MRI – Basic principles of medical imaging

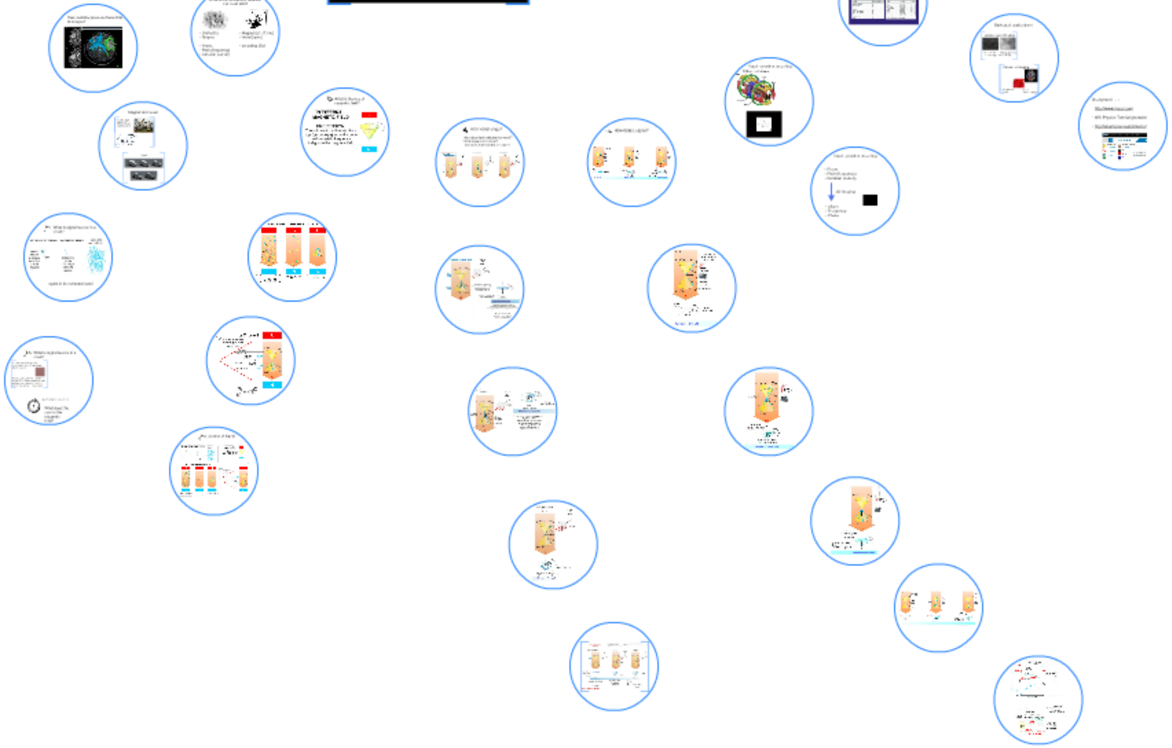
Krisztián Szigeti

Biophysics and Radiation Biology

1947 NMR material science (1952 - Nobel prize):
- Felix Block
- Edward M. Purcell

1977 Clinical MRI (2003):
- Paul Lauterbur
- Peter Mansfield

- Raymond Damadian



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Semmelweis NIVIC
Nanobiotechnológiai és In Vivo Képalkotó Központ
Nanobiotechnology and In Vivo Imaging Center

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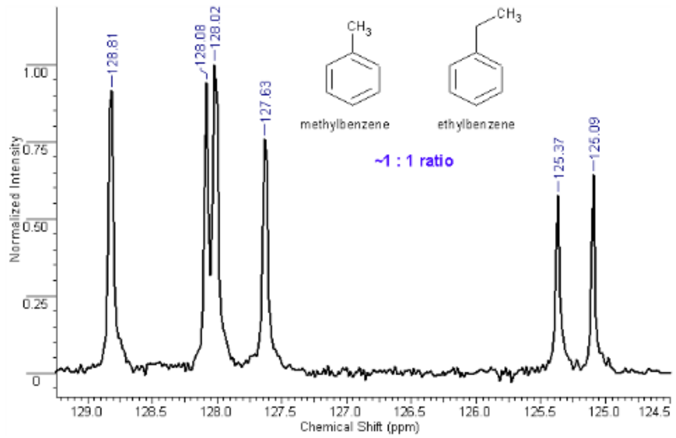

1977 Clinical MRI (2003):

- Paul Lauretbur
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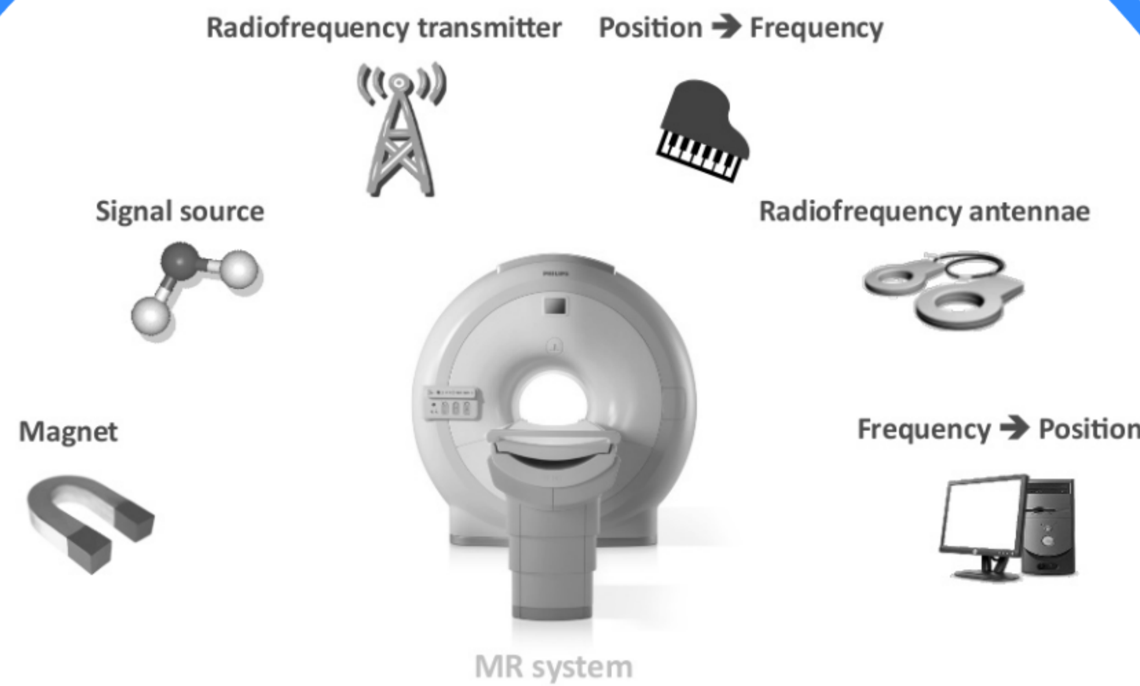
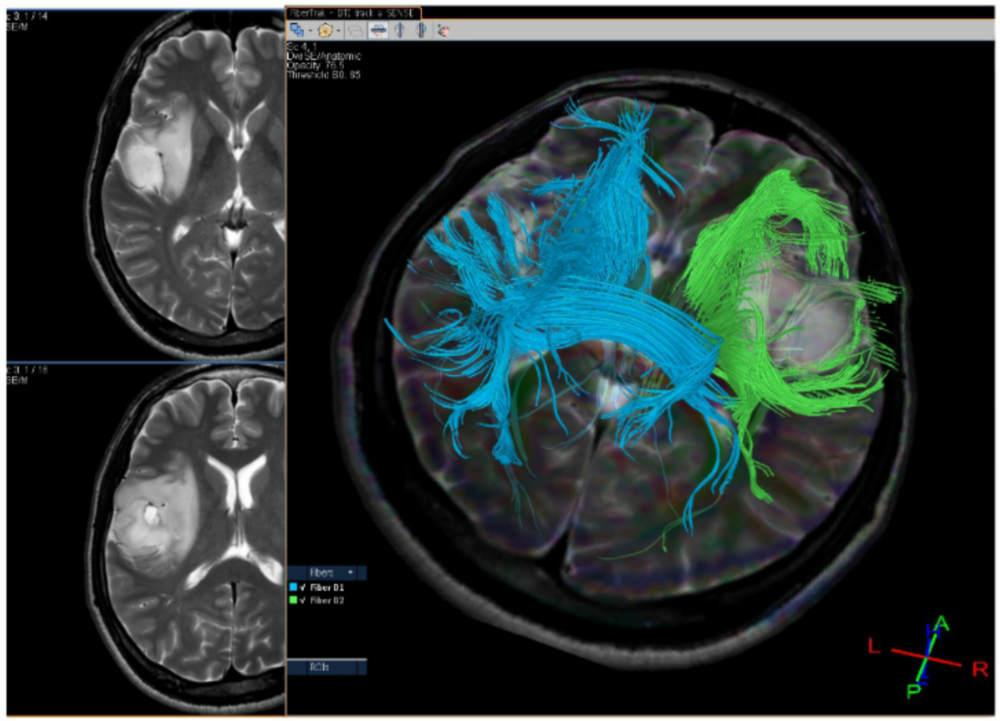
How does MRI work?



- Patient in a strong homogeneous magnetic field
- Excitation of a part of patient tissue by radiofrequency pulses
- Receive emitted radiofrequency signal from the patient
- Repeat the former two steps voxel by voxel in a plane

How could be produce these kind of images?



What is the connection between choir and MRI?

- Orchestra
- Singers

- Floors
- Pitch (frequency)
- Duration (canon)

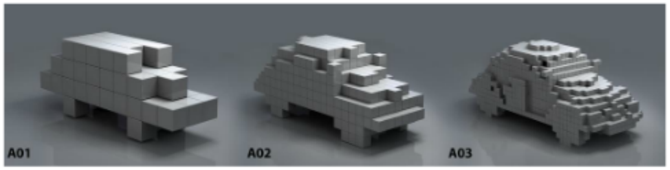
- Magnet (pl: 3T, He)
- Voxel (spins)

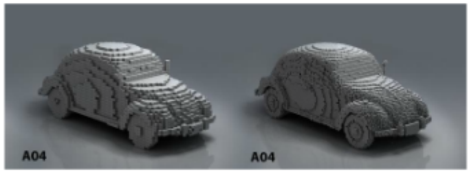
- Encoding (3D)

Magnet and voxel

- Earth: 30uT
- MRI: 0.3-12T
  (100,000x)

Voxel





- Earth: 30uT
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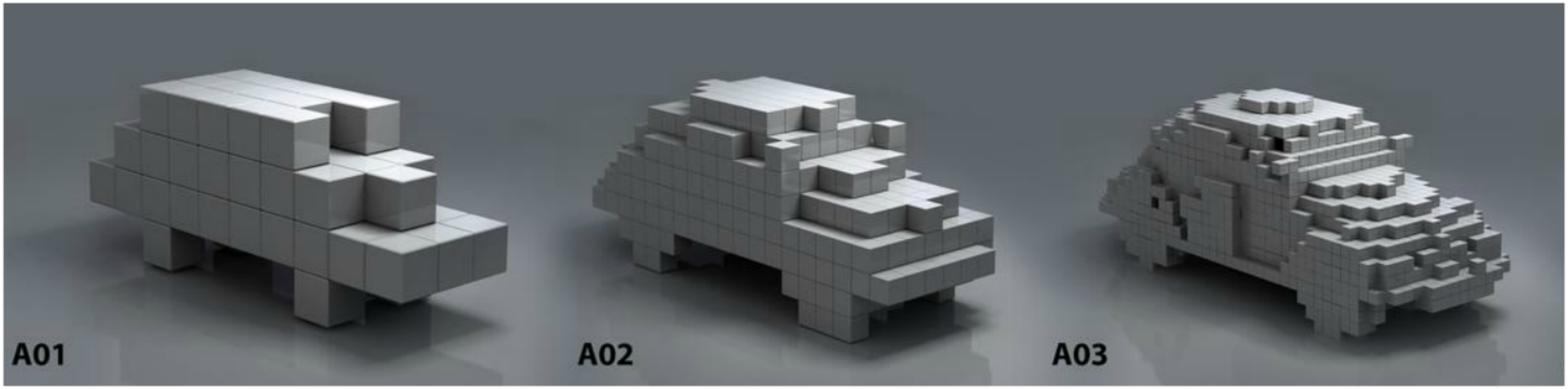
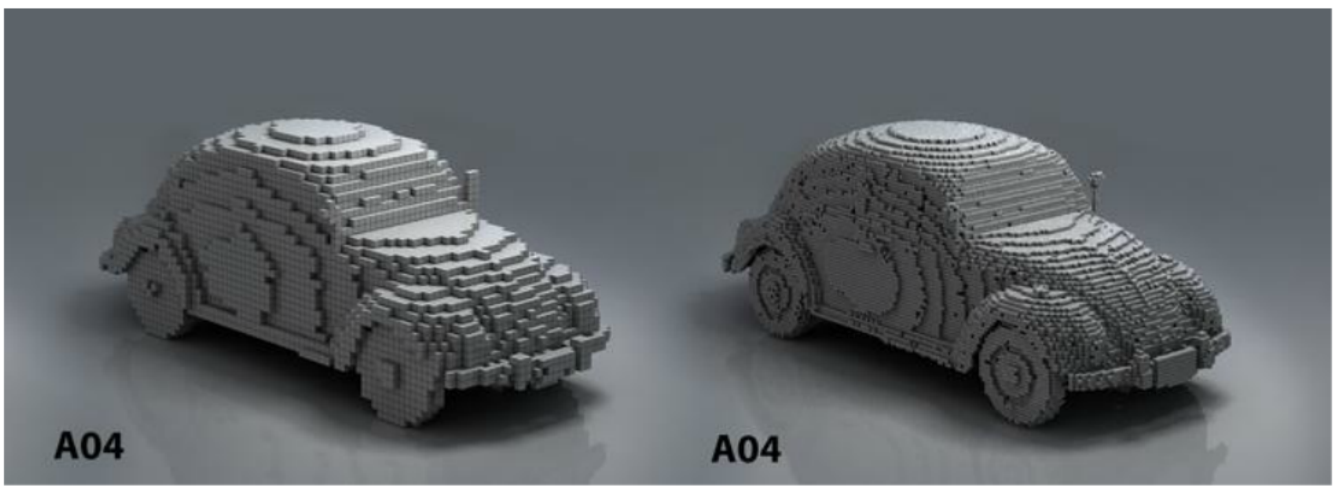
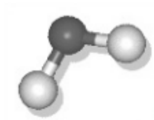
Voxel



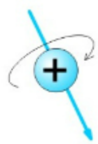




What is signal source in a voxel?

WITHOUT EXTERNAL MAGNETIC FIELD

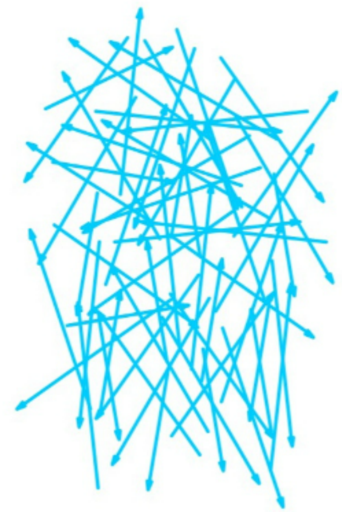
due to its spin a proton acts like a little magnet



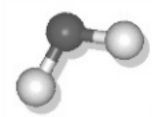
spin

magnetic vector of a single spinning proton

spins are not ordered

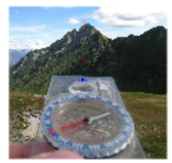


Spins in the selected voxel



What is signal source in a voxel?

A compass is a navigational instrument that shows directions (North - South)



The magnetic compass contains a magnet that interacts with the earth's magnetic field and aligns itself to point to the magnetic poles (N-S)

Spin = atomic level compass

What does the spin in the magnetic field?

A compass is a navigational instrument that shows directions (North - South)

The magnetic compass contains a magnet that interacts with the earth's magnetic field and aligns itself to point to the magnetic poles (N-S)

Spin = atomic level compass

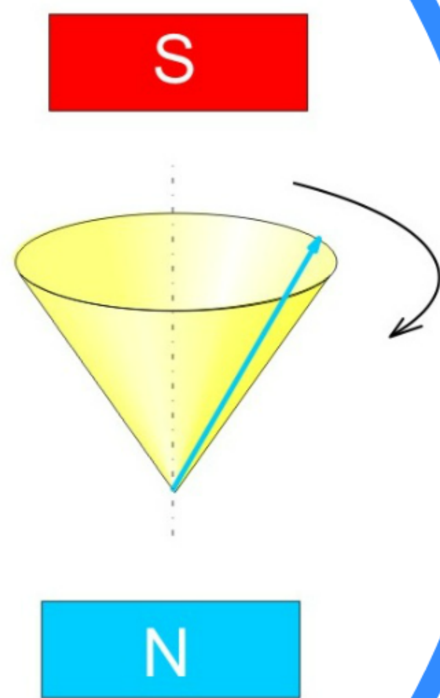
What does the spin in the magnetic field?

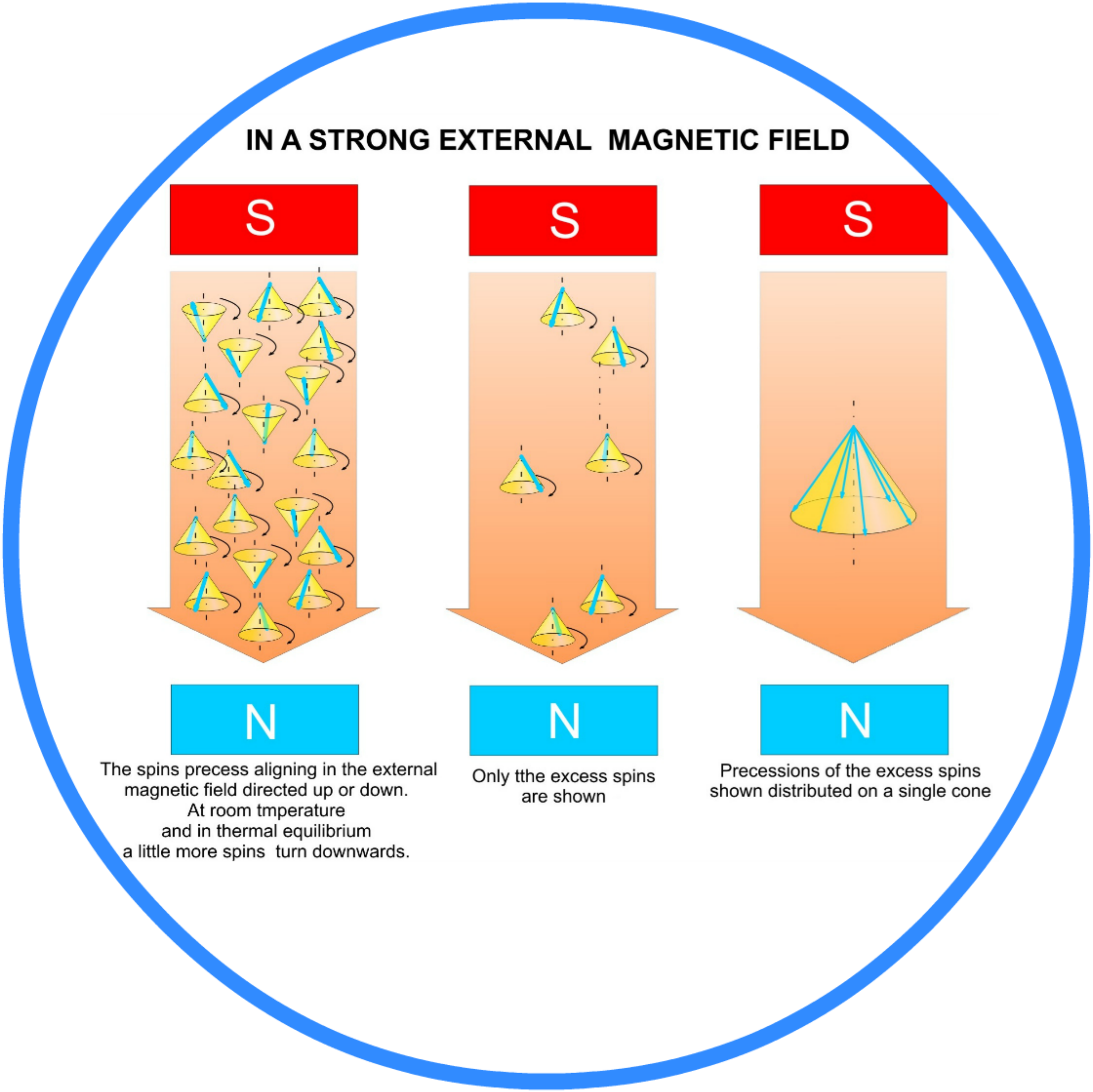
What is the role of magnetic field?

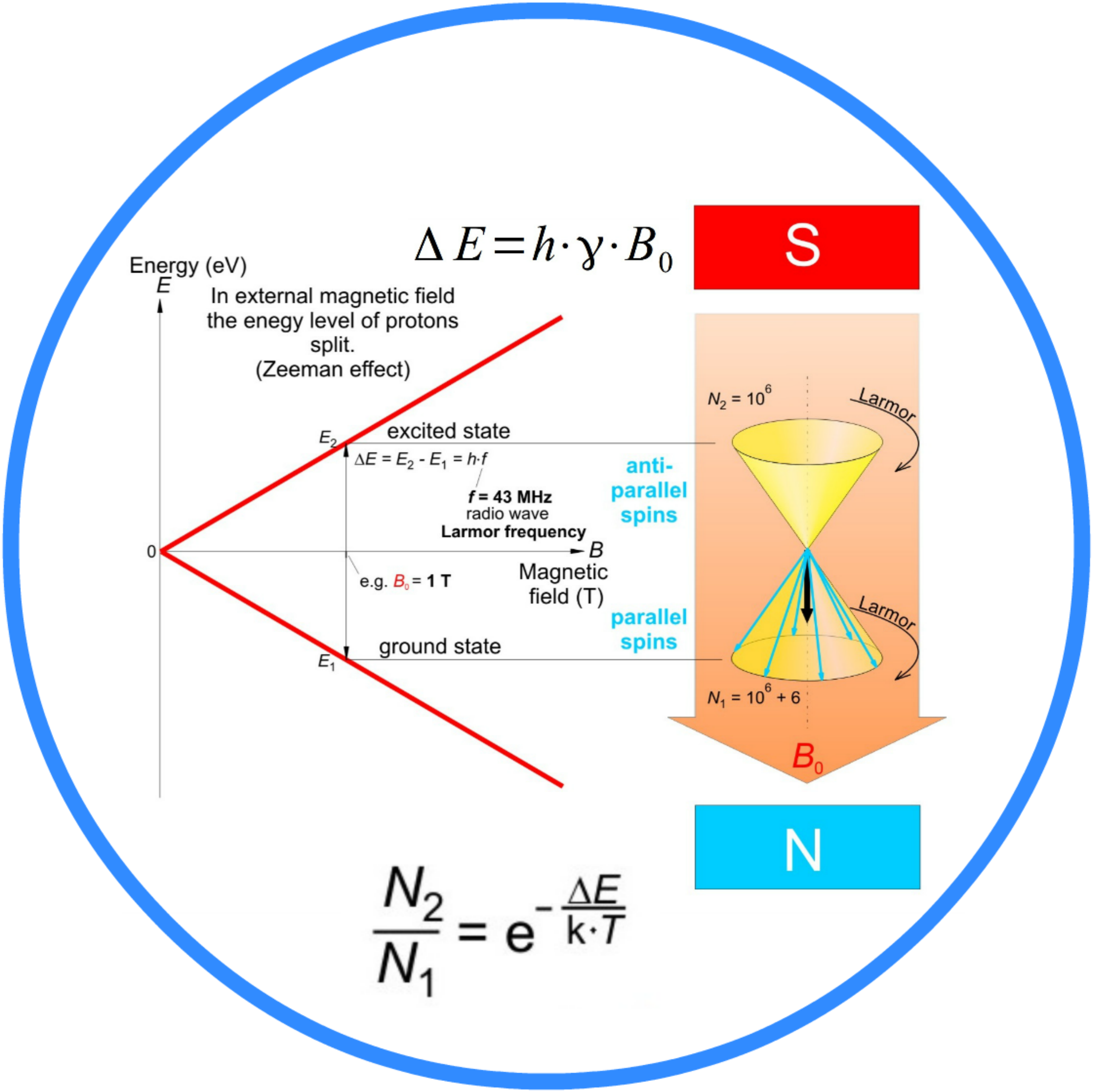
IN EXTERNAL MAGNETIC FIELD

PRECESSION:

The spin vector will rotate like a **top (gyroscope)** around a cone with a certain frequency.
It aligns to the magnetic field.

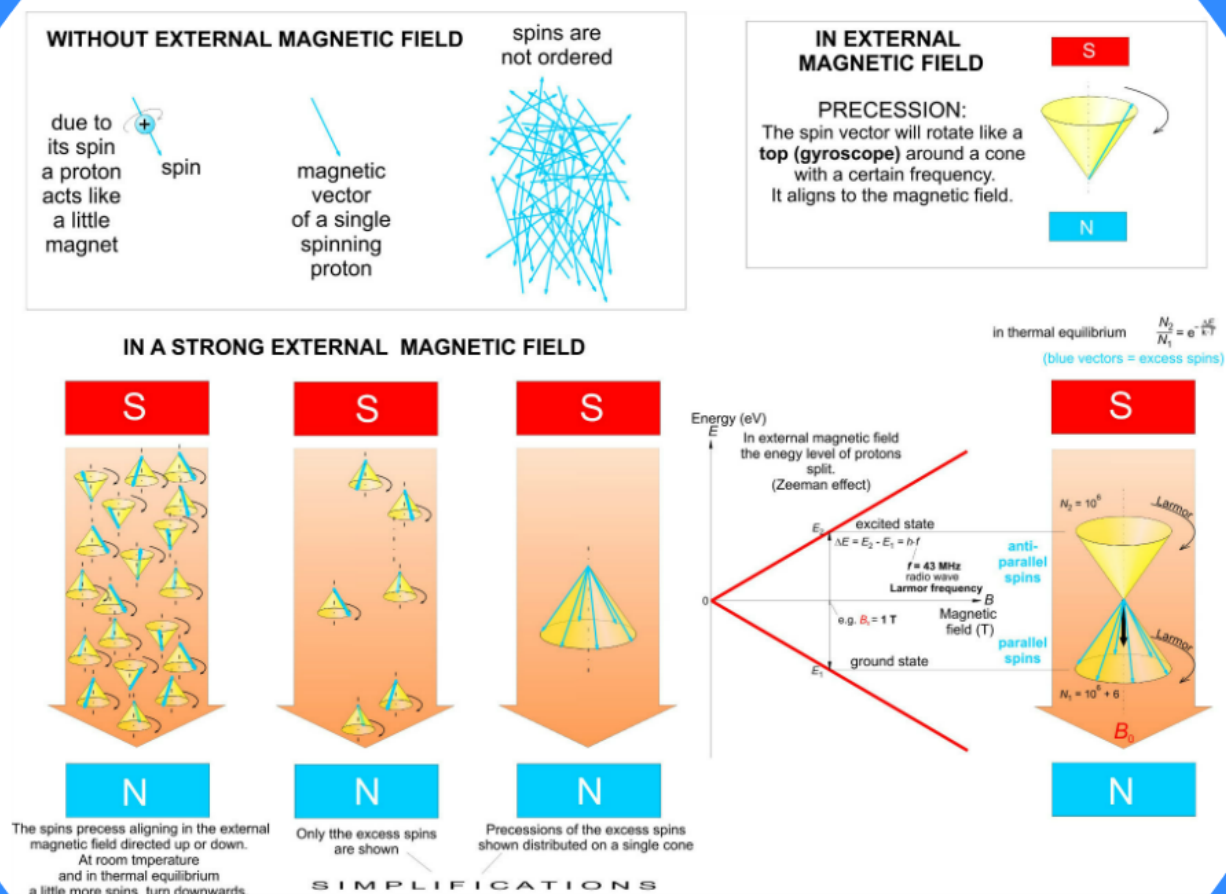



IN A STRONG EXTERNAL MAGNETIC FIELD
S
S
S
N
N
N
The spins precess aligning in the external magnetic field directed up or down. At room tmperature and in thermal equilibrium a little more spins turn downwards.
Only tthe excess spins are shown
Precessions of the excess spins shown distributed on a single cone



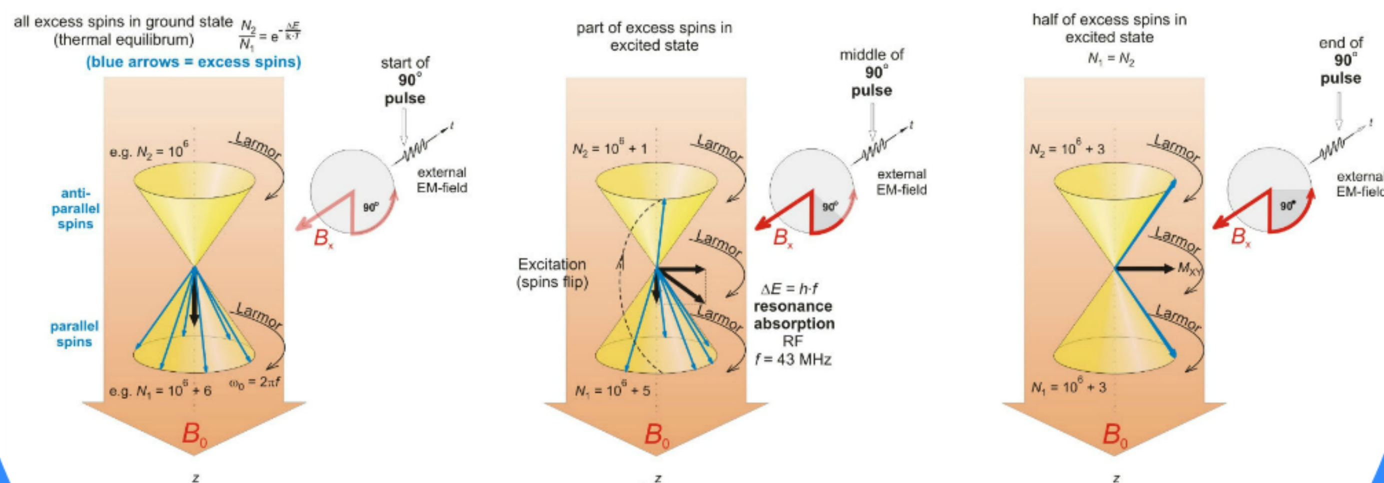
$\Delta E = h \cdot \gamma \cdot B_0$
S
Energy (eV)
E
In external magnetic field the enegy level of protons split.
(Zeeman effect)
$N_2 = 10^6$
Larmor
E_2
excited state
$\Delta E = E_2 - E_1 = h \cdot f$
anti-parallel spins
f = 43 MHz
radio wave
Larmor frequency
0
B
Magnetic field (T)
e.g. B_0 = 1 T
parallel spins
Larmor
ground state
E_1
$N_1 = 10^6 + 6$
B_0
N
$\frac{N_2}{N_1} = e^{-\frac{\Delta E}{k \cdot T}}$

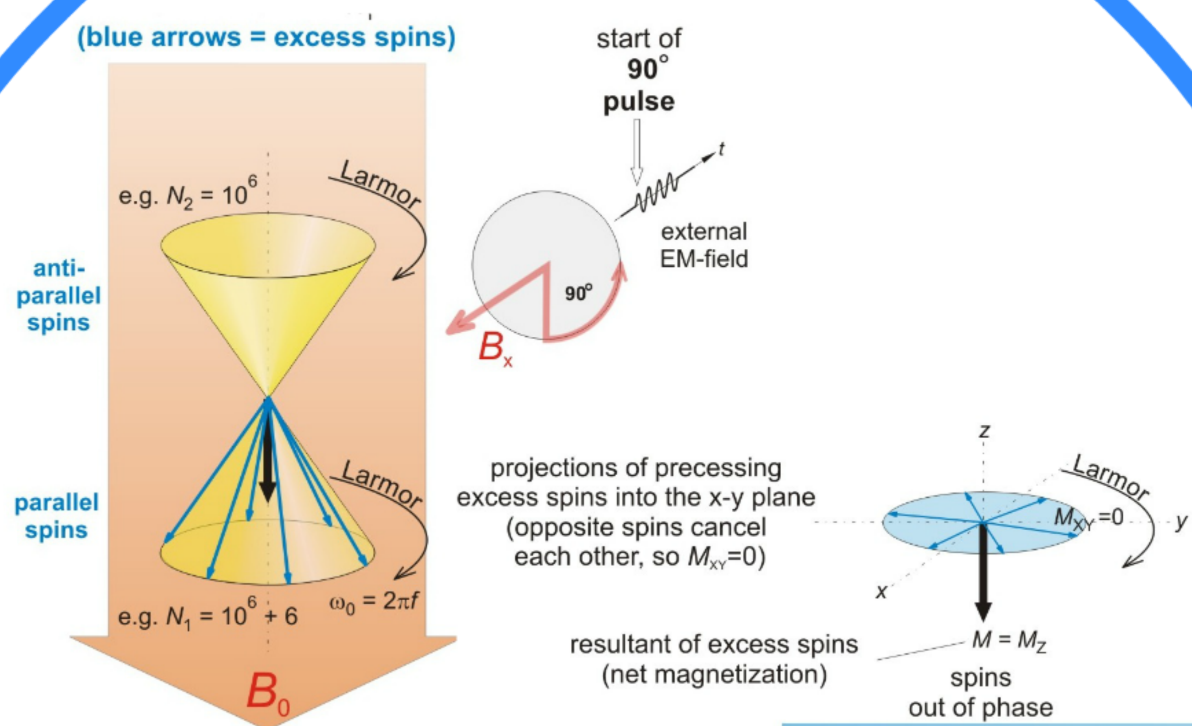
Source of signal



How voxel sings?

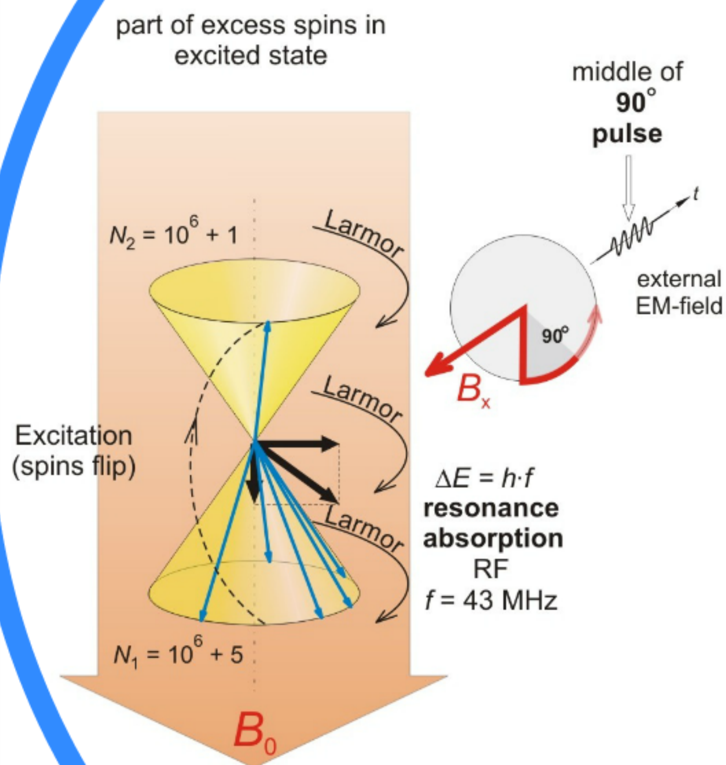
- How absorbed radiation by voxel?
- What happens in voxel?
- How does voxel produce signal?

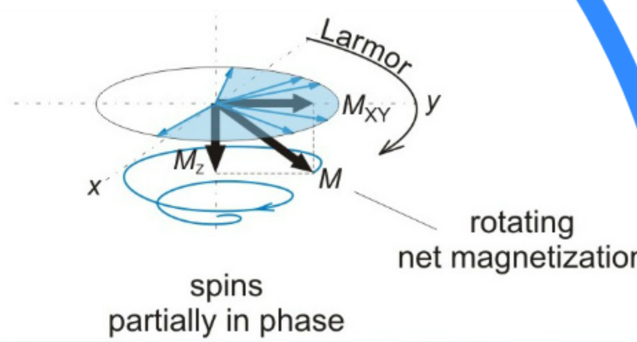




Horizontal component of spins
with random phase cancel each other,
the x-y projection of the magnetization is zero

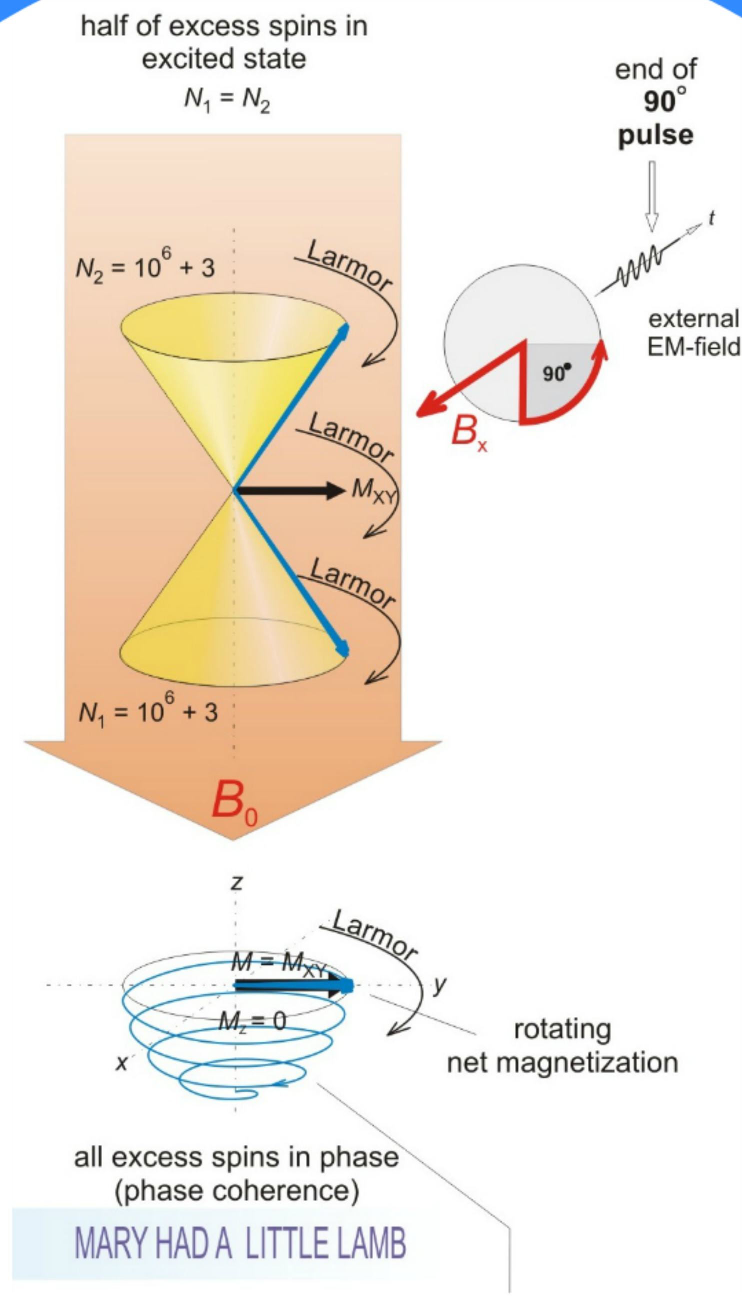
M_Z spins around itself
and aligns to the huge B_0
so it is not detectable!



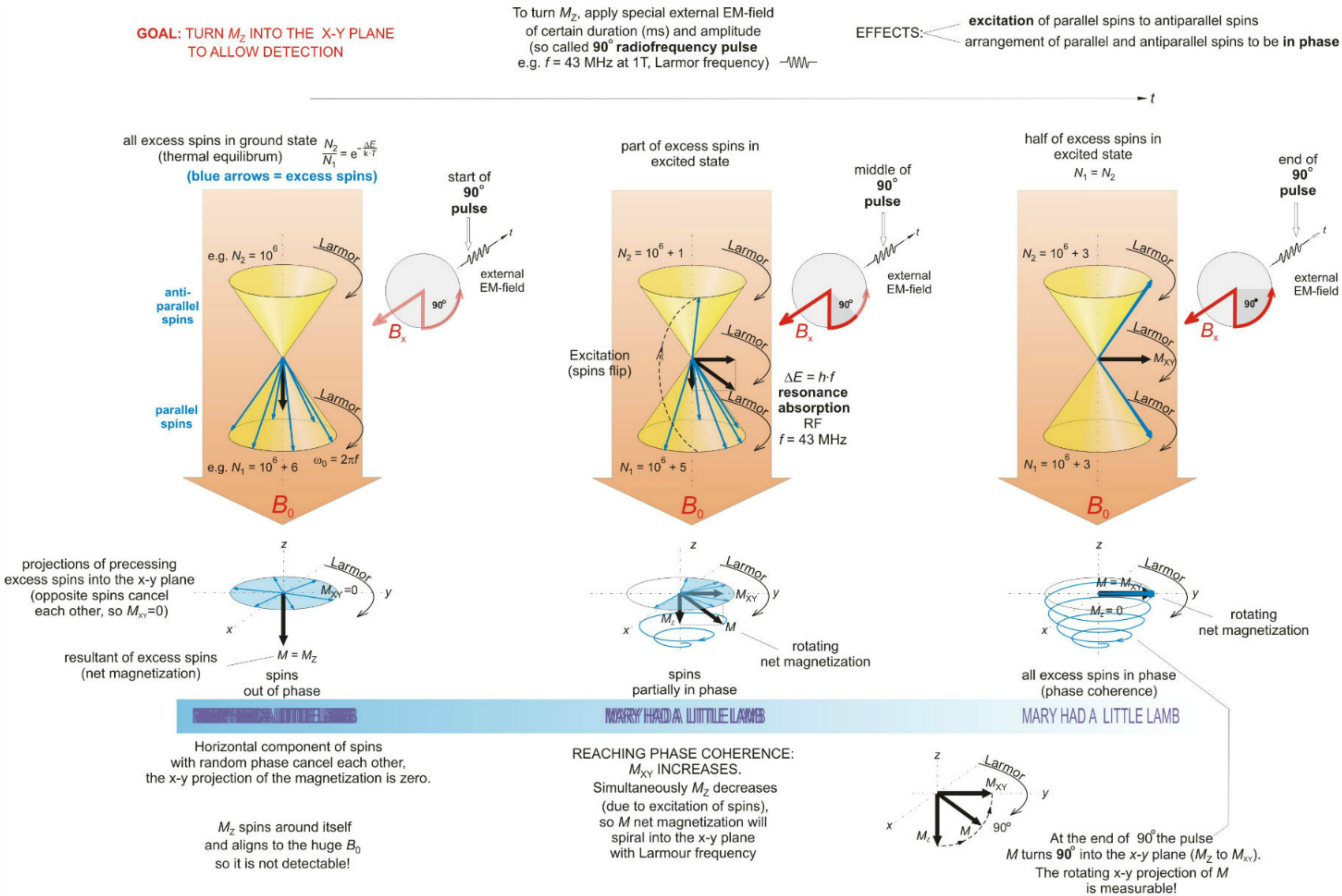


MARY HADA LITTLE LAMB

REACHING PHASE COHERENCE:
M_{XY} INCREASES.
Simultaneously M_Z decreases (due to excitation of spins), so M net magnetization will spiral into the x-y plane with Larmour frequency

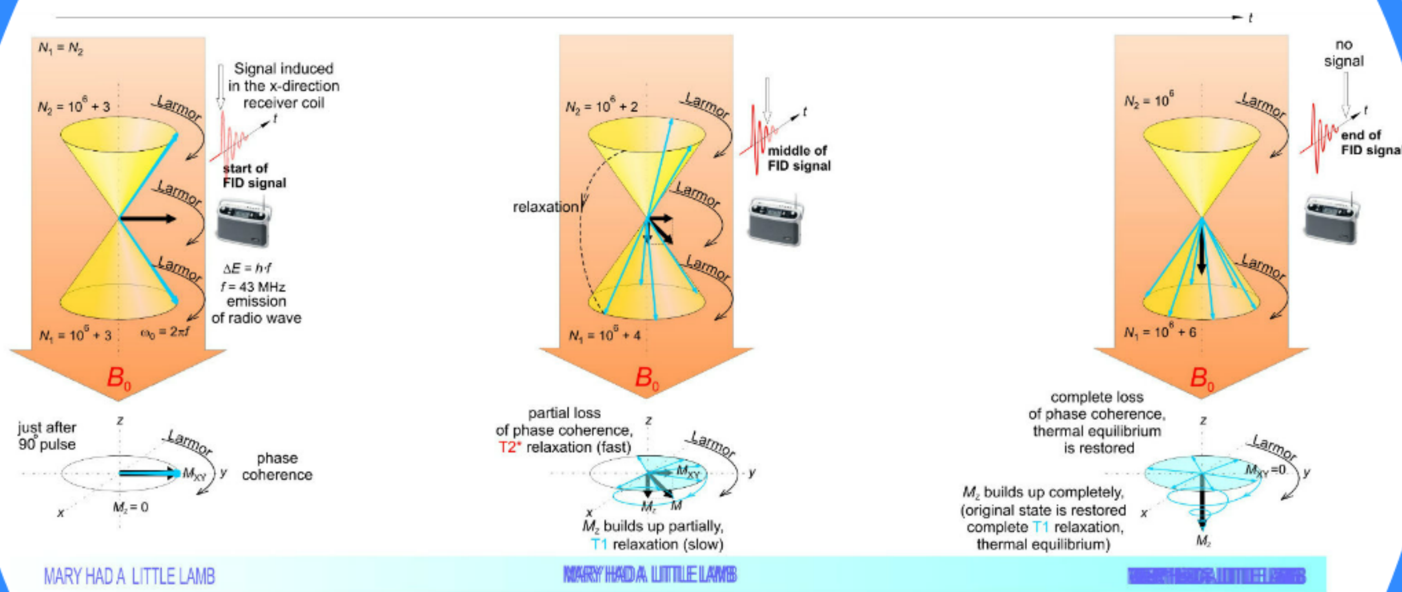


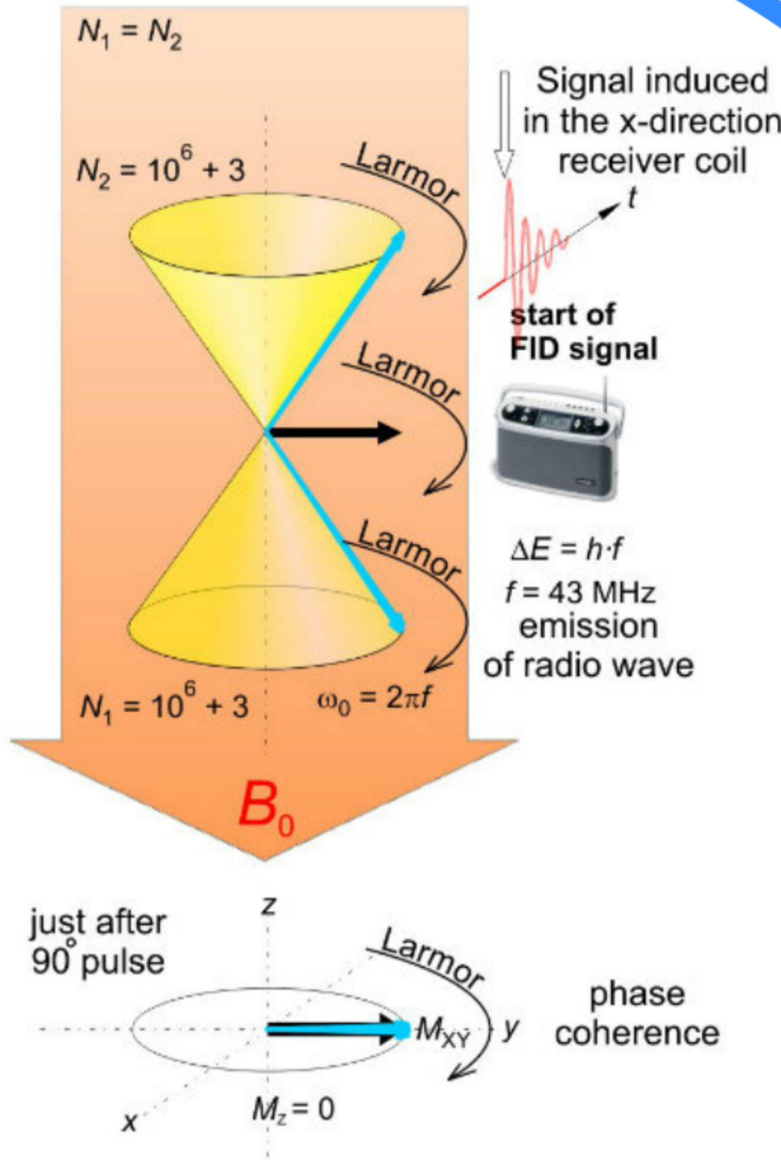
half of excess spins in excited state
$N_1 = N_2$
end of 90° pulse
$N_2 = 10^6 + 3$
Larmor
Larmor
M_{XY}
Larmor
external EM-field
90°
B_x
$N_1 = 10^6 + 3$
B_0
z
Larmor
$M = M_{XY}$
y
$M_z = 0$
x
rotating net magnetization
all excess spins in phase (phase coherence)
MARY HAD A LITTLE LAMB



EXCITATION BY 90° RF- PULSE

How detect signal?





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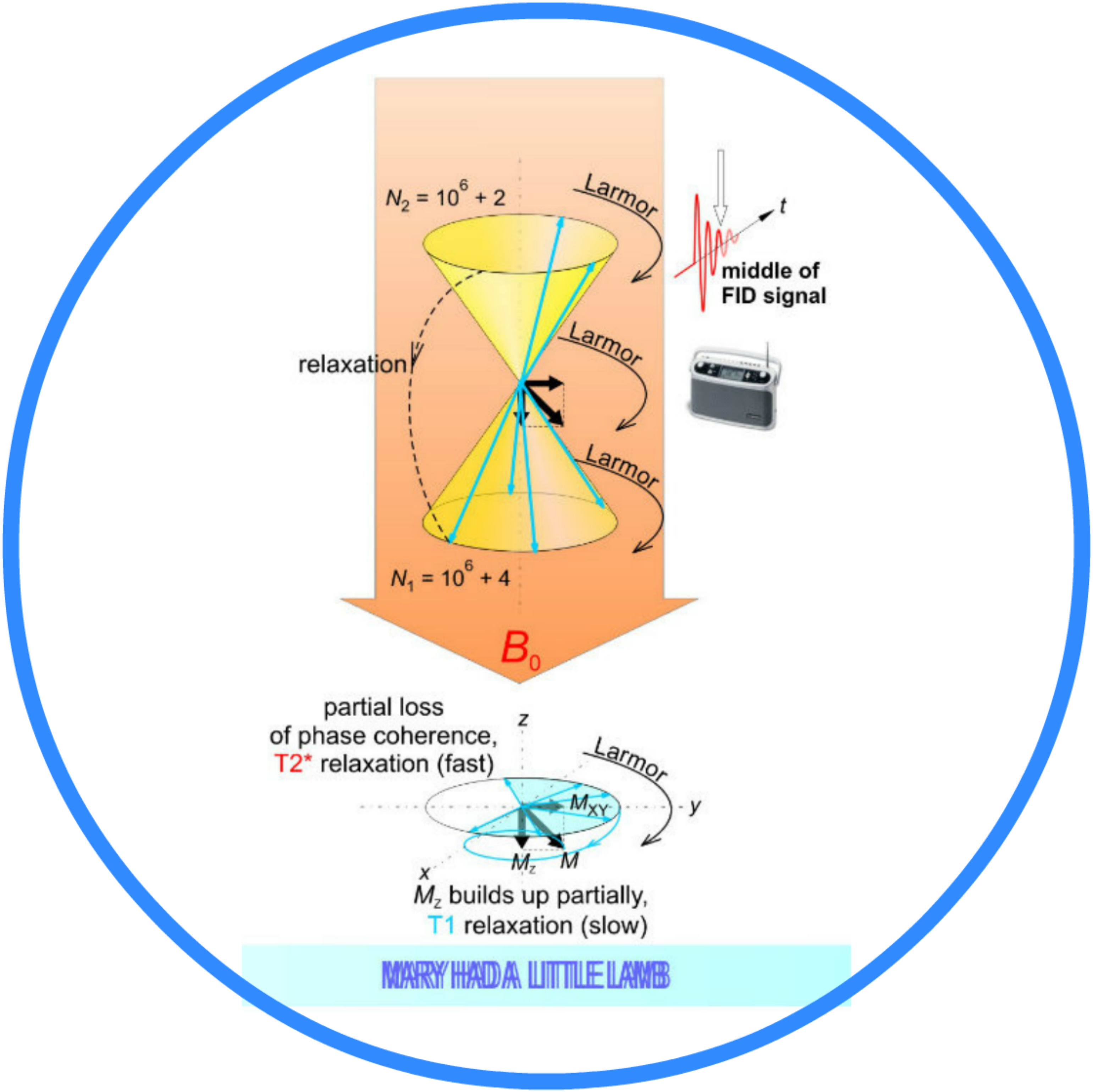
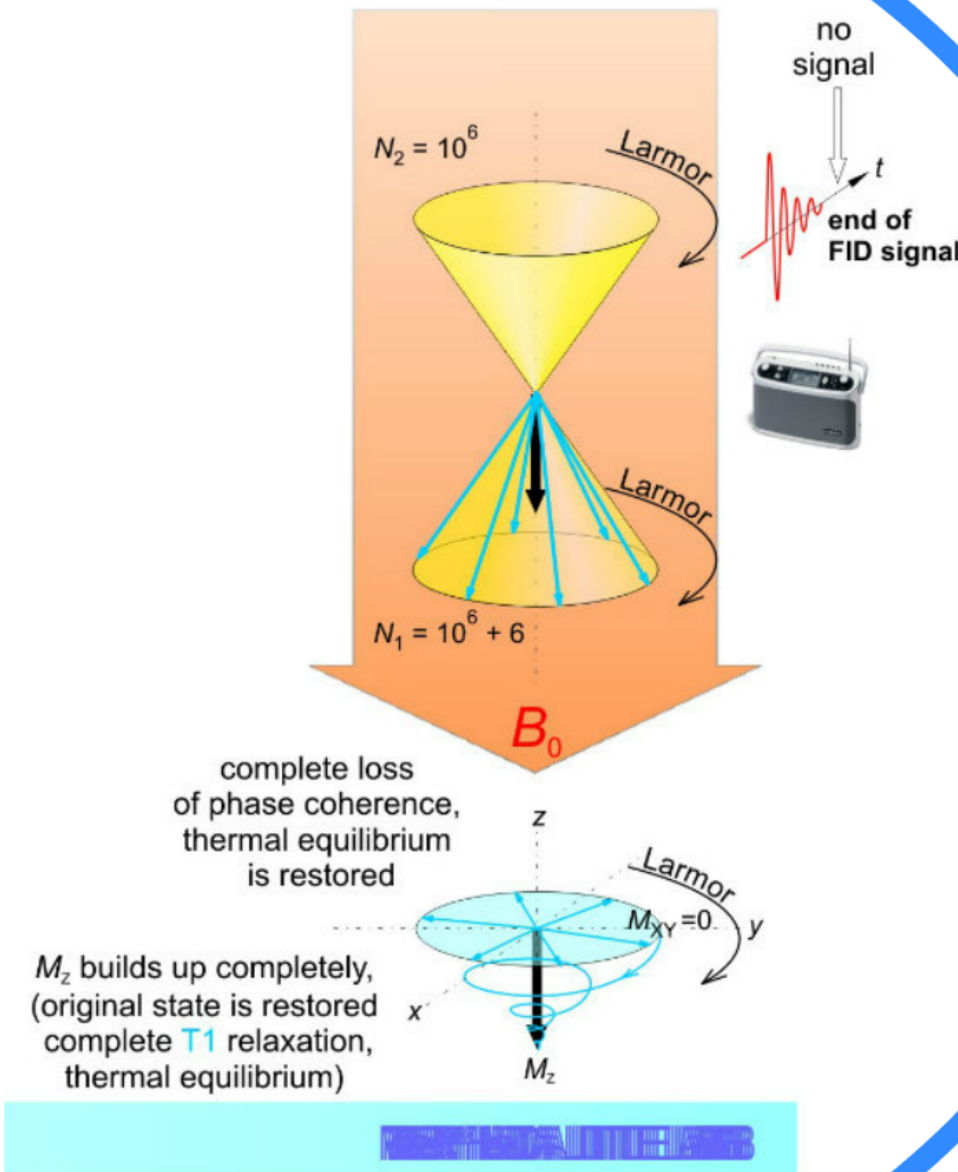
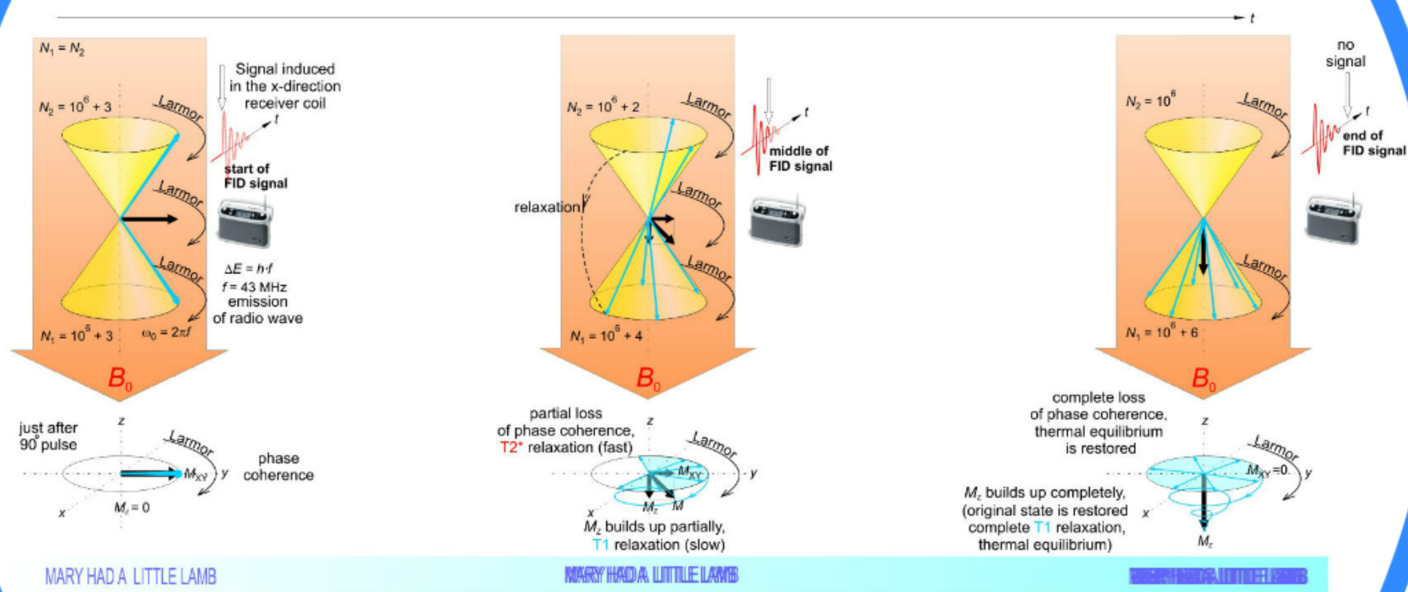


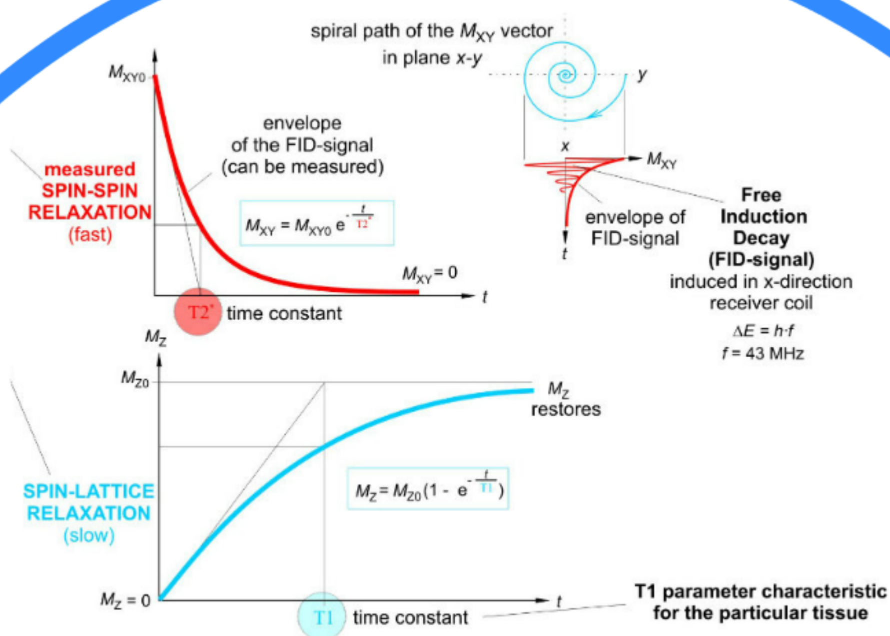
N2 = 10^6 + 2
Larmor
t
middle of
FID signal
Larmor
relaxation
Larmor
N1 = 10^6 + 4
B0
partial loss
of phase coherence,
T2* relaxation (fast)
z
Larmor
MXY
y
x
Mz
M
Mz builds up partially,
T1 relaxation (slow)
MARY HAD A LITTLE LAMB



no
signal
t
end of
FID signal
$N_2 = 10^6$
Larmor
Larmor
$N_1 = 10^6 + 6$
B_0
complete loss
of phase coherence,
thermal equilibrium
is restored
z
Larmor
M_{XY} =0
y
x
M_z builds up completely,
(original state is restored
complete T1 relaxation,
thermal equilibrium)
M_z



t
N1 = N2
N2 = 10^6 + 3
Larmor
Signal induced in the x-direction receiver coil
start of FID signal
ΔE = h·f
f = 43 MHz emission of radio wave
N1 = 10^6 + 3
ω0 = 2πf
B0
just after 90° pulse
phase coherence
Mz = 0
N2 = 10^6 + 2
middle of FID signal
relaxation
N1 = 10^6 + 4
partial loss of phase coherence, T2* relaxation (fast)
Mz builds up partially, T1 relaxation (slow)
no signal
N2 = 10^6
end of FID signal
N1 = 10^6 + 6
complete loss of phase coherence, thermal equilibrium is restored
Mz builds up completely, (original state is restored complete T1 relaxation, thermal equilibrium)
MXY = 0
MARY HAD A LITTLE LAMB
MARY HAD A LITTLE LAMB



after the 90° pulse:

1. Spins **lose their phase coherence** fast — Exponential decay, caracterised by T2* relaxation time
2. Slow relaxation of **antiparallel spins to parallel spins** — Exponential decay, caracterised by T1 relaxation time

reasons of losing phase coherence:

- **inhomogenity** of magnetic field $\boldsymbol{B_0}$ ($T2_{rev}$)
- **inhomogenity** of magnetisation **in tissue** (T2)

$$\frac{1}{T2^*} = \frac{1}{T2} + \frac{1}{T2_{rev}}$$

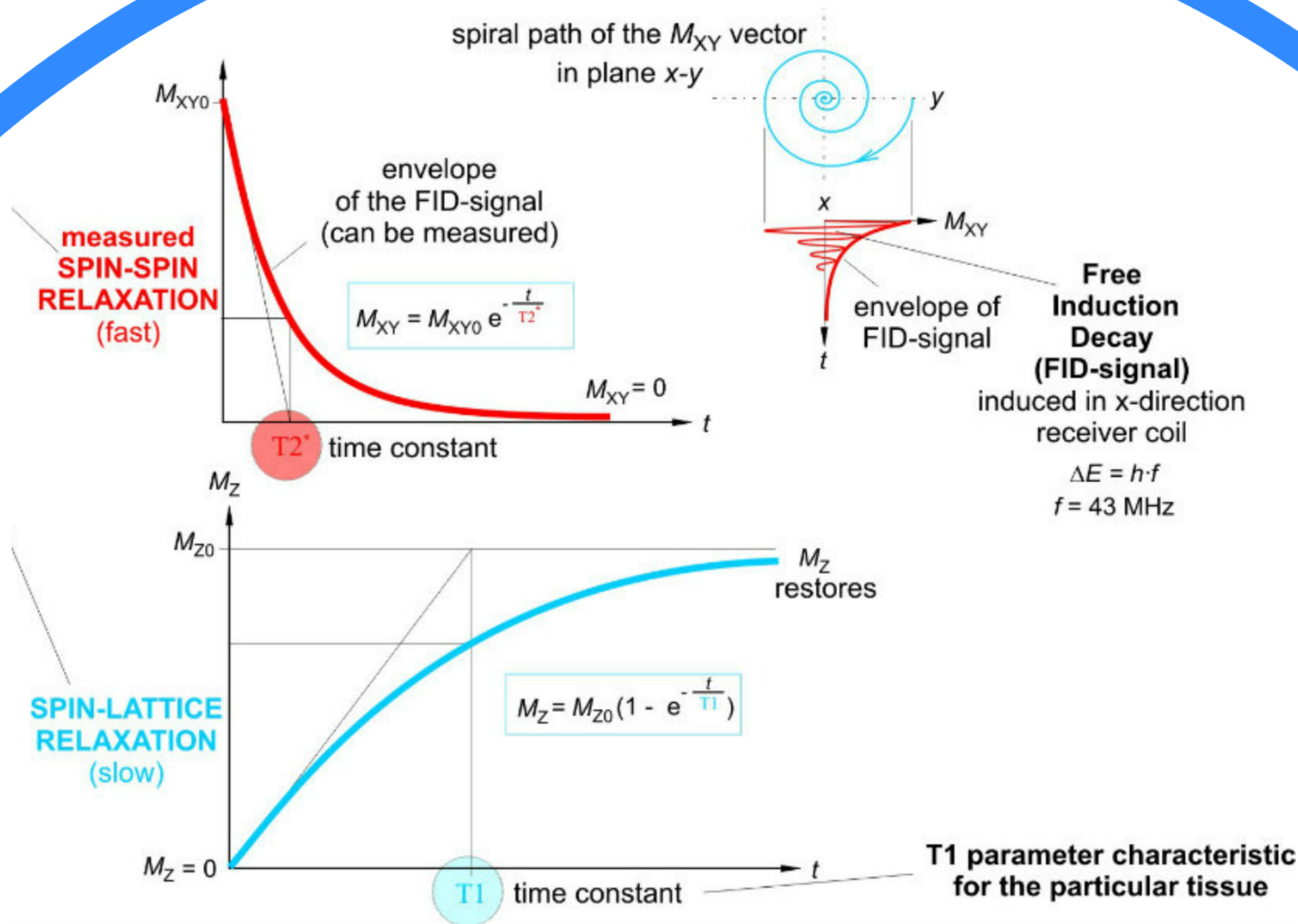
time constant of measured SPIN-SPIN RELAXATION and inhomogenity of B_0 together (T2*)

time constant of **SPIN-SPIN RELAXATION** in tissue (T2) — **T2 parameter characteristic of the particular tissue**

time constant caused by inhomogenity of magnetic field B_0 (technical inconvinience, constant in time) ($T2_{rev}$)

Only T2* can be measured. Spin-echo technique reveals T2.

RELAXATION, LOSS OF PHASE COHERENCE, DETECTING MRI SIGNALS



spiral path of the M_{XY} vector in plane x-y
y
x
M_{XY}
t
envelope of FID-signal
Free Induction Decay (FID-signal)
induced in x-direction receiver coil
$\Delta E = h \cdot f$
f = 43 MHz
M_{XY0}
envelope of the FID-signal (can be measured)
measured SPIN-SPIN RELAXATION (fast)
$M_{XY} = M_{XY0}\, e^{-\frac{t}{T2^*}}$
$M_{XY} = 0$
t
T2* time constant
M_Z
M_{Z0}
M_Z restores
SPIN-LATTICE RELAXATION (slow)
$M_Z = M_{Z0}(1 - e^{-\frac{t}{T1}})$
$M_Z = 0$
t
T1 time constant
T1 parameter characteristic for the particular tissue

after the 90° pulse

1. Spins **lose their phase coherence** fast — Exponential decay, caracterised by T2* relaxation time

2. Slow relaxation of **antiparallel spins to parallel spins** — Exponential decay, caracterised by T1 relaxation time

reasons of losing phase coherence

- **inhomogenity** of magnetic field $\boldsymbol{B}_0$ $(T2_{rev})$
- **inhomogenity** of magnetisation in **tissue** (T2)

$$\frac{1}{T2^*} = \frac{1}{T2} + \frac{1}{T2_{rev}}$$

time constant of measured SPIN-SPIN RELAXATION and inhomogenity of B_0 together

time constant of **SPIN-SPIN RELAXATION** in tissue

T2 parameter characteristic of the particular tissue

time constant caused by inhomogenity of magnetic field B_0 (technical inconvinience, constant in time)

Only T2* can be measured. Spin-echo technique reveals T2.

RELAXATION, LOSS OF PHASE COHERENCE, DETECTING MRI SIGNALS

What is the connection between choir and MRI?

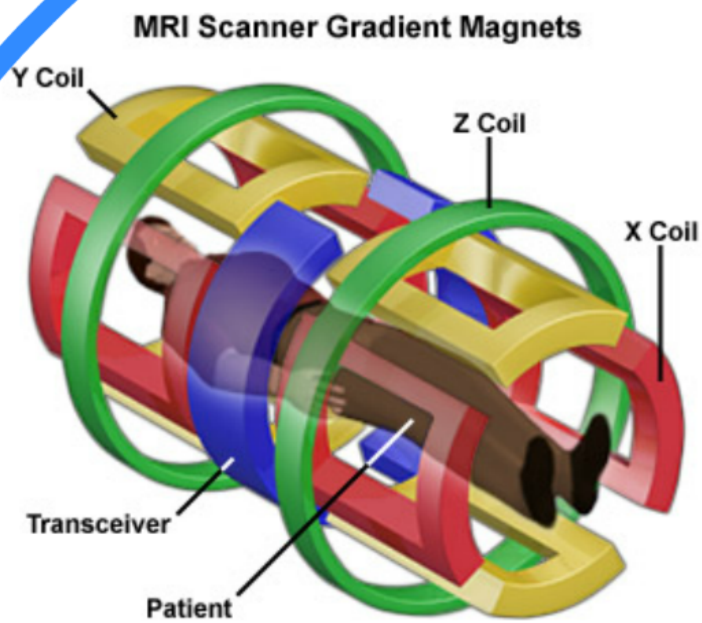
- Orchestra
- Singers

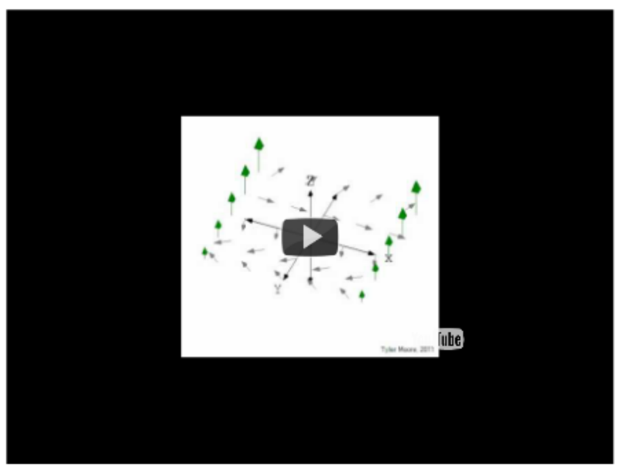
- Floors
- Pitch (frequency)
- Duration (canon)

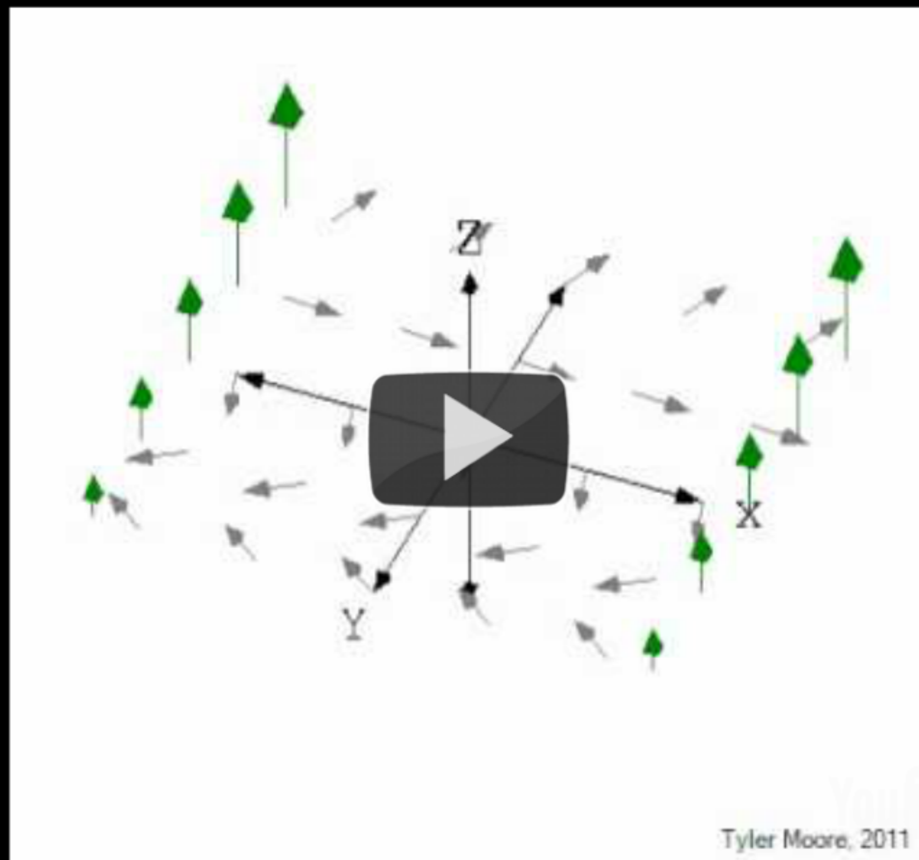
- Magnet (pl: 3T, He)
- Voxel (spins)

- Encoding (3D)

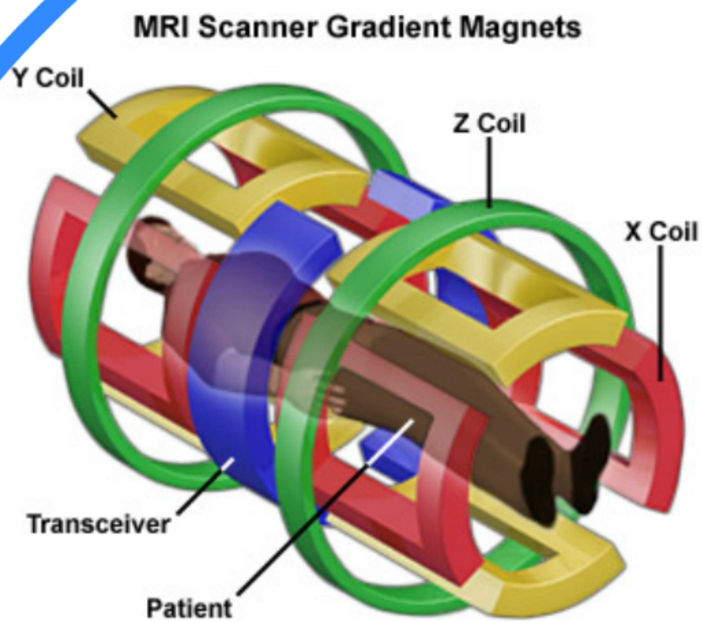
Voxel - position encoding

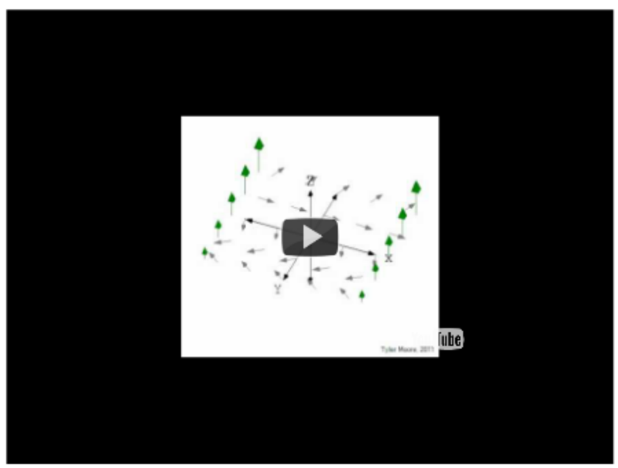





Z
X
Y
Tyler Moore, 2011

Voxel - position encoding



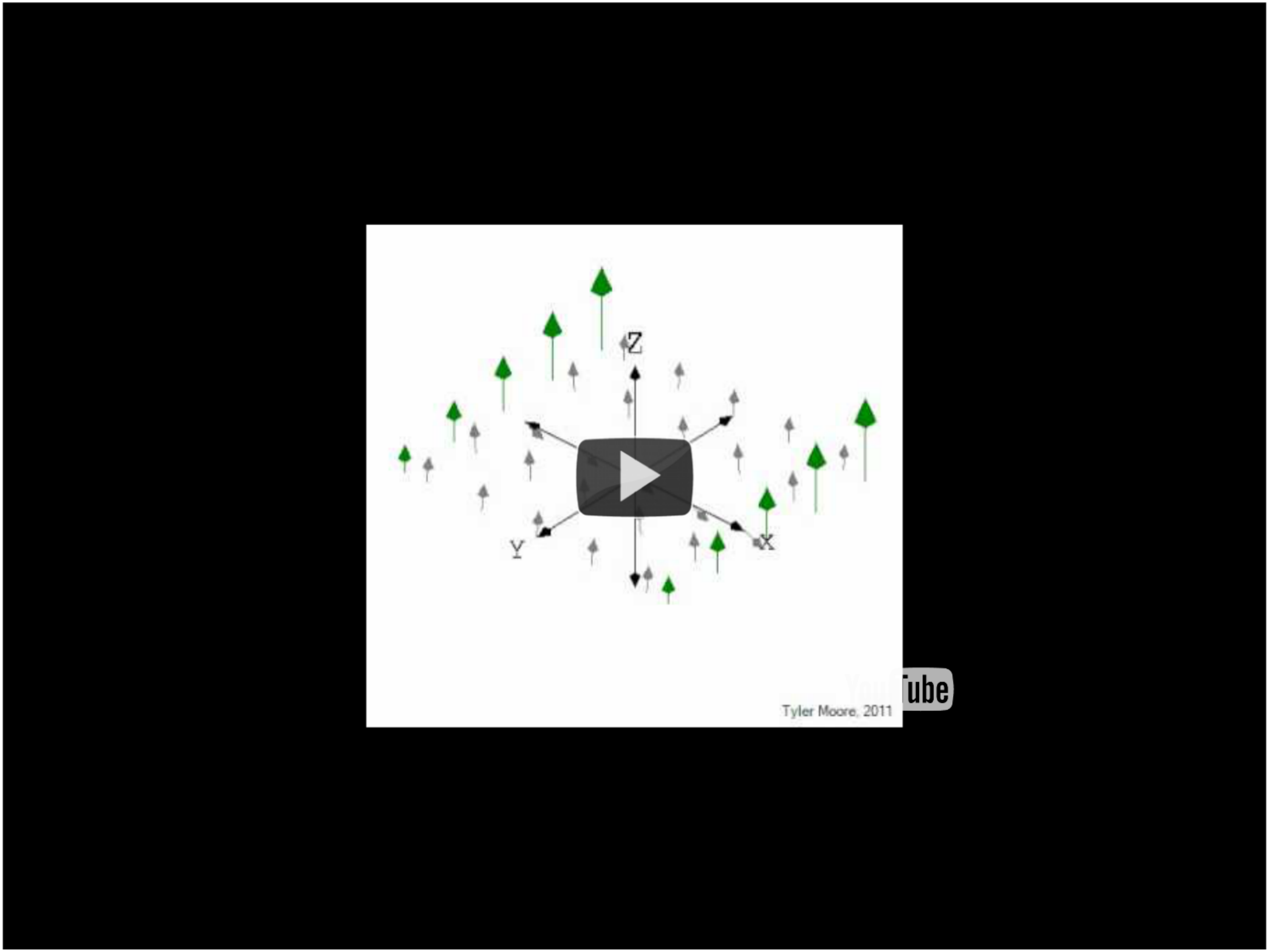


Voxel - position encoding

- Floors
- Pitch (frequency)
- Duration (canon)

3D imaging

- Slices
- Frequency
- Phase


Z
Y
X
Tyler Moore, 2011

Now Can We Make A Useful Image?

Table XIV
Water content of fat-free normal human tissue

Tissue	Water content (%)
Skeletal muscle	79
Myocardium	80
Liver	71
Kidney	81
Brain white matter	84
Brain gray matter	72
Nerve	56
Femur cortex	12
Teeth	10

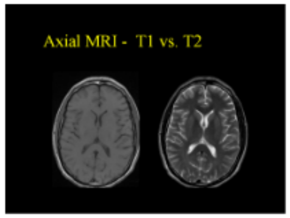
Table XV
The spin–lattice relaxation time (T_1) and spin–spin relaxation time (T_2) of various biological tissues at 0.2 tesla

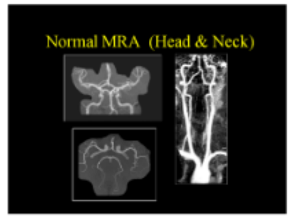
Tissue	T_1, msec	T_2, msec
Fat	240 ± 20	60 ± 10
Muscle	400 ± 40	50 ± 10
Gray matter	495 ± 85	100 ± 10
White matter	390 ± 70	90 ± 20
Lung	460 ± 90	80 ± 30
Kidney	670 ± 60	50 ± 10
Liver	380 ± 20	40 ± 20
Liver metastases	570 ± 190	40 ± 10
Lung carcinoma	940 ± 460	20 ± 10

Source: Morgan and Hendee, 1984

Biological applications

Morphological imaging

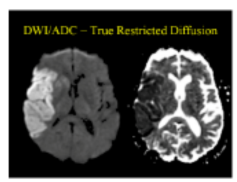


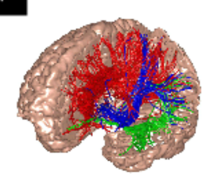


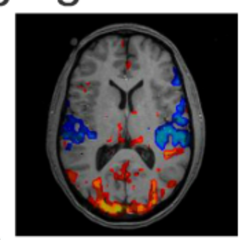
- T1 "anatomy"
- T2 "pathology"

- Angiography (T1)
(Gd contast)

Functional imaging



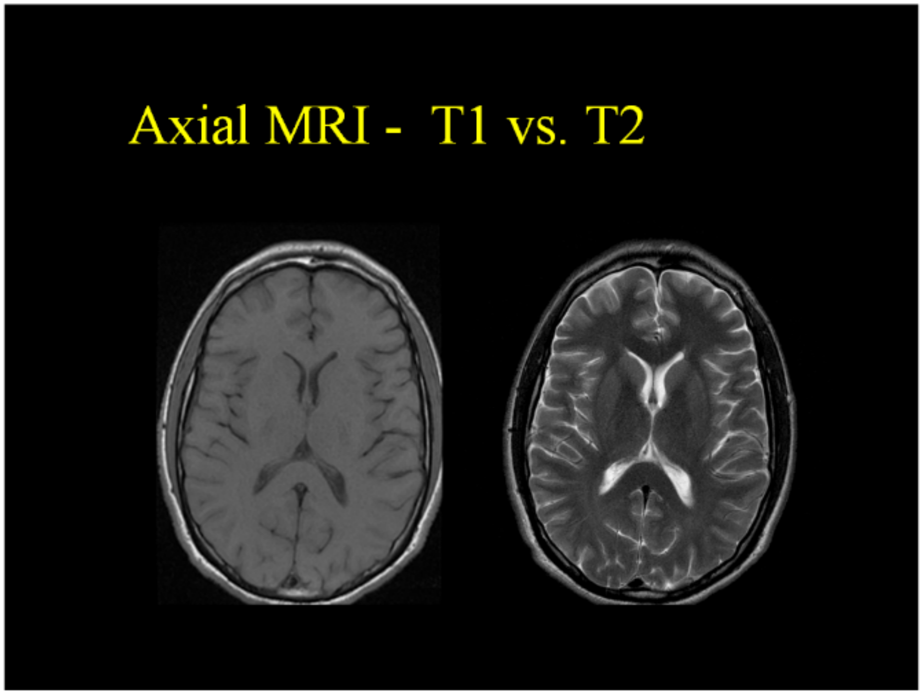


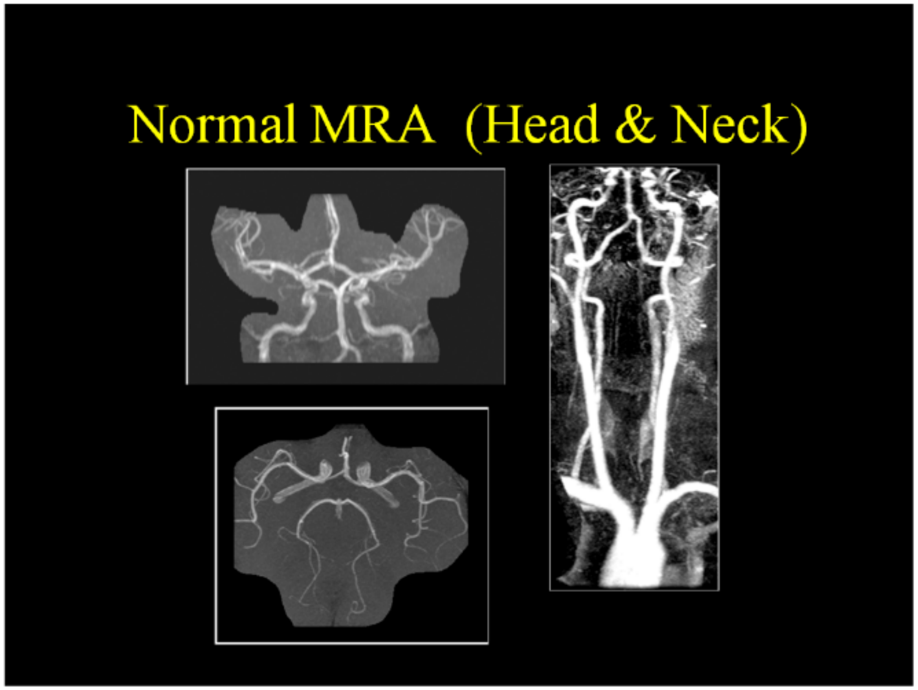


- Diffusion coeff
  (water)

- Blood
  (oxiFe - deoxiFe)

Morphological imaging





- T1 "anatomy"
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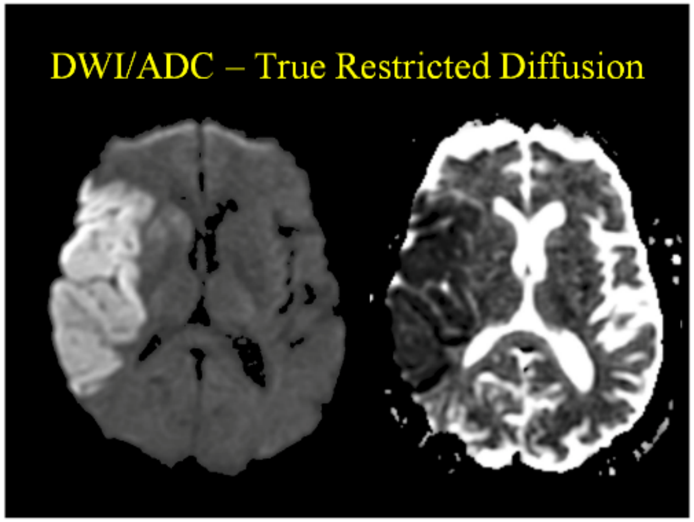
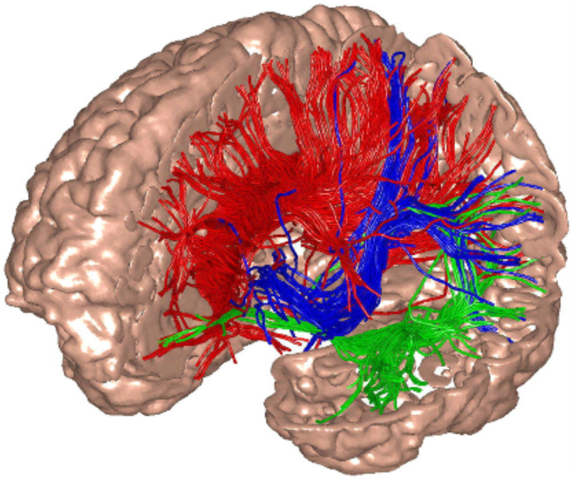
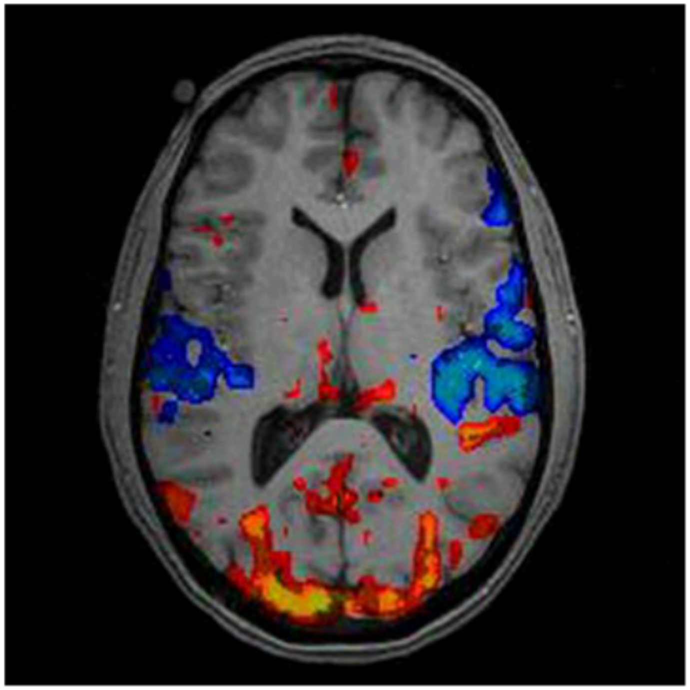
Functional imaging

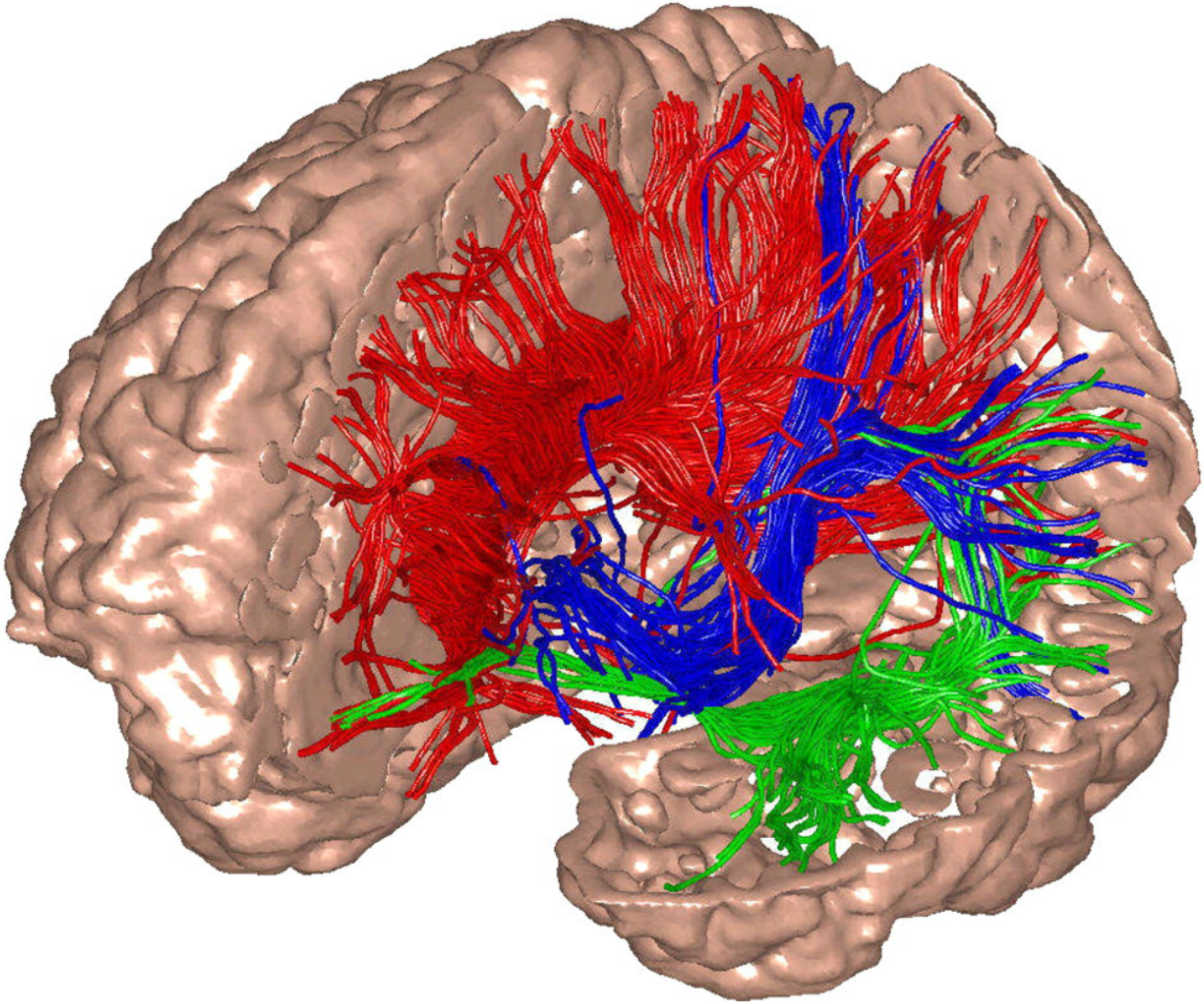




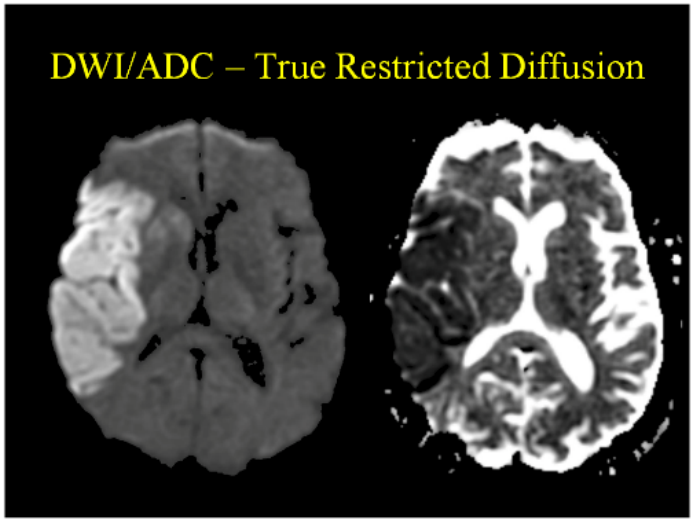


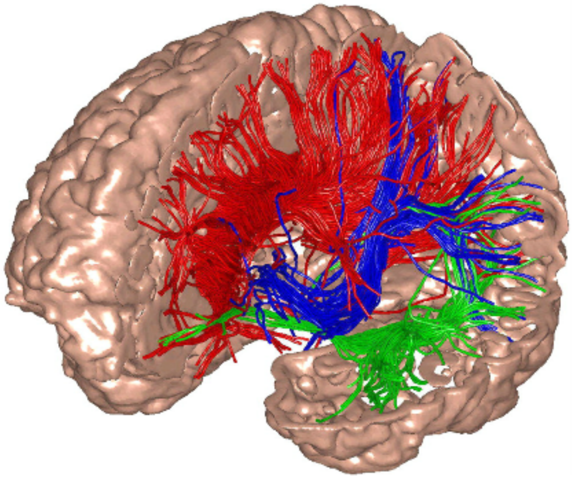
- Diffusion coeff (water)

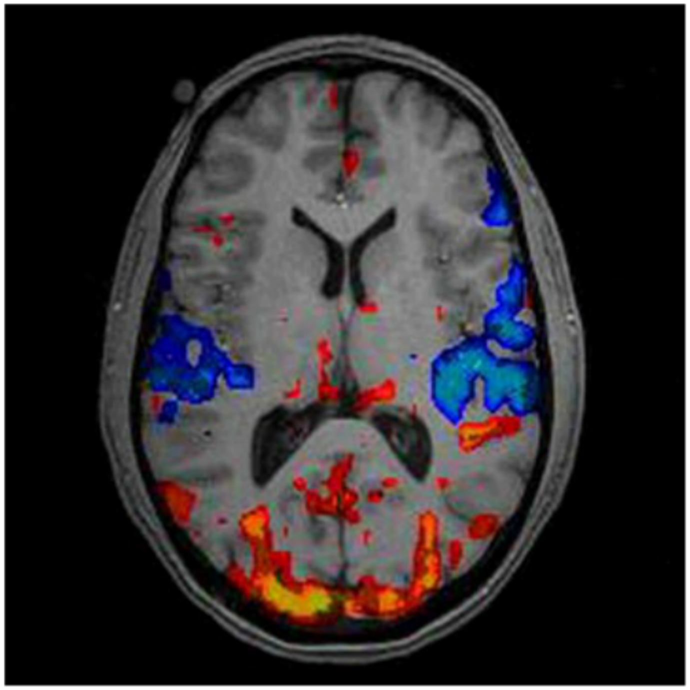
- Blood (oxiFe - deoxiFe)



Functional imaging







- Diffusion coeff (water)

- Blood (oxiFe - deoxiFe)

Background ... :

- http://www.imaios.com

- MRI Physics Tutorial (youtube)

- http://oftankonyv.reak.bme.hu/