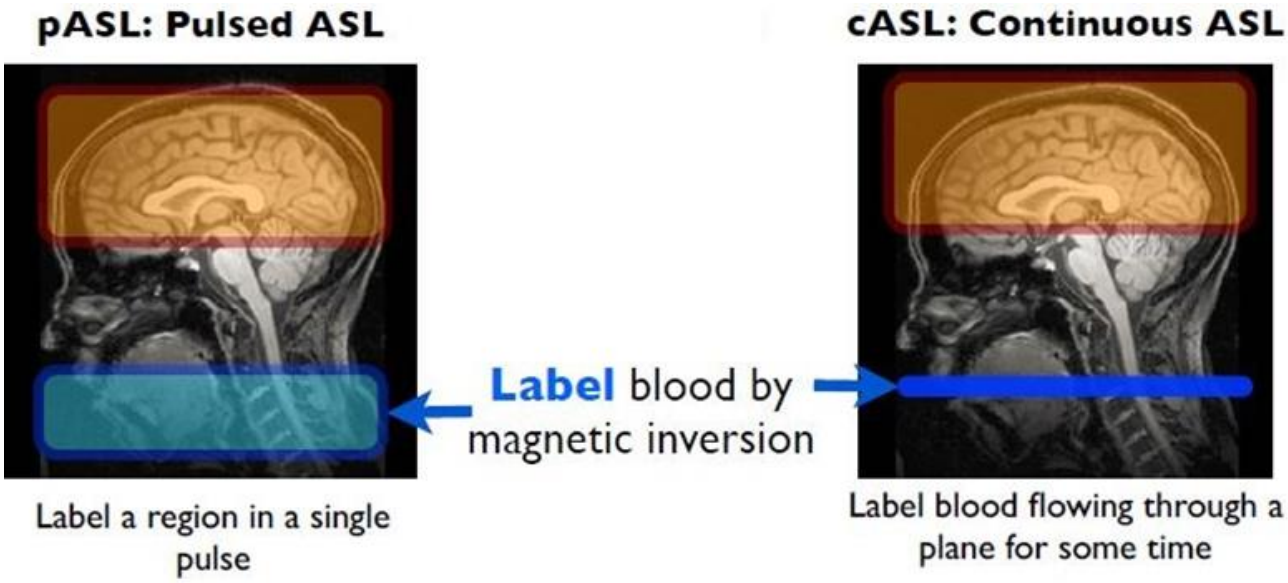


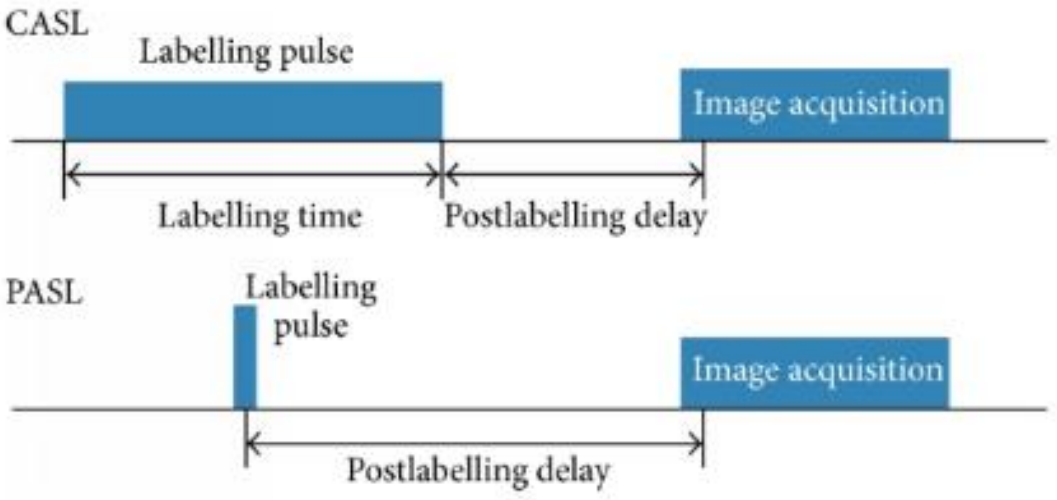
ASL Acquisition

- A tracer experiment with an endogenous tracer: blood water.

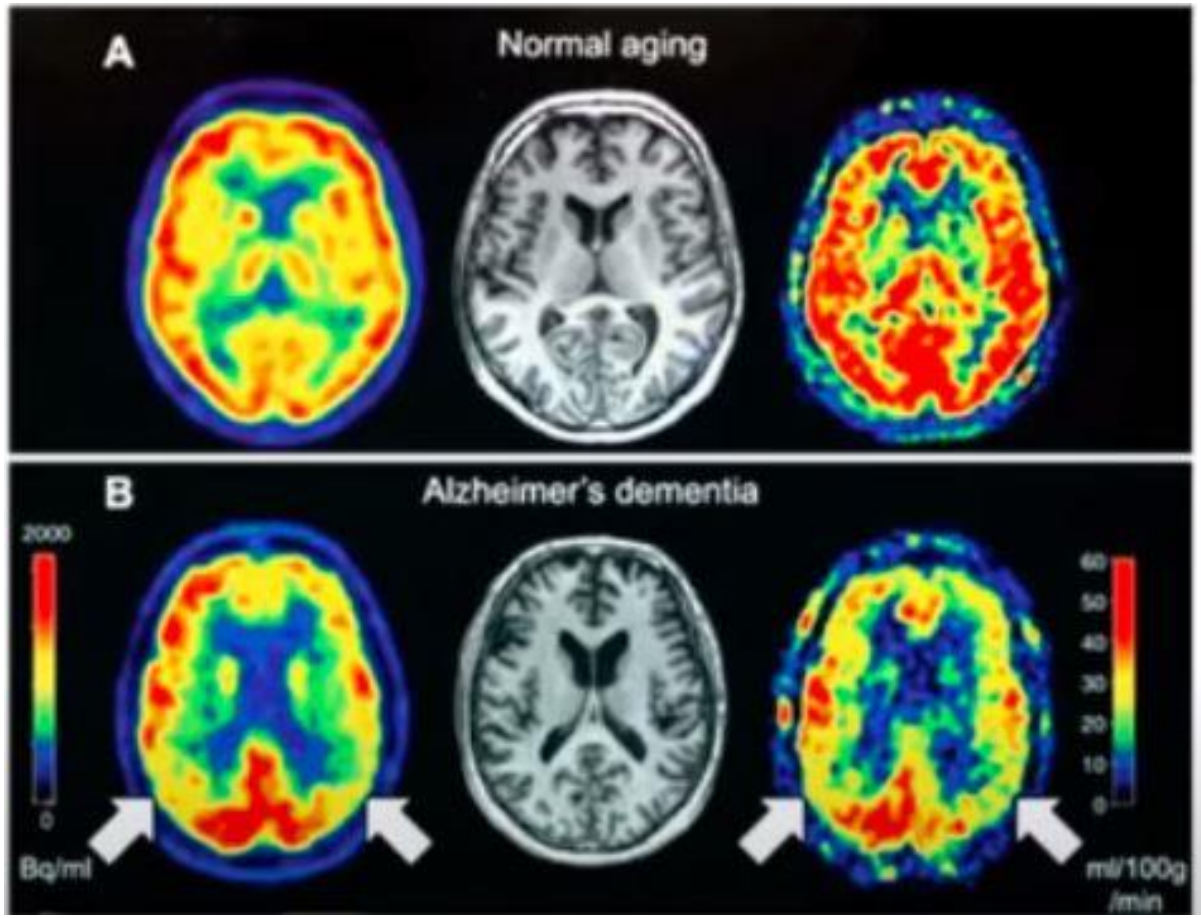


ASL Sequences (PASL & CASL)



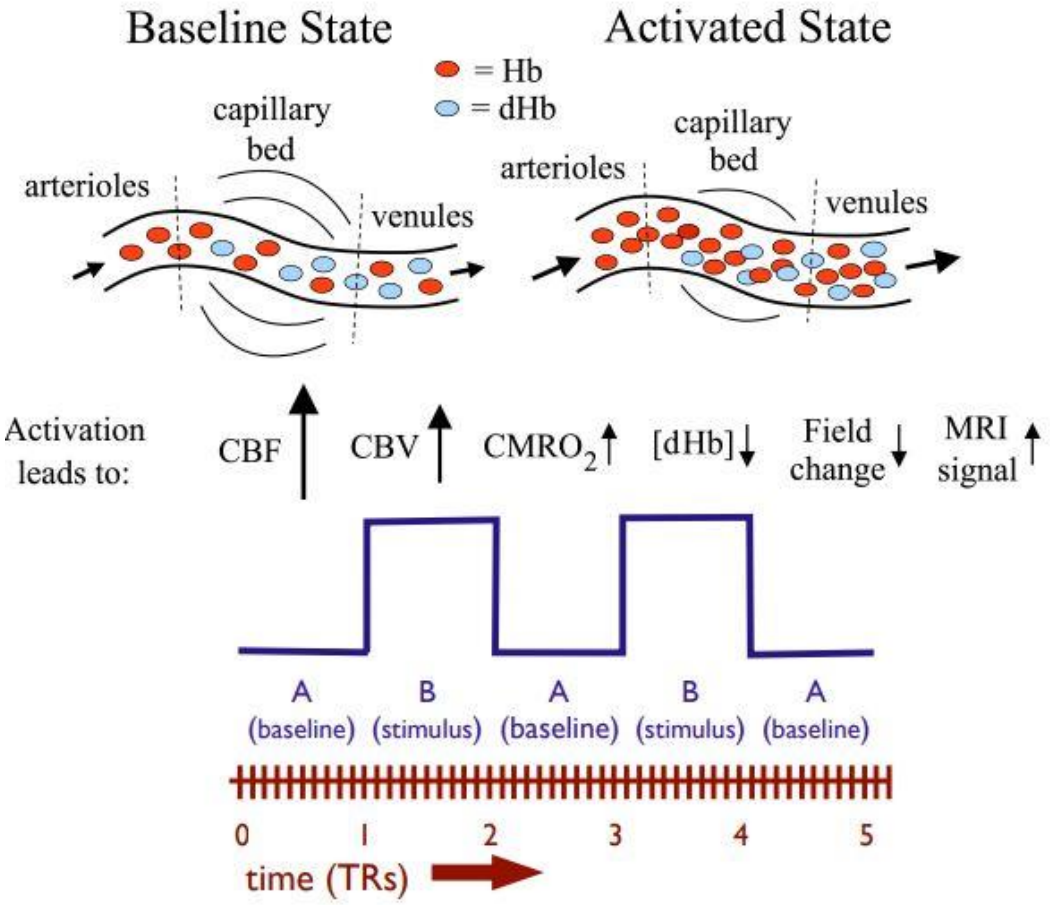


Example: ASL Application



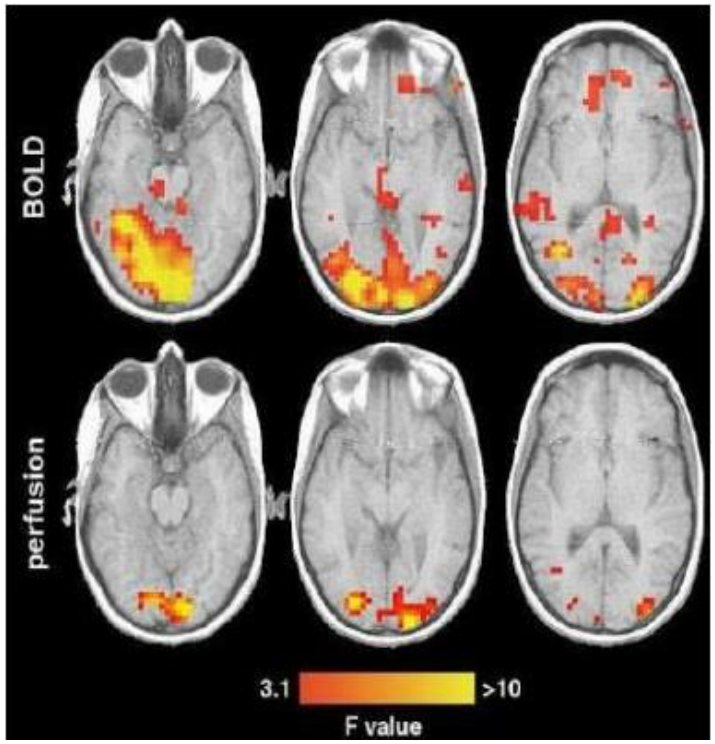
ASL for fMRI

- ASL is not BOLD!
  - CBF change is a component of the BOLD signal.
  - ASL can make absolute measurements under different conditions.
  - ‘Rest’ and ‘task’ don’t even need to be in the same session.



ASL versus BOLD fMRI

- Measuring CBF instead of oxygenation level!
- Absolute value compared to relative BOLD measures.
- Changes in perfusion are more localized, whereas BOLD changes are tied to the veins and venules.
- Lower SNR & It does take longer to collect a single ASL image.
- We get less slices at a time with ASL, and they tend to be thicker.



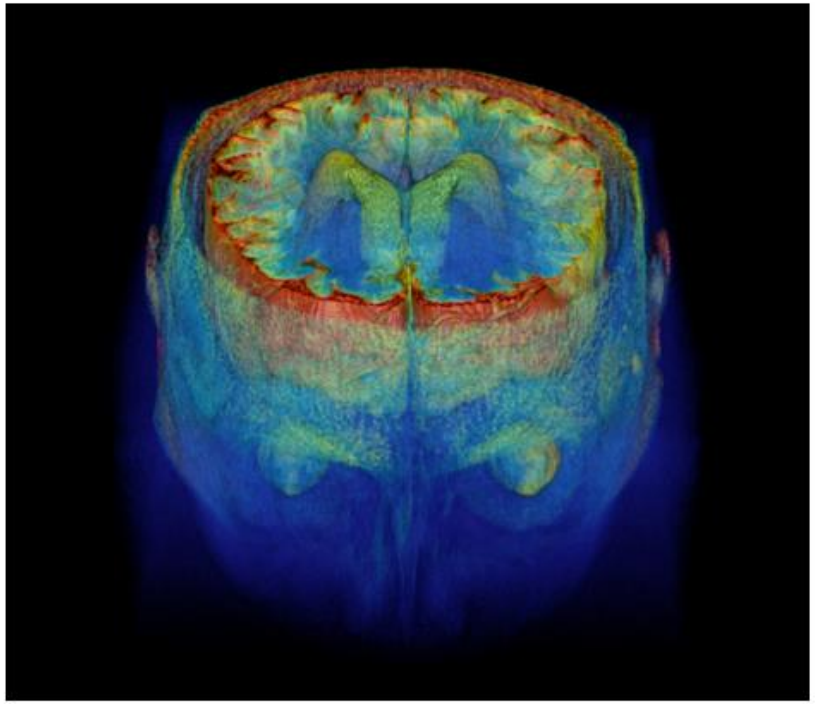
MRI Brain Mapping & Connectome Project

- Structural MRI
- Resting-state fMRI
- DTI Tractography

CONNECTOME
COORDINATION FACILITY

NY Times articles provide an "inside-the-scanner" look at HCP

Author: Jenn Elam
Published: Jan 06, 2014
Study: HCP Young Adult



A journey of a thousand miles must begin with a single step.

Lao Zi

Thank you …