UNIVERSITÀ DI TRENTO

CIMeC Center for Mind/Brain Sciences

Magnetic Resonance Imaging: Basic Introduction

Louvain-la-Neuve - Neuroimaging Workshop 2019

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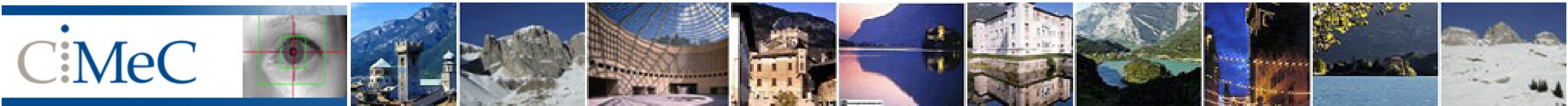


Introduction

Center for Mind/Brain Sciences, University of Trento, Italy

MRI Methods Group: http://r.unitn.it/en/cimec/mri

Focus on: Quantification of brain plasticity

General: Develop & apply novel MRI techniques to quantify brain plasticity

Specific: Optimize accuracy, reproducibility and sensitivity of brain plasticity metrics derived from anatomical, diffusion and functional MRI.

Developments

- Contrast optimization
- Distortion correction
- Reproducibility
- Multicentric harmonization
- Ex-vivo validations

MRI Tools

- Anatomical
- Diffusion
- rsfMRI

1.5T, 3T, 7T, 9.4T

Applications

- Healthy
- Blind
- Deaf
- Dementia
- Psychosis
- Schizophrenia
- Surgery
- Proton therapy

3T Prisma Siemens, CIMeC

Through collaborations

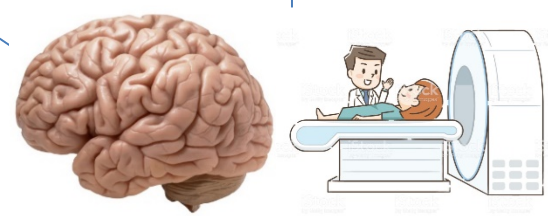
Concept map for lectures

Lecture 1

NMR Signal origin
- Powerful magnet
- Radio frequency
- Magnetic field gradients

MR Image & Contrast
- Spatial encoding
- Magnetic gradients
- Pulse sequences

MR Safety
- Powerful magnet
- Radio frequency
- Magnetic field gradients



Lecture 2

Structural MRI
- Contrast, important parameters
- Sequences & artifacts
- Analyses & applications

Lecture 3

Diffusion MRI
- Contrast, important parameters
- Sequences & artifacts
- Analyses & applications

Lecture 4

Functional MRI
- Contrast, important parameters
- Sequences & artifacts
- Pre-processing

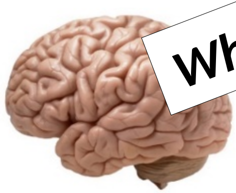
Lecture 1 outline

NMR: Nuclear Magnetic Resonance

- **What is the source of the NMR signal?**
- **How do we measure it?**
- **How do we make images from it?**

The «magic» of MRI

One non-invasive instrument



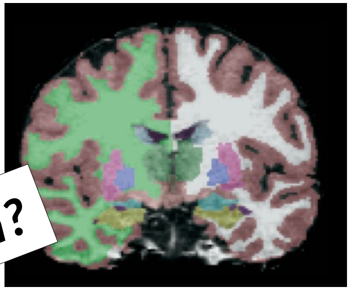
Where do foundations come from?

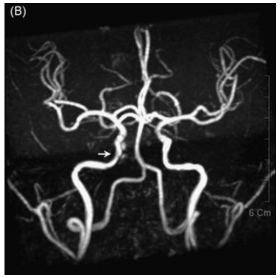
Pulse Sequences

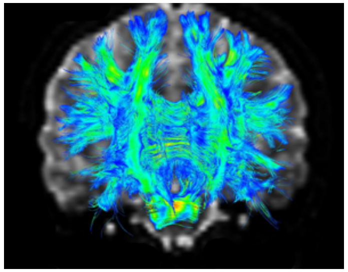
Analyses Models

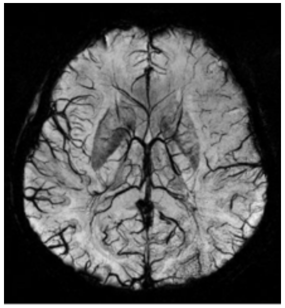
Quantum mechanics

Quantification of multiple tissue and physiology properties

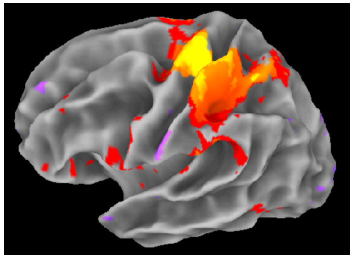


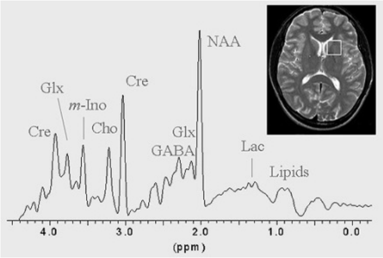






Etc.



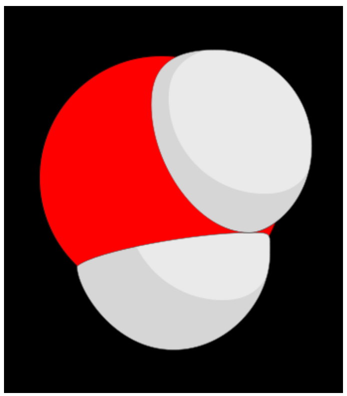


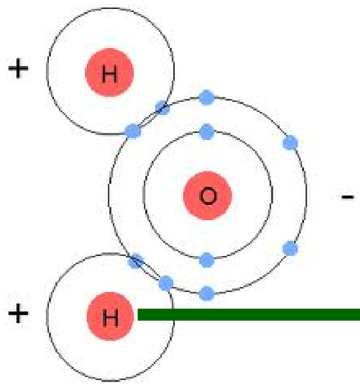
Pendulum analogy

What is the source of an NMR signal?

When considering typical experiments with biologic tissue

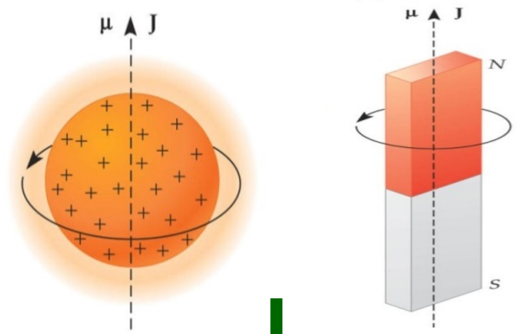
Water molecules (H_2O)



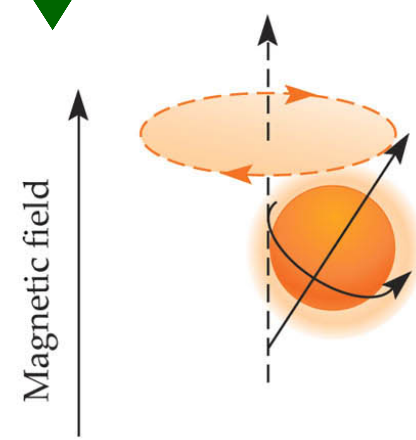


have hydrogen atoms, each with a proton

The proton has a spin (little magnet)



Proton follows external magnetic field



Angular rotation: $\omega = \gamma$ B

ω: Larmor frequency
γ: giromagnetic ratio (42.58 MHz/T)
B: local magnetic field

How do we obtain an NMR signal?

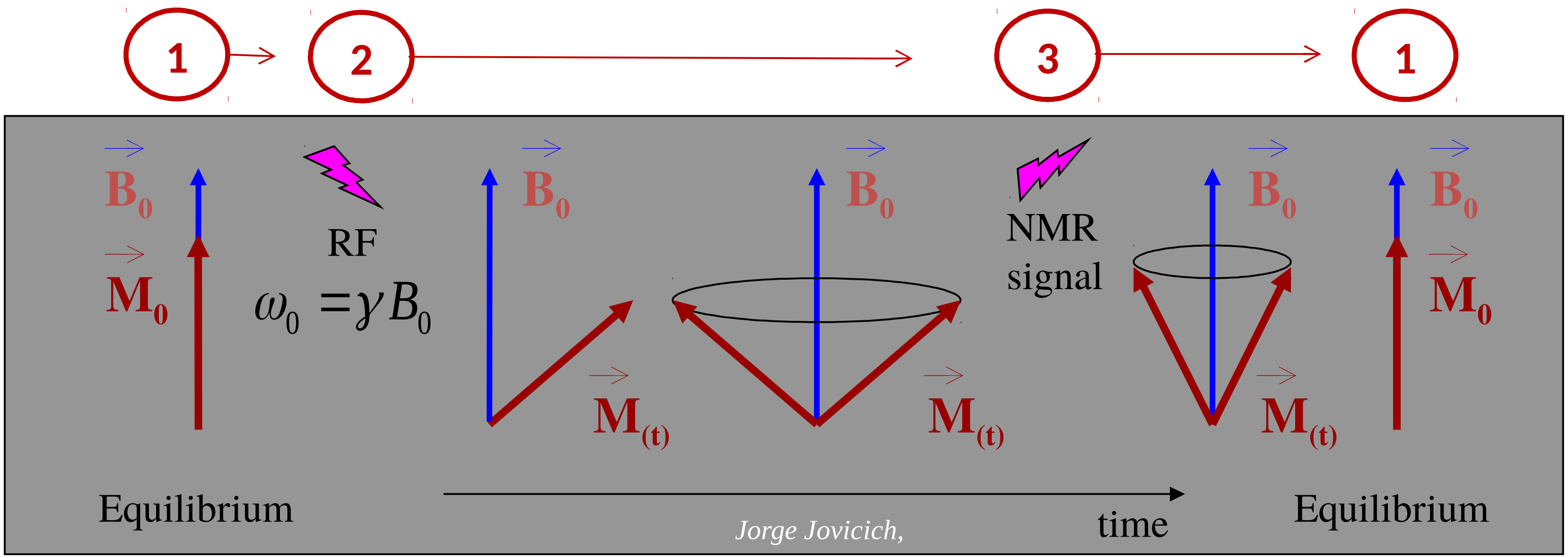
1) Create an equilibrium magnetization (M_0)

Put subject in a strong static magnetic field (e.g., 3T)

2) Excite the magnetization away from equilibrium

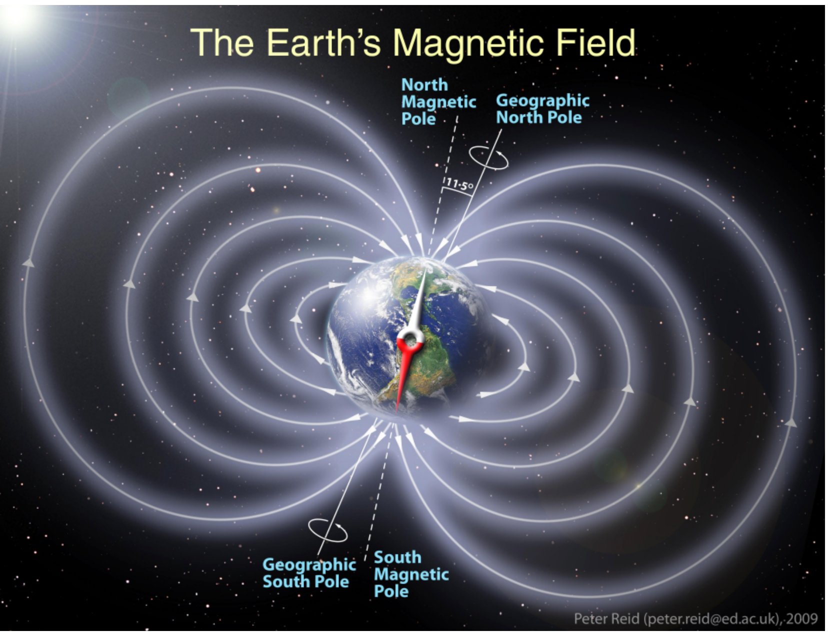
Transmit radio waves into subject [2~10 ms, mT]

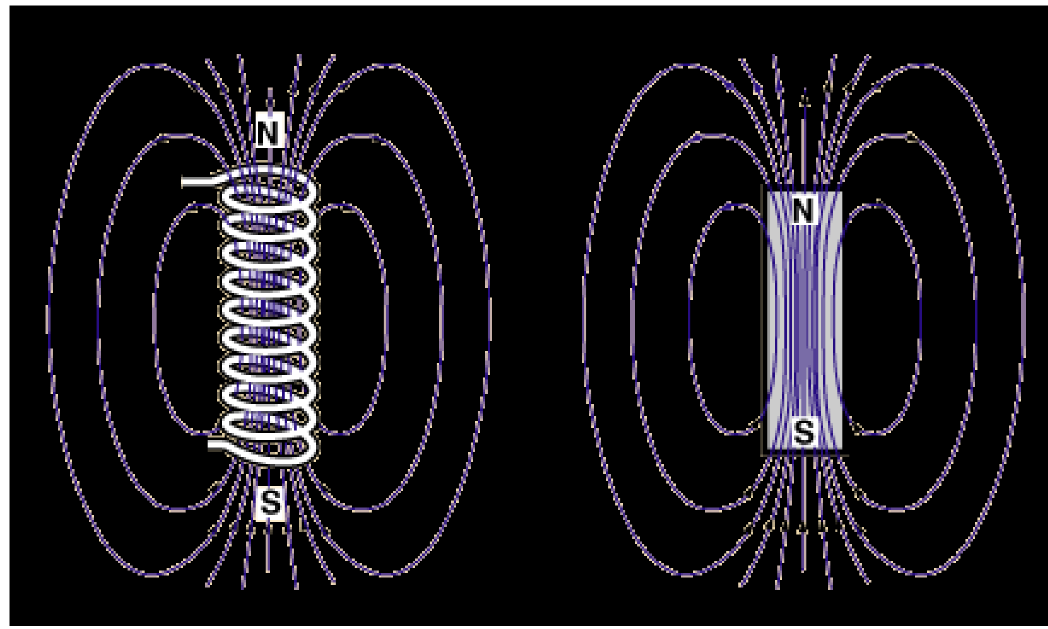
3) Measure the signal induced as the magnetization relaxes to equilibrium



Need for a strong and uniform magnetic field

- 1 Tesla = 20,000x Earth's magnetic field





Magnetic field from a coil & current

Magnetic field from a bar magnet

Where is the magnetic field in the MRI scanner?

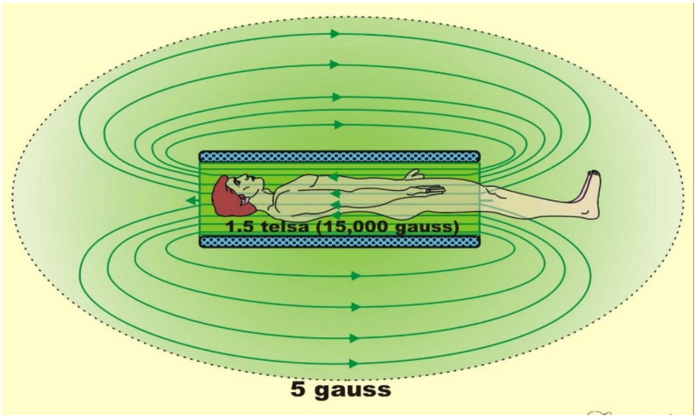
- B0 = constant magnetic field

  (always on!)
- Along z-axis
- Superconducting coil
- For fMRI

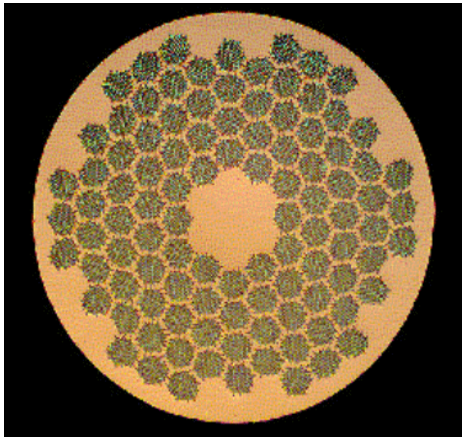
  1.5T, 3T, 4T,

  7T, and above…

How do we generate a static magnetic field?

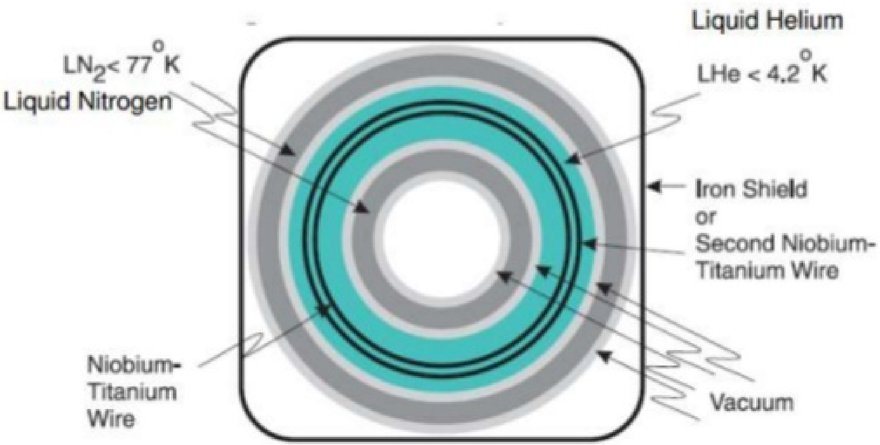


http://www.sprawls.org/mripmt/MRI02

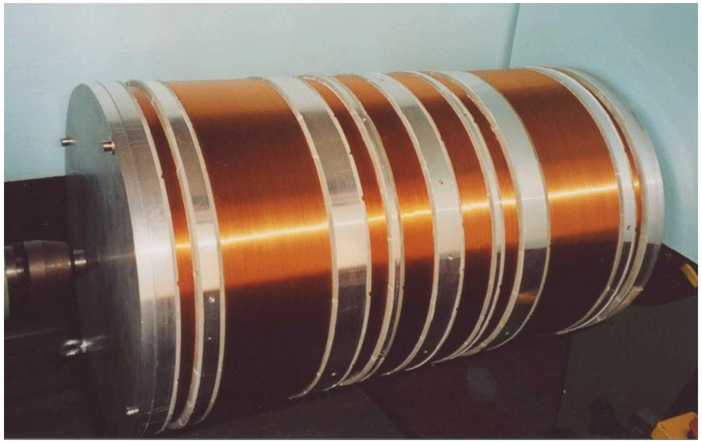


Cross section of winding from a superconductive magnet with NbTi multifiliments embedded in a Cu core

http://mriquestions.com/superconductive-design.html



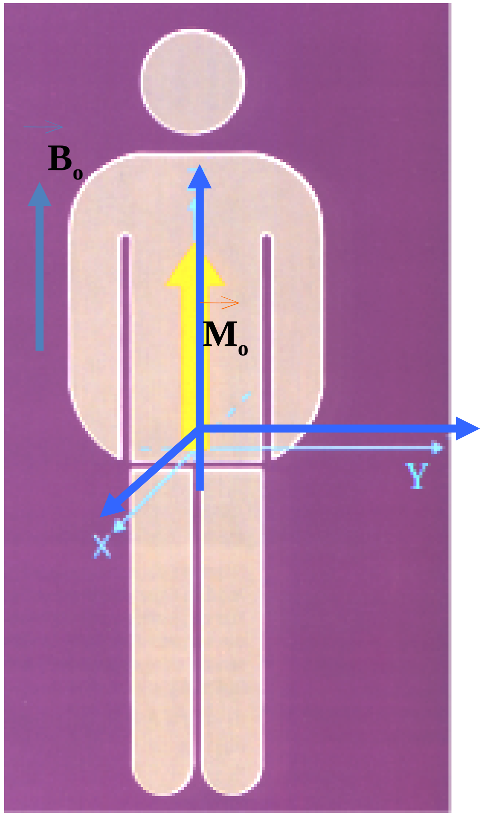
https://www.slideshare.net/padmanishailesh/mri-hardware

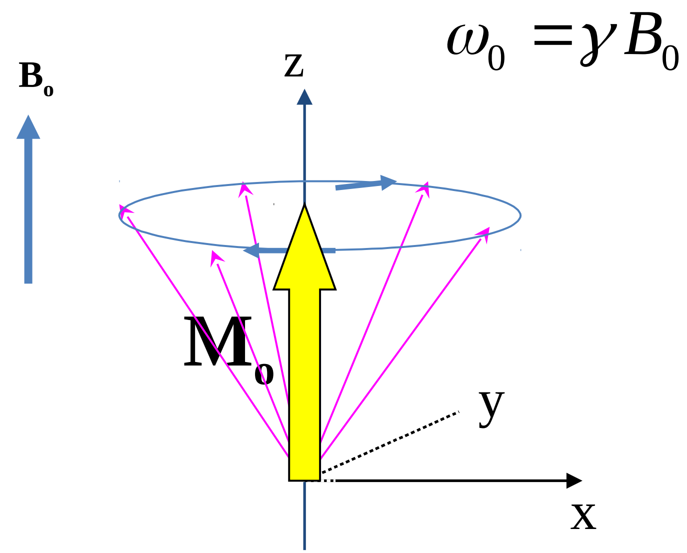


Quick review

- **NMR Signal**
  - Equilibrium magnetization (**Mo**)
  - Excitation of **Mo** away from equilibrium
  - Relaxation of **Mo** to equilibrium

Sample in static magnetic field: equilibrium magnetization





B_0 : uniform static magnetic field

M_0 : static macroscopic magnetization

ω_0 : Larmor frequency

Net Equilibrium magnetization $\mathbf{M_0}$:

- M_z aligned always with $\mathbf{B_0}$
- $M_{xy} = 0$
- M_0 is the vectorial sum of millions of small magnetizations from the protons, which are all rotating at the same Larmor frequency, but out of phase

Quick review

- **NMR Signal**
  - Equilibrium magnetization (**Mo**)
  - Excitation of **Mo** away from equilibrium
  - Relaxation of **Mo** to equilibrium

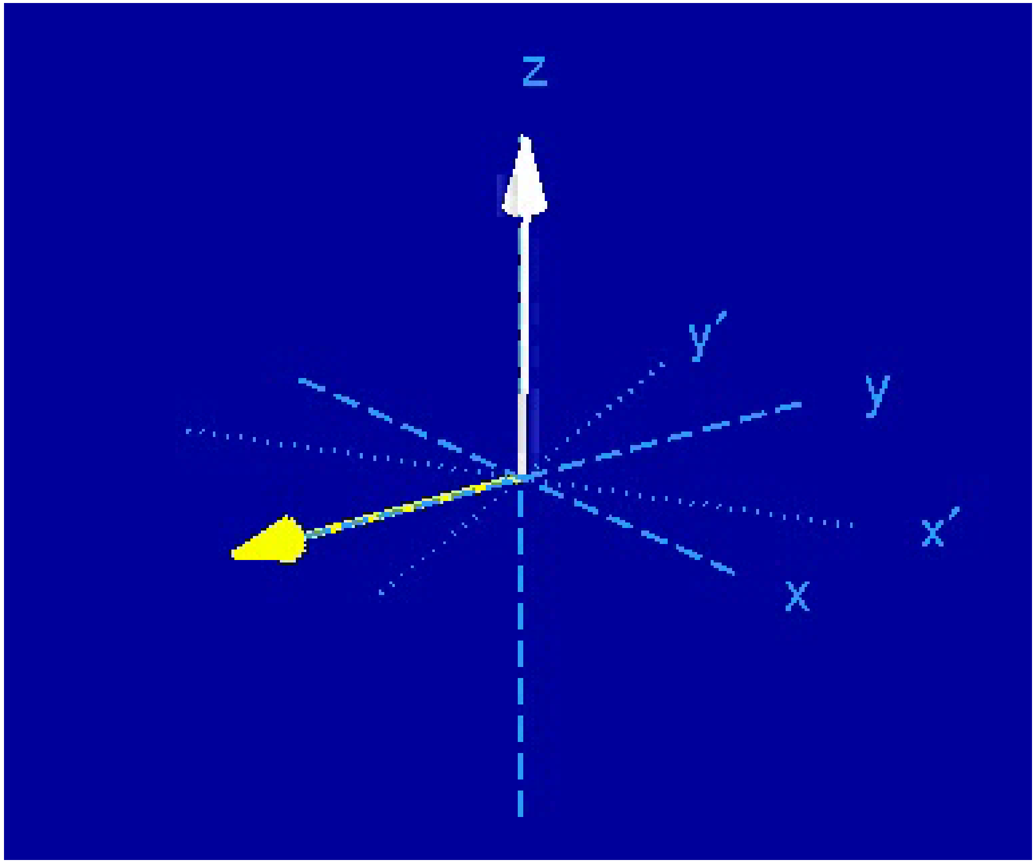
Magnetization excitation needs resonance

Magnetization excitation: radio frequency (RF) pulse at Larmor frequency

Need a resonant driving force

- Like pushing a child on a swing
- Child will absorb energy only if transmitted at the right frequency

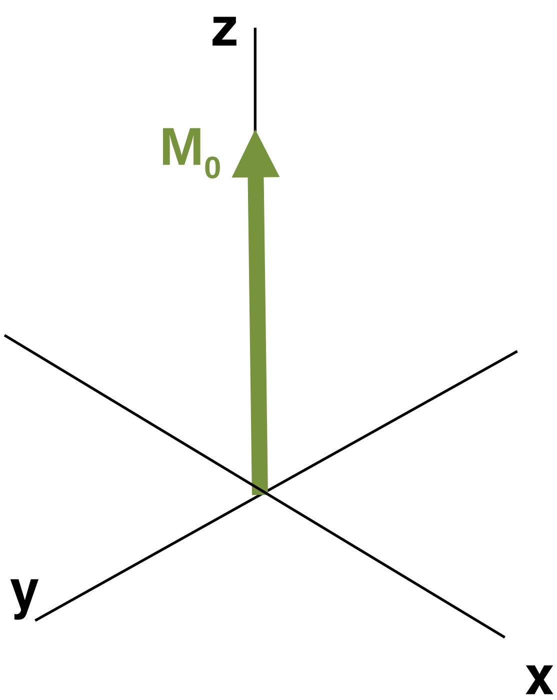
Excitation of the magnetization with an external RF field



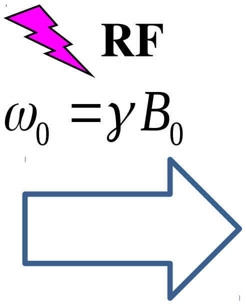
Source: Brian Hargreaves (mrsrl.stanford.edu/~brian/mri-movies/)

What happens immediately after a RF pulse?

Equilibrium magnetization in B_0 magnetic field

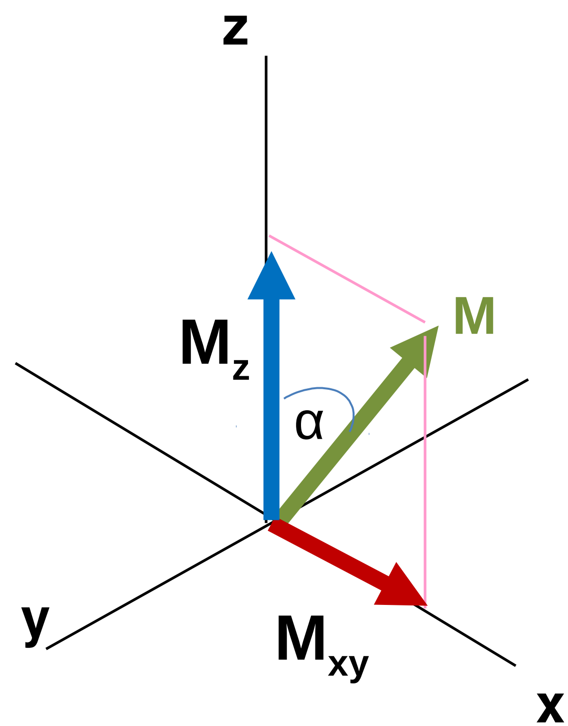


RF excitation
flip angle α



$$\omega_0 = \gamma B_0$$

Magnetization after absorbing the RF energy and rotating a fling angle α



M_0: magnetization at equilibrium

M: magnetization rotated by RF pulse

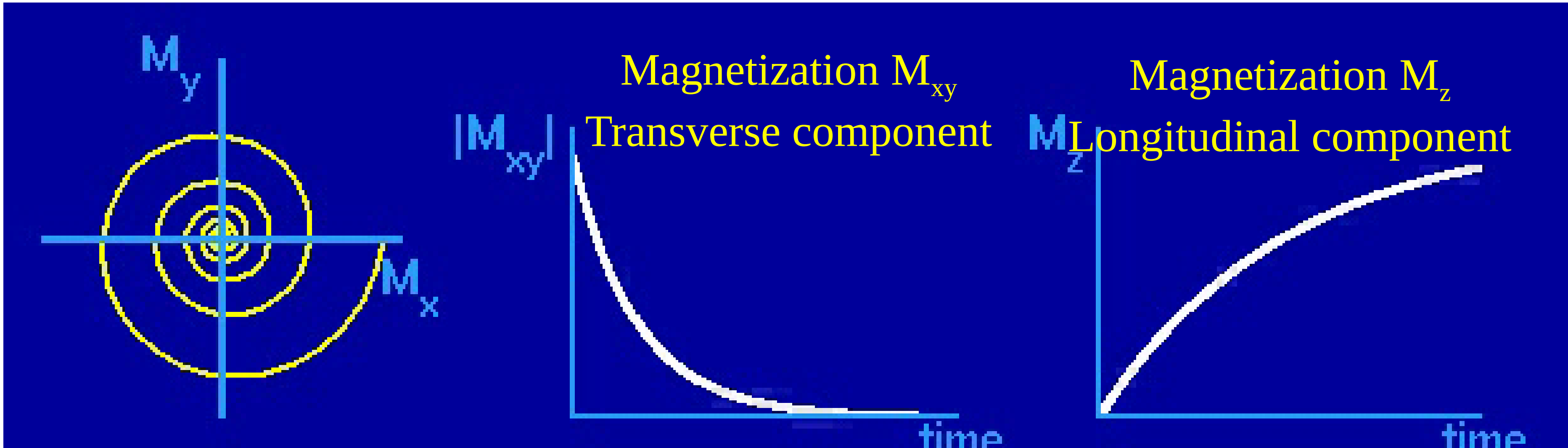
M_z = M_0 cos(α), longitudinal magnetization

M_{xy} = M_0 sin(α), transverse magnetization

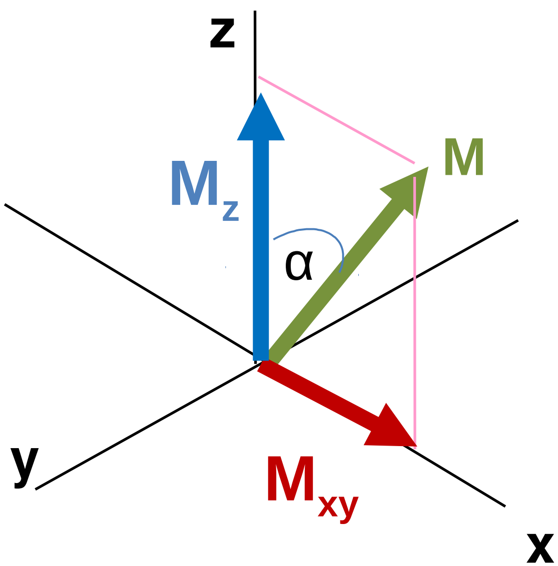
Quick review

- **NMR Signal**
  - Equilibrium magnetization (**Mo**)
  - Excitation of **Mo** away from equilibrium
  - Relaxation of **Mo** to equilibrium

Transverse and longitudinal magnetization relaxation to equilibrium



Source: Brian Hargreaves (mrsrl.stanford.edu/~brian/mri-movies/)



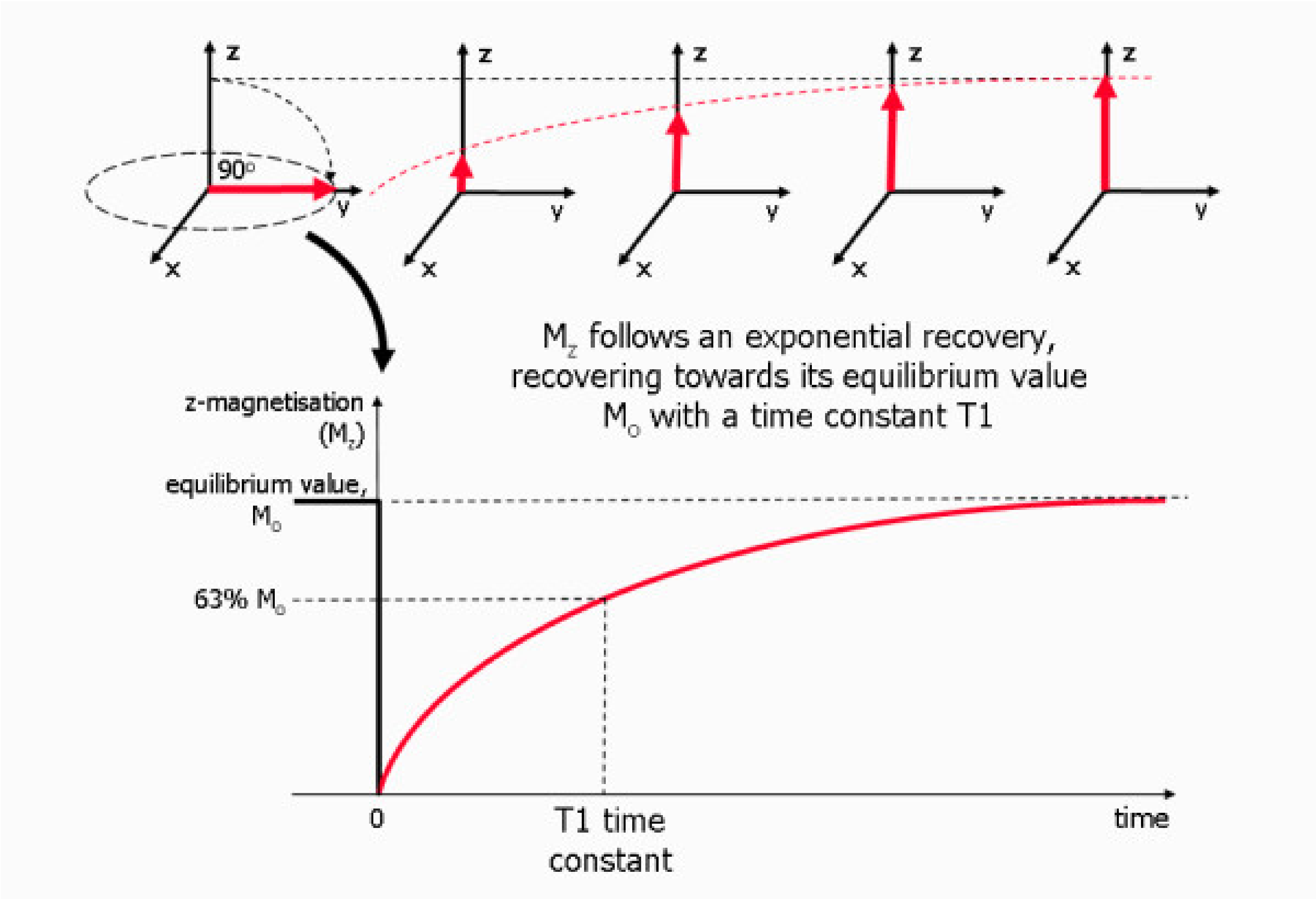
- **Decay of M_{xy} to equilibrium**
- **Exponential**
- **T_2: Charateristic decay time**

$$\boxed{M_{xy}(t) = M_{xy}(t=0)\,e^{-t/T_2}}$$

- **Recovery of M_z to equilibrium**
- **Exponential**
- **T_1: Charateristic recovery time**

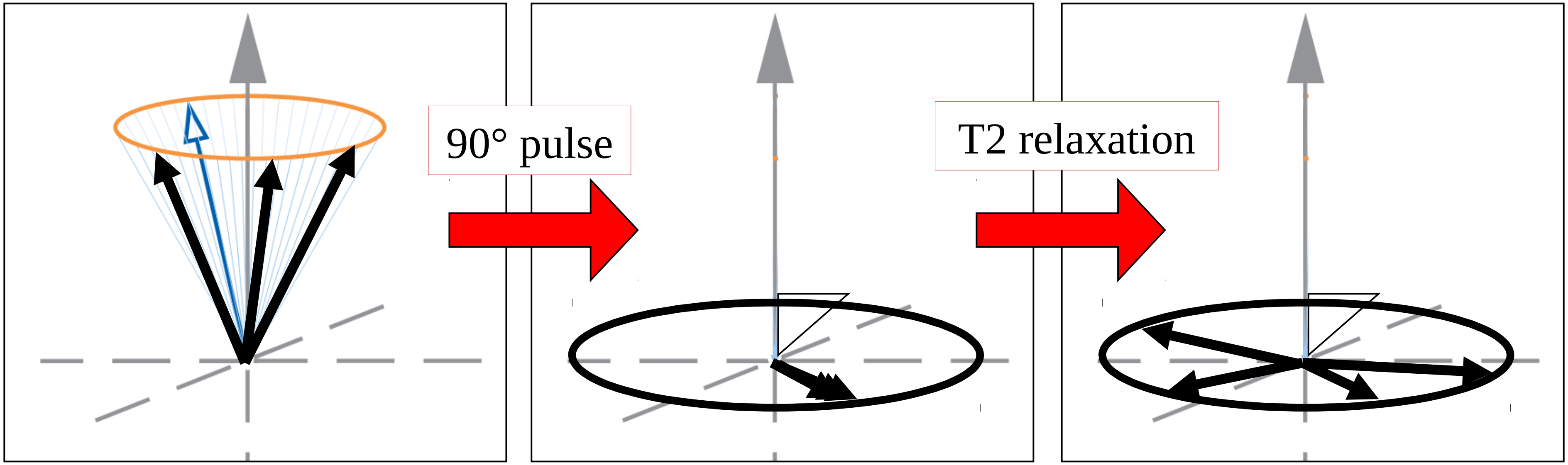
$$\boxed{M_z(t) = M_0\left(1 - e^{-\frac{t}{T_1}}\right)}$$

What is the T1 relaxation?



What is the T2 relaxation?

- After the RF, each proton spin has a slightly different $\omega_0=\gamma B_0$
- Some go slower, some faster $\Rightarrow$ they come out of phase
- Net transverse magnetization M_{xy} decays to zero (equilibrium)

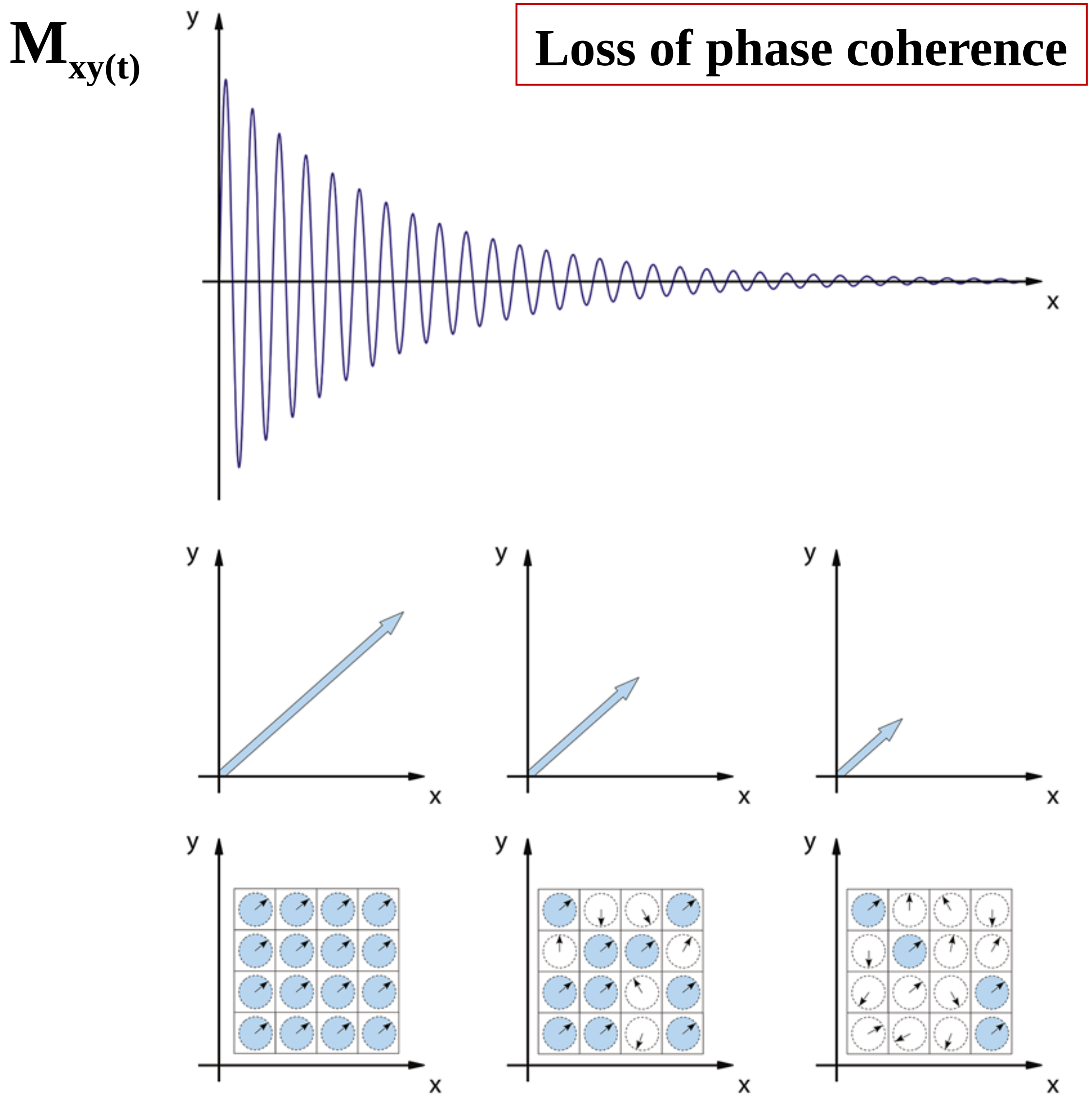


Equilibrium

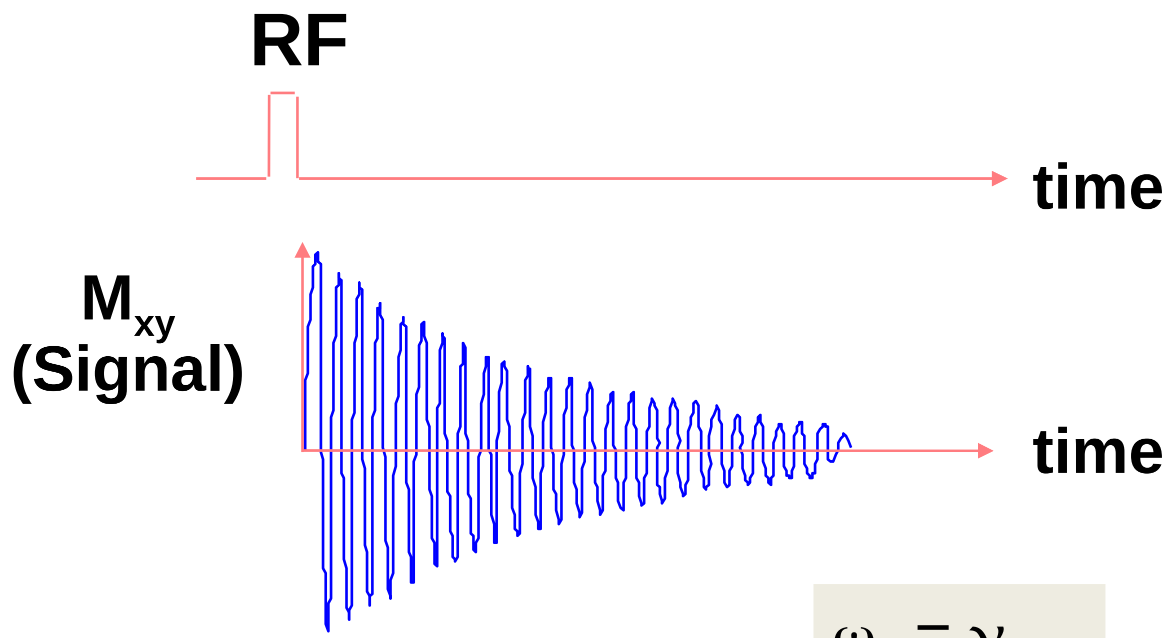
Immediately after RF pulse

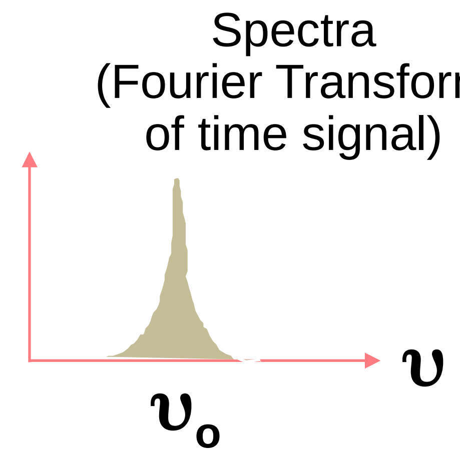
After RF pulse

What is happening during T2 relaxation?

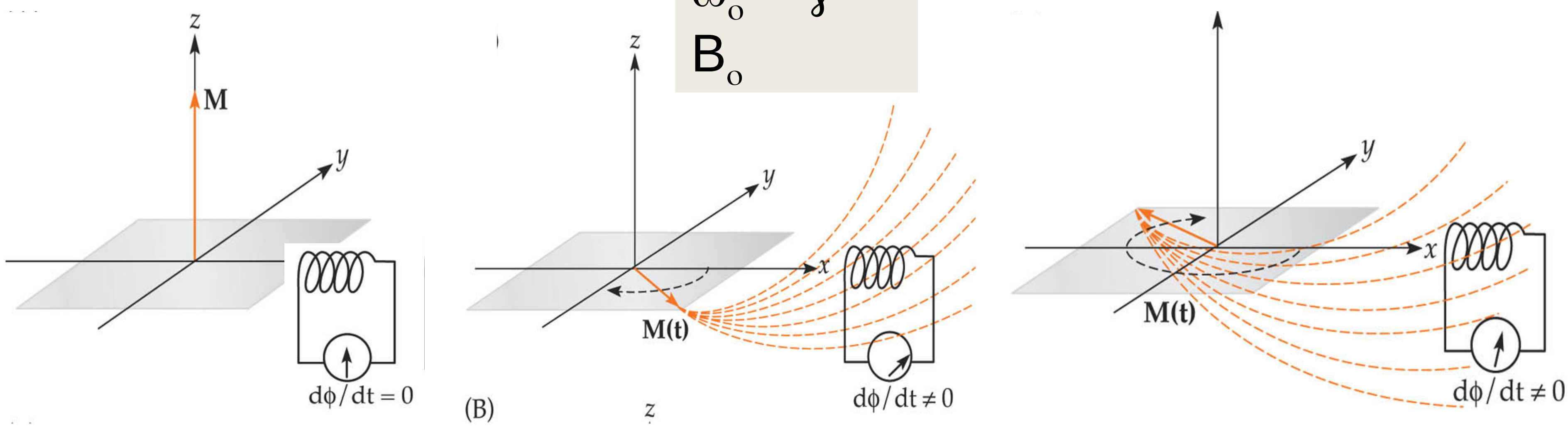


Where is the NMR signal coming from?



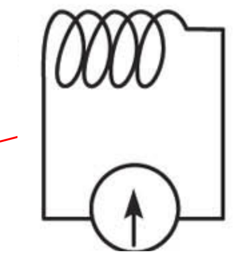


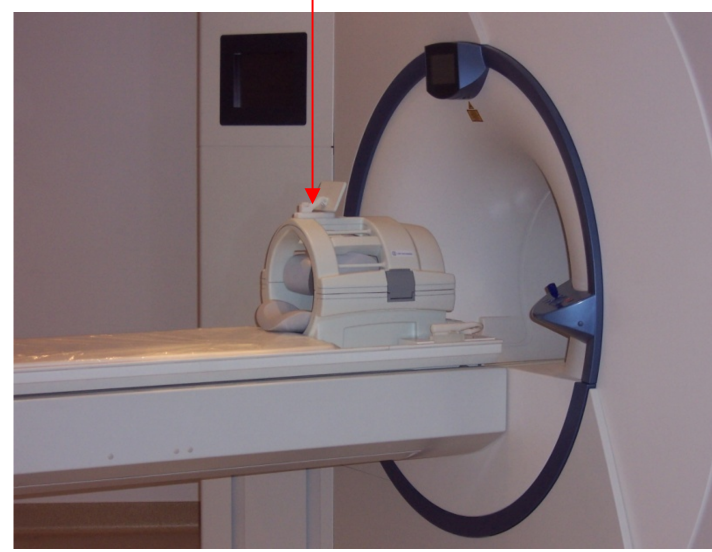
$\omega_o = \gamma$ B_o



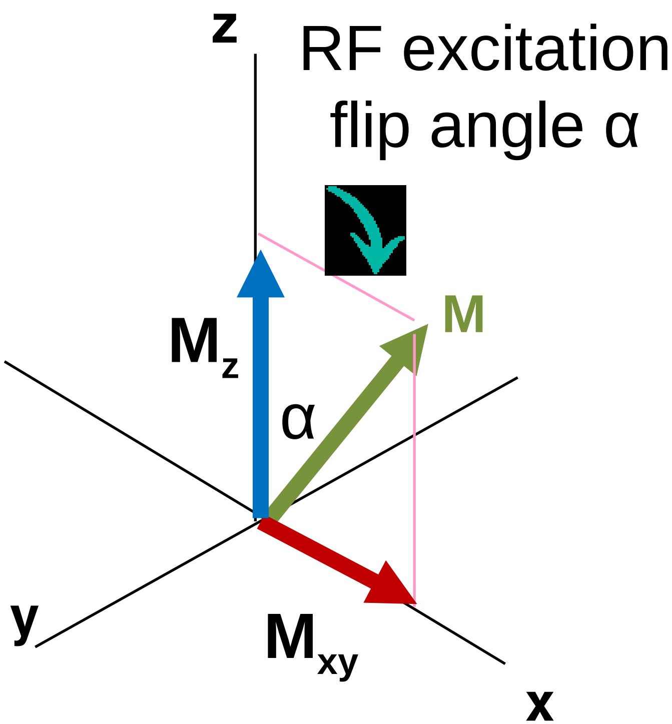
The radiofrequency (RF) coil

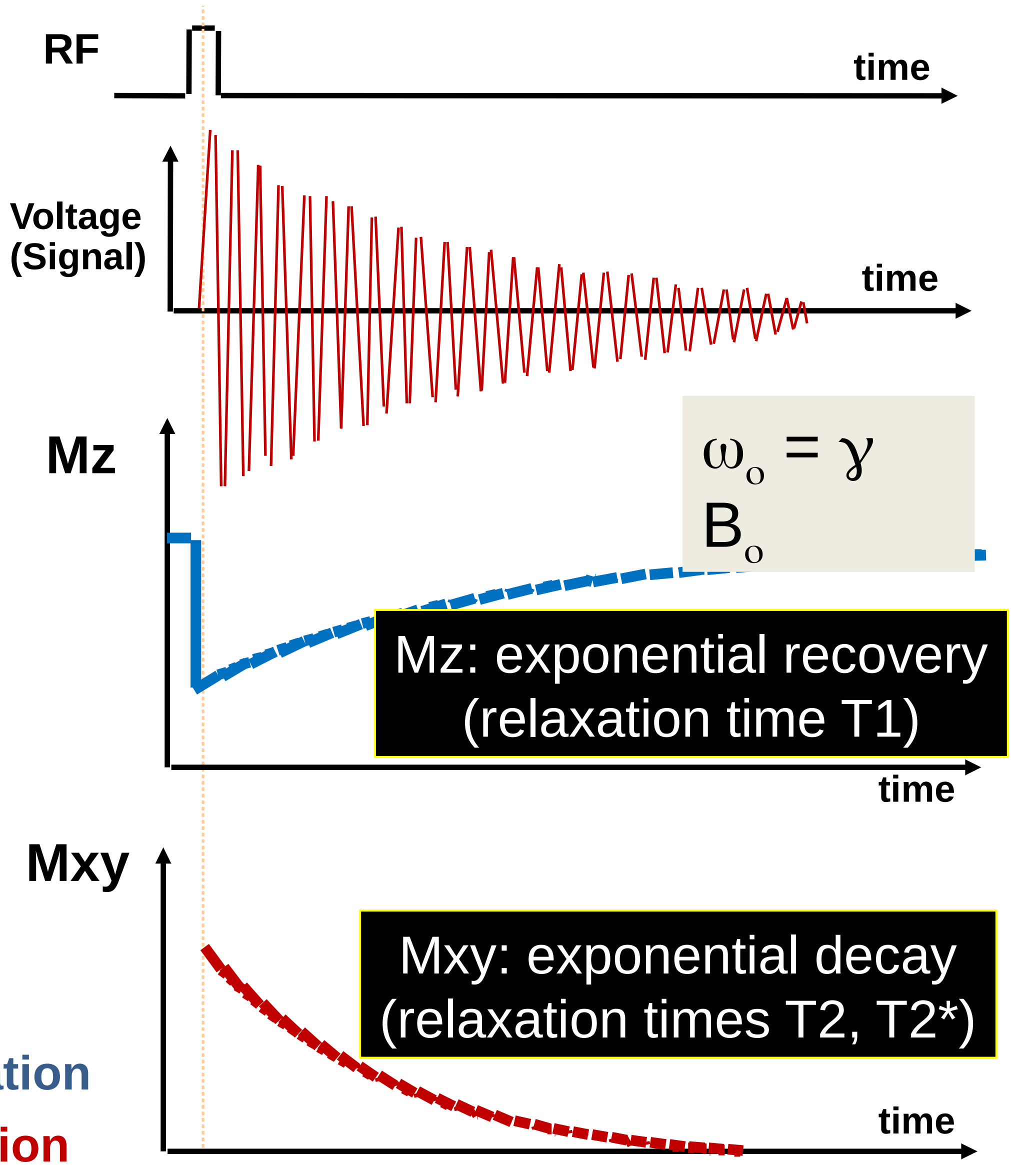
- Transmits RF excitation pulse
- Receives RF induction signal





Relaxation of magnetization to equilibrium





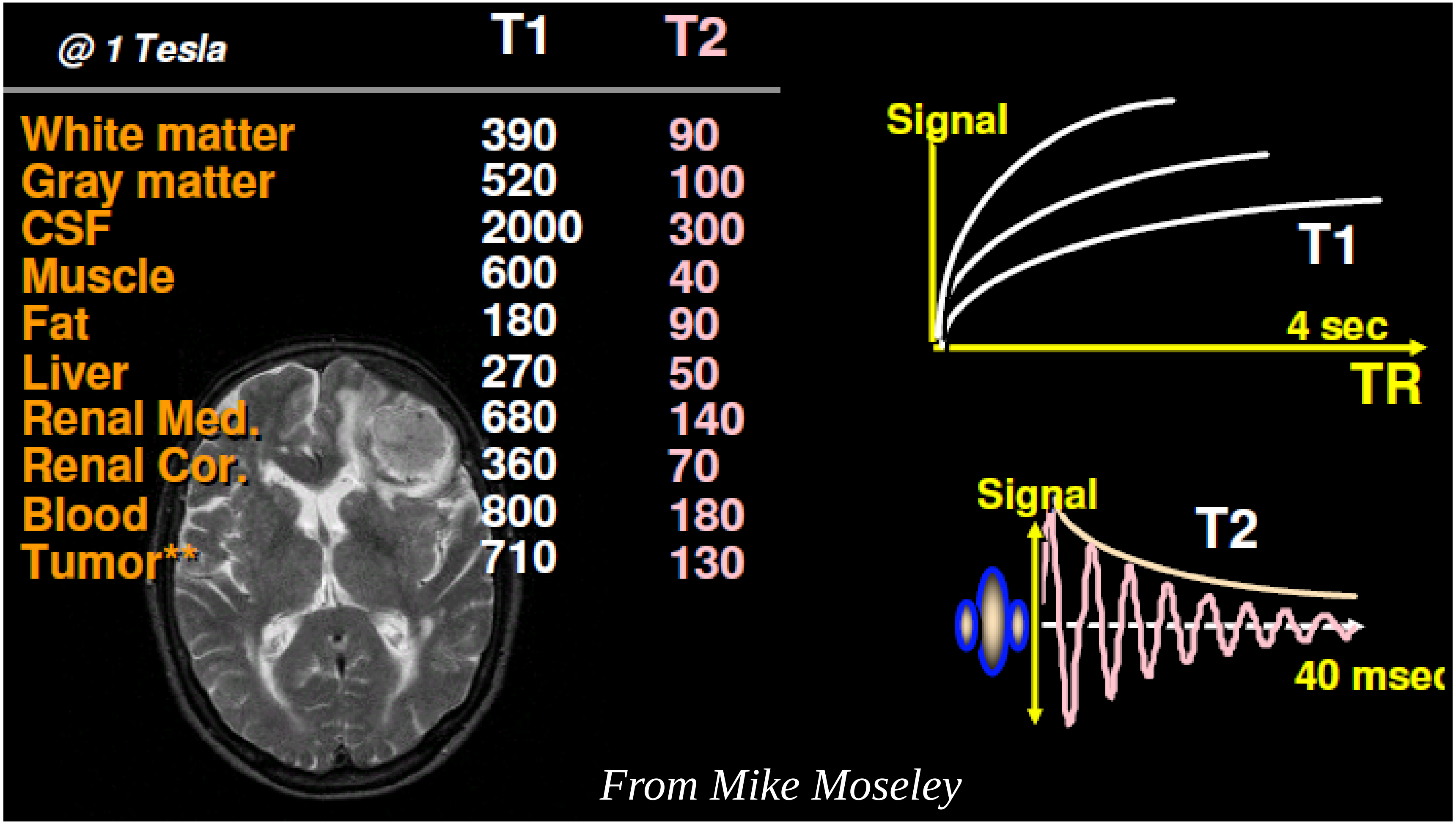
M: magnetization rotated by RF pulse

M_z = M cos(α), longitudinal magnetization

M_{xy} = M sin(α), transverse magnetization

Why are relaxation times so important?

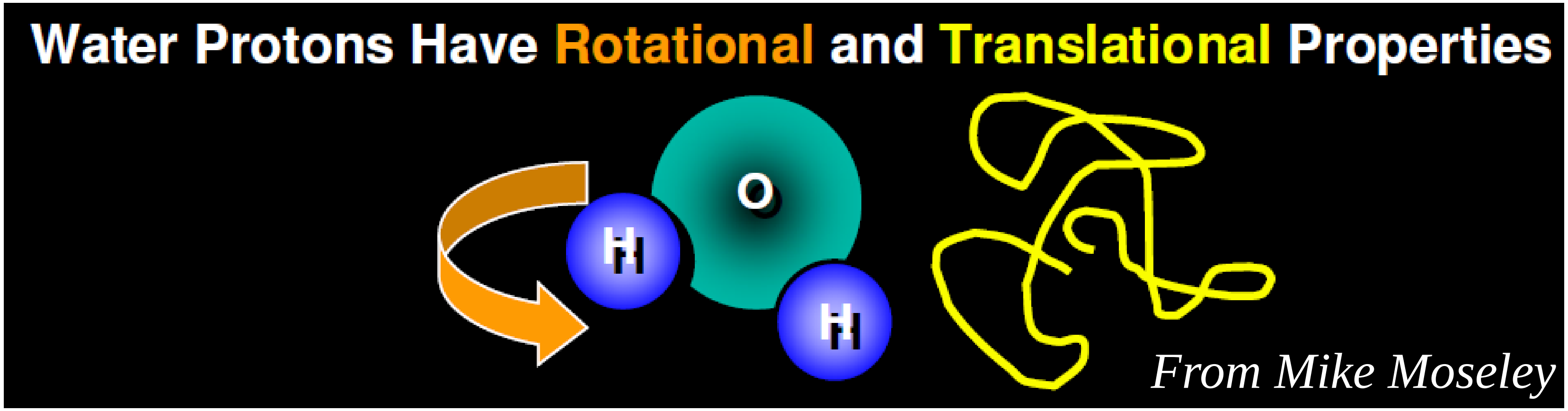
T1 and T2 reflect the local tissue environment



@ 1 Tesla	T1	T2
White matter	390	90
Gray matter	520	100
CSF	2000	300
Muscle	600	40
Fat	180	90
Liver	270	50
Renal Med.	680	140
Renal Cor.	360	70
Blood	800	180
Tumor**	710	130

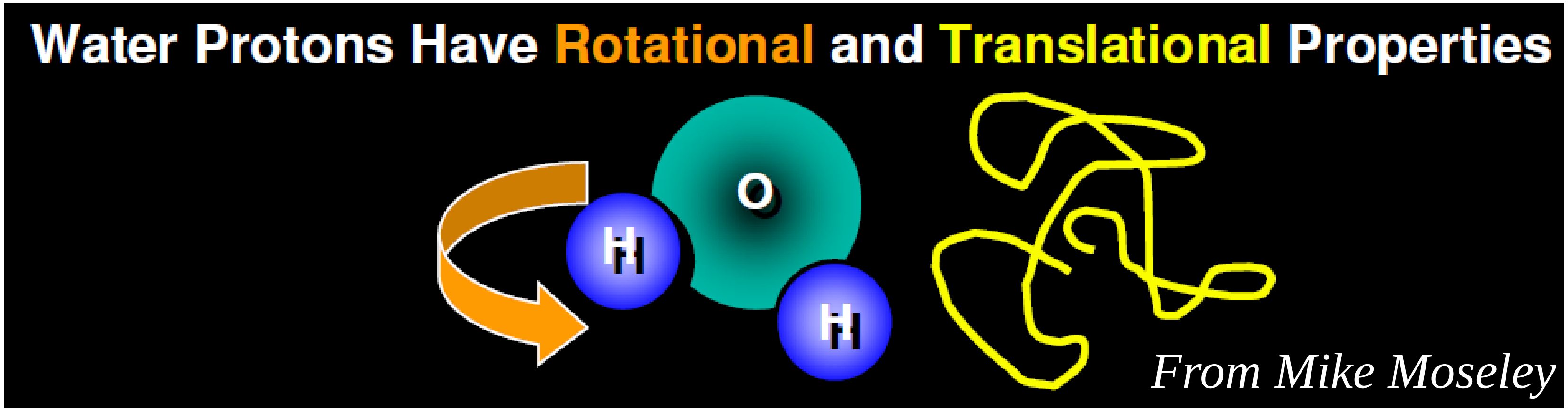
From Mike Moseley

What do relaxation times actually mean?



- **T1 relaxation**
  - Related to water **rotational times**
  - Free protons (cerebral spinal fluid) -> long T1 relaxation
  - Bound protons (myelin water) -> short T1 relaxation

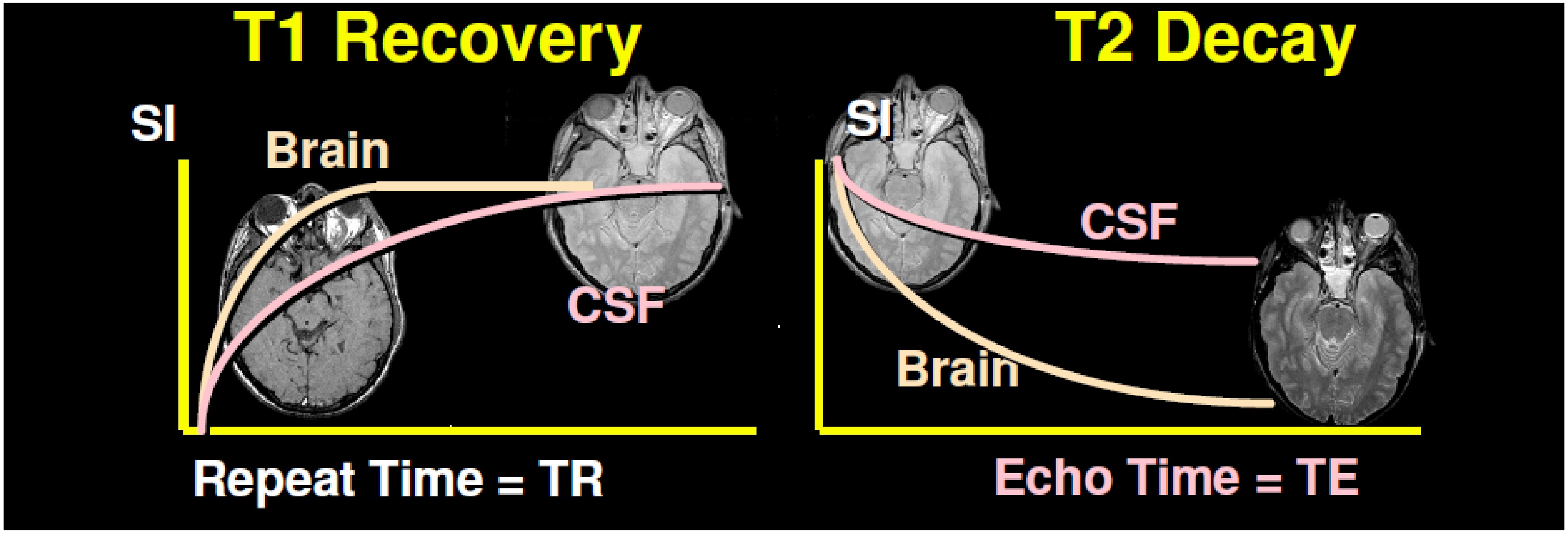
What do relaxation times actually mean?



- **T1 relaxation**
  - Related to water **rotational times**
  - Free protons (cerebral spinal fluid) -> long T1 relaxation
  - Bound protons (myelin water) -> short T1 relaxation

- **T2 relaxation**
  - Related to water **translational (diffusion) times**
  - Free protons (cerebral spinal fluid) -> long T2 relaxation
  - Bound protons (myelin water) -> short T2 relaxation

What do relaxation times actually mean?



Brain tissue
- Bound protons
- Short T1 relaxation
- Short T2 relaxation

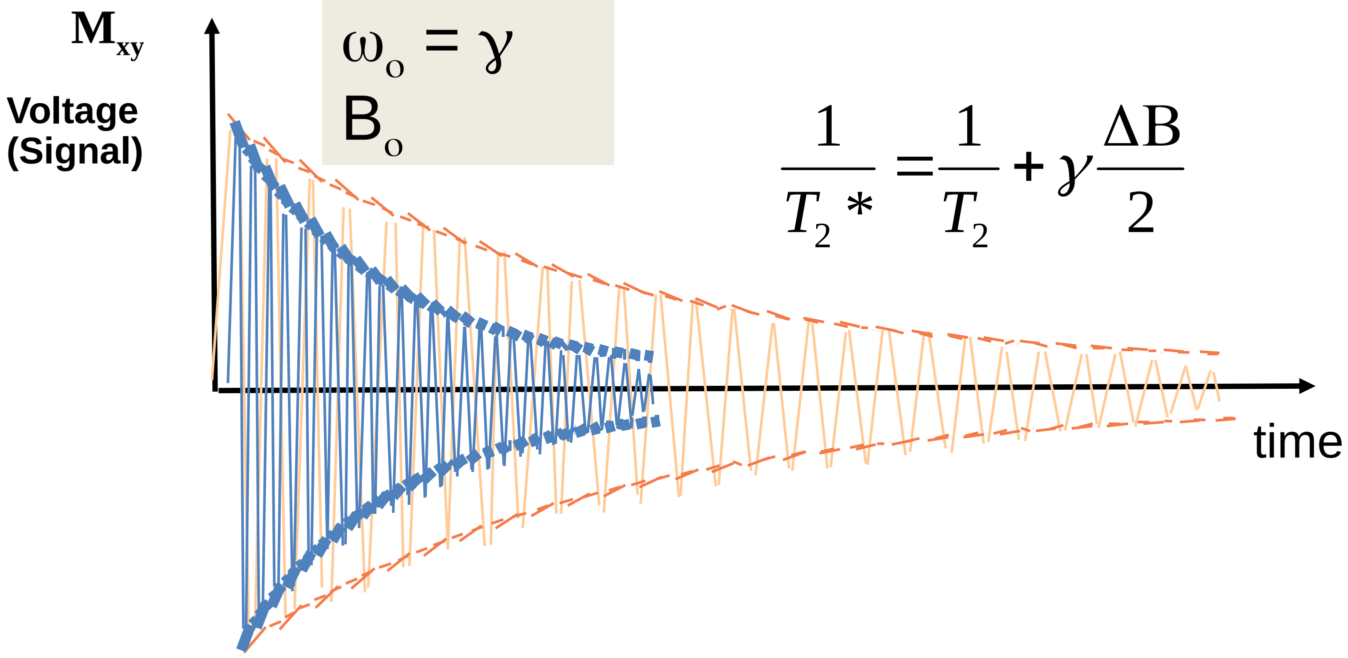
Cerebral Spinal Fluid (CSF)
- Free protons
- Long T1 relaxation
- Long T2 relaxation

An imperfect world: T_2^* decay

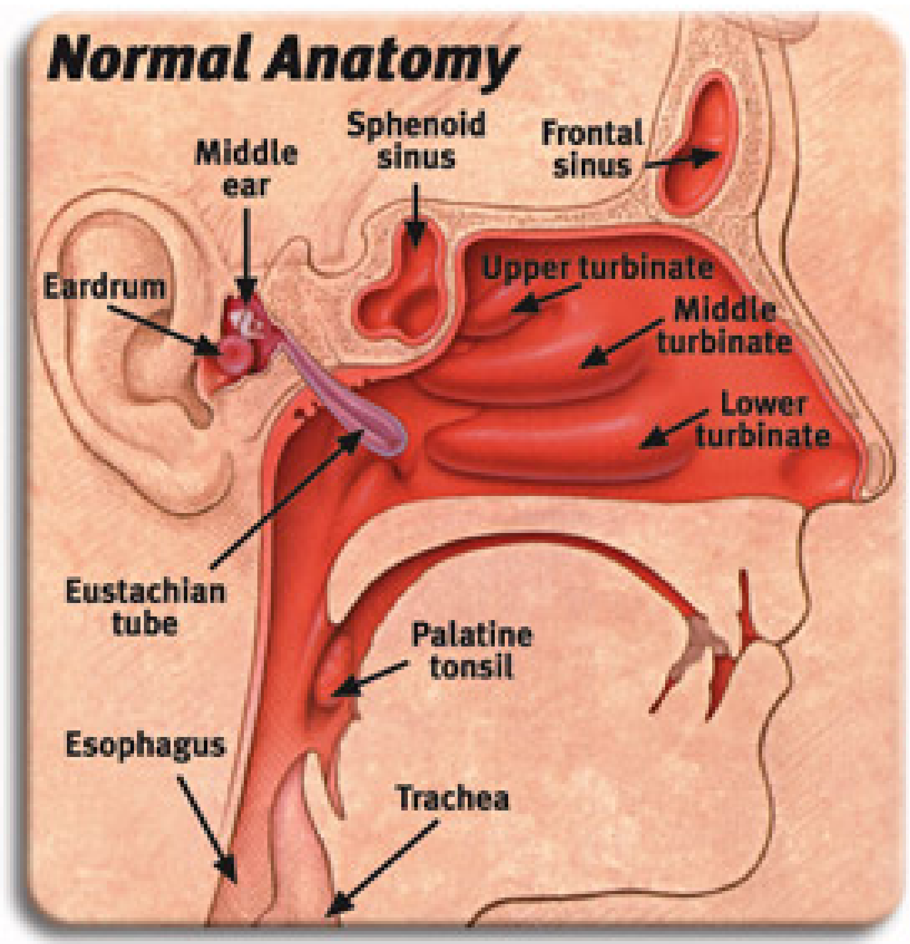
- Real signal decays faster than T_2 predictions
- Pure T_2: random spin-spin interactions with perfect homogeneous external B0
- In reality: Field is inhomogeneous ($B_{real} = B_0 + \Delta B$)
- Signal decay due to random and fixed dephasing effects: T_2^*

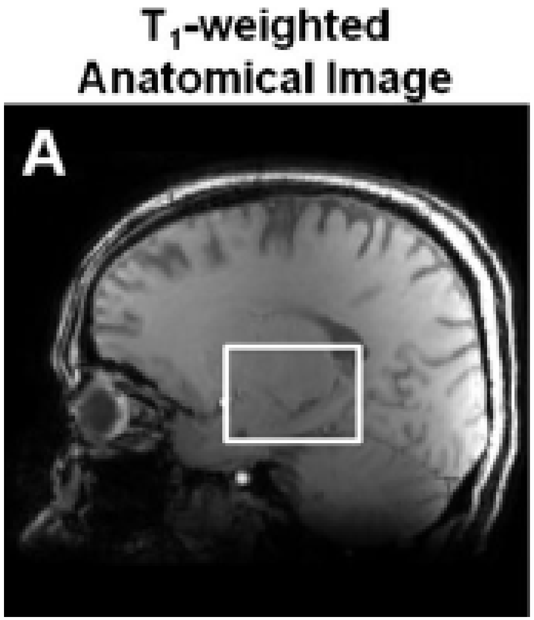
$\omega_o = \gamma B_o$

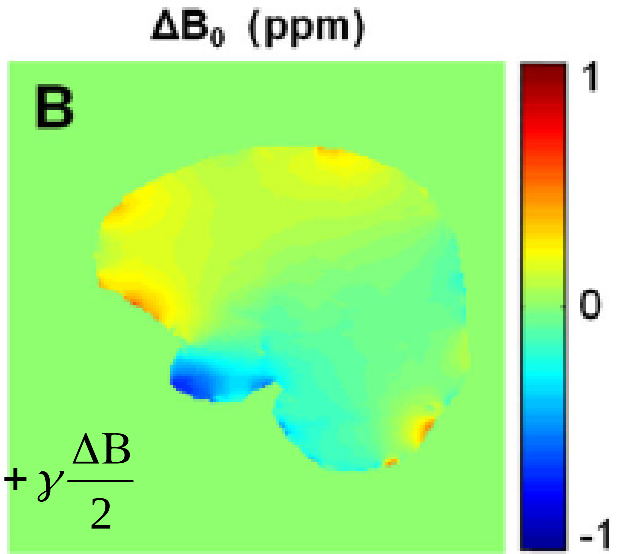
$$\frac{1}{T_2^*} = \frac{1}{T_2} + \gamma\frac{\Delta B}{2}$$



Where in the head is T2* short?





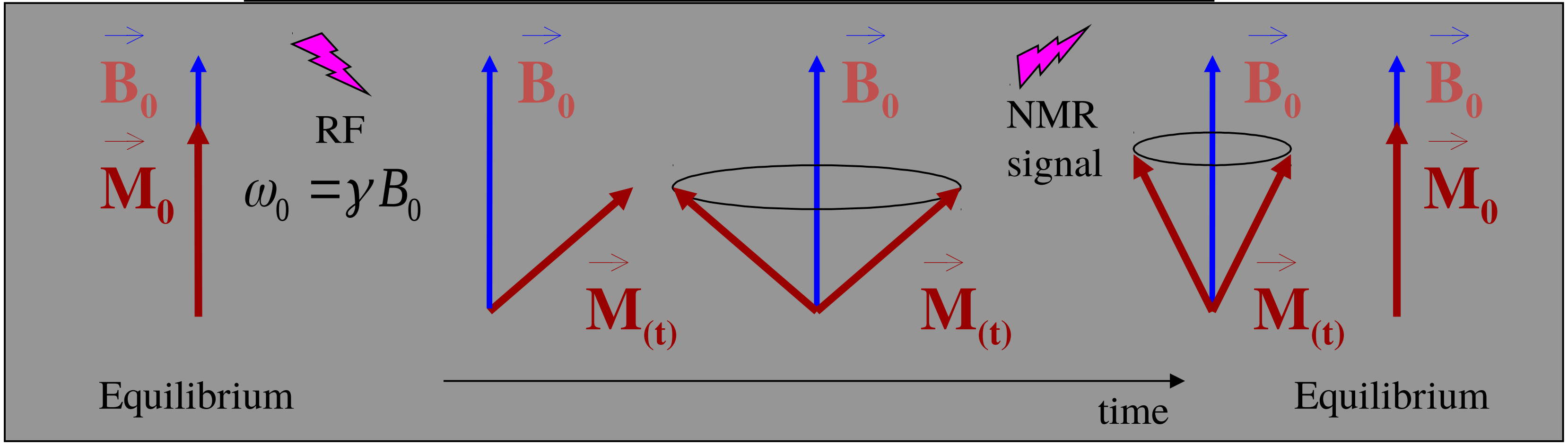


The brain that is close to the frontal sinues will be challenging for fMRI

$$\frac{1}{T_2*} = \frac{1}{T_2} + \gamma\frac{\Delta B}{2}$$

Magnetization dynamics

- Geometrical description: damped precession



- Mathematical Description: precession + relaxation (Bloch equations)

$$\frac{d\vec{M}_{(t)}}{dt} = \vec{M}_{(t)} \times \gamma \vec{B}_{ext(t)} - \frac{(M_x \hat{i} + M_y \hat{j})}{T_2^*} - \frac{(M_z - M_0)}{T_1} \hat{k}$$

Quick review

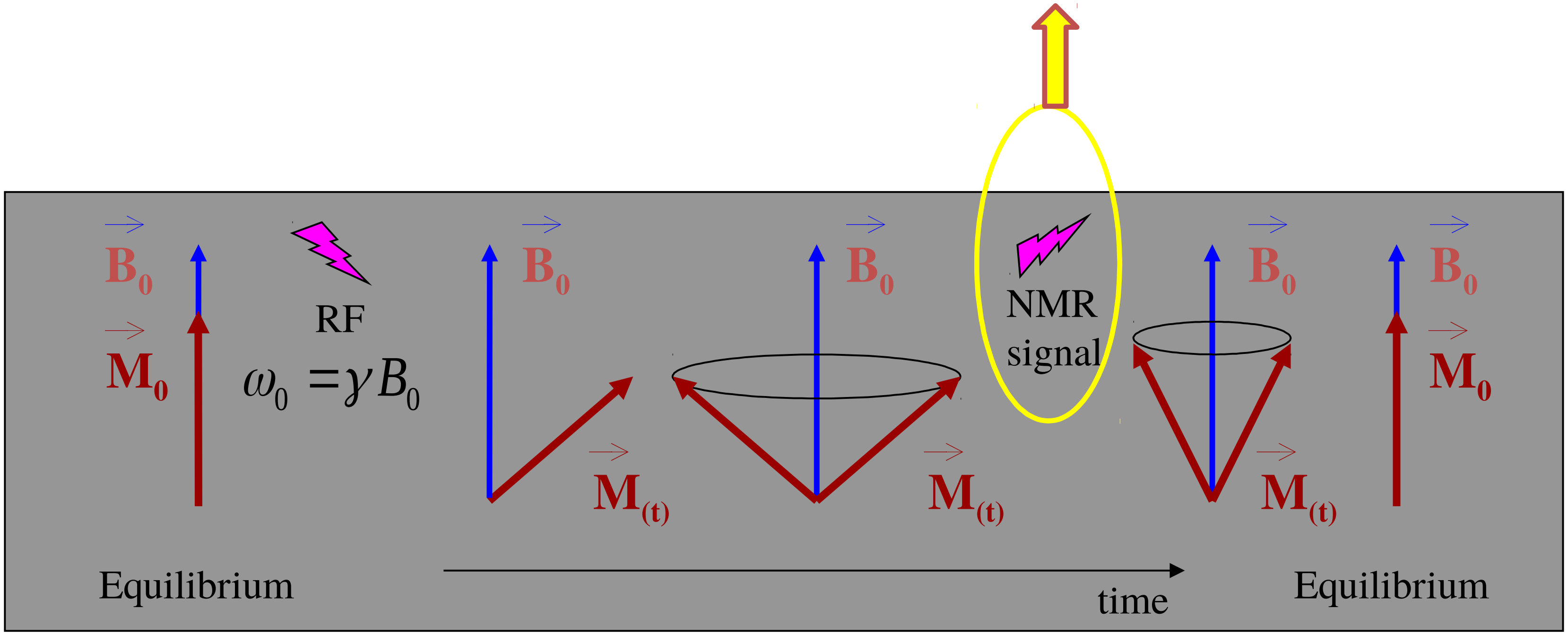
- **NMR Signal**
  - Equilibrium magnetization (**Mo**)
  - Excitation of **Mo** away from equilibrium
  - Relaxation of **Mo** to equilibrium

Summary of concepts introduced

- **What is the source of the NMR signal?**
  - The equilibrium magnetization when sample is at B_0
  - The magnetization comes from protons, mostly in H_2O
  - Precession frequency at equilibrium: $\omega_0 = \gamma B_0$
- **What do we need to measure an NMR signal?**
  - Excitation pulse (B_1), must be on resonance ($\perp$ to B_0)
  - Magnetization rotated away from equilibrium (flip angle)
- **What are T1, T2 and T2* relaxation?**
  - T1: Longitudinal magnetization recovery to equilibrium
  - T2: Transverse magnetization recovery to equilibrium (zero) considering only proton-proton magnetic field interactions
  - T2*: like T2, but adding contributions from static magnetic field inhomogeneities
  - T1, T2 and T2* depend on local tissue environments

So far no image...

- **From the whole sample**
- **No spatial selectivity**

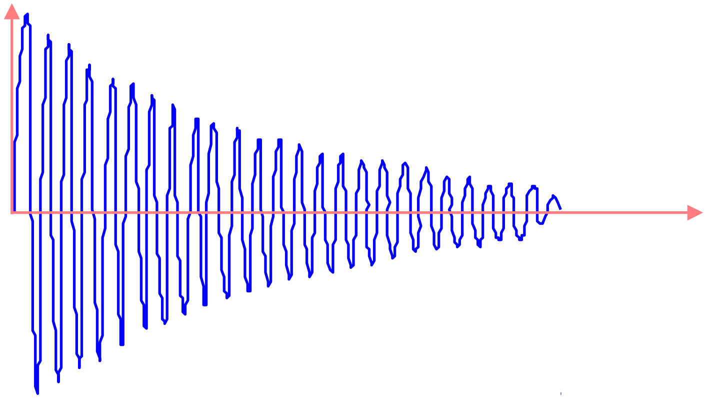


Spatial encoding concepts

After the RF excitation, in a uniform static magnetic field B_0, the NMR signal:

- <u>Comes from the whole sample: no spatial information</u>
- It decays exponentially with T2*
- It oscillates at ω_o

$$\omega_0 = \gamma B_0$$



If I could vary net magnetic field in <u>space</u> ($B=B_0$ + something)

- Then the measured frequency will change following the same law
- Then frequency and space will be related
- Then measuring frequencies tells us where the signal comes from
- We are encoding spatial information in the signal

Spatial encoding with a magnetic field gradient

WHY?? To modulate the resonance frequency as function of space
WHY?? To measure frequencies and know where they come from

$$\omega_{(x)} = \omega_0 + \gamma G_x \, x$$

linear magnetic field gradient

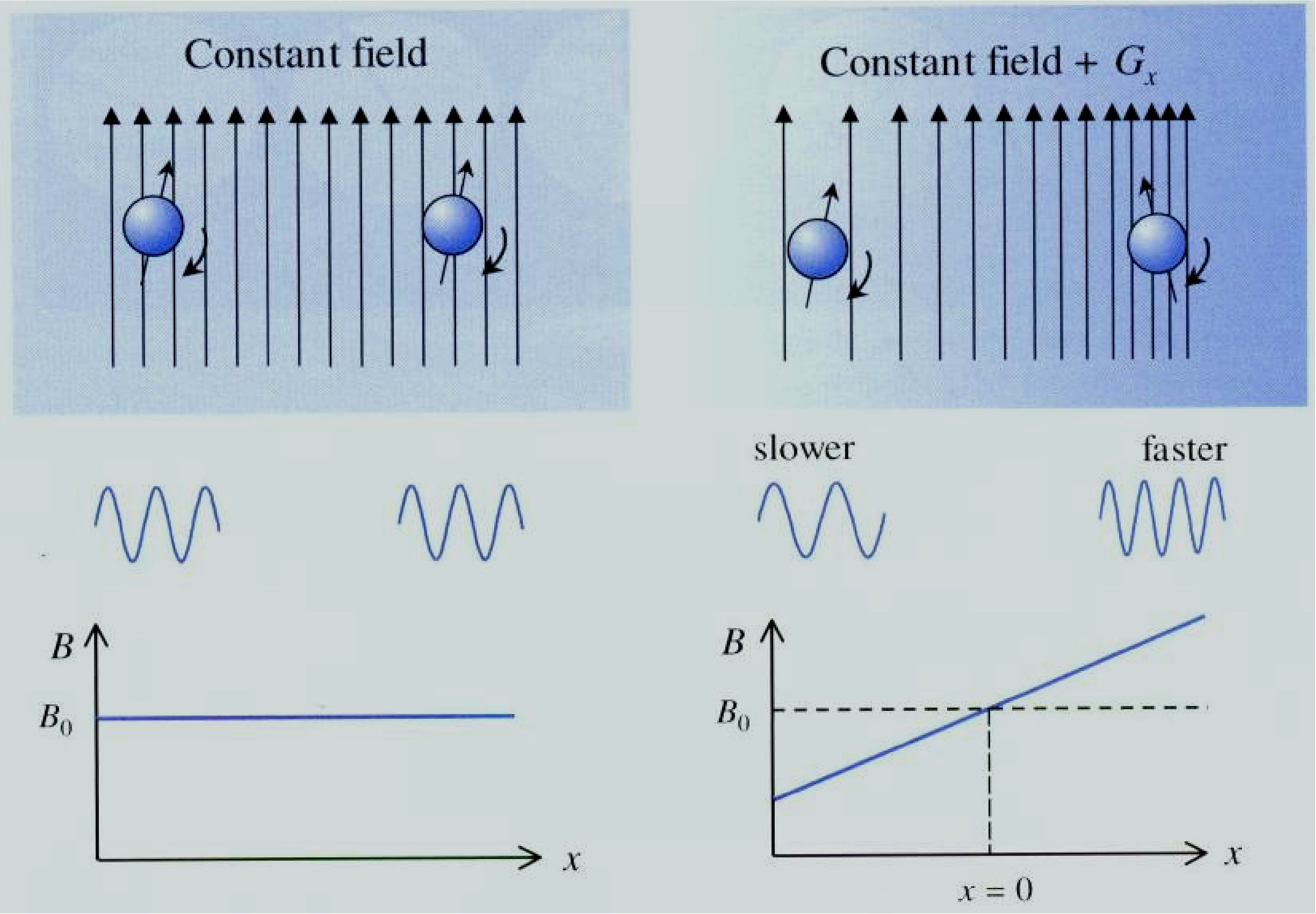
I know these

Then:

If I can measure this

I can calculate this

Effect of a magnet gradient

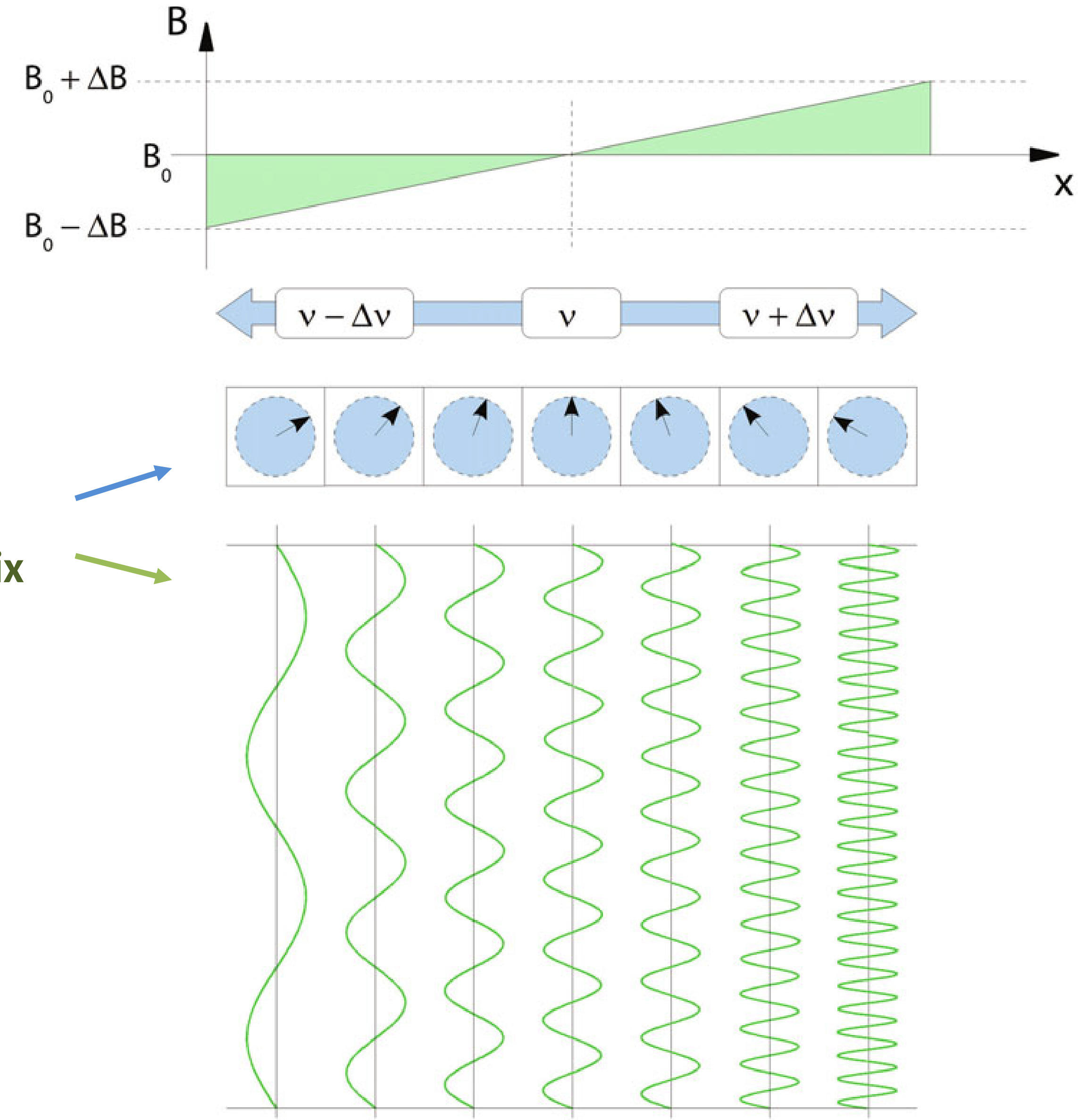


Magnetic gradients: phase and frequency

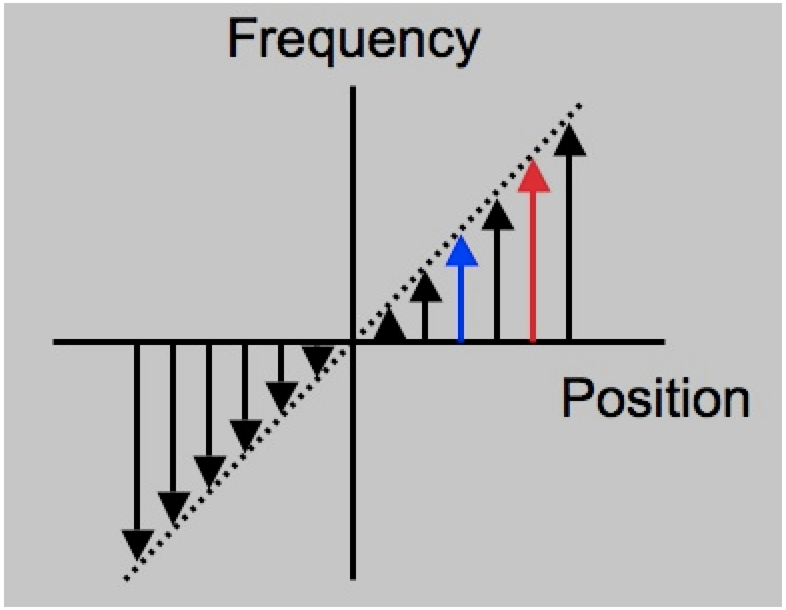
- Gradient along x-axis

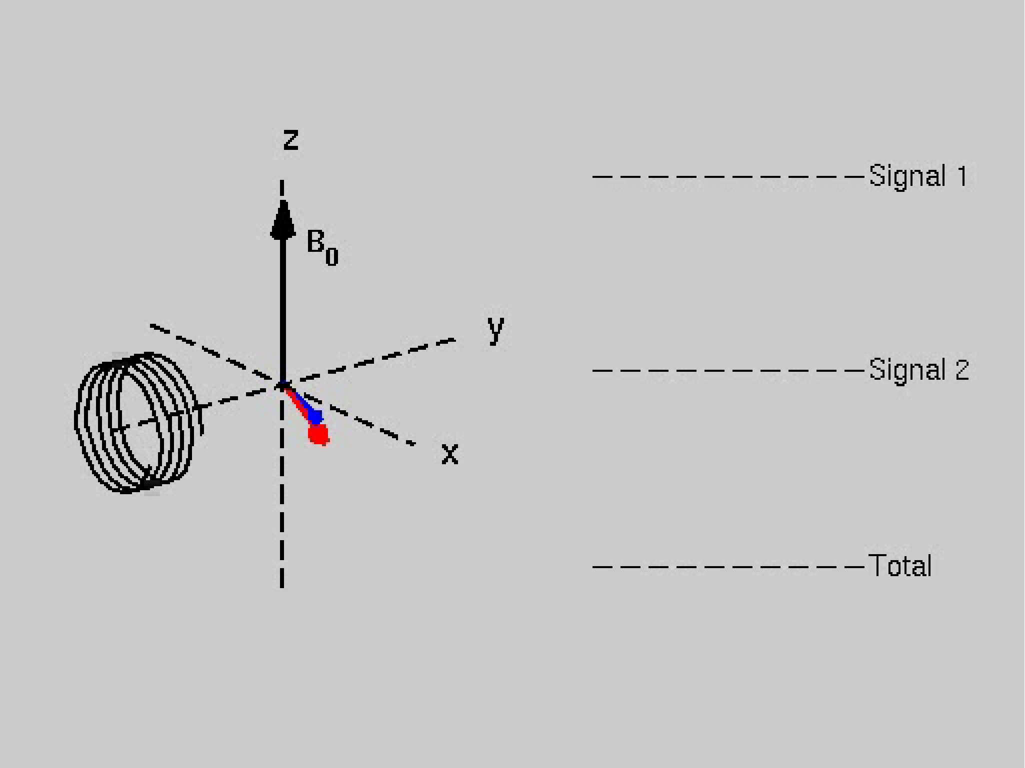
- Two spatial-encoding possibilities for the magnetization:

  - Phase changes along x-axis
  - Frequency changes along x-axix



Effect of a magnet gradient





- A linear gradient is turned on
- Let's look spins in the blue and red position

Source: http://mrsrl.stanford.edu/~brian/mri-movies

Spatial encoding concepts

- **Key points so far**:
  - Magnetic field gradients encode spatial information in the frequency of the NMR signal: $\omega_{(x)} = \omega_0 + \gamma G_x x$
  - <u>So</u>: the **spatial information** is in the **signal frequency**
  - <u>But</u>: the NMR signal measured is a signal that changes in time
  - <u>So</u>: To get spatial information we need to transform temporal information into frequency information

    We need a Fourier Transform ‘massage’

    to transform the measured signal (time)

    into an image (signal of frequency)

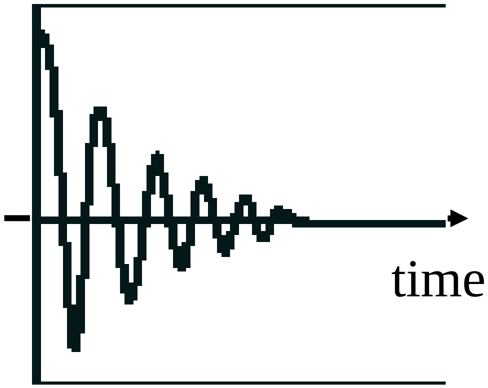
Decomposing complex signals in simple waves

https://www.youtube.com/watch?v=cZgl7rJKs3A

The Fourier transform

What is the Fourier Transform of a signal?

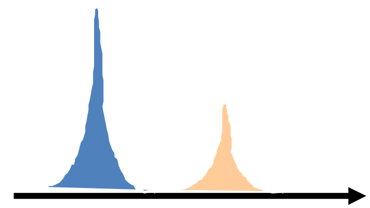
Signal Intensity as function of time



Fourier Transform

Equivalent descriptions!

Signal Intensity as function of frequency



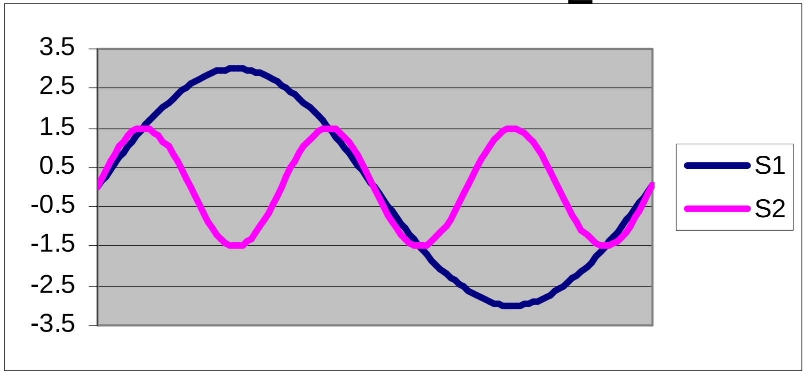
Joseph Fourier (1768-1830)

Signal as function of time $$s_{(t)} = \frac{1}{2\pi}\int_{\infty}^{+\infty} S_{(w)} e^{i\omega t} \mathrm{d}\omega$$

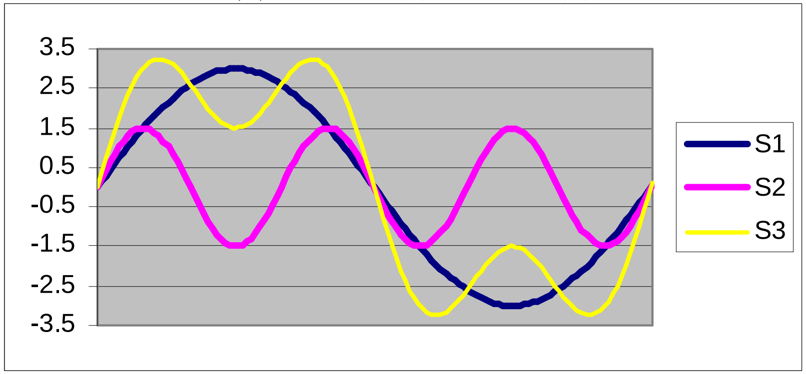
Signal as function of frequency $$S_{(\omega)} = \int_{\infty}^{+\infty} s_{(t)} e^{-i\omega t} \mathrm{d}t$$

Fourier transform concepts

$$s_{1(t)} = A\sin(w_0 t) \qquad s_{2(t)} = \frac{A}{2}\sin(3w_0 t)$$



$$s_{3(t)} = s_{1(t)} + s_{2(t)}$$



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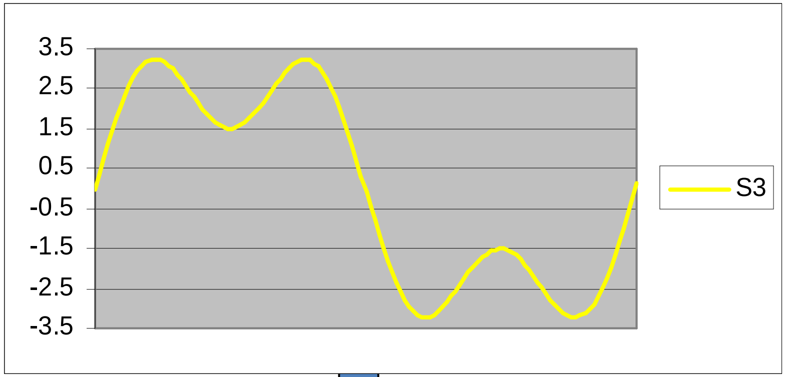
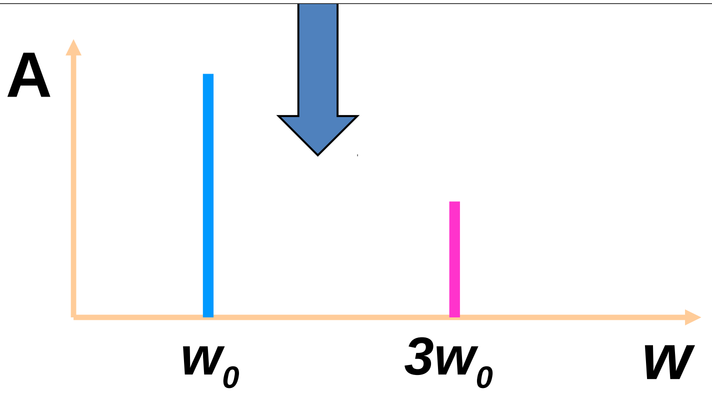
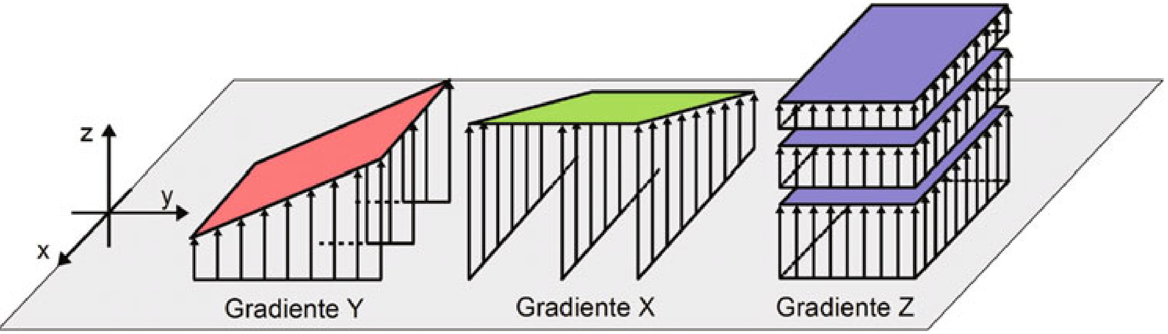




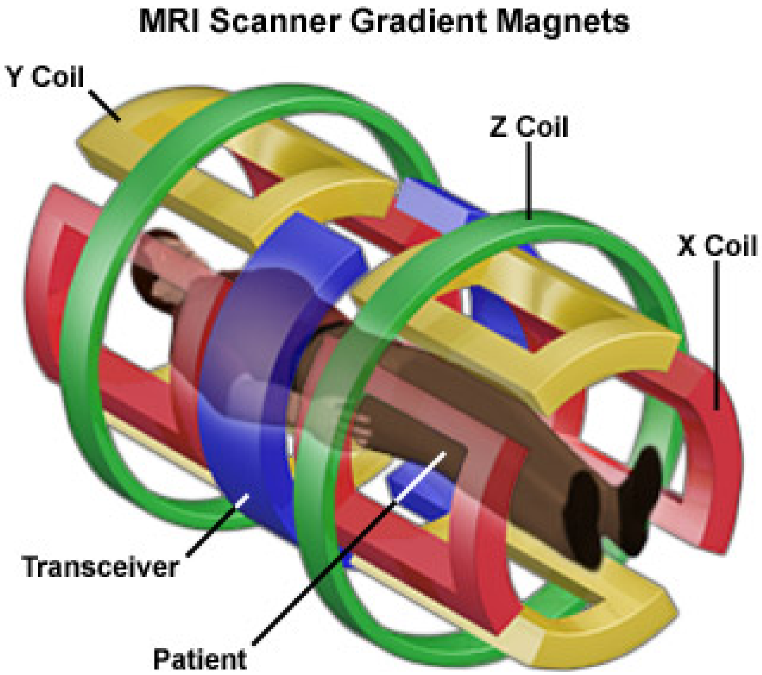
Fourier Transform: strength of signal at each frequency

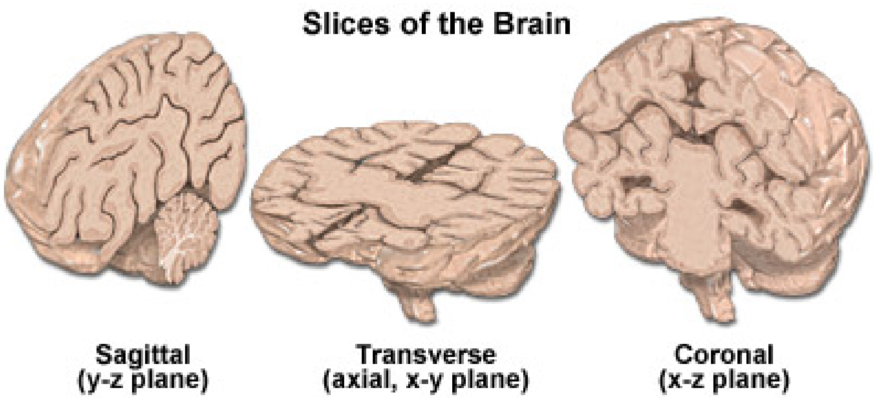
Magnetic field gradients in 3 dimensions



Need three orthogonal magnetic gradients

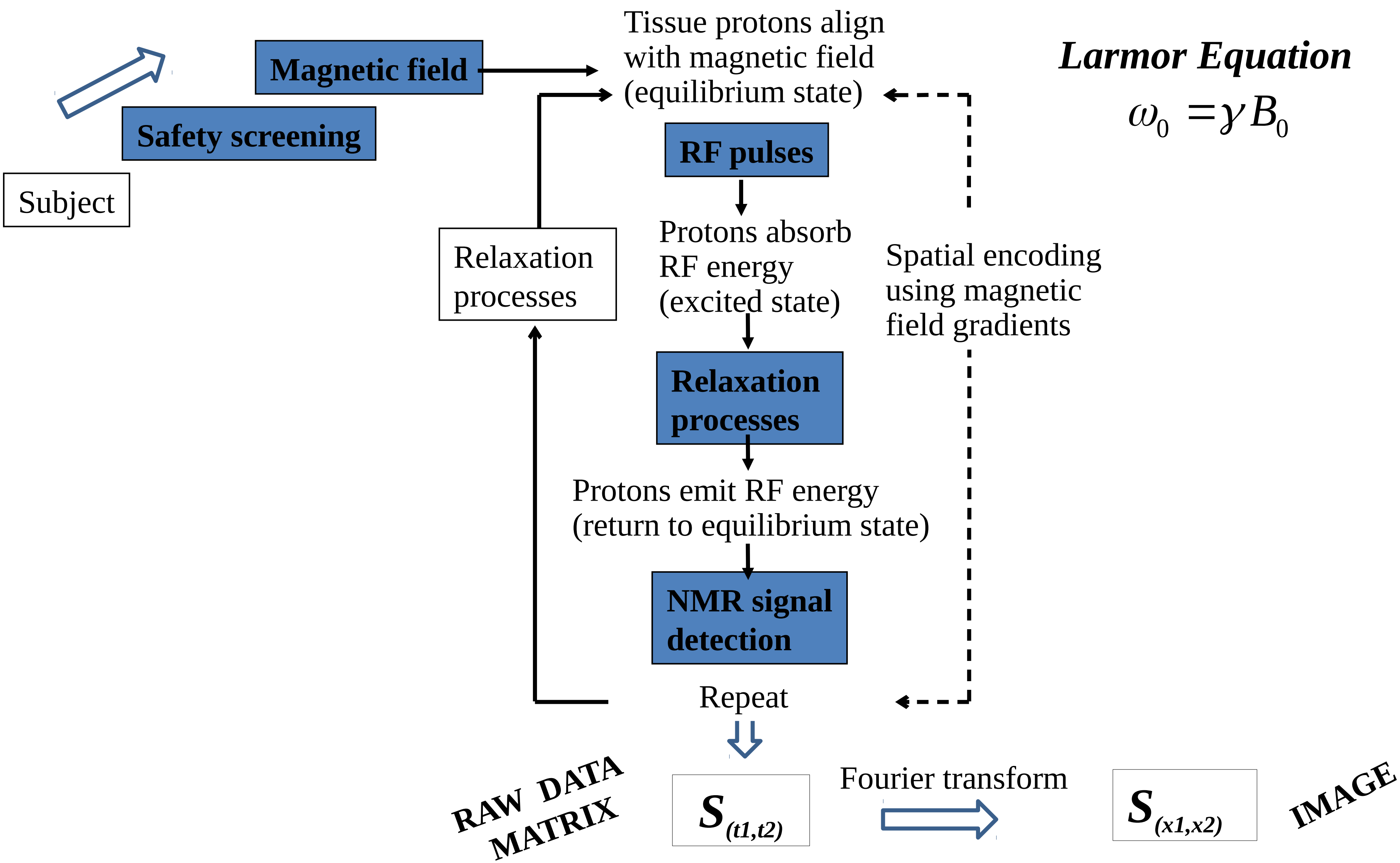
- *Slice selection*
- *Phase encoding*
- *Frequency encoding*





Images: http://www.magnet.fsu.edu/education/tutorials/magnetacademy/mri/page5.html

Overview of an MRI procedure

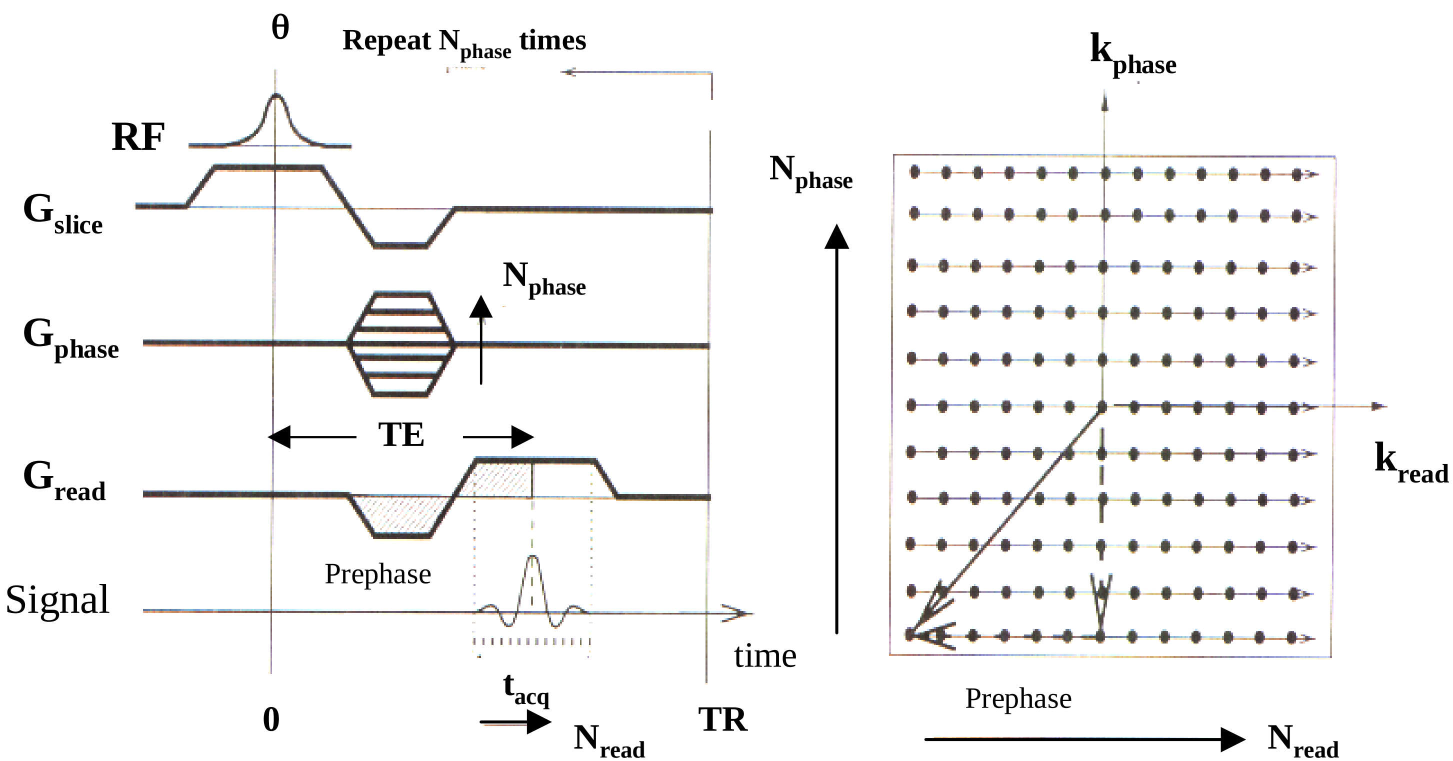


Larmor Equation

$$\omega_0 = \gamma B_0$$

What is an NMR or MRI pulse sequence?

A sequence of RF and gradient pulses which gives NMR signals

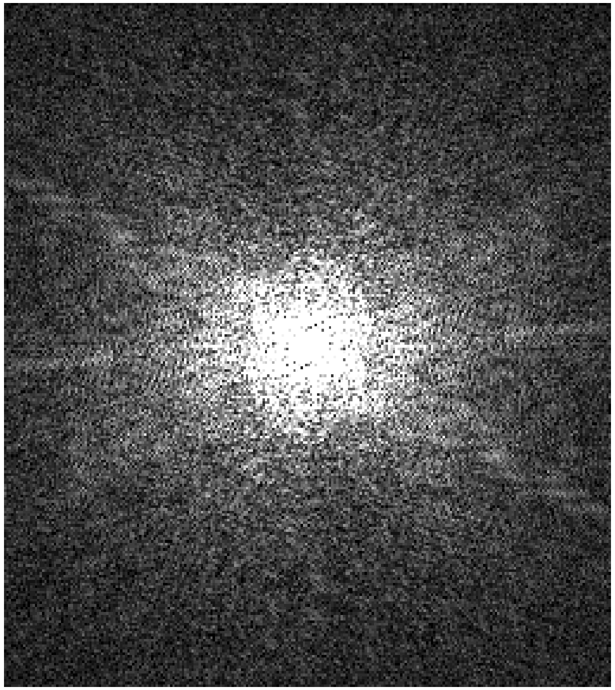


The signal we measure is in spatial frequency space (k-space)

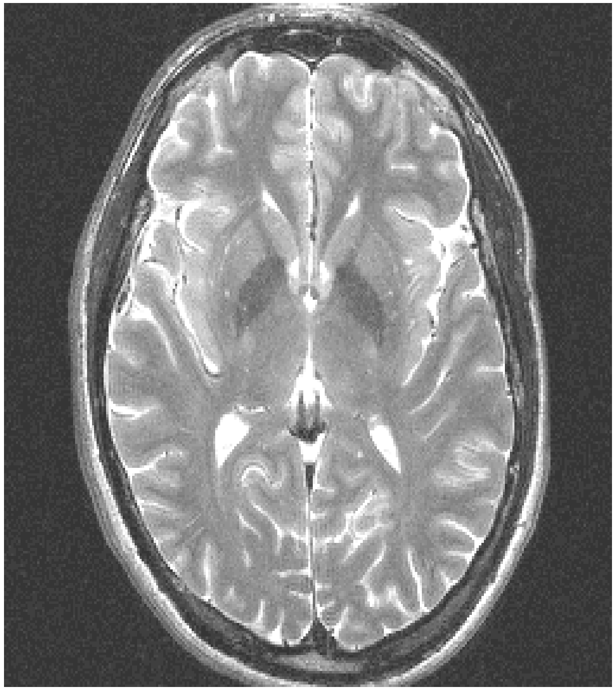
Why are we talking about this?

What we actually measure

What we want



Fourier Transform →

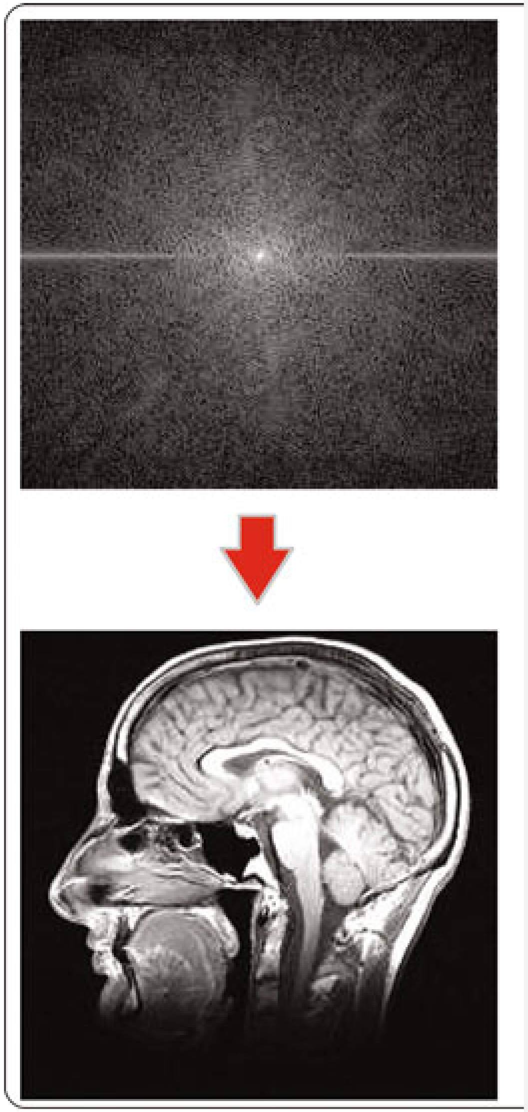


Data in: K-space
("signal space")

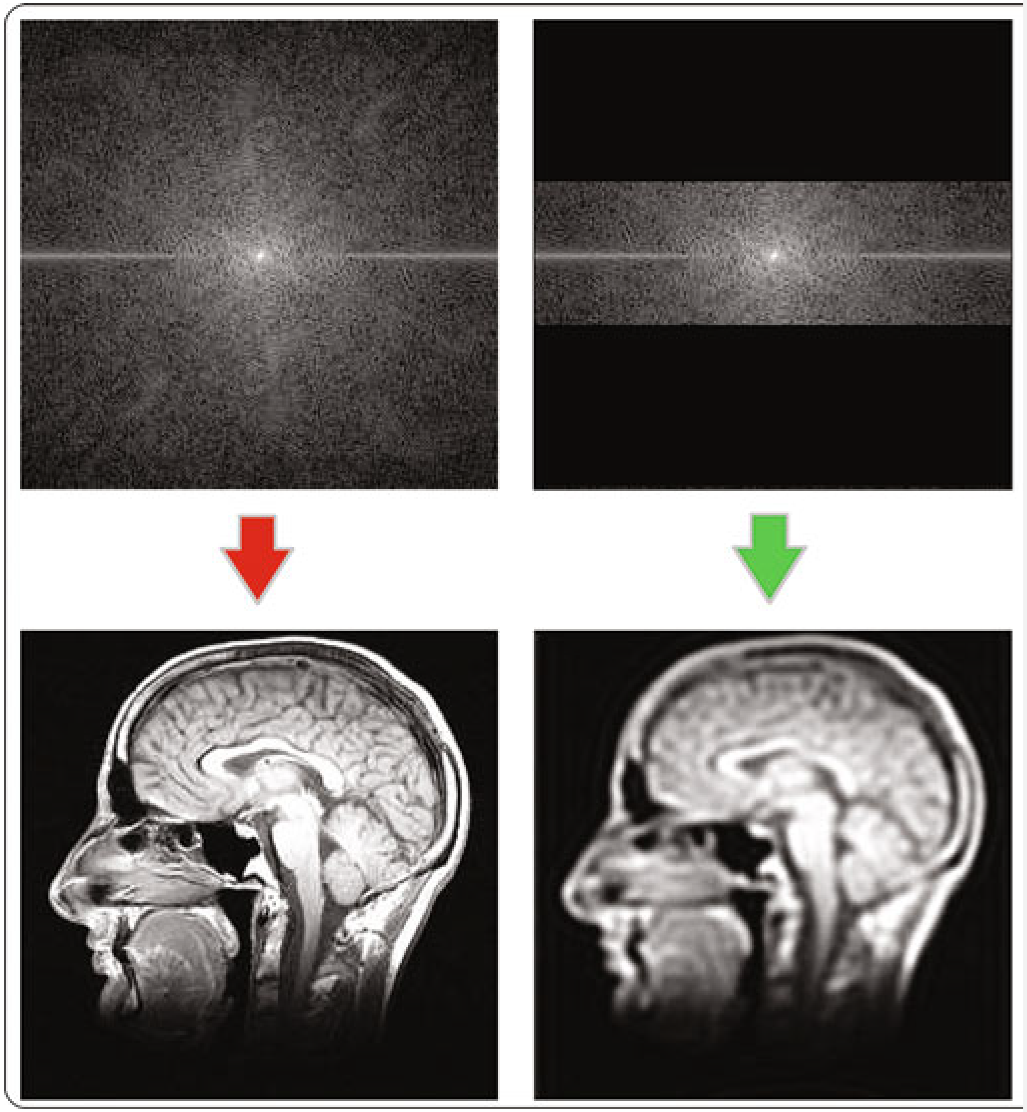
Same data in image space
(frequency of signals)

The <u>spatial information</u> is in the <u>frequency of the measured signal</u>

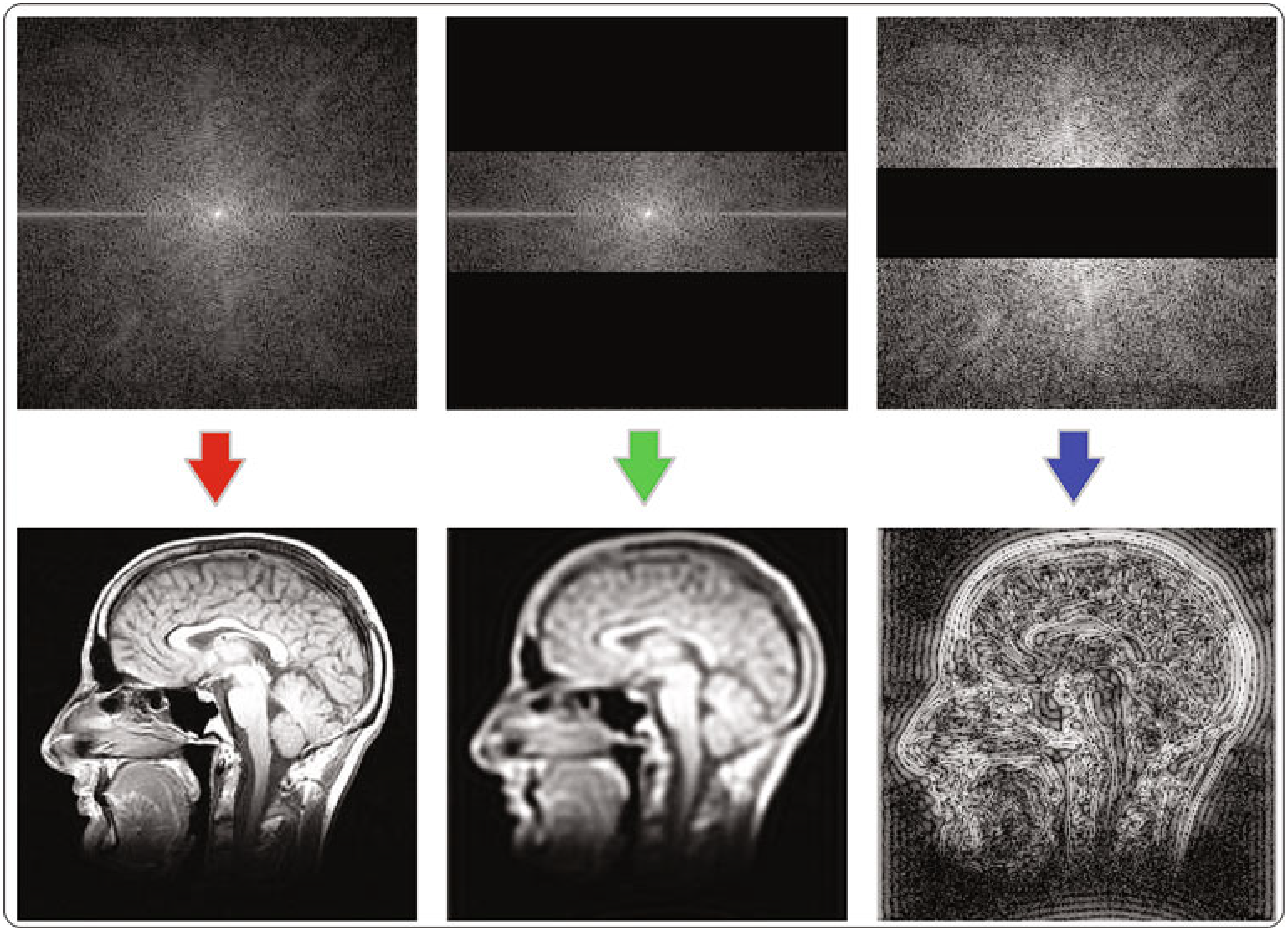
Understanding k-space



Understanding k-space



Understanding k-space

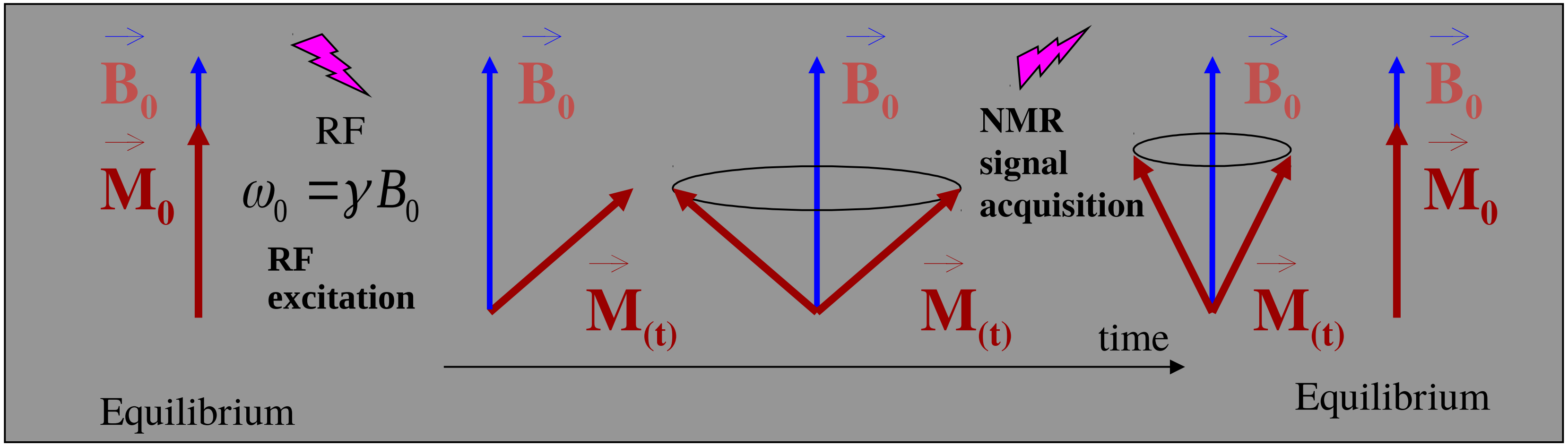


What is needed to obtain an MRI?

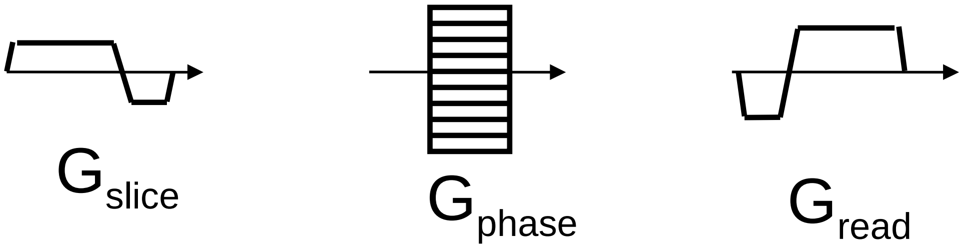
NMR experiment combining these three gradients:

- Select a slice (RF excitation + Gslice)
- Select a row (signal acquisition + Gread)
- Select a column (Gphase before signal)

For the NMR signal:



For spatial encoding of the NMR signal:

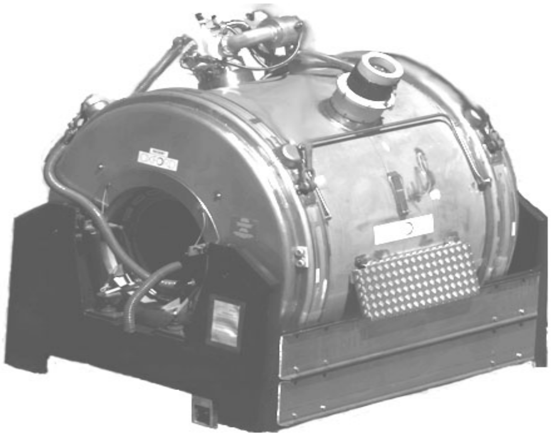


Summary of concepts introduced

- **What is the source of the NMR signal?**
- **What do we need to measure an NMR signal?**
- **What are T1, T2 and T2* relaxation?**
- **How is spatial information encoded in the NMR?**
- **What is a pulse sequence?**

MRI Risks & Safety

Static magnet **(always on)**
(1.5T , 3T, 7T– 11.7 T)
Earth ~10^{-5} T

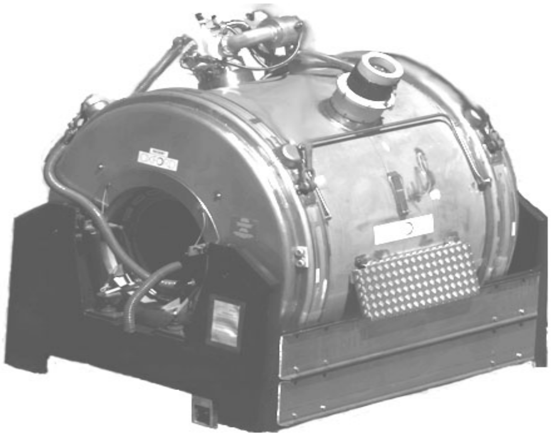


Projectiles

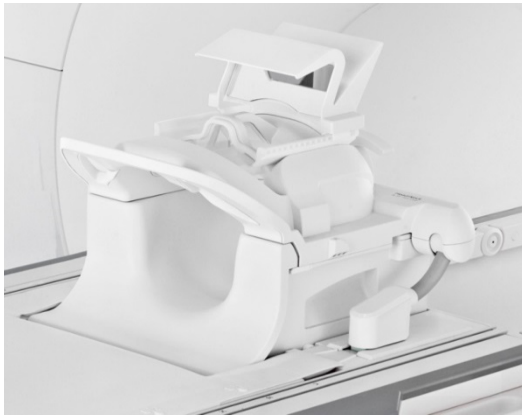
https://www.dailymotion.com/video/x2y23p7

MRI Risks & Safety

Static magnet (always on)
(1.5T , 3T, 7T– 11.7 T)
Earth ~10^{-5} T

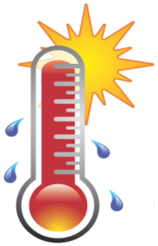


RF Coil
(8-64 channels)

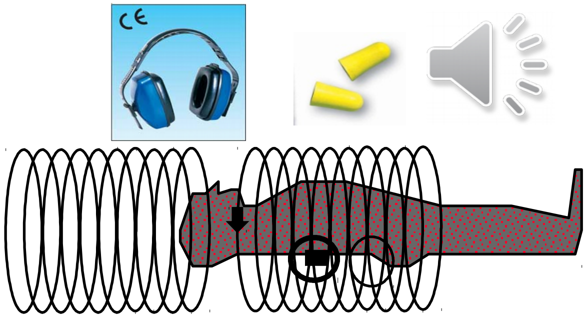


Magnetic gradient coil
(40-100 mT/m
~100 A in ~100 μs)

Projectiles

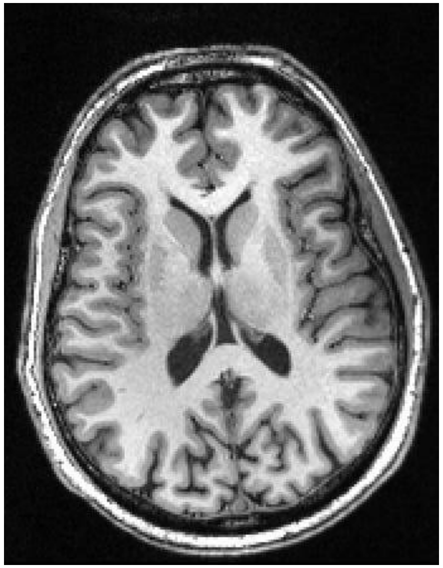


Heating

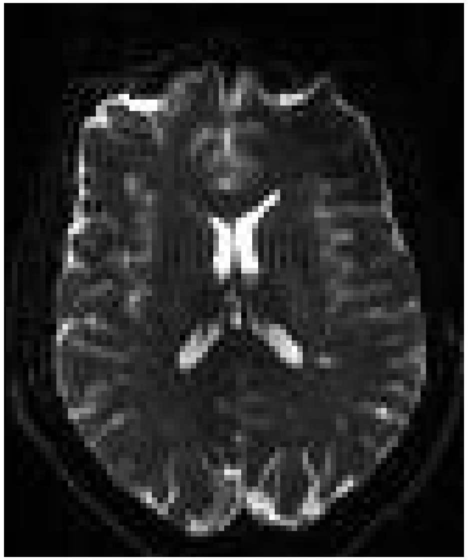


Peripheral nerve stimulation
Acoustic noise

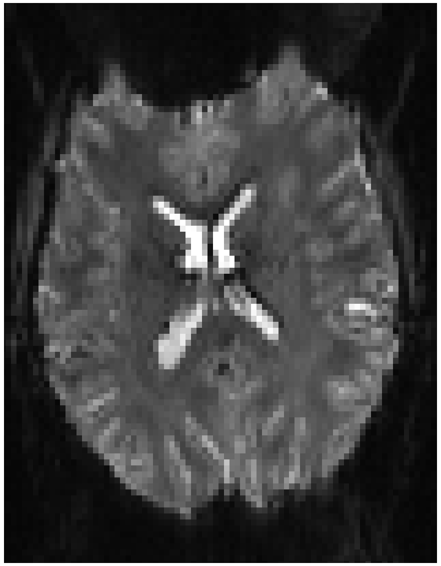
Acoustic stimulation during MRI



Structural
MPRAGE



Structural
Diffusion



Functional
EPI

Risks and safety procedures are known

Unfortunately, accidents still happen


Mirror's November 11, 2014,
exclusive report on the accident

Mumbai Mirror

TWO STUCK TO MRI MACHINE FOR 4 HRS


NEWS SHOWS VIDEO CBSN MORE

CBS/AFP / January 30, 2018, 9:48 AM

Fatal MRI machine accident brings arrests, investigations

MRI Risks & Safety

- **MRI studies are safe if proper precautions are taken**
- **Summary of precautions**
  - Annual safety training review (MRI lab staff and users)
  - Always be aware of the potential dangers of MRI
  - Never take anything metal into the scan room
  - Always make safety a top priority while in the MRI environment
- **More information about MRI safety issues:**
  - **http://www.mrisafety.com/**
  - **http://www.radiology.upmc.edu/MRsafety/**

MRI educational links include:

General MRI information sites include:

- http://www.cis.rit.edu/htbooks/mri
- http://mriquestions.com/
- http://www.fmri4newbies.com/
- https://www.imaios.com/en/e-Courses/e-MRI

Other:

- http://matt.might.net/articles/ways-to-fail-a-phd/
- https://gate.nmr.mgh.harvard.edu/wiki/whynhow/

Concept map for lectures

Lecture 1

NMR Signal origin

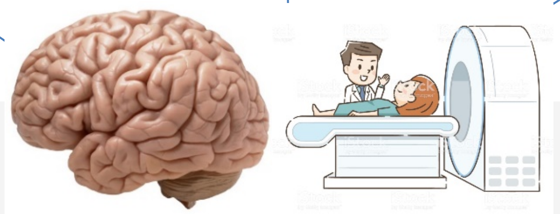
- Powerful magnet
- Radio frequency
- Magnetic field gradients

MR Image & Contrast

- Spatial encoding
- Magnetic gradients
- Pulse sequences

MR Safety

- Powerful magnet
- Radio frequency
- Magnetic field gradients



Lecture 2

Structural MRI

- Contrast, important parameters
- Sequences & artifacts
- Analyses & applications

Lecture 3

Diffusion MRI

- Contrast, important parameters
- Sequences & artifacts
- Analyses & applications

Lecture 4

Functional MRI

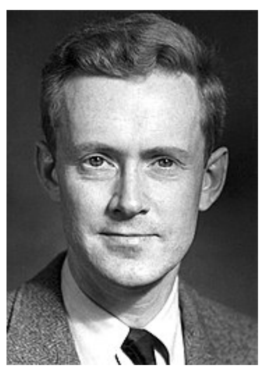
- Contrast, important parameters
- Sequences & artifacts
- Pre-processing

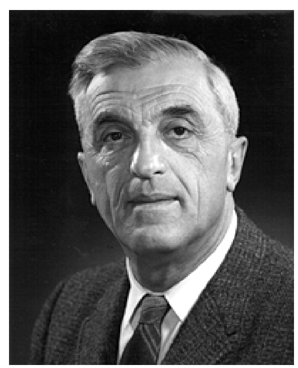
What is the source of an NMR signal?

Historical perspective

- Atoms ("indivisible" in Greek, Democritus 460-370 BC)
- Atomic theory & experiments: hydrogen (Cavendish, ~1766)
- Atomic nuclei, proton (Rutherford, ~1911)
- Quantum theory (Planck, Einstein, Bohr, etc. starts early 1900)
- Atomic nuclei: spin (Pauli, 1924)
- Atomic nuclei in a gas can absorb energy in a magnetic field (Rabi, 1937)
    - Nuclear Magnetic Resonance (NMR)
- NMR possible also in solid & liquids (Purcell & Bloch, 1945)
- Magnetic gradients proposed to create MRI (Lauterbur & Mansfield, 1972)

Isidor Isaac Rabi
Nobel Price 1944





Edward Purcell & Felix Bloch
Nobel Price 1952

P. Lauterbur & P. Mansfield
Nobel Price 2003