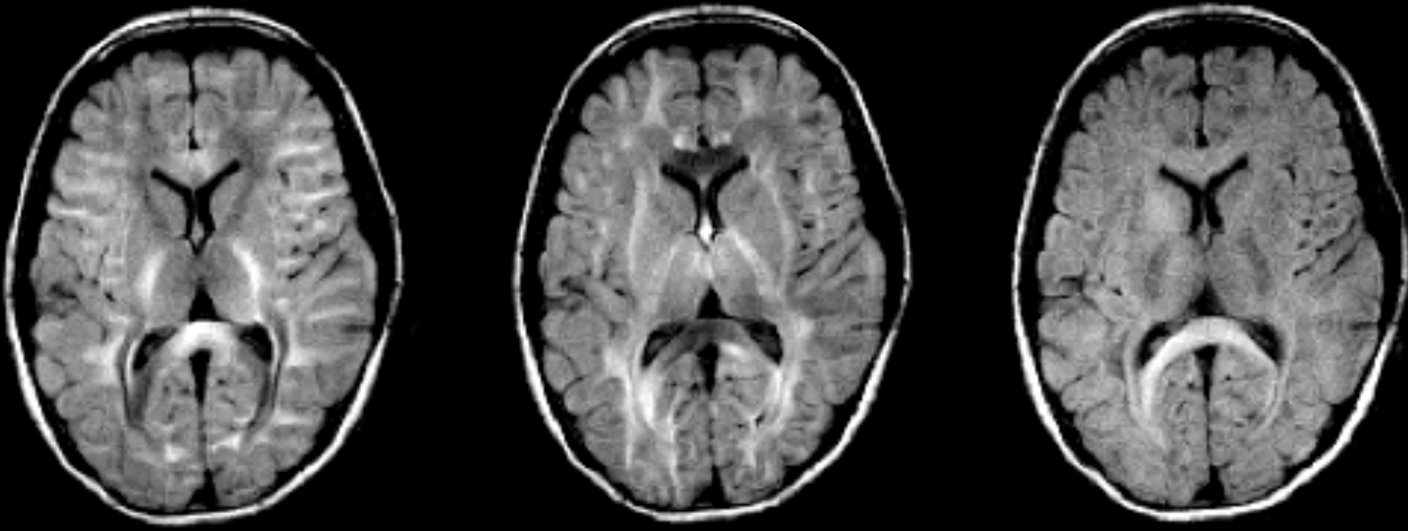


Diffusion Weighted Contrast

FSL Course, 2012 - Bristol, UK
Sean Foxley, FMRIB

MRI Physics

- ★ MRI physics recap
- ★ Pulse sequences
  - ✦ Gradient vs. spin echo
- ★ Diffusion MRI
  - ✦ Isotropic and anisotropic diffusion
  - ✦ Useful quantities derived from the tensor

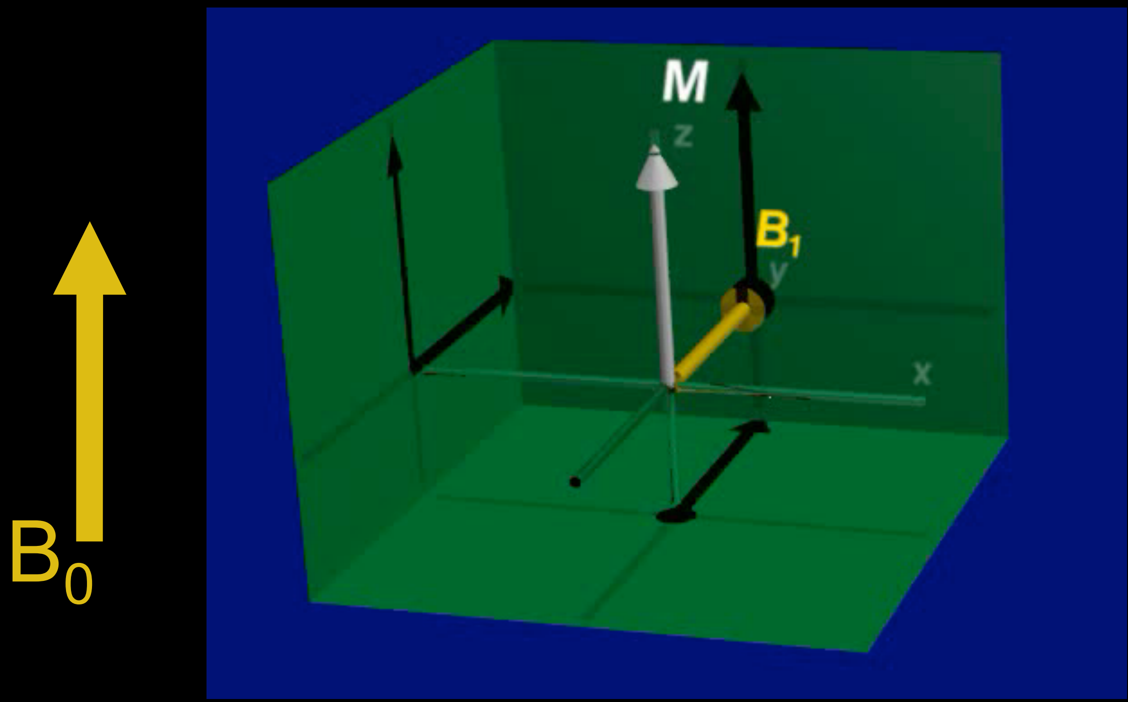
Excitation

courtesy of William Overall

$$\omega = \gamma B$$

In a frame that rotates with B_1, magnetization is simply “flipped” out of alignment with B_0

Excitation



courtesy of William Overall

$$\omega = \gamma B$$

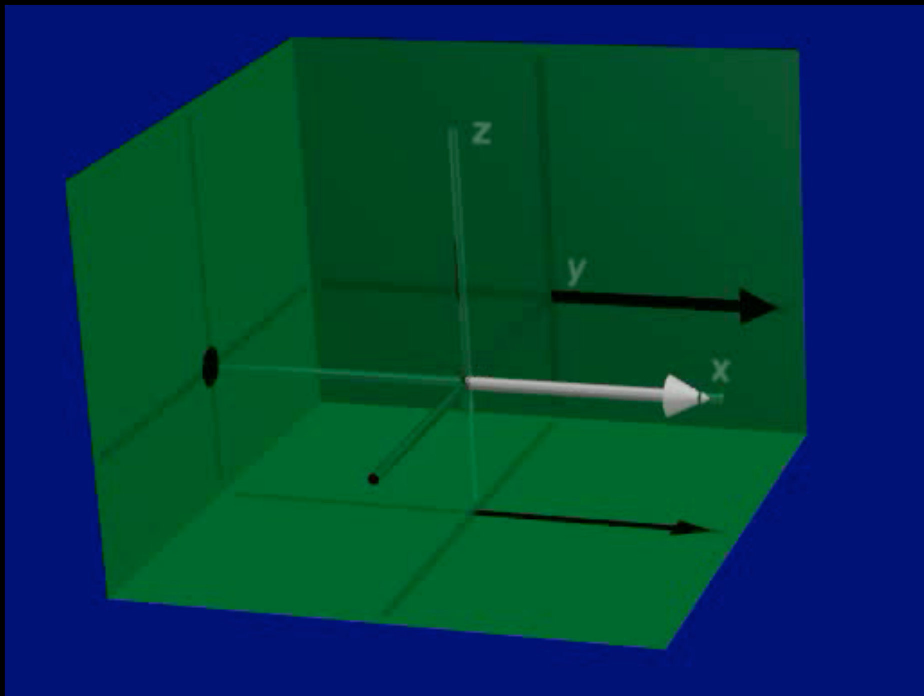
In a frame that rotates with B_1, magnetization is simply “flipped” out of alignment with B_0

Relaxation

courtesy of William Overall

Speed of relaxation has time constants: T_1 and T_2

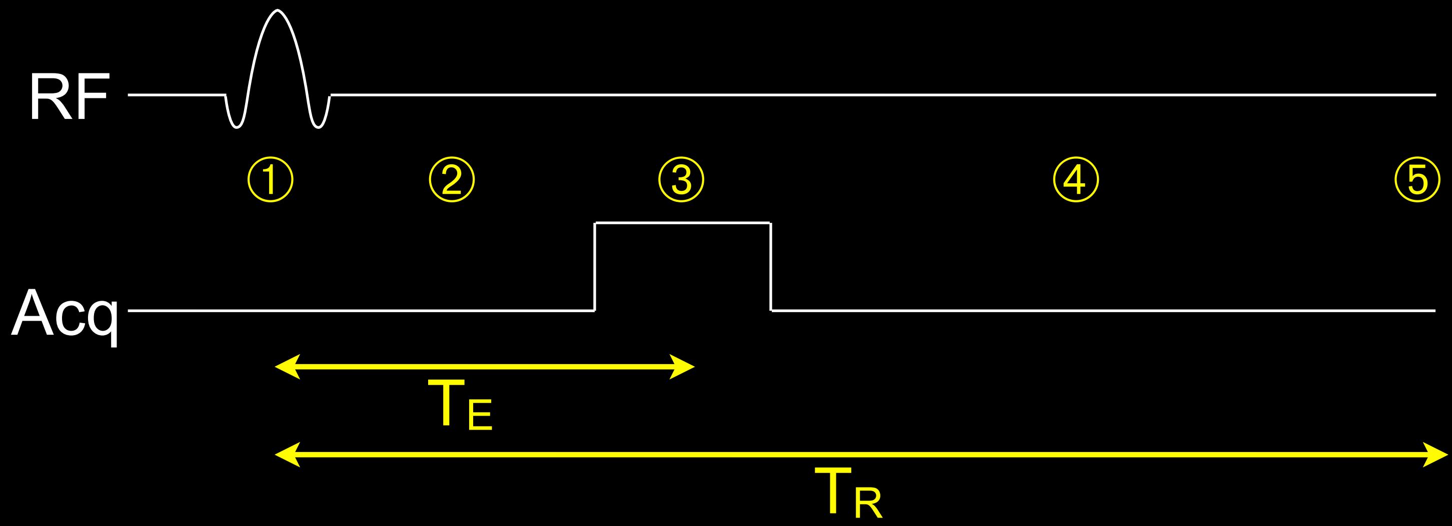
Relaxation



courtesy of William Overall

Speed of relaxation has time constants: T_1 and T_2

Simple MRI "pulse sequence"



① Excite magnetization (transmit RF pulse)

② Wait for time T_E ("echo time")

③ Acquire signal from transverse magnetization (M_{xy})

④ Wait until time T_R ("repetition time")

⑤ Repeat from ①

What's My Contrast?

	Short TE	Long TE
Short TR	T_1-weighted	T_1 *and* T_2 weighted
Long TR	Proton density	T_2-weighted

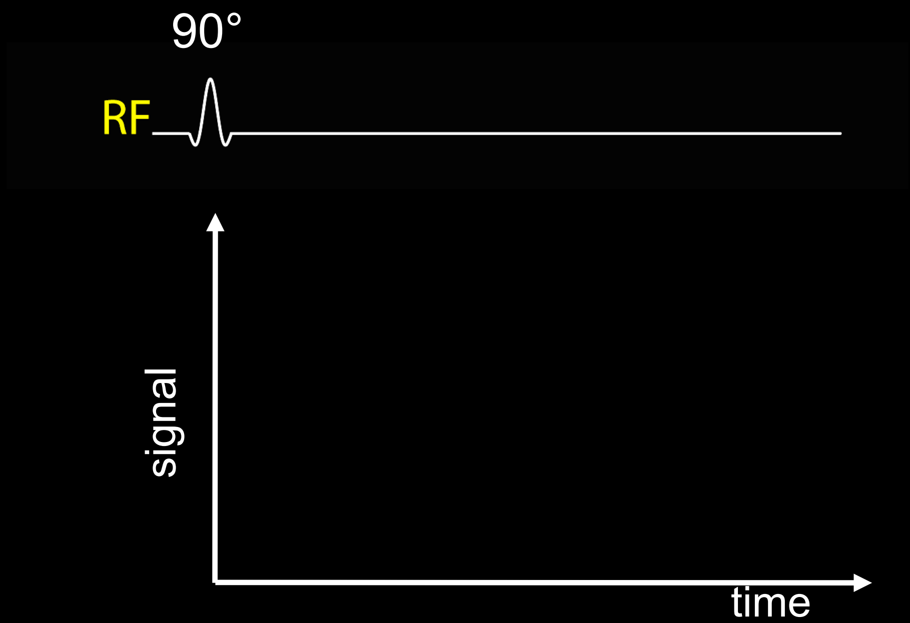
What's My Contrast?

	Short TE	Long TE
Short TR	T_1-weighted	~~T_1 *and* T_2 weighted~~
Long TR	Proton density	T_2-weighted

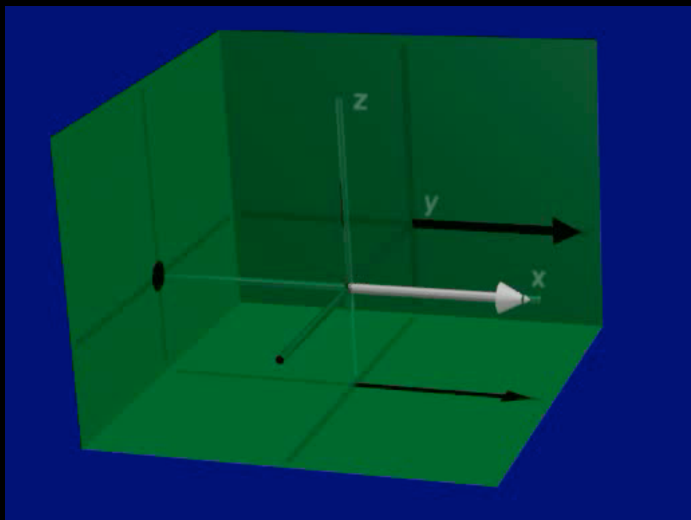
MRI Physics

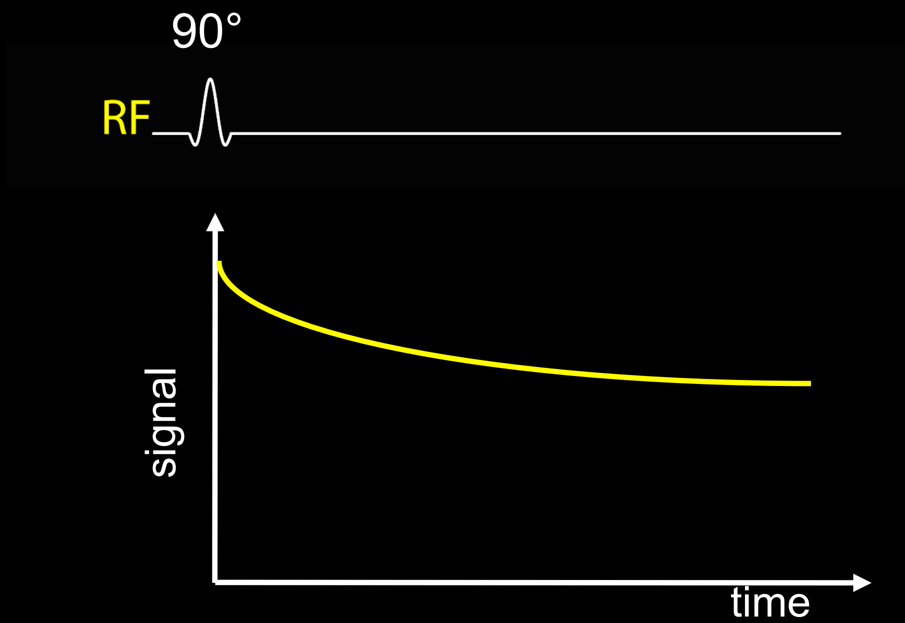
- MRI physics recap
- Pulse sequences
  - Gradient vs. spin echo
- Diffusion MRI
  - Isotropic and anisotropic diffusion
  - Useful quantities derived from the tensor

T_2 Relaxation



T_2 Relaxation



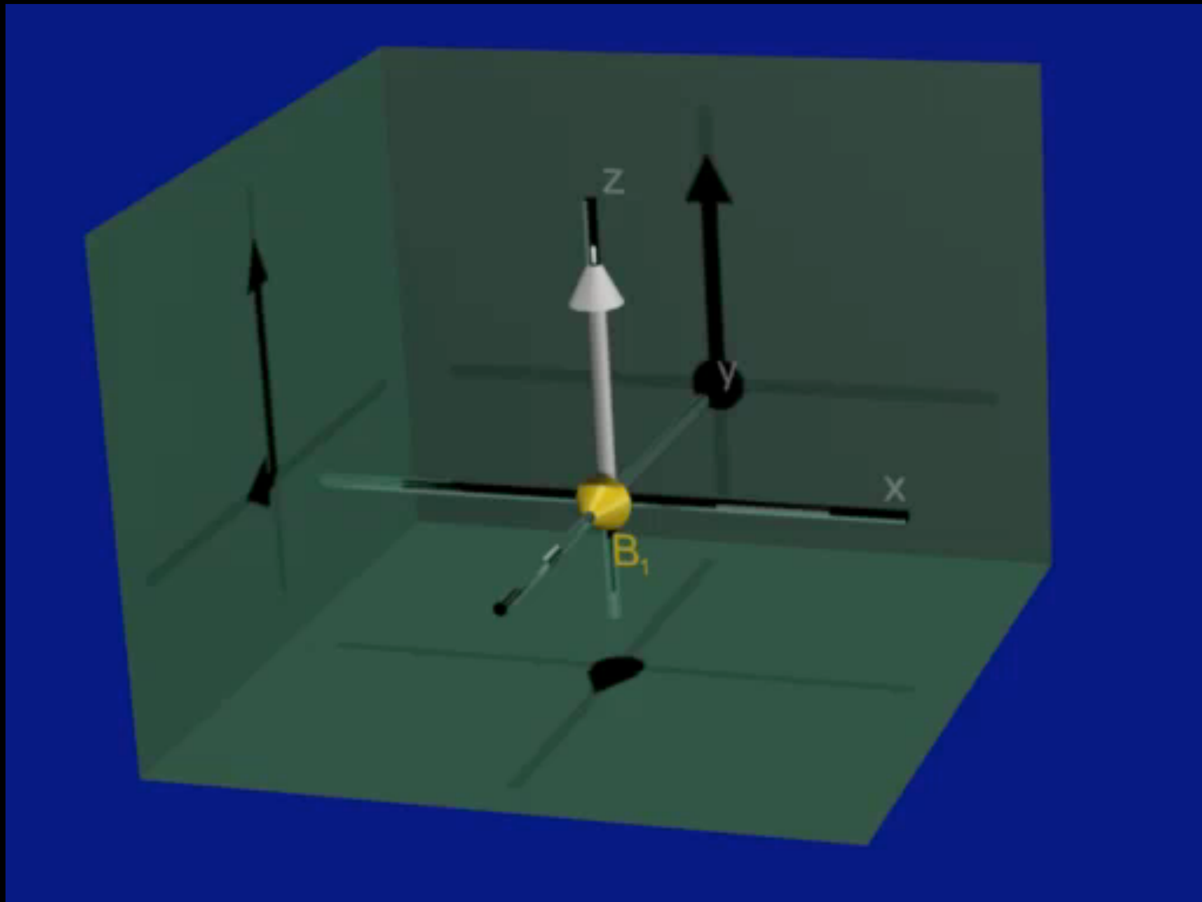


Magnetic field imperfections: T_2*

Always some local imperfections in magnetic field
= range of precession frequencies in a voxel

Over time, spins lose alignment ("dephase")

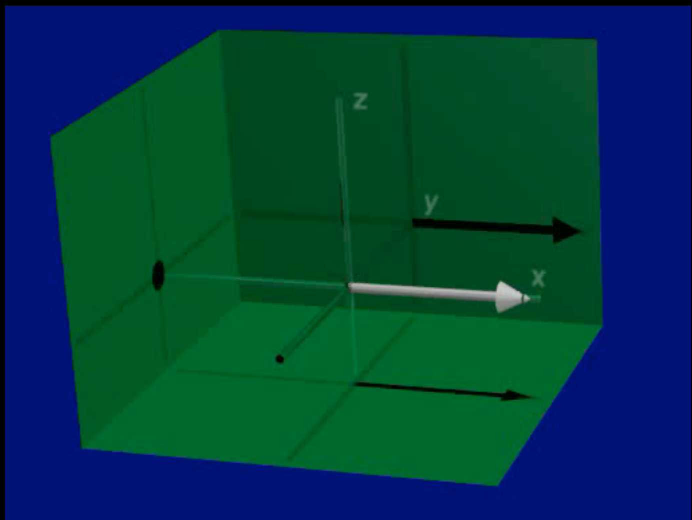
Magnetic field imperfections: T_2*

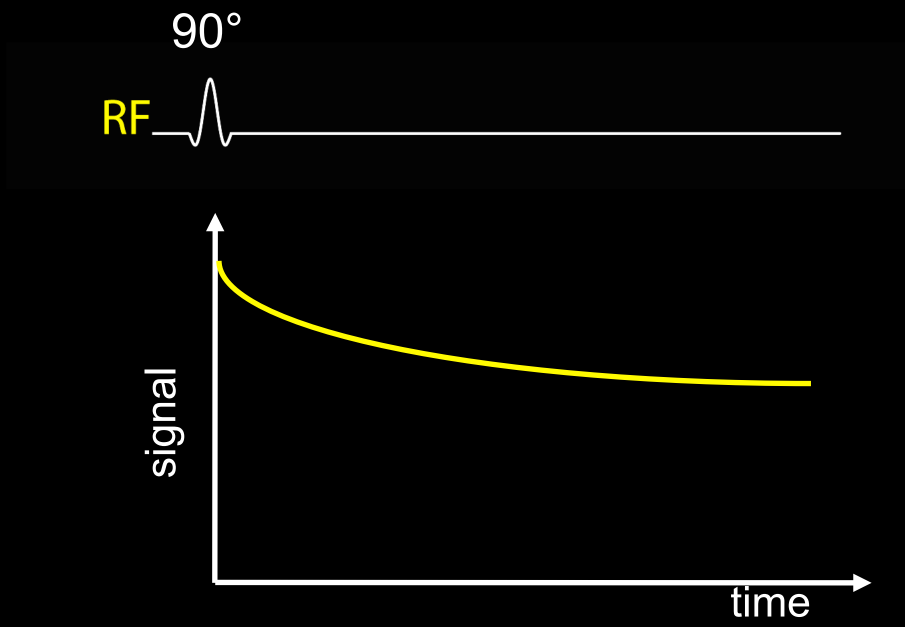


Always some local imperfections in magnetic field = range of precession frequencies in a voxel

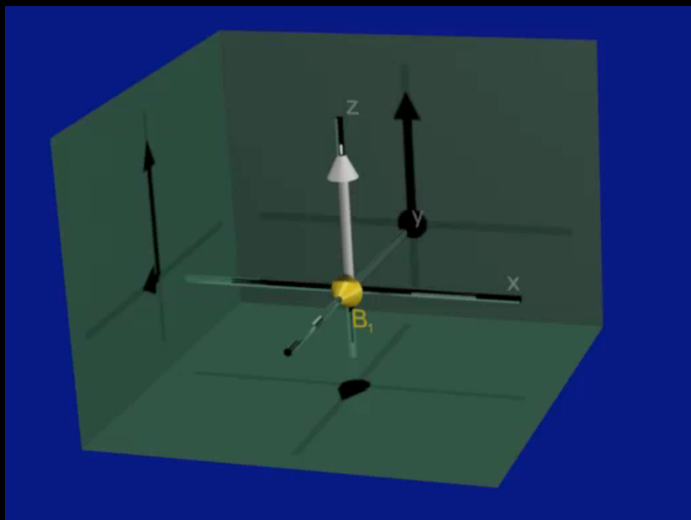
Over time, spins lose alignment (“dephase”)

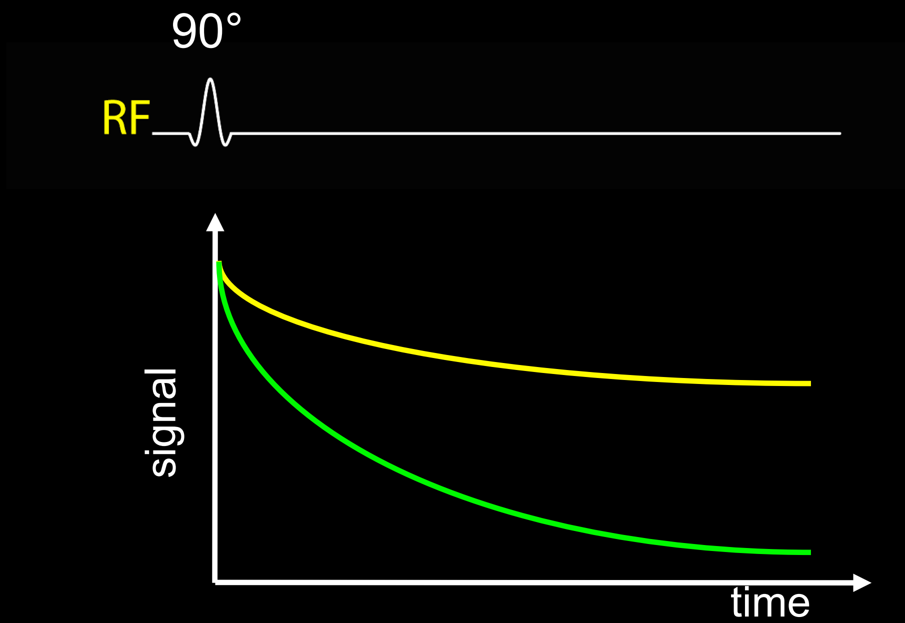
T_2* Relaxation



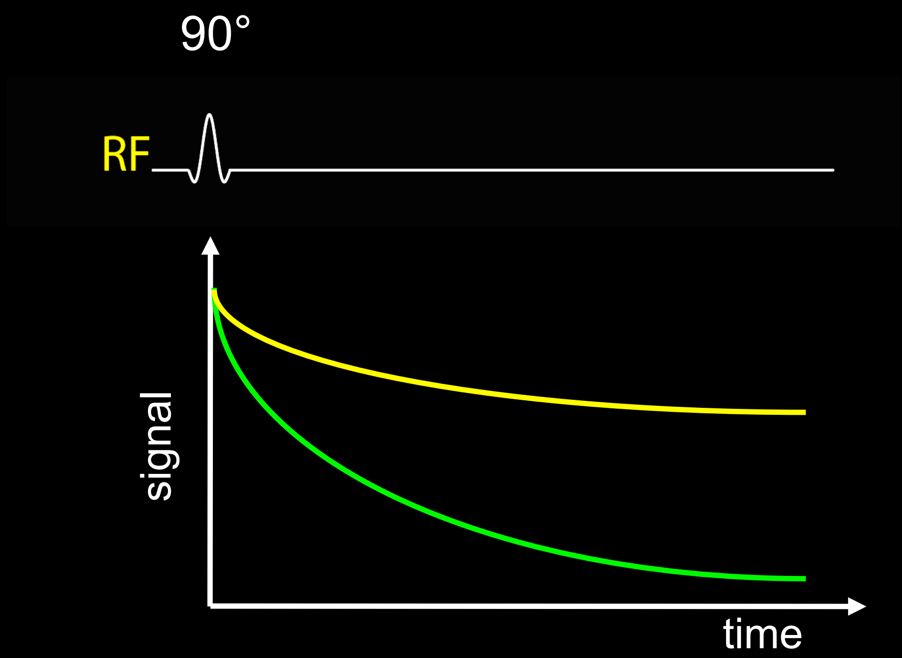


T_2* Relaxation



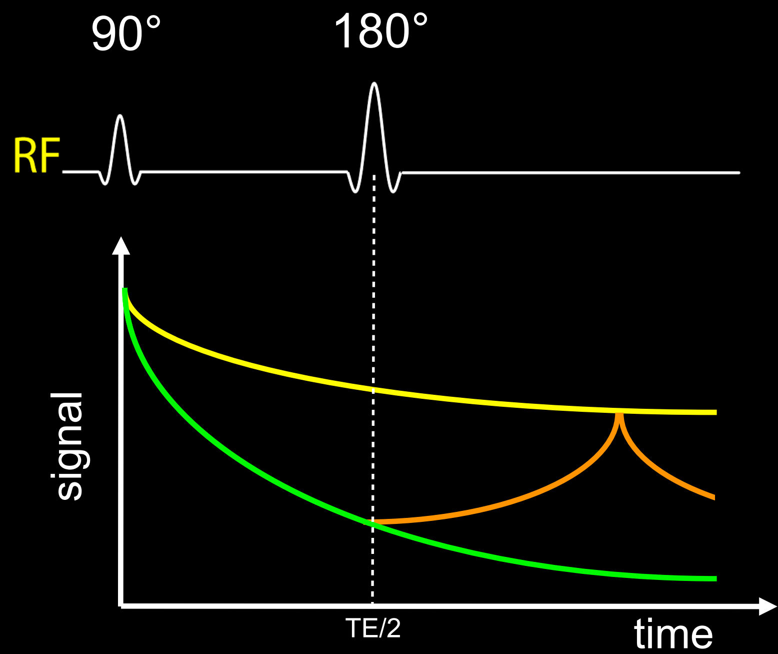


Gradient echo vs. spin echo



GRE signal
(sometimes called a Free Induction Decay = FID)

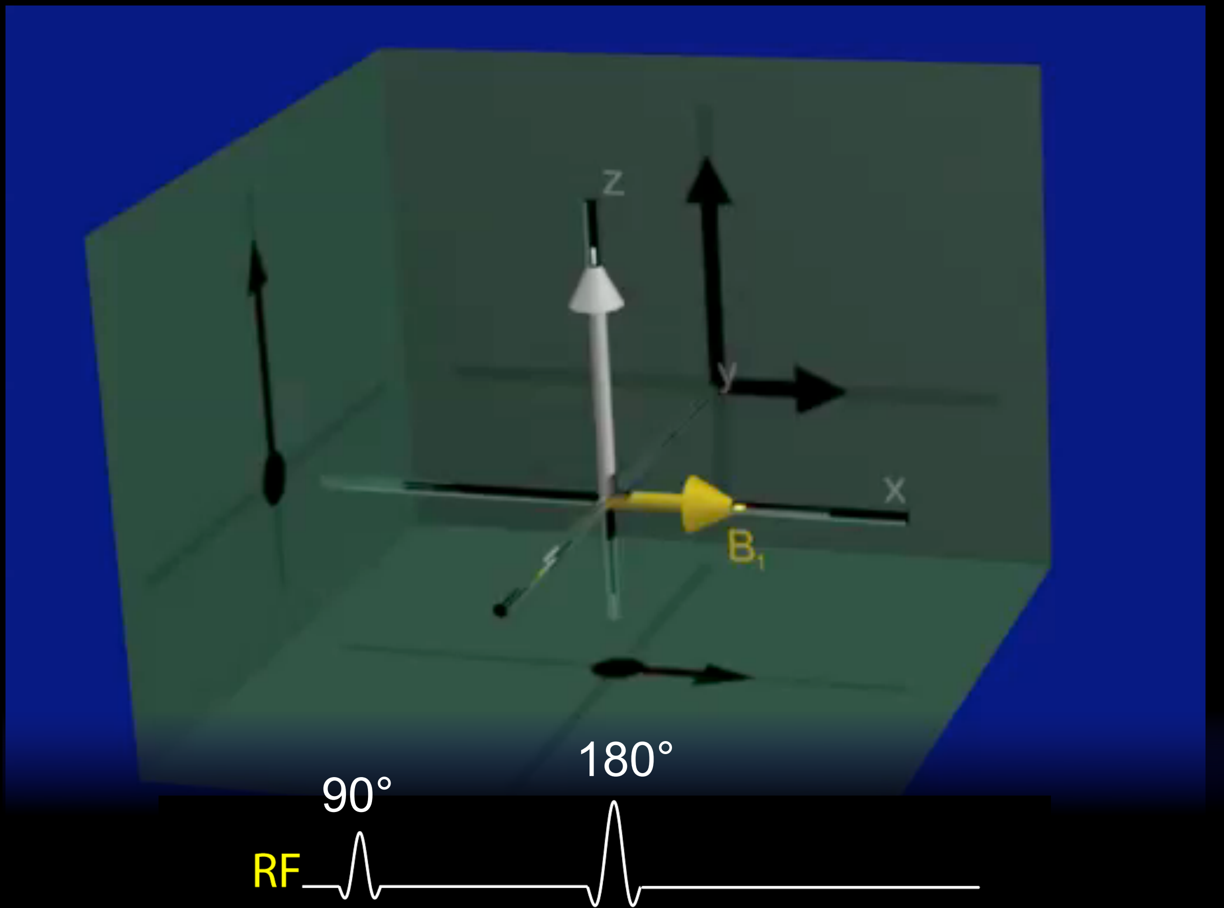
Gradient echo vs. spin echo



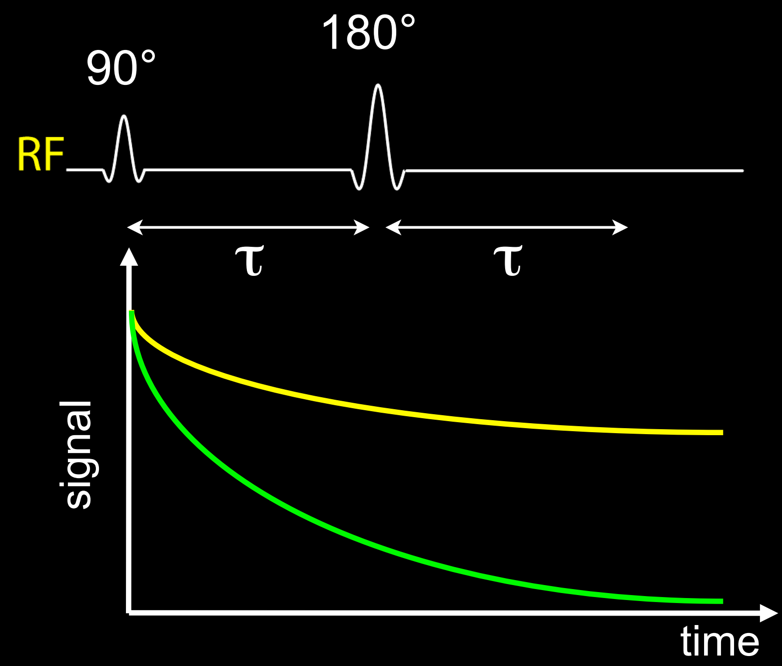
SE signal
(signal decays, then
comes back as “echo”)

Refocusing (180^o RF pulse)

Refocusing (180^o RF pulse)



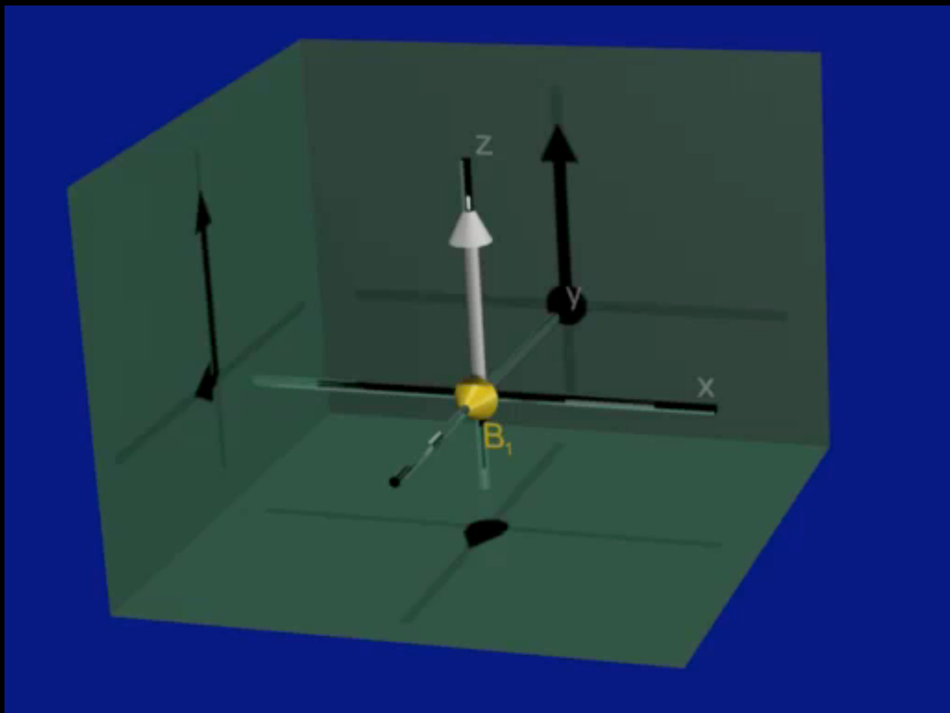
Spin Echo

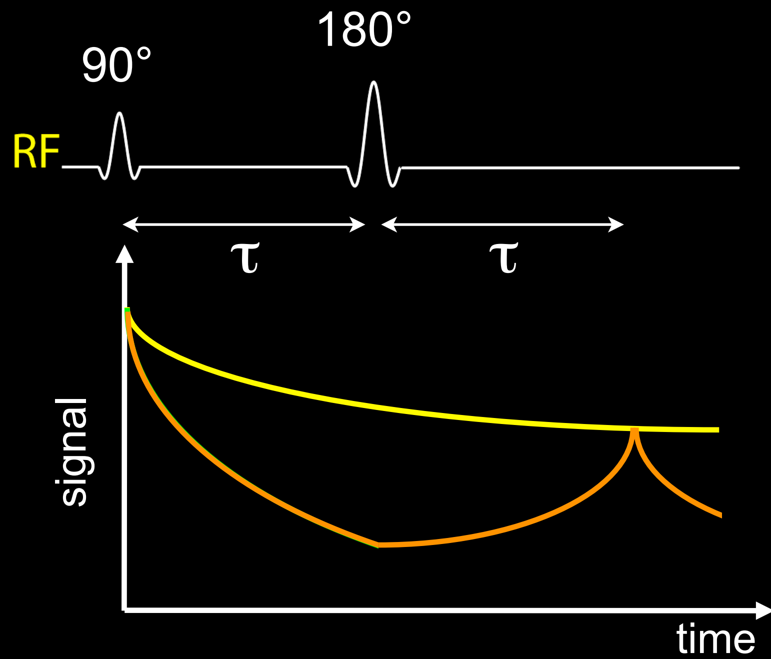


Spin echo: The time at which the spins are re-aligned

Refocusing pulse: 180° pulse that creates a spin echo

Spin Echo





Spin echo: The time at which the spins are re-aligned

Refocusing pulse: 180° pulse that creates a spin echo

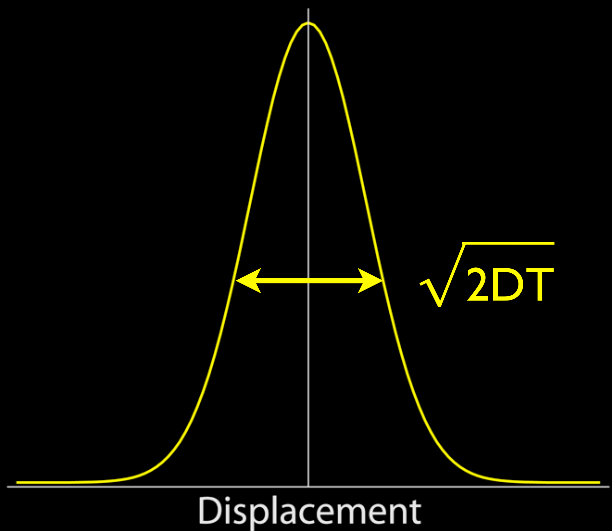
MRI Physics

- MRI physics recap
- Pulse sequences
  - Gradient vs. spin echo
- Diffusion MRI
  - Isotropic and anisotropic diffusion
  - Useful quantities derived from the tensor

What is diffusion?

What is diffusion?

What is diffusion?



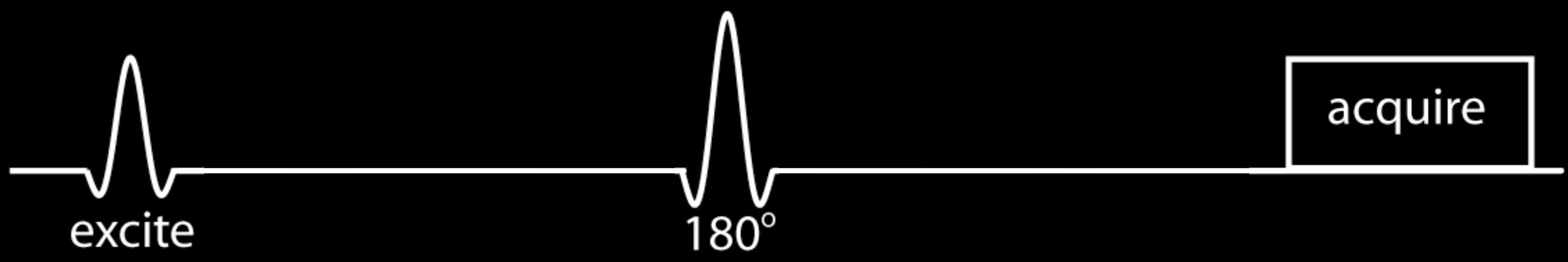
Random motion of particles due to thermal energy

Water molecules collide and experience net displacement

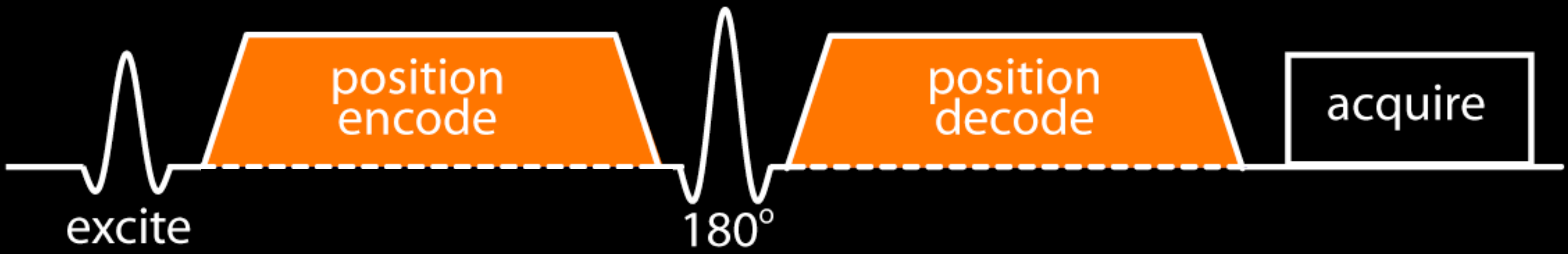
Displacement described by diffusion coefficient (D)

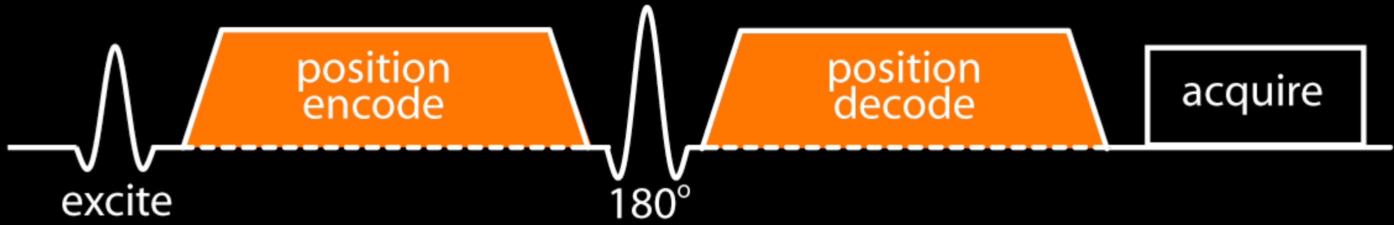
Normally, diffusion is isotropic (equal in all directions)

Diffusion-weighted spin echo

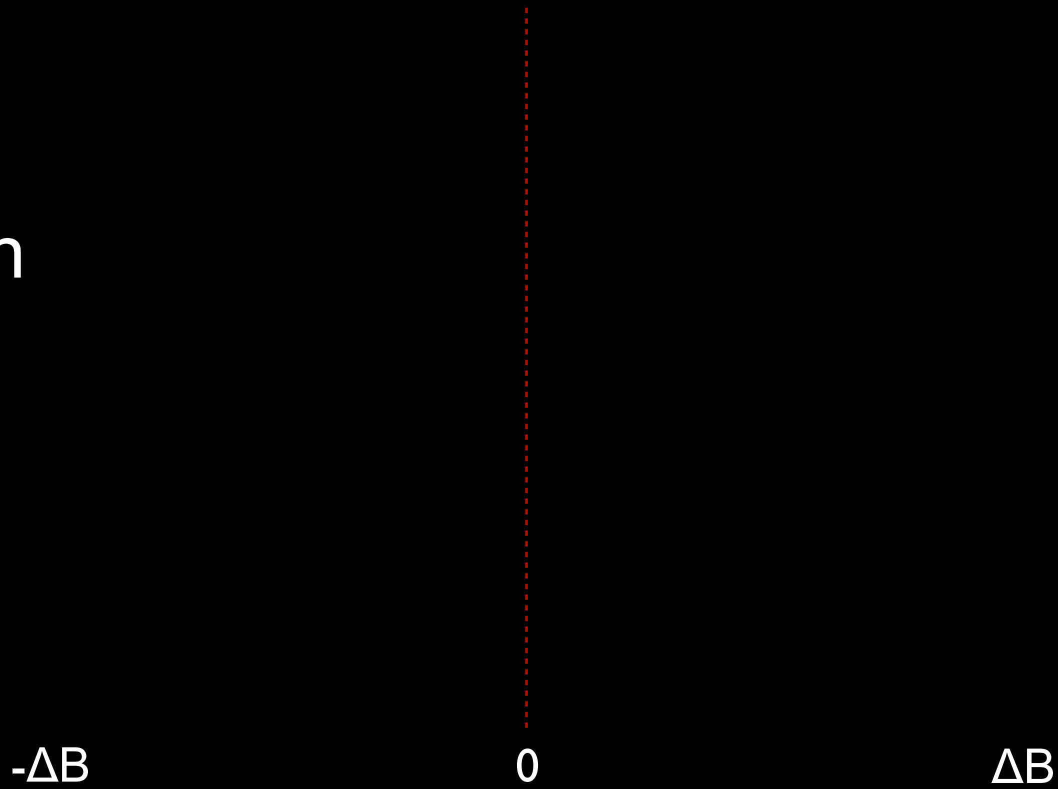


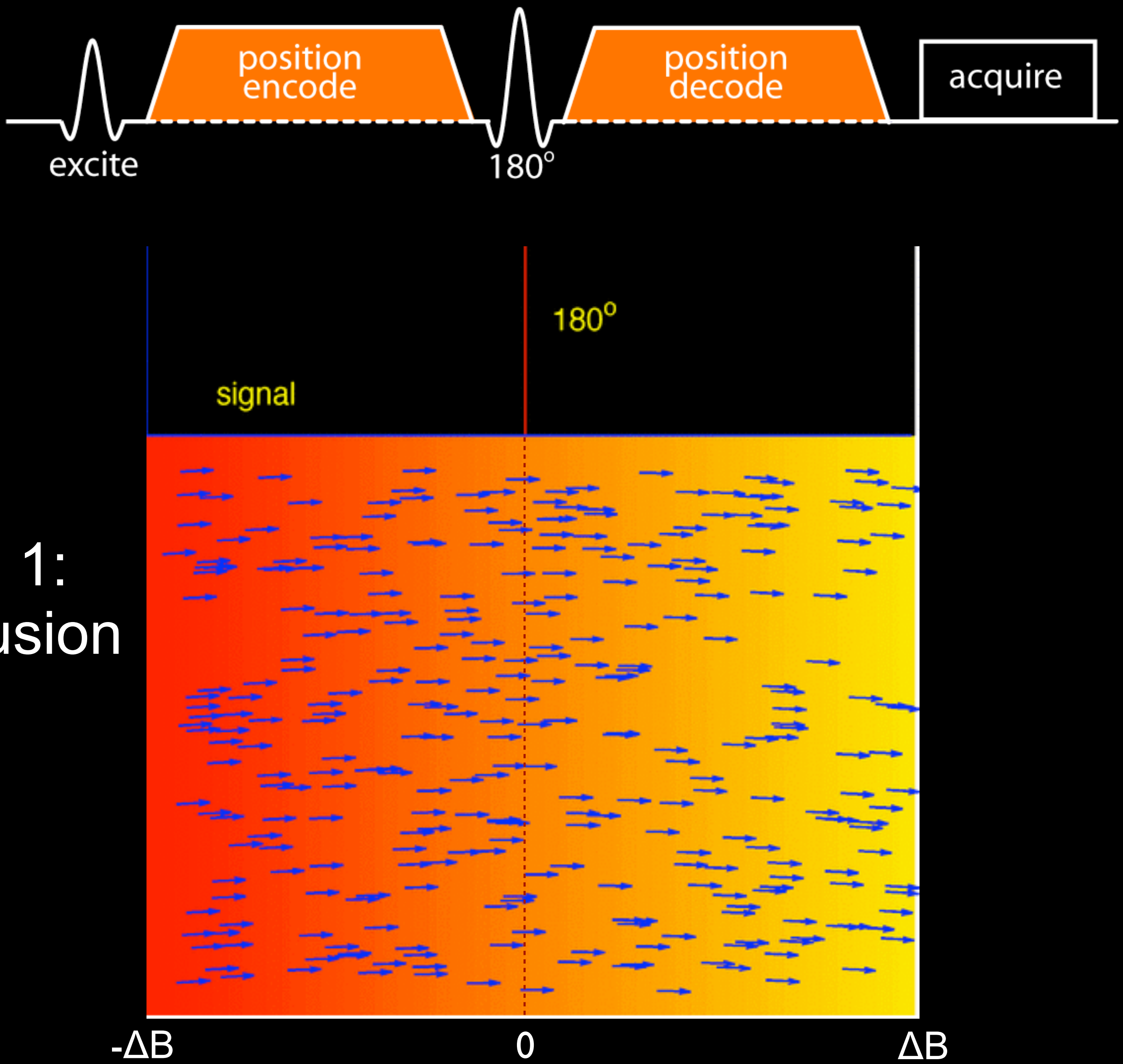
Diffusion-weighted spin echo



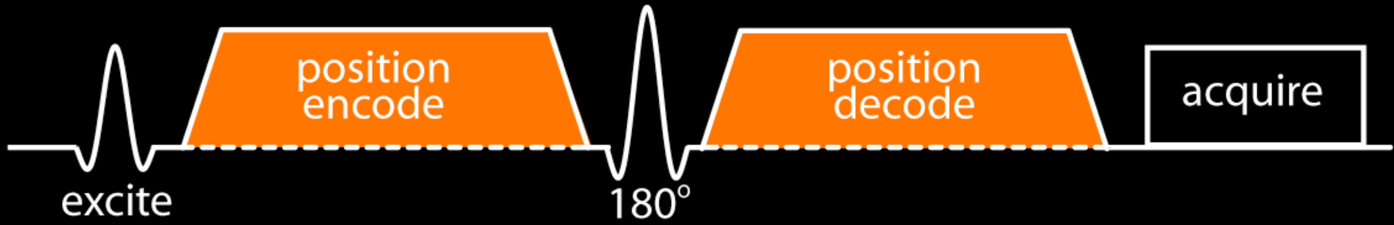


Case 1:
No diffusion





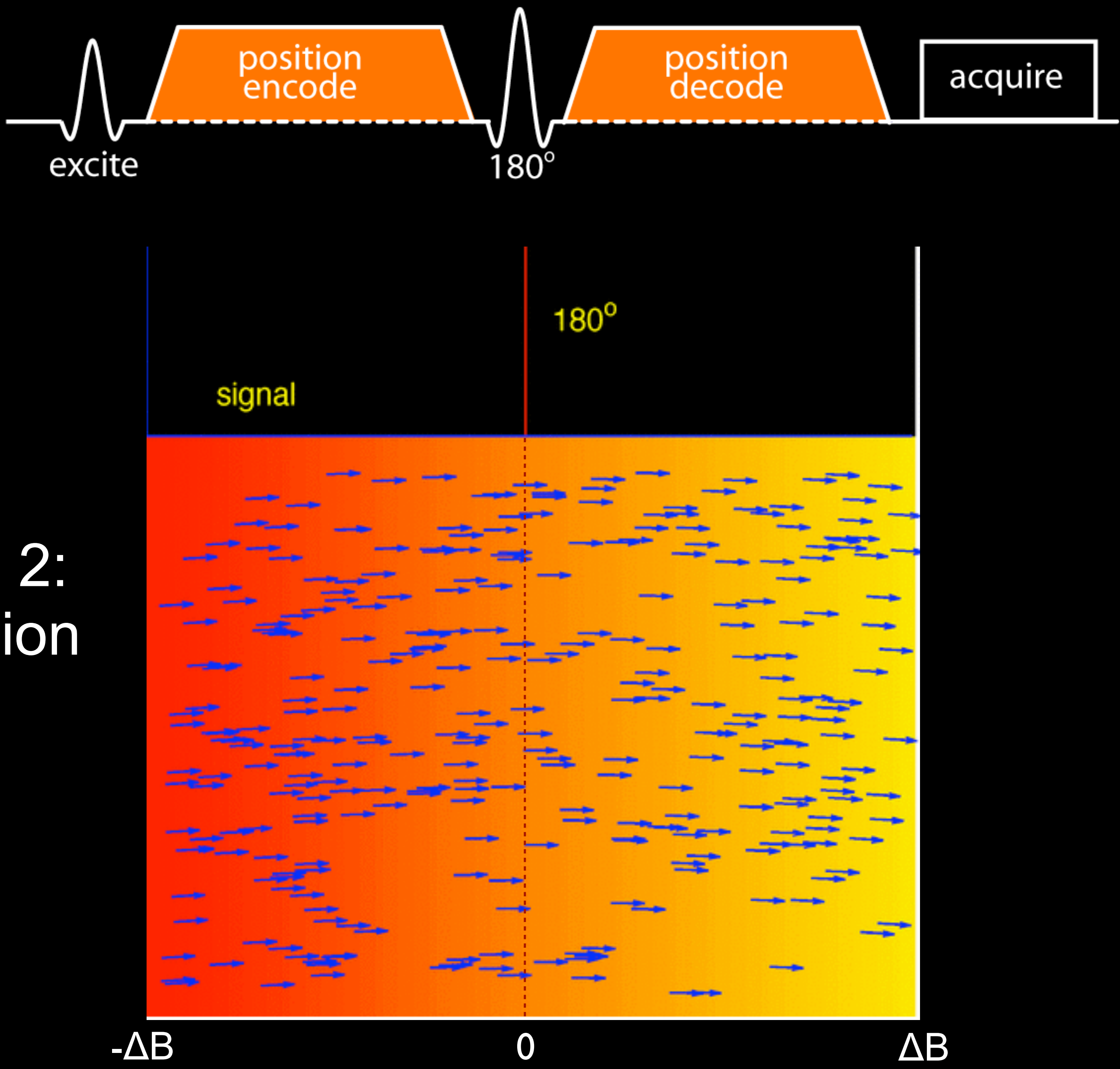
Case 1:
No diffusion



Case 2:
Diffusion

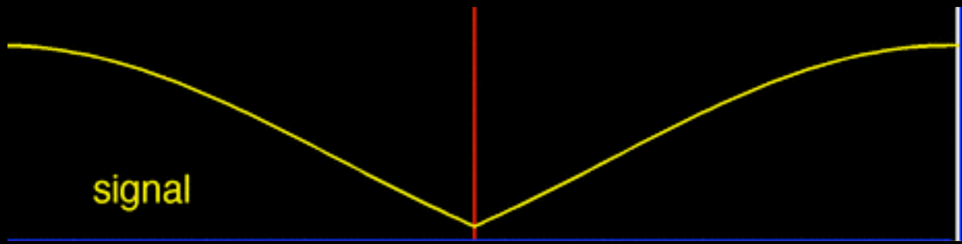
-ΔB 0 ΔB

Case 2:
Diffusion

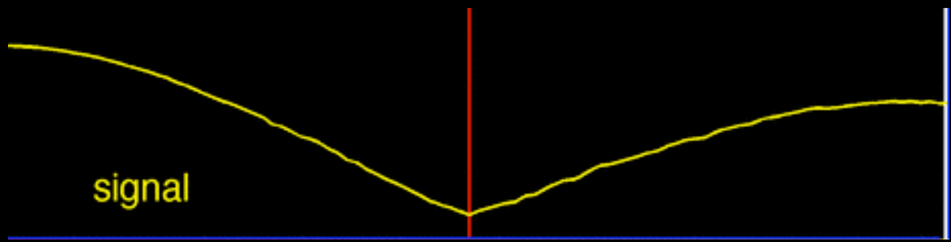


Diffusion contrast

No diffusion



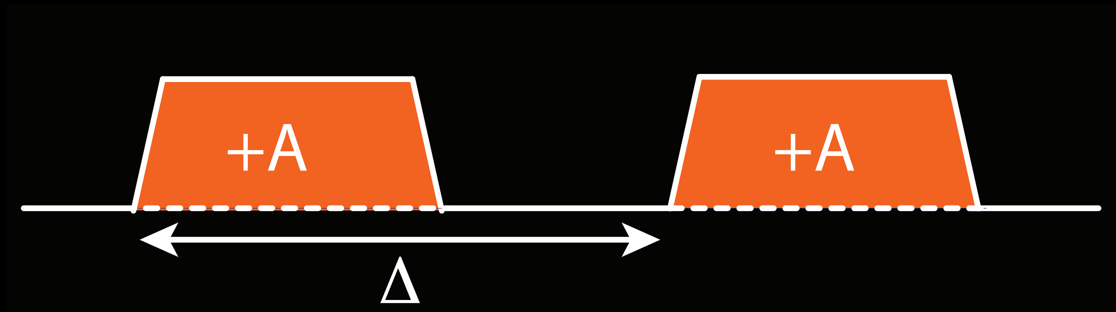
Diffusion

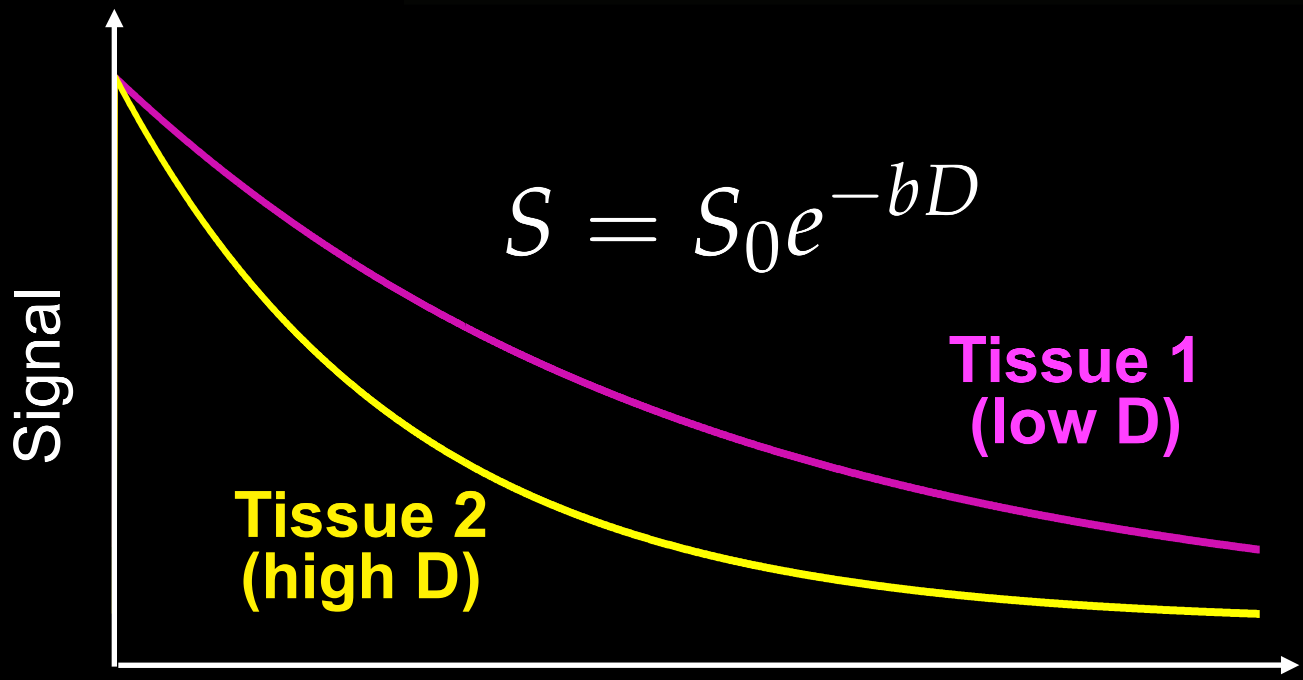


If diffusion is present, gradients cause a drop in signal.

Faster Diffusion = Less Signal

Diffusion contrast

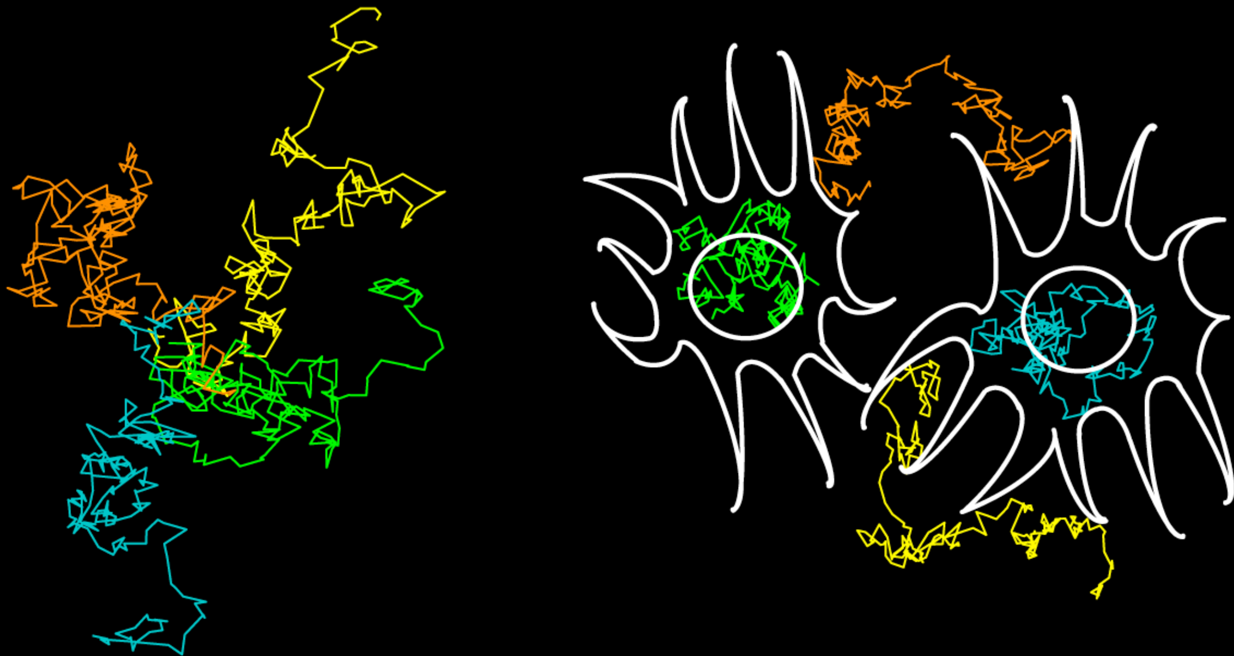




$$S = S_0 e^{-bD}$$

$$b \propto A^2 \Delta$$

Why is diffusion interesting?

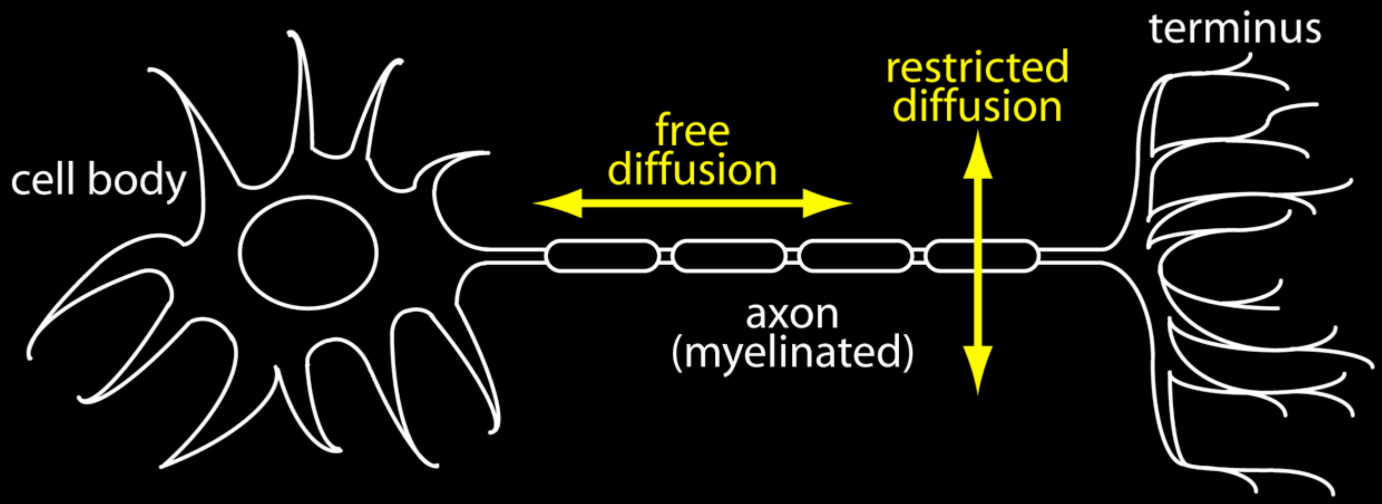


Unrestricted | Tissue boundaries

Diffusion is restricted by tissue boundaries, membranes, etc

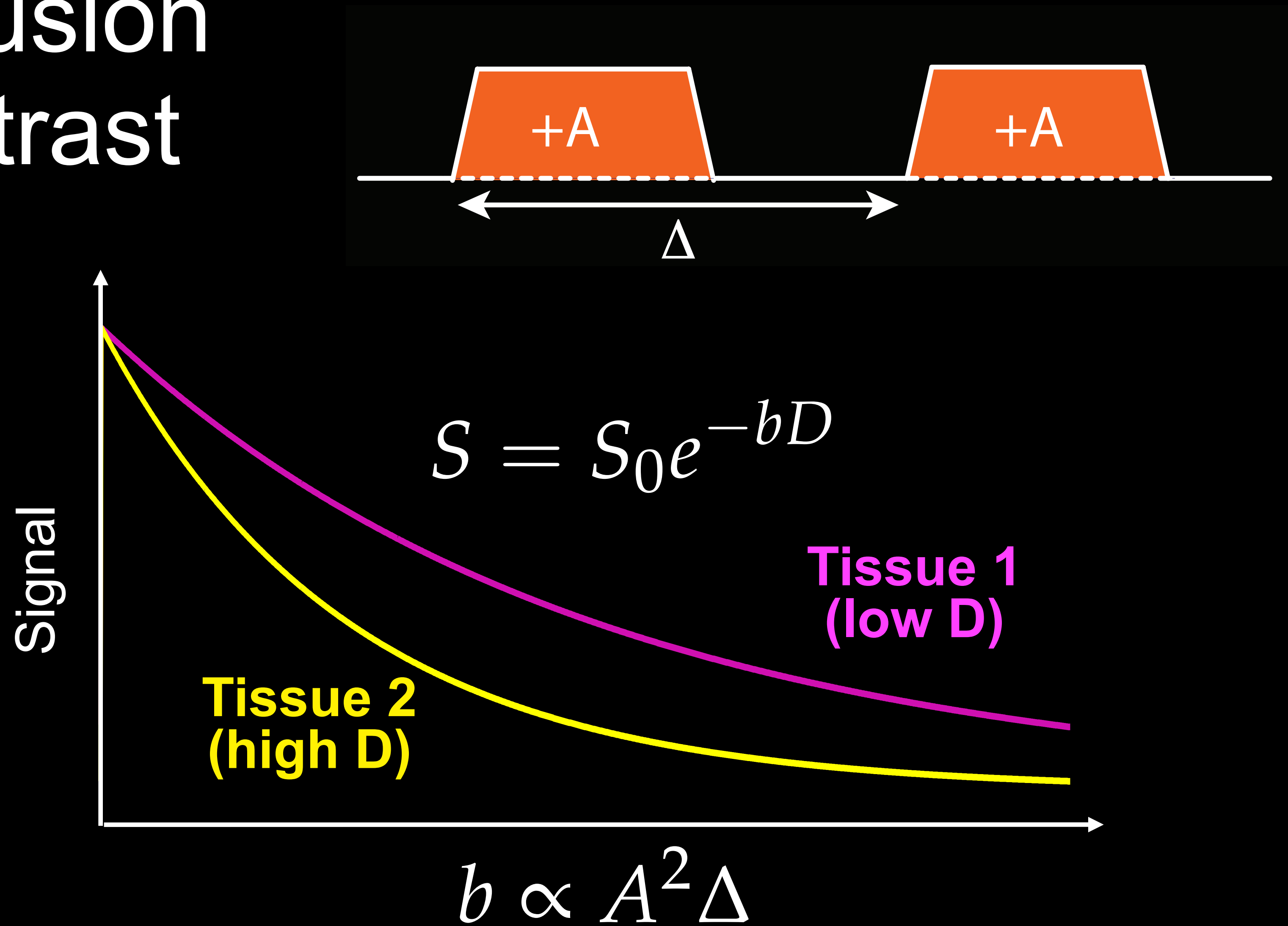
Marker for tissue microstructure (healthy and pathology)

Diffusion anisotropy in white matter

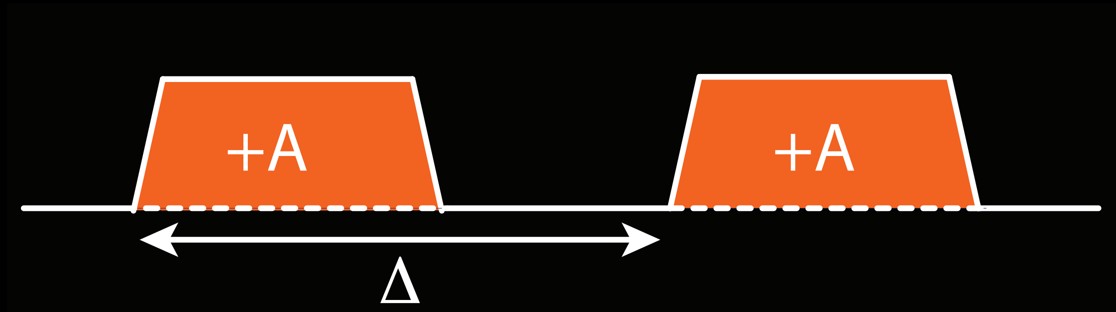


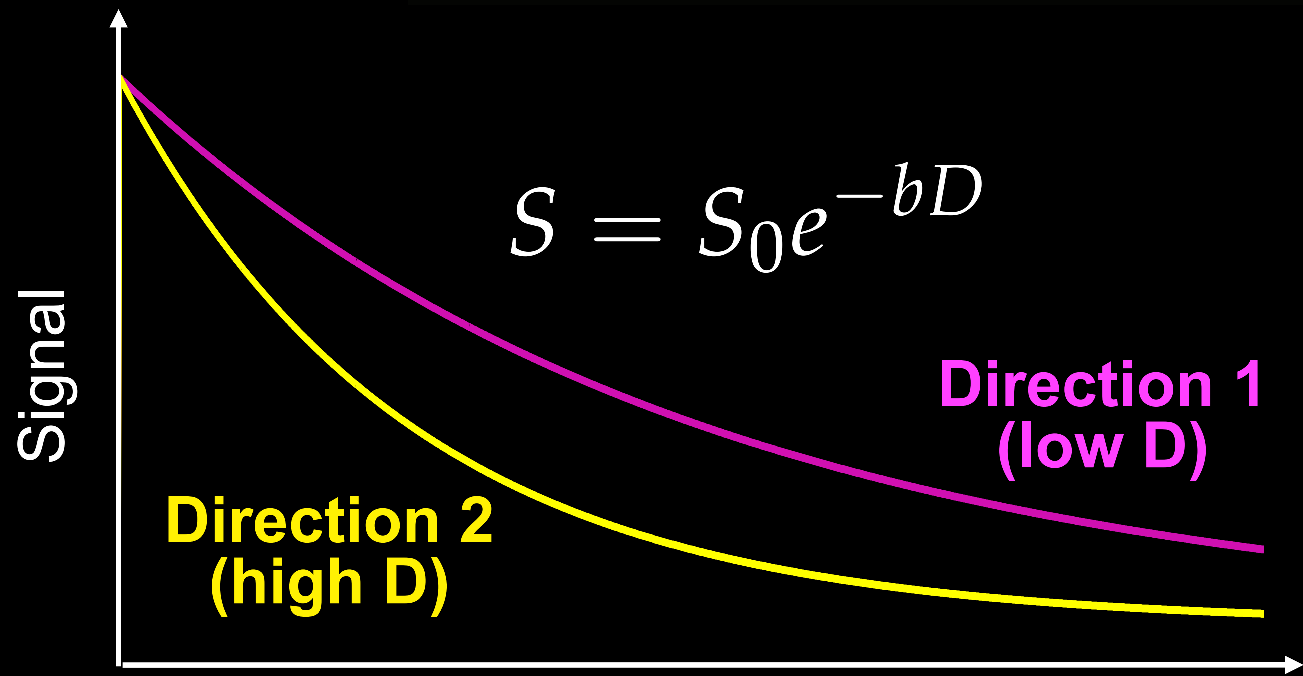
Water can diffuse more freely along white matter fibers than across them

Diffusion contrast



Diffusion contrast

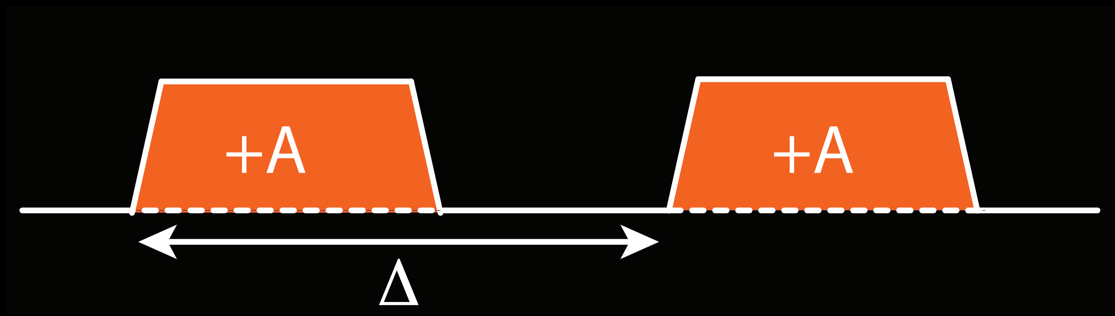




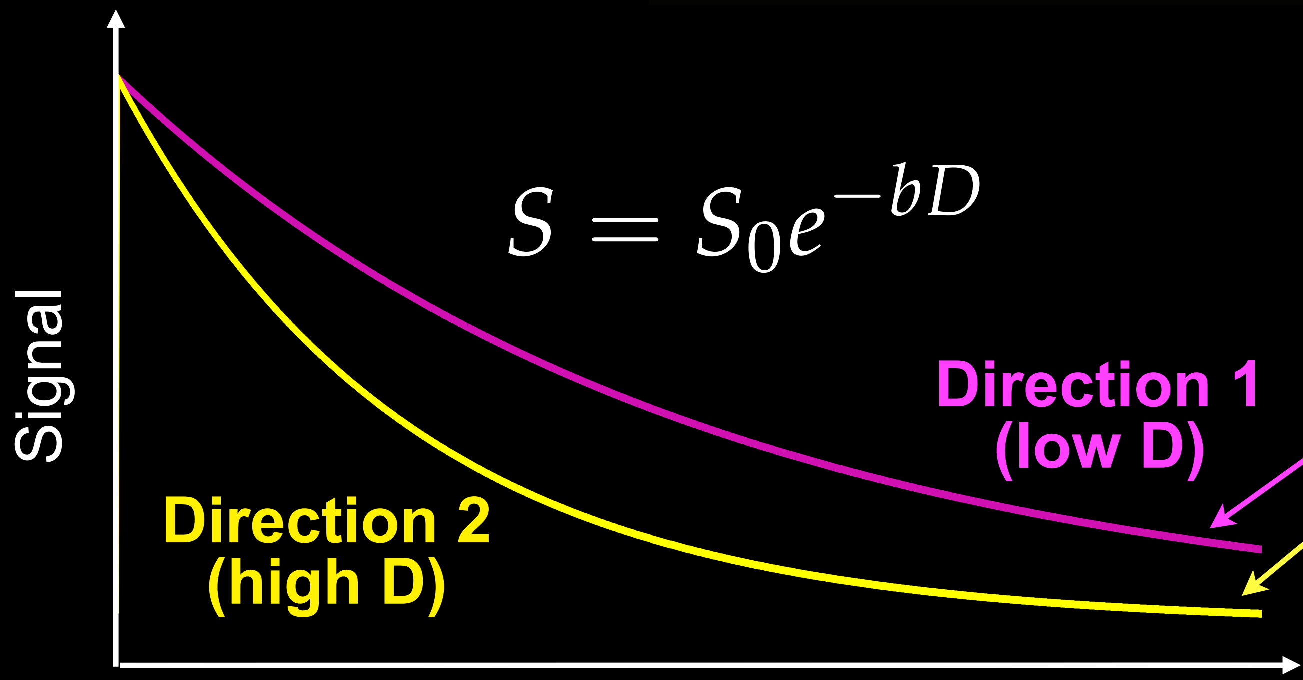
$$b \propto A^2 \Delta$$

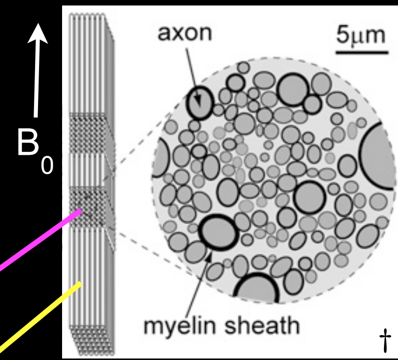
† Lee, et al. *PNAS*, 2010;107(11):5130-35

Diffusion contrast



$$S = S_0 e^{-bD}$$

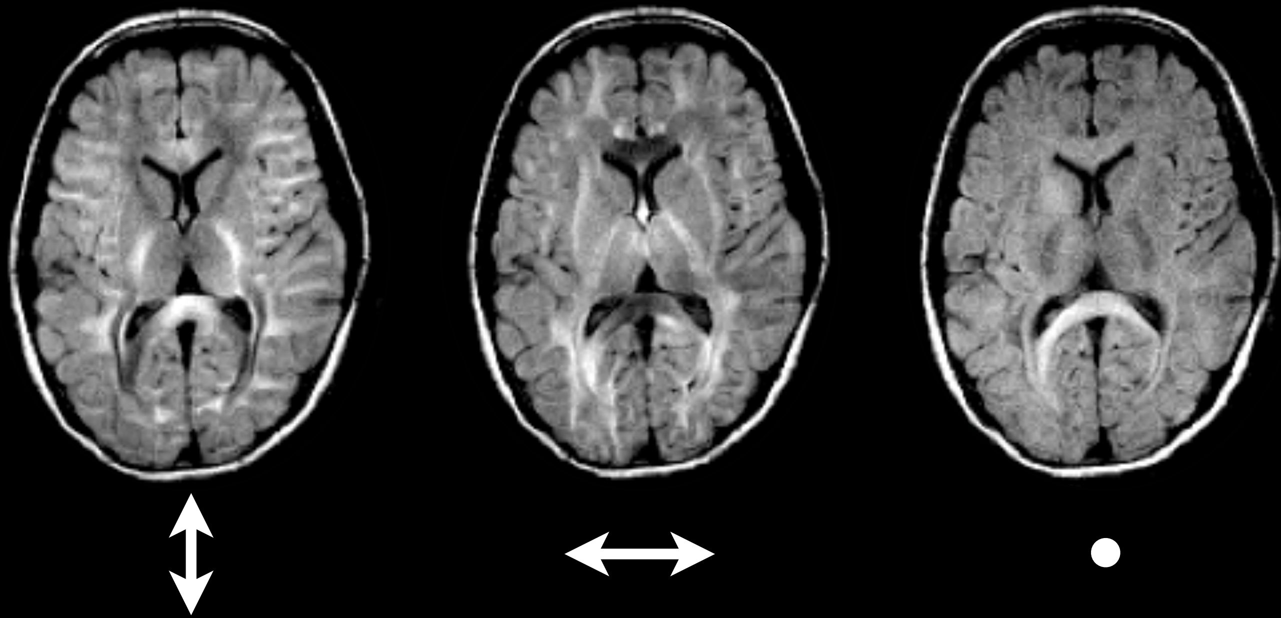




$$b \propto A^2 \Delta$$

† Lee, et al. *PNAS*, 2010;107(11):5130-35

Diffusion contrast

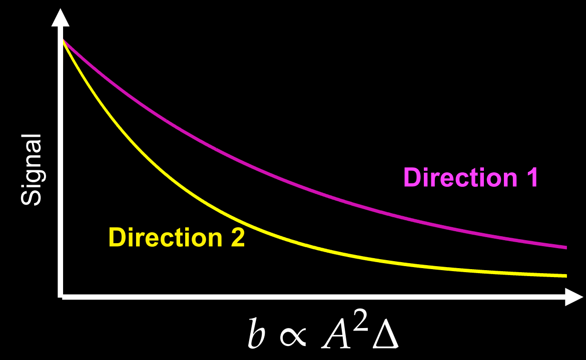


Posterior region of the Corona Radiata
Corpus Callosum
Forceps Major
Posterior limb of internal capsule
Anterior limb of internal capsule
Exterior capsule

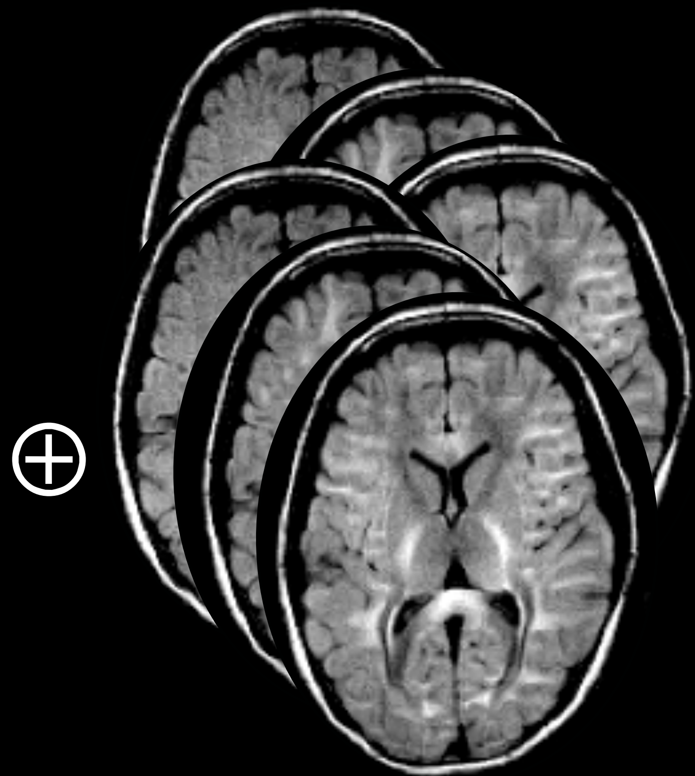
If diffusion is prese … a drop in signal.

Faste … Signal

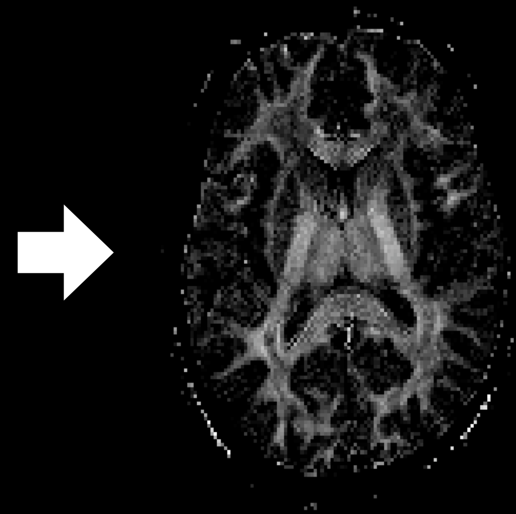
Diffusion-weighted imaging



b=0

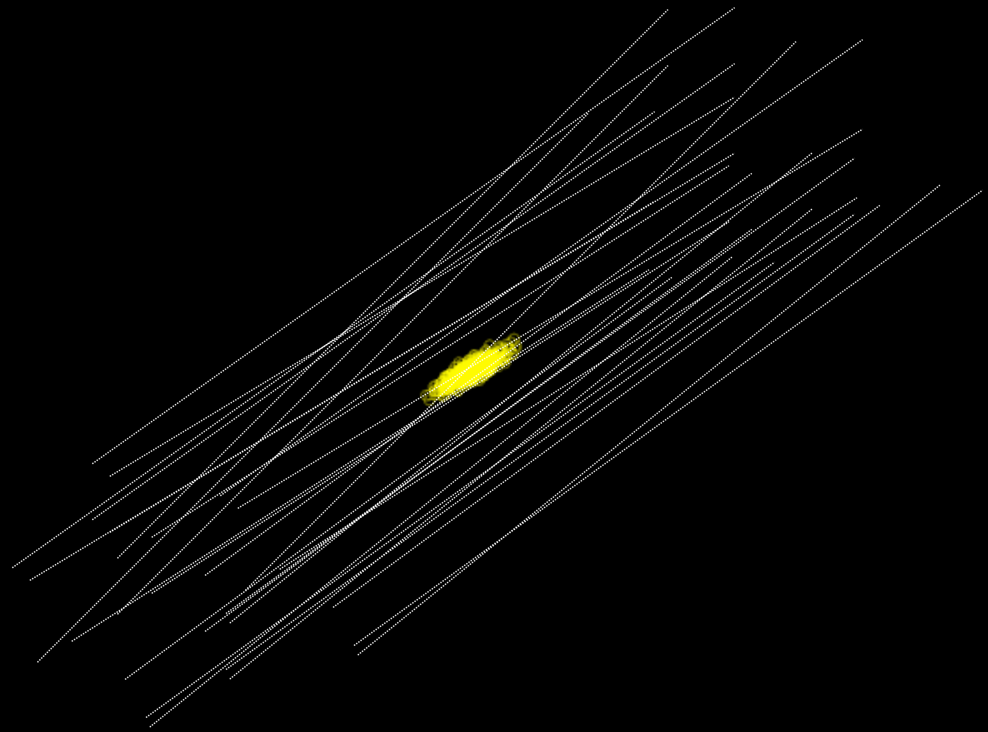


Directional encoding



Fitted parameter maps

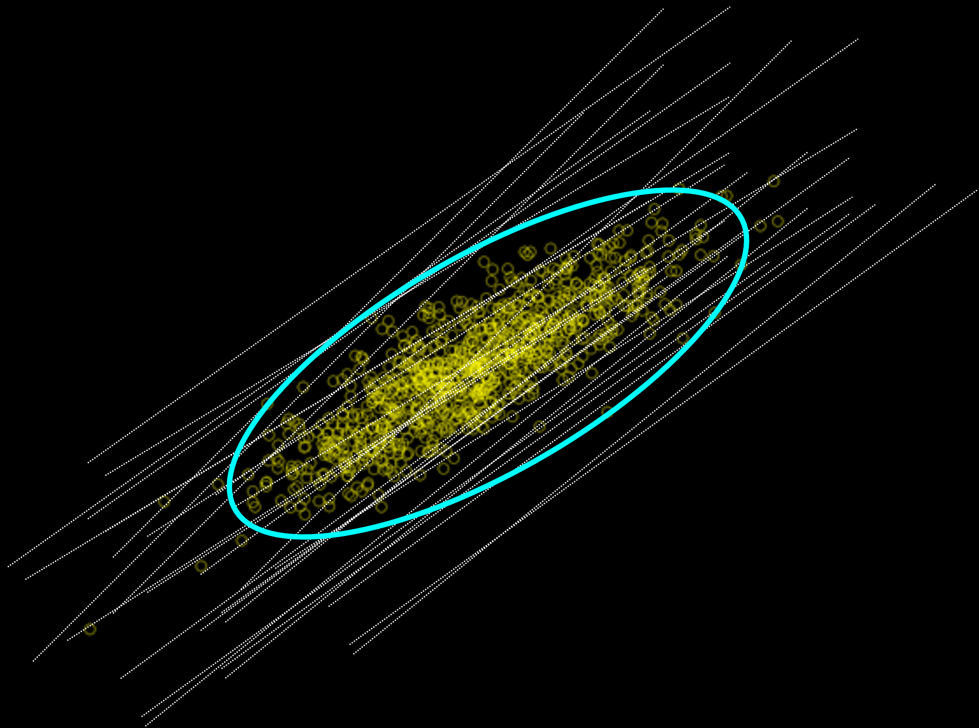
Diffusion anisotropy in white matter



Diffusion in white matter fibers is “anisotropic”

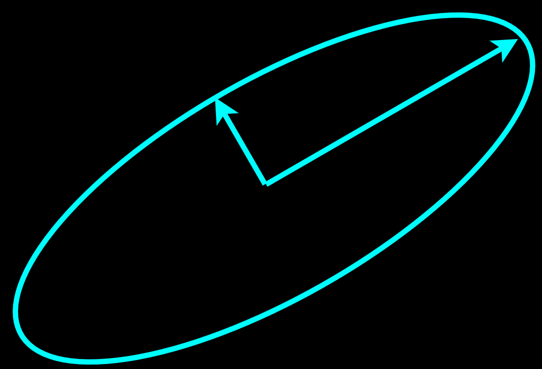
Directionality of diffusion tells us about fiber integrity/ structure and orientation

The diffusion tensor



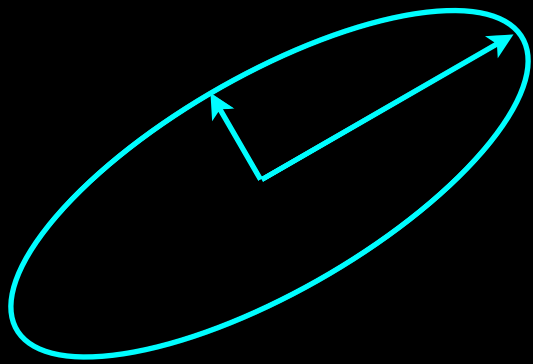
Displacement due to diffusion is approximately ellipsoidal

The diffusion tensor



Displacement due to diffusion is approximately ellipsoidal

The diffusion tensor

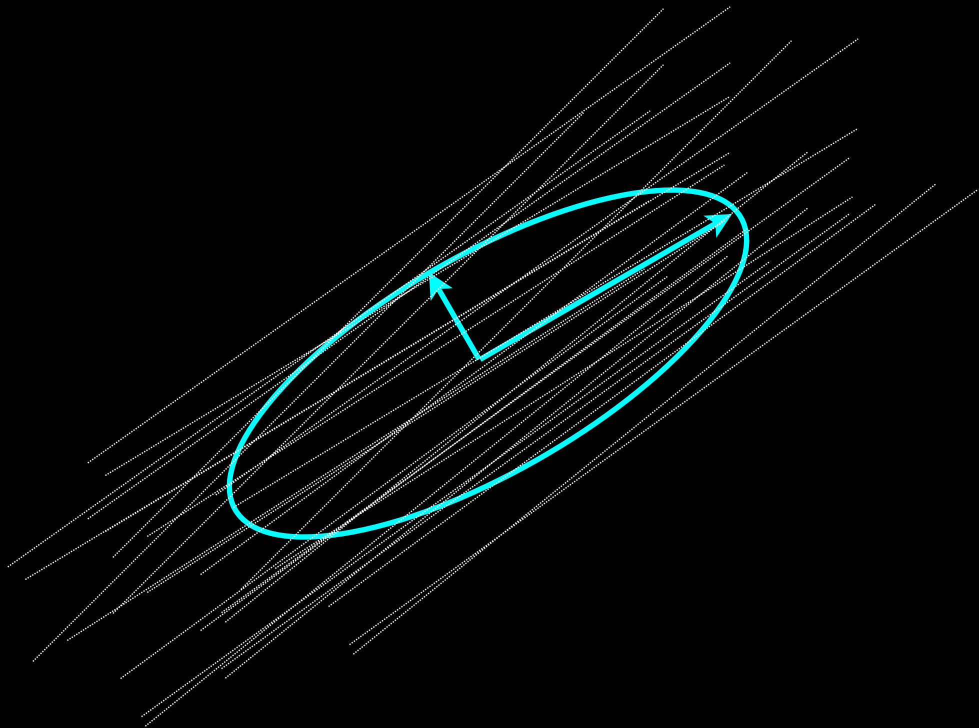


Displacement due to diffusion is approximately ellipsoidal

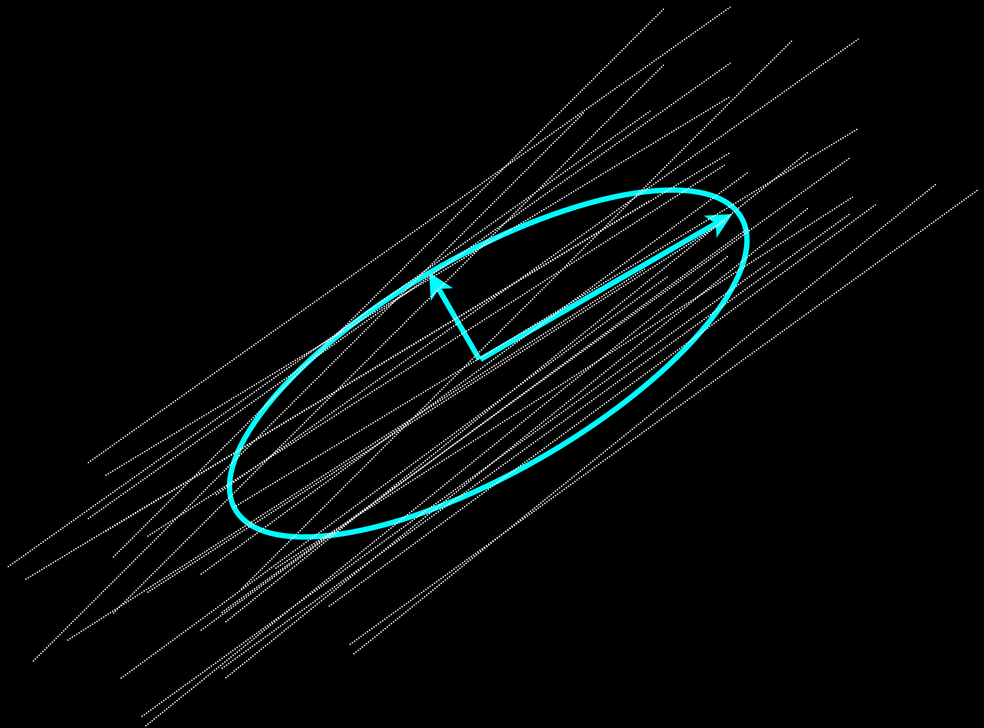
Eigenvectors = axes of ellipsoid (direction of fibers)

Eigenvalues = size of axes (strength of diffusion)

The diffusion tensor: Useful quantities

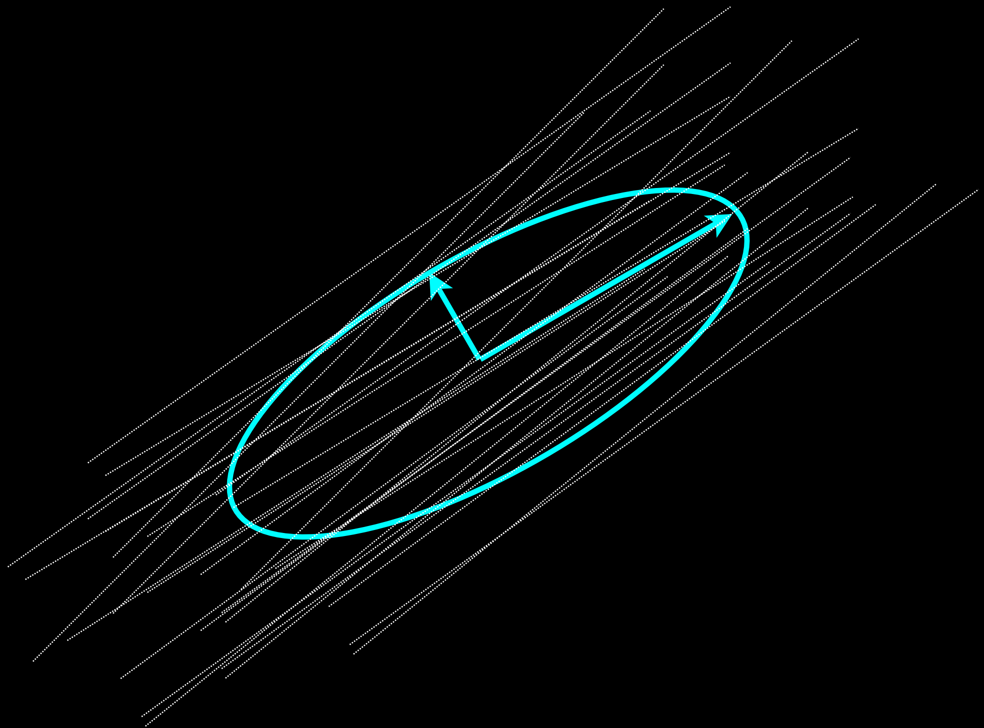


The diffusion tensor: Useful quantities



Mean diffusivity (MD): Info about tissue integrity

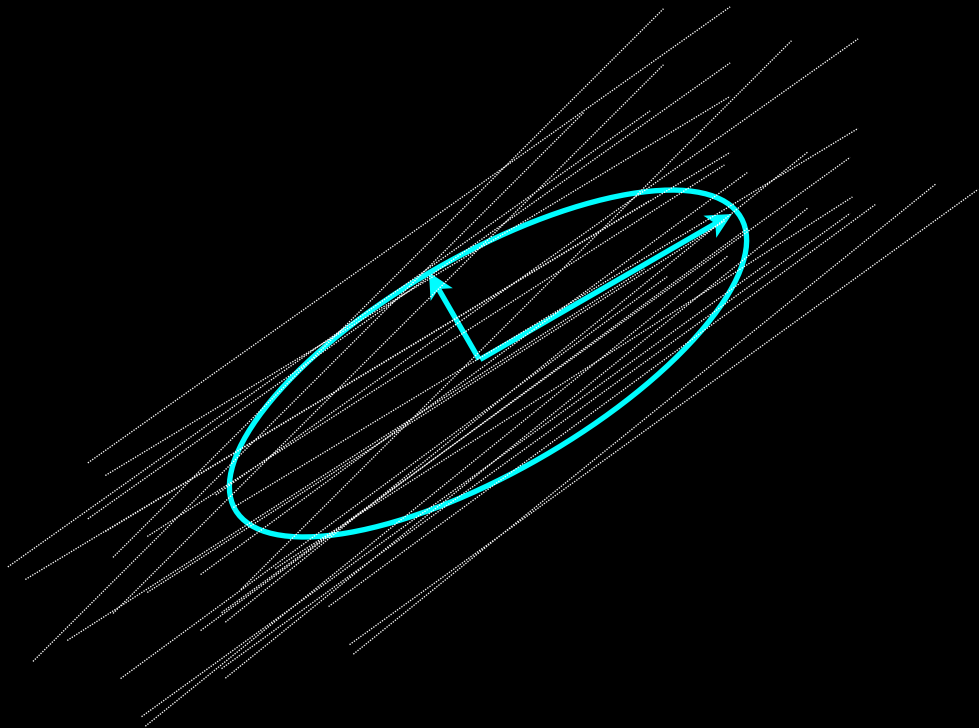
The diffusion tensor: Useful quantities



Mean diffusivity (MD): Info about tissue integrity

Fractional anisotropy (FA): how elongated is the ellipsoid? Info about fiber integrity

The diffusion tensor: Useful quantities



Mean diffusivity (MD): Info about tissue integrity

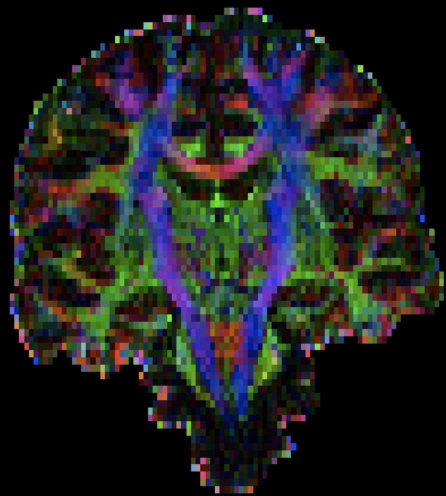
Fractional anisotropy (FA): how elongated is the ellipsoid? Info about fiber integrity

Principal diffusion direction (PDD): what direction is greatest diffusion along? Info about fiber orientation

Diffusion tensor imaging

Mean diffusivity (MD)

Fractional anisotropy (FA)



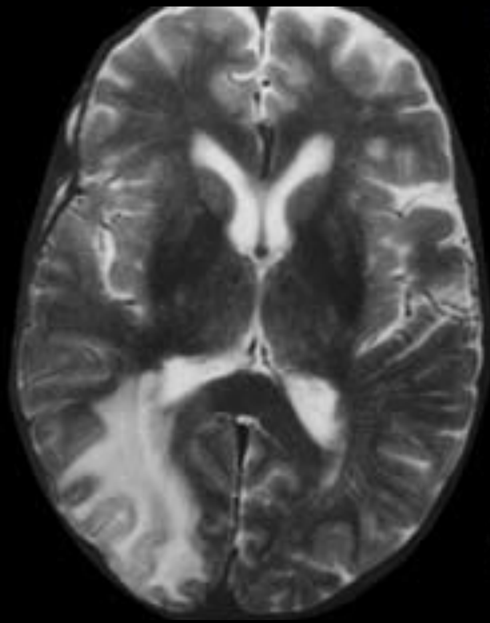
Principal diffusion direction (PDD)

At each voxel, fit the diffusion tensor model

Can then calculate MD, FA, PDD from fitted parameters

Mean diffusivity (MD)

Control MD



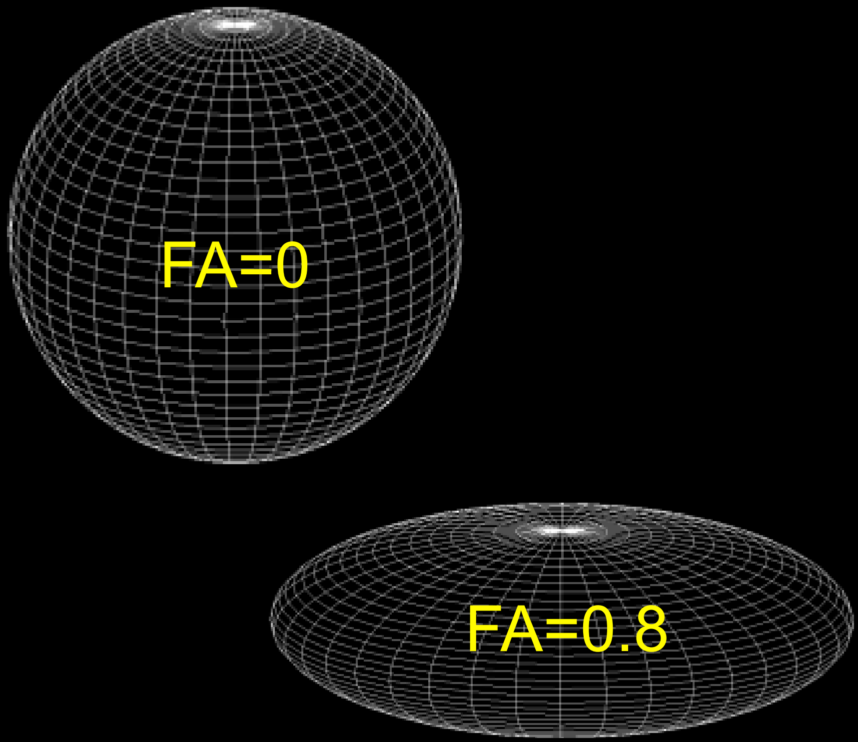
Acute Stroke

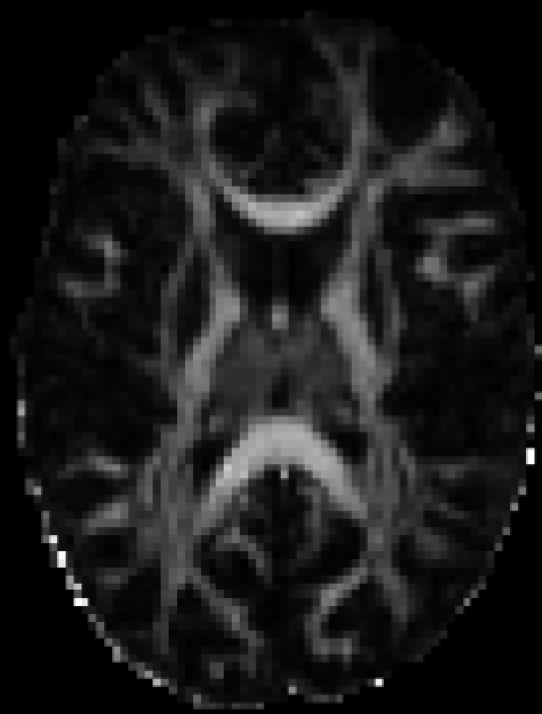
Mean diffusion coefficient across all directions

Correlate of tissue integrity (white and gray matter)

Example: MD is altered in acute and chronic stroke

Fractional Anisotropy (FA)



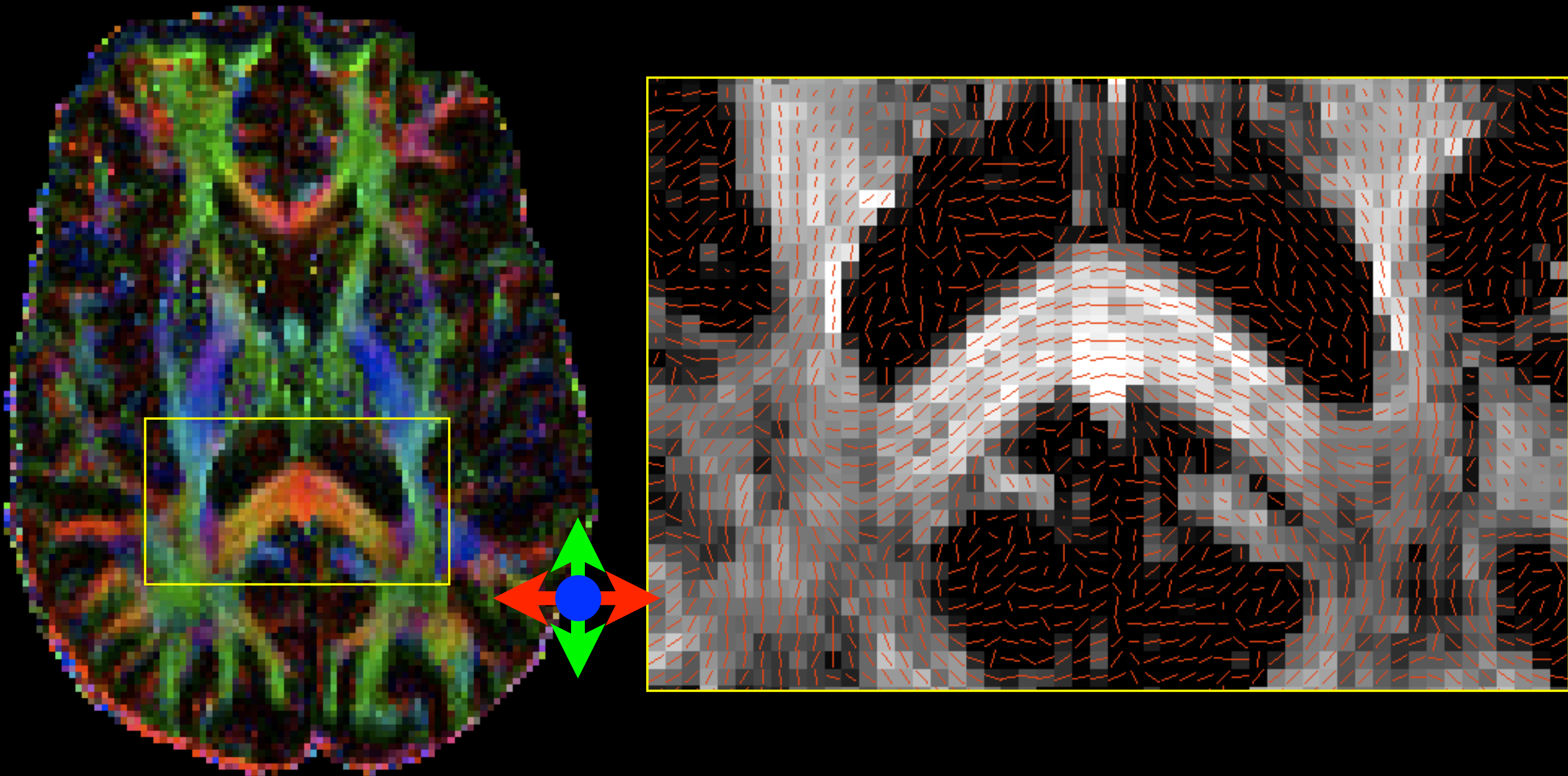


Variance of diffusion coefficient across different directions

High in regions where diffusion is most directional

Relates to integrity of white matter fiber bundles

Principal diffusion direction (PDD)

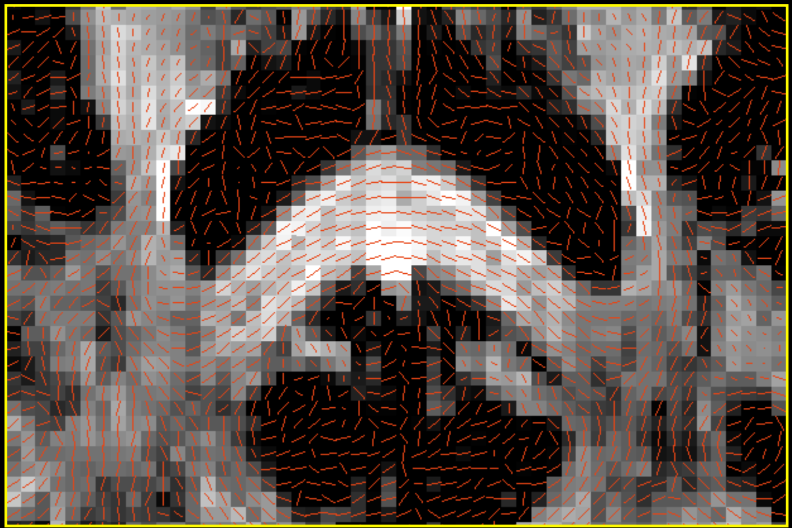


Direction along which greatest diffusion occurs

Relates to direction of fiber orientations

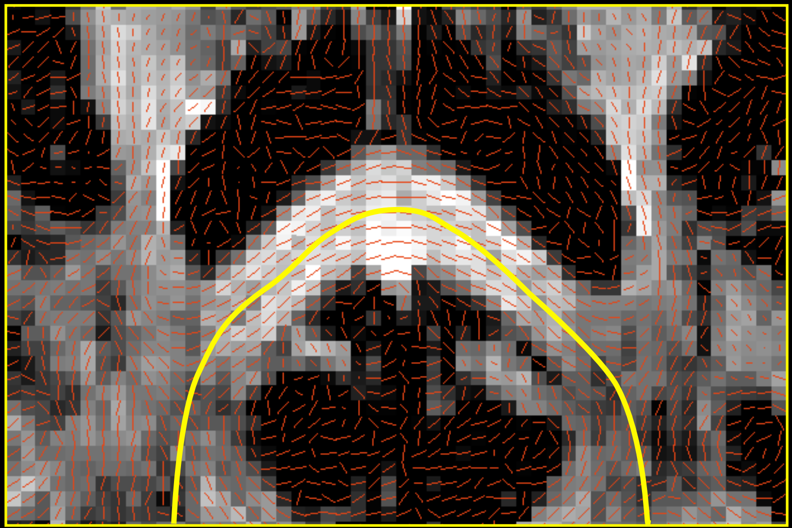
Diffusion tractography

Follow PDD to trace white matter fibers ("tractography")



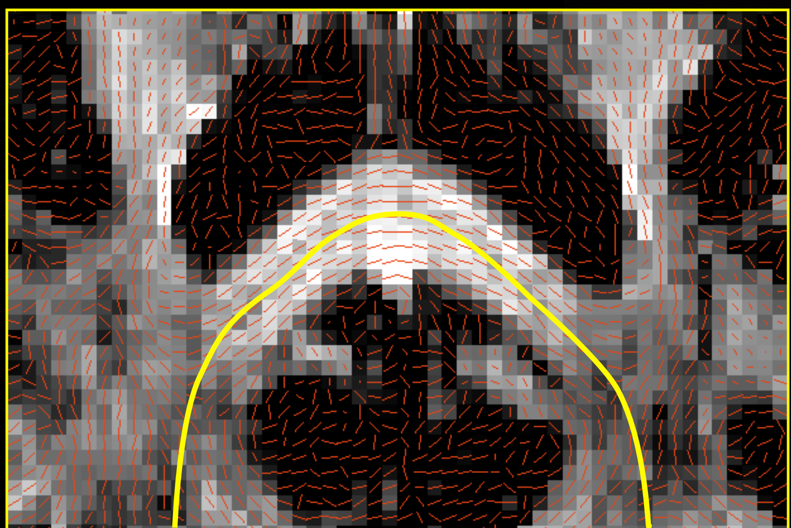
Diffusion tractography

Follow PDD to trace white matter fibers ("tractography")



Diffusion tractography

Follow PDD to trace white matter fibers ("tractography")



Jones et al

Typical* Diffusion Imaging Parameters

* Typical, *not* fixed!!

Parameter	Value	Relevant points
T_E (echo time)	100 ms	Limited by b-value
Matrix size / Resolution	128x128 / 2 mm	Limited by distortion, SNR
Number of directions	6-60	Lower limit: tensor model Upper limit: scan time
b-value	1000 s/mm^2	Larger b = more contrast Smaller b = more signal

Acknowledgements

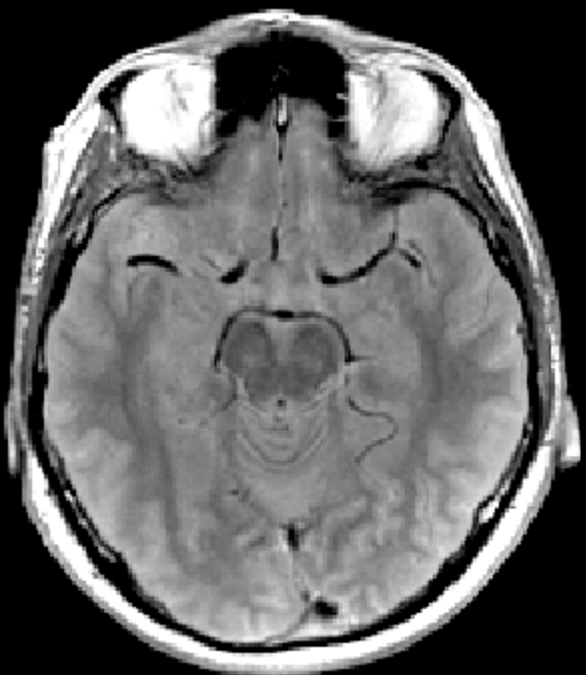
- Karla Miller for the slides
- Previous years lecture (and more) available at www.fmrib.ox.ac.uk/~karla
- Animations: Spinbench

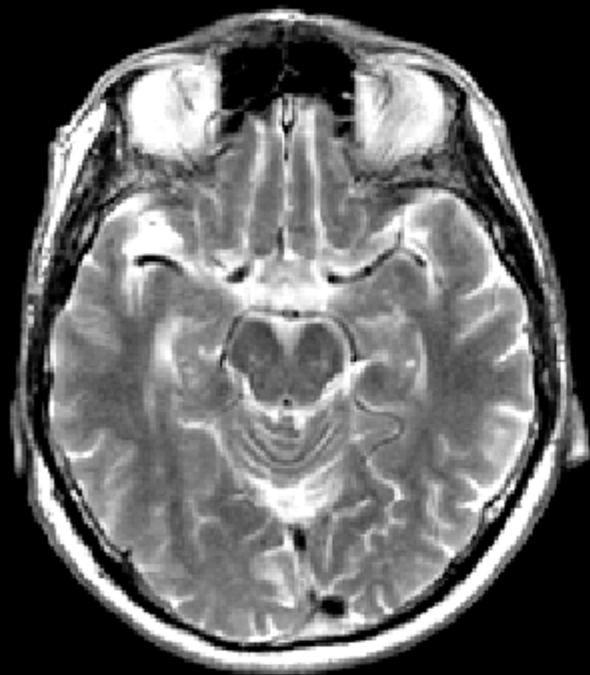
Thank you for your attention!

MRI Physics

- Spin vs. gradient echo
- Fast imaging & artefacts
- Diffusion MRI
  - Diffusion weighting
  - Acquisition techniques
  - Tradeoffs & complications

Image Contrast



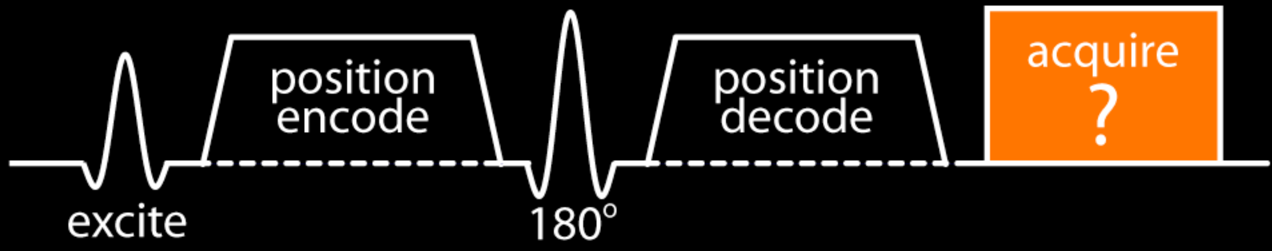


PD-weighted T_1-weighted T_2-weighted

MRI Physics

- Spin vs. gradient echo
- Fast imaging & artefacts
- Diffusion MRI
  - Diffusion weighting
  - Acquisition techniques
  - Tradeoffs & complications

Acquiring the image

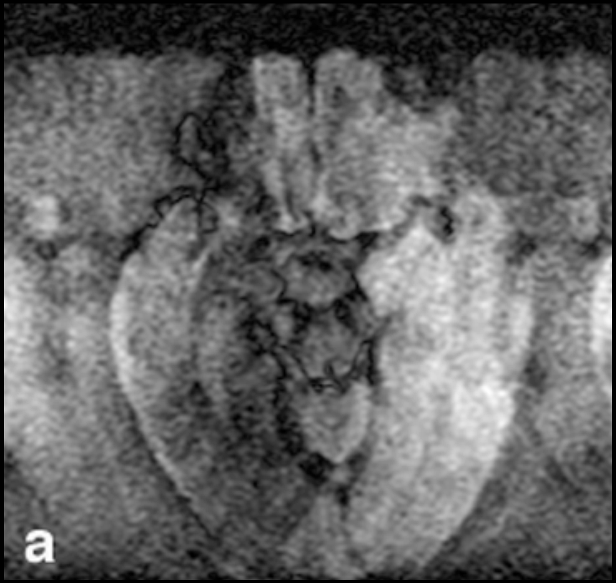


Theoretically, any acquisition can be used

- linescan
- rapid scan (EPI)
- etc...

In practice, motion sensitivity dictates what is possible

Motion in DWI



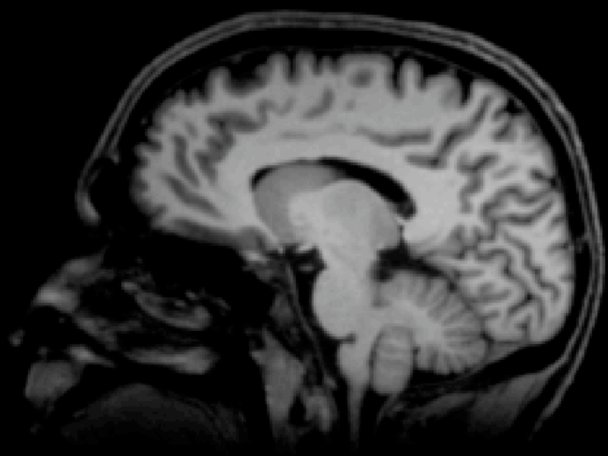
Linescan diffusion image

Diffusion gradients encode tiny displacement

Subject motion is also accidentally encoded

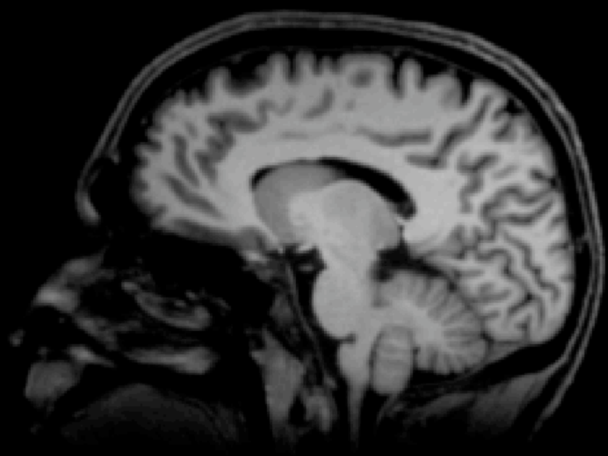
Image artefacts if we try to combine data from multiple excitations (different motion)

Can motion be avoided?



Subject restraints can reduce bulk motion, but...

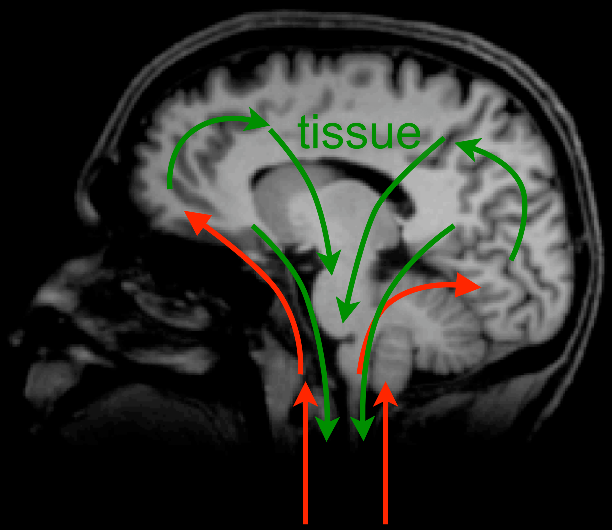
Can motion be avoided?



Subject restraints can reduce bulk motion, but...

...in the brain, there is significant non-rigid motion from cardiac pulsatility

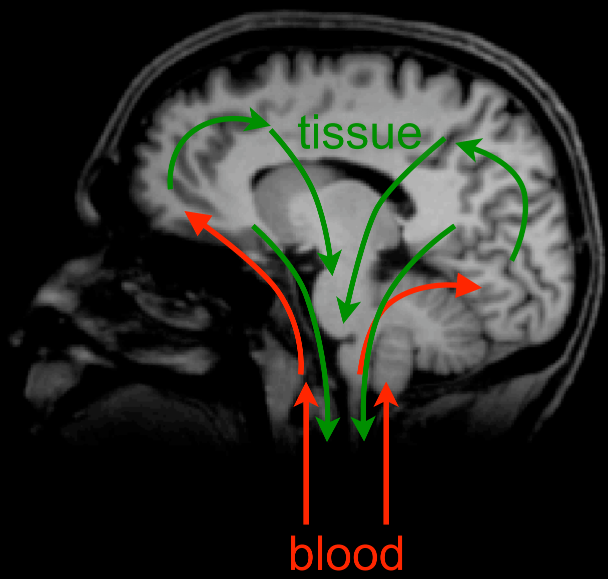
Can motion be avoided?



Subject restraints can reduce bulk motion, but...

...in the brain, there is significant non-rigid motion from cardiac pulsatility

Can motion be avoided?

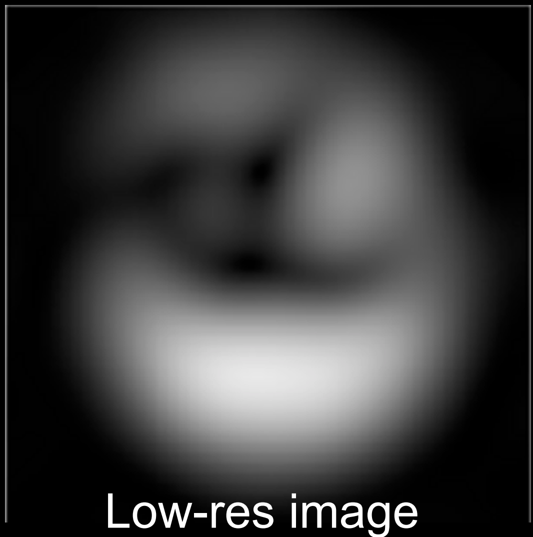


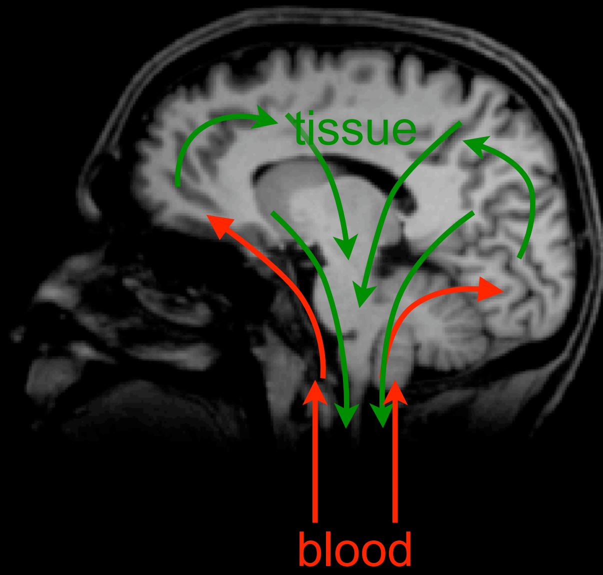
Subject restraints can reduce bulk motion, but...

...in the brain, there is significant non-rigid motion from cardiac pulsatility

cardiac gating helps, but brain is never very still!

Can motion be avoided?



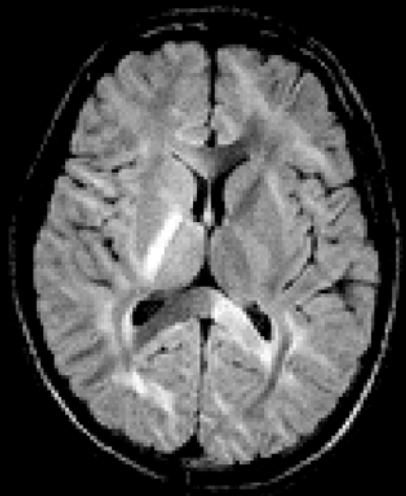


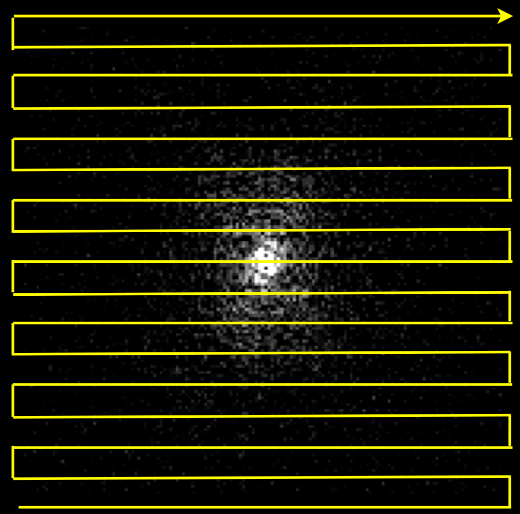
Subject restraints can reduce bulk motion, but...

...in the brain, there is significant non-rigid motion from cardiac pulsatility

cardiac gating helps, but brain is never very still!

Single-shot echo-planar imaging (EPI)





magnetization EPI acquisition $b=1000\ s/mm^2$

Single-shot imaging freezes motion

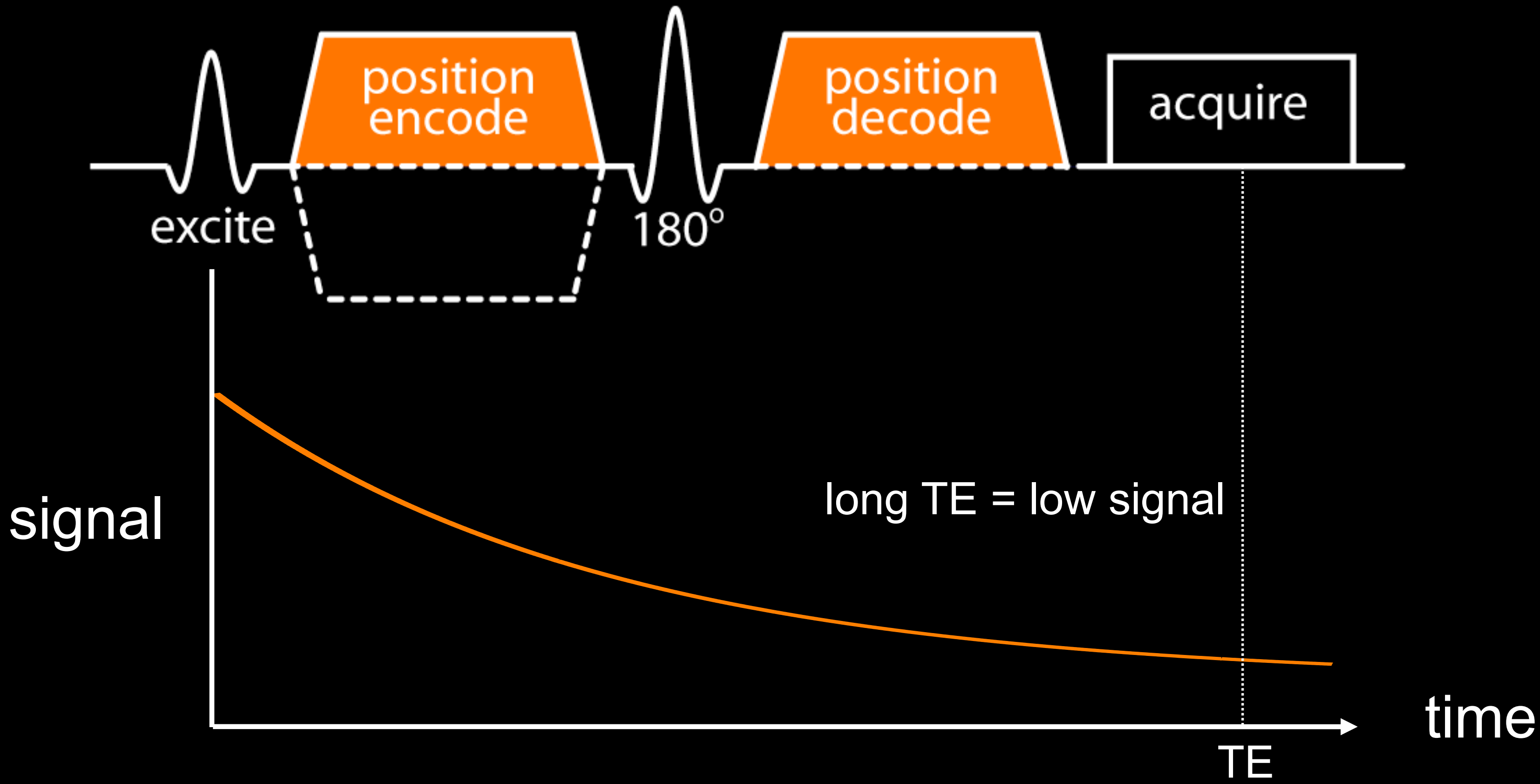
Most common method is echo-planar imaging (EPI)

Images have distortion and limited resolution

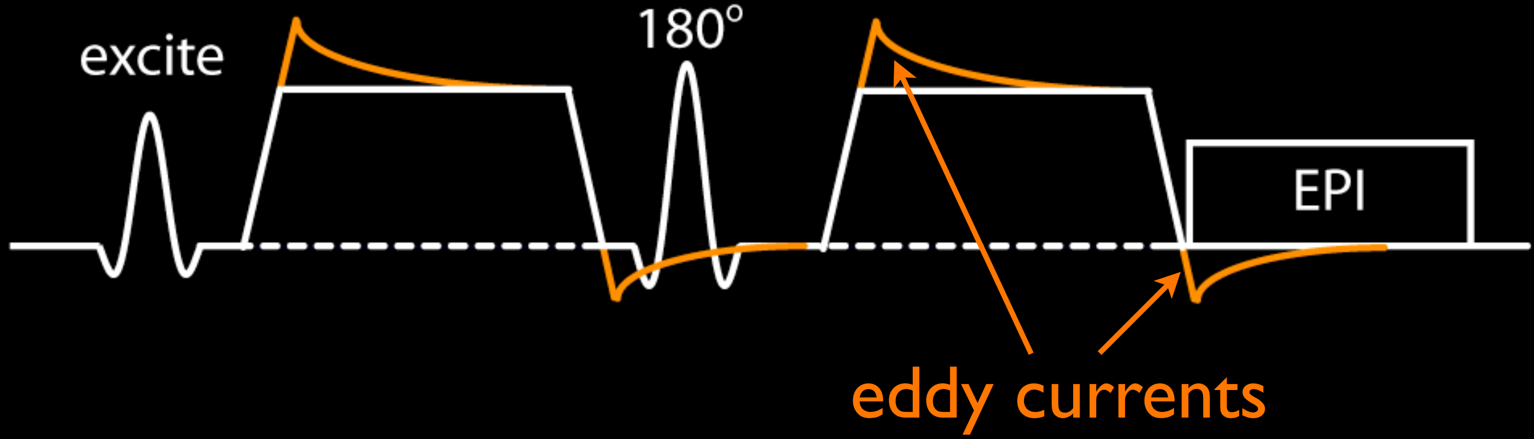
MRI Physics

- Spin vs. gradient echo
- Fast imaging & artefacts
- Diffusion MRI
  - Diffusion weighting
  - Acquisition techniques
  - Tradeoffs & complications

Tradeoff: diffusion weighting vs TE



Eddy Currents

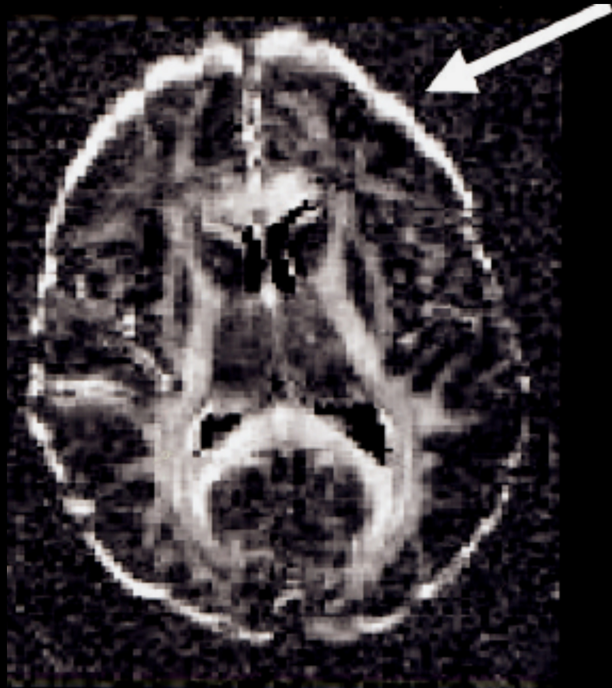


Diffusion gradients create large eddy currents, which persist into acquisition window

Distort the k-space trajectory, casing shears/scaling of images

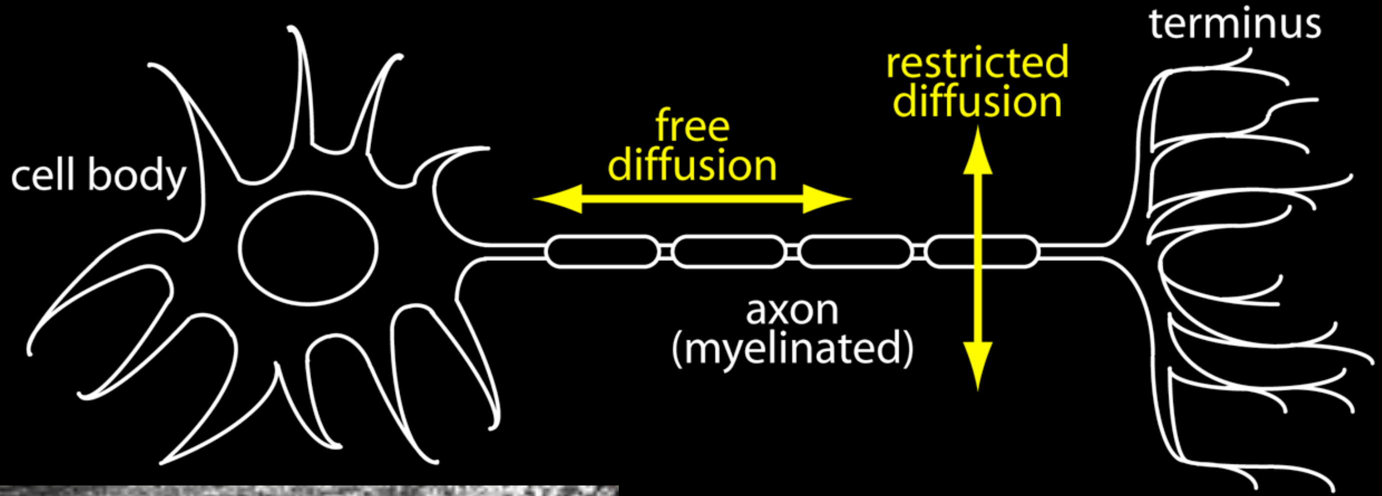
Eddy Currents

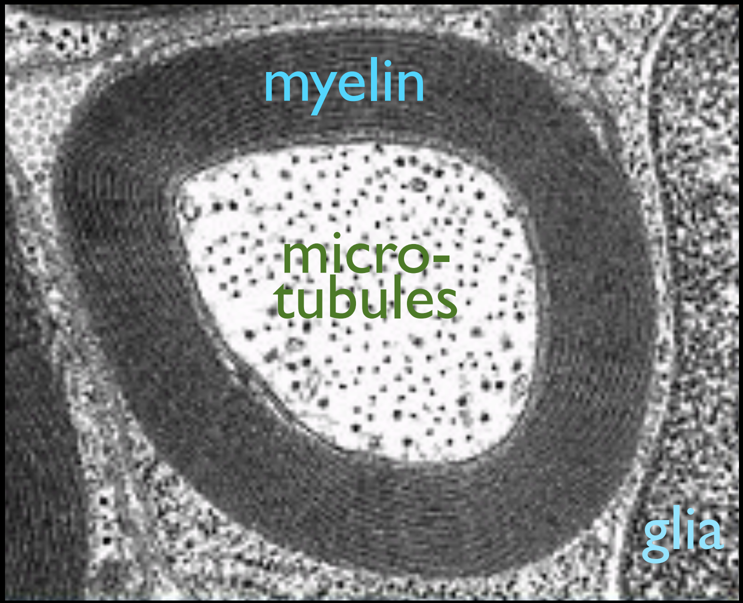
Diffusion-weighted
directions



Fractional Anisotropy
(“variance”)

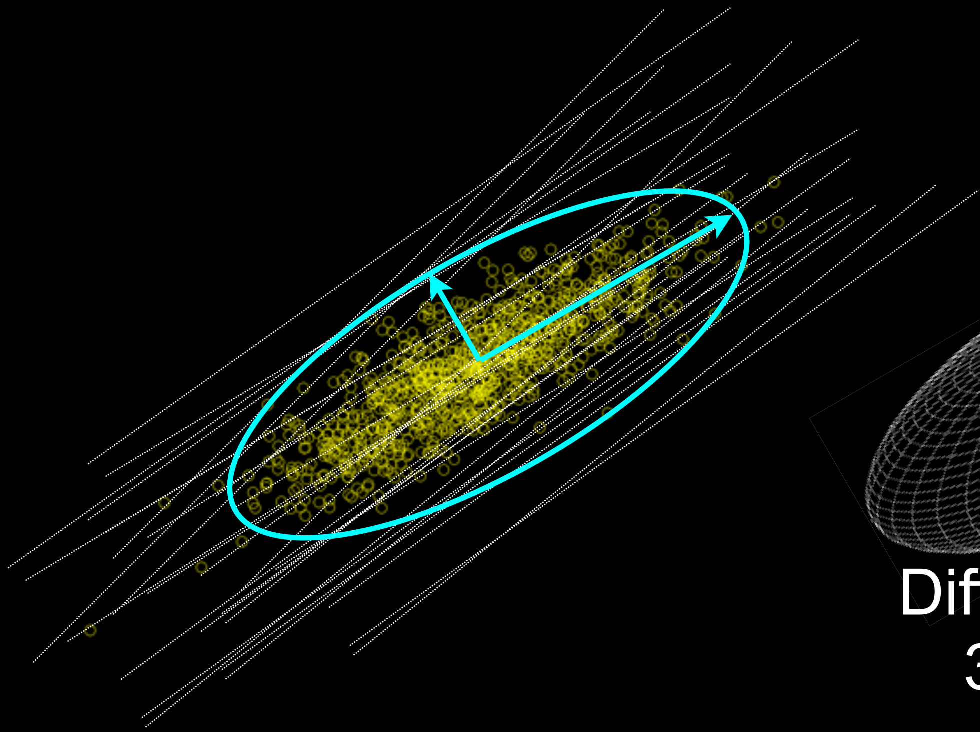
Biological interpretation: what is "integrity"?

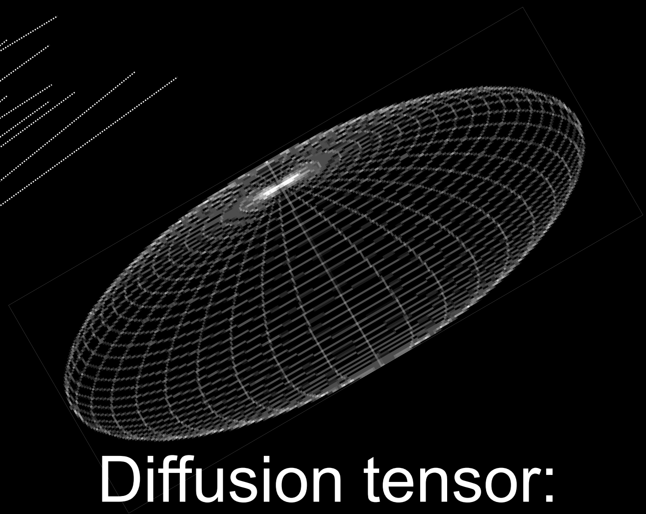




Changes in FA could reflect:
- myelin sheath
- membrane integrity
- axon density
- glial density
- fiber coherence
- etc etc

The diffusion tensor



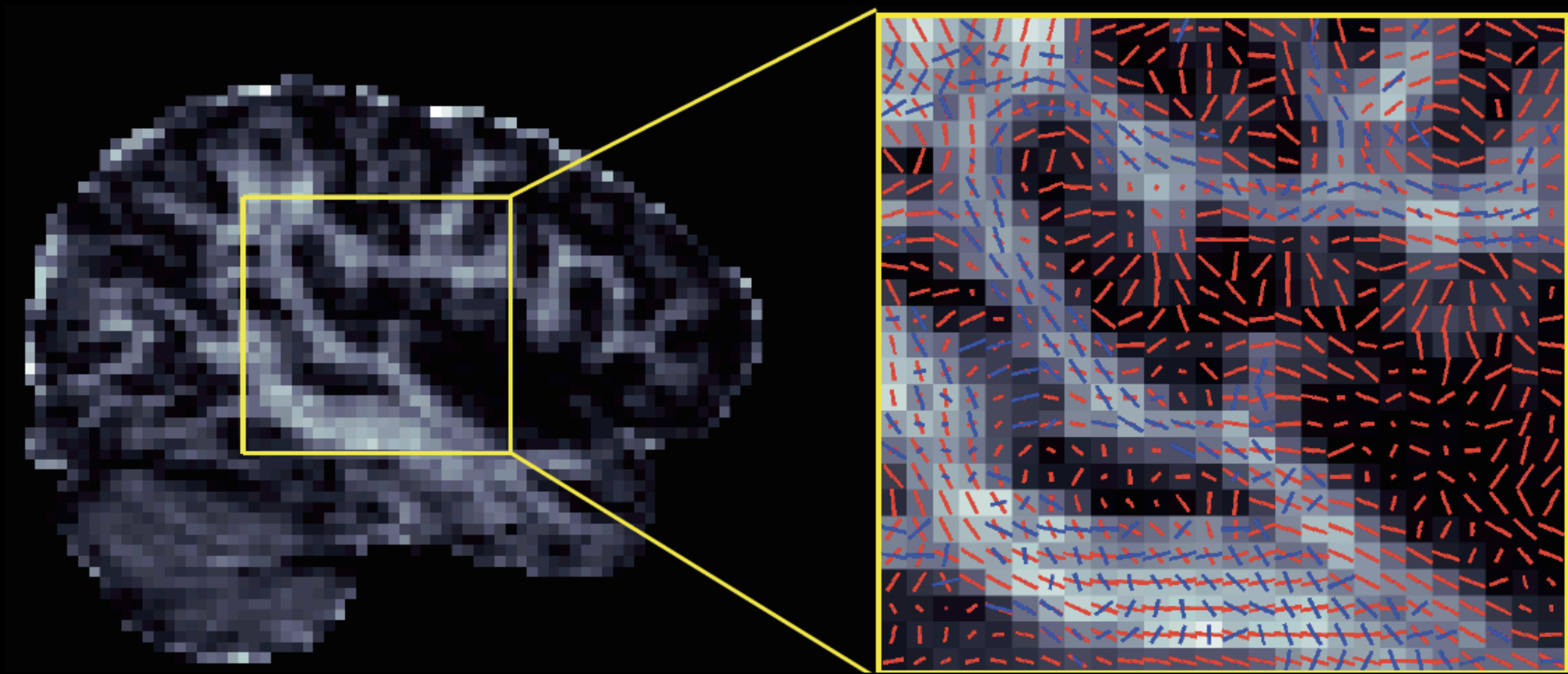


Diffusion tensor:
3D ellipsoid

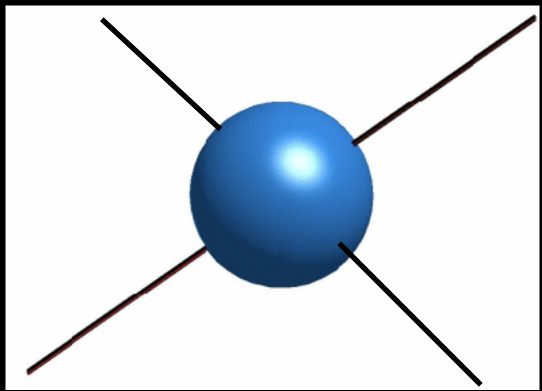
The diffusion tensor is just one possible signal model

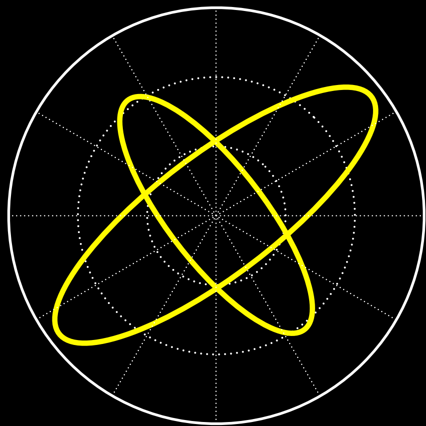
Voxels containing multiple fibres

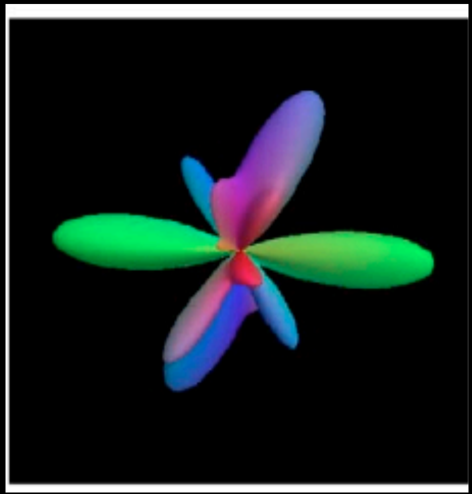
Voxels containing multiple fibres



How to encapsulate multiple fibres?



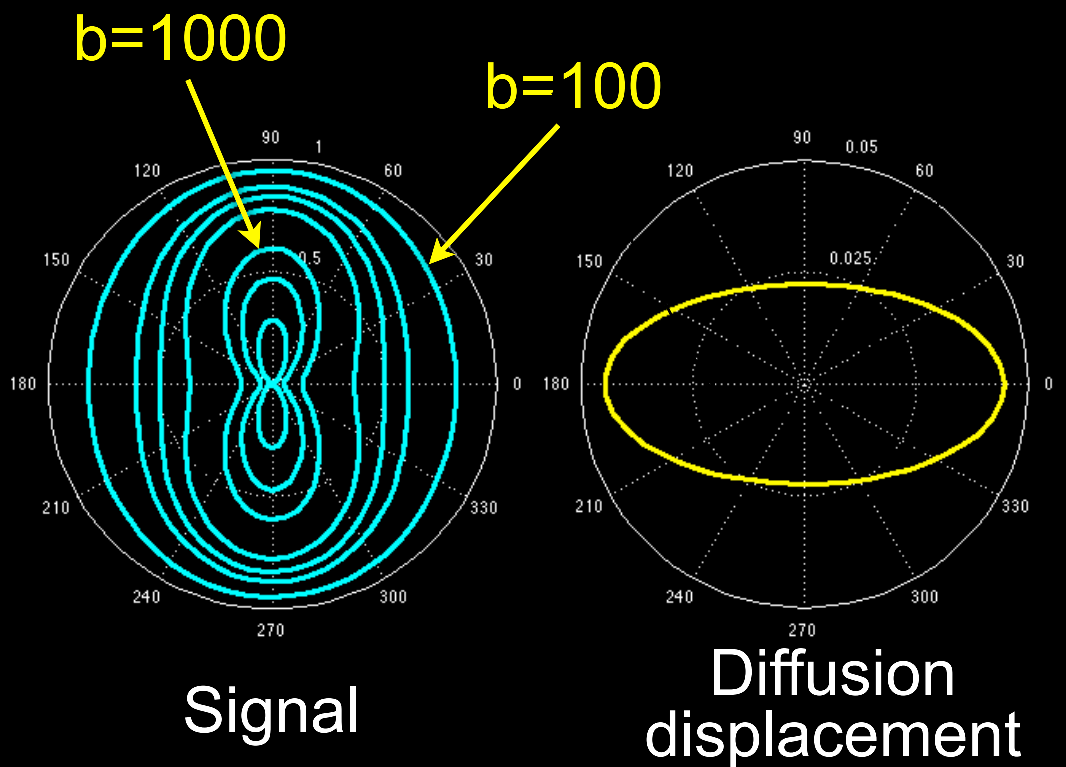




How to model more complex architecture

- Multiple sticks?
- Multiple tensors?
- More sophisticated models?

b-value: how high is enough?

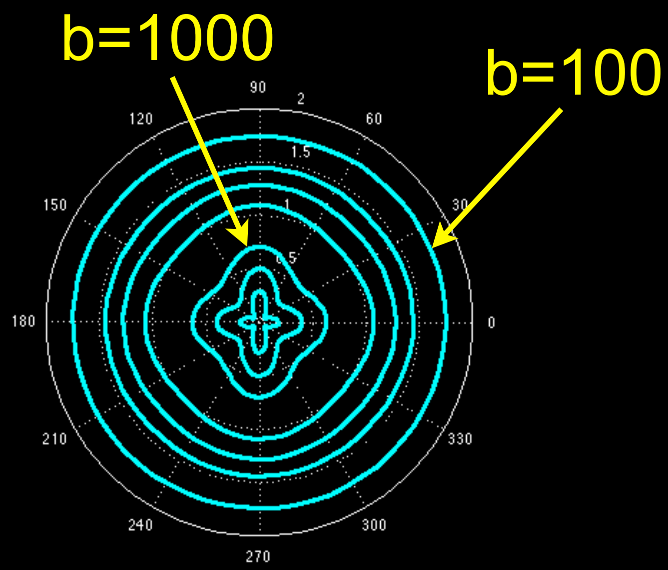


Common rule of thumb: set b=1/D

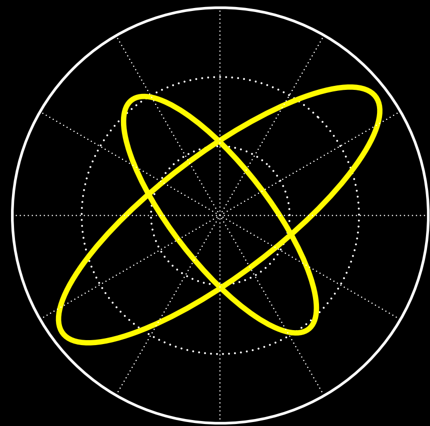
In white matter, that gives b≈1000 s/mm^2

Need some “shape” to the signal profile

b-value: how high is enough?



Signal



Diffusion displacement

What if there are multiple fibres in a voxel?

Shape at a given b-value is less distinct

Directions: how many are enough?

Few directions | More directions

Single fibre

Two fibres