MRI basics

MR Physics for SPM

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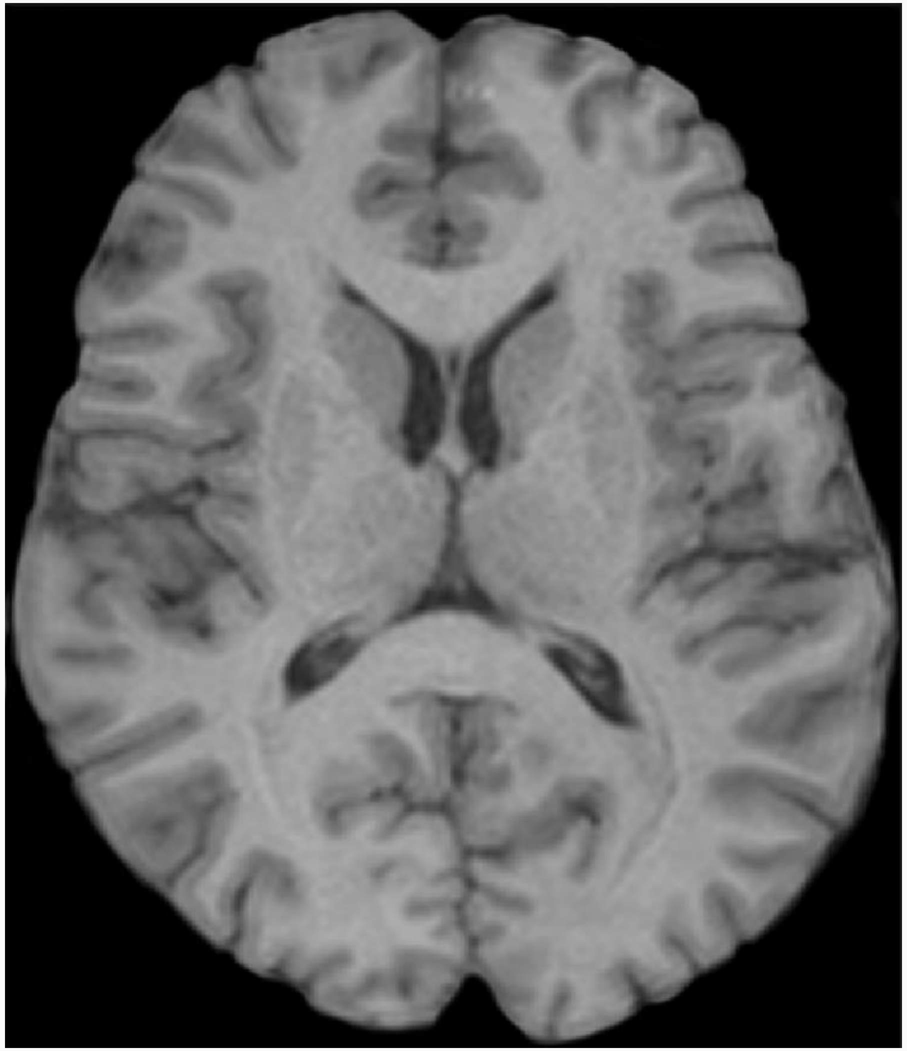
MR Physics for SPM - May 2026

Functional Imaging Laboratory
Department of Imaging Neuroscience

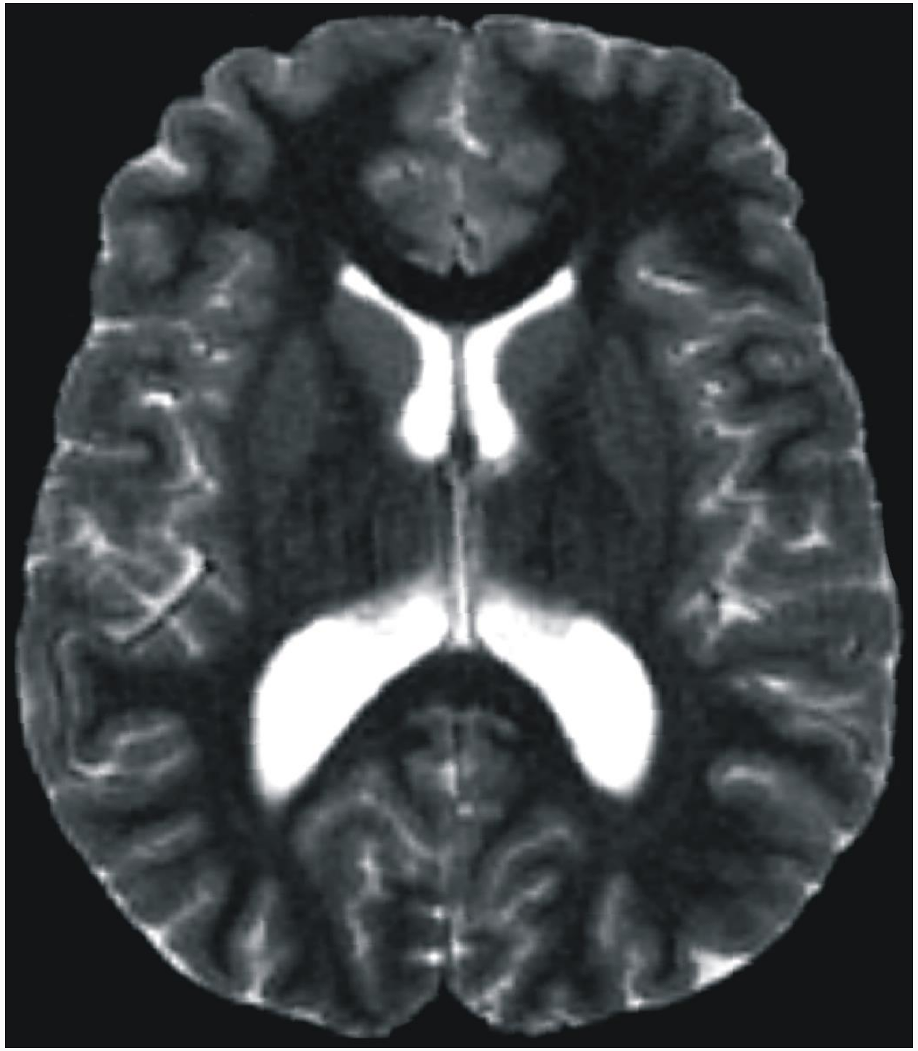
Introduction



MRI provides 3D images of the brain with great contrast between structures:

→ Where does the signal come from ?
→ How do we measure the signal ?

Introduction



MRI provides 3D images of the brain with great contrast between structures:

➔ Where does the signal come from ?
➔ How do we measure the signal

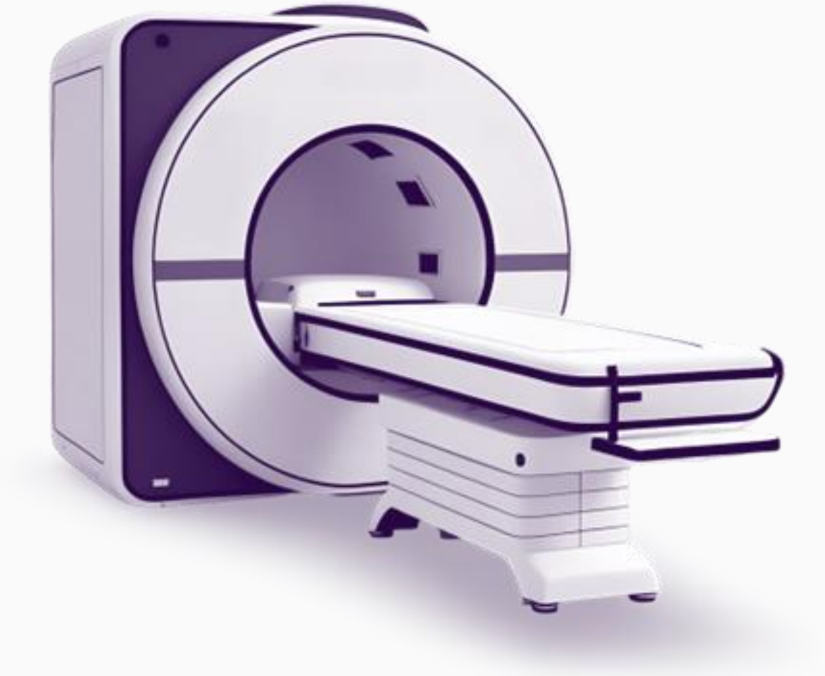
MRI can provide different types of contrasts to highlight specific structures

➔ How can we control image contrast ?

Objectives

- To introduce basic concepts behind MRI and the key hardware components
- To provide some intuition for image contrast
- To understand an MRI methods section in publication

Magnetic fields in MRI



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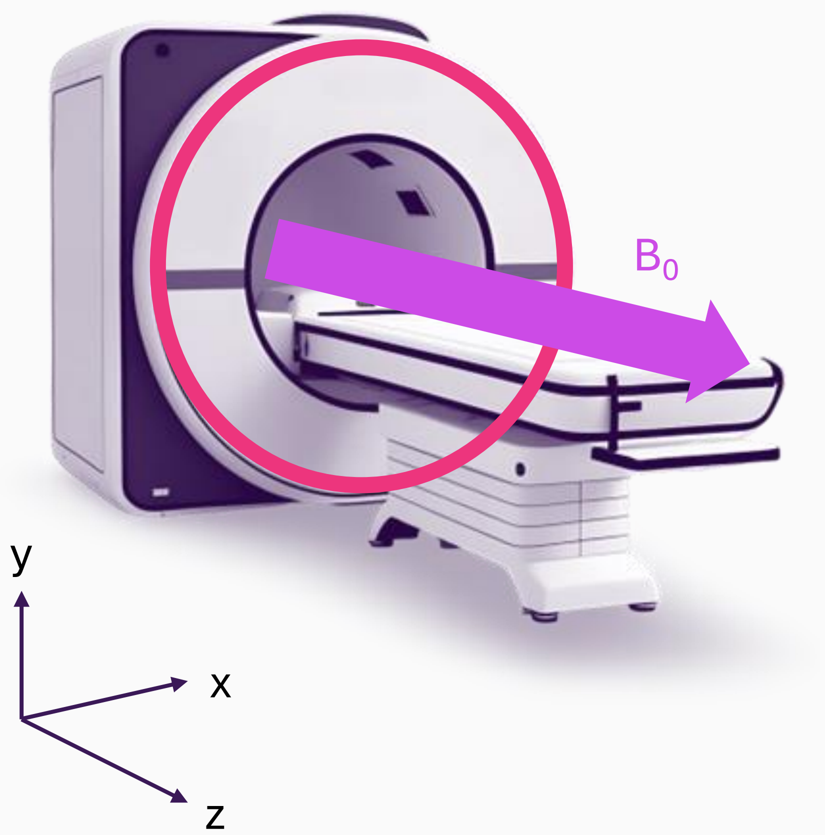
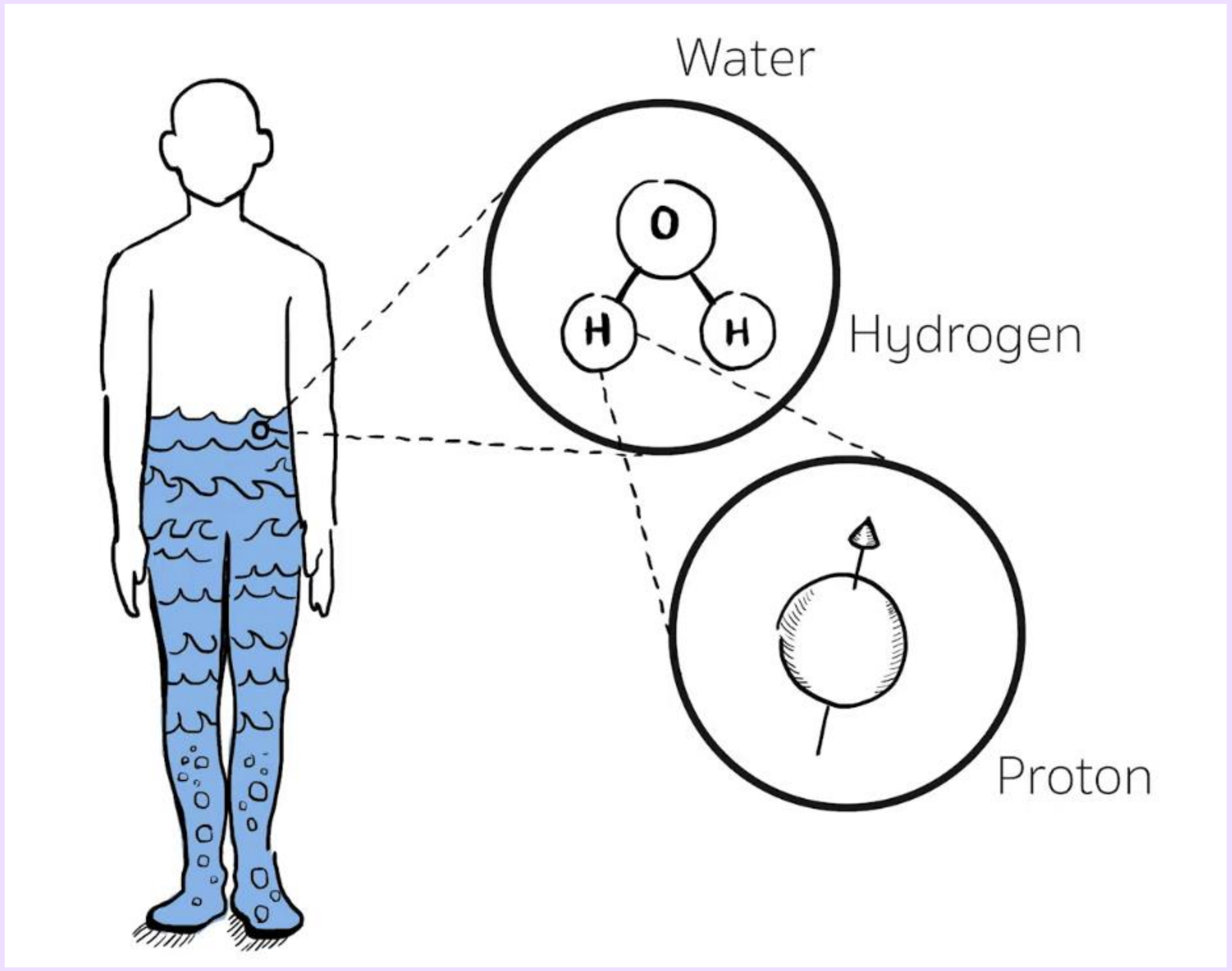
Magnetic fields in MRI



B_0 is the main magnetic field

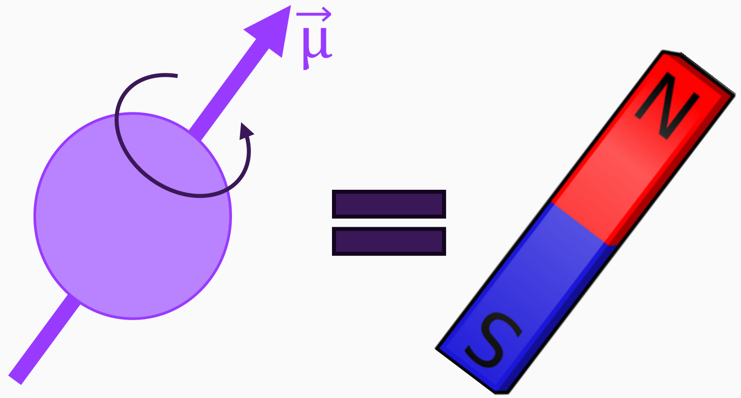
- It points out of the scanner (z by convention)
- It is always ON
- Its amplitude is constant (3T for example)

Magnetic fields in MRI



Illustrations: Nadine Graëdel & Alice Haskel

- Atoms with an odd number of protons or neutrons, like hydrogen protons, have ”spin”
- Atoms with spin have magnetic properties that make them act like small magnets

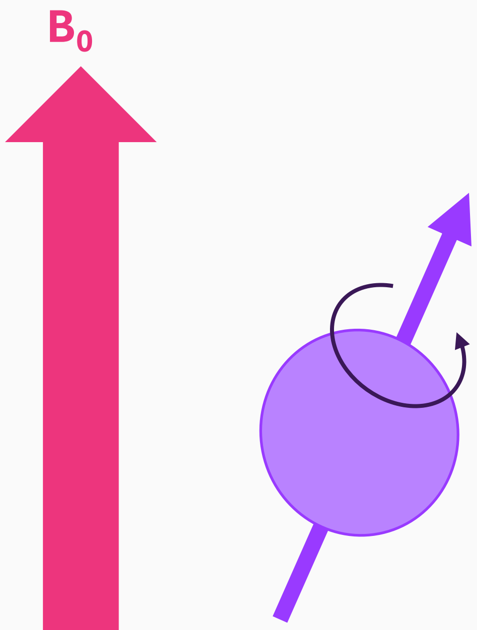


Hydrogen Proton

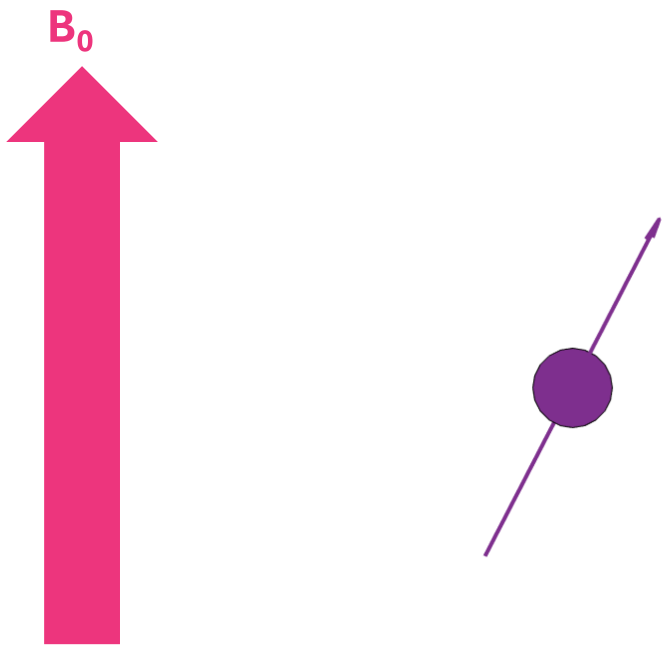
$\vec{\mu}$: magnetic moment

- When an object is spinning , it will rotate around the direction of an applied force
- *E.g.* if this object was stationary, it would fall over if tipped
- This is called a movement of **precession**

Think Spinning top or gyroscope



- With an external magnetic field B_0, all protons precess around the B_0 axis
- The rotation frequency is defined by the **Larmor frequency**
- The gyromagnetic ratio of the hydrogen proton is $\gamma = 240e^6\ rad.s^{-1}.T^{-1}\ \left(\frac{\gamma}{2\pi} = \frac{42\ MHz}{T}\right)$



Larmor equation

$$\boldsymbol{\omega = \gamma B}$$

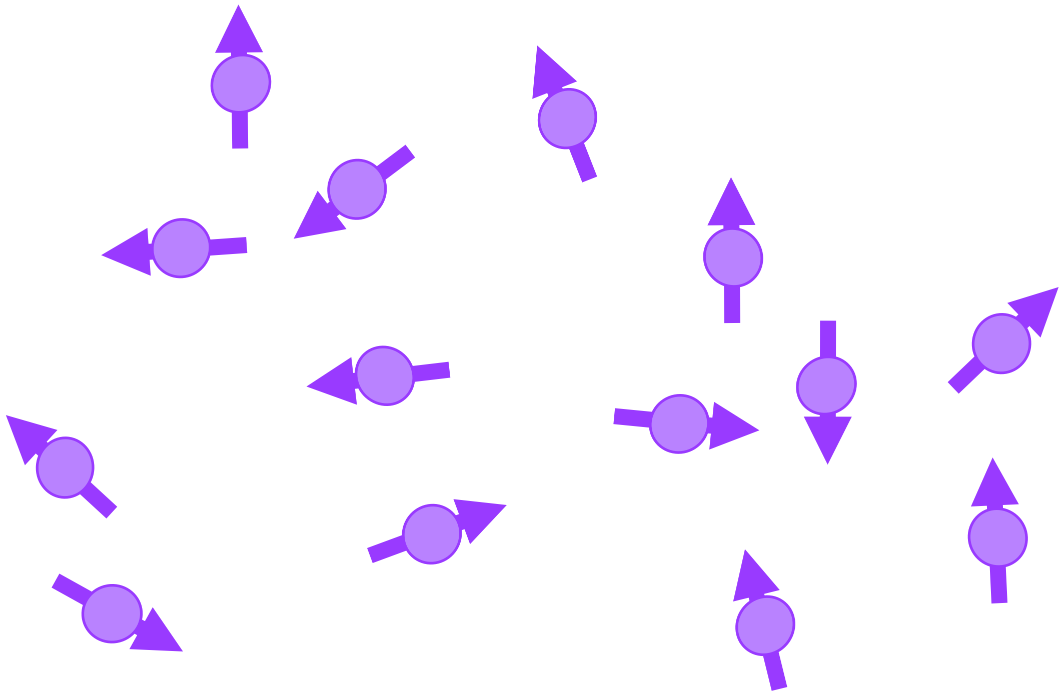
At 3T, the resonance frequency of the hydrogen proton is 128 MHz at 3 T (3T*42 MHz/T)

Equation of motion :

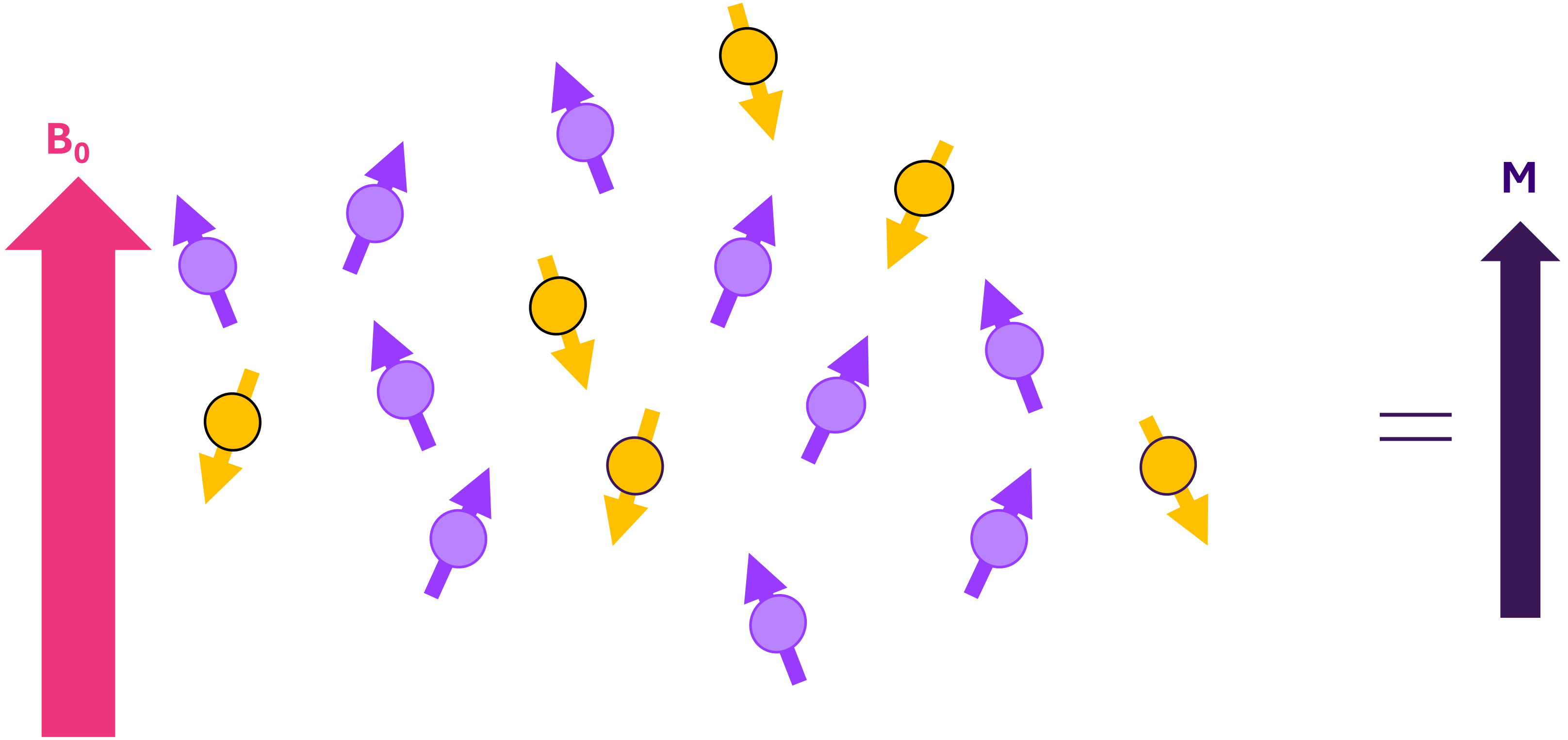
$\overrightarrow{B_0}$ applies a torque on $\vec{\mu}$:

$$\frac{d\vec{\mu}}{dt} = \gamma\vec{\mu} \times \overrightarrow{B_0}$$

- Without an external magnetic field, the orientation of the protons is random



- With an external magnetic field, at equilibrium, only two orientations (two opposite angles from B_0) are possible (“parallel” and “anti-parallel”)
- Slightly more protons are in the low energy level (parallel)
- This ratio increases with the amplitude of the external magnetic field
- This results in **a net magnetization** parallel to B_0



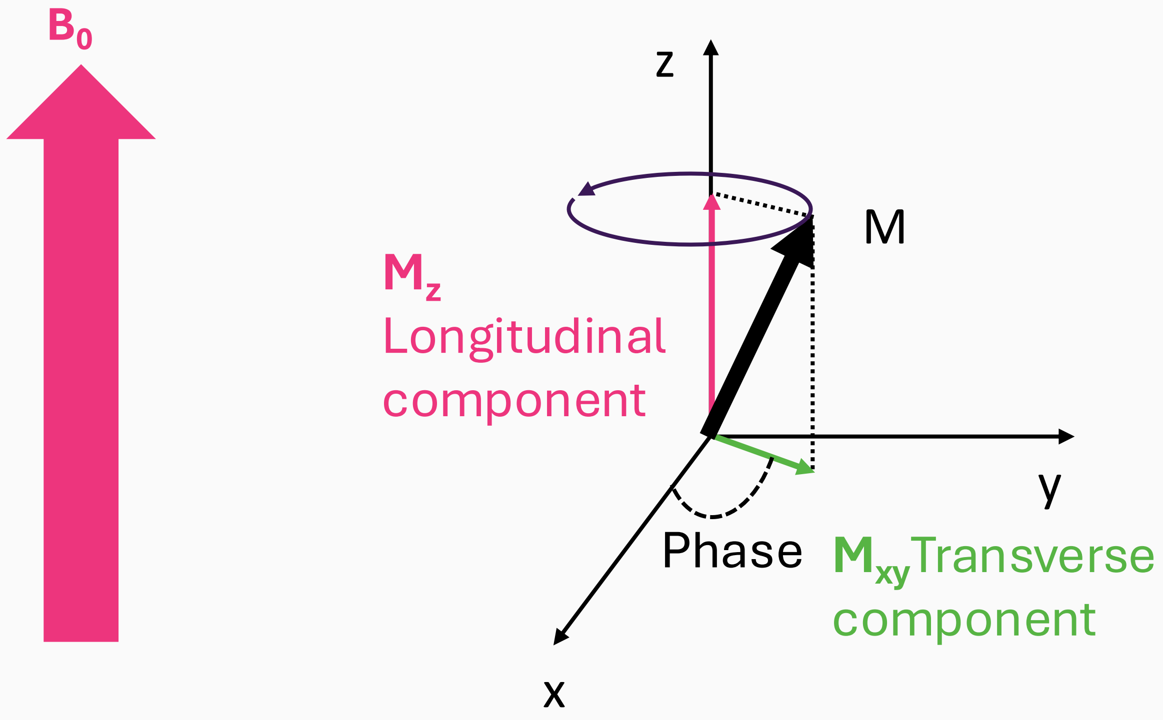
With an external magnetic field, the tiny magnets add up to create a net magnetization M, parallel to B_0 at the equilibrium

M is the quantity of interest here !

$$\vec{M} = \sum_{Voxel} \vec{\mu_i}$$

The net magnetization M

- The vector M can be decomposed in two components
- **In MRI, we only measure the transverse component which is null at the equilibrium**
- M also precesses at the **Larmor frequency** around the magnetic field when disturbed from this equilibrium state

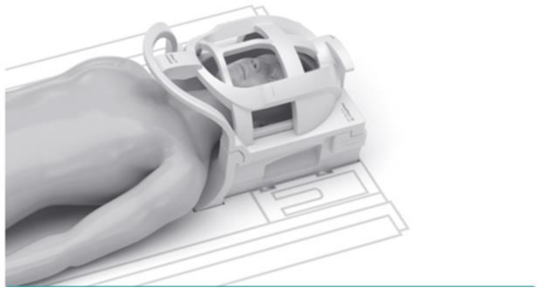


Equation of motion :

$$\vec{M} = \sum_V \vec{\mu_i} \quad and \quad \frac{d\vec{\mu}}{dt} = \gamma\vec{\mu} \times \overrightarrow{B_0}$$

$$\sum_V \frac{d\vec{\mu_i}}{dt} = \sum_V \gamma\vec{\mu_i} \times \overrightarrow{B_0} \Rightarrow \frac{d\vec{M}}{dt} = \gamma\vec{M} \times \overrightarrow{B_0}$$

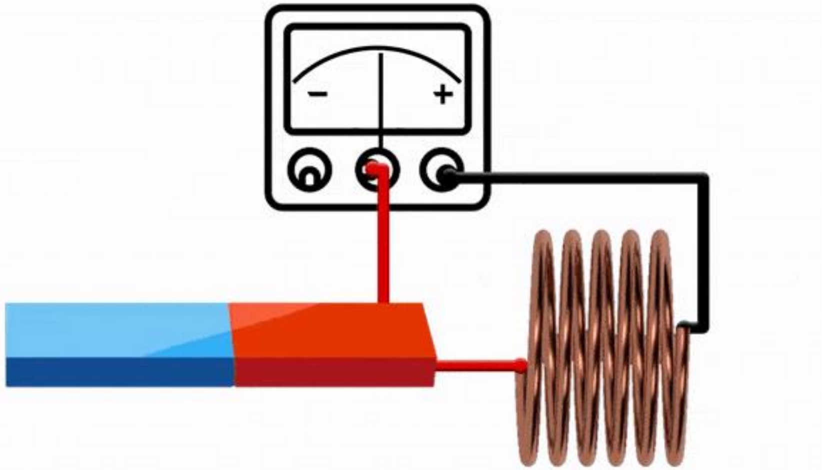
How do we measure a signal ?



- Radiofrequency coils are used to measure the signal
- The principle relies on the Faraday's law

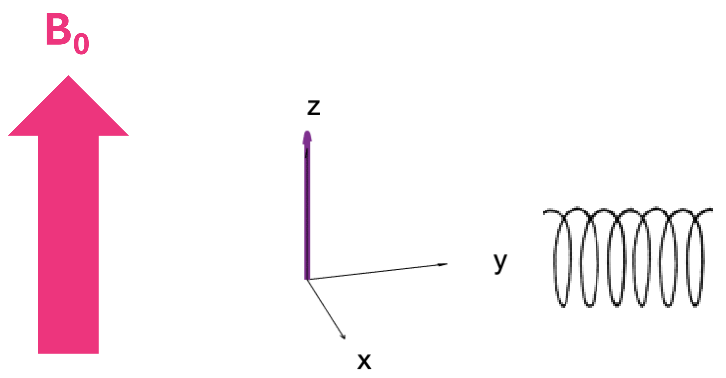
Faraday's Law

The induced electromotive force in any closed circuit is equal to the negative of the time rate of change of the magnetic flux through the circuit.

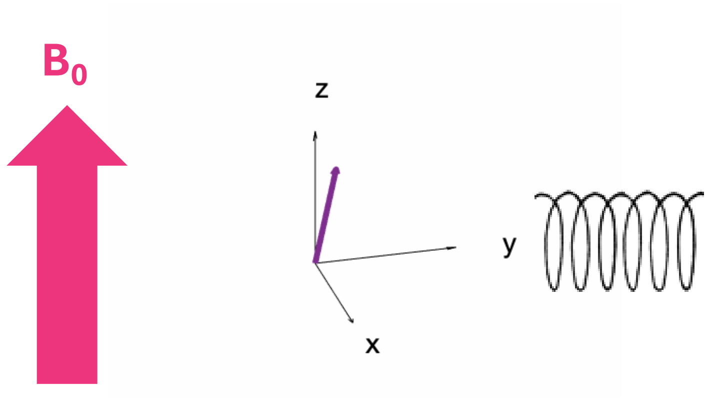


Think
Bike
Dynamo

How do we measure a signal ?

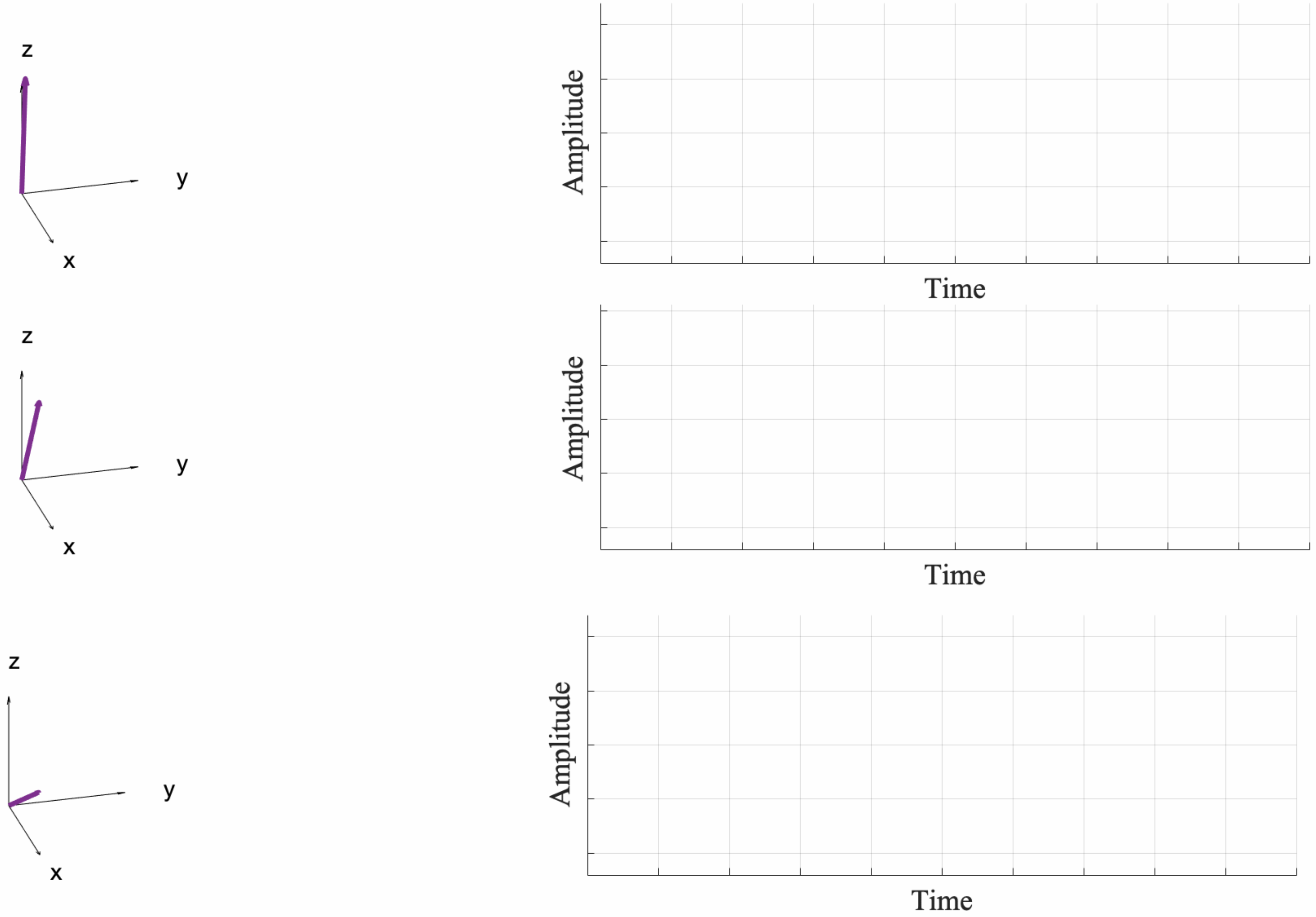


- In the equilibrium state, M is aligned with B_0
- It's static and its amplitude does not vary, NO SIGNAL !
- The trick is to disturb the equilibrium state !

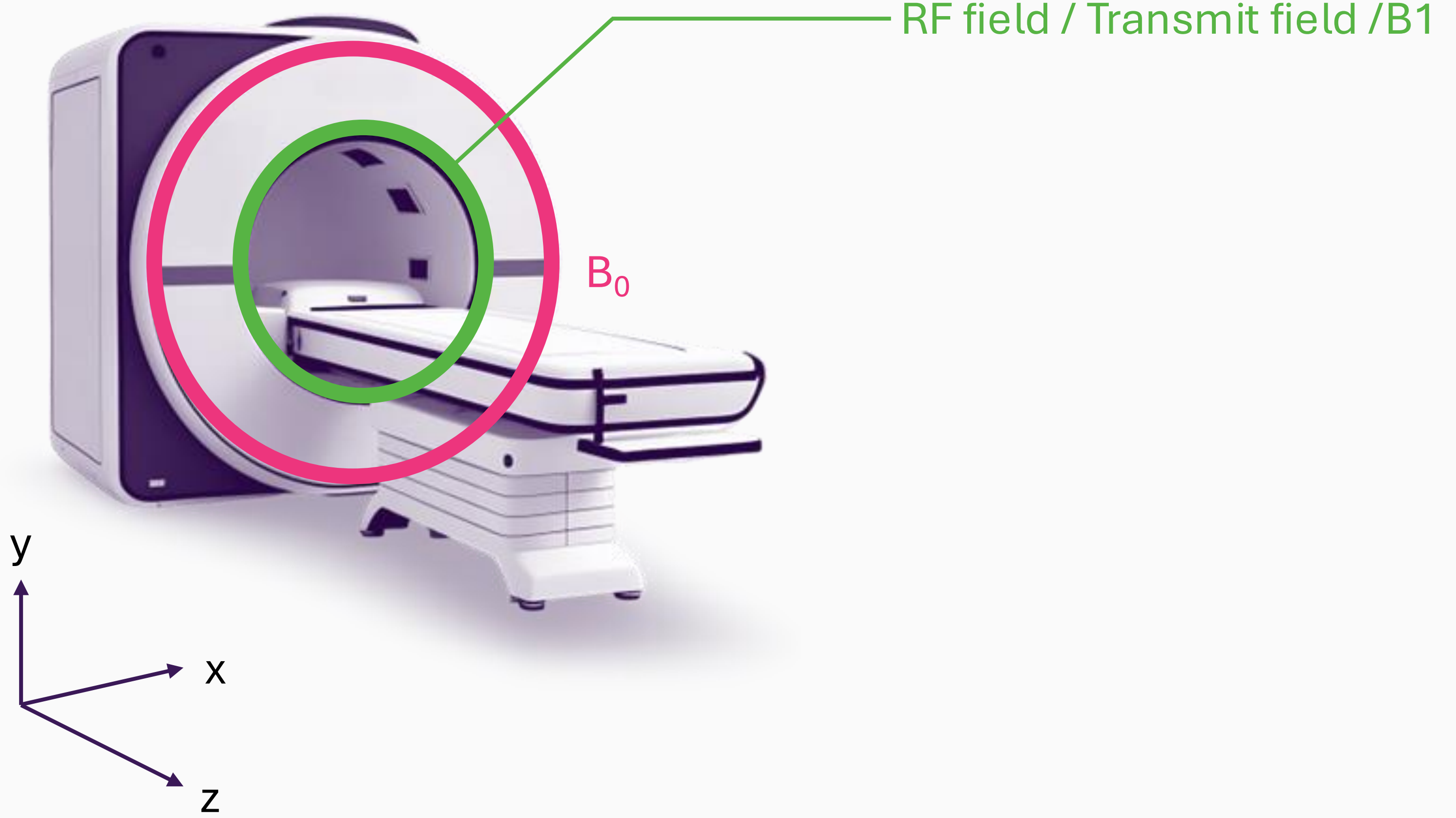


- If the net magnetization is flipped onto the transverse plane, a transverse component is created
- M precesses around B_0 at the **Larmor frequency**
- My and Mx components vary over time

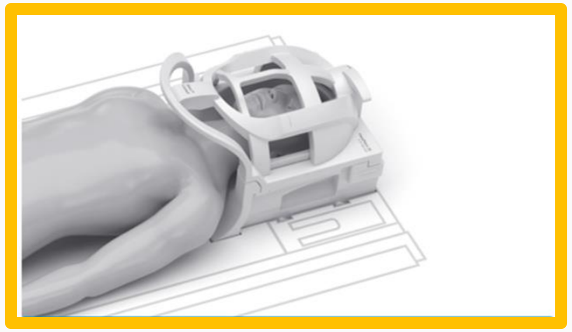
How do we measure a signal ?



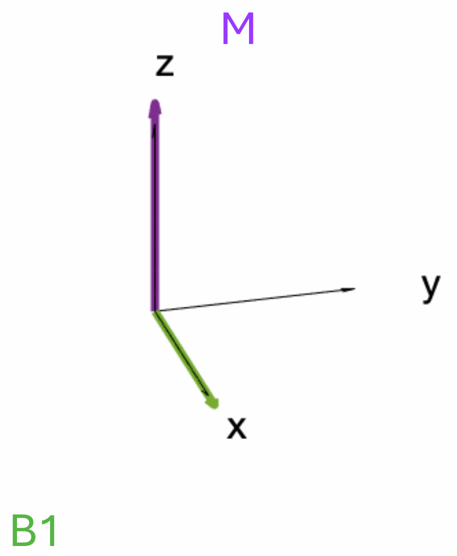
How do we generate a detectable signal ?



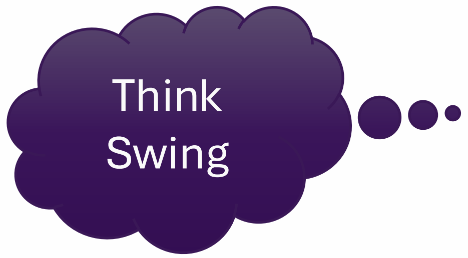
Receive RF coil



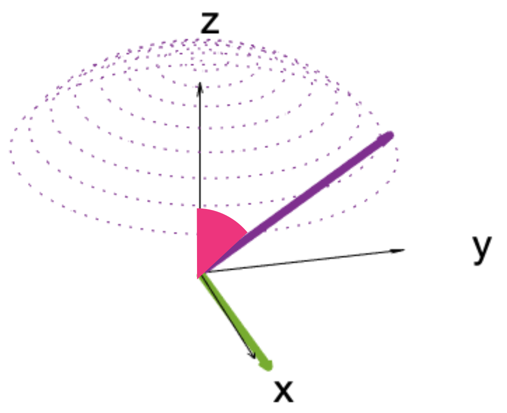
The RF Field: B_1



- This field is turned on to disturb the system from equilibrium
- This field is much smaller (in μT) and turned on for a short duration (from μs to ms)
- This field is not static but oscillates and has a frequency
- To maximize efficiency, it must oscillate at the Larmor frequency
- When B_1 is turned on, the M vector still precesses around B_0 but also around B_1 which, itself, rotates around B_0



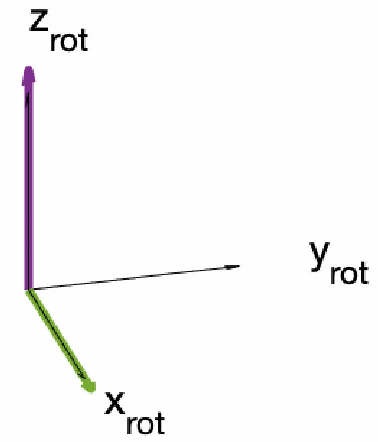
The RF Field: B_1



Flip angle

- This process of disturbance is called "Excitation"
  - The amount of "excitation" is the **flip angle**
- The flip angle increases with the amplitude of the B_1 field and its duration

The RF Field: B1

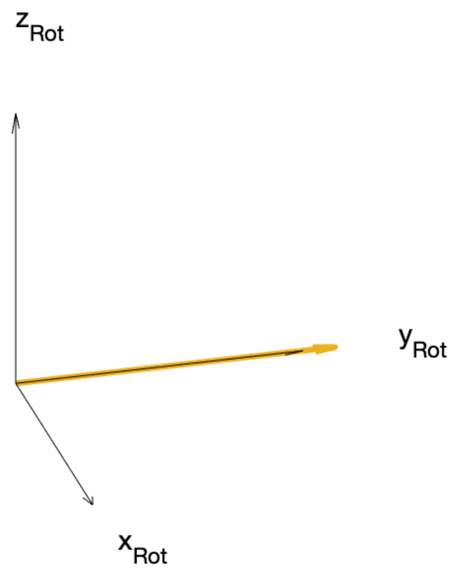


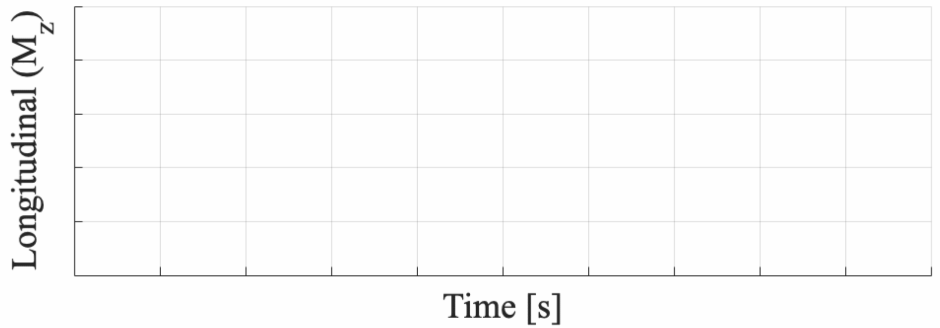
- In the **rotating frame of reference**, the excitation simplifies to only a rotation about B_0

Think Carousel

Relaxation

- Once detectable signal is generated, it decays
  - Remember the magnetisation wants to be aligned with the strong main field!

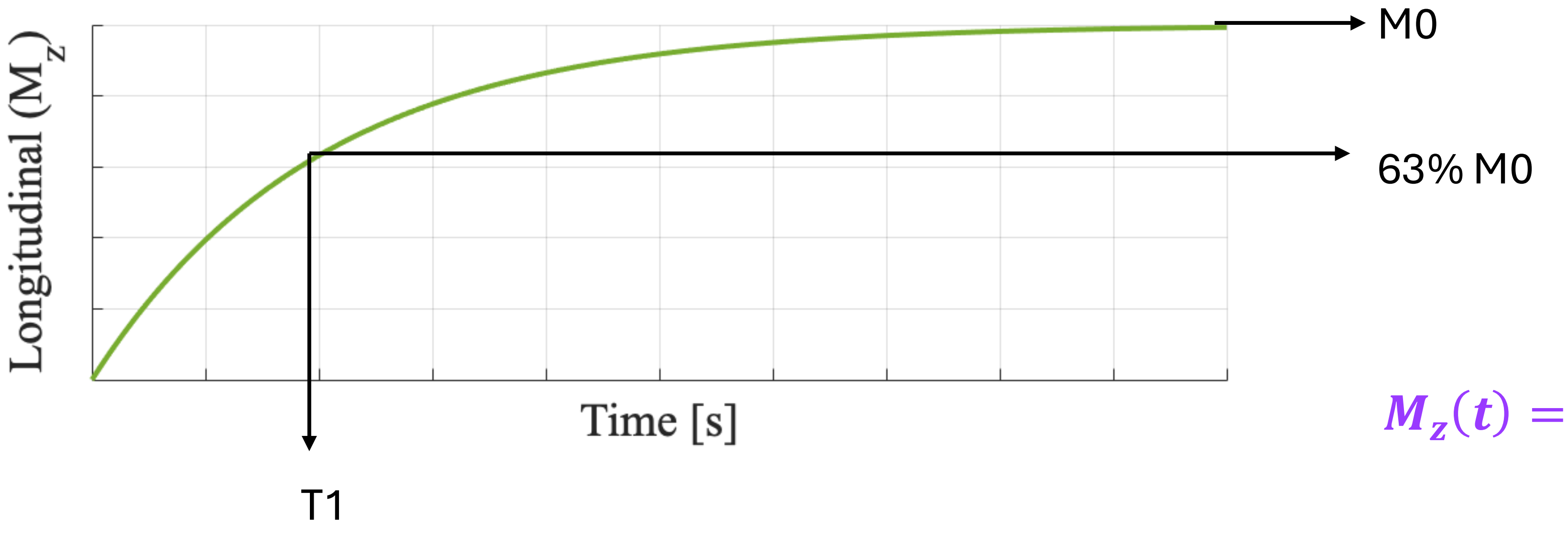




- T_1 Recovery / Relaxation of longitudinal magnetisation occurs again

T1 Relaxation Time

- Exponential recovery curve described by a time constant T1
- The time taken depends on the ability of the local environment to facilitate relaxation

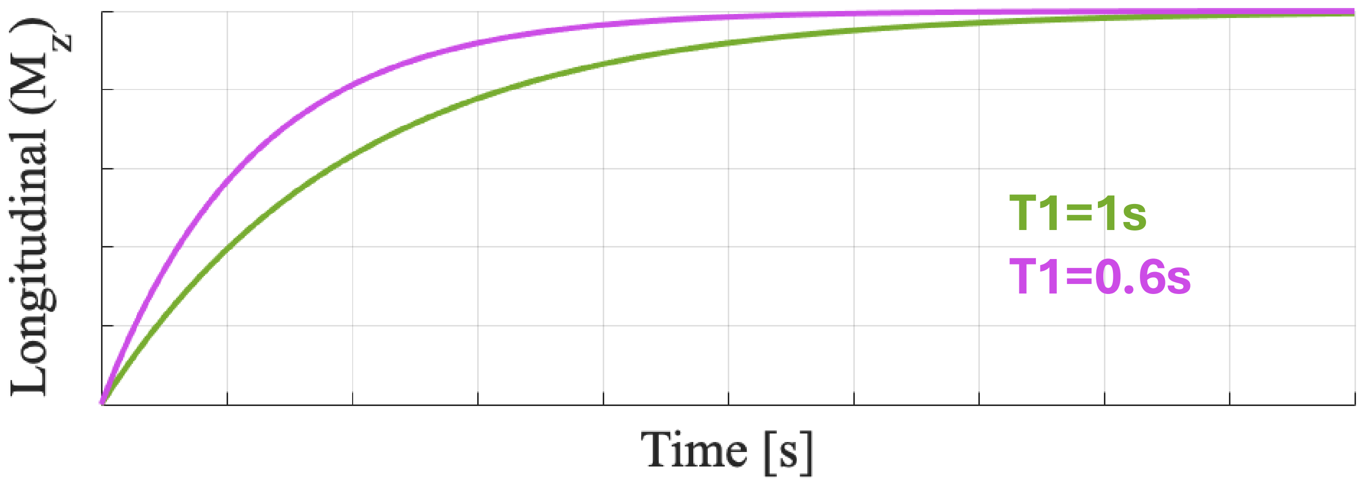


$$M_z(t) = M_0\left(1 - \exp\left(-\frac{t}{T1}\right)\right)$$

$$M_z(T1) = M_0\big(1 - \exp(-1)\big) = 0.63\mathrm{M}_0$$

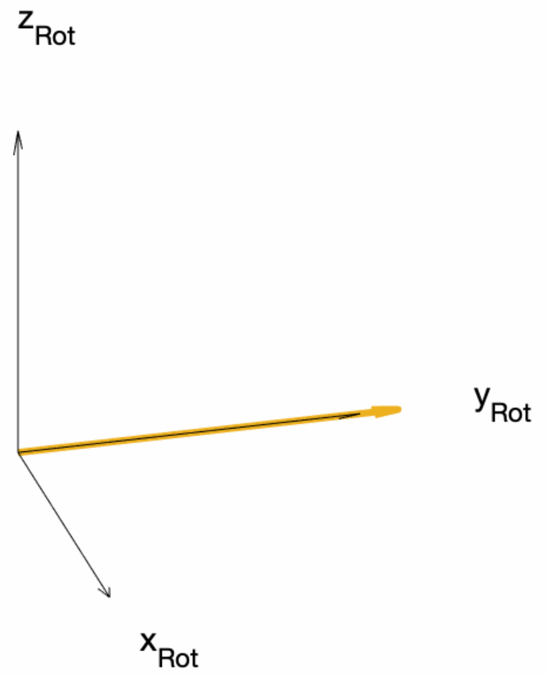
T1 Relaxation Time

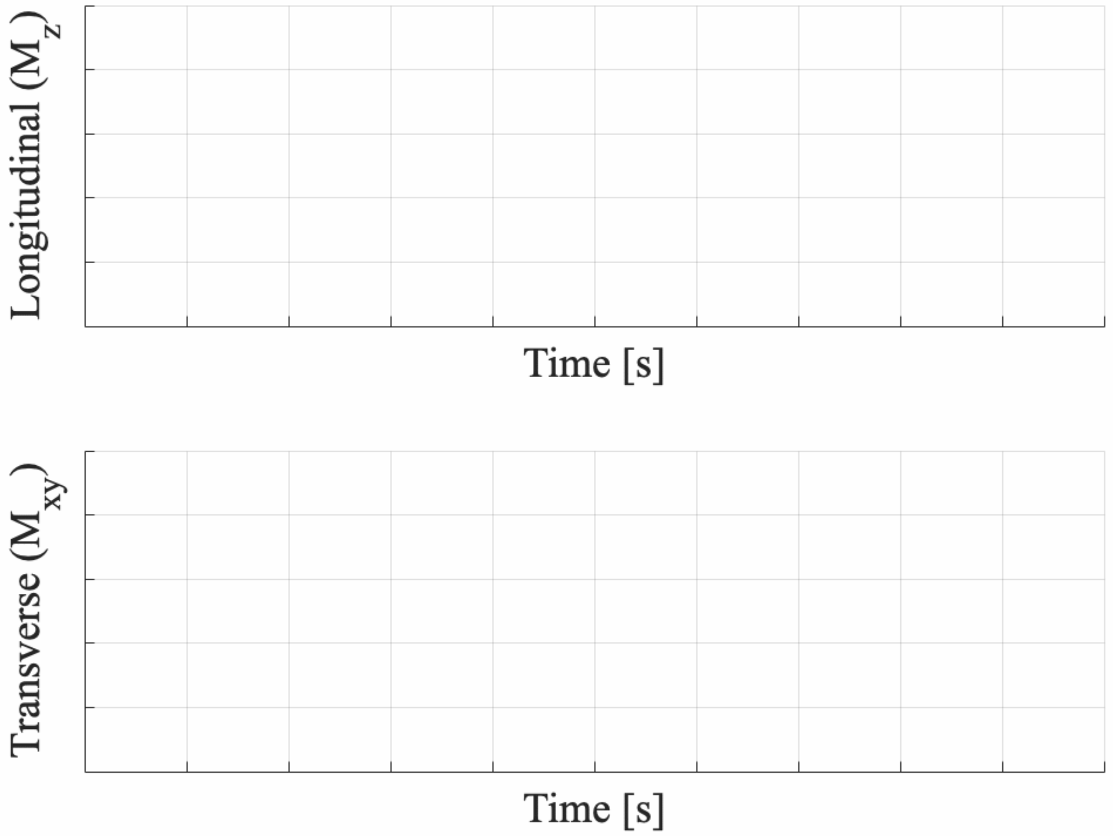
- Different tissues have different time constants which gives us insight into the microstructure of the tissue
- We can exploit this difference to alter contrast



Once detectable signal is generated, it decays …

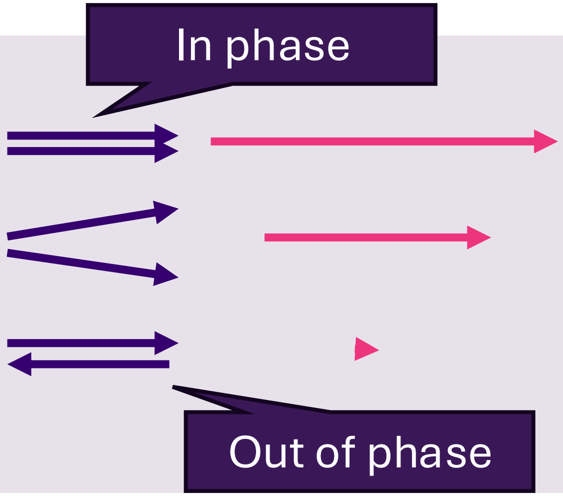
- T_1 Recovery / Relaxation of longitudinal magnetisation occurs again
- T_2 decay of transverse component also occurs, much more rapidly





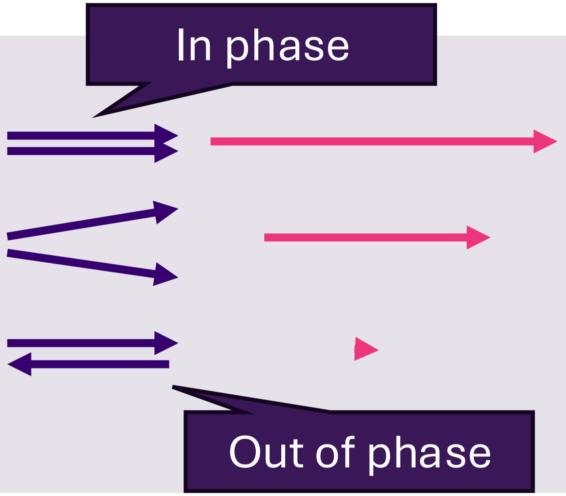
T2 Relaxation Time

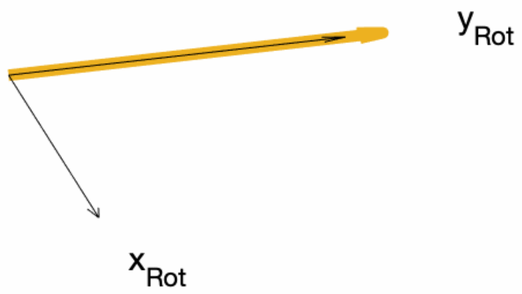
Remember M is the sum of multiple vectors (as many as there are protons in a voxel)



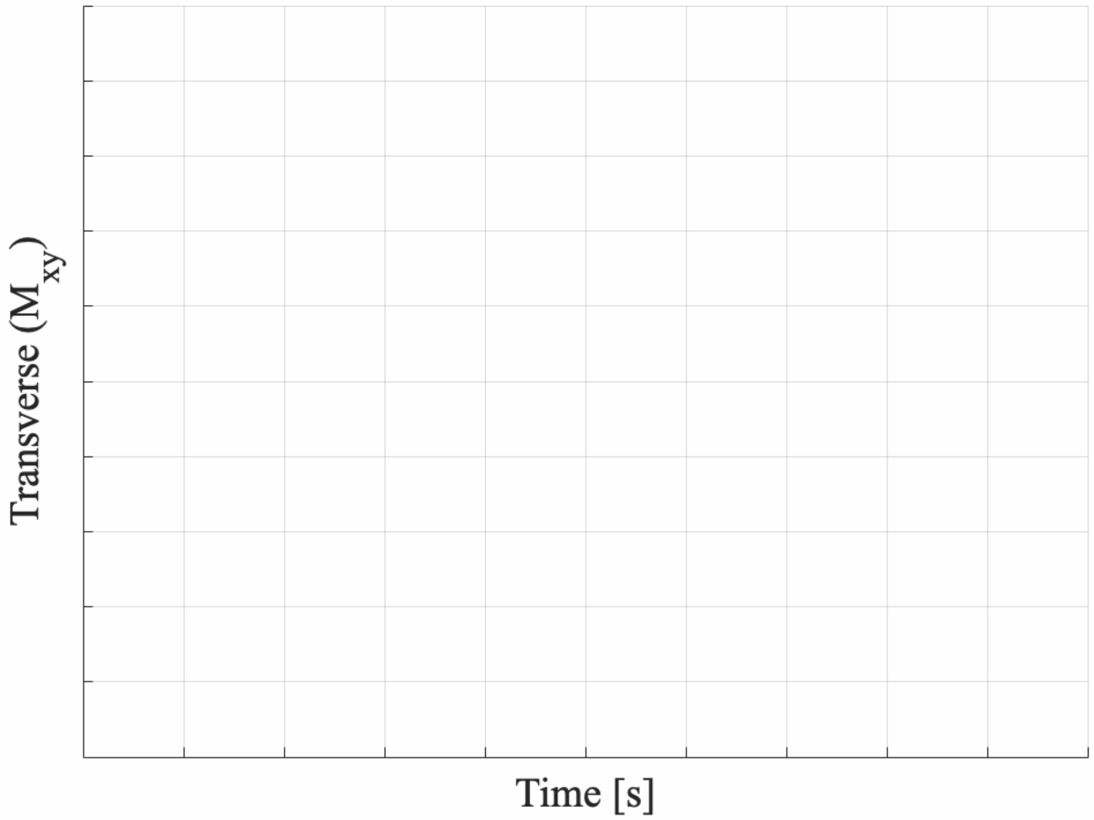
T2 Relaxation Time

Remember M is the sum of multiple vectors (as many as there are protons in a voxel)



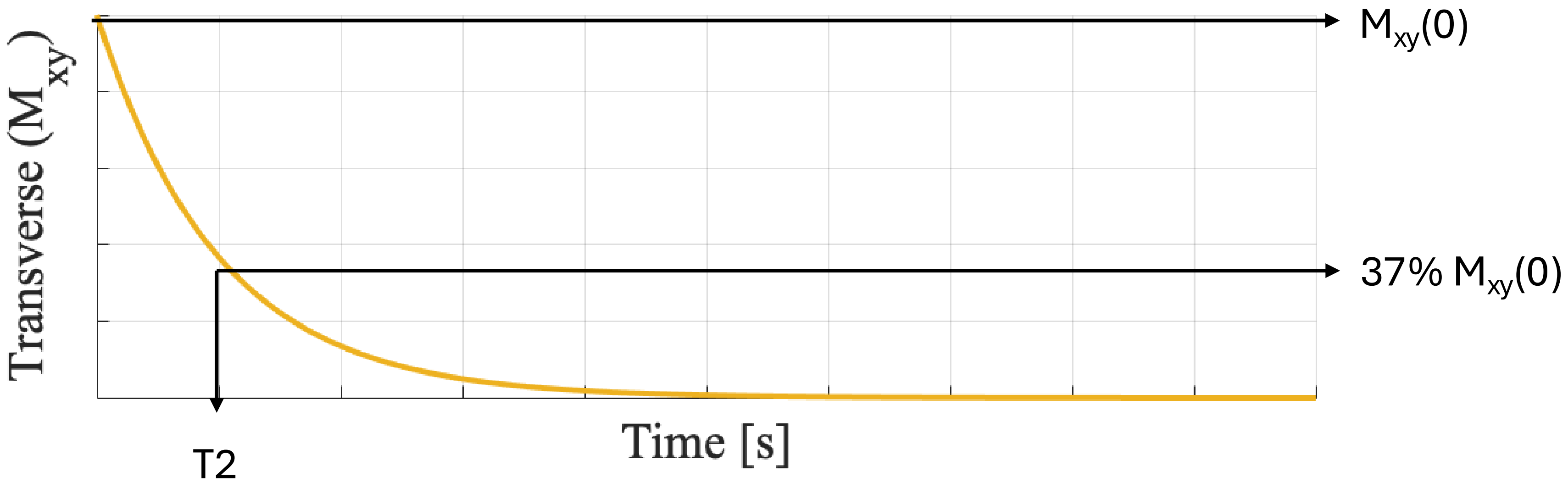


T2 decay: Nuclei alter the field experienced by each other and lead to a difference of precession frequency between the nuclei and therefore lead to “dephasing” and signal loss



T2 Relaxation Time

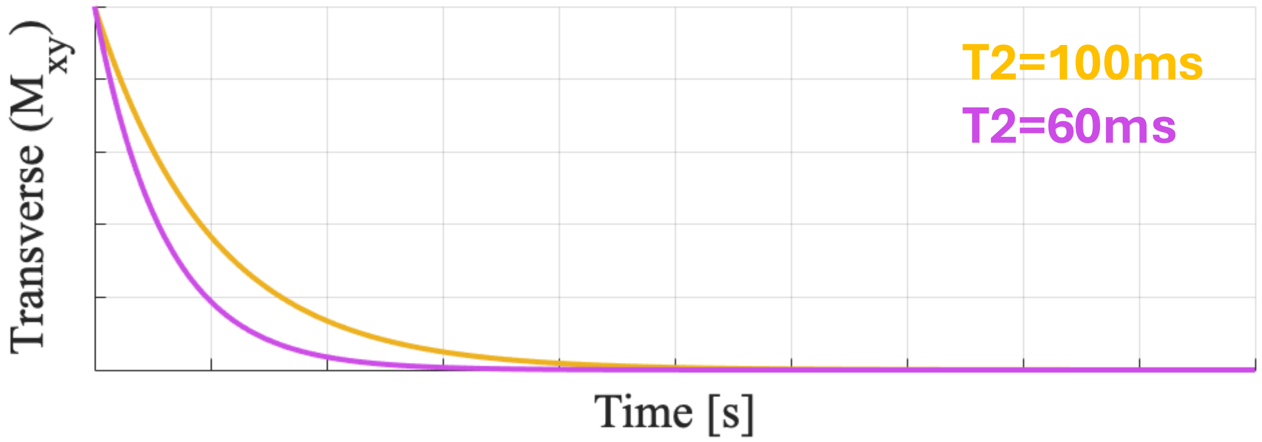
- Exponential Decay Curve described by a time constant T2
- T_2 is the time taken to decay to 37% of its original value
- The time taken depends on how quickly the spins get out of phase



$$\boldsymbol{M_{xy}(t) = M_{xy}(0)\exp\left(-\frac{t}{T2}\right)}$$

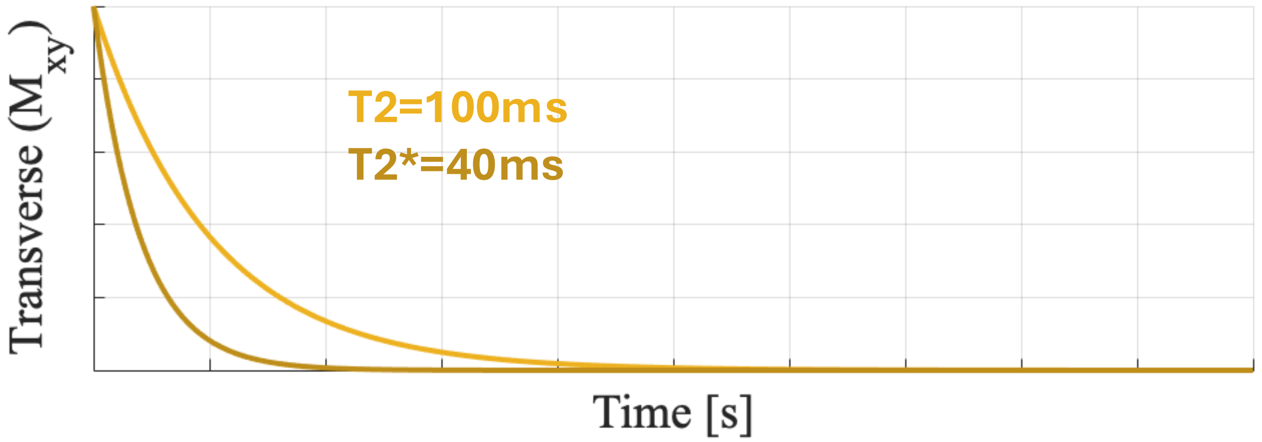
$$M_{xy}(T2) = M_{xy}(0)\exp(-1) = 0.37\mathrm{M}_{xy}(0)$$

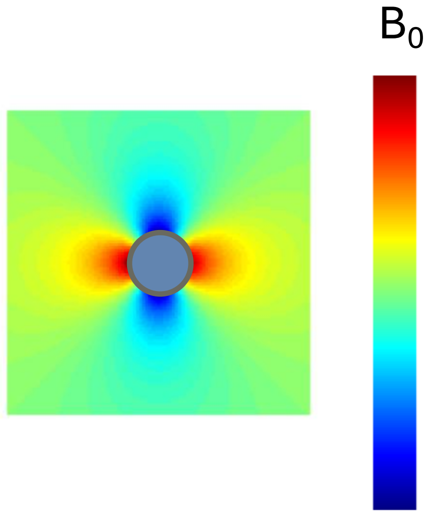
T2 Relaxation Time



- Different tissues have different time constants which gives us insight into the microstructure of the tissue
- We can exploit this difference to alter contrast

T2* Relaxation Time



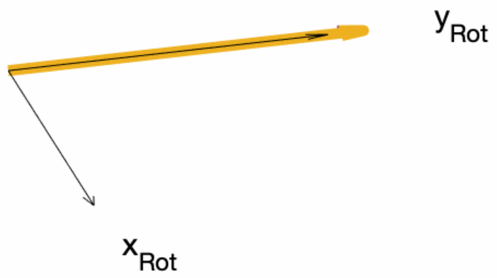


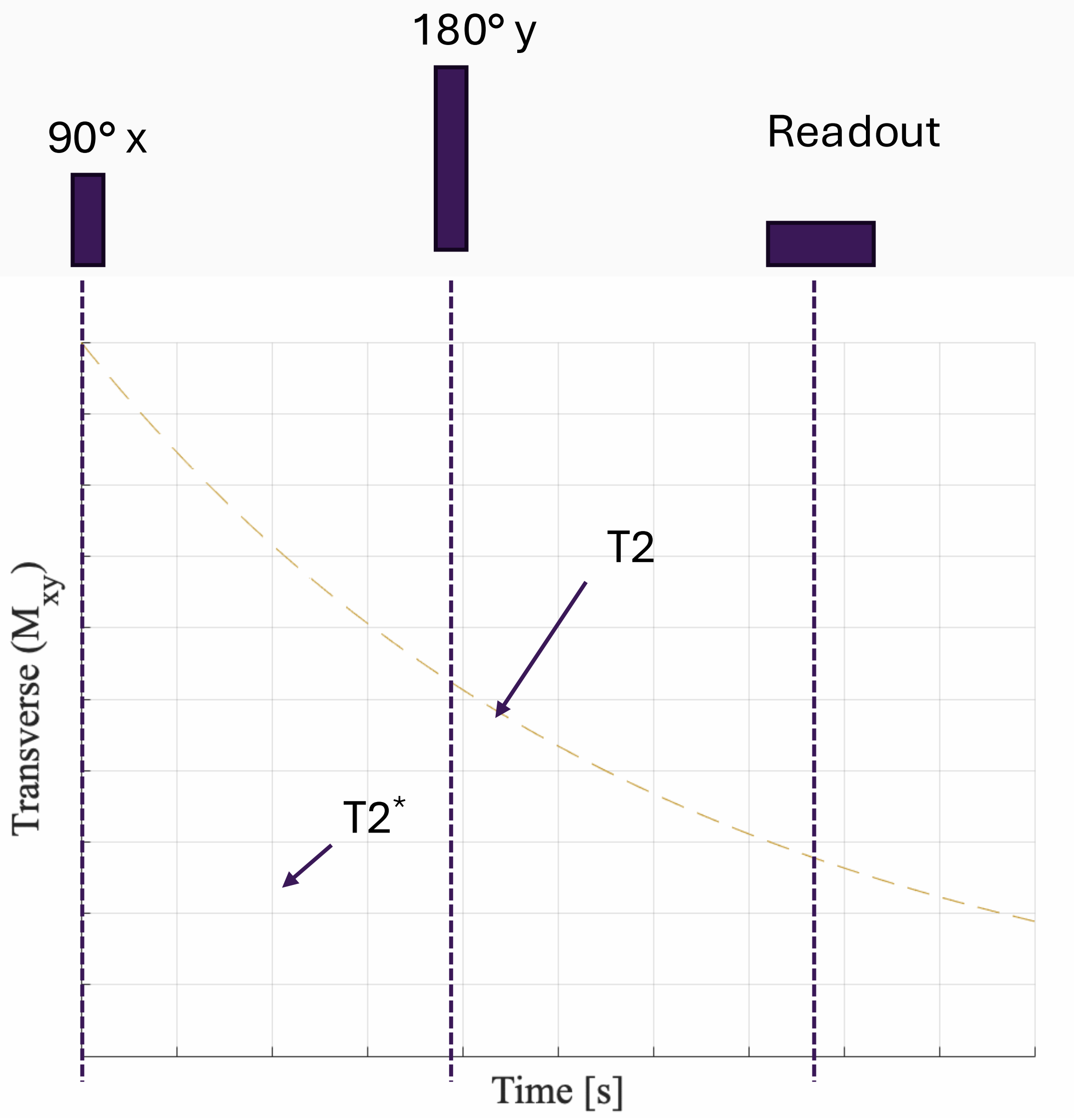
$$\frac{1}{T2^*} = \frac{1}{T2} + \frac{1}{T2'}$$

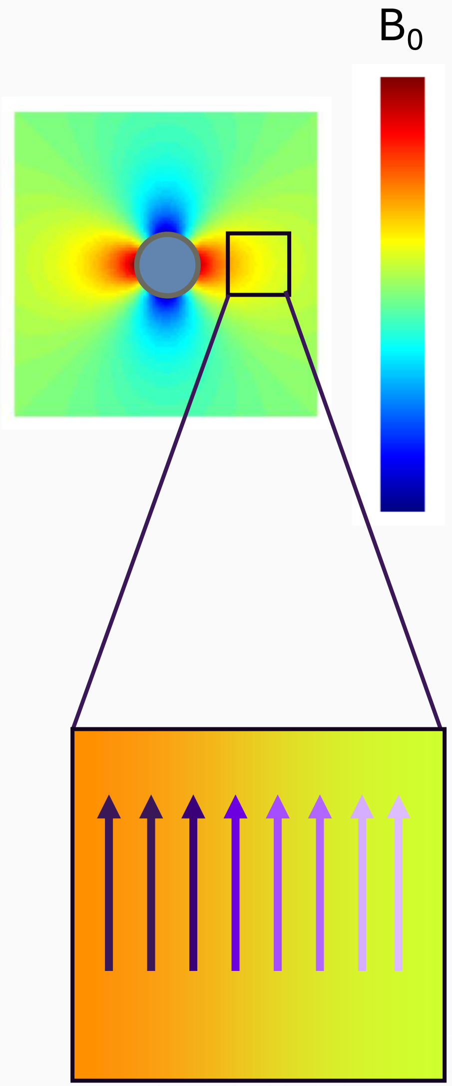
- Additional T2' decay of transverse component also occurs
- Any tissue or object with magnetic properties causes local changes of magnetic field
- Field inhomogeneities of B_0 cause T2' decay
- The relaxation time which encompasses T2 and T2' decay is called T2*

T2* Relaxation Time

- Signal loss due to spin-spin interactions cannot be recovered
- Signal loss due to B0 inhomogeneity can be recovered with a spin echo (180° pulse at TE/2)
- **Creating an echo** = rephasing, refocussing, recovering some of the signal

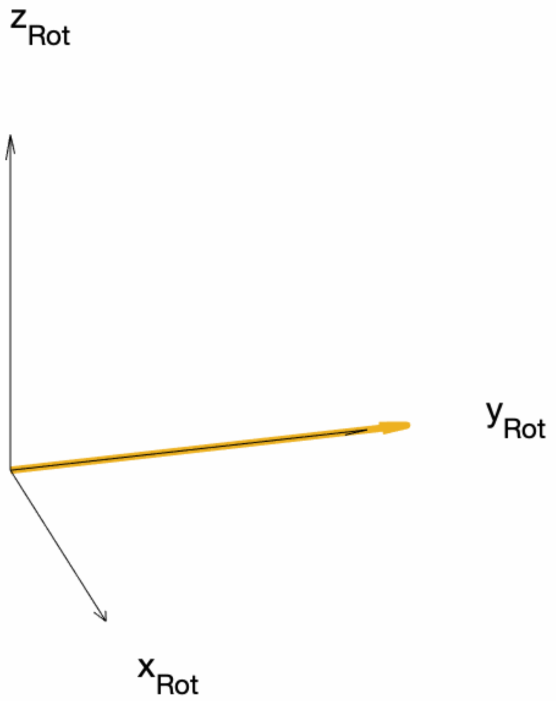


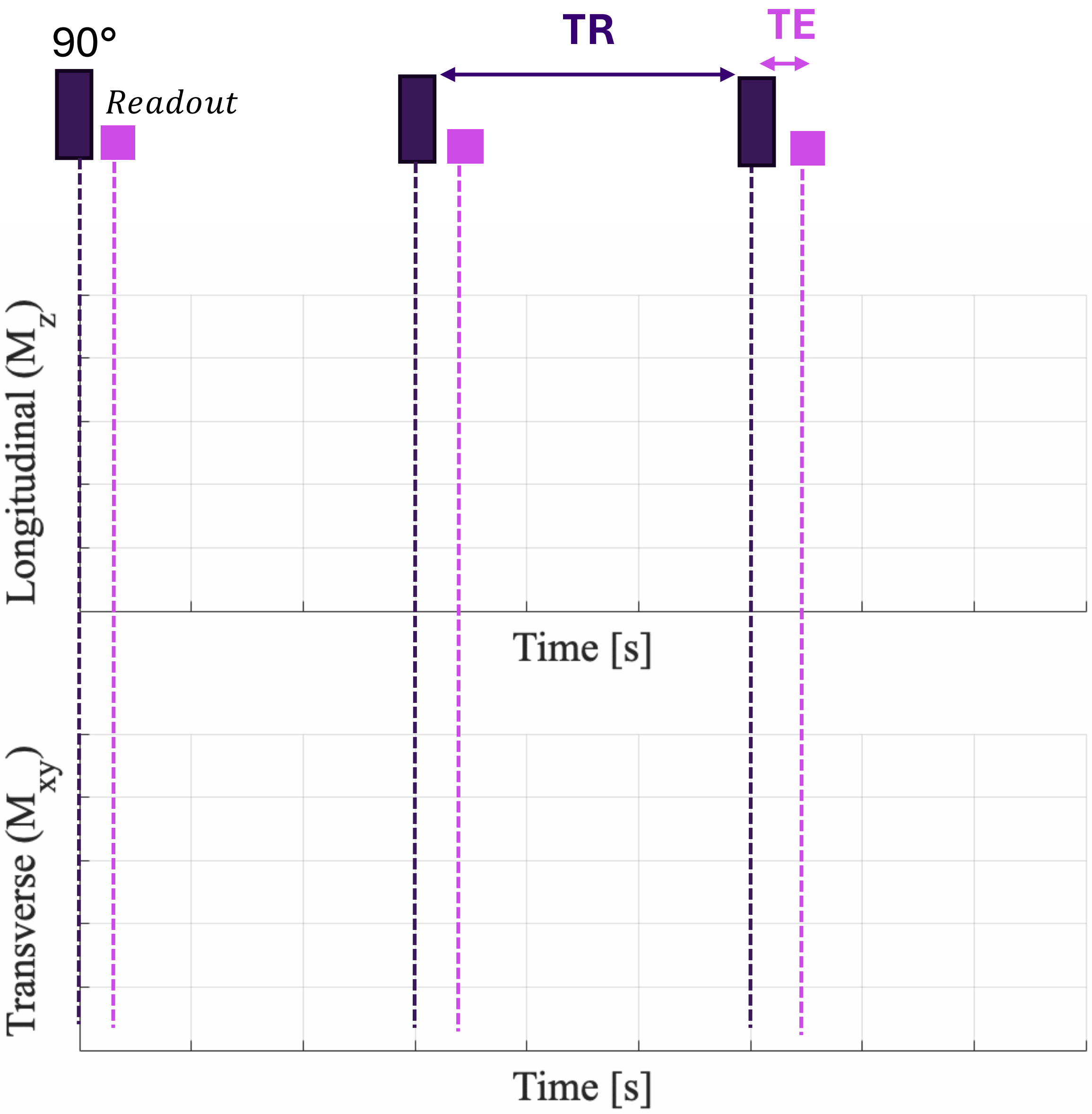




In MRI, we repeat multiple times the same sequence of events …

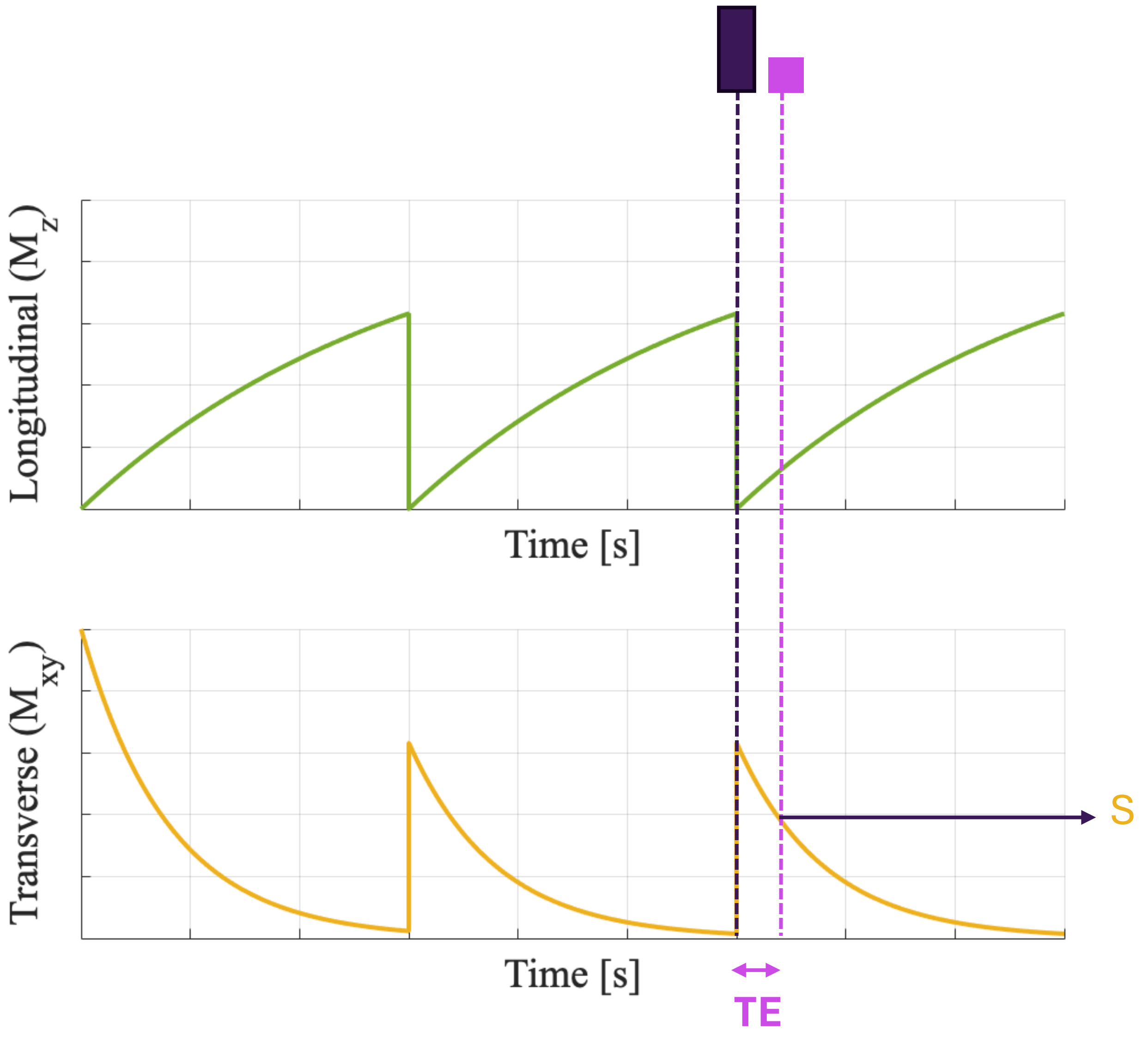
- The **Repetition Time (TR)** is the duration between 2 excitation pulses of the same volume/slice
- The **Echo Time (TE)** is the duration between the excitation pulse and the signal readout





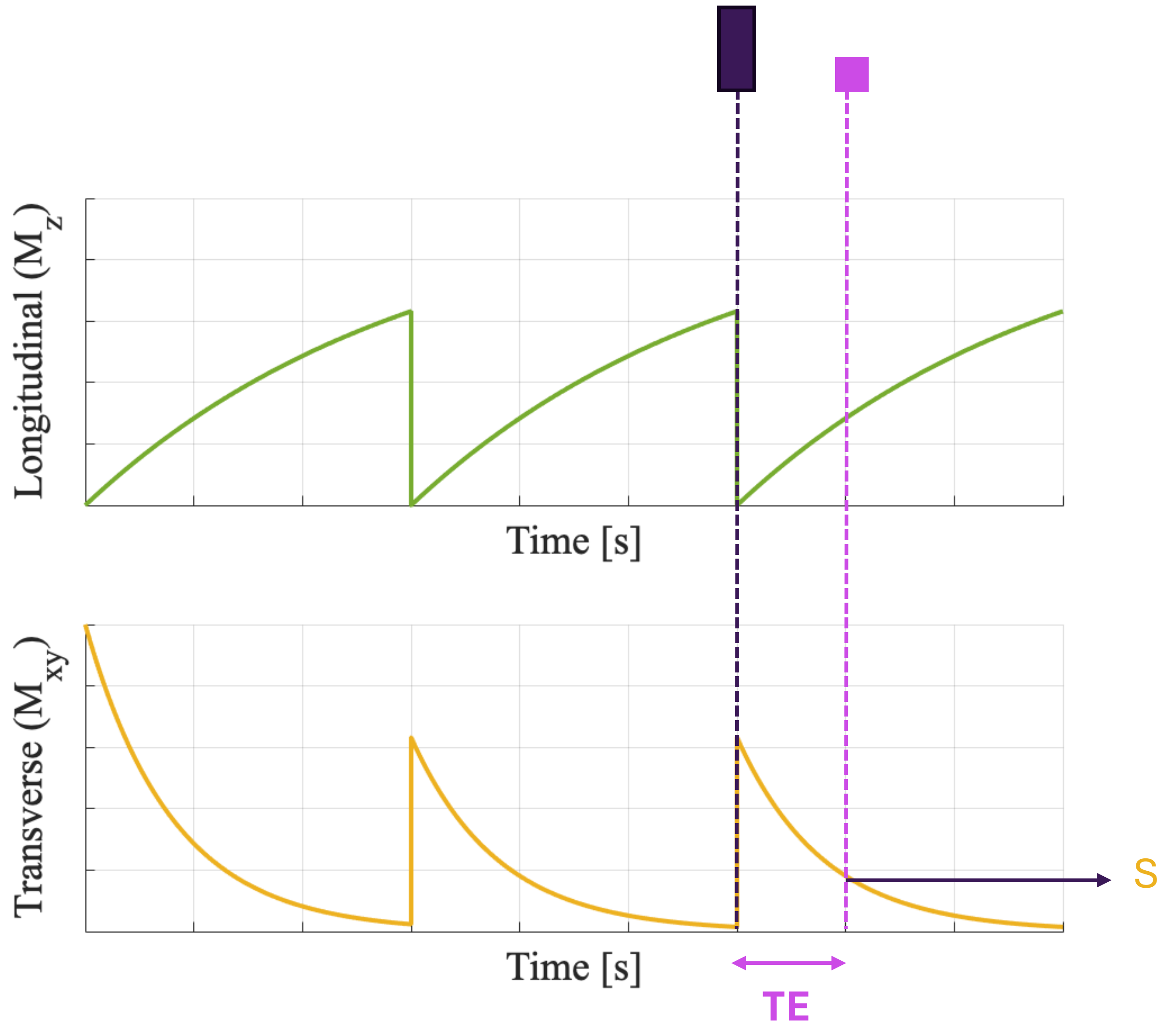
The Echo Time : TE

- The signal is measured at the echo time TE
- The signal is the amplitude of the transverse component at TE

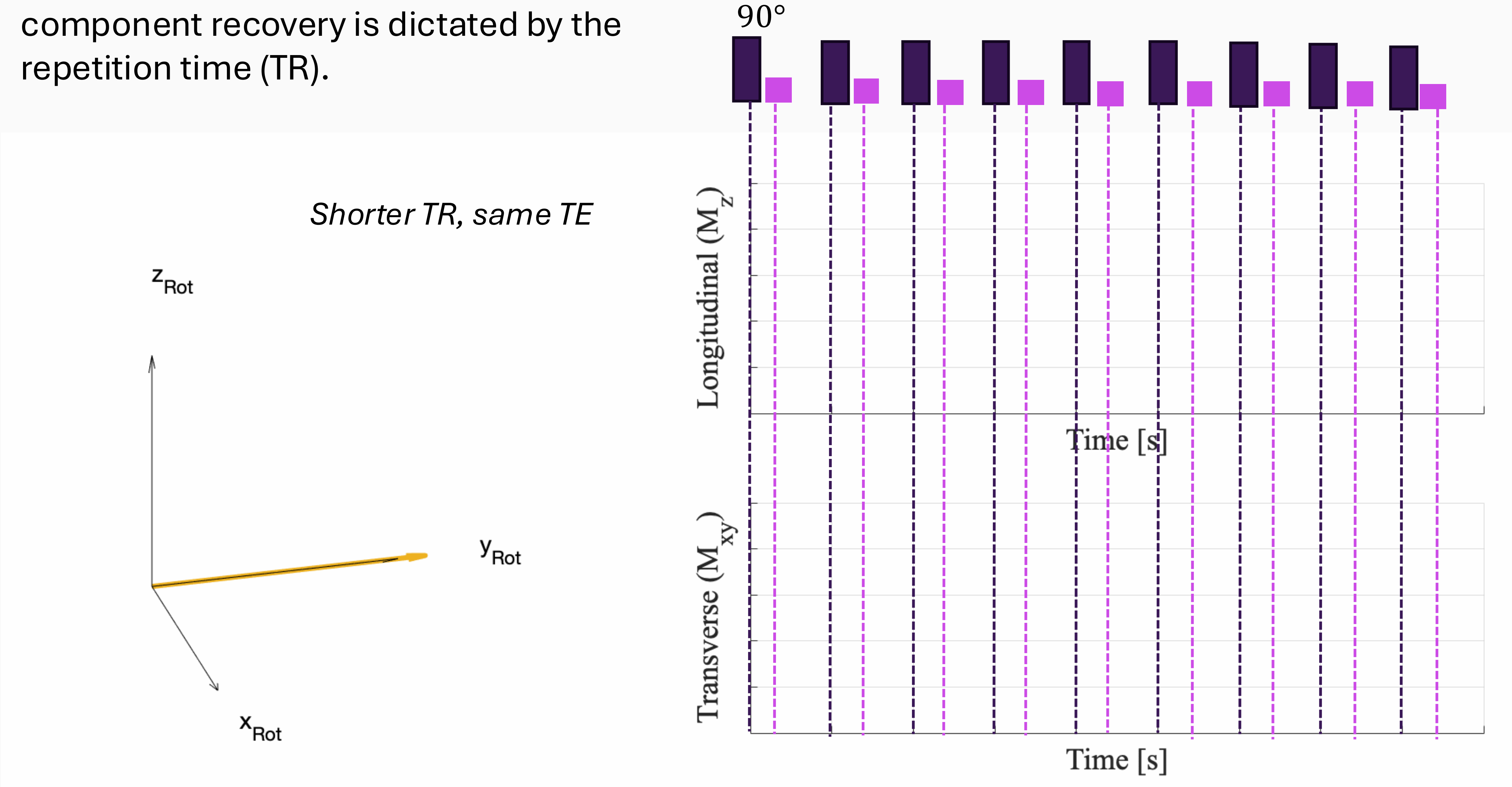


The Echo Time : TE

- The signal is measured at the echo time TE
- The signal is the amplitude of the transverse component at TE
- The signal decreases when increasing TE

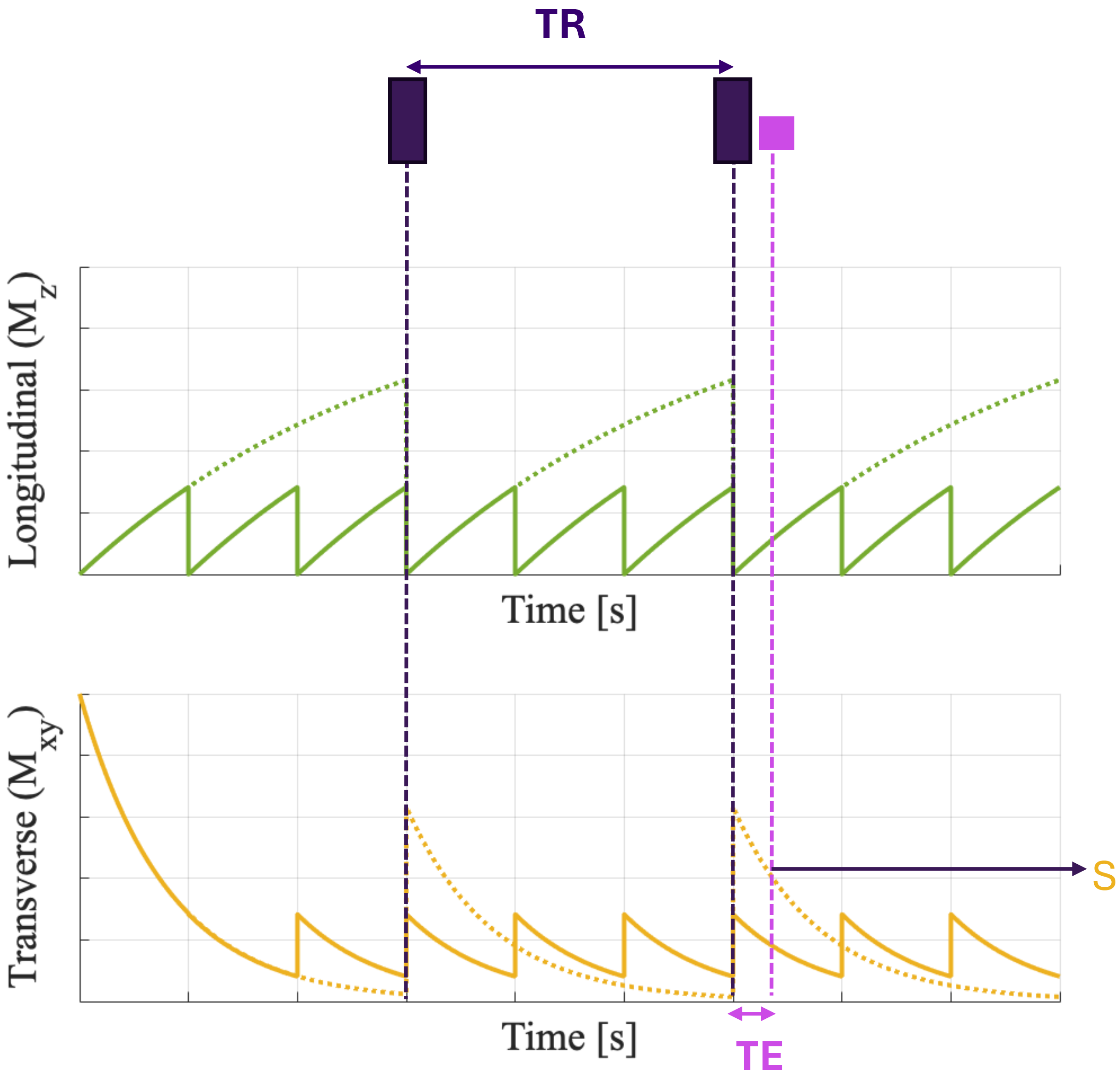


- Only the transverse component is measured in MRI but the recovery of the longitudinal component is indirectly observed though the transverse component
- The sensitivity to the longitudinal component recovery is dictated by the repetition time (TR).



The Repetition Time : TR

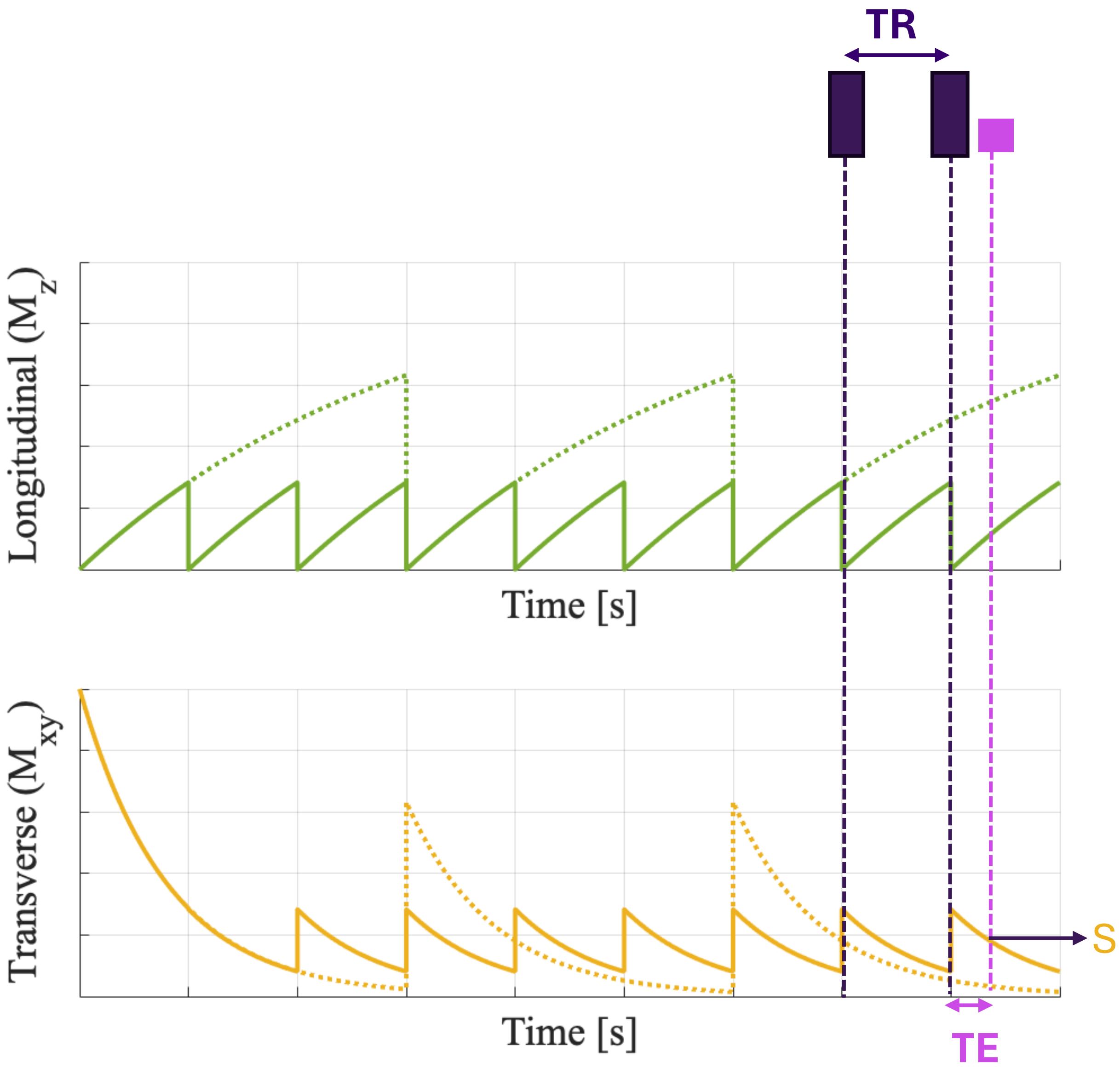
- The signal is indirectly related to the longitudinal component at TR



The Repetition Time : TR

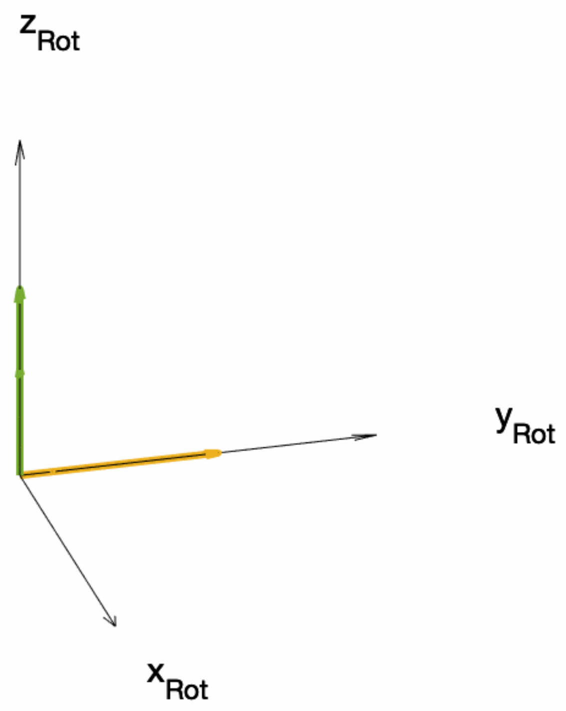
- The signal is indirectly related to the longitudinal component at TR

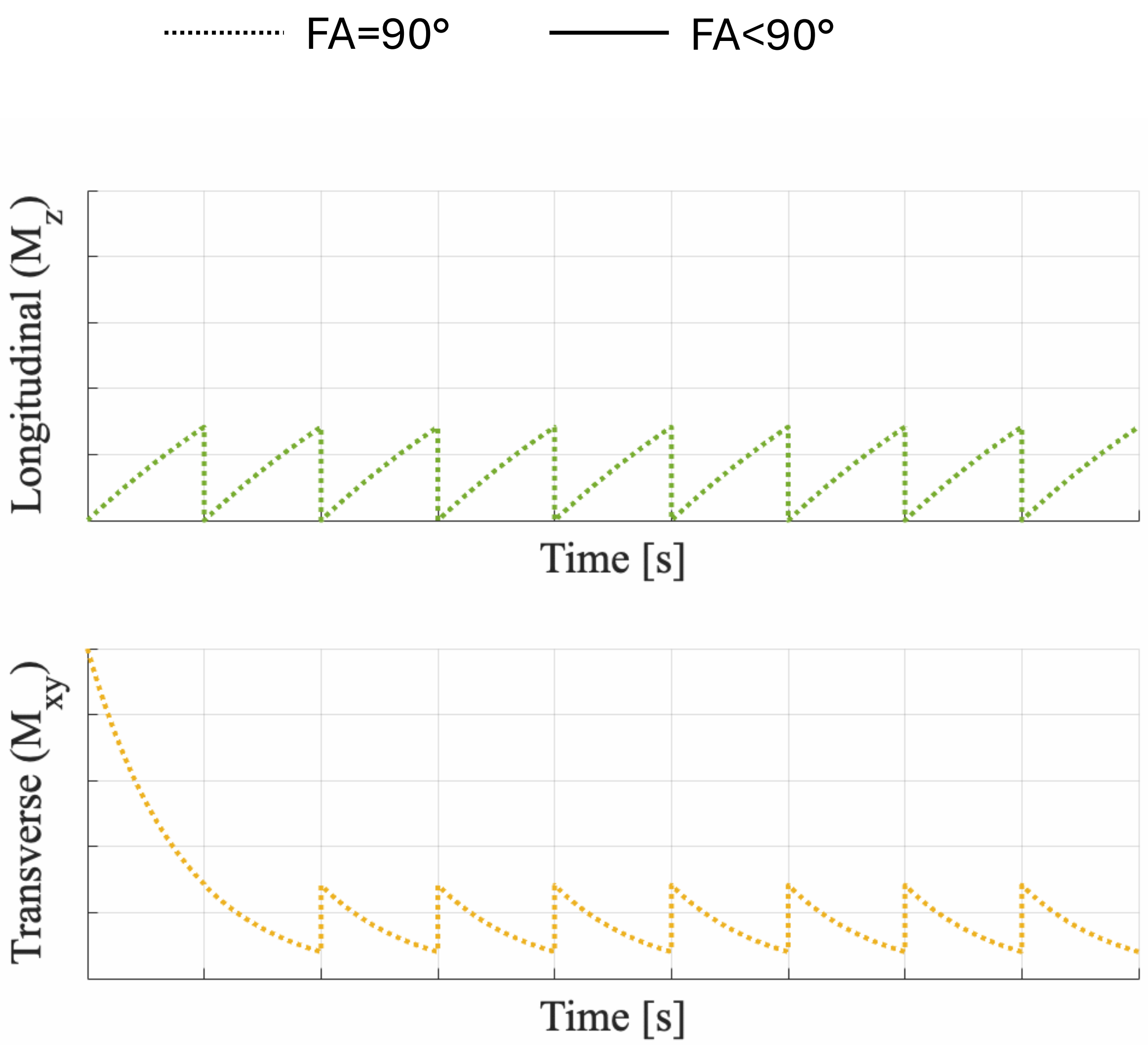
- For the same TE, the signal decreases when decreasing TR



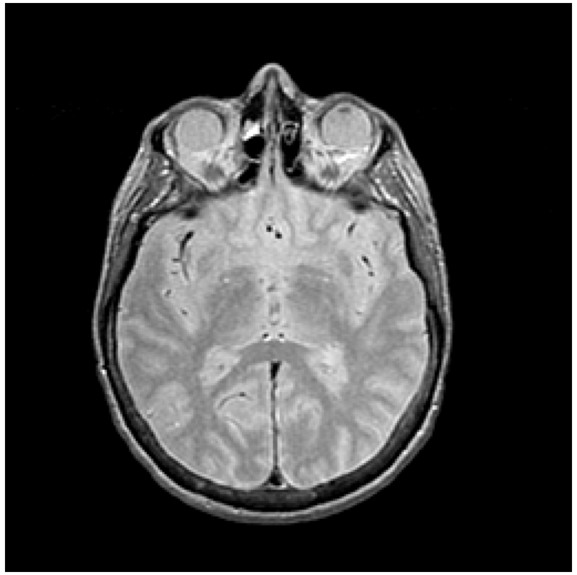
The Flip Angle

- The measured signal is also dictated by the flip angle
- Note that it can take a couple of TR to reach a steady state. That's why we use **dummy scans …**



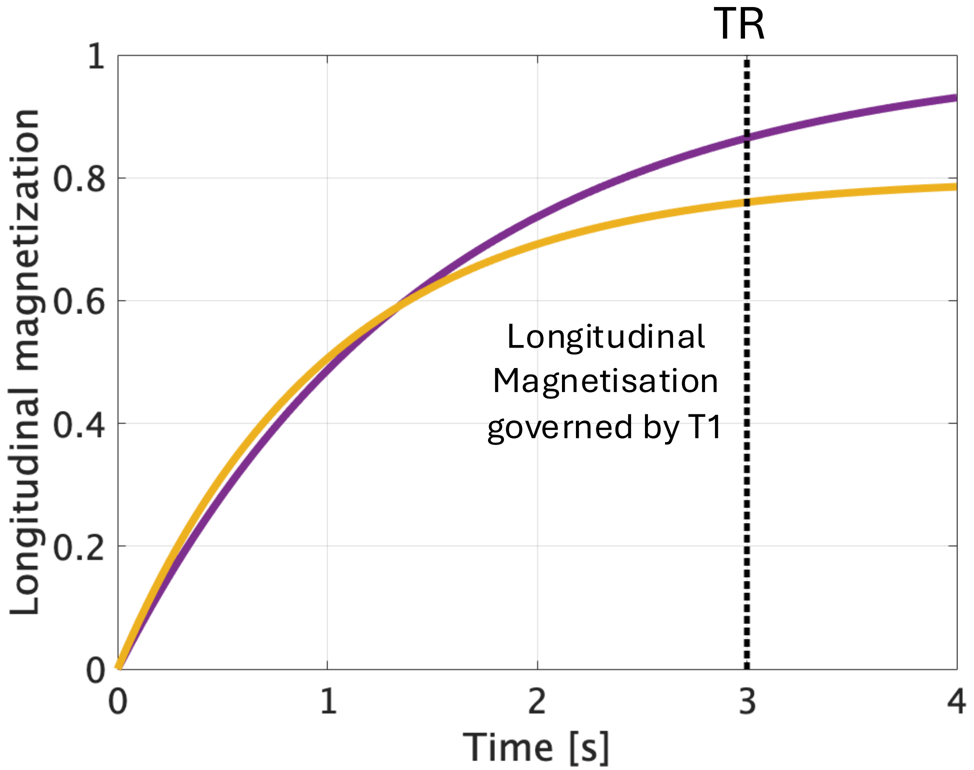


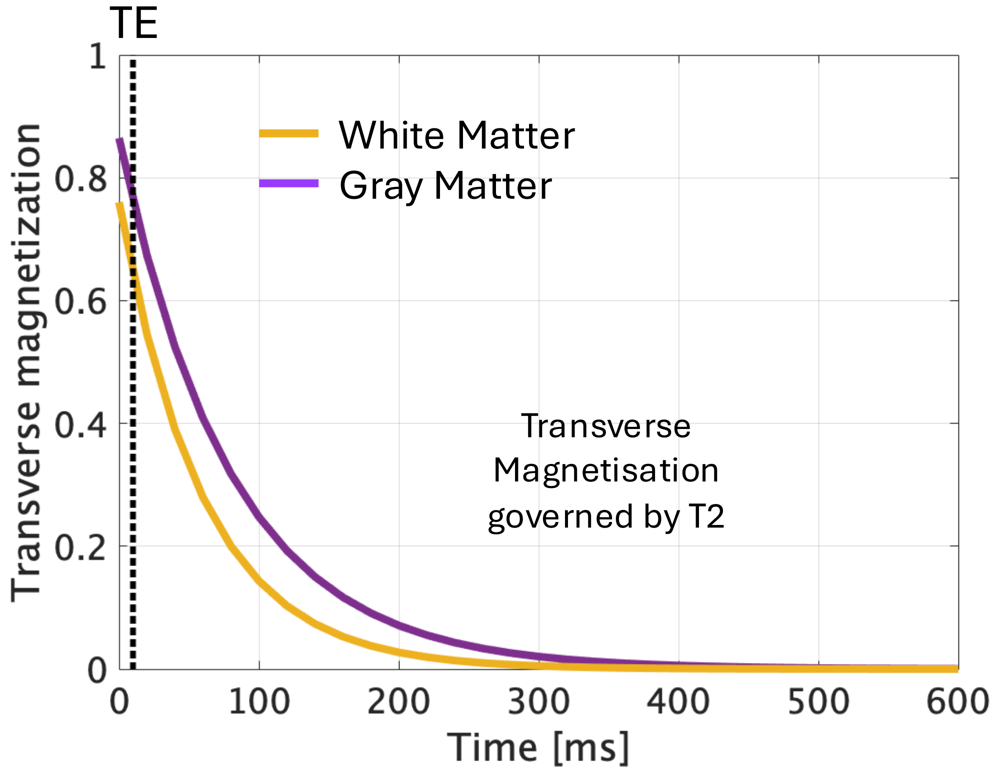
PD-weighted image



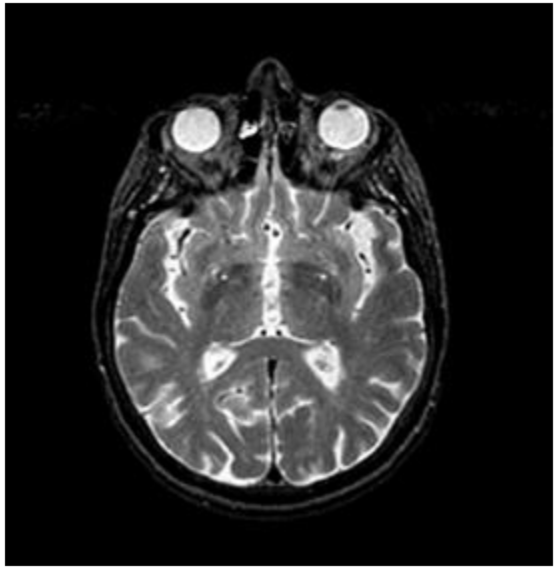
Pick a **long TR** for fully aligned magnetisation and a **short TE** so that the signal is dominated by the density of protons.

E.g. TR = 2.5 s, TE = 10 ms



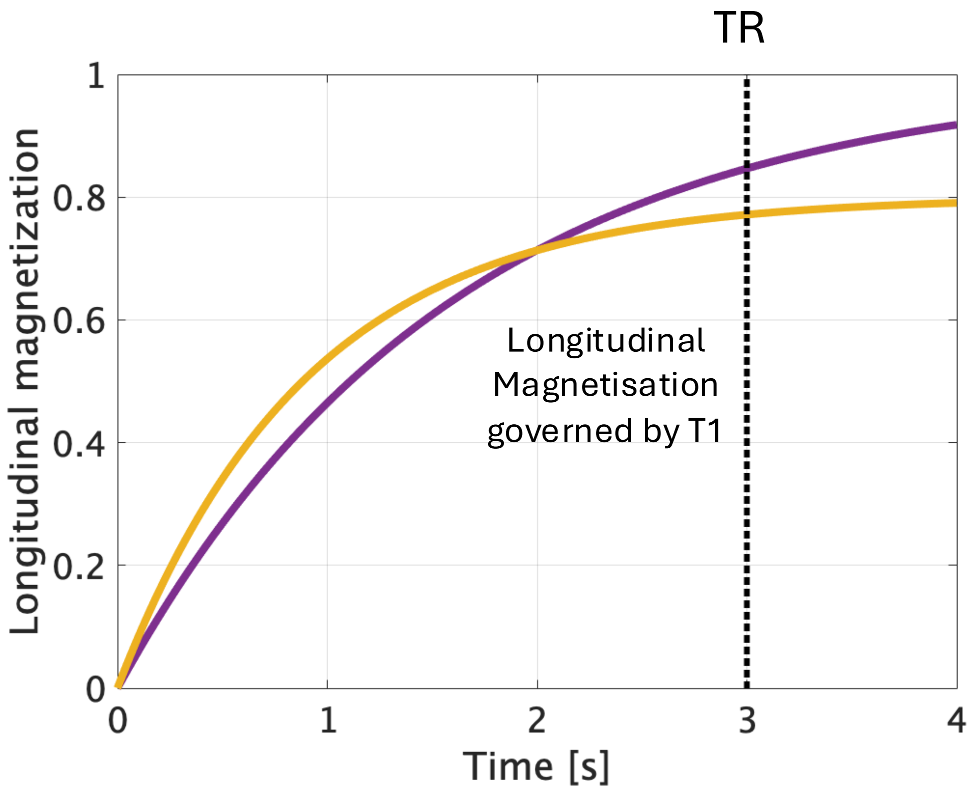


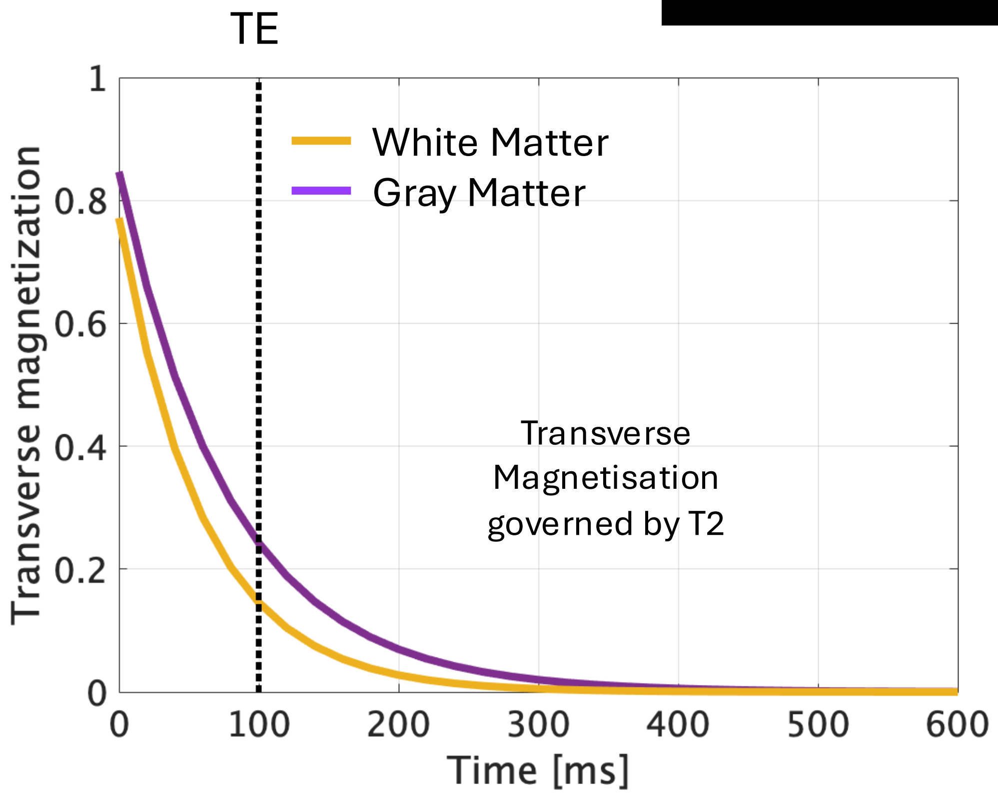
T2-weighted image



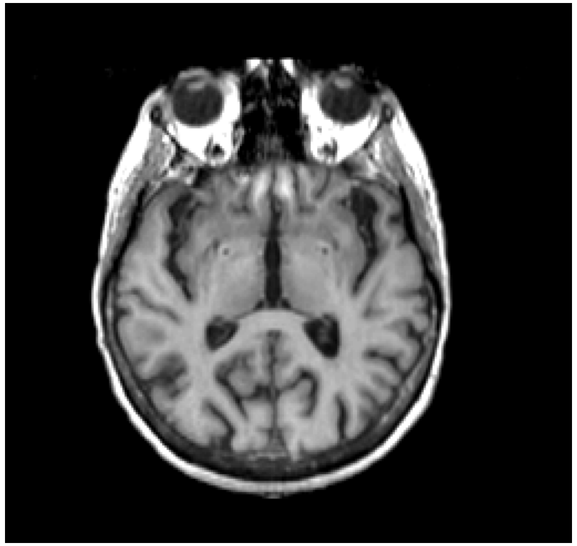
Pick a **long TR** for fully aligned magnetisation and a **long TE** so that the signal is dominated T_2 differences.

E.g. TR = 2.5 s, TE = 100 ms



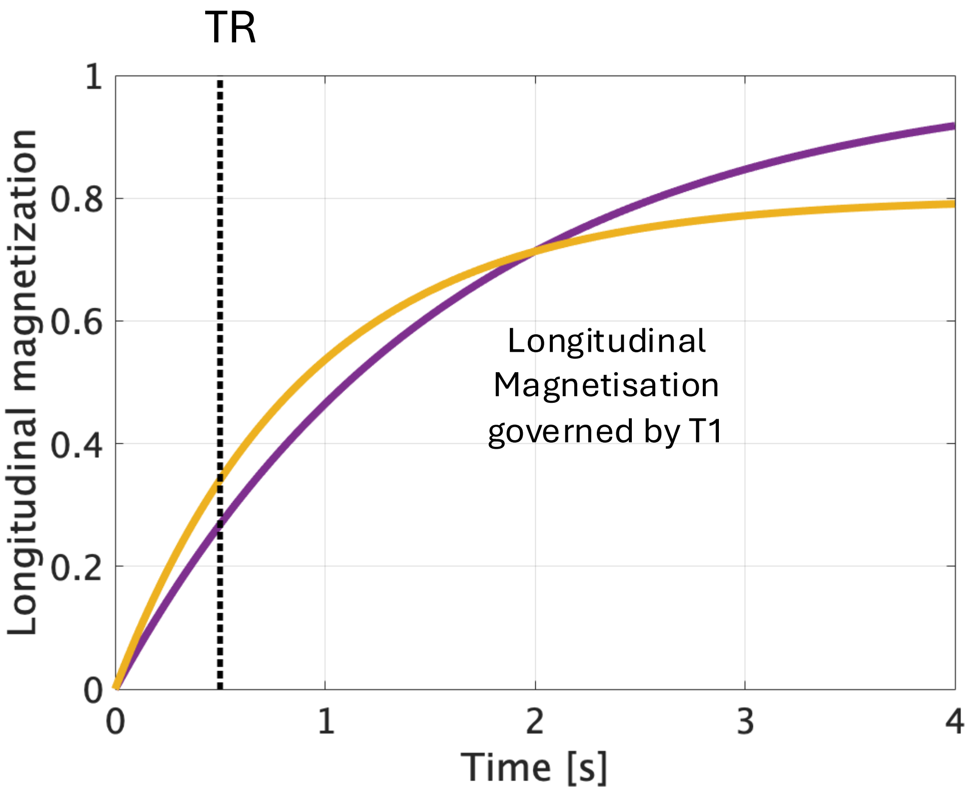


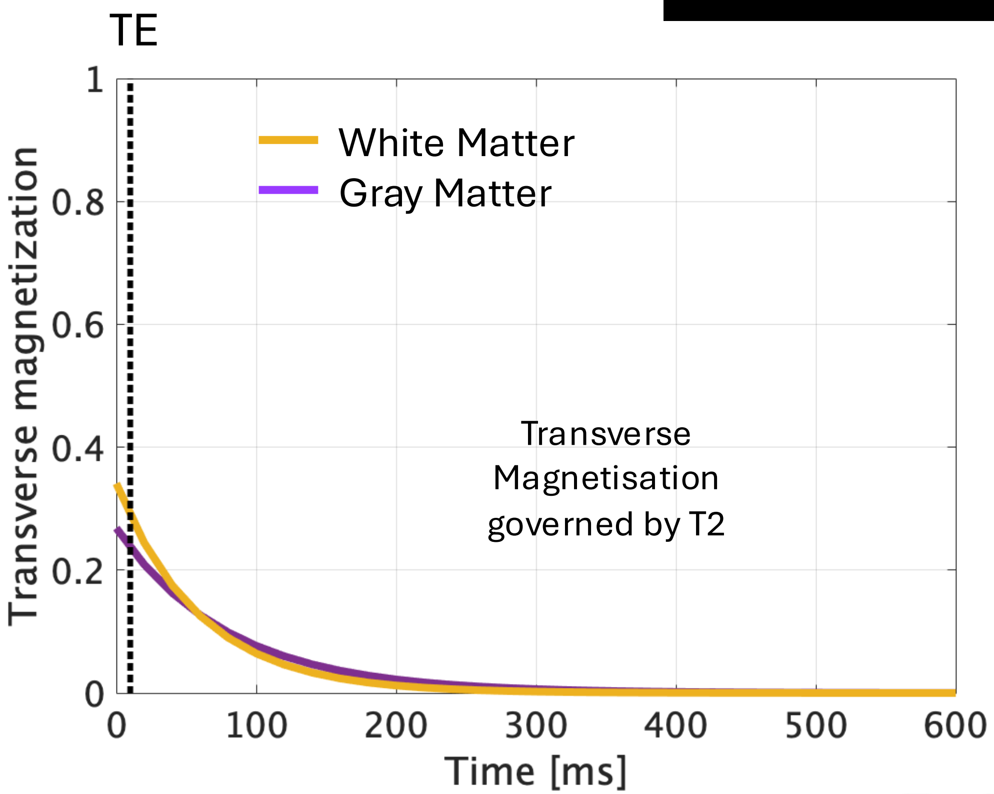
T1-weighted image



Pick a **short TR** for differentially aligned magnetisation and a **short TE** so that the signal is dominated T_1 differences.

E.g. TR = 0.5 s, TE = 10 ms





To sum up ...

- ✓ Subject in strong magnetic field, B_0.
- ✓ Individual ^1H nuclei act as tiny magnets
- ✓ They precess about B_0 at the Larmor Frequency $\omega_0 = \gamma B_0$
- ✓ They combine to make magnetization M aligned with B_0
- ✓ RF pulse is an additional B_1 field that rotates M into the x-y plane where it precesses
- ✓ Once detectable signal is generated, it decays
- ✓ The regrowth of the longitudinal component is described by T1
- ✓ The decay of the transverse component is described by T2
- ✓ More rapid decay of the transverse component, described by the T2*, is due to B_0 inhomogeneity
- ✓ TE and TR dictate the image contrast

Methods section

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NeuroImage

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NeuroImage 31 (2006) 818 – 831

Task-induced deactivations during successful paired associates learning: An effect of age but not Alzheimer's disease

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Image acquisition

Functional and structural data were acquired on the 3 T Bruker scanner at the Wolfson Brain Imaging Centre, Cambridge. In each functional time series, T2*-weighted images depicting BOLD contrast were acquired using an interleaved echo planar (EPI) sequence at 21 whole-brain axial slices (TR = 3020 ms, TE = 27 ms, flip angle = 90°, matrix = 128 × 128, field of view = 25 cm^2, interslice distance = 5 mm, slice thickness = 5 mm). Seven initial EPI volumes were discarded to allow for magnetic stabilization in each functional time series. Each scan run lasted a maximum of 8 min or until 4 problems at each of the 3 levels of difficulty had been successfully completed. All participants received 3 scanning runs apart from 2 participants who only received 2 scanning runs due to technical difficulties. Imaging data from one younger adult had to be discarded due to problems with fMRI data acquisition. Three-dimensional, high resolution whole-brain axial images were also acquired for each participant.

B_0

Type of contrast

Repetition Time

Flip Angle

Echo Time

Dummy scans