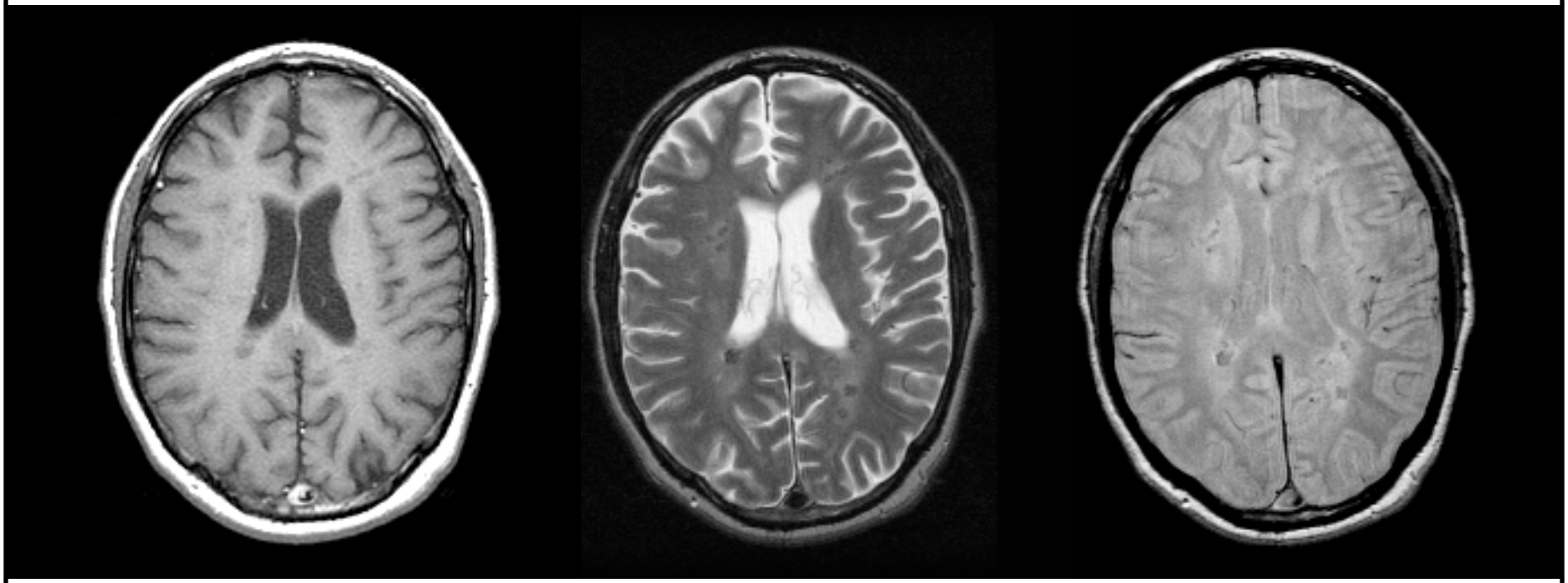
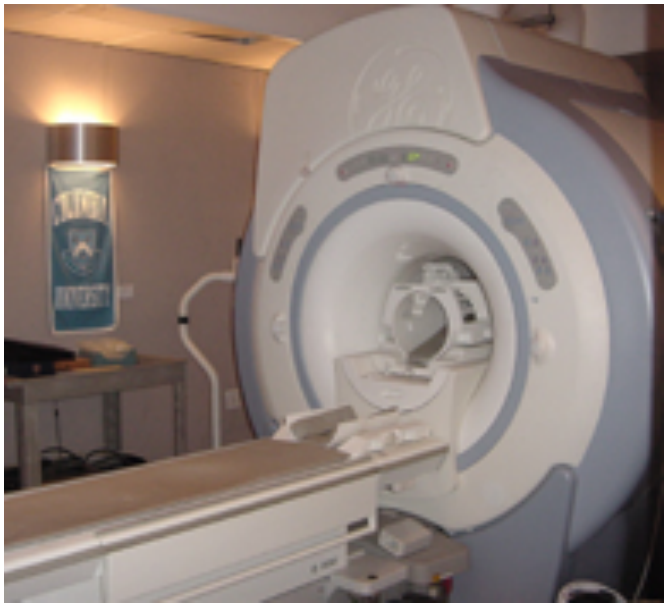
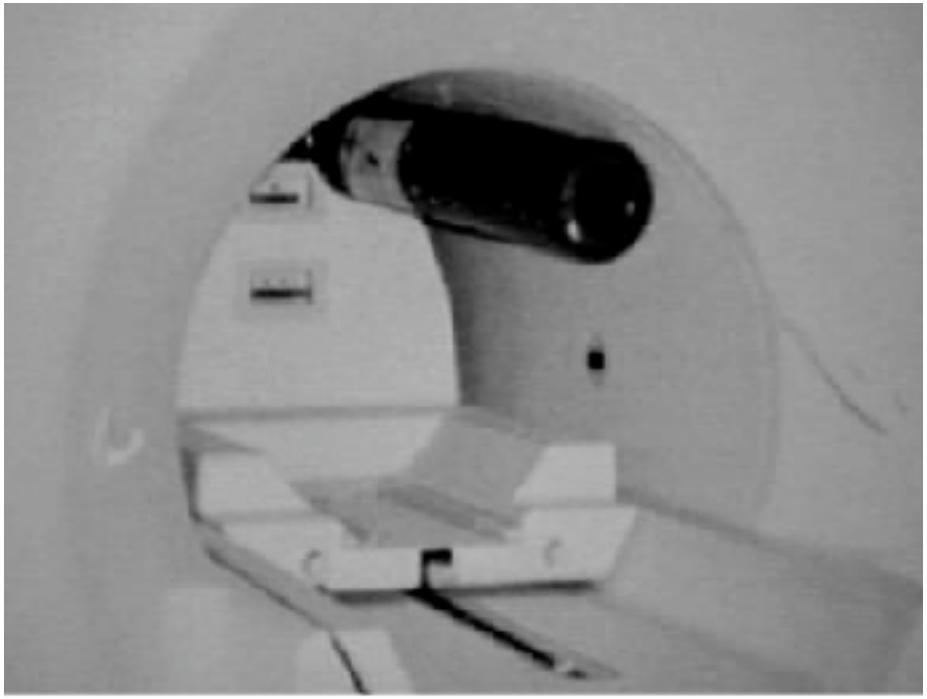
Introduction to MRI



The magnet



Field strength

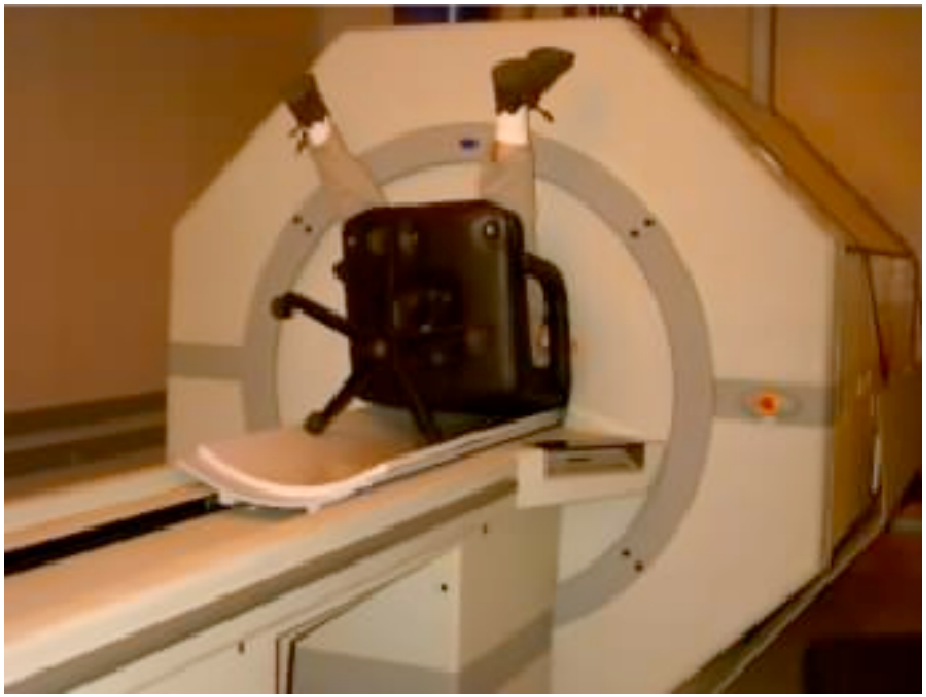


Field strength

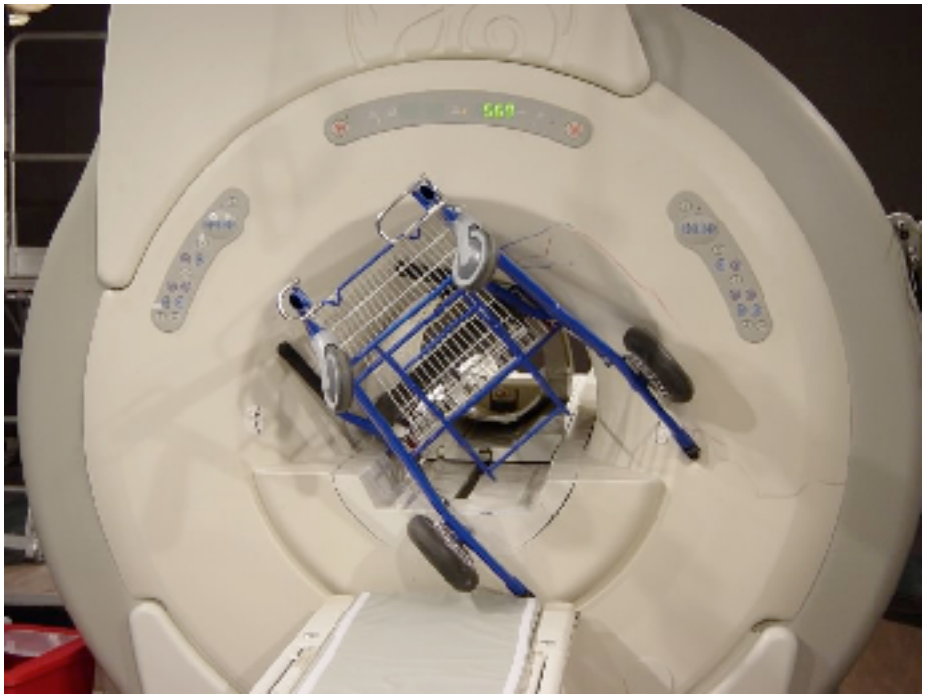
Field strength

Field strength

Field strength

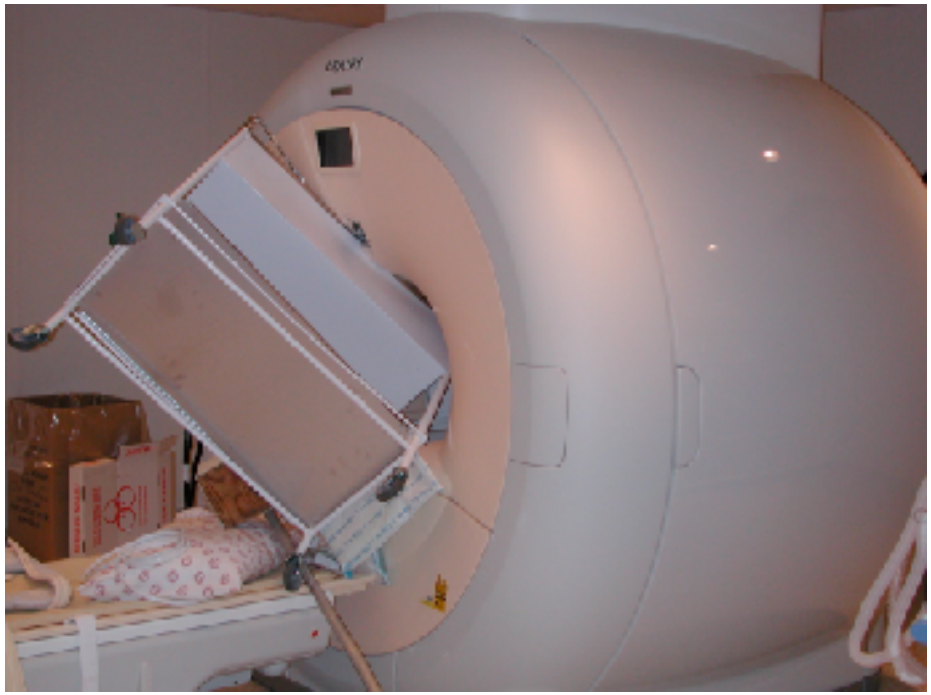


Field strength



Field strength

Field strength



Field strength

Field strength

Field strength

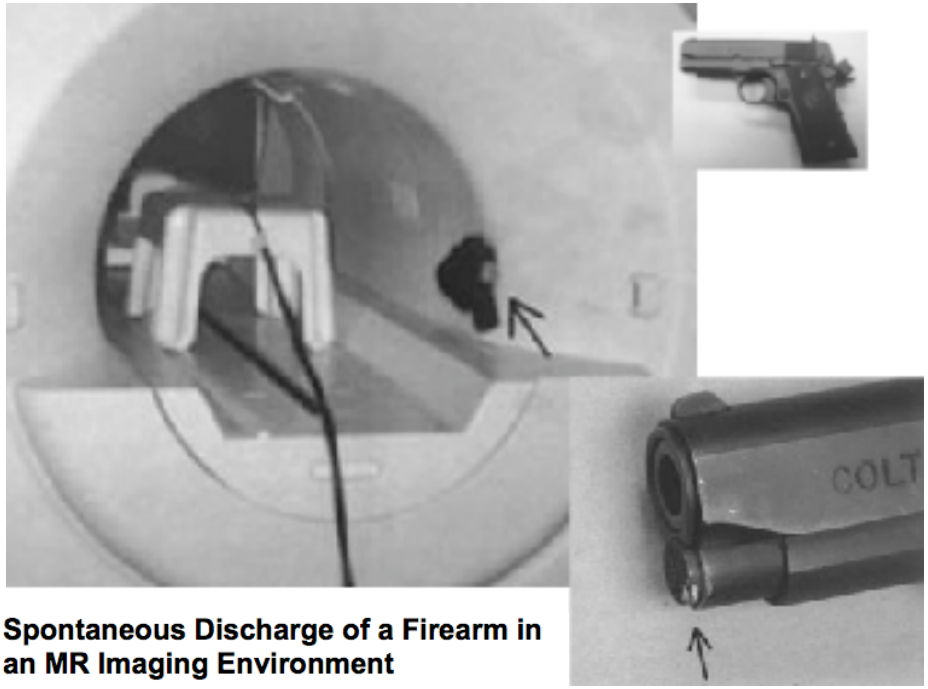
Field strength

Field strength

Field strength

Field strength

Field strength



American Journal of Roentgenology

Spontaneous Discharge of a Firearm in an MR Imaging Environment

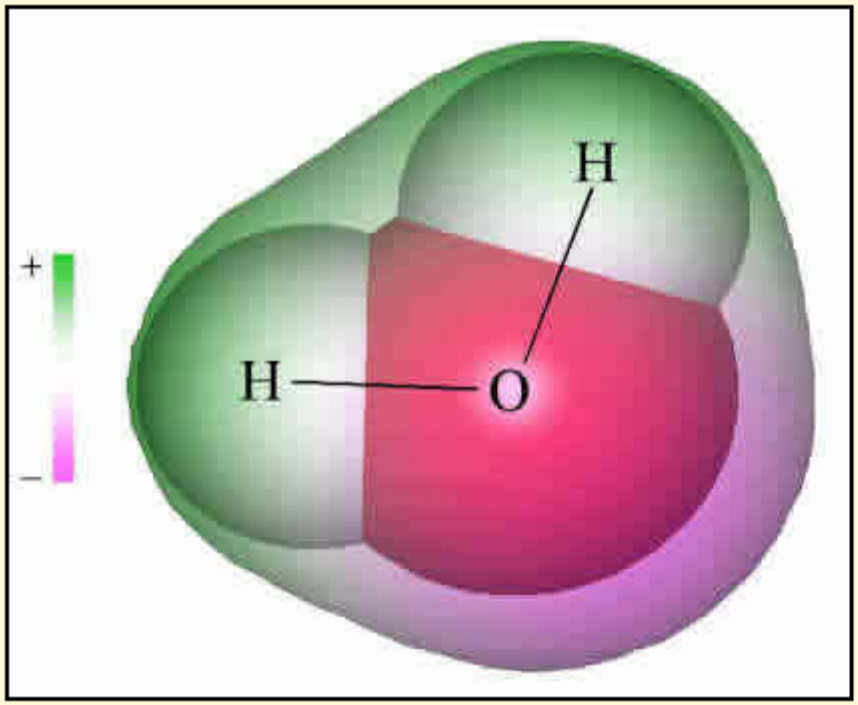
Anton Oscar Beitia[1], Steven P. Meyers[1], Emanuel Kanal[2] and William Bartell[3]

[1] Department of Radiology, University of Rochester Medical Center, 601 Elmwood Ave., Box 648, Rochester, NY 14642.
[2] Department of Radiology (D-132), University of Pittsburgh Medical Center, 200 Lothrop St., Pittsburgh, PA 15213.
[3] Rochester Police Department, Rochester, NY 14624.

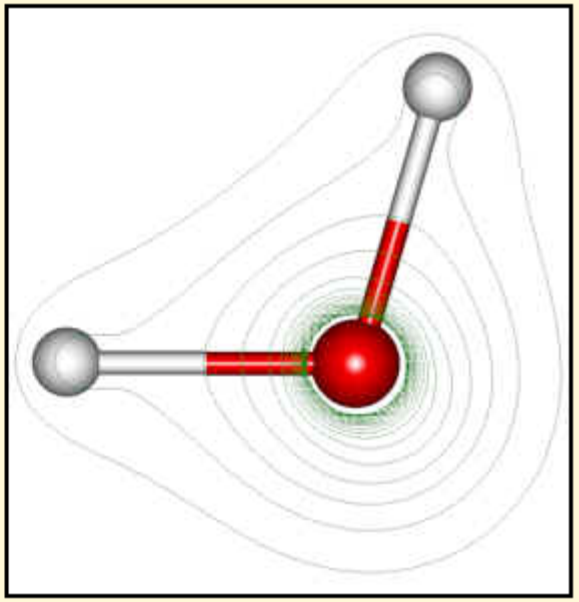
Received September 4, 2001; accepted after revision November 6, 2001.

Field strength

Water



The approximate shape and charge distribution of water.



Note that the average electron density around the oxygen atom is about 10x that around the hydrogen atoms.

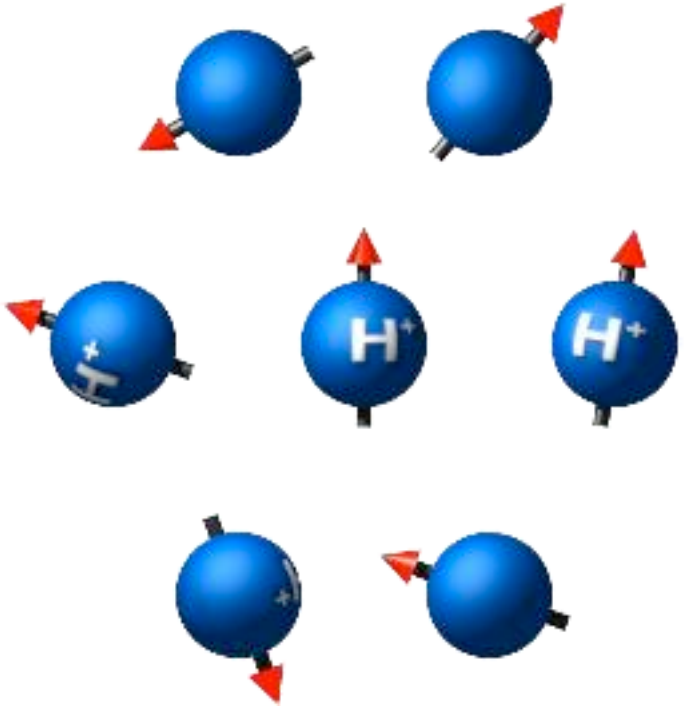
Other nuclei such as 13C, 19F, 31P, 23Na have a net nuclear spin and can be imaged in MRI.

www.lsbu.ac.uk/water/

Proton

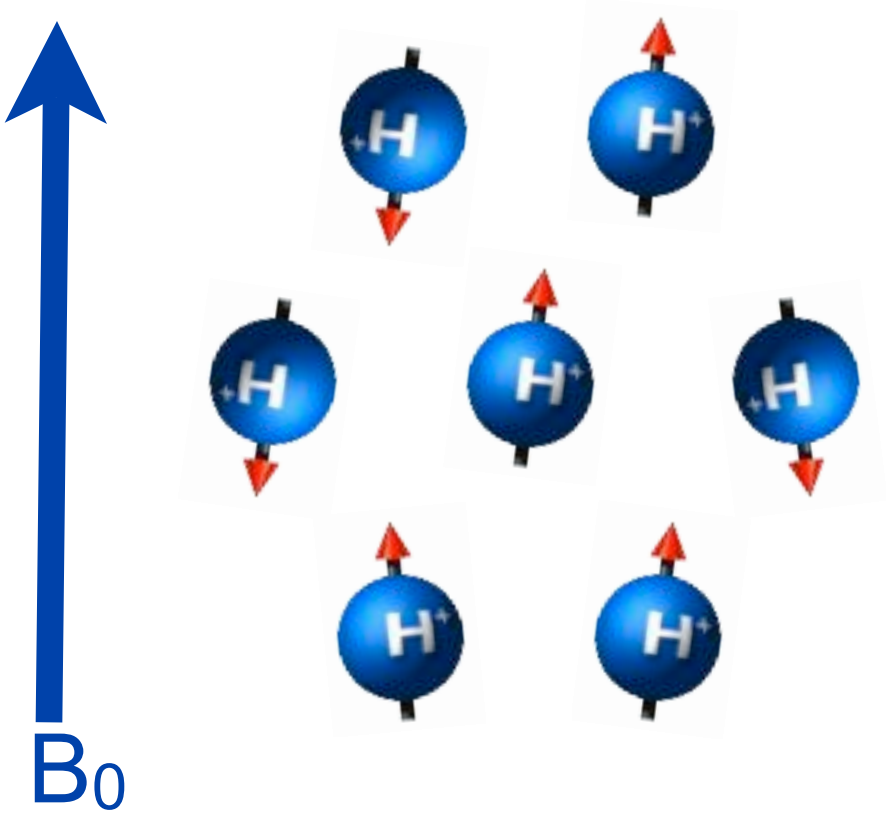
Proton

Protons in uniform B_0 field

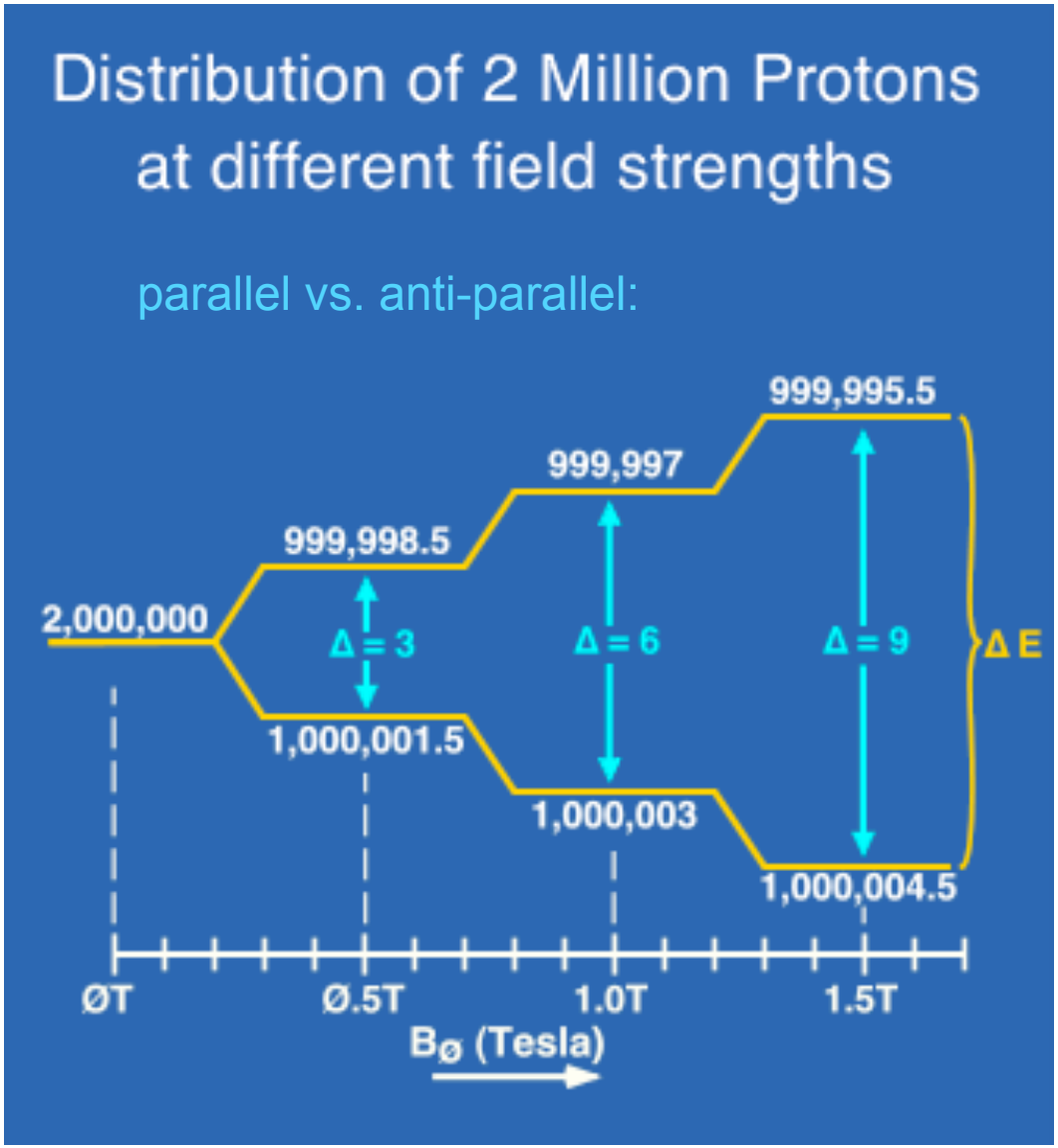


As spins do not rotate in phase, the sum of all the microscopic magnetizations of each spin is a null macroscopic magnetization.

Alignment with B_0 field



Alignment with B_0 field



Alignment with B_0 field

How many excess protons are there in a single voxel at 1.5T?

- Assume a voxel is
  2 x 2 x 5 mm = 0.02 ml
- Avogadro's Number says there are 6.02×10^{23} molecules per mole.
- 1 mole of water weights 18 grams ($O^{16} + 2H^{1}$) has 2 moles of hydrogen and fills 18 ml, so.....

Alignment with B_0 field

- 1 voxel of water has

  $2 \times 6.02 \times 10^{23} \times 0.02 / 18 =$

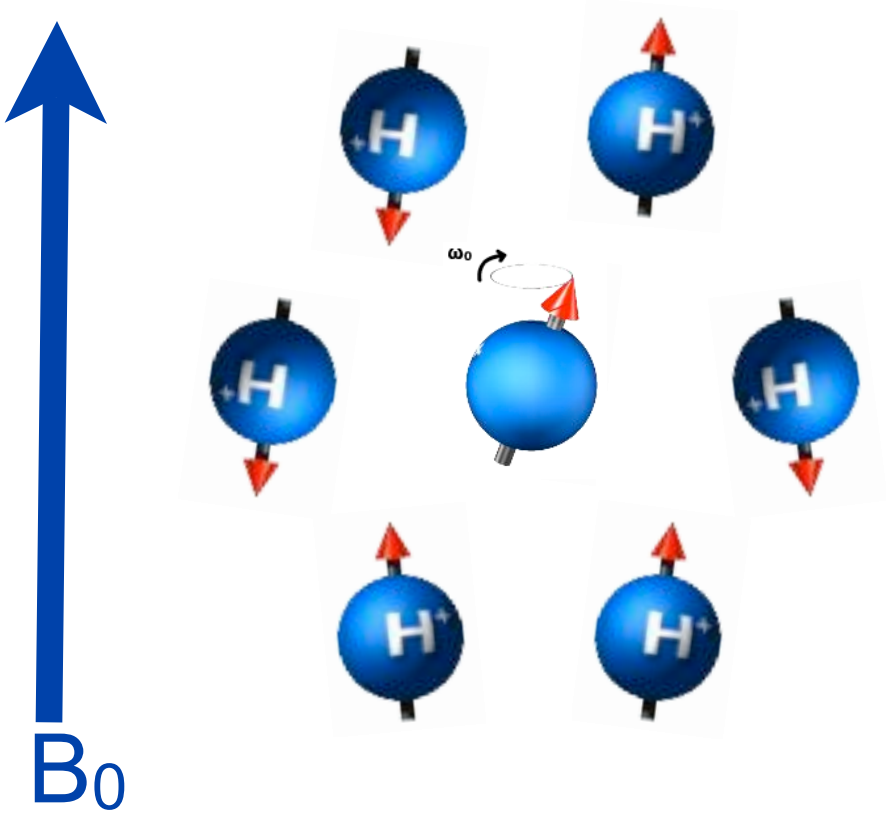
  1.338×10^{21} total protons

- The total number of excess protons =

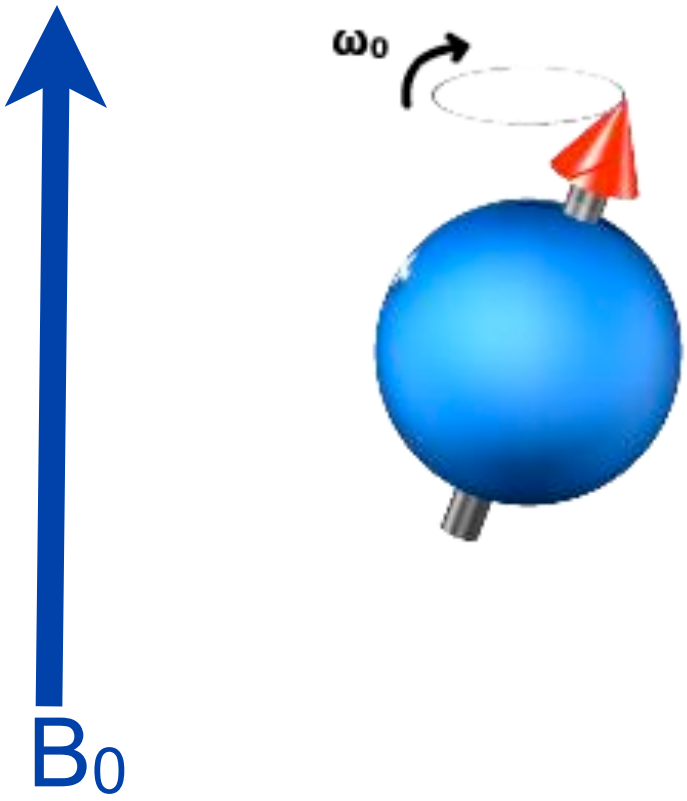
$$\frac{1.338 \times 10^{21} \times 9}{2 \times 10^{6}} = 6.02 \times 10^{15}$$

Or.... 6 million billion!

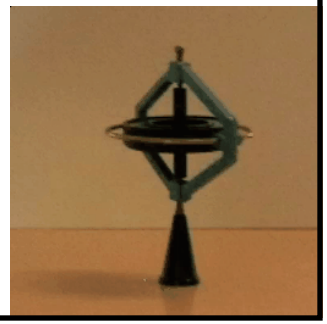
Alignment with B_0 field



Larmor precession



Spins in a static magnetic field precess



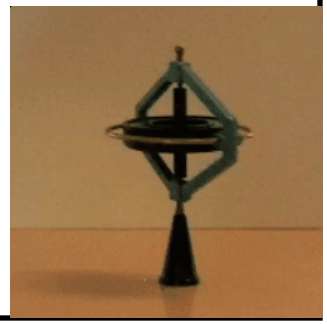
Larmor precession

$$\omega = \gamma B_0$$

ω, = precession frequency (Hz)
γ = gyromagnetic ratio (Hz/T)
for protons: 42.58 MHz/T
B_0 = static (external) magnetic field (Tesla)

Torque:

$$\vec{\Gamma} = \gamma \vec{J} \times \vec{B}$$ ($\vec{J}$ = angular momentum)

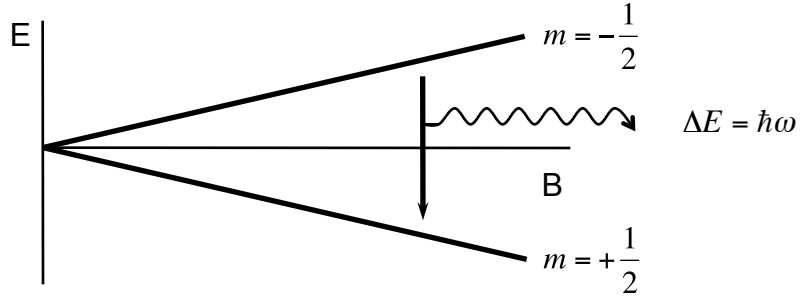


Resonant frequency

$$\Delta E = \hbar\omega$$

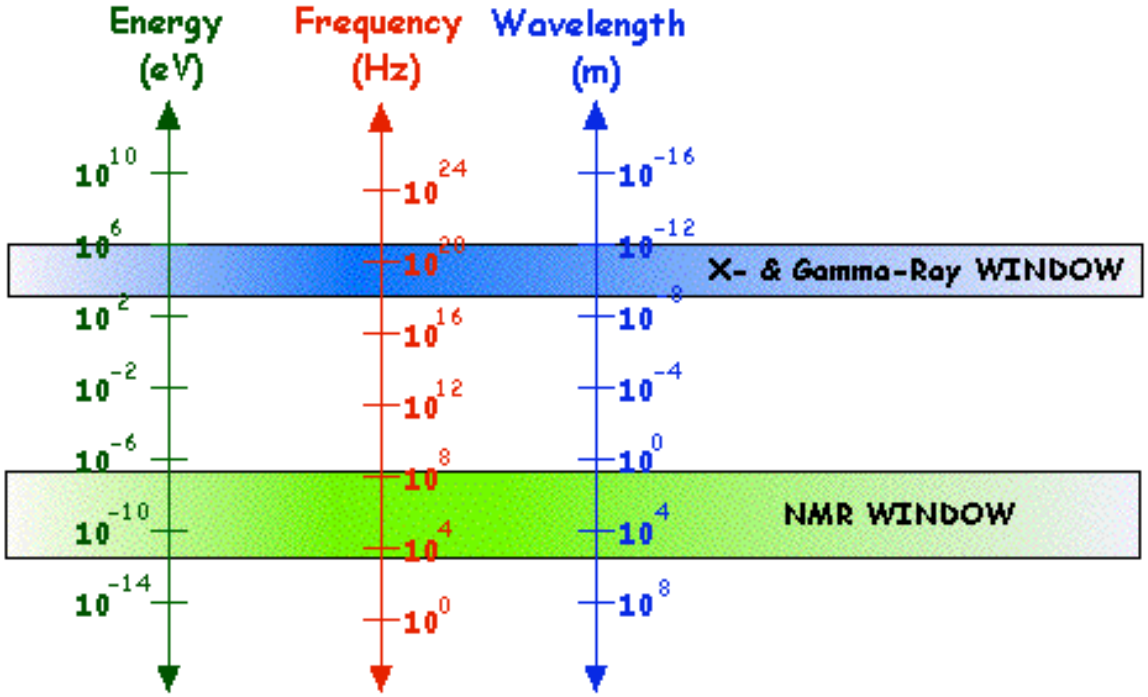
Exchange of energy between two systems at a specific frequency is called resonance. Magnetic resonance corresponds to the energetic interaction between spins and electromagnetic radiofrequency (RF).

Transition from high to low energy state emits radiation with characteristic frequency:

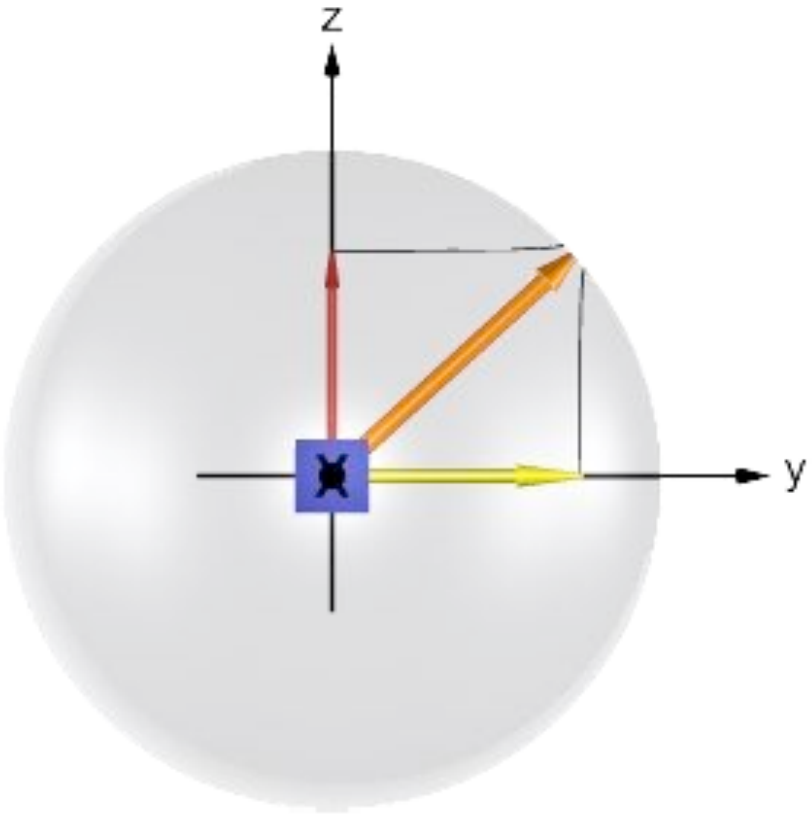


Resonant frequency

$$\Delta E = \hbar\omega$$



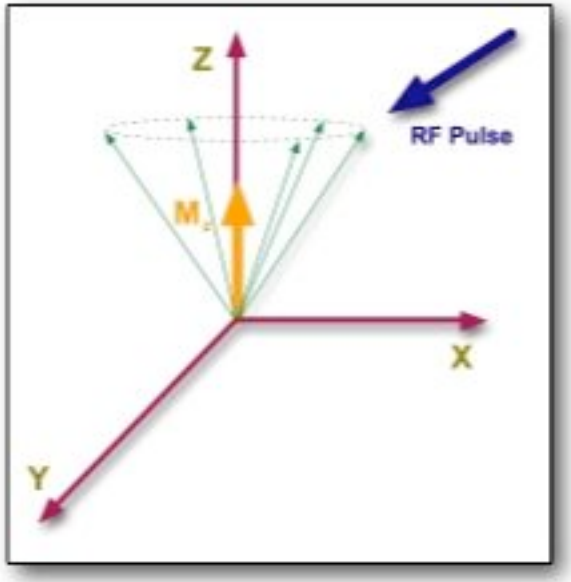
Precession components

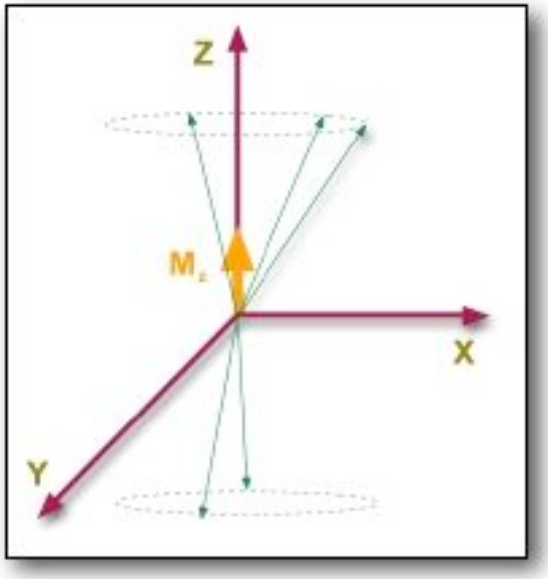


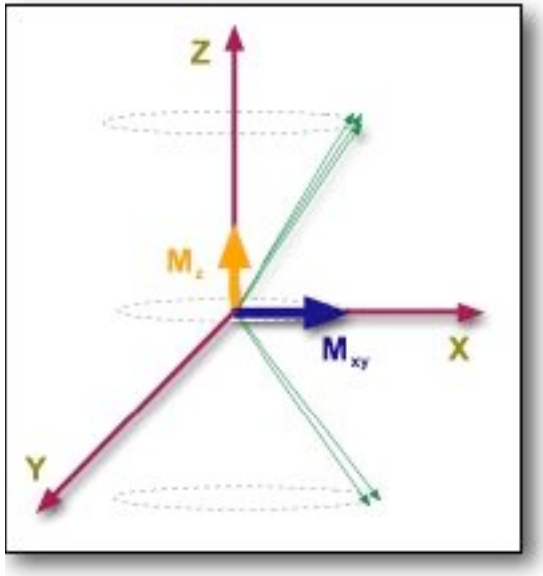
Longitudinal magnetization is due to a difference in the number of spins in parallel and anti-parallel state.

Transverse magnetization is due to spins getting into phase coherence.

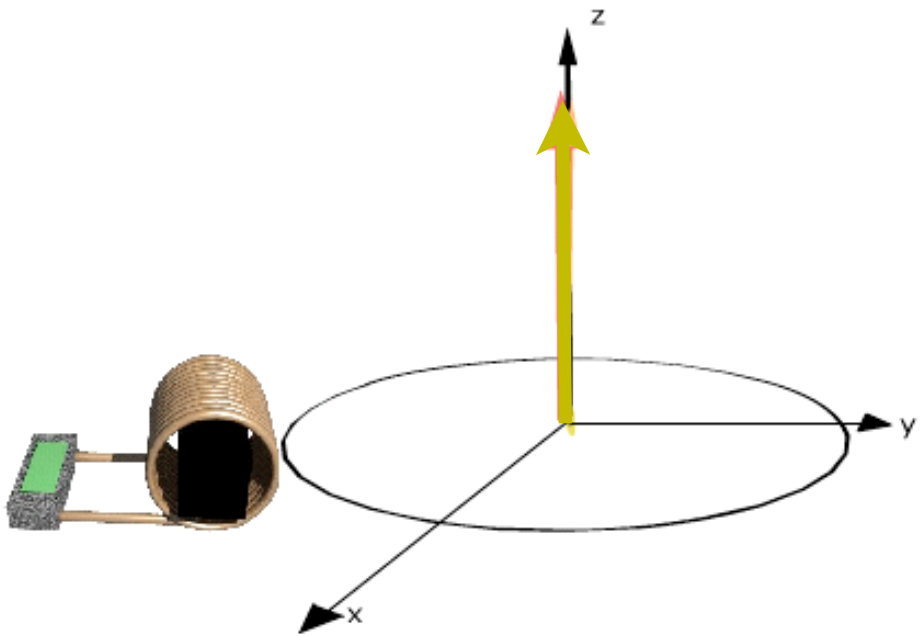
Precession components



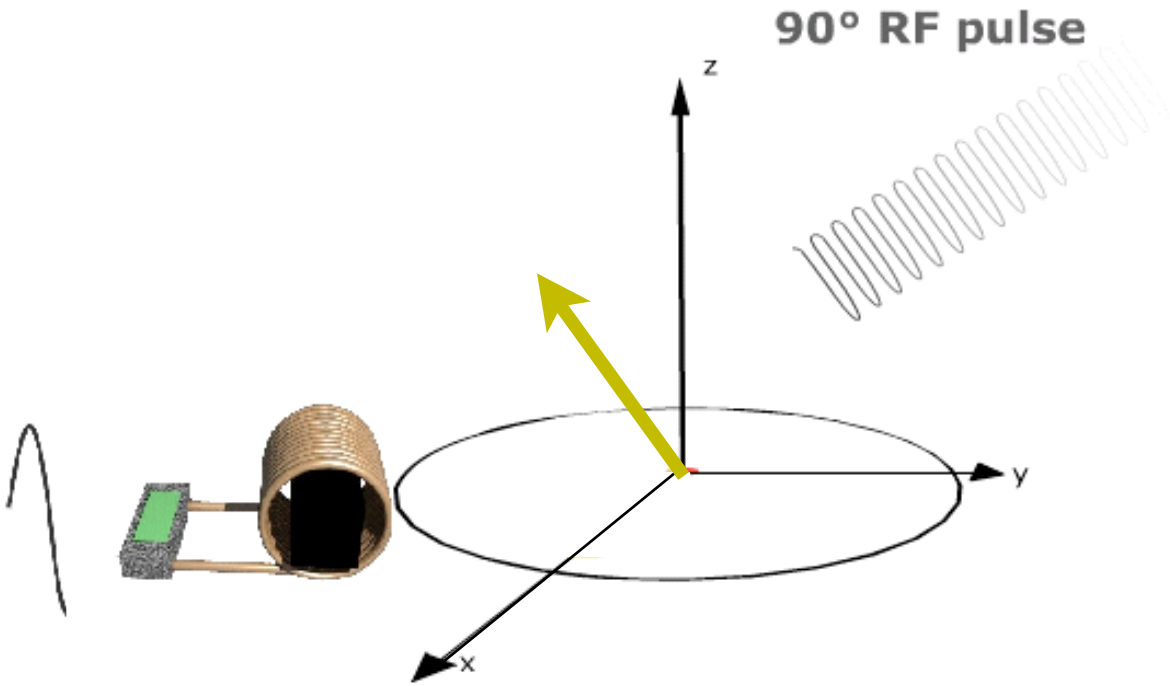




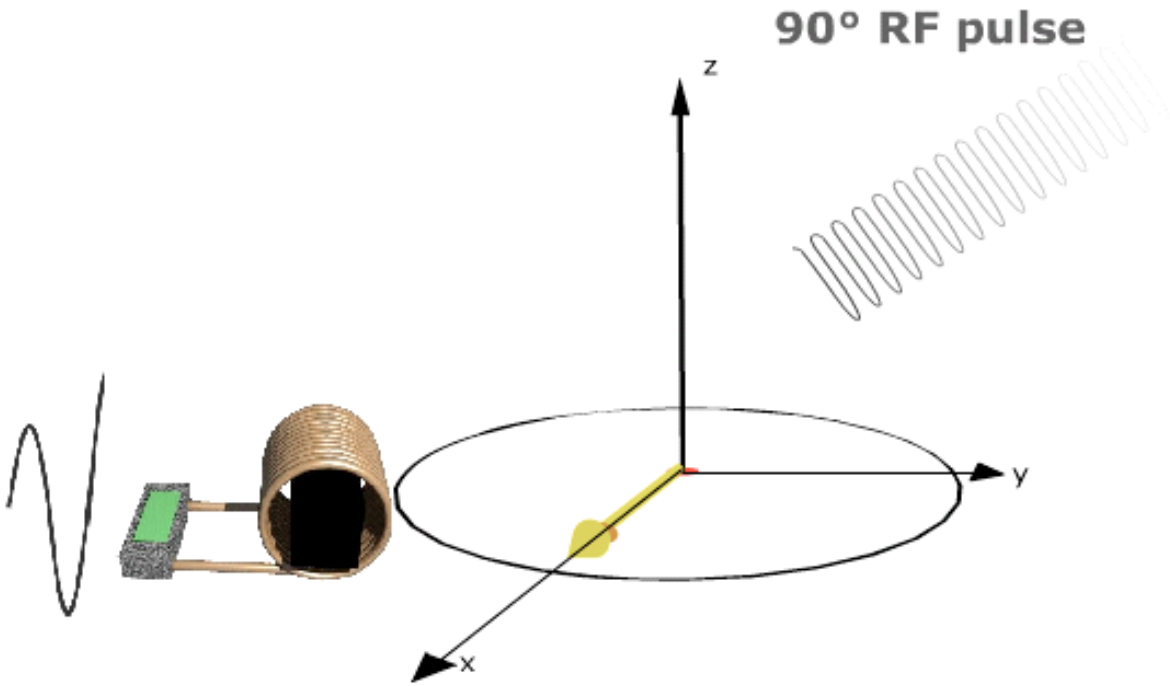
Signal: excitation & relaxation



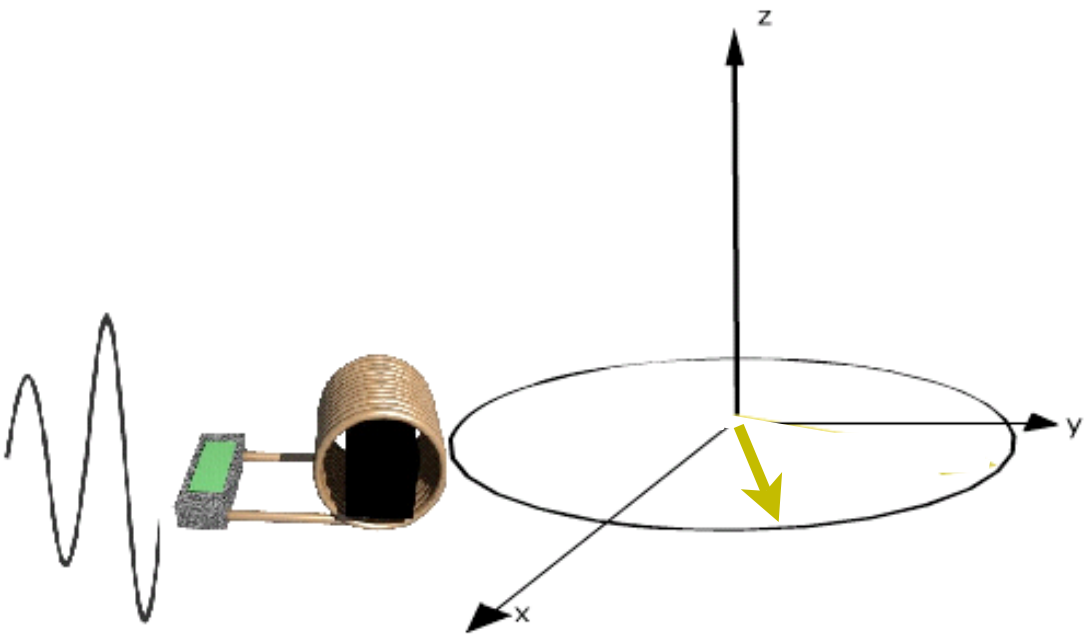
Excitation



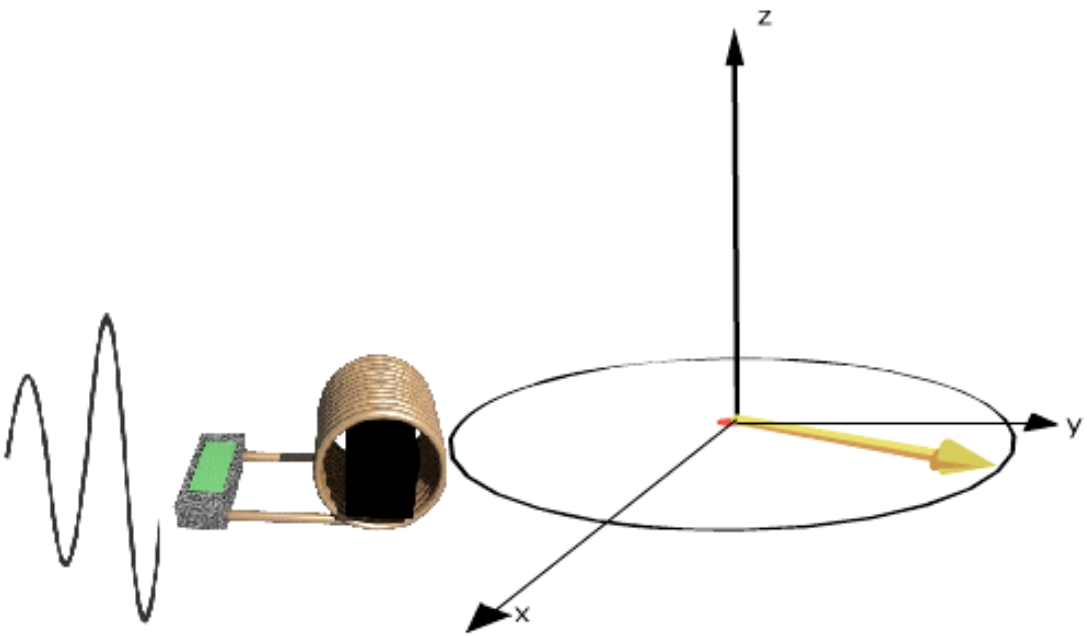
Excitation



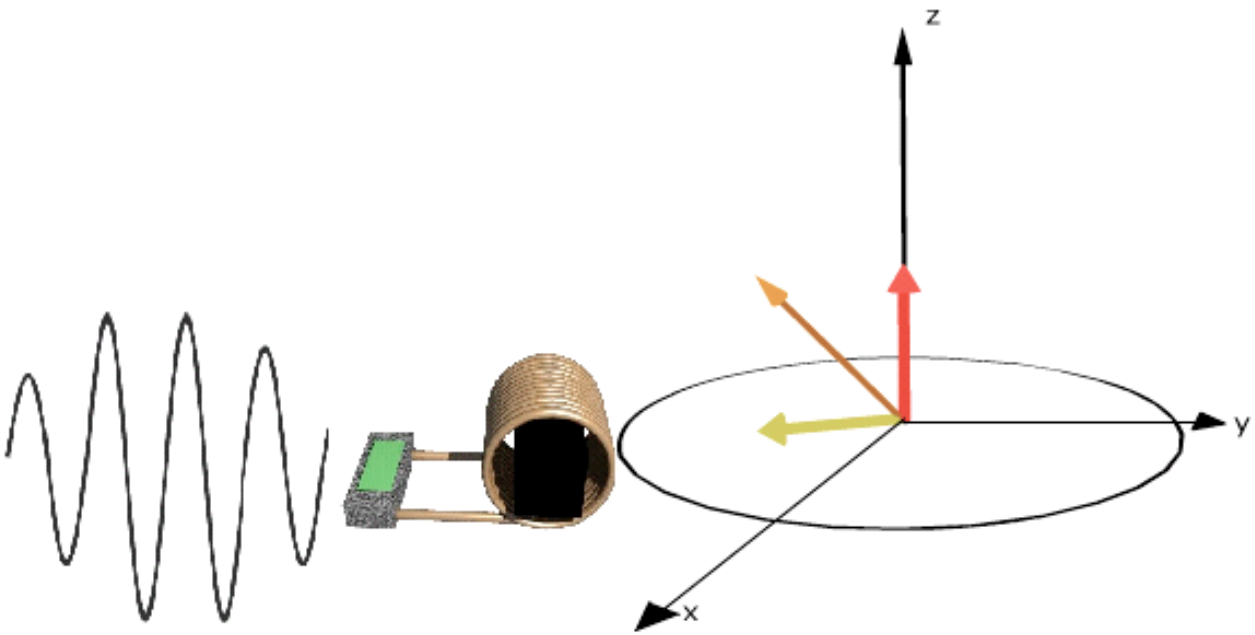
Relaxation



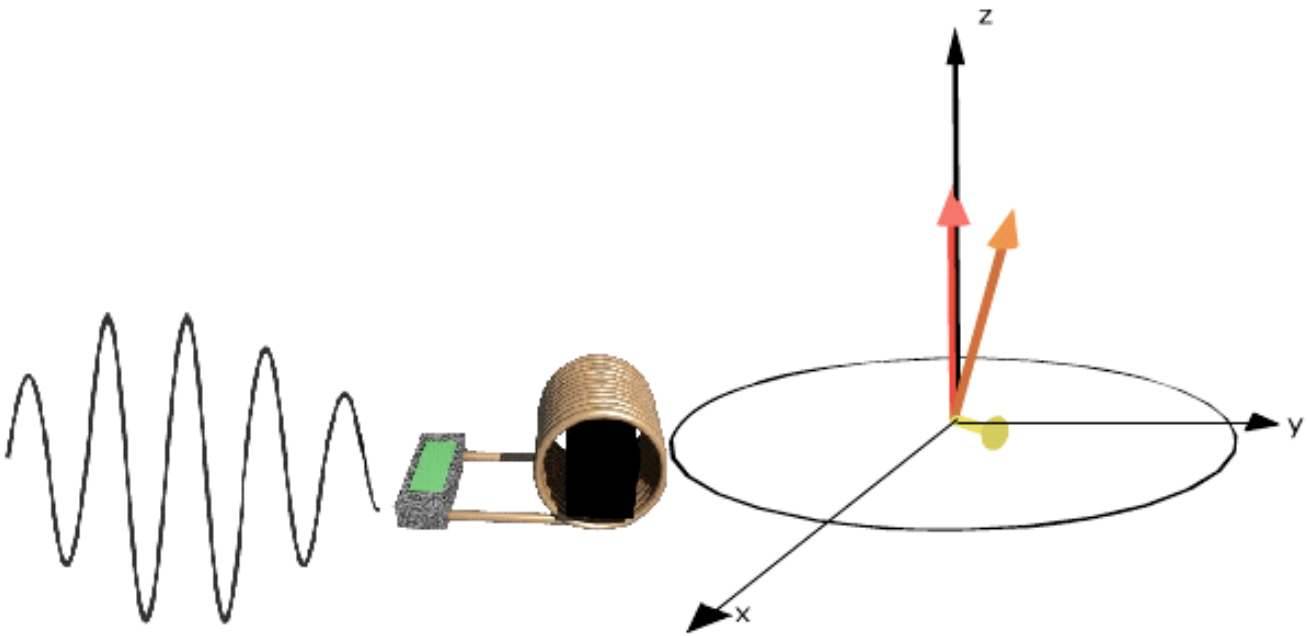
Relaxation



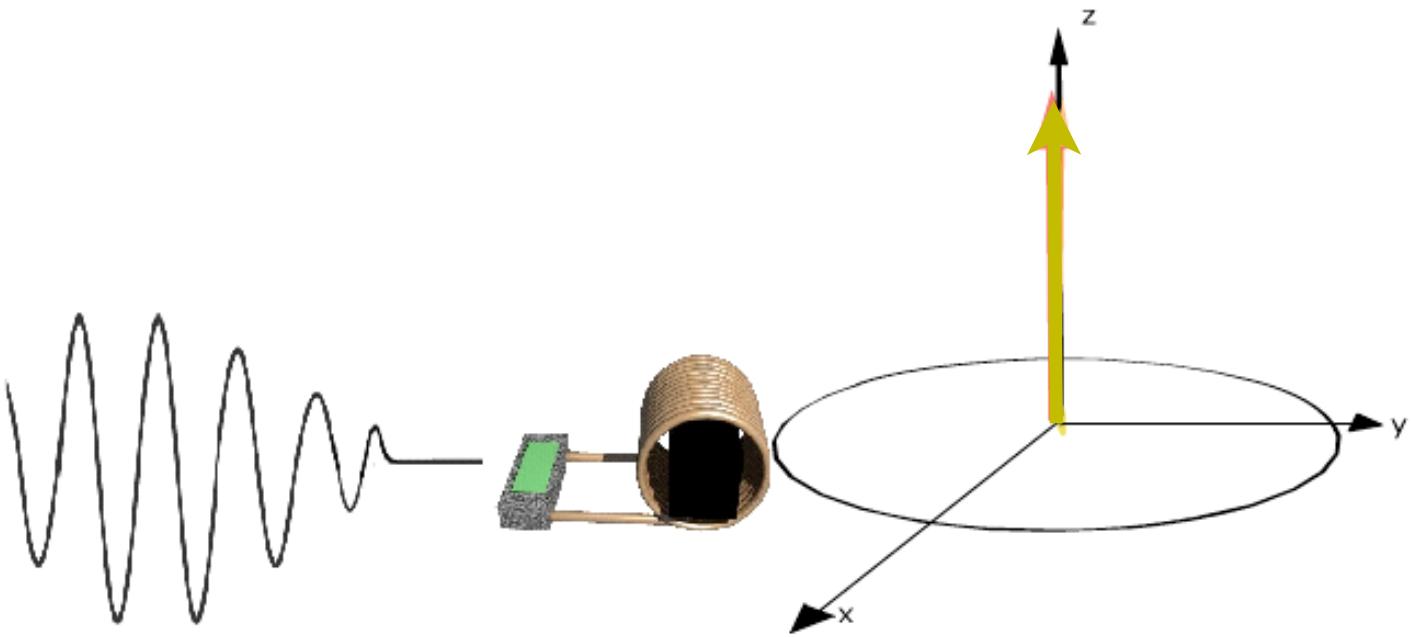
Relaxation



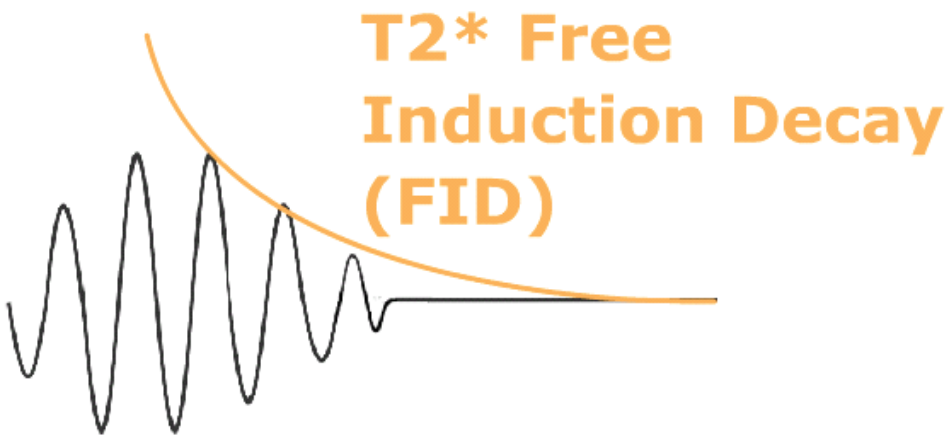
Relaxation



Relaxation

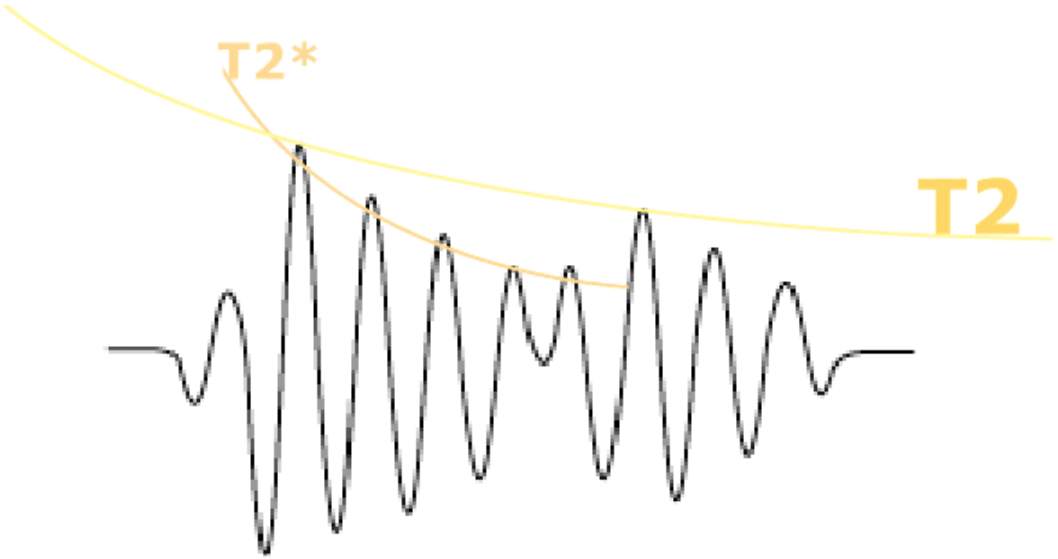


Relaxation



Static inhomogeneities in magnetic fields accelerate spins dephasing.

Spin-echo

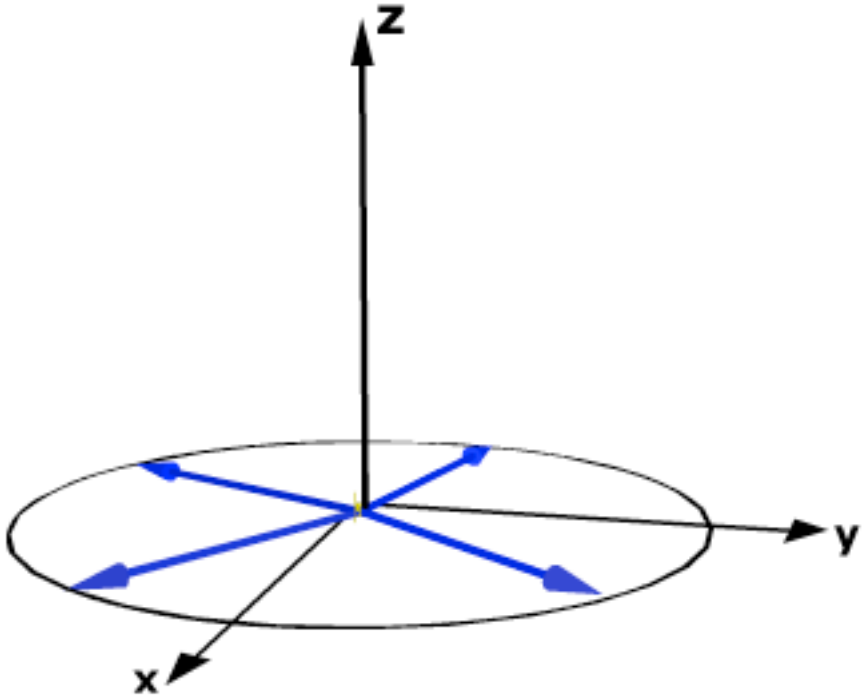


$$\frac{1}{T2^*} = \frac{1}{T2} + \frac{1}{T_{inh}}$$

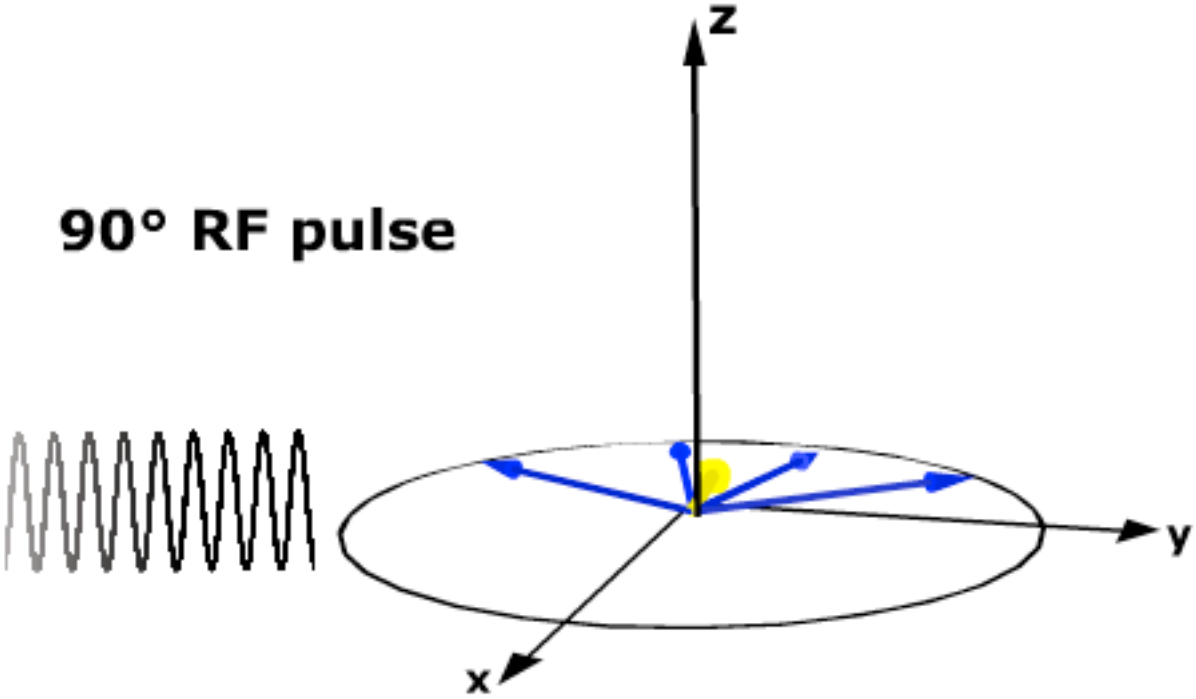
Tissue-specific spin-spin relaxation is responsible for pure T2 decay.

http://www.e-mri.org/signal-contrast/180-rf-pulse.html

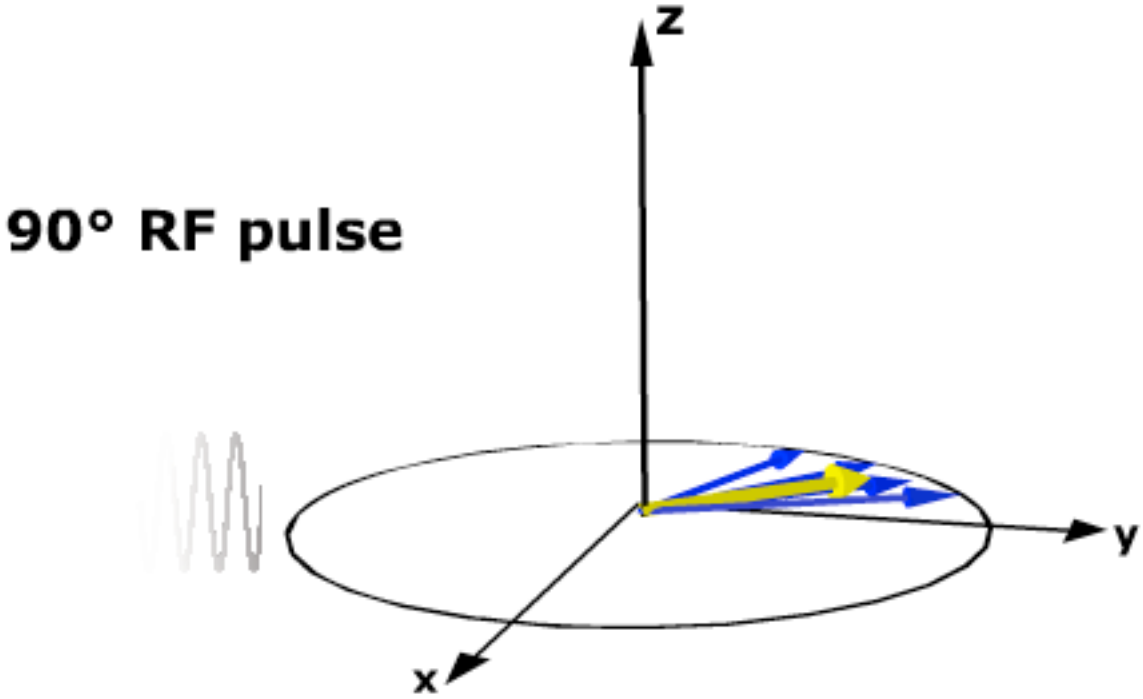
Spin-echo



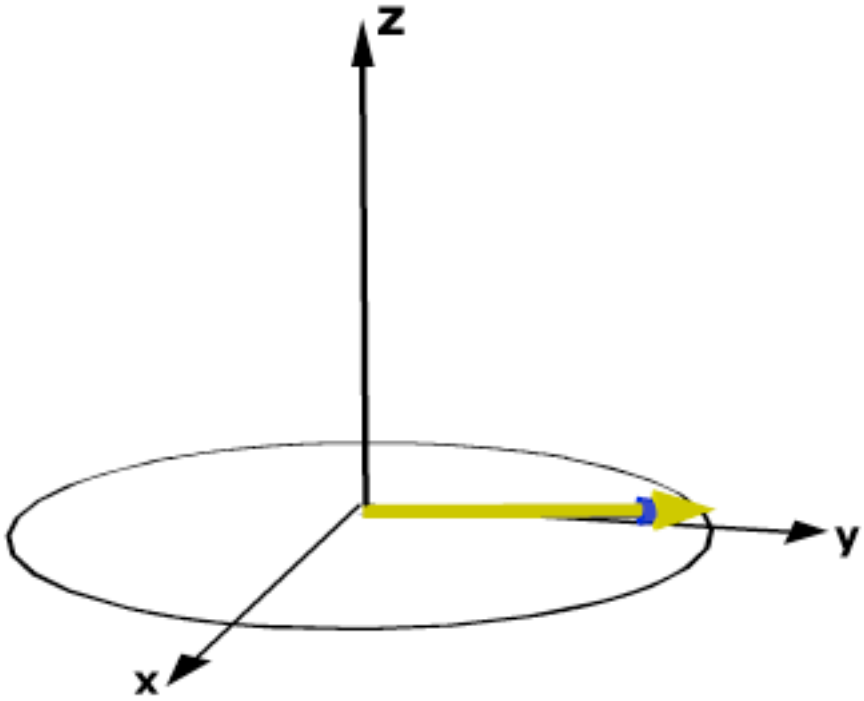
Spin-echo



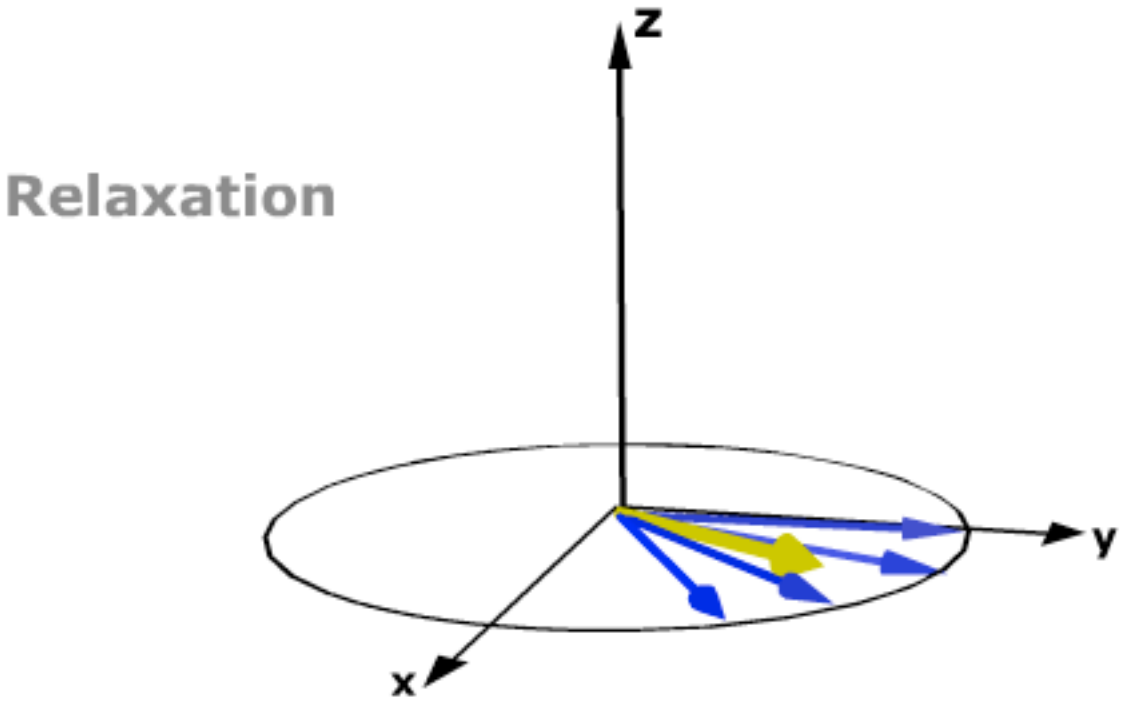
Spin-echo



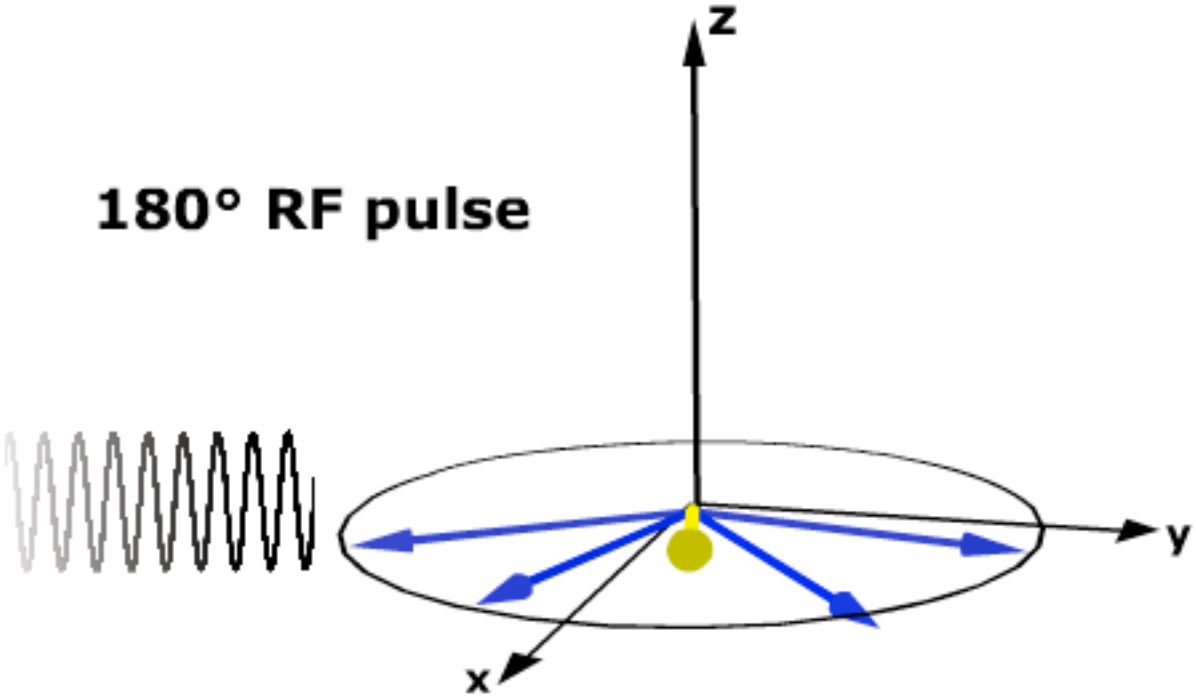
Spin-echo



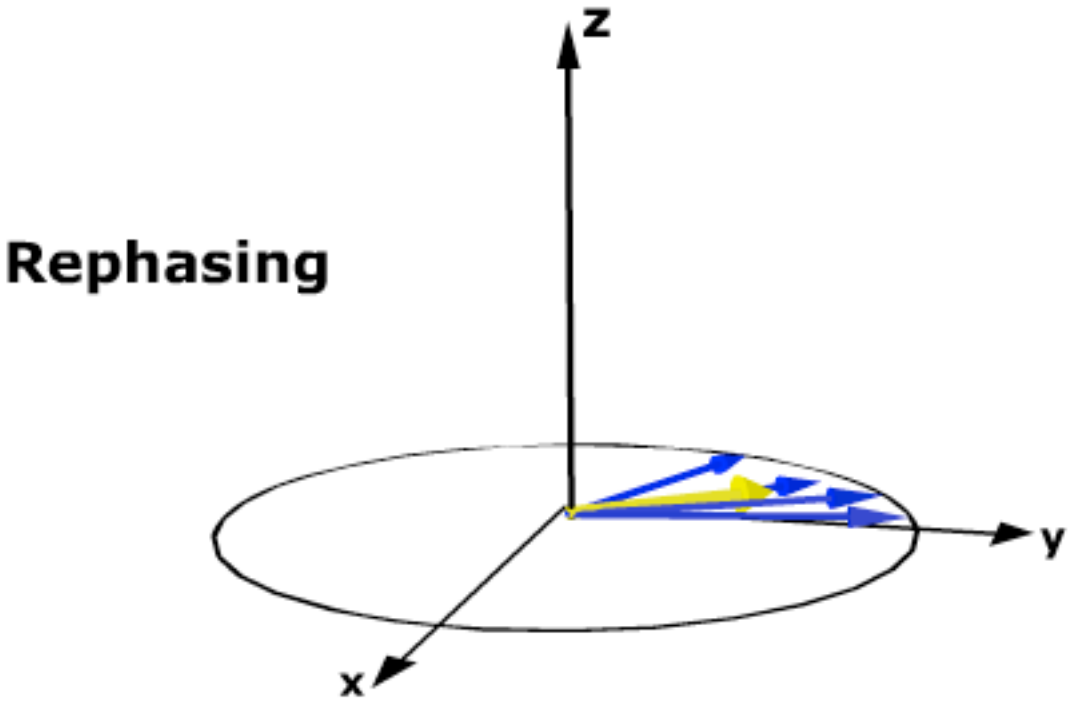
Spin-echo



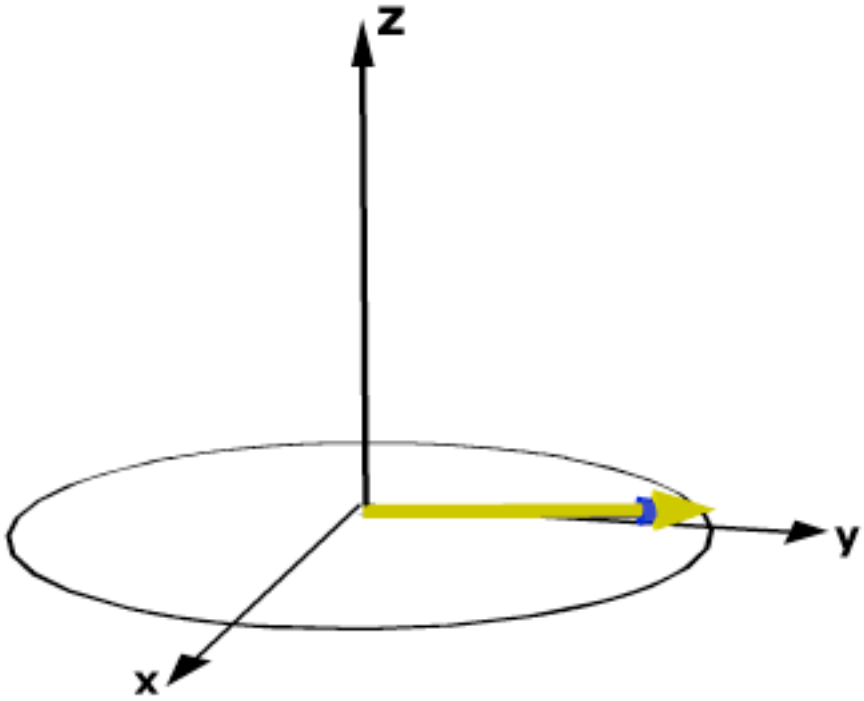
Spin-echo



Spin-echo

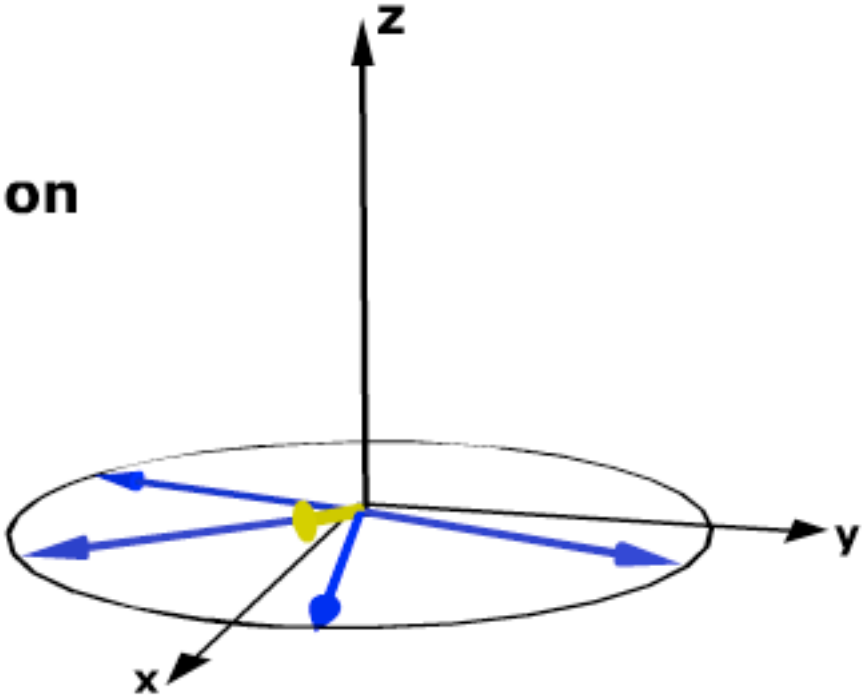


Spin-echo



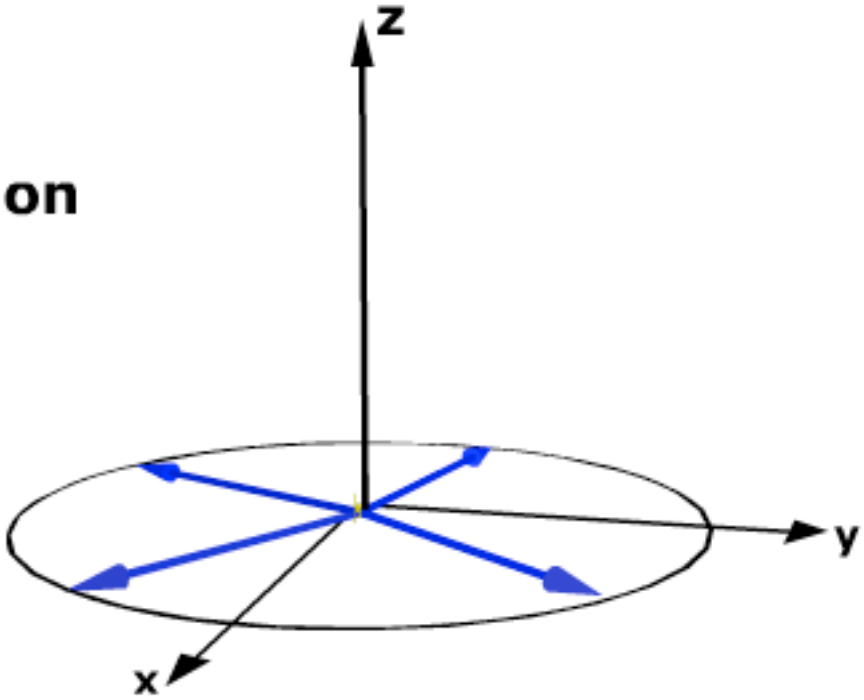
Spin-echo

Relaxation

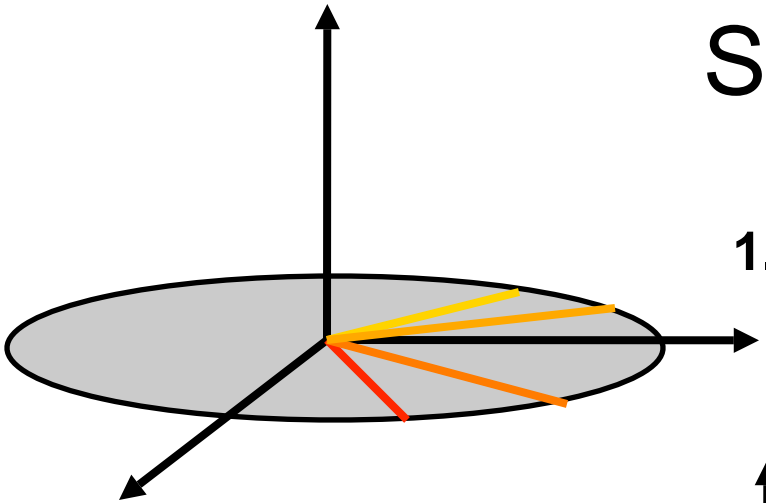


Spin-echo

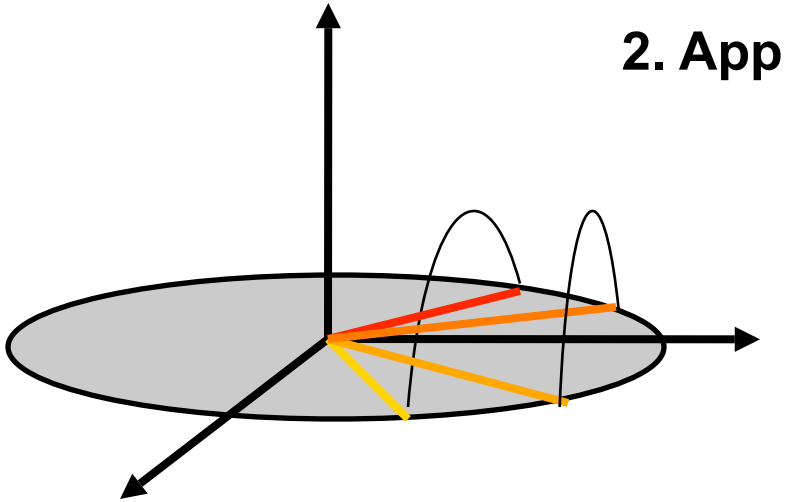
Relaxation



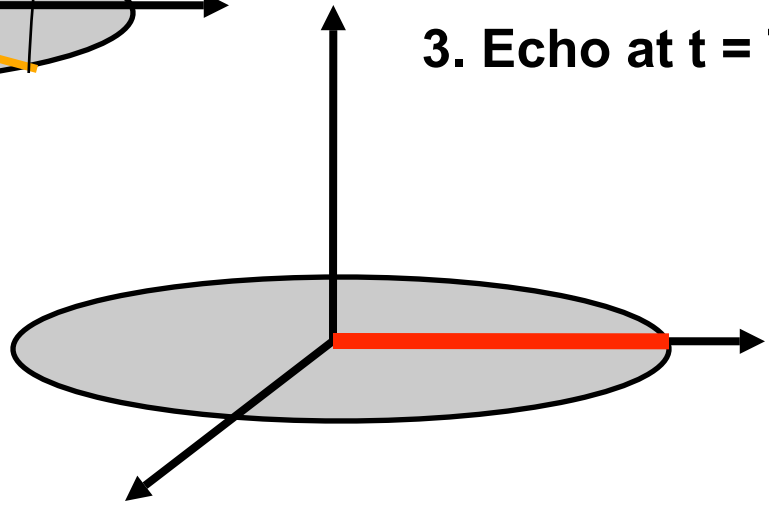
Spin-echo



1. Spins dephase: fast and slow

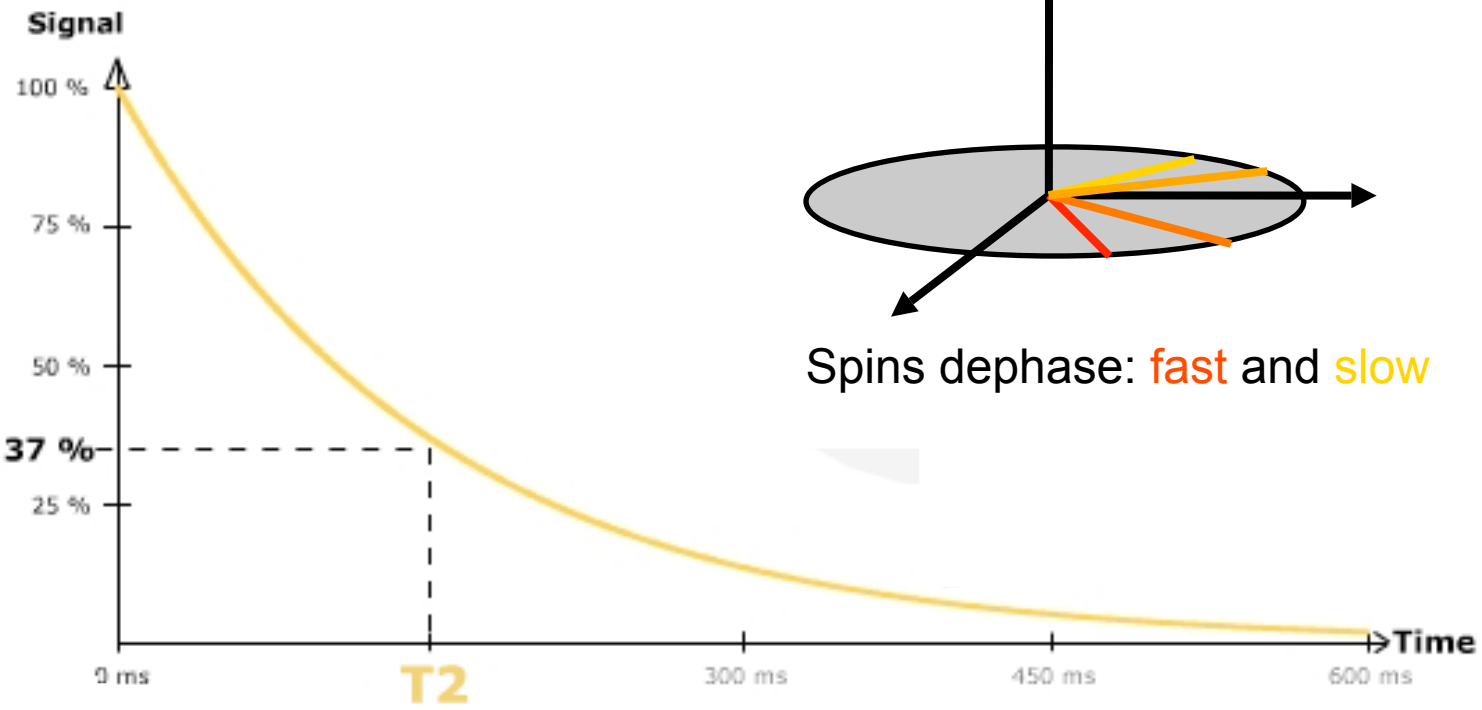


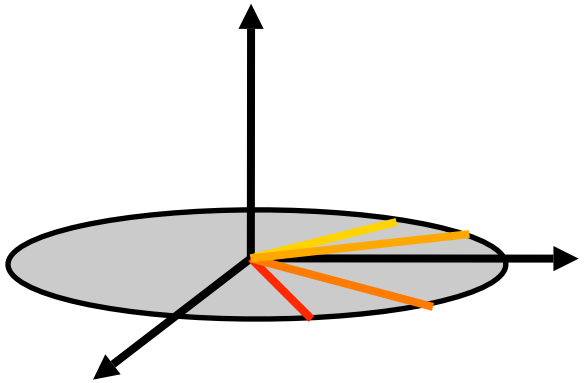
2. Apply 180° at t = TE/2



3. Echo at t = TE

Relaxation

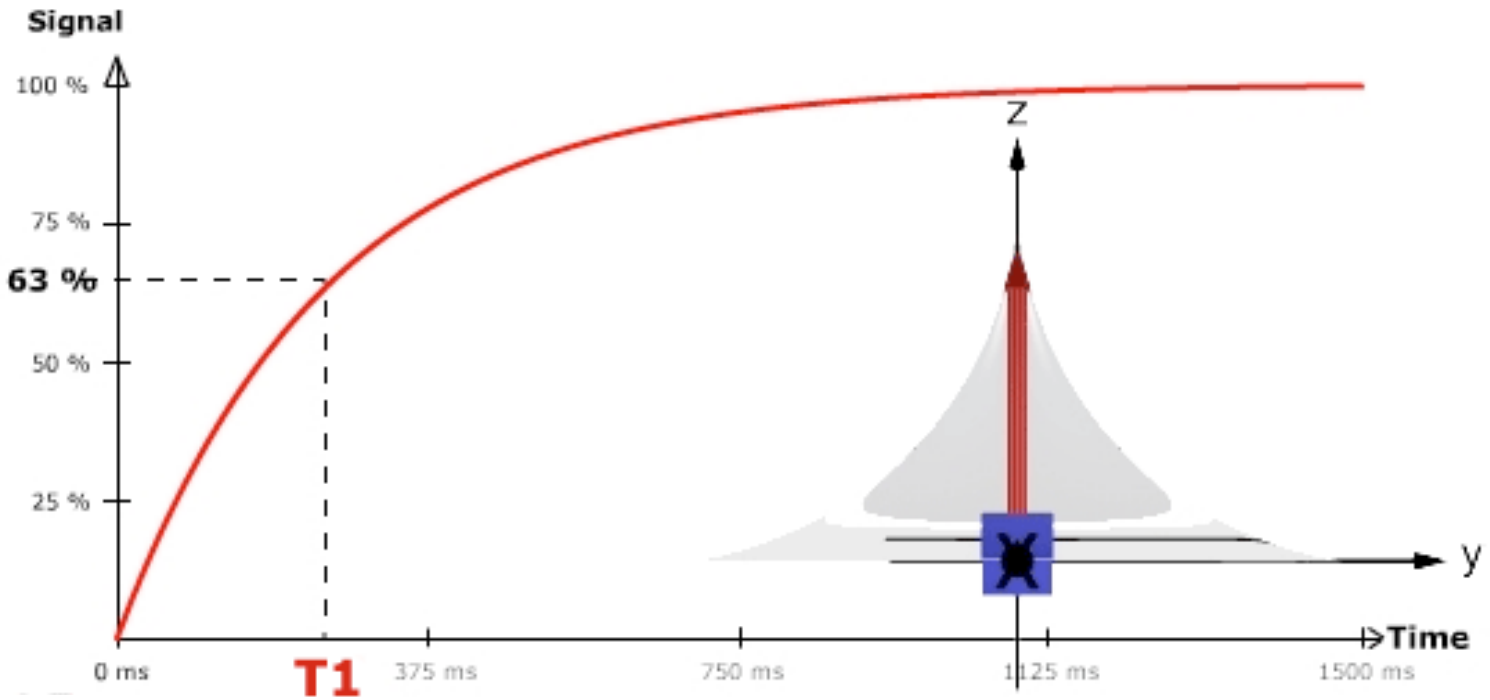




Spins dephase: fast and slow

Decay of transverse magnetization, due to spins getting out of phase (spin-spin interactions), according to an exponential curve characterized by time constant T2.
T2 values are lower than T1 values and are unrelated to field strength.

Relaxation



Recovery of longitudinal magnetization, aligned with B_0,
following an exponential curve characterized by time constant T1.
With a 1.5 T field strength, T1 values are about 200 to 3000 ms.
T1 values are longer at higher field strengths.

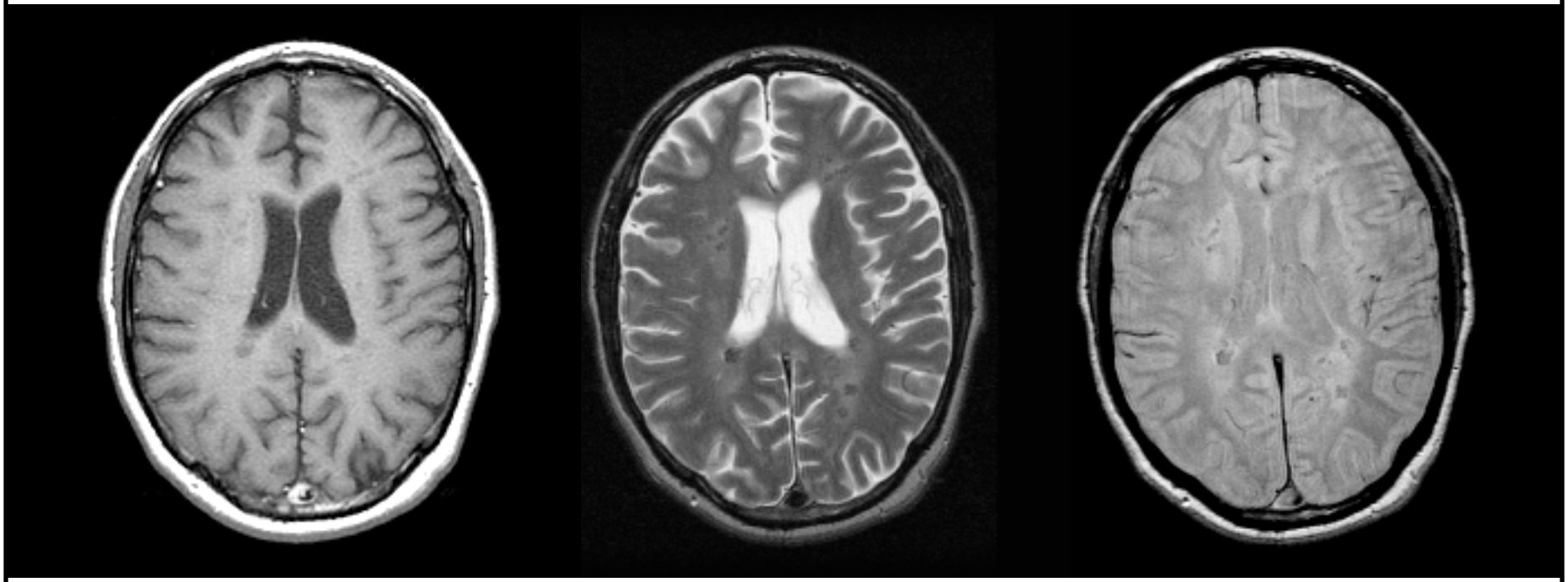
Relaxation

	T_1 (ms)	T_2 (ms)
Water	3000	3000
Gray matter	810	100
White matter	680	90
Liver	420	45
Fat	240	85
Gadolinium	Reduces T_1 and T_2 times	

In clinical practice:

- TE is always shorter than TR
- A short TR = value approximately equal to the average T_1 value, usually lower than 500 ms
- A long TR = 3 times the short TR, usually greater than 1500 ms
- A short TE is usually lower than 30 ms
- A long TE = 3 times the short TE, usually greater than 90 ms

Tissue contrast



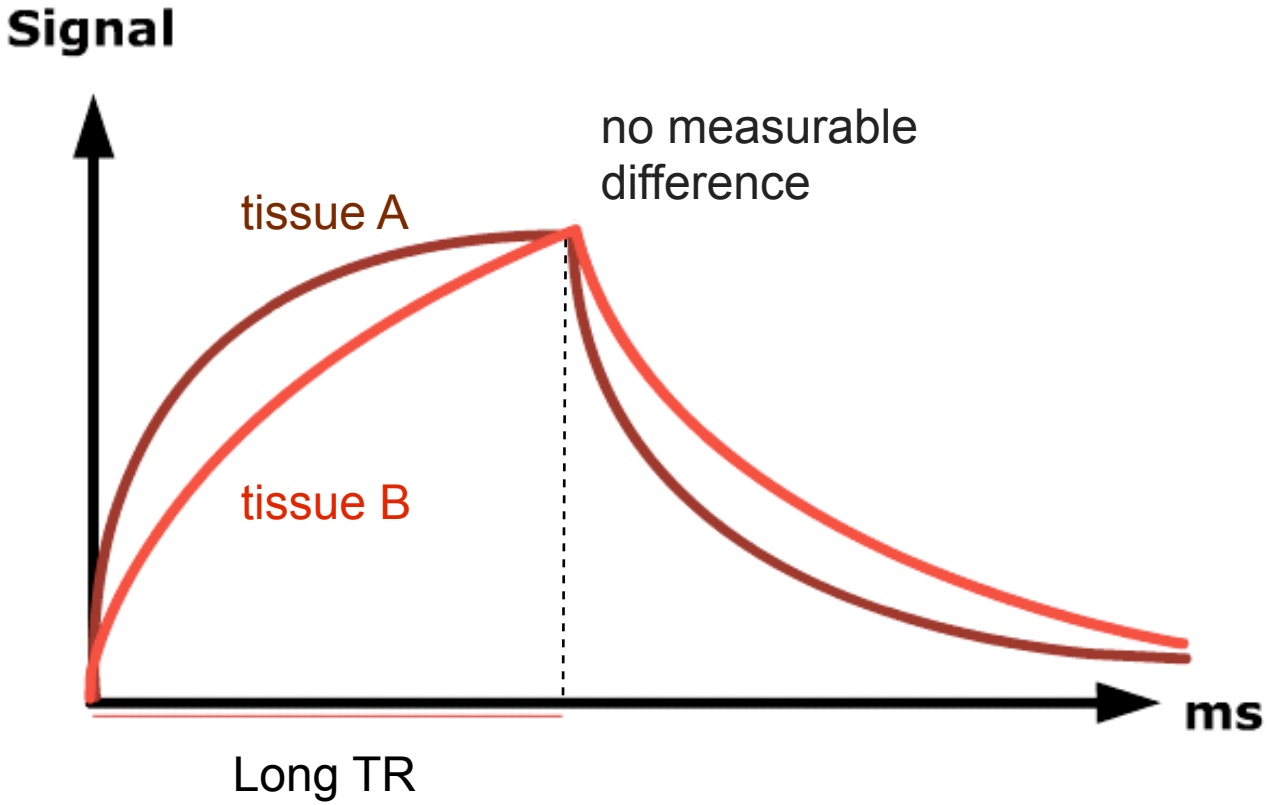
T1

T2

PD

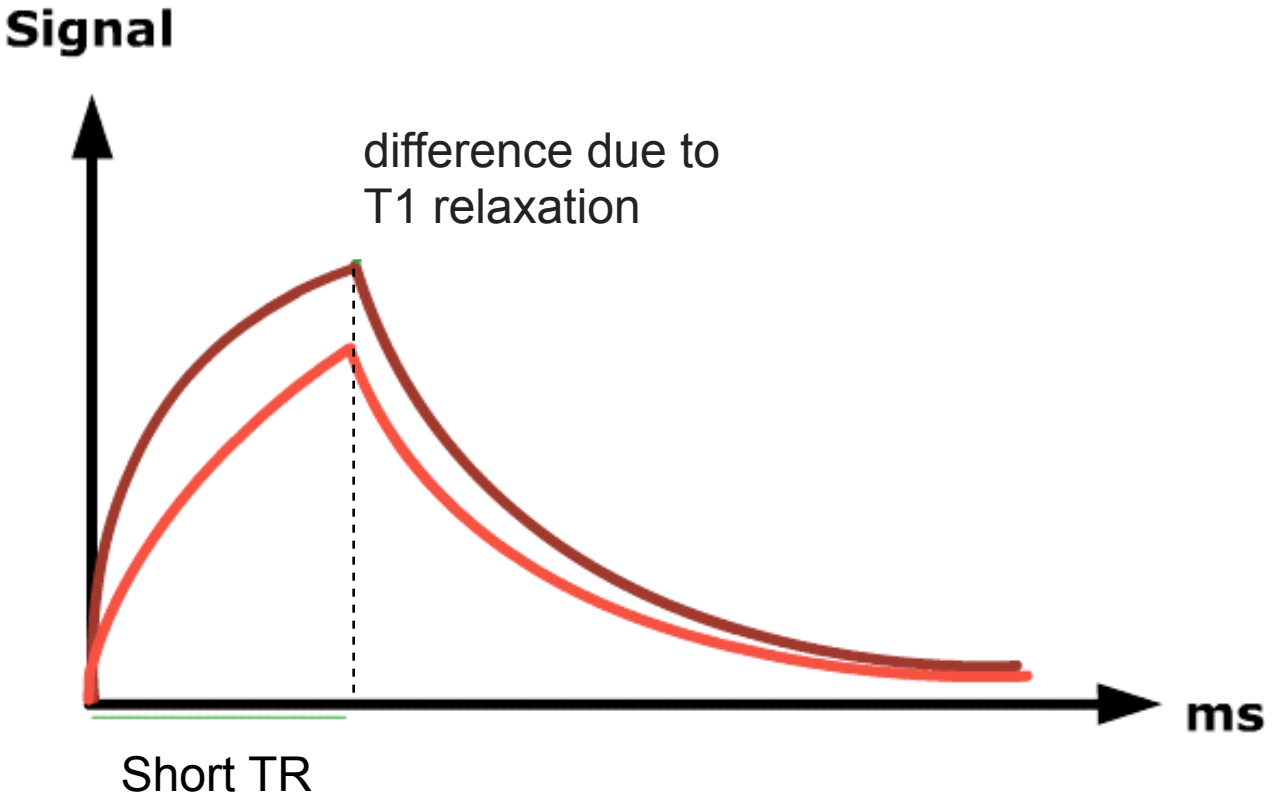
(proton density)

Tissue contrast



t = TR × [# phase encoding steps] × [# acquisitions to average]

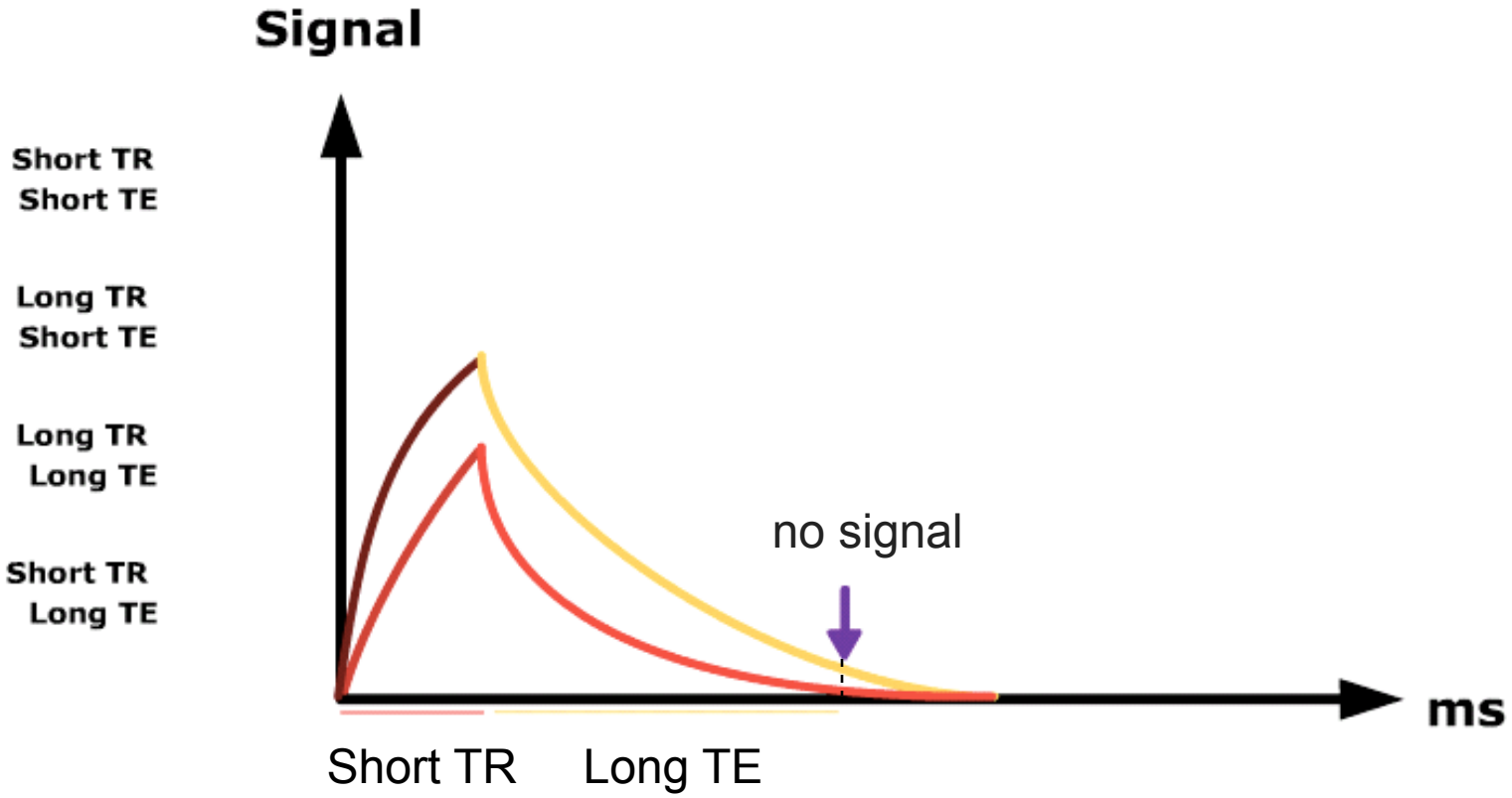
Tissue contrast



By setting the TR to short values, tissue contrast will depend on differences in longitudinal magnetization recovery (T1).

Tissue contrast

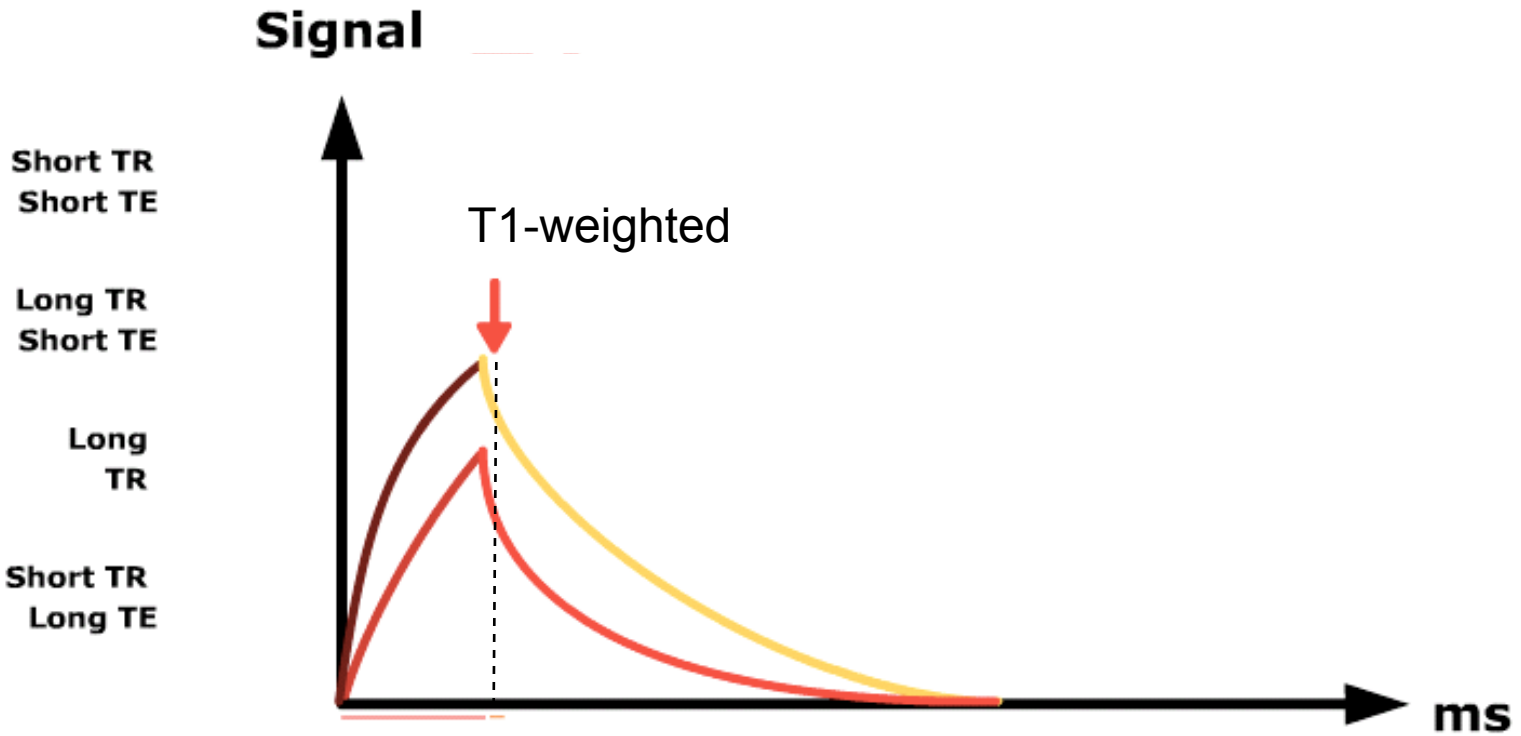
(Spin-echo)



Echo Time (TE) is the time between 90° RF pulse and MR signal sampling.
The 180° RF pulse is applied at time TE/2.

Tissue contrast

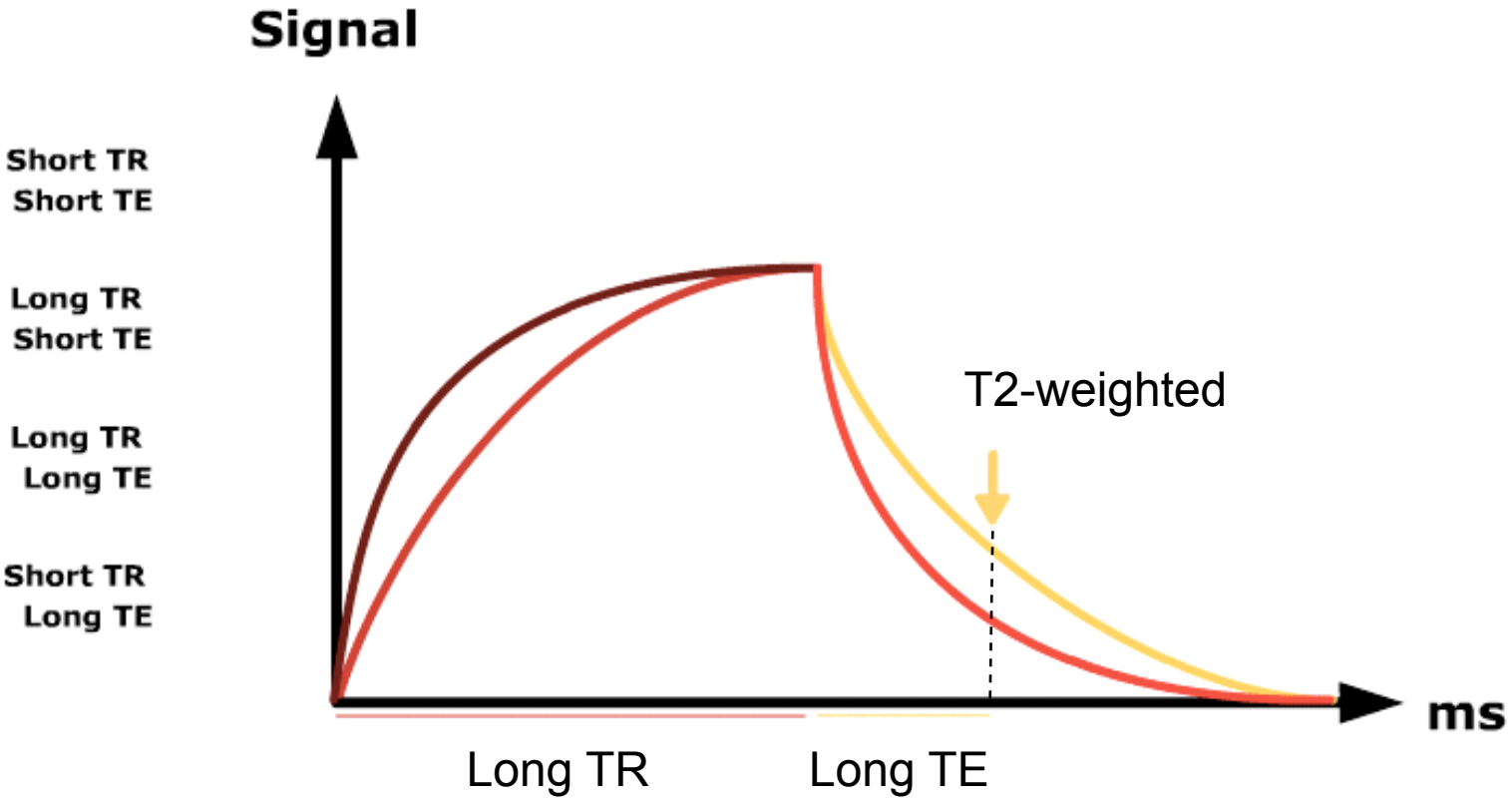
(Spin-echo)



Short TR, Short TE

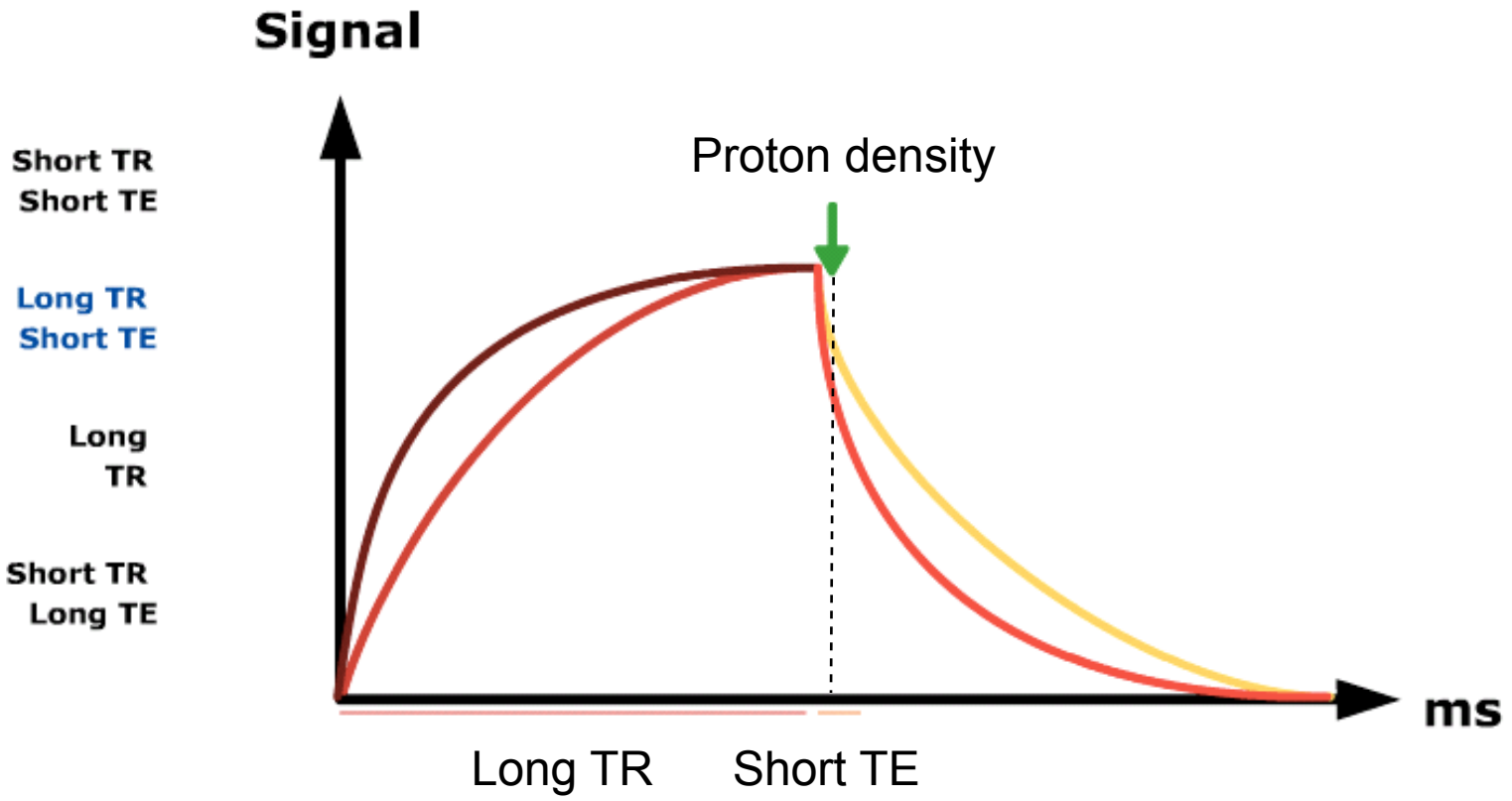
Tissue contrast

(Spin-echo)

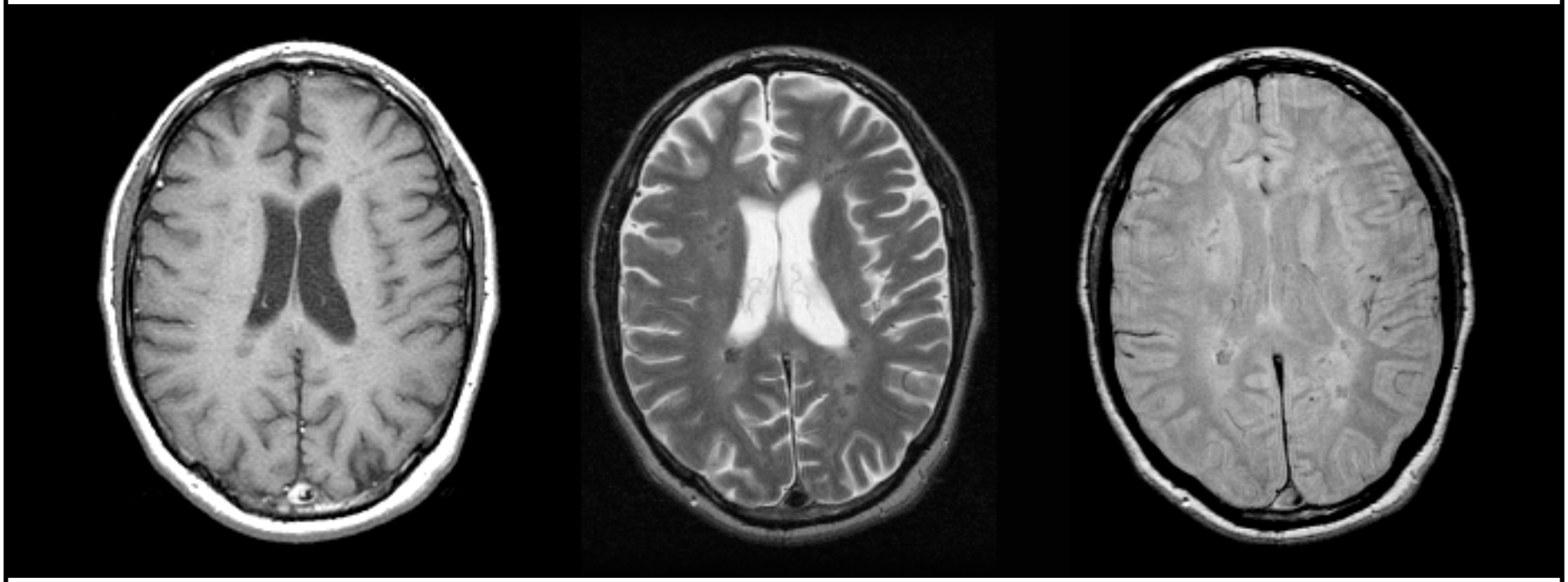


Tissue contrast

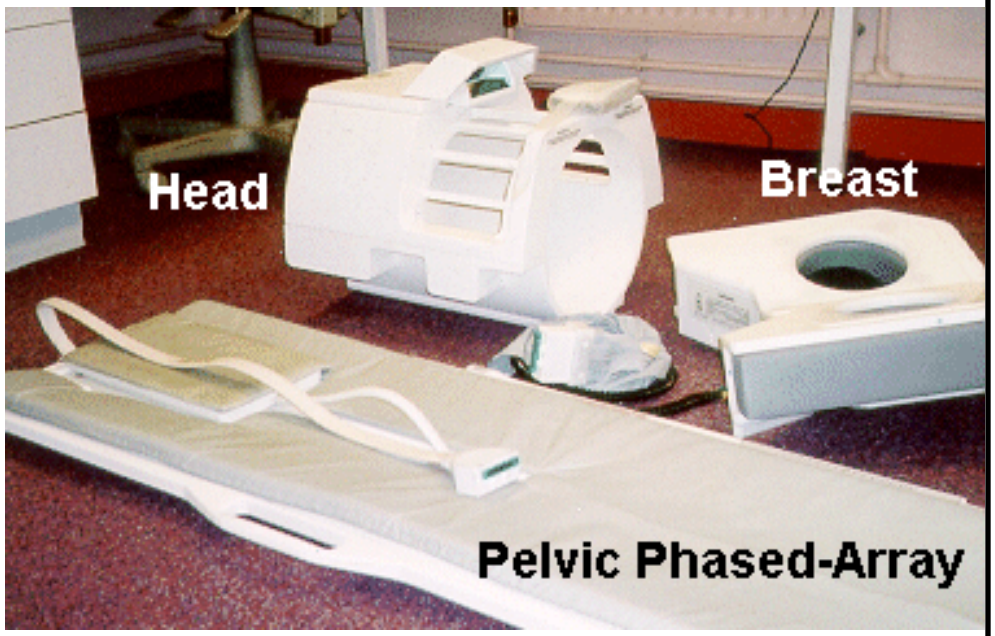
(Spin-echo)



Spatial encoding

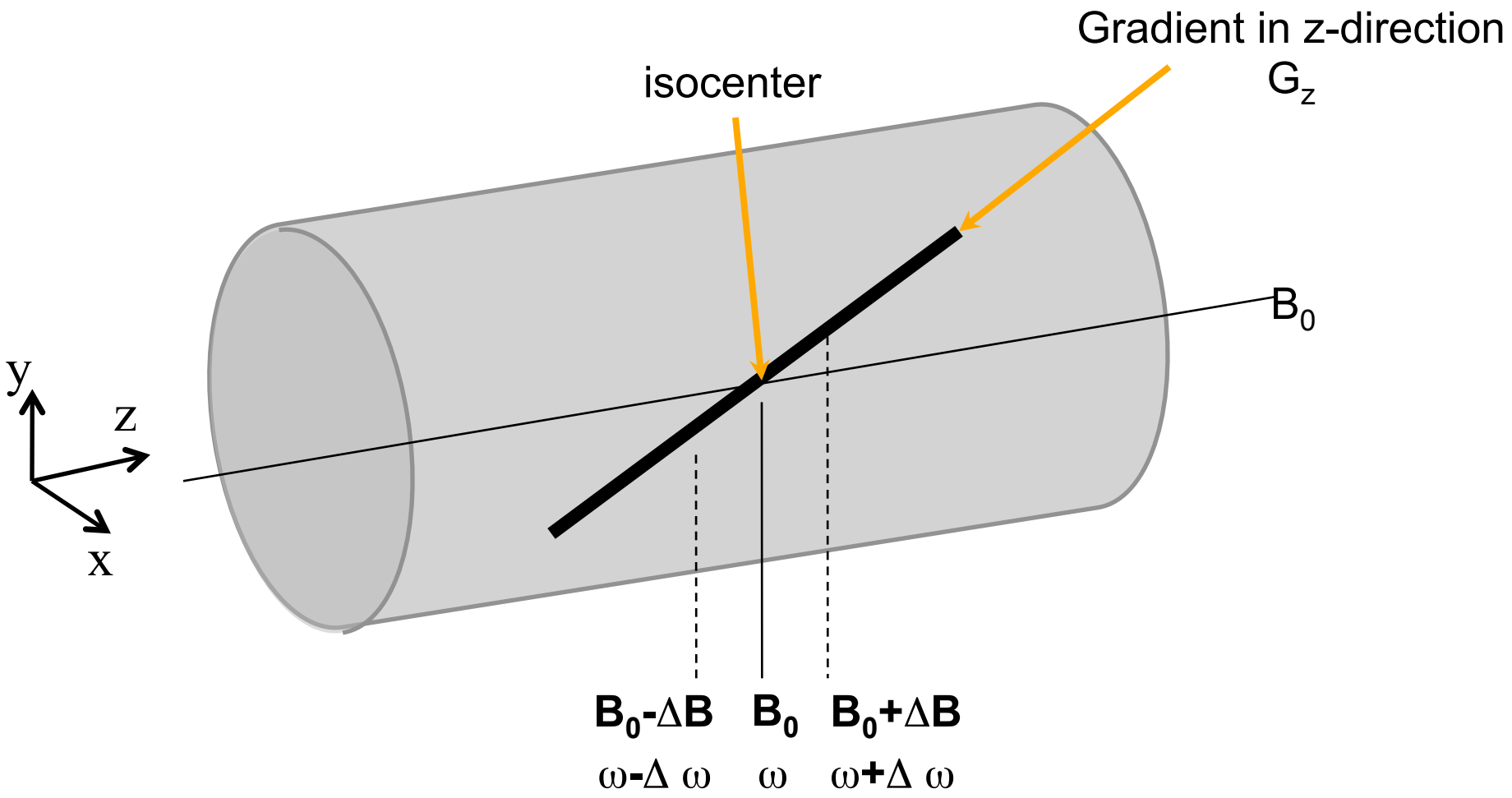


Spatial encoding



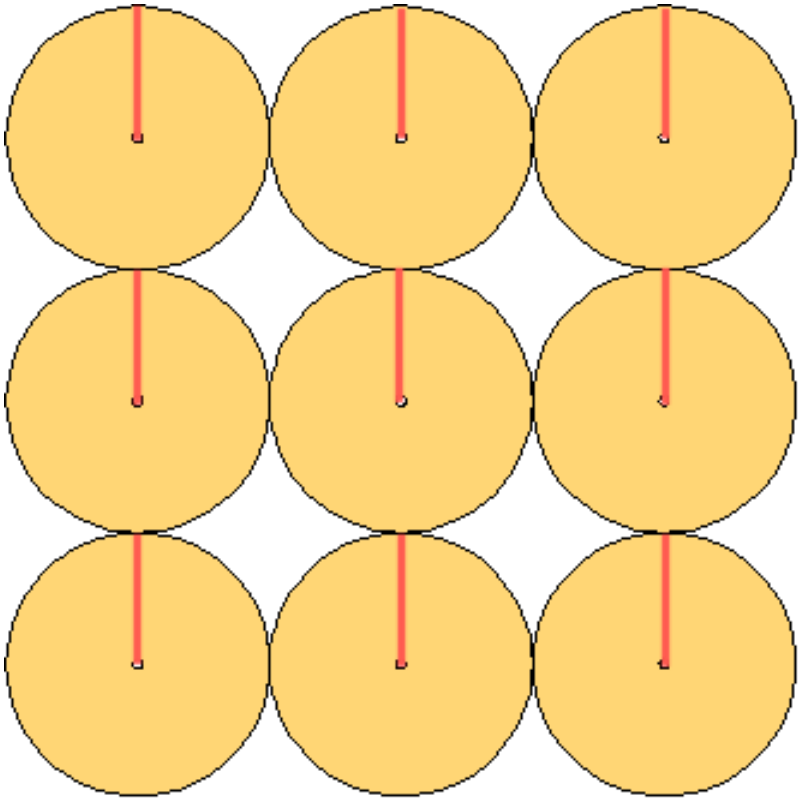
Spatial encoding

Slice selection in z



Spatial encoding

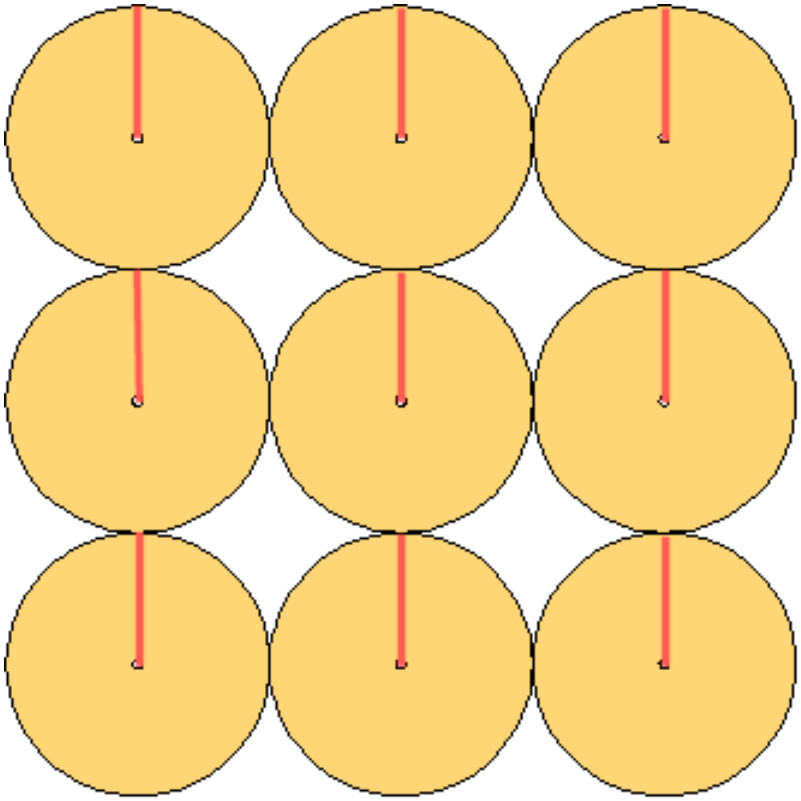
Phase selection in y



All spins have same precessional frequency

Spatial encoding

Phase selection in y

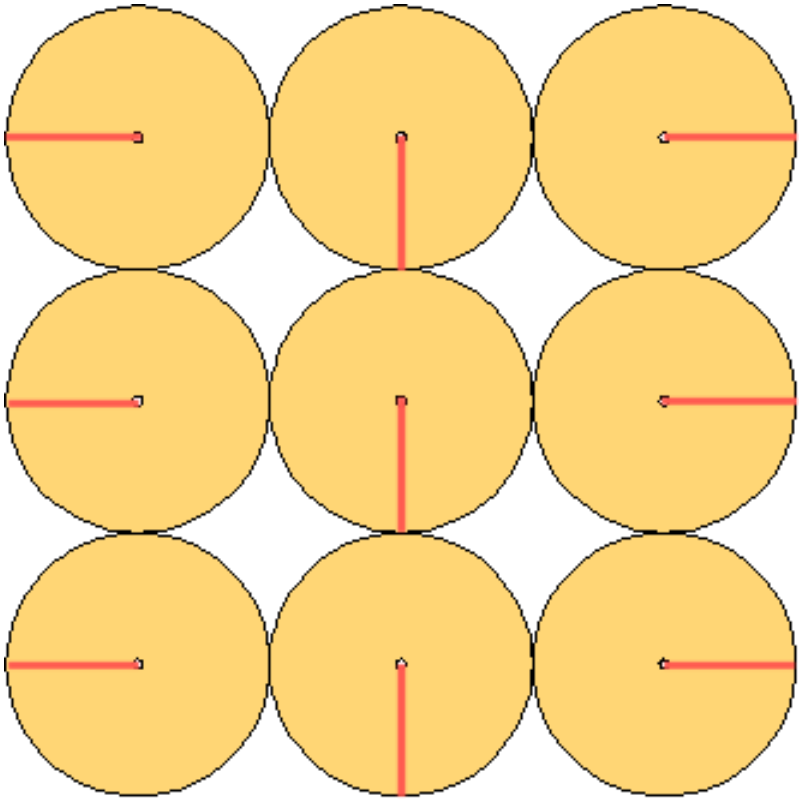


Apply Phase Encoding Gradient

Slower **unchanged** **faster**

Spatial encoding

Phase selection in y

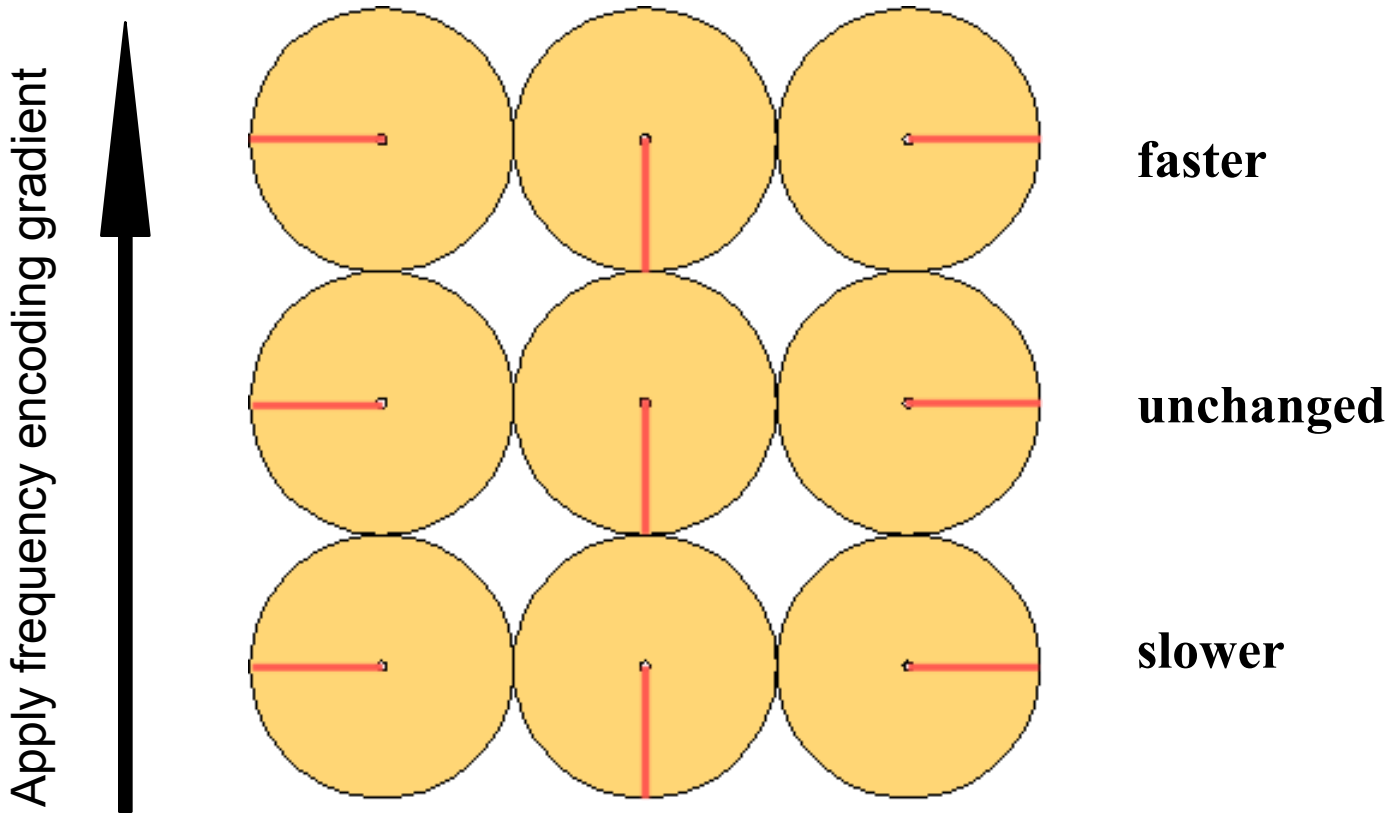


After PE gradient turned off, all spins have same frequency again, but different phase:

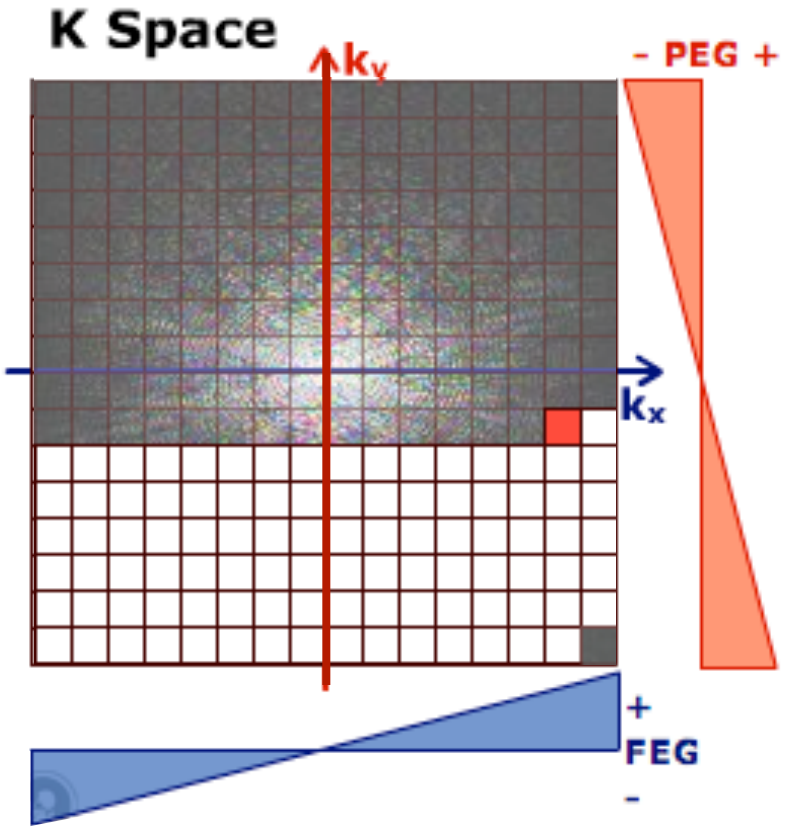
+90° **0°** **-90°**

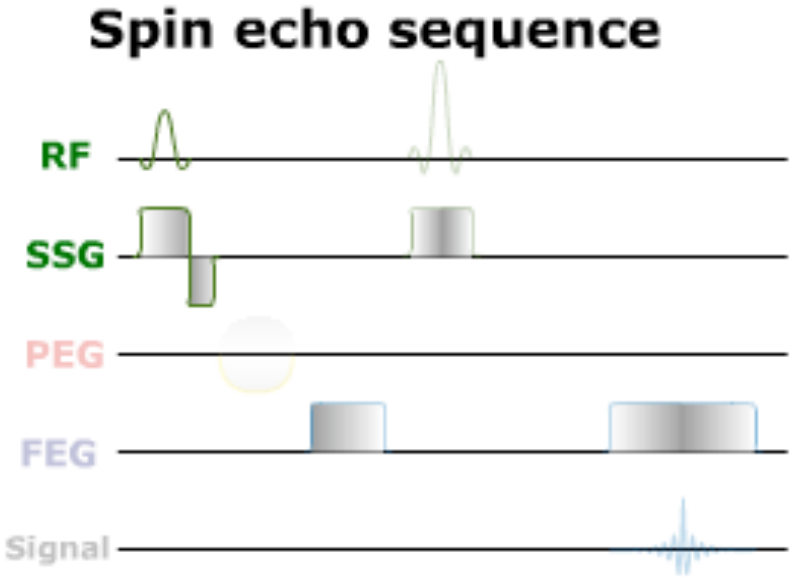
Spatial encoding

Frequency selection in x



Spatial encoding

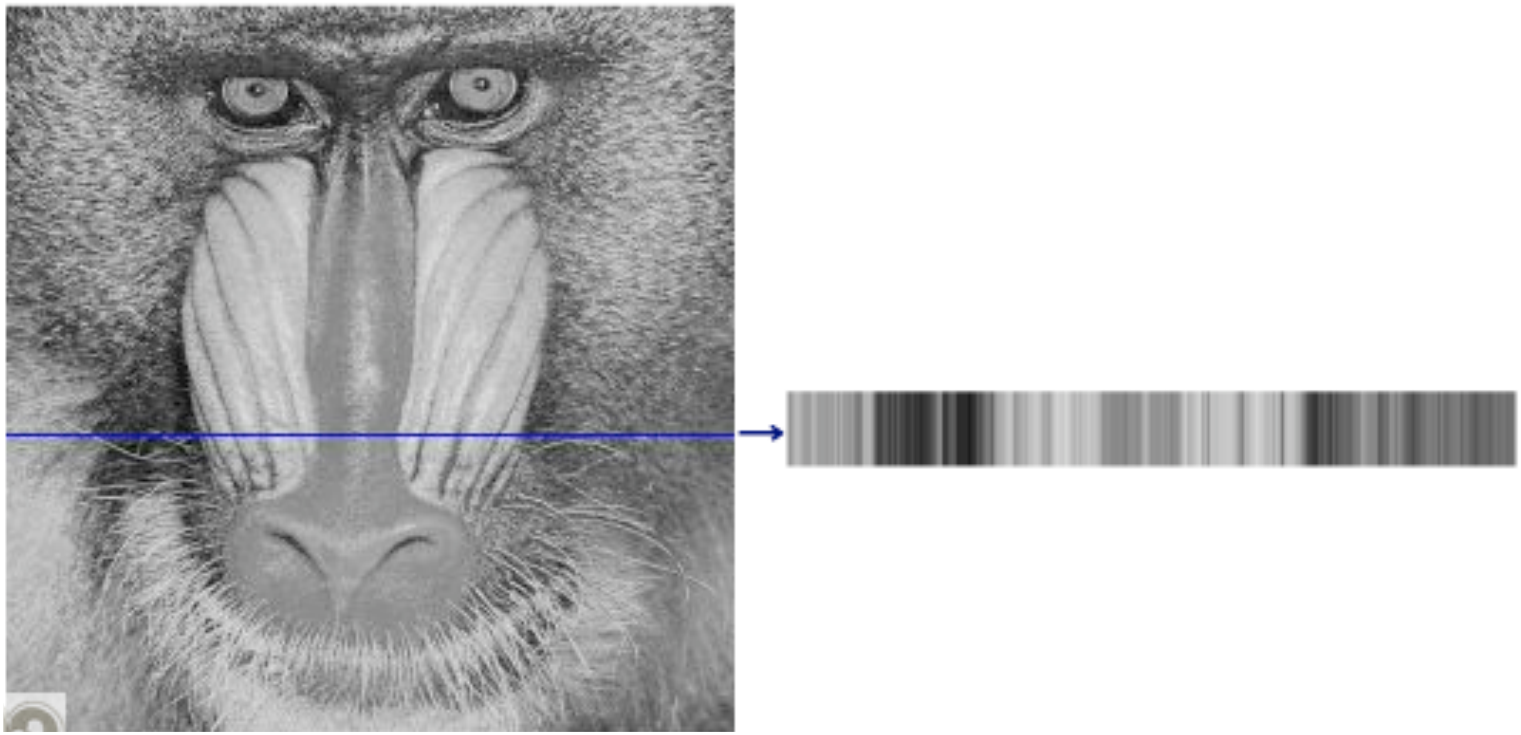




1. RF pulse + Slice select gradient
2. Phase encoding gradient
3. Frequency encoding gradient (dephasing lobe)
4. 180 RF pulse + Slice select gradient
5. Frequency encoding gradient + Signal recording

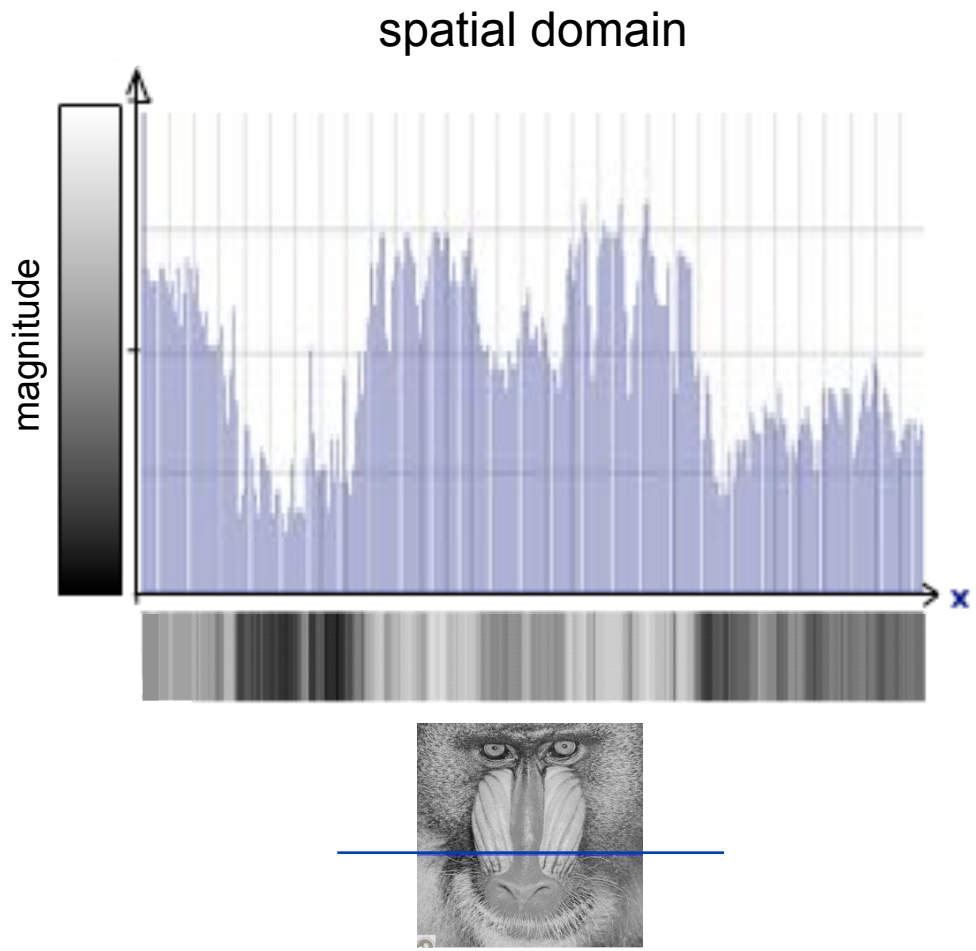
Fourier transform

(spatial)



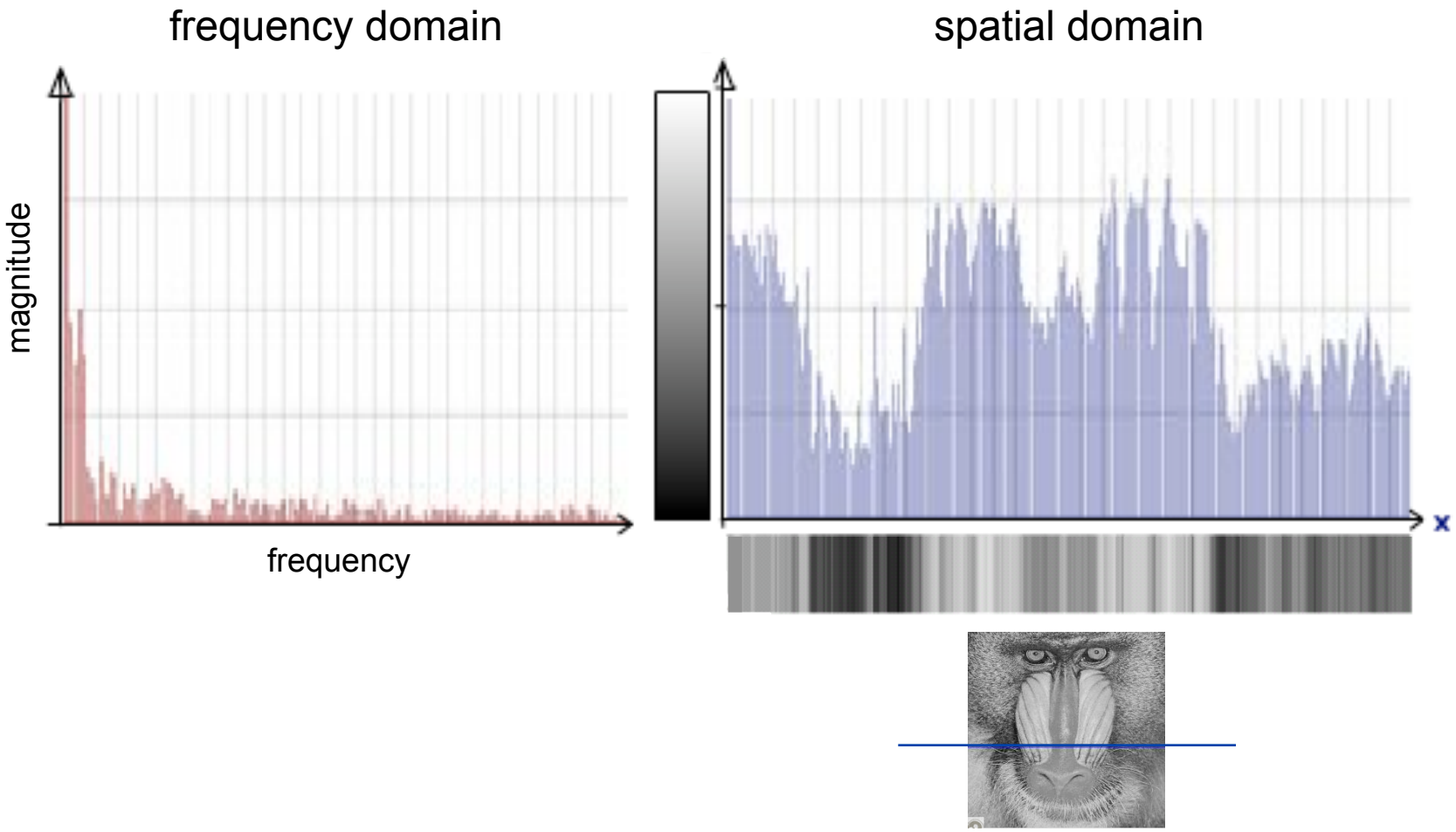
Fourier transform

(spatial)



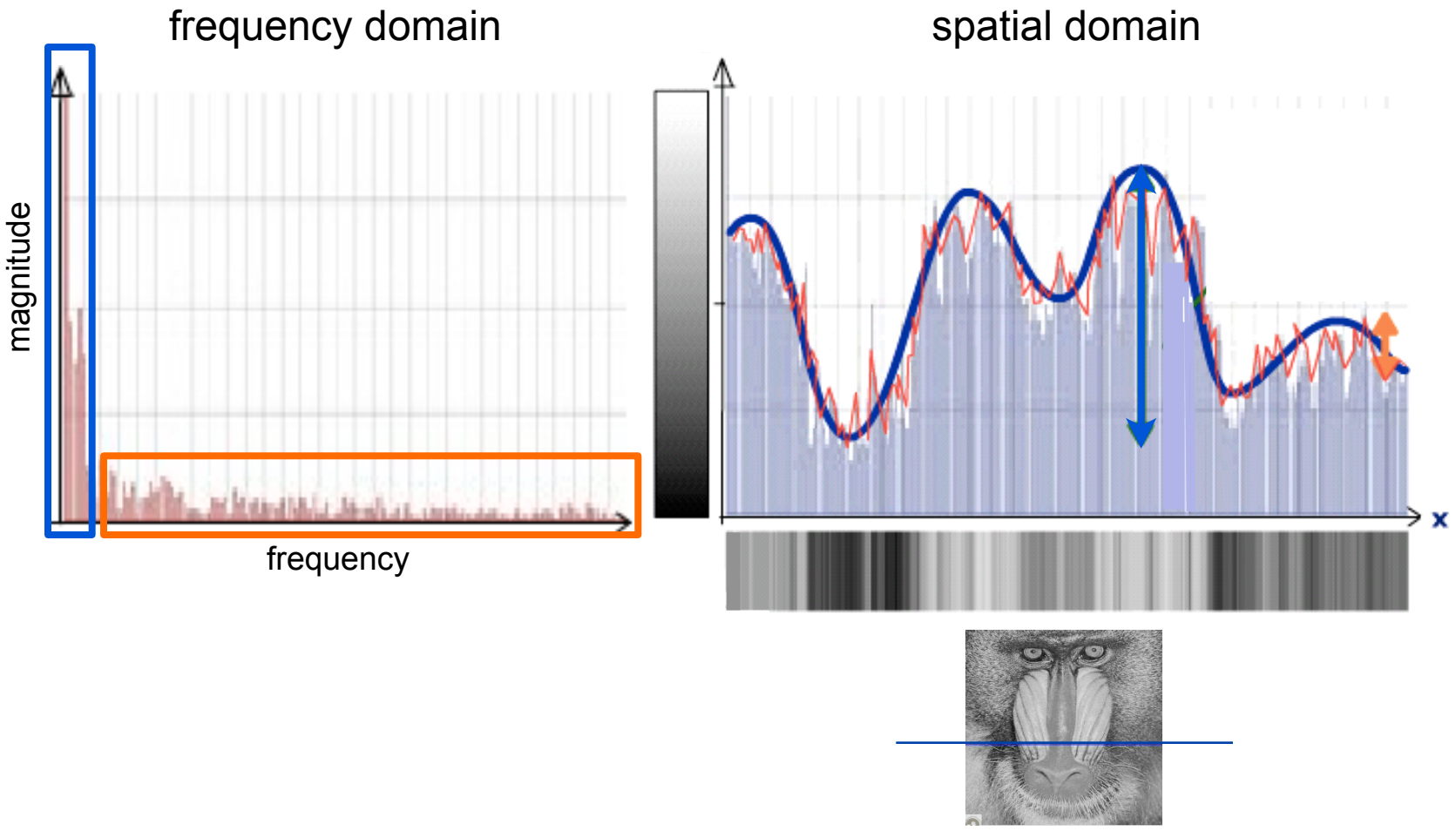
Fourier transform

(spatial)

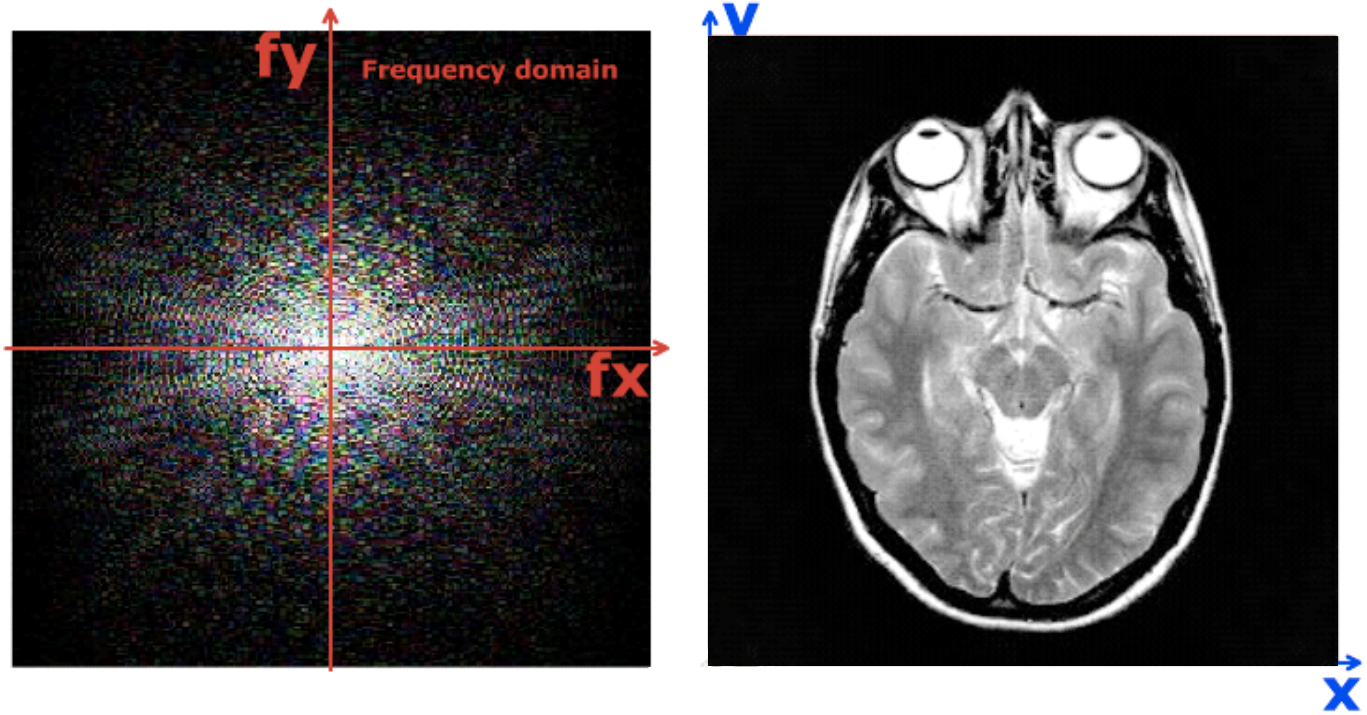


Fourier transform

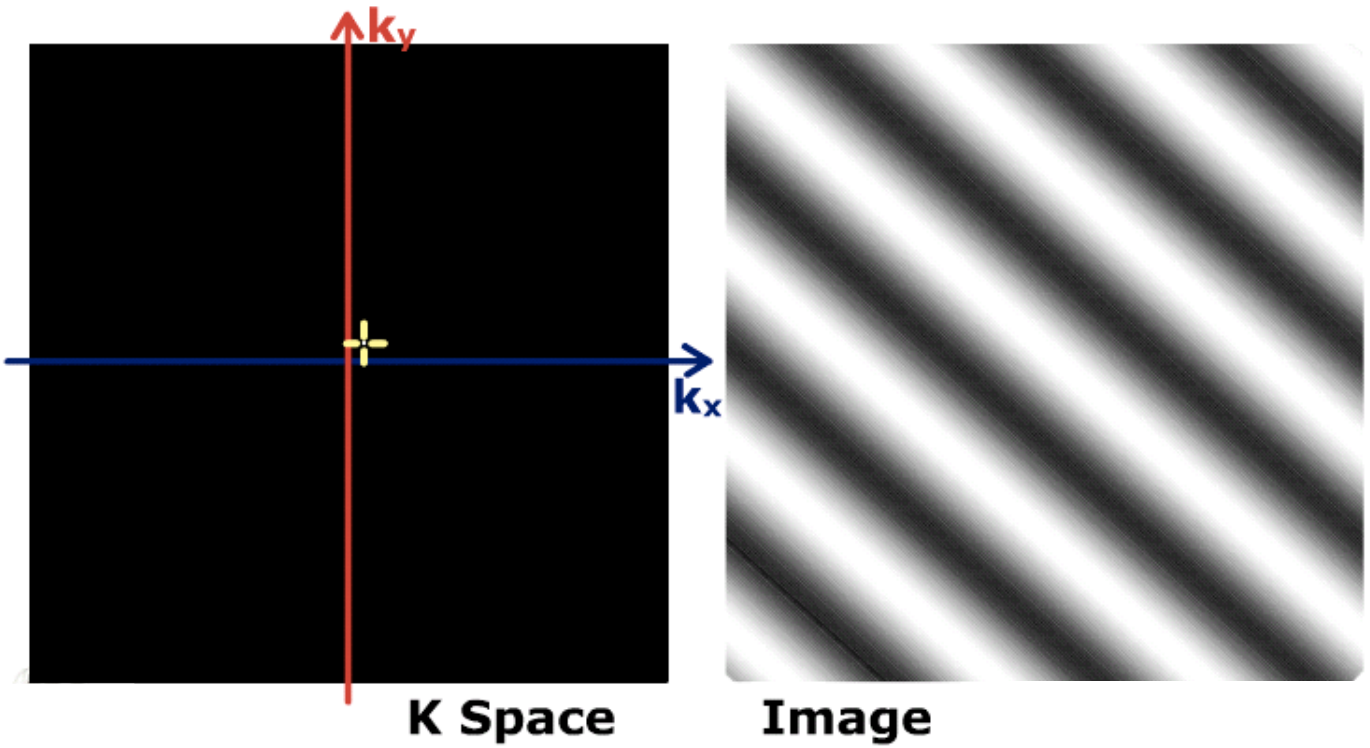
(spatial)



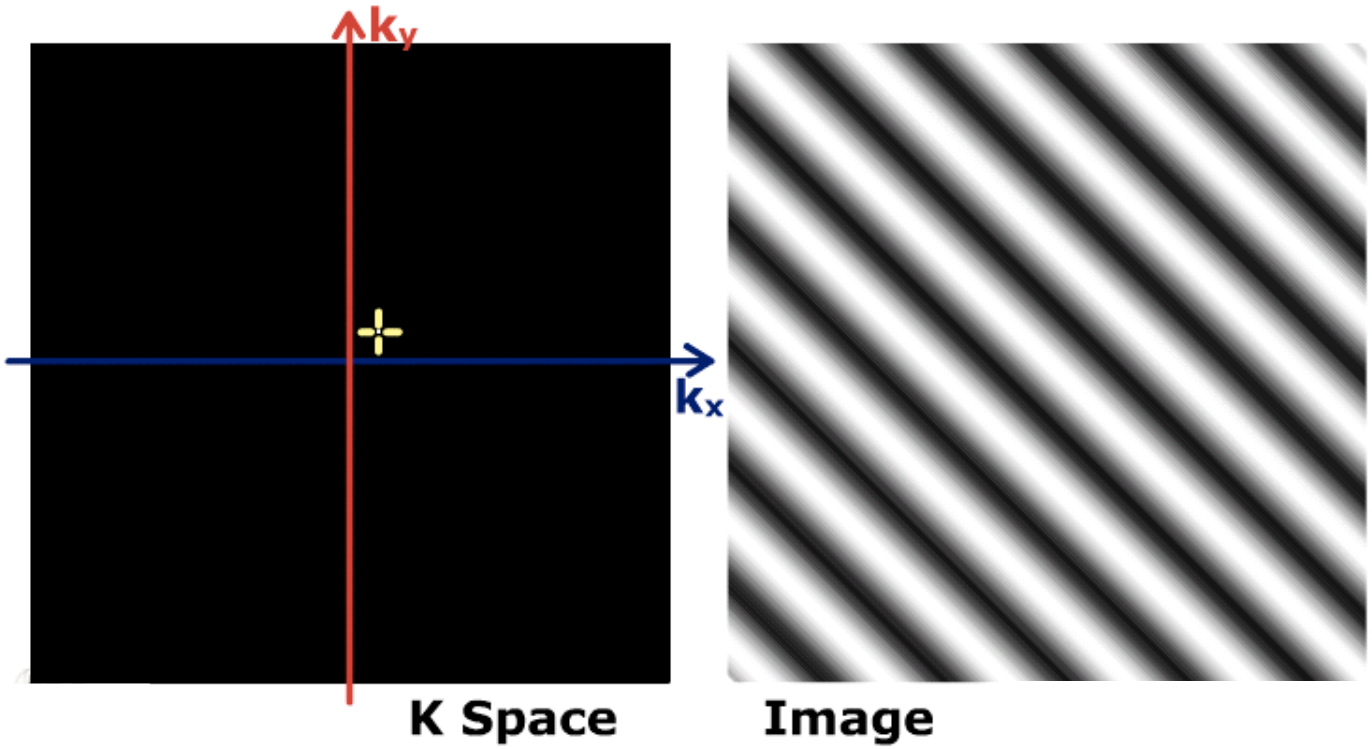
k-space



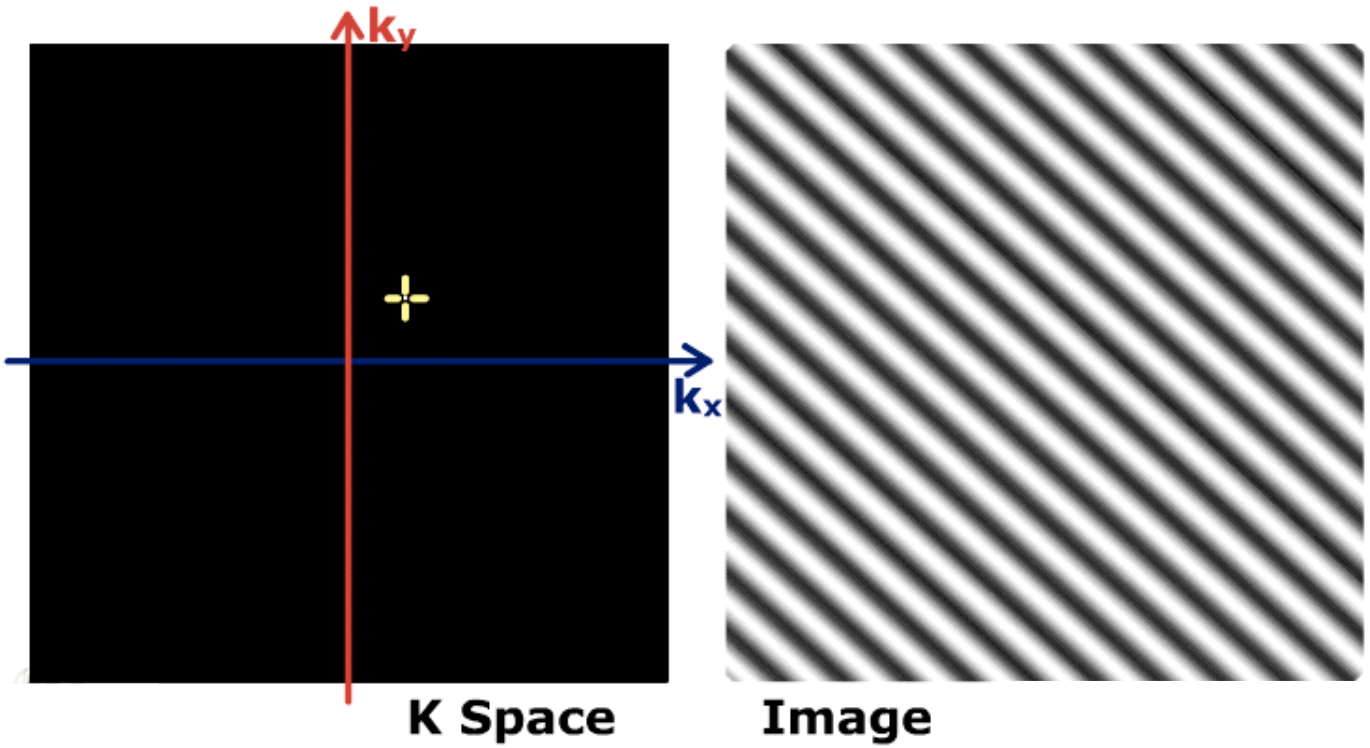
k-space



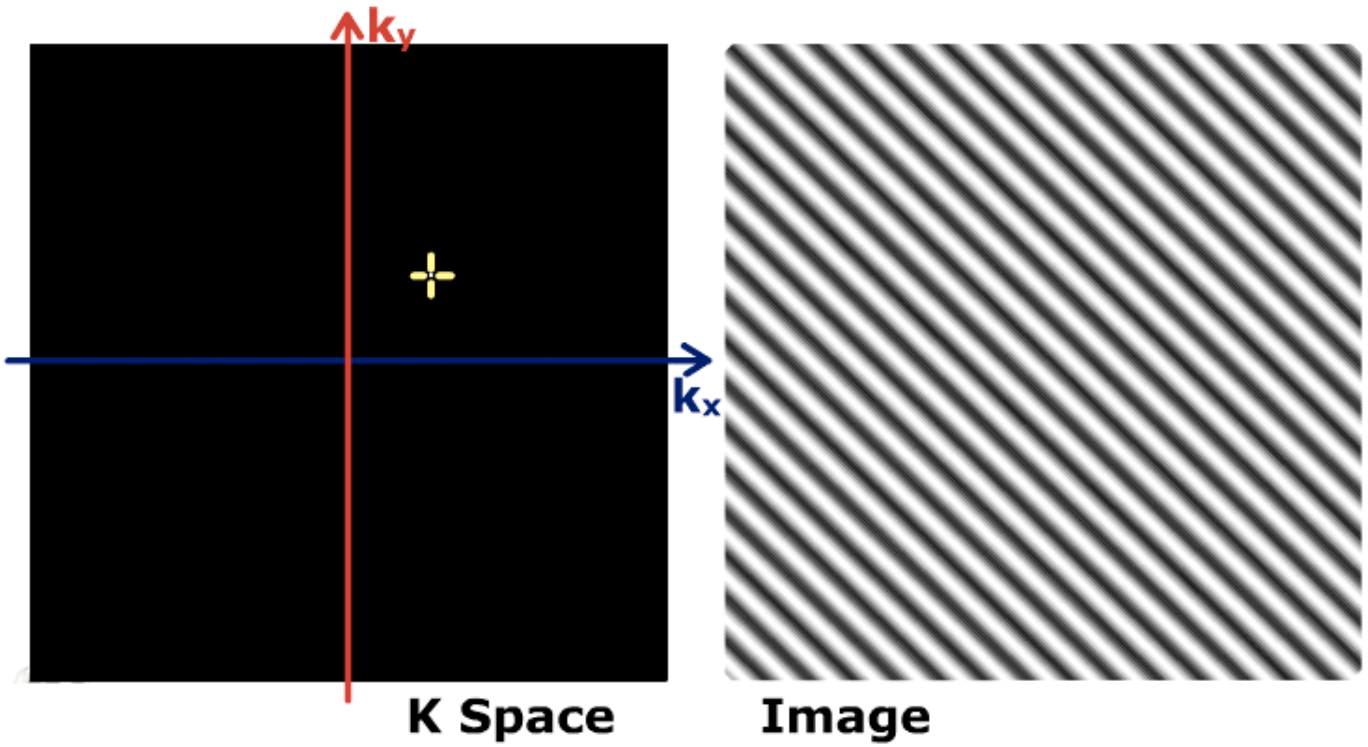
k-space



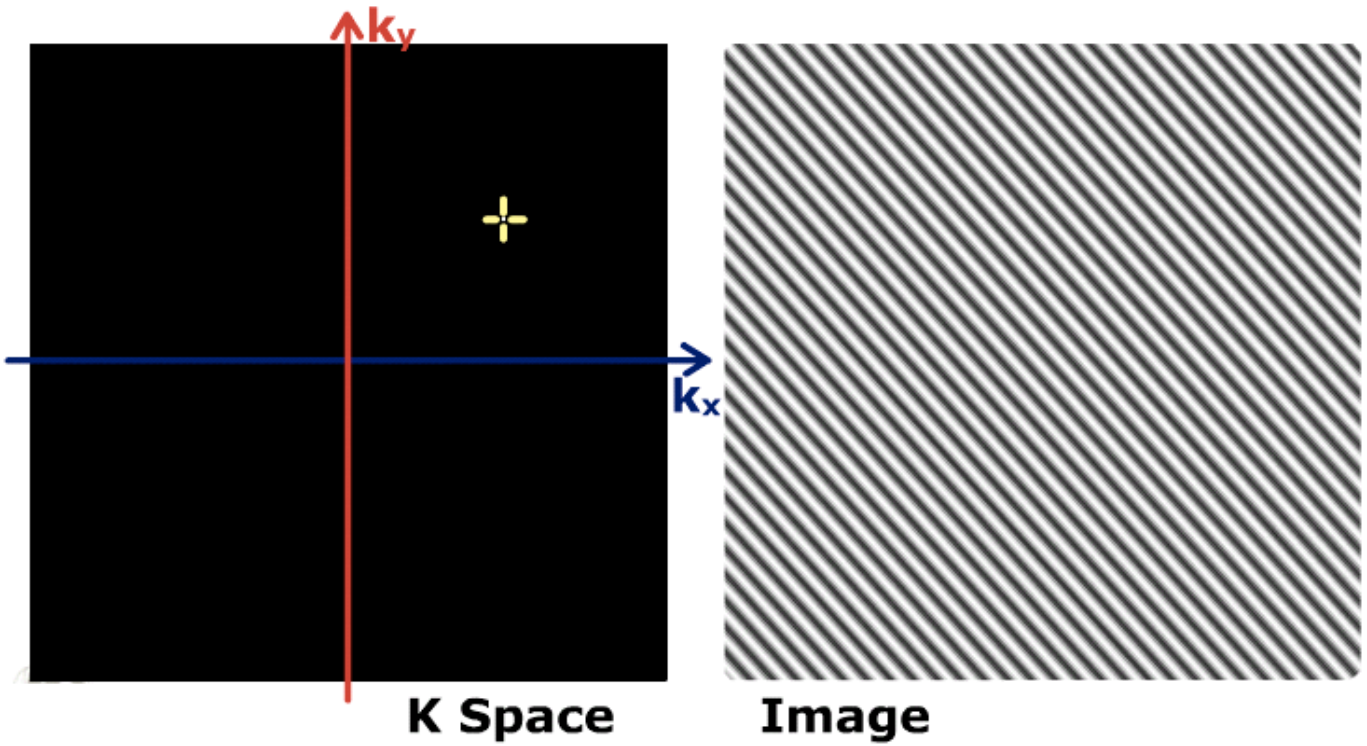
k-space



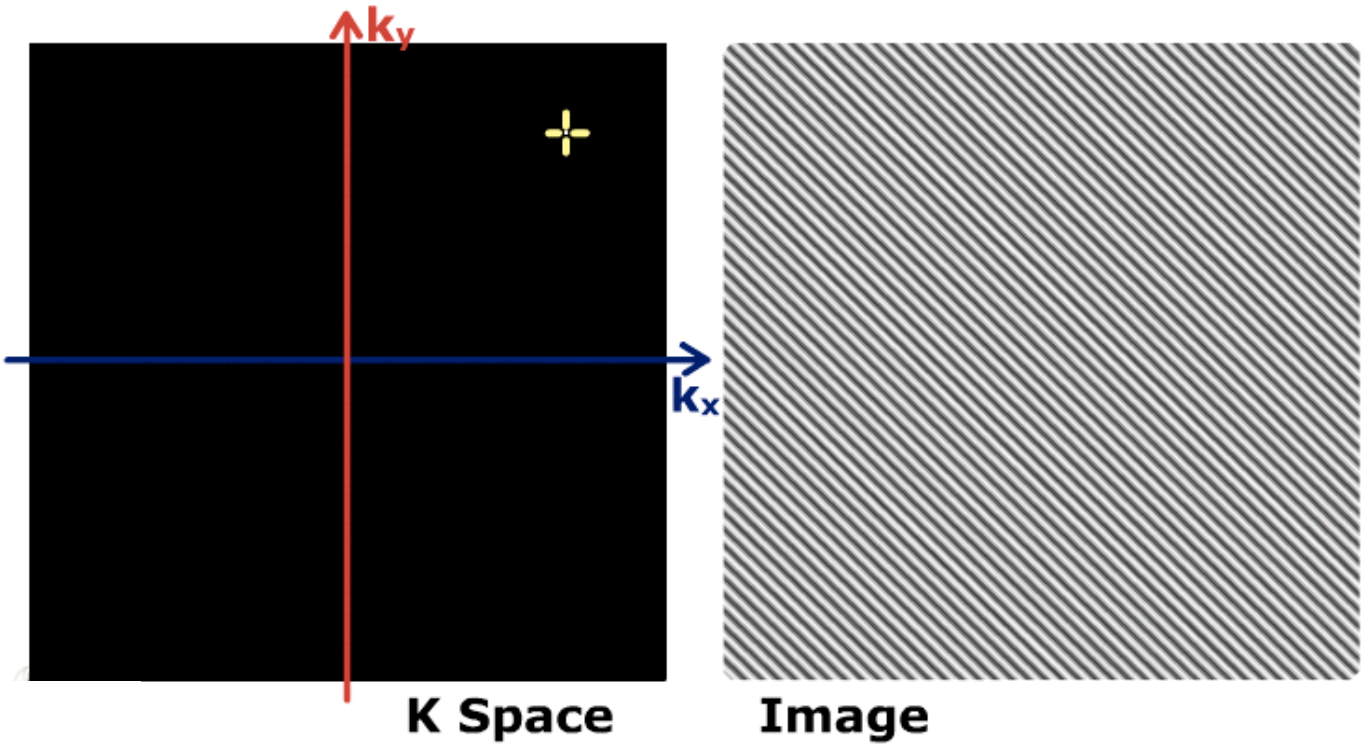
k-space



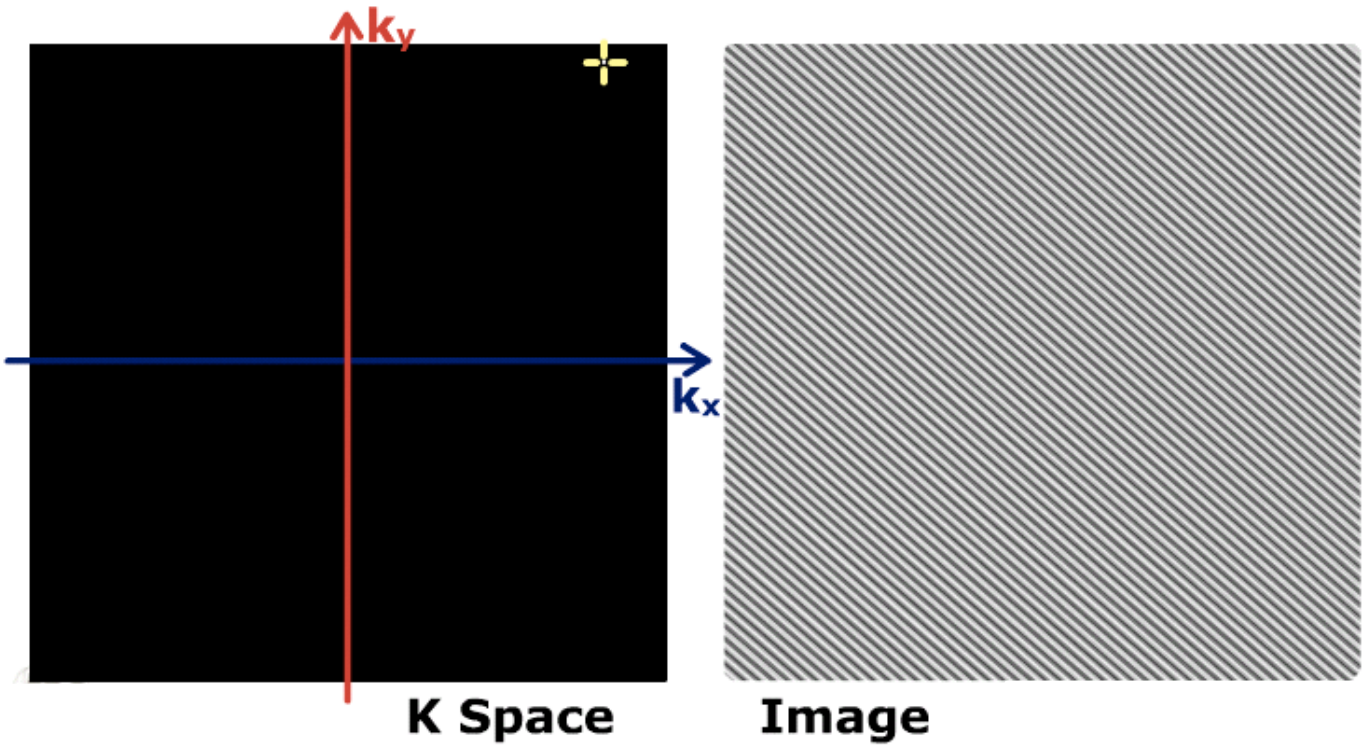
k-space



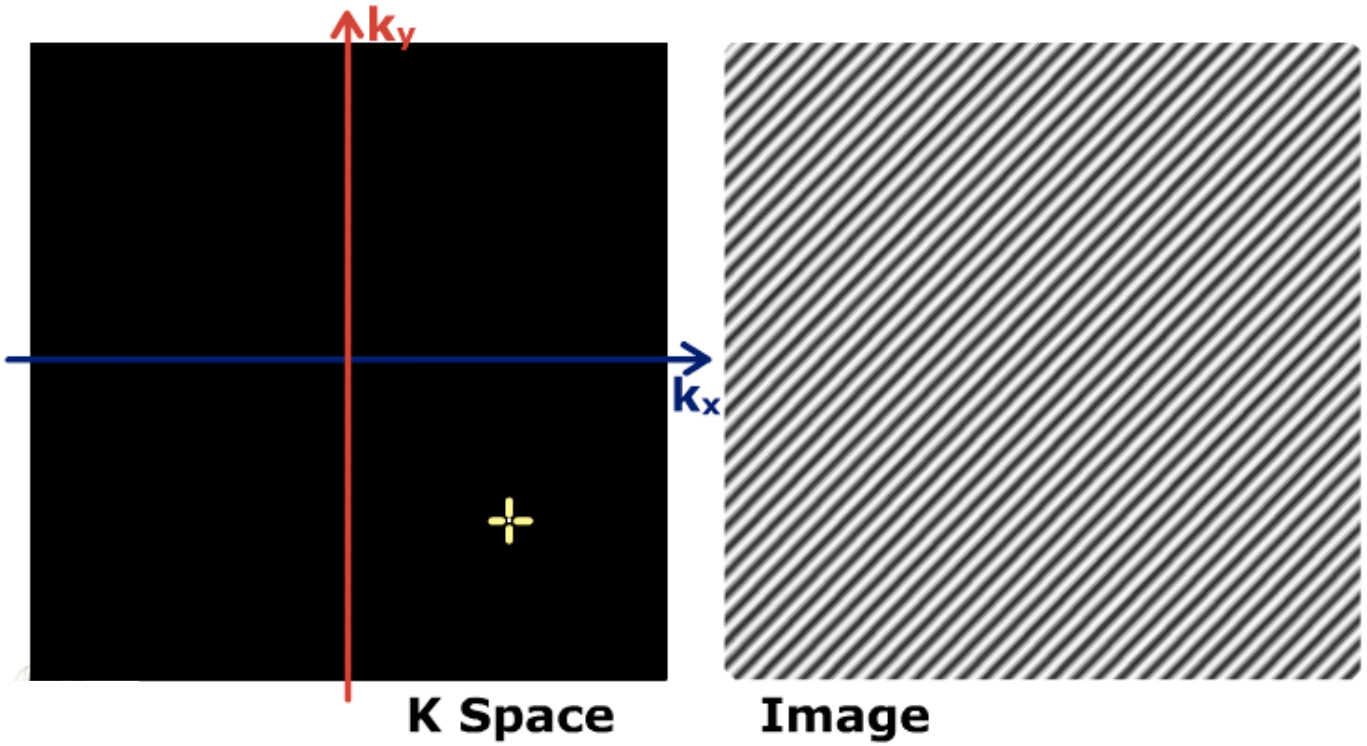
k-space



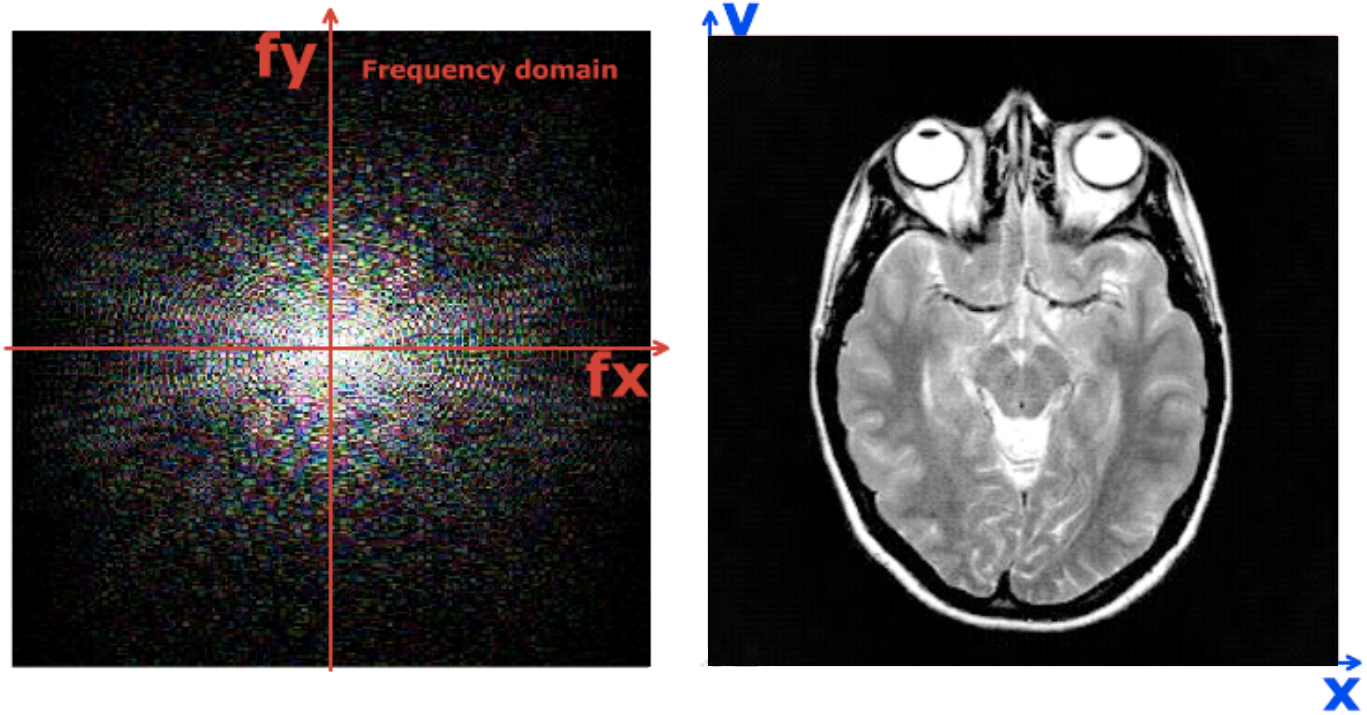
k-space



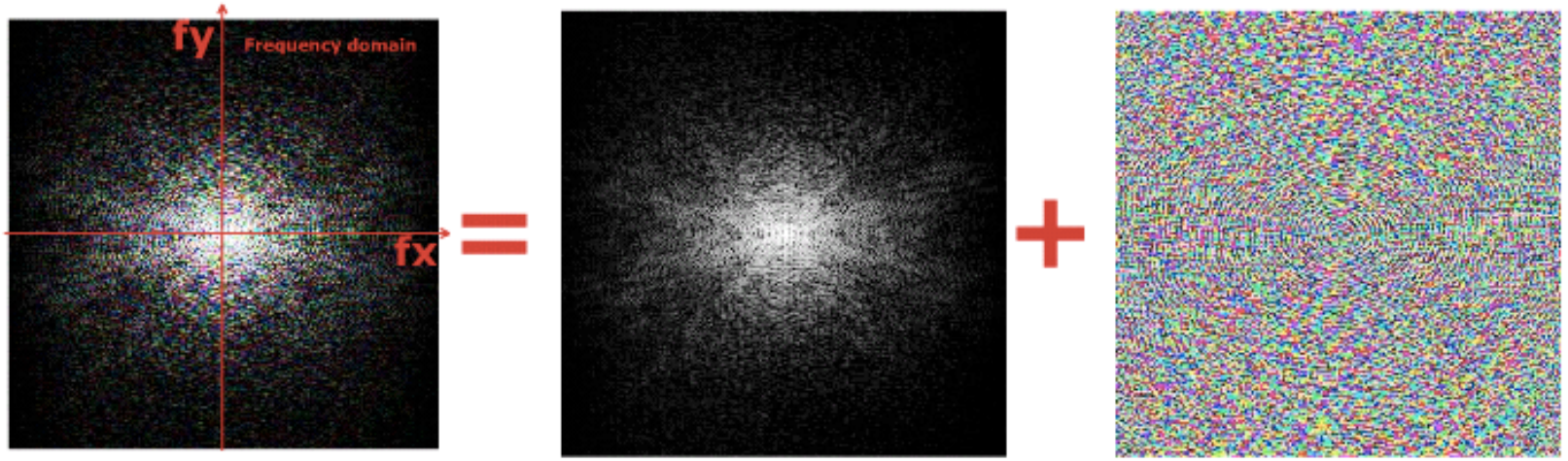
k-space



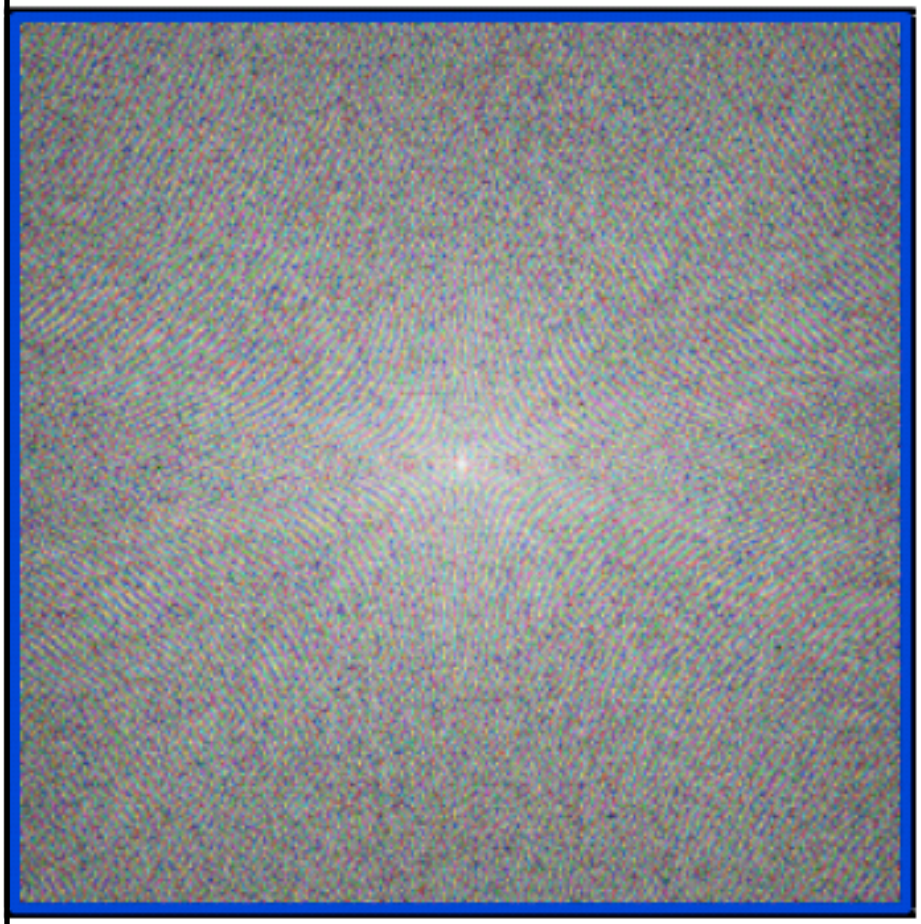
k-space

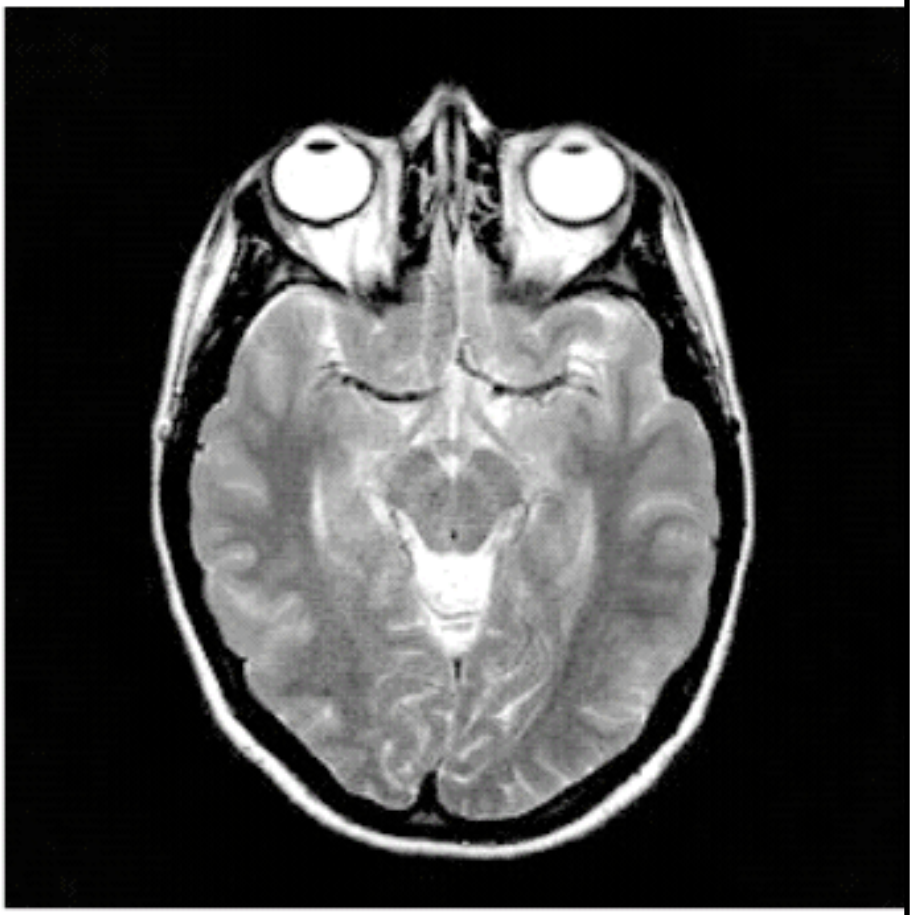


k-space

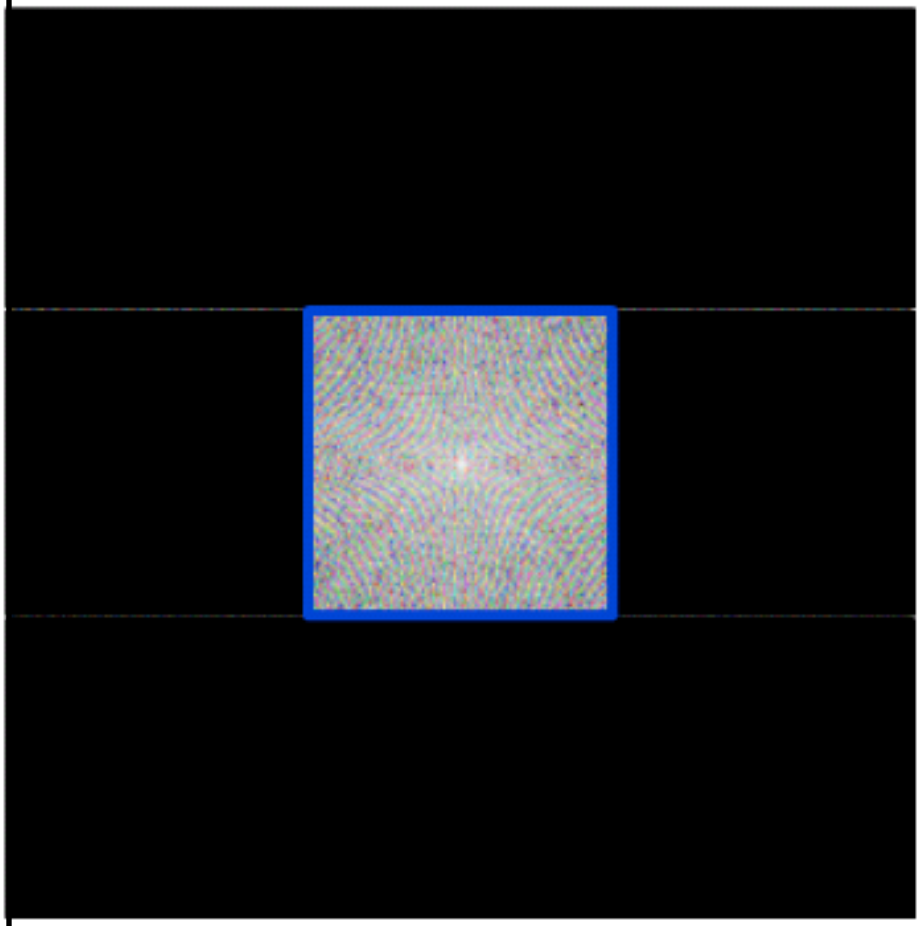

fy
Frequency domain
fx
=
+
Fourier
Magnitude
Phase
of each frequency component along
x and y

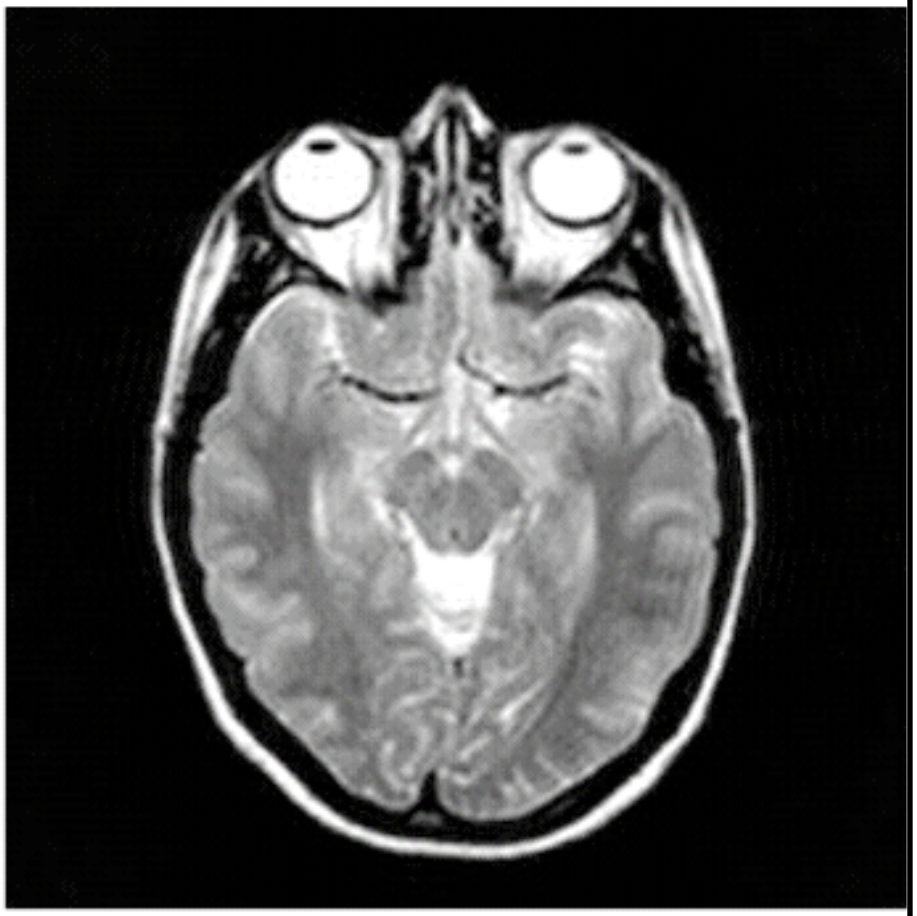
k-space



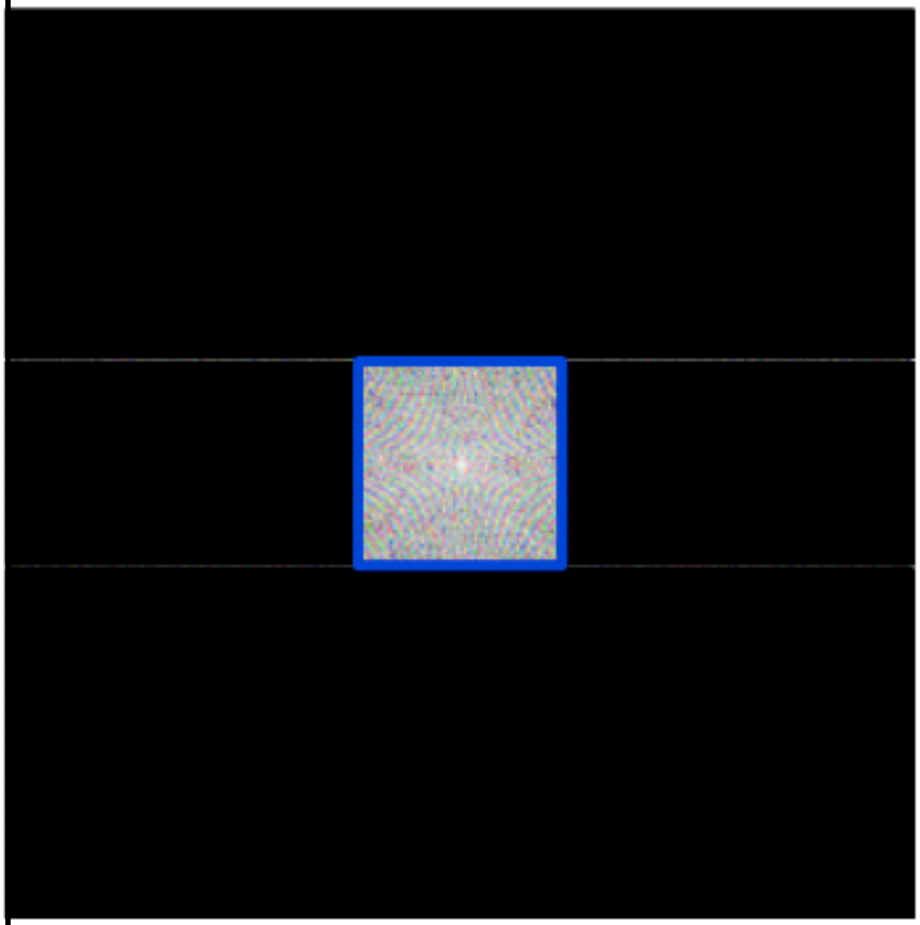


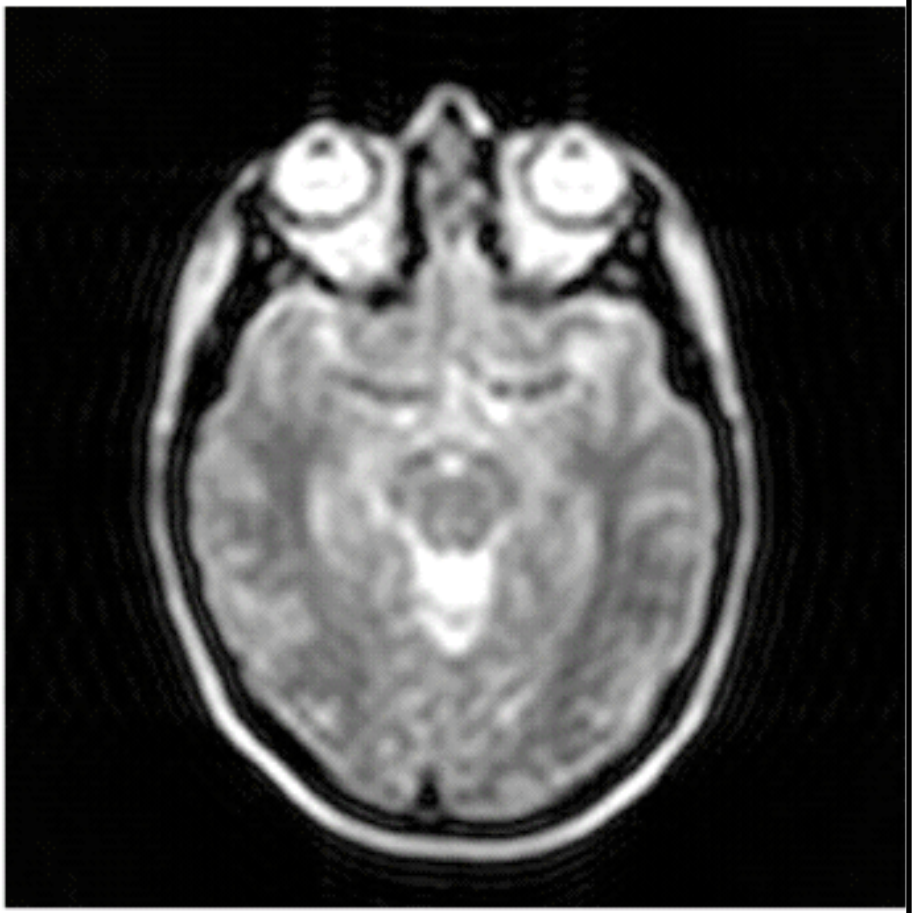
k-space



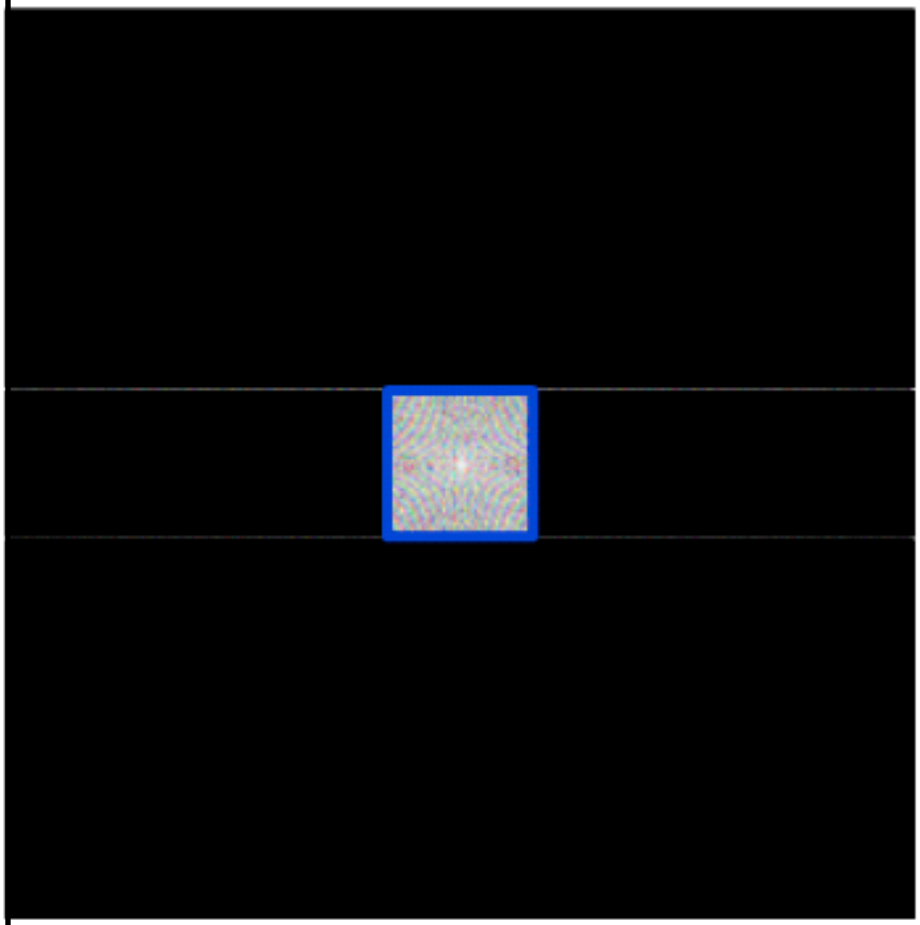


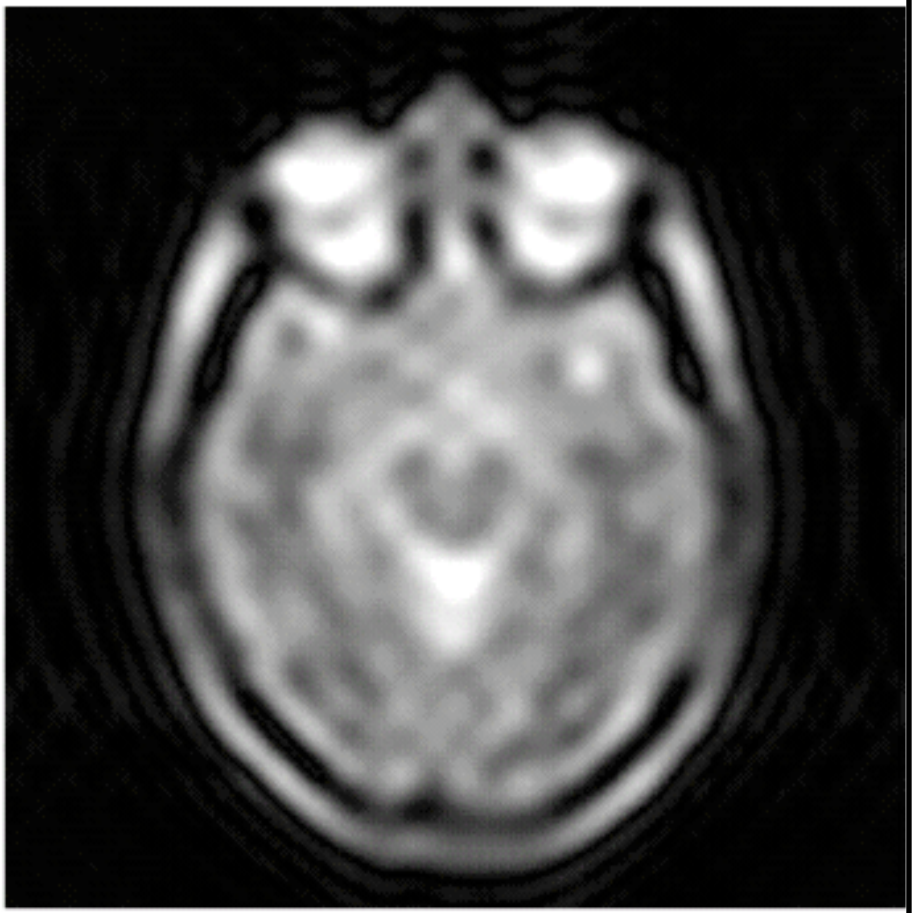
k-space



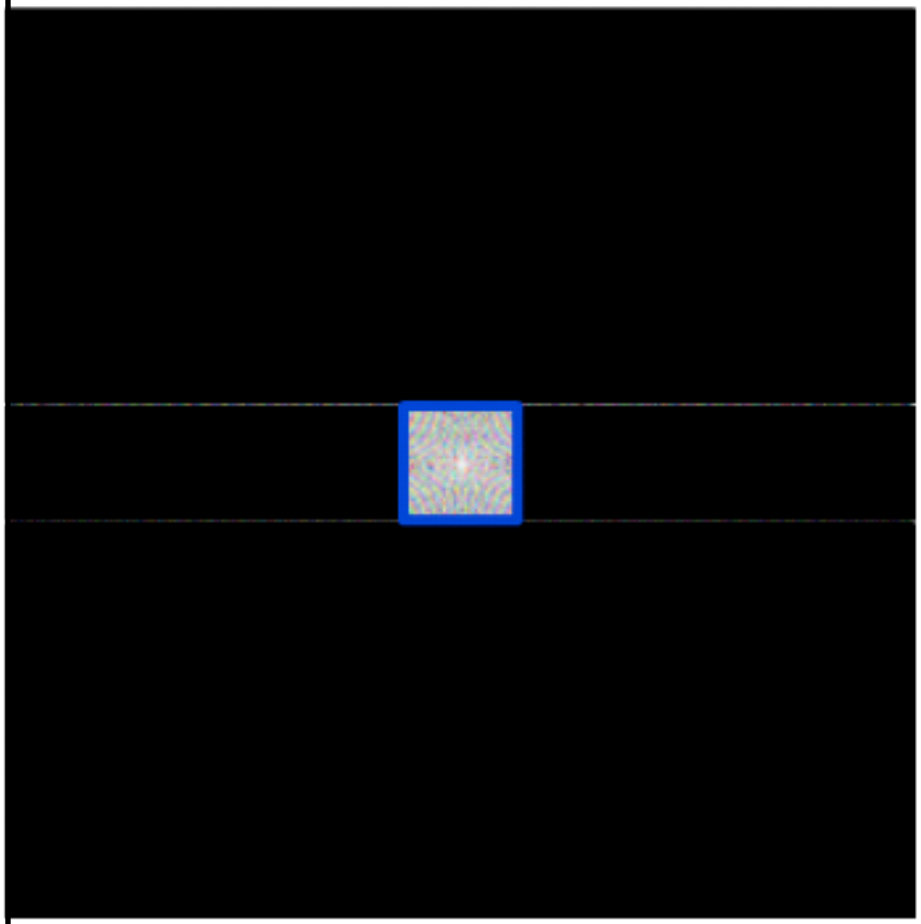


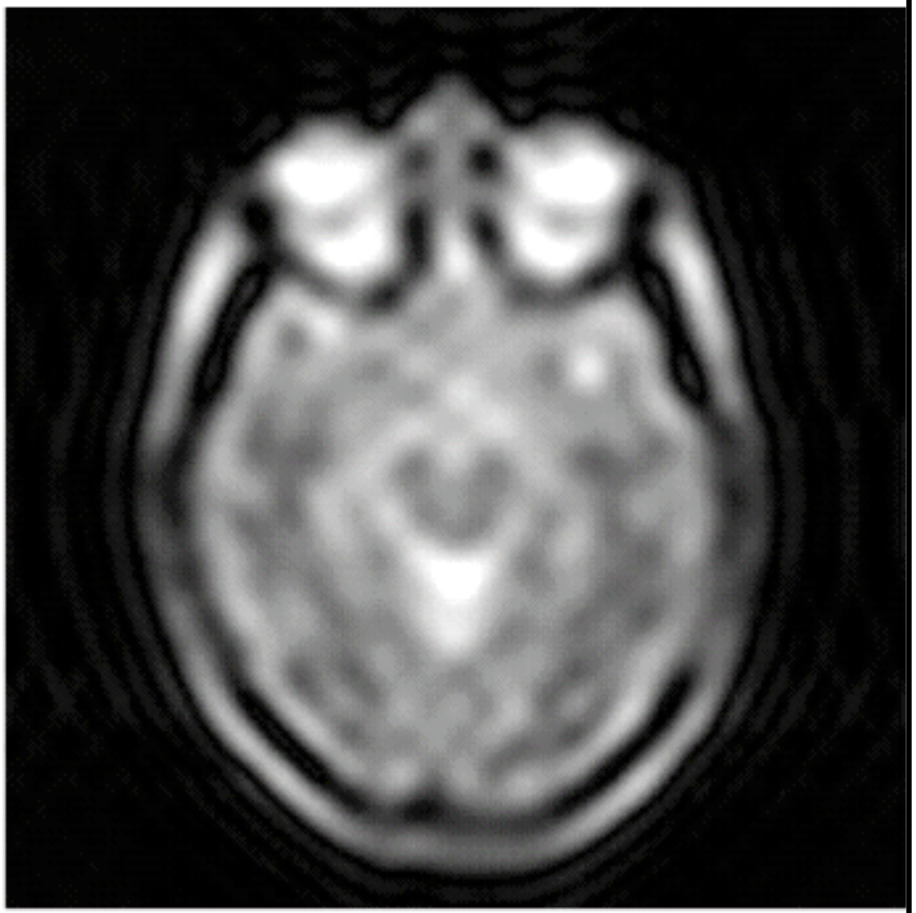
k-space



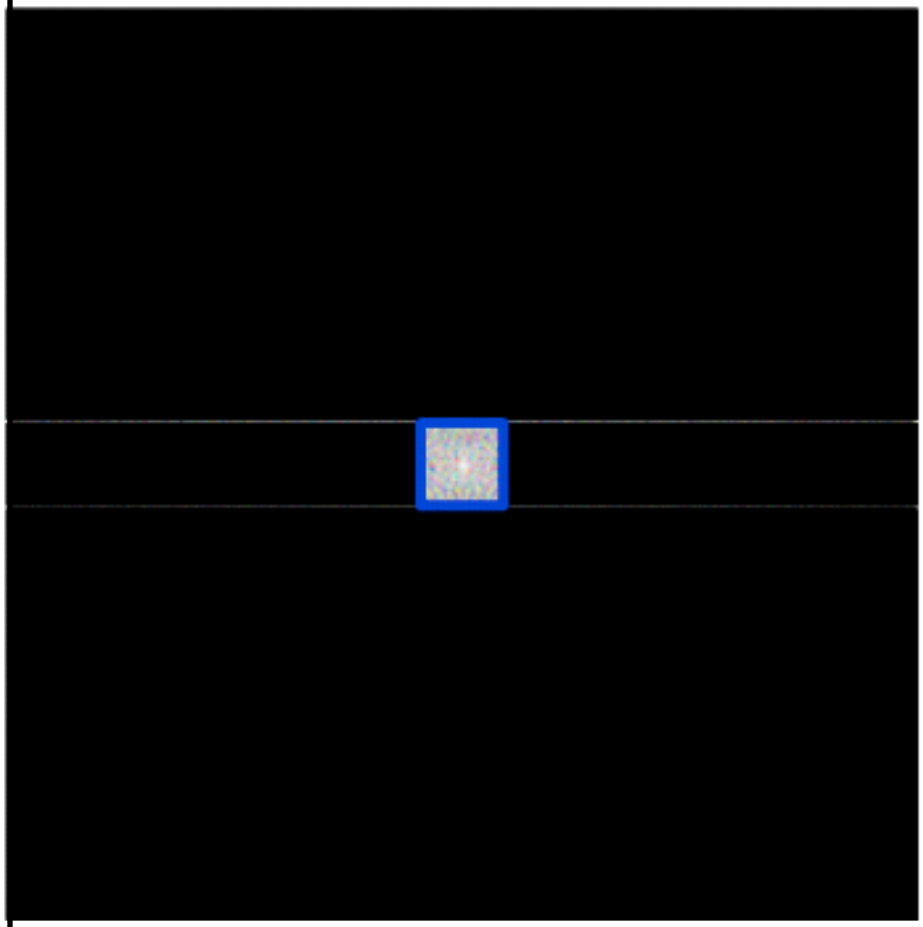


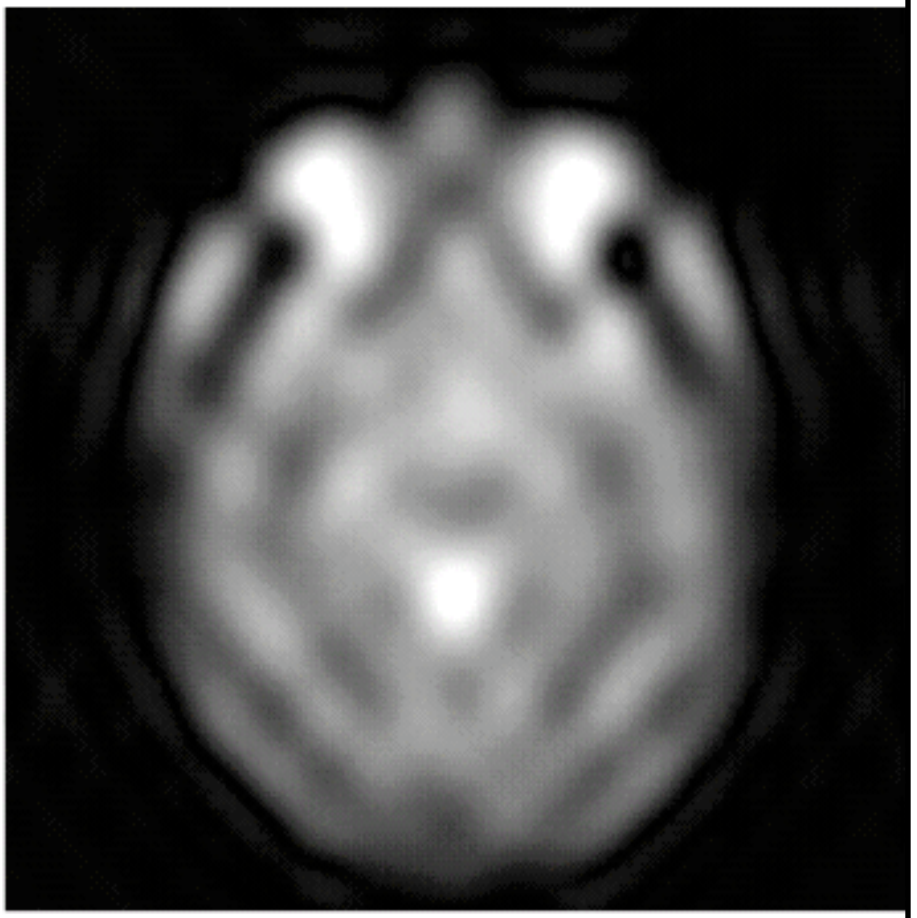
k-space



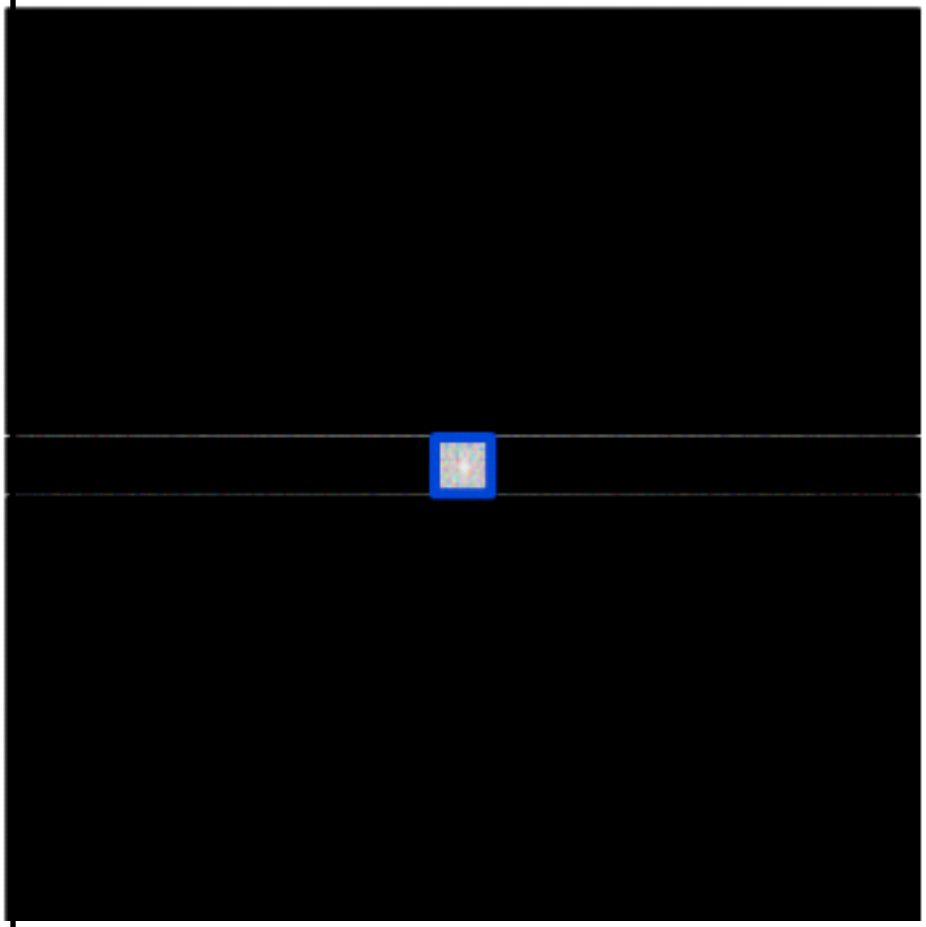


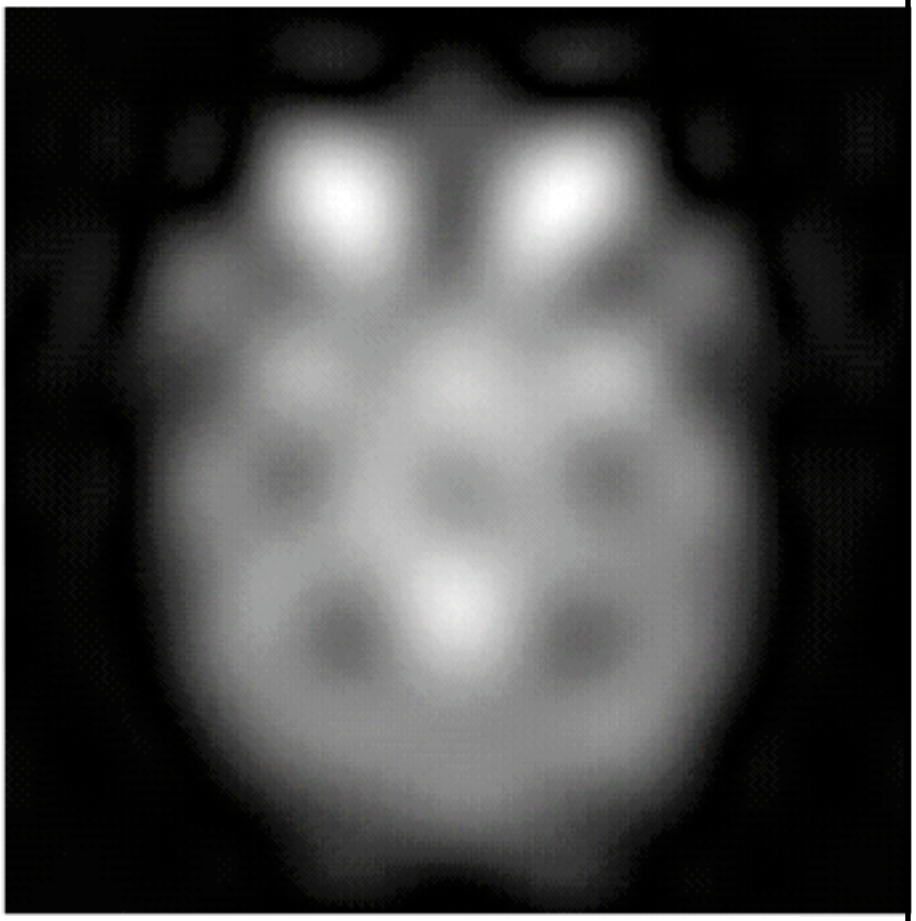
k-space



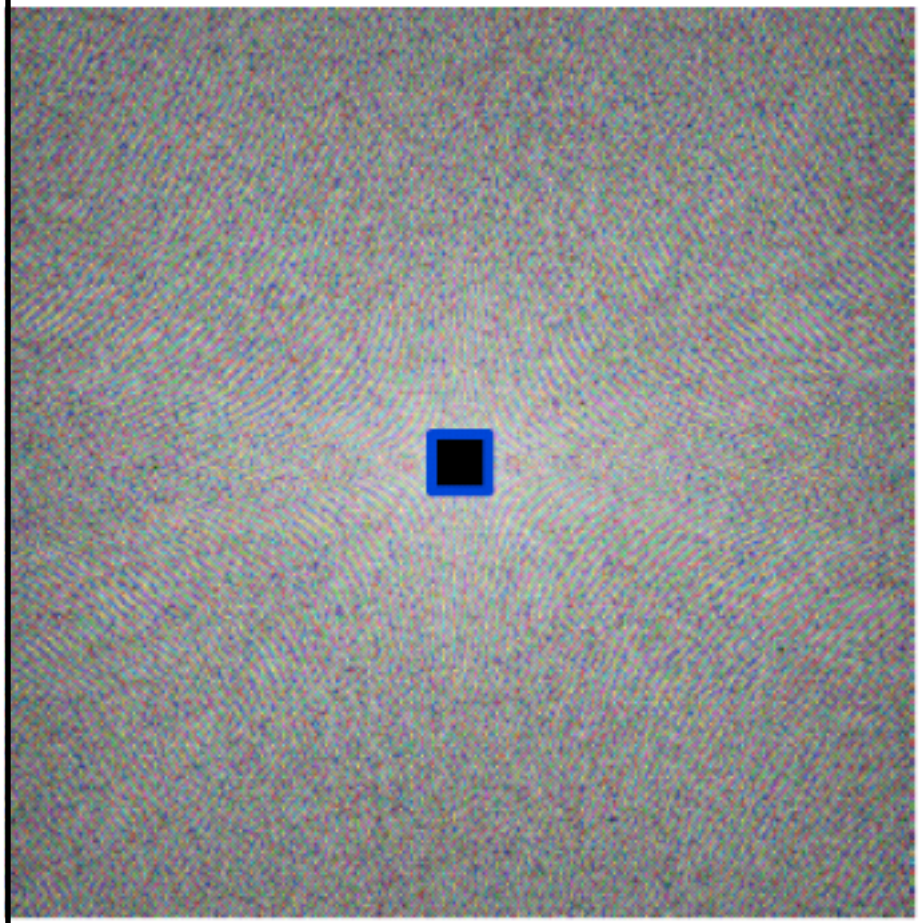


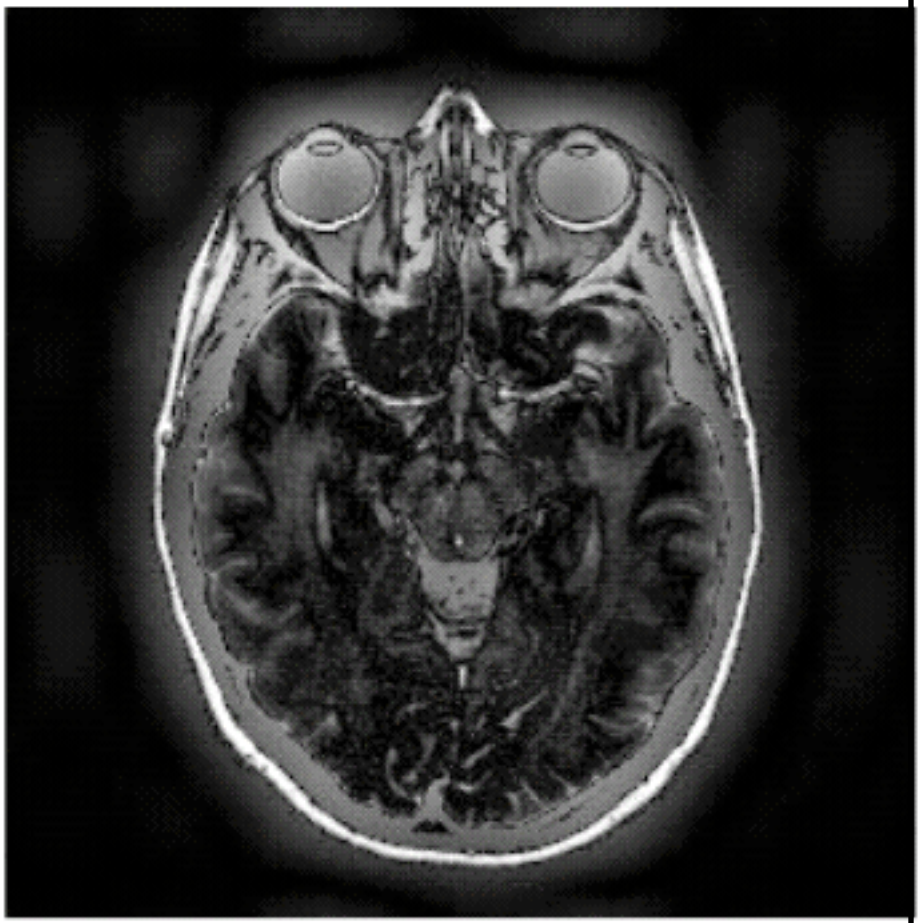
k-space



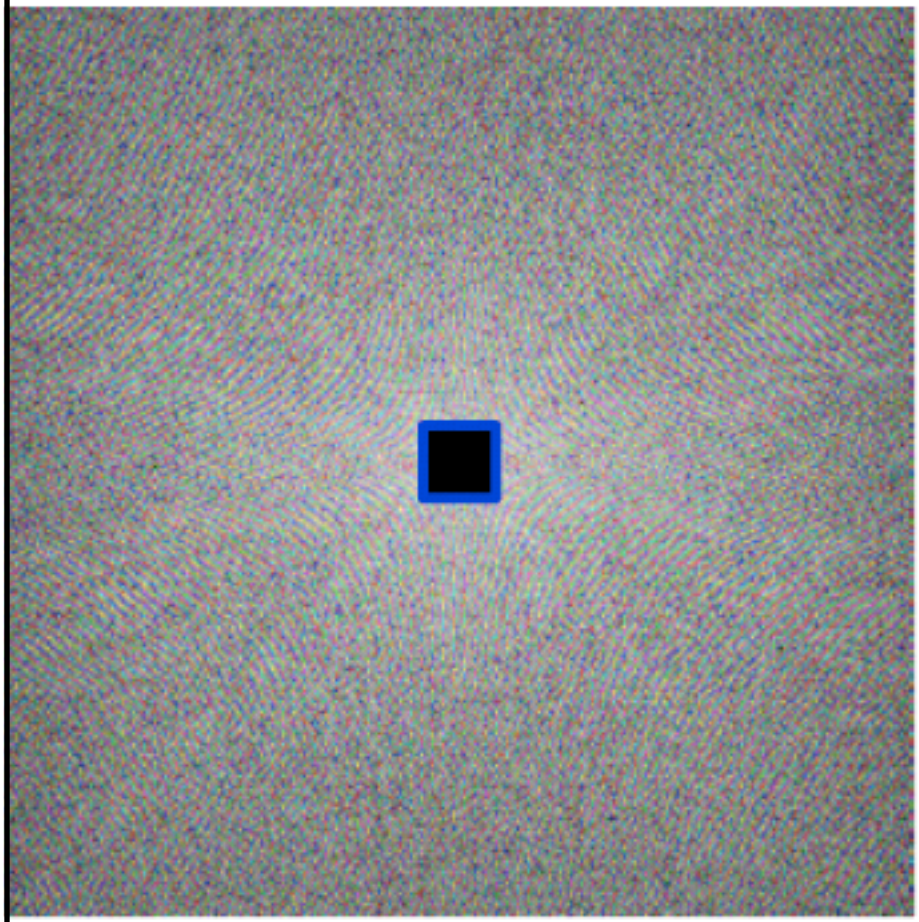


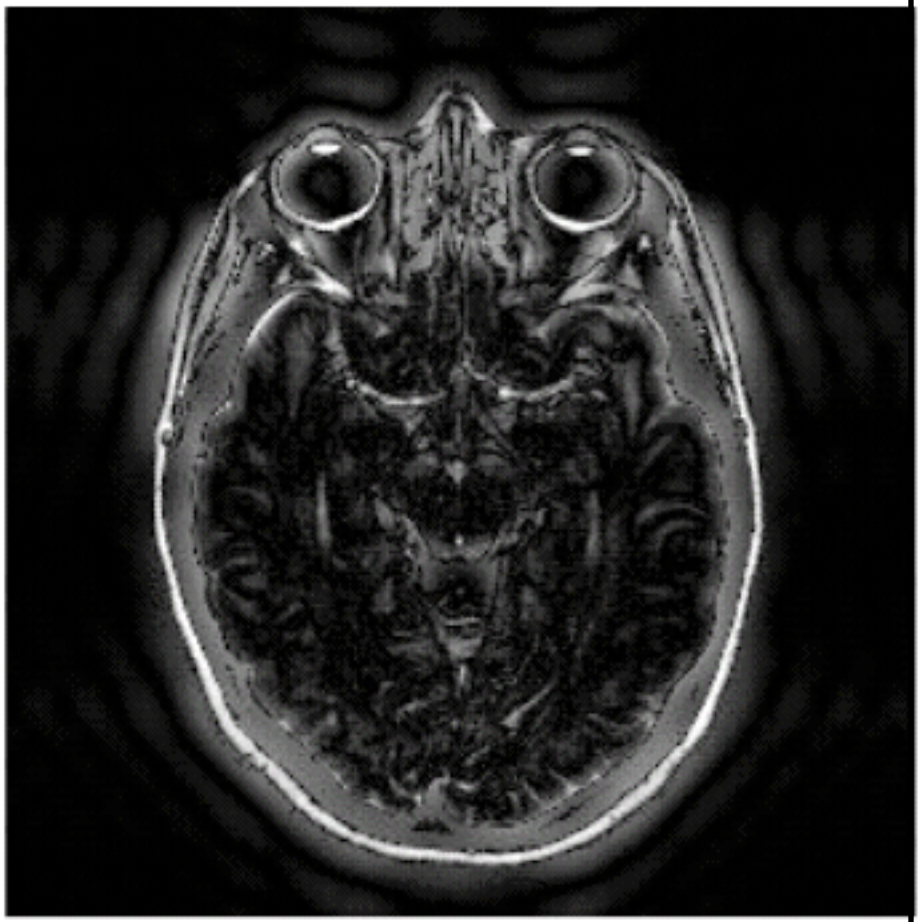
k-space



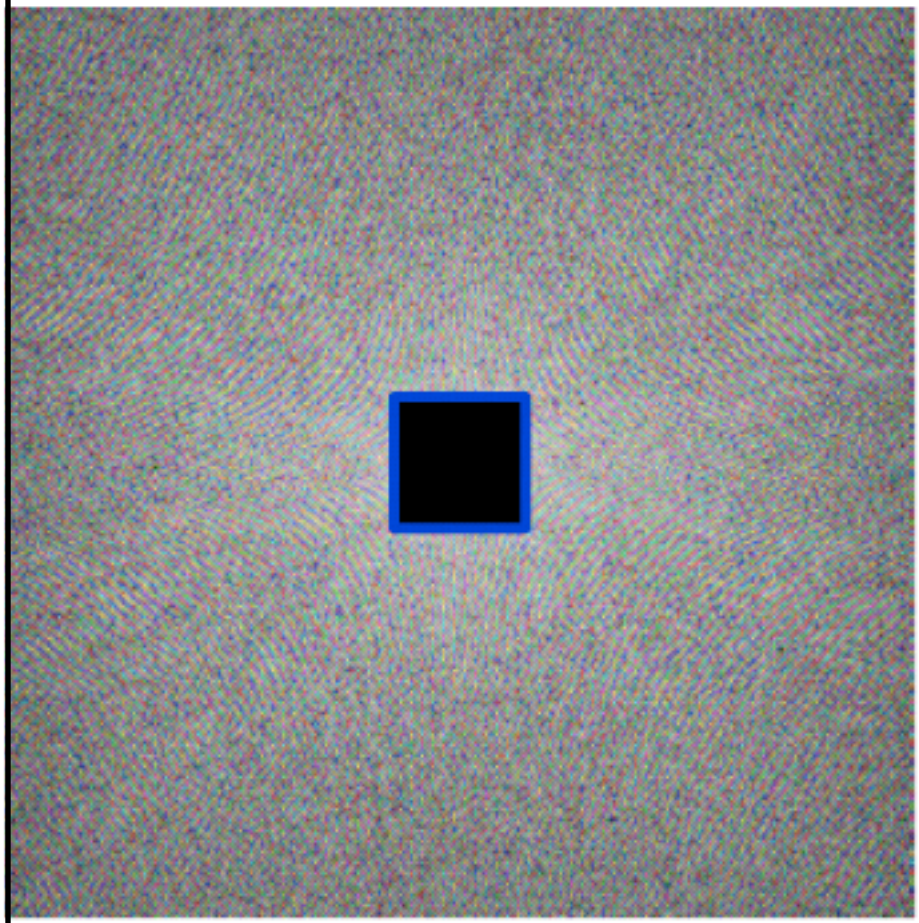


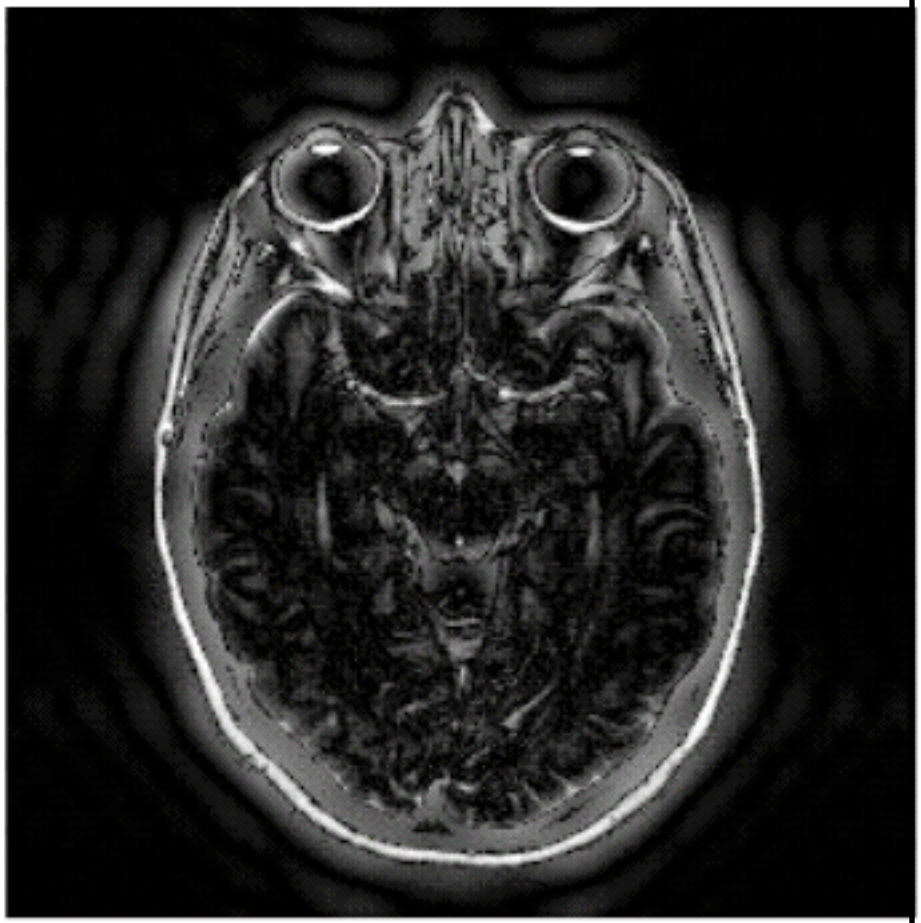
k-space



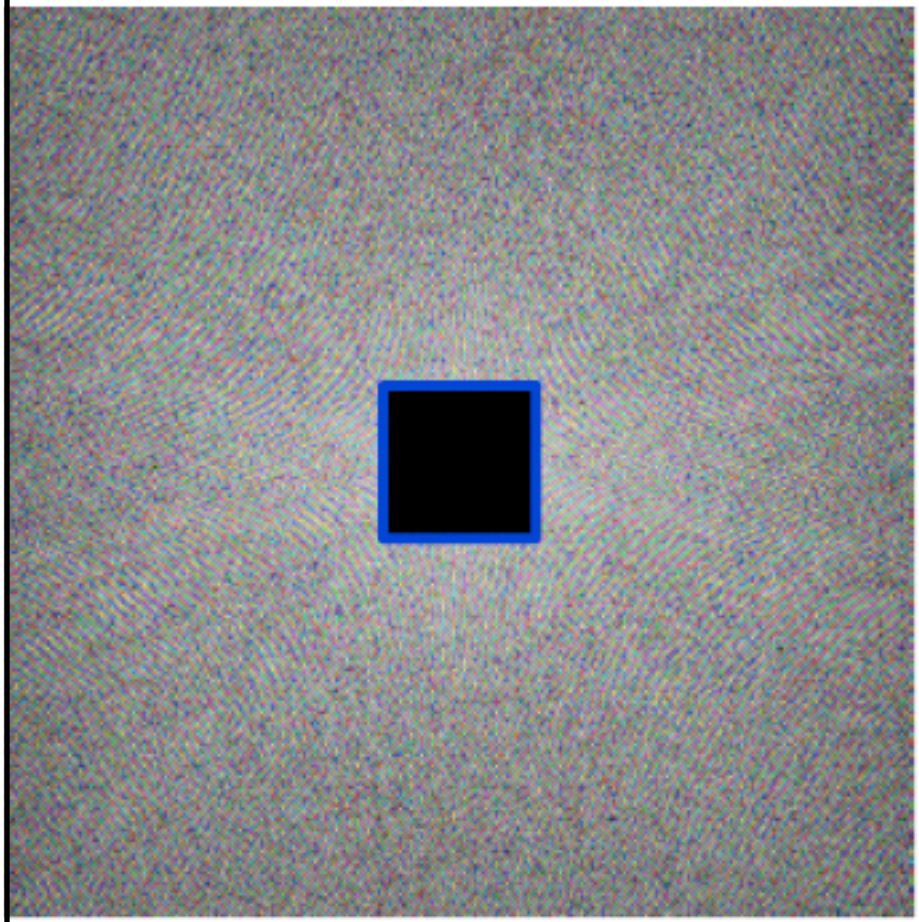


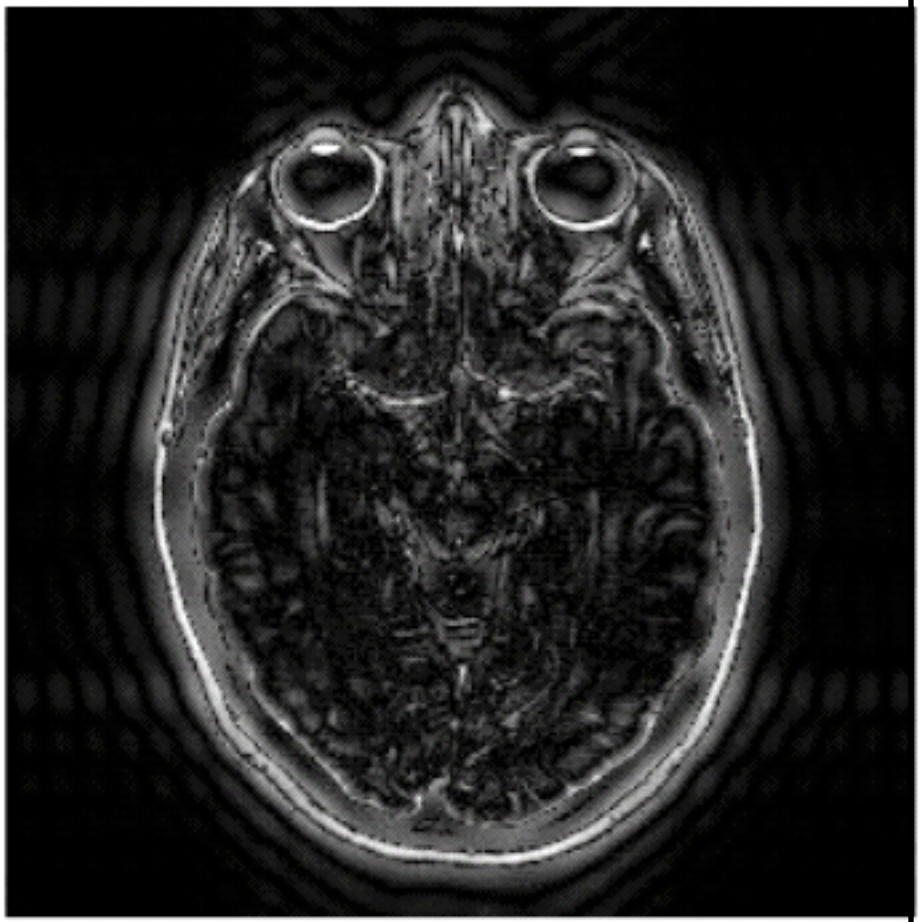
k-space



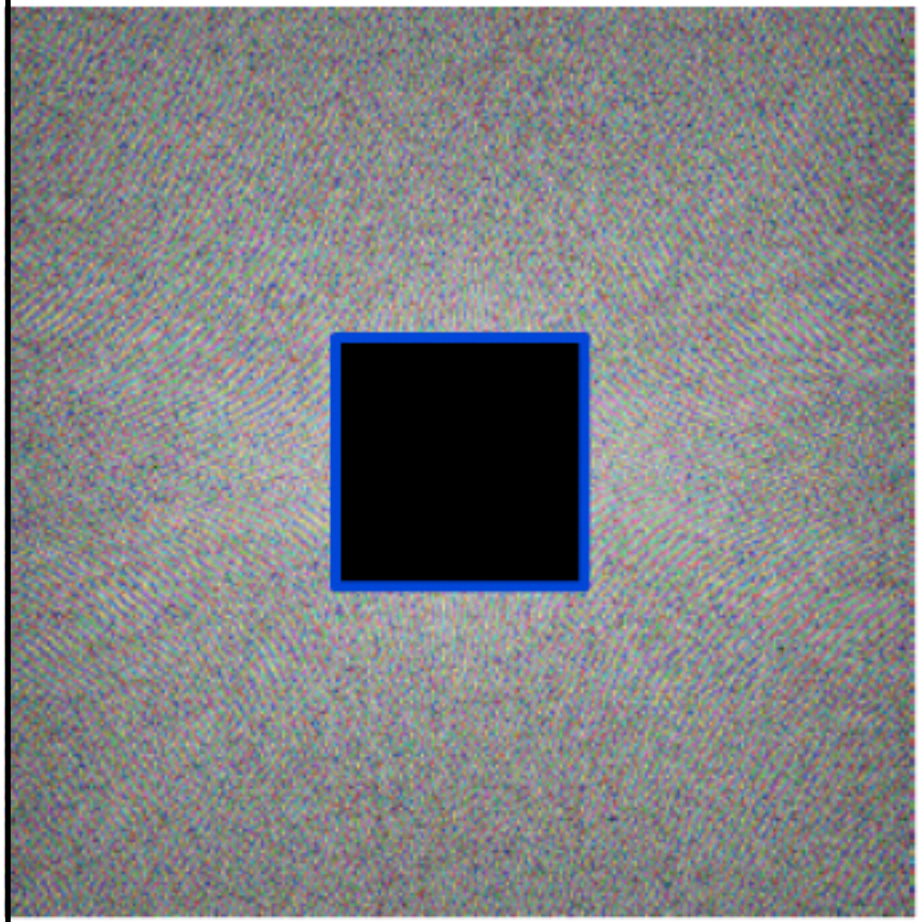


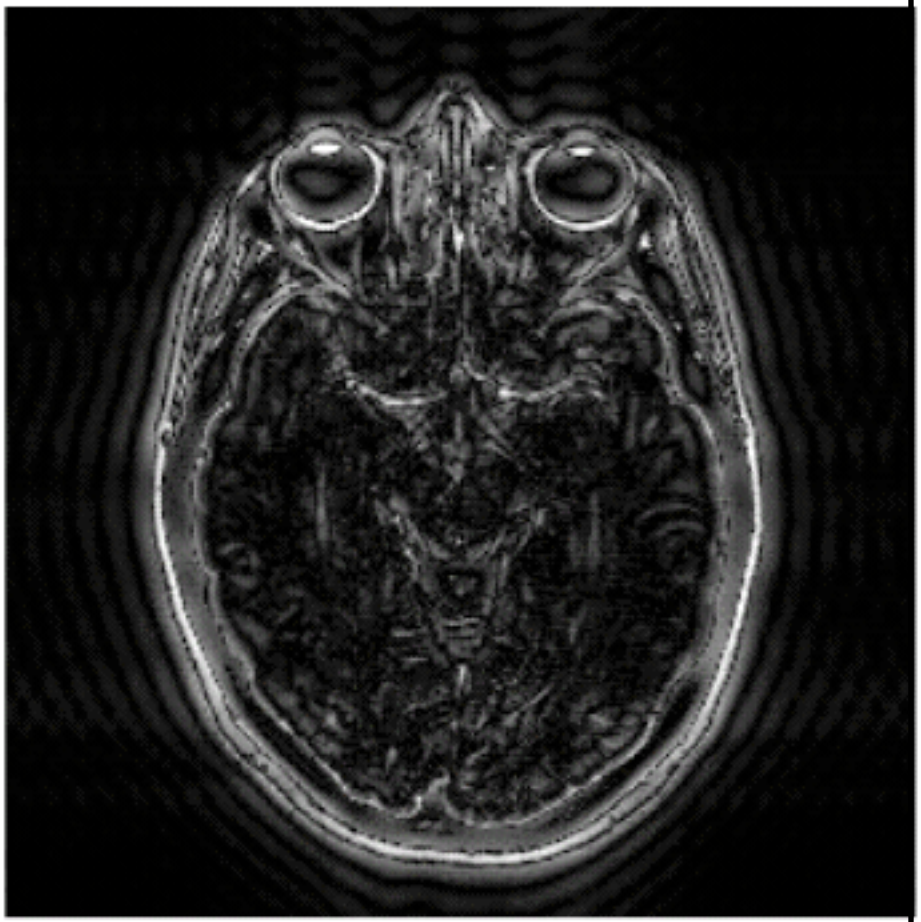
k-space



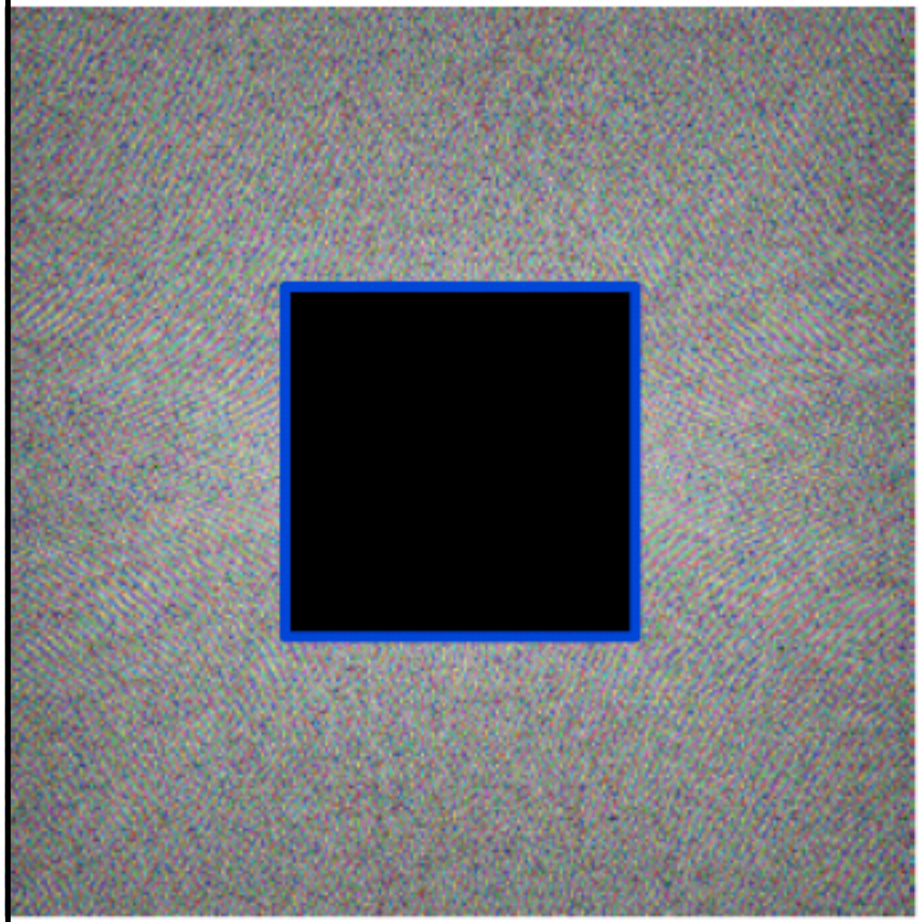


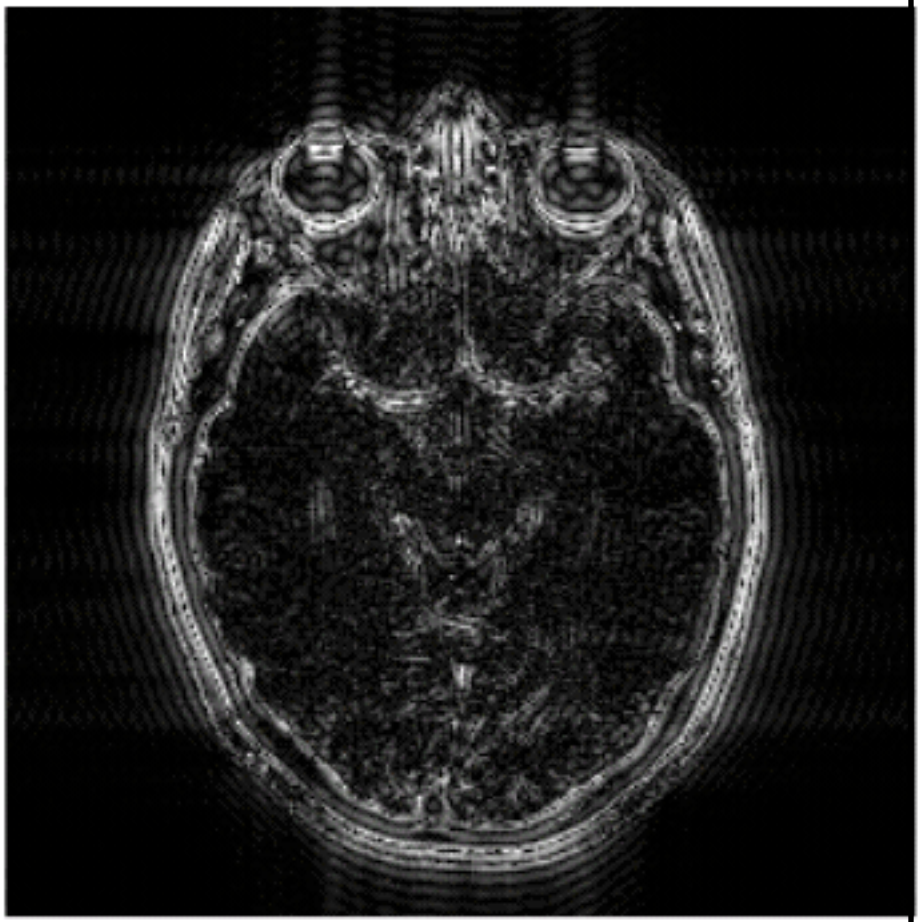
k-space



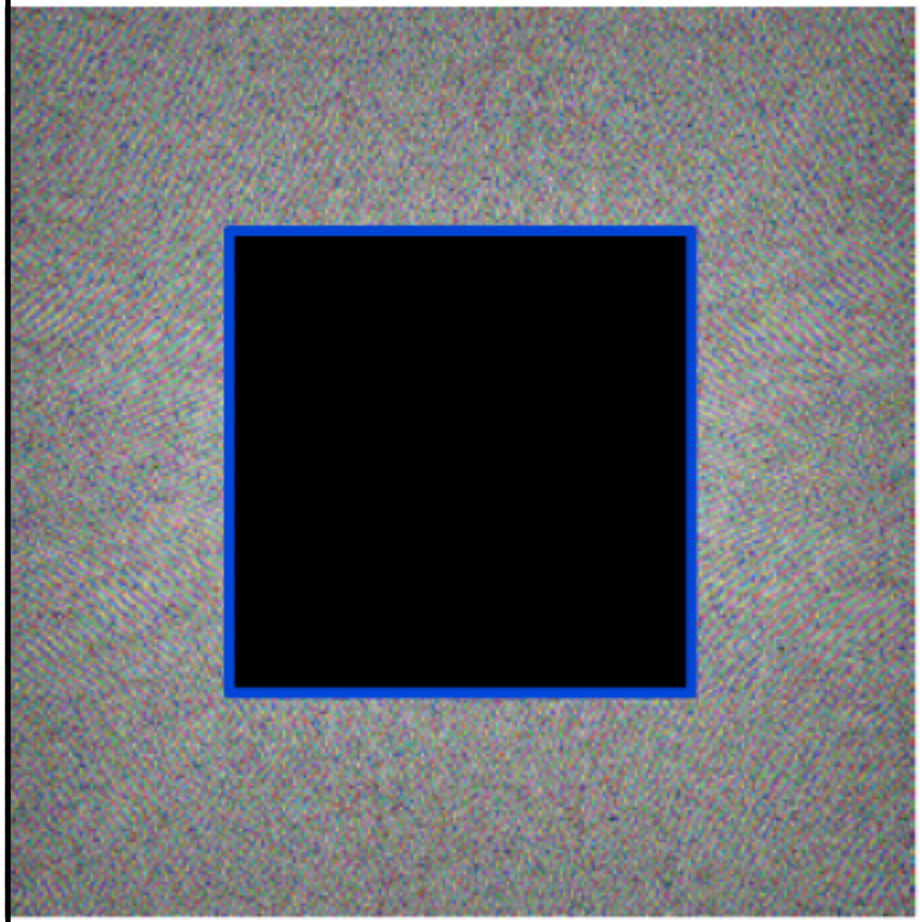


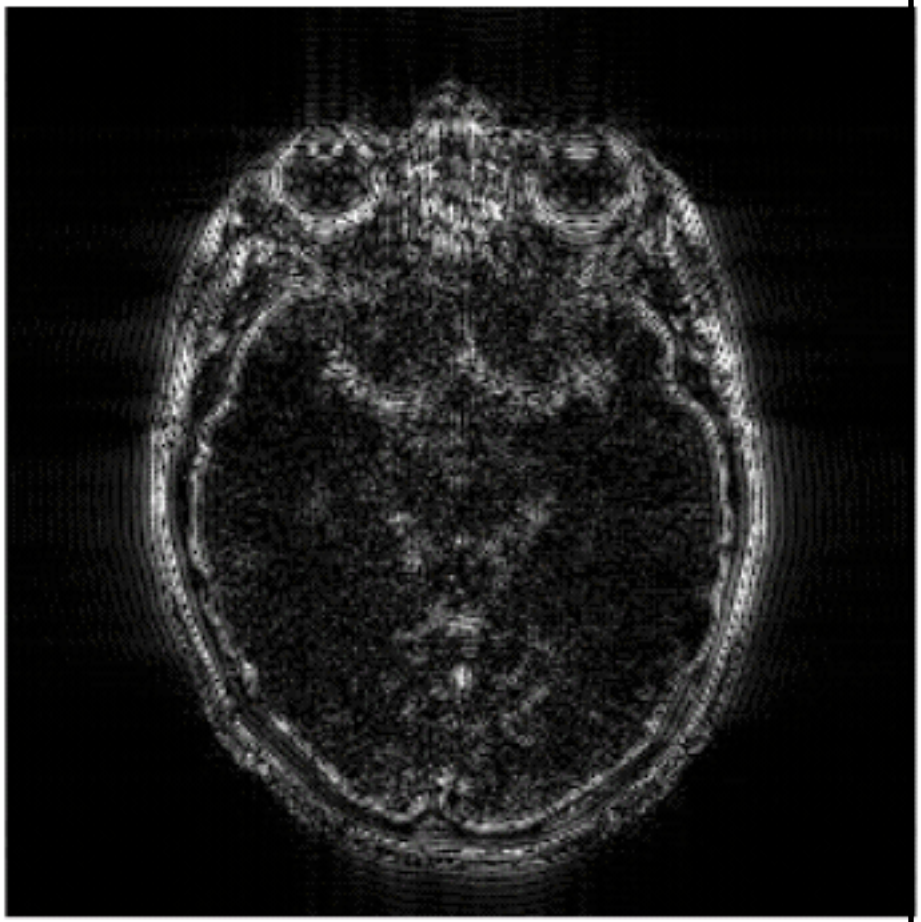
k-space



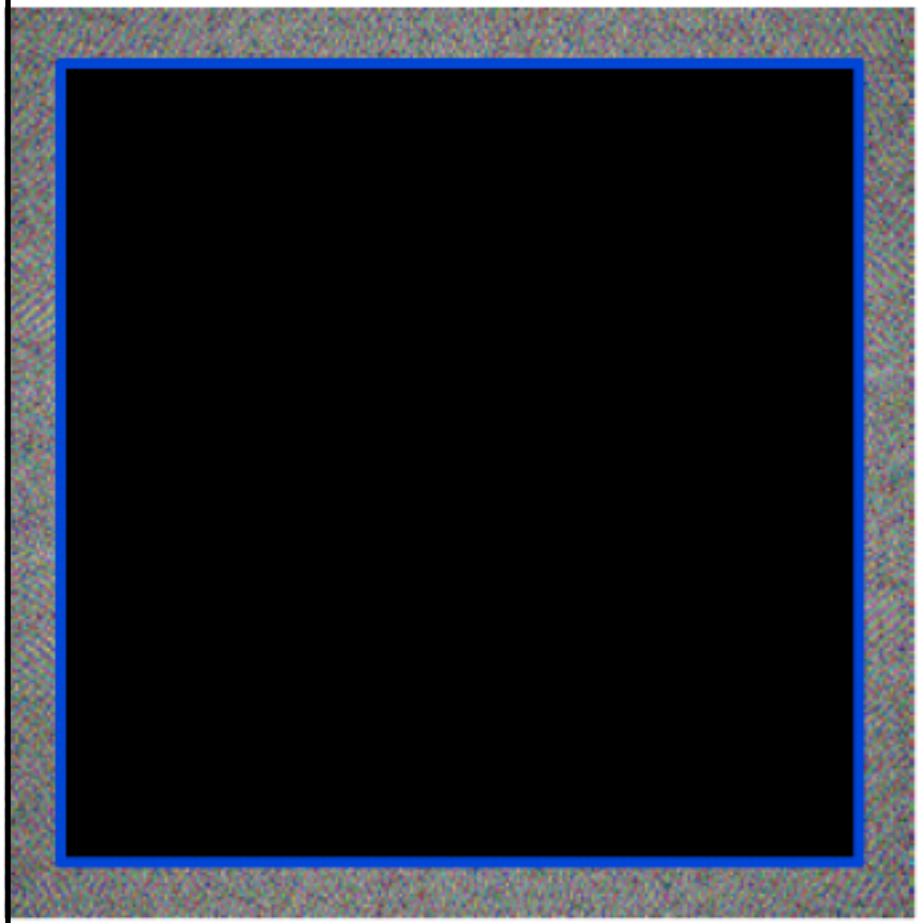


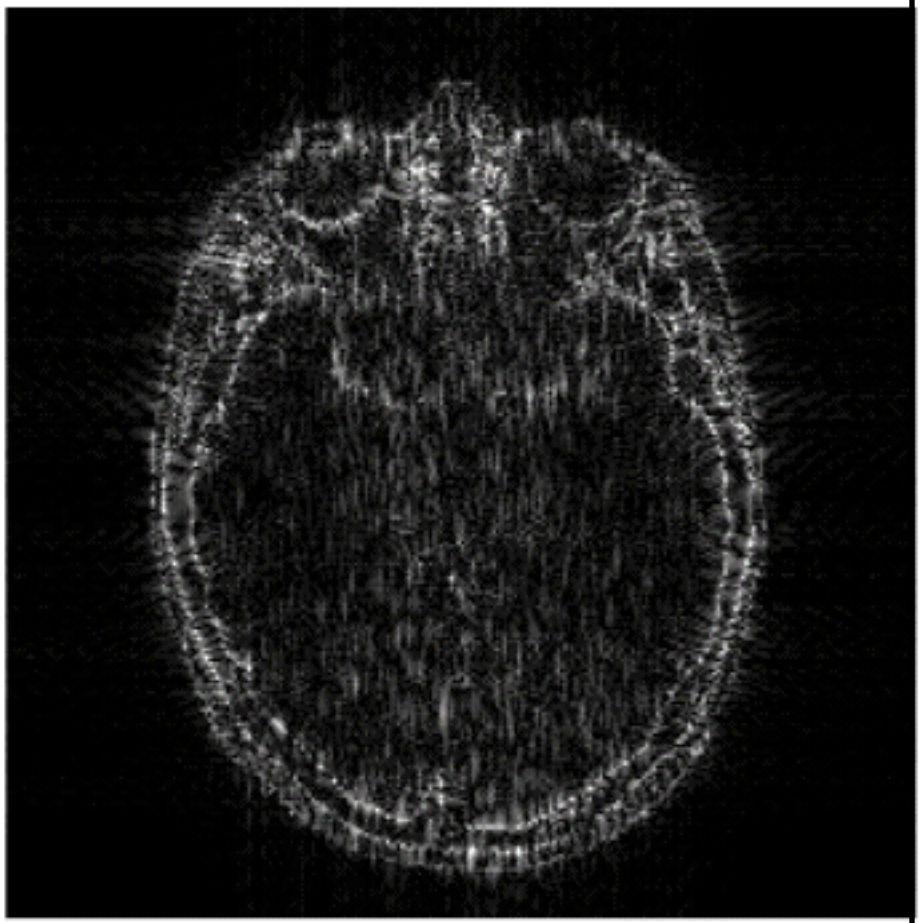
k-space



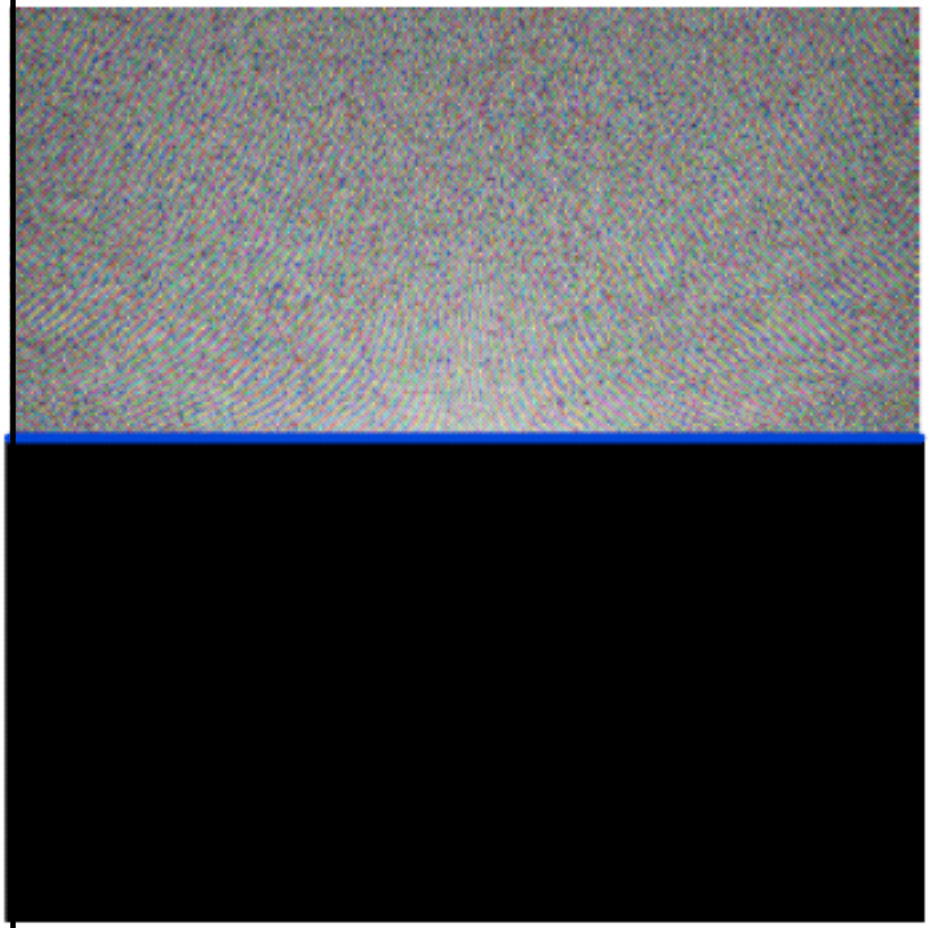


k-space

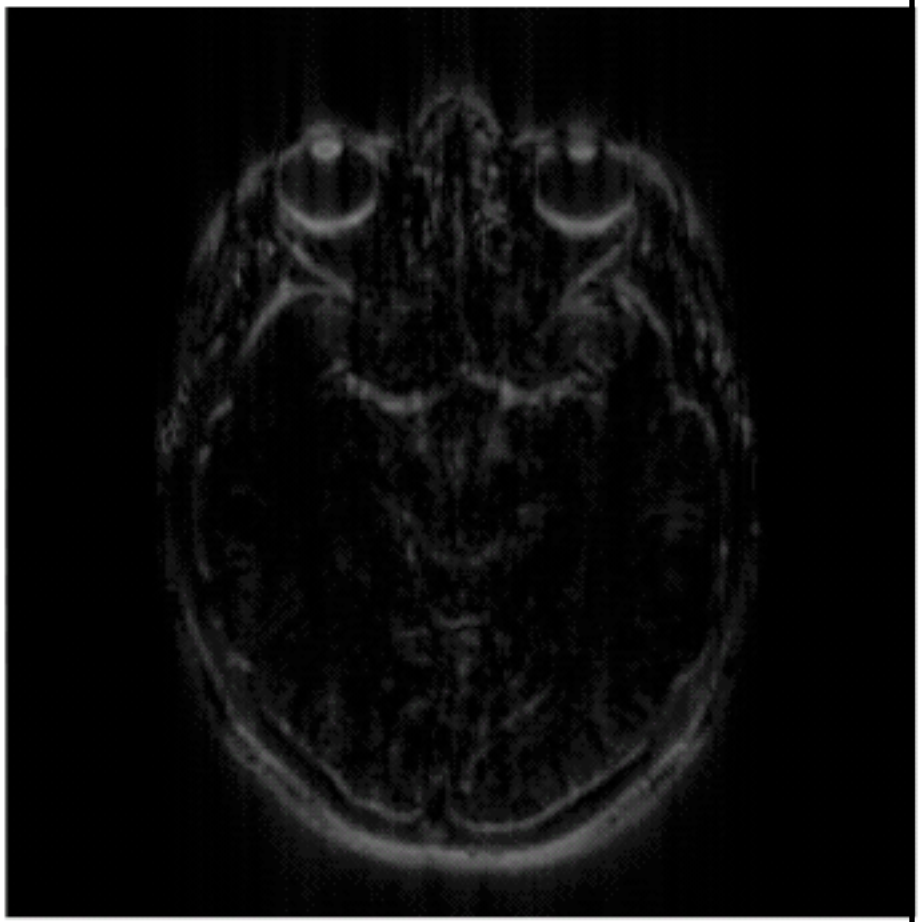




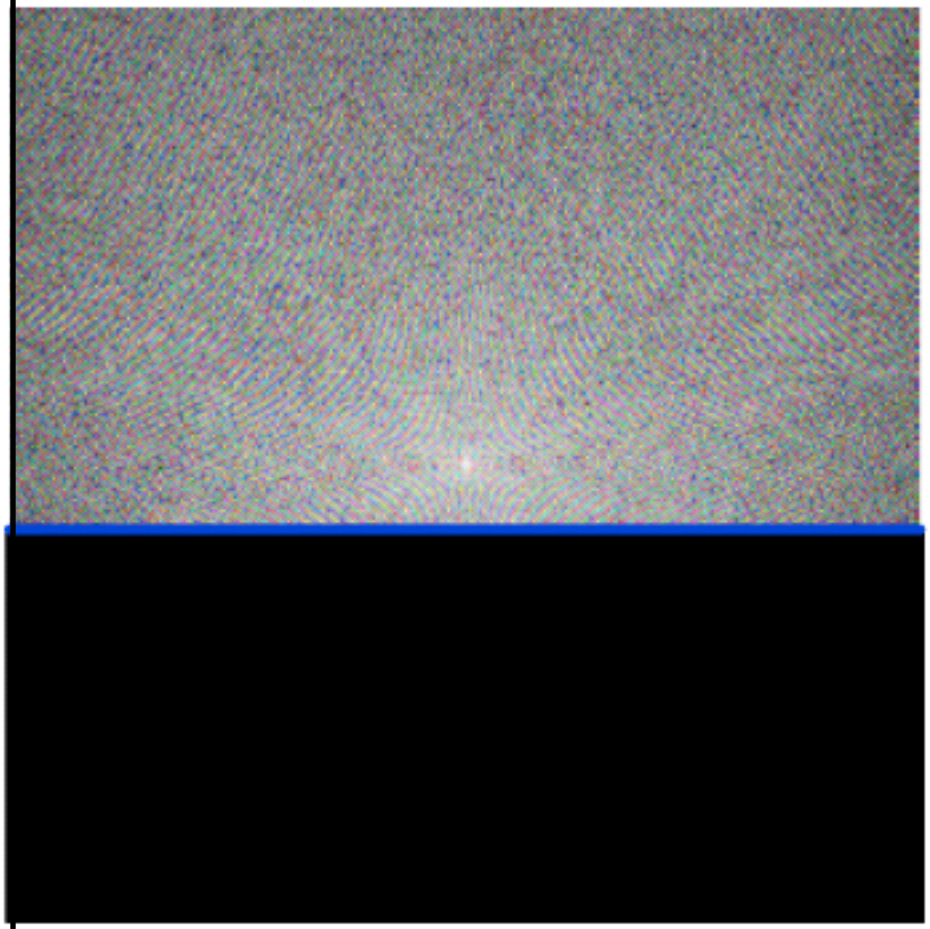
k-space

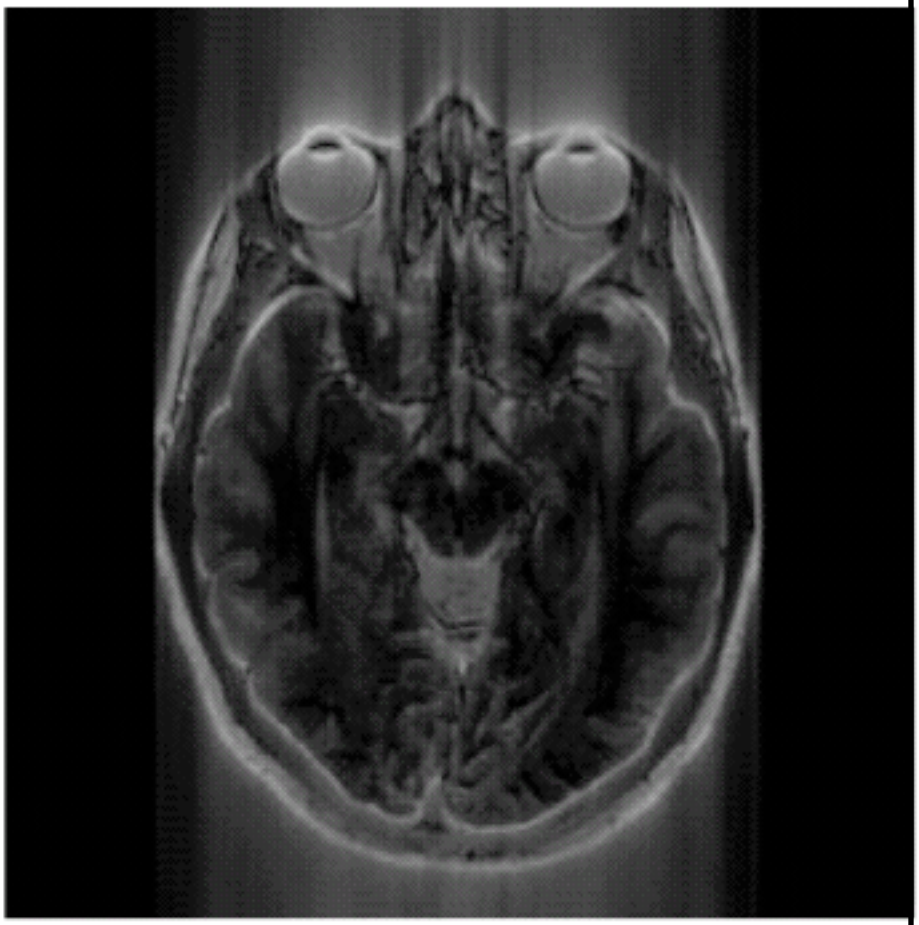


Linear trajectory

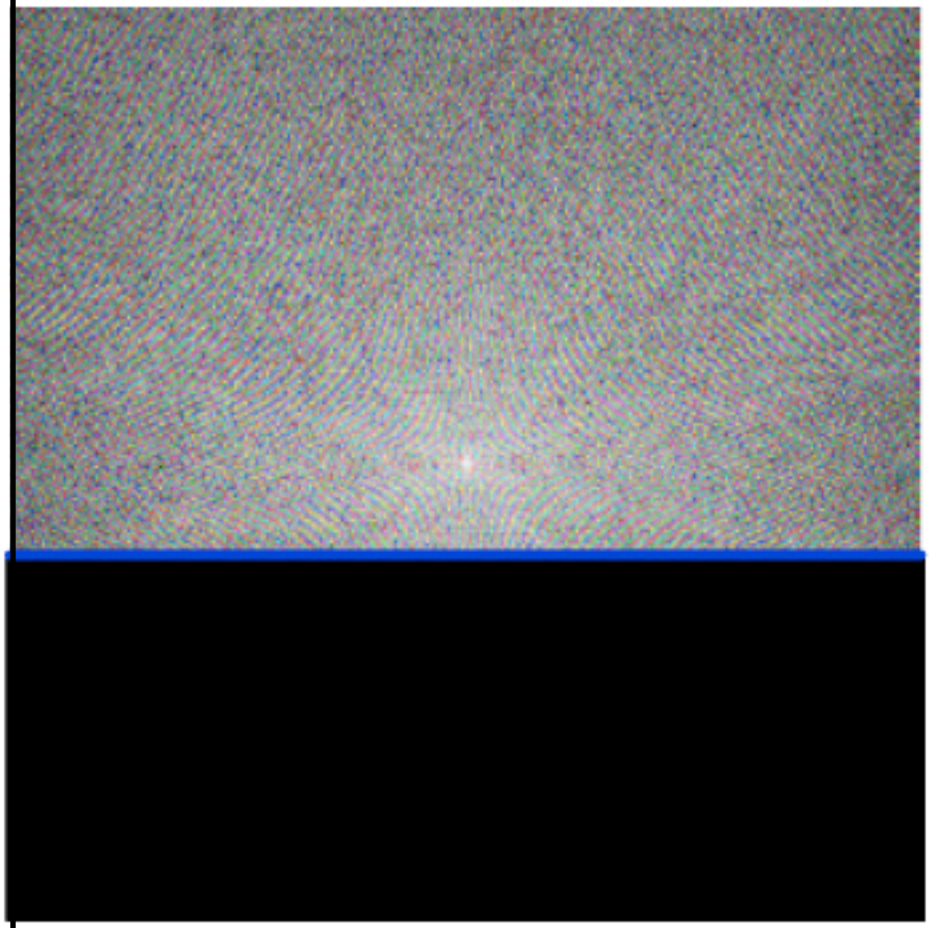


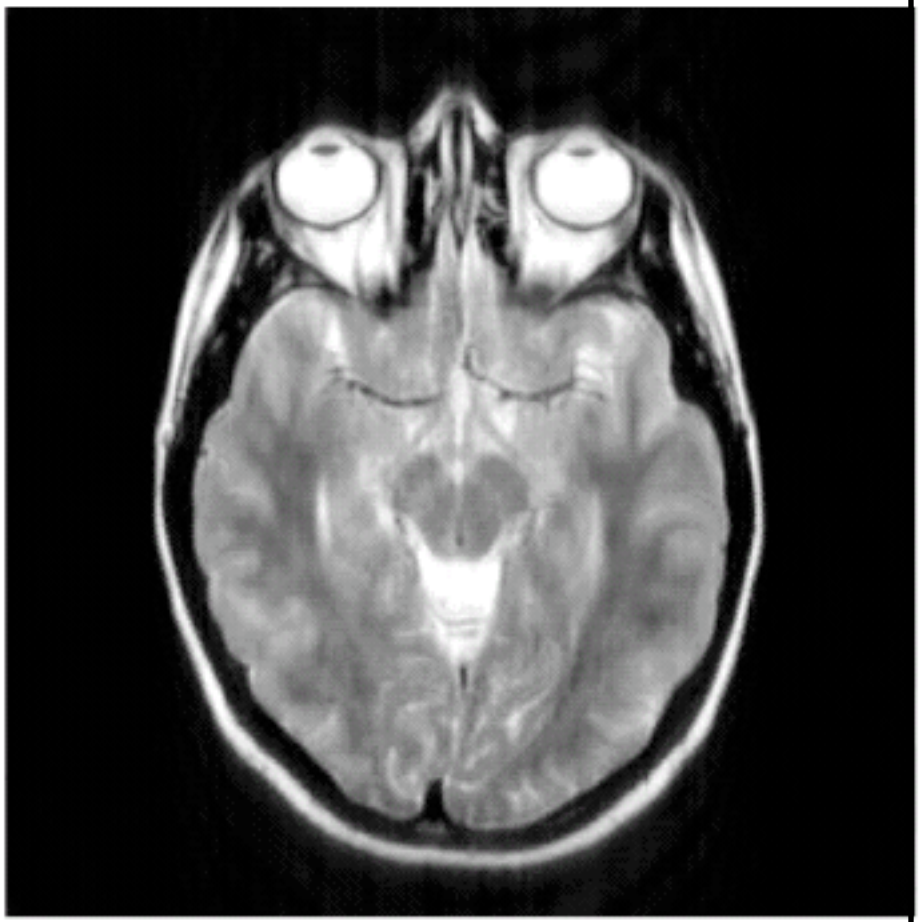
k-space



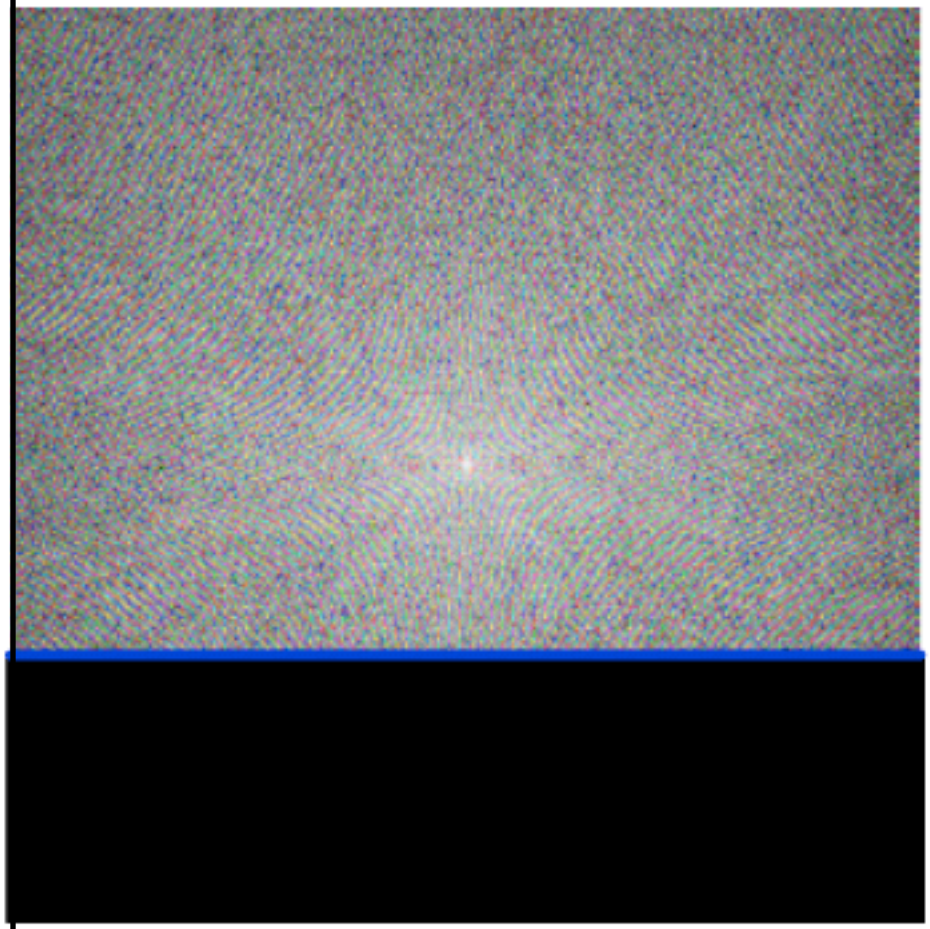


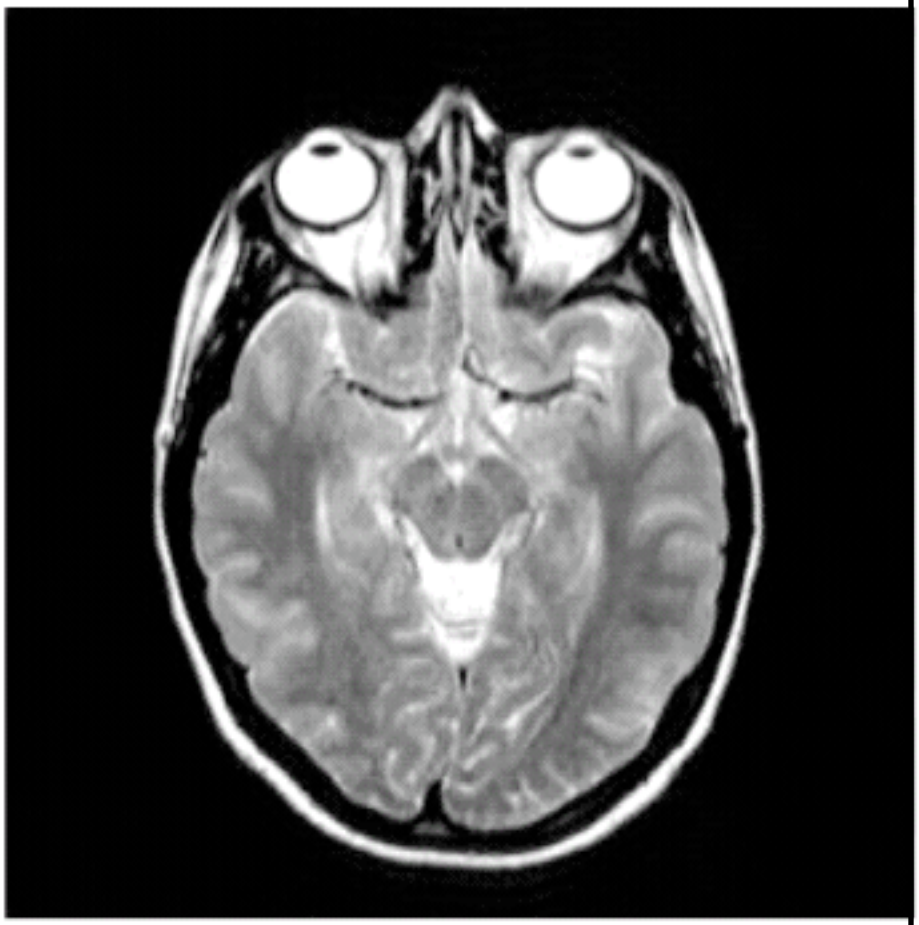
k-space



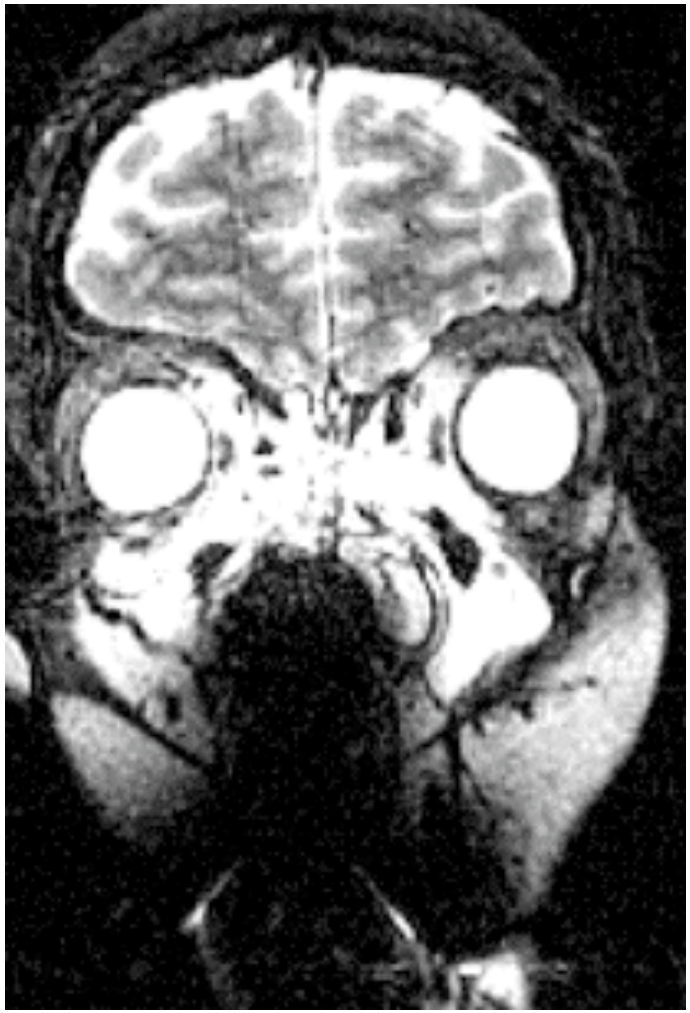


k-space

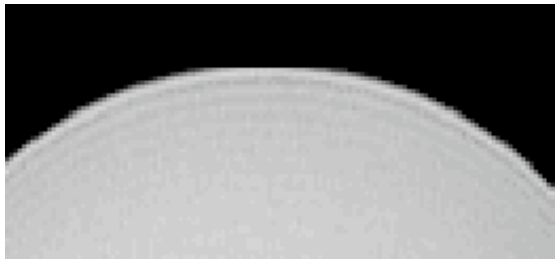




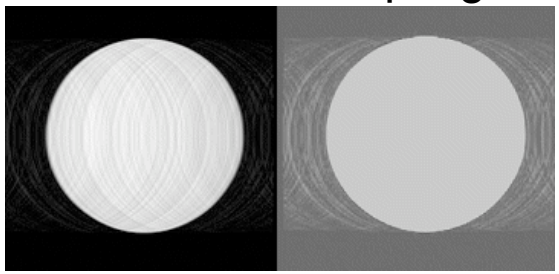
MRI artifacts



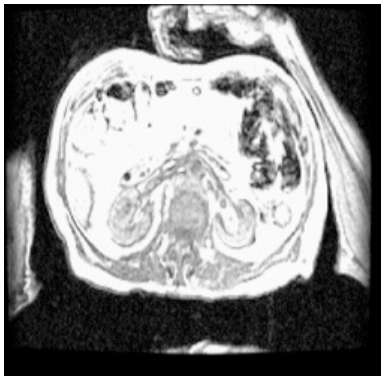
susceptibility (braces)



truncated sampling



motion



wrapping

References

http://www.e-mri.org/

http://www.cis.rit.edu/htbooks/mri/inside.htm

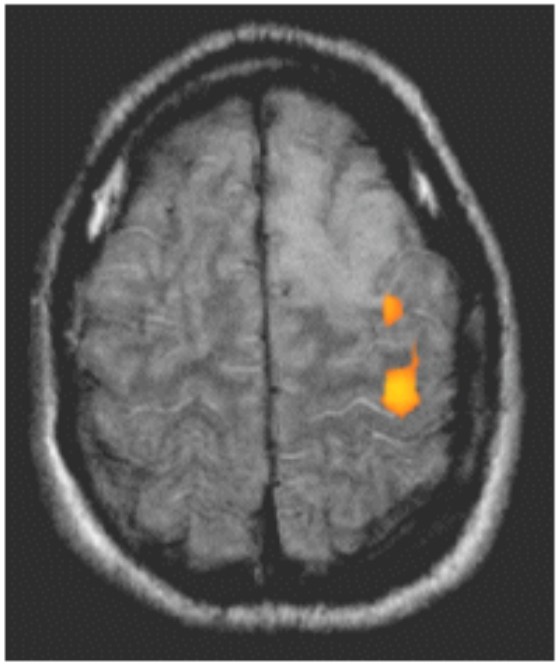
http://www.simplyphysics.com

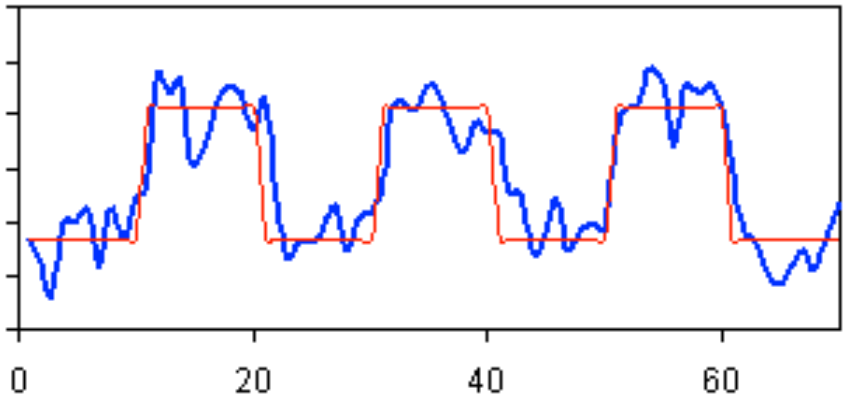
http://www.hull.ac.uk/mri/lectures/gpl_page.html

http://vision.psych.umn.edu/users/caolman/courses/Fall2006/Lectures/Lecture1.ppt

http://upload.wikimedia.org/wikibooks

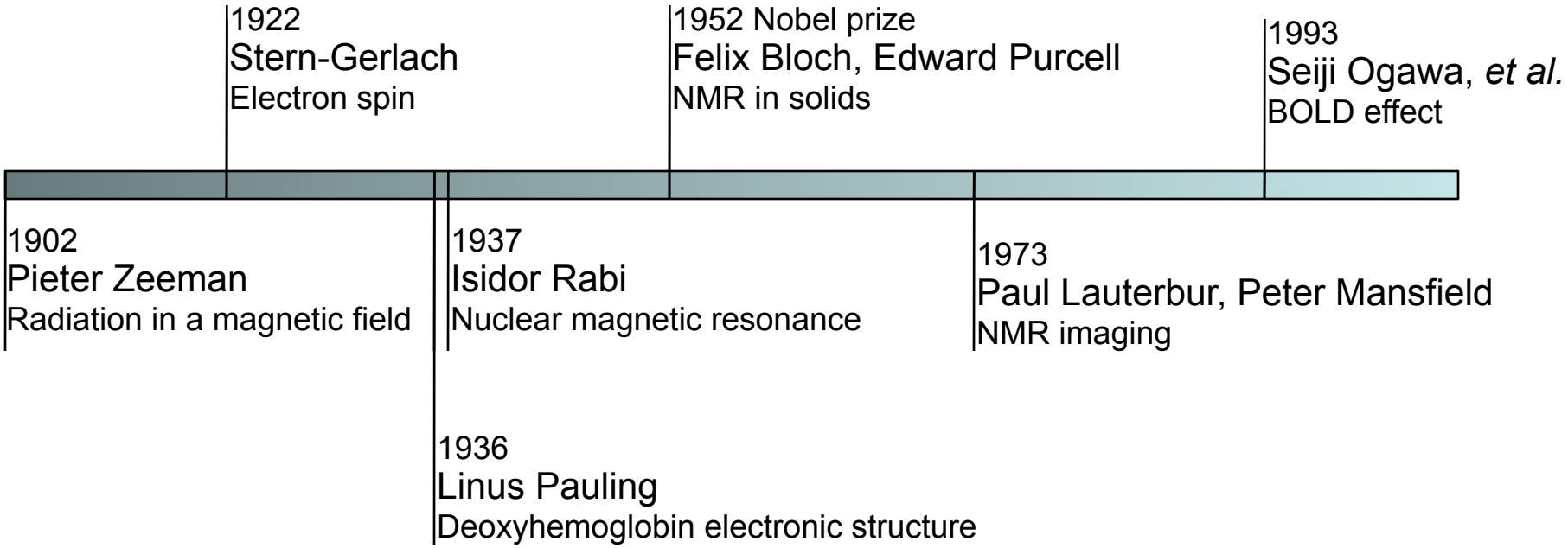
functional MRI





Activation of an area of the brain causes an increase in blood flow to that area
that is greater than that needed to keep up with the oxygen demands of the tissues.
This results in a net increase in intravascular oxyhemogobin and a decrease in deoxyhemoglobin.
Deoxyhemoglobin is paramagnetic, resulting in shortening of the T2* relaxation and decrease in signal.
Less deoxyhemoglobin as a result of increase in blood flow results in an overall increase in signal.
The increase in signal detected ranges from 1-5% on a 1.5T MR system.

NMR - MRI - fMRI timeline



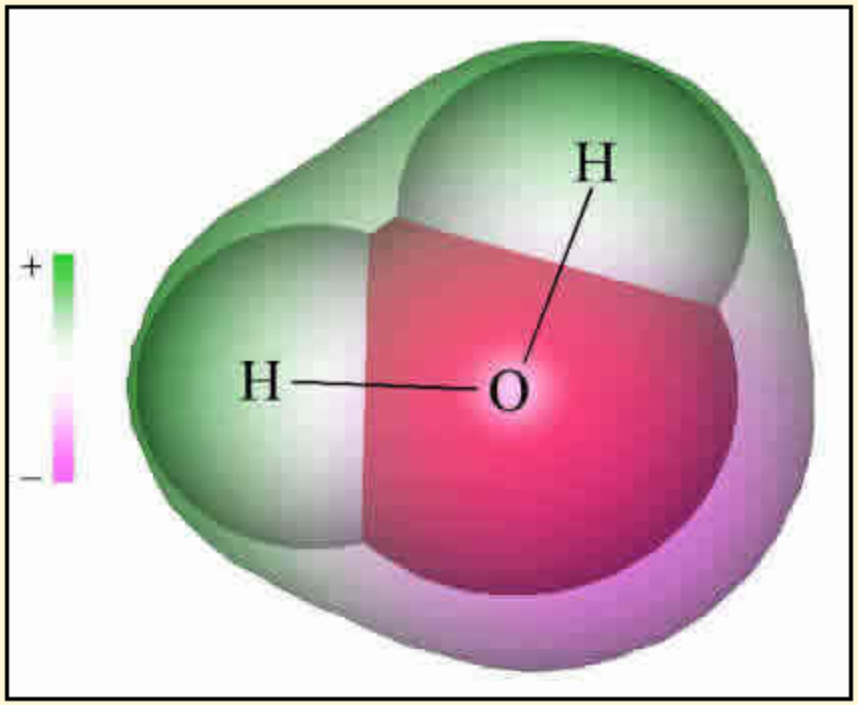
Gyromagnetic ratio

Table 1. Spin, gyromagnetic ratios, NMR frequencies (in a 1 T (10 kG) field) and the natural abundance of selected nuclides)*

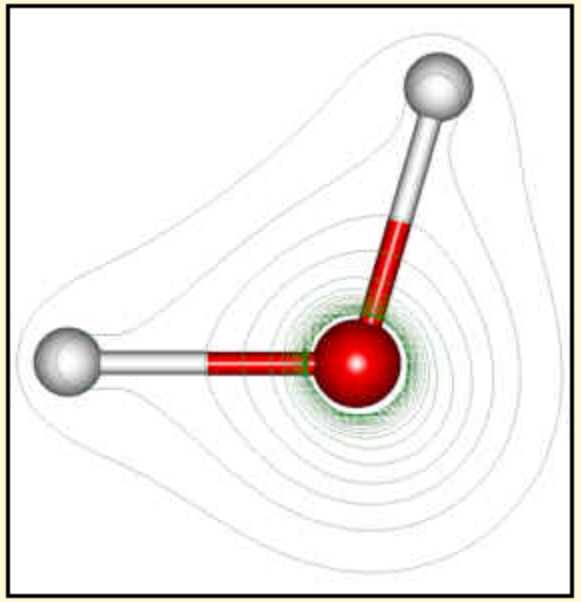
Nucleus	Spin	Gyromagnetic Ratio, γ ($10^7 T^{-1} s^{-1}$)	ν (MHz)	Natural Abundance (%)
^{1}H	1/2	26.75	42.576	99.985
^{2}H	1	4.11	6.536	0.015
^{13}C	1/2	6.73	10.705	1.108
^{19}F	1/2	25.18	40.054	100.00
^{14}N	1	1.93	3.076	99.63
^{15}N	1/2	**-2.71****	4.31	0.37
^{31}P	1/2	10.84	17.238	100.0

* T stands for Tesla (1 Tesla = 10^4 Gauss. The earth's magnetic field is around 0.5 Gauss)

** What is the physical meaning of a negative gyromagnetic constant?



The approximate shape and charge distribution of water.


Note that the average electron density around the oxygen atom is about 10x that around the hydrogen atoms.

The Water Molecule

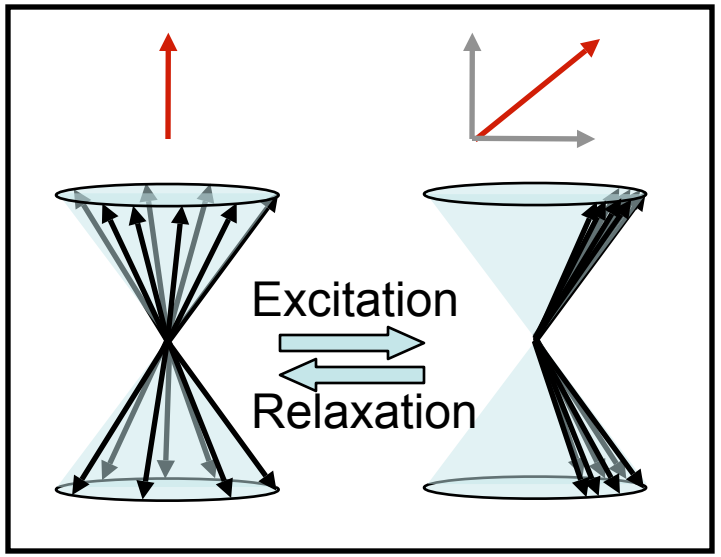
Other nuclei such as 13C, 19F, 31P, 23Na have a net nuclear spin and can be imaged in MRI.

Water is a tiny V-shaped molecule with the molecular formula H_2O [a]. In the liquid state, in spite of 80% of the electrons being concerned with bonding, the three atoms do not stay together as the hydrogen atoms are constantly exchanging between water molecules due to protonation/deprotonation processes. Both acids and bases catalyze this exchange and even when at its slowest (at pH 7), the average residence time is only about a millisecond. As this brief period is, however, much longer than the timescales encountered during investigations into water's hydrogen bonding or hydration properties, water is usually treated as a permanent structure.

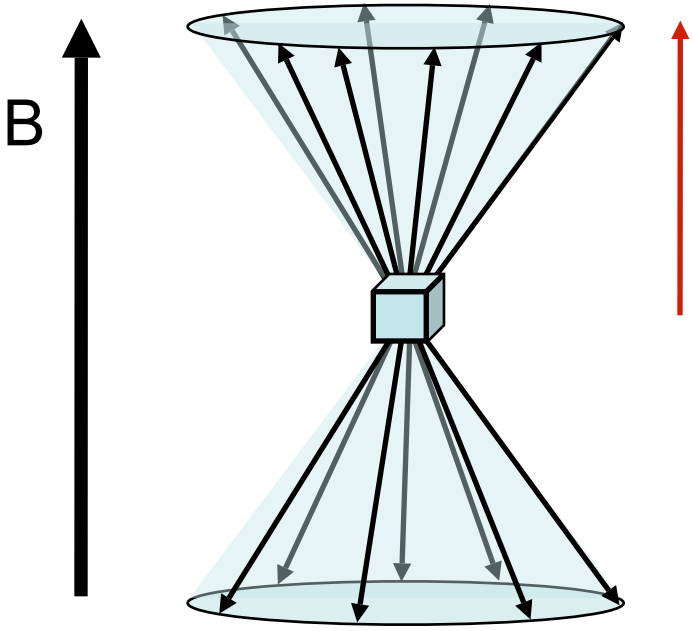
www.lsbu.ac.uk/water/

Bulk magnetization

- Resonant frequency depends on
  - Static magnetic field
  - Molecule
- Relaxation rate depends on physical environment
  - Microscopic field perturbations
    - Tissue interfaces
    - Deoxygenated blood
  - Molecular environment
    - Gray matter
    - White matter
    - CSF



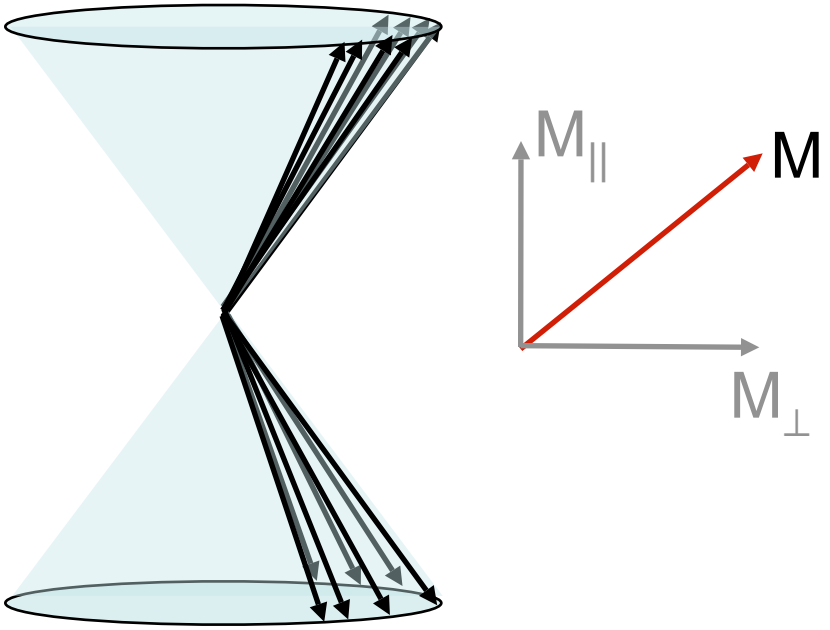
Many spin-1/2 particles in an external magnetic field



M: net (bulk) magnetization

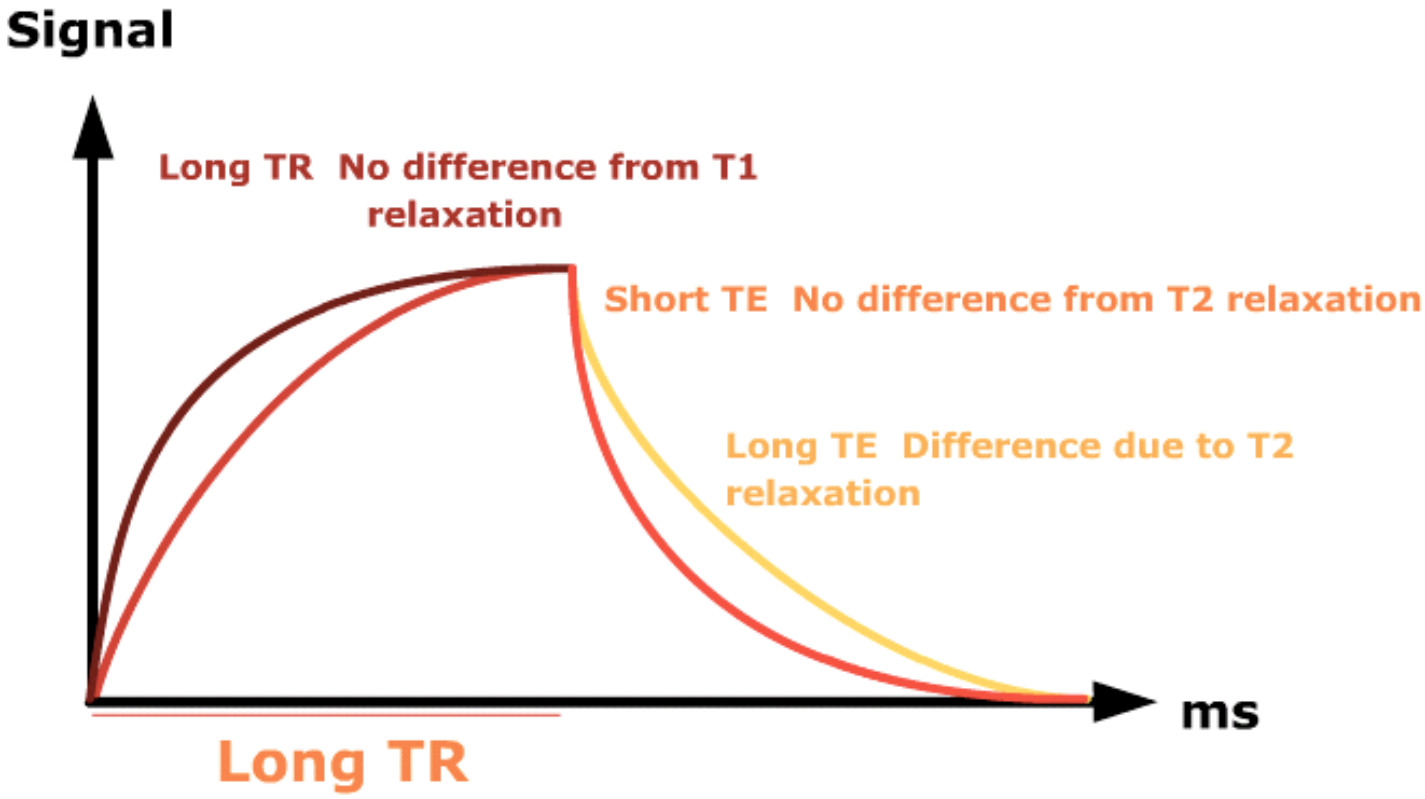
Equilibrium: ~ 1 ppm excess in spin-up state creates a net magnetization

Excitation affects phase and distribution between spin-up and spin-down, rotating bulk magnetization



Tissue contrast

(Spin-echo)



By setting the TR to long values, the T1 effect on tissue contrast will be reduced. If TE is long enough, differences in transverse relaxation will alter contrast (the T2 effect).