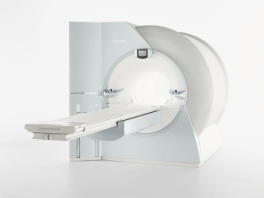
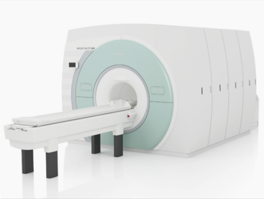
Magnetic Resonance Imaging

Magnetic Resonance Imaging

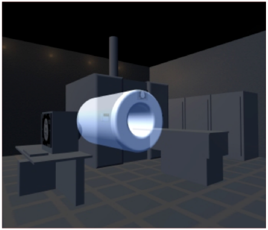
Introduction



Mangetom Symphony 1.5T



Mangetom Symphony 7T

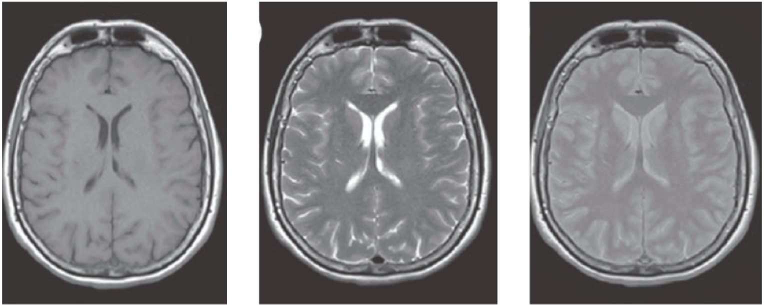


- T ... Tesla (unit for magnetic field density)
- For comparison: Earth's magnetic field: 5×10^{-5}T

Image courtesy of Siemens Healthcare.

Magnetic Resonance Imaging

Examples



From *left to right*: T_1-weighted, T_2-weighted, Proton density

At the end of the lecture, we should be able to explain the different appearances of the tissue types.

Magnetic Resonance Imaging

Introduction

With MR Imaging ...

- ... we get high-resolution information of anatomic structures
- ... we get high-contrast for soft-tissue types
- ... we have *no* exposure to radiation!

However,

- ... we have more complicated instrumentation
- ... scan acquisition takes longer (problem with patient motion)
- ... precautions must be taken to keep metal objects away
- ... imaging is expensive (acquisition, maintenance, operation)

To understand MR imaging, we need to understand Nuclear Magnetic Resonance (NMR) first.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

- Spin is a fundamental property of nature (like electric charge)
- Spin comes in multiples of $1/2$ and can be positive or negative
- Protons/electrons/neutrons possess spin of $+1/2$ or $-1/2$
- Particles of opposite spin eliminate observable spin

Unpaired spins

In nuclear magnetic resonance, *unpaired* nuclear spins are of importance.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

A nucleus consists of protons and neutrons (aka “nucleons”).

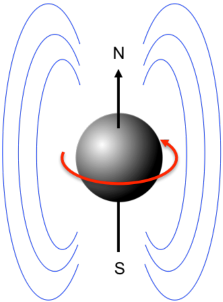
When the total number of protons and neutrons is *odd*, or the number of protons is odd, the spin gives the nucleus

1. (spin) angular momentum, and
2. magnetic moment.

Formulated very simplistically, the spin causes the nucleus to behave like a *tiny magnet*.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)



Spin angular momentum is quantized, i.e.,

$$|\mathbf{s}| = \sqrt{q(q+1)}\hbar$$

with $q = {}^{n}/_{2}$, $n \in \mathbb{N}_+$ and $\hbar$ being the *reduced Planck constant*.

The magnetic moment of the nucleus is

$$\boldsymbol{\mu} = \gamma \boldsymbol{s}, \text{ with } \gamma = \frac{g\mu_m}{\hbar}$$

being the gyromagnetic ratio.

For ^{1}H (hydrogen), $n = 1 \Rightarrow q = 1/2$ and ${}^{\gamma}/_{2\pi}$ is 42.58Mhz/T.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

Note

Spin angular momentum only says something about the *speed* of rotation, *not* about the orientation direction.

Nuclei with spin can be imaged by MRI! Below is a table[1] with isotopes relevant to MRI:

Nucleus	Spin	$\gamma/2\pi$ Mhz/T	Concentration
Hydrogen ^{1}H	$1/2$	42.58	88M
Sodium ^{23}Na	$3/2$	11.27	80mM
Oxygen ^{17}O	$5/2$	-5.77	16mM

[1] M…Molar, mM…milliMolar

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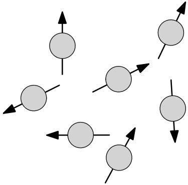
Physics primer – Nuclear Magnetic Resonance (NMR)

In the absence of external magnetic field, the spin orientations of the nuclei are *random* and cancel each other.



Without external magnetic field
(the distribution of magnetic moments is isotropic)

Particles with $q = 1/2$ have $(2q + 1)$ energy sublevels with slightly different energy; these are *degenerate* without an external field.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

When placed in an (external) magnetic field $\mathbf{B}_0$, the energy of a nucleus is

$$E = -\langle \boldsymbol{\mu}, \mathbf{B}_0 \rangle$$

In general, for the z-component of $\boldsymbol{\mu}$ we have

$$\mu_z = \gamma m \hbar$$

with m as the *magnetic quantum number* $m = -q, -q+1, \ldots, +q$.

By convention, we consider an external magnetic field $\mathbf{B}_0$, aligned with the z-direction. We get (for the energy)

$$E_m = -\mu_z B_0 = -\gamma m B_0 \hbar$$

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

Example for ^{1}H, i.e., $m = \pm 1/2$:

$$E_{+1/2} = -\gamma 1/2 B_0 \hbar$$
$$E_{-1/2} = +\gamma 1/2 B_0 \hbar$$

Consequently, $\Delta E = \gamma \hbar B_0$, or

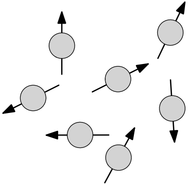
$$\Delta E = \gamma \hbar B_0 = \gamma \frac{h}{2\pi} B_0 = h \underbrace{\frac{\gamma}{2\pi} B_0}_{\nu_L} = h \nu_L,$$

where ν_L is referred to as the Lamor frequency.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

At the same time, in the presence of an external magnetic field spins tend to align with the magnetic field lines.



Without external magnetic field

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Physics primer – Nuclear Magnetic Resonance (NMR)

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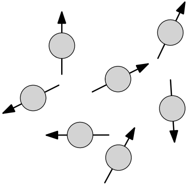

Without external magnetic field

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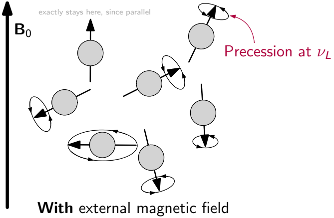

With external magnetic field

(the distribution of magnetic moments is slightly **skewed** now)

We do observe a torque of

$$\mathbf{t} = \boldsymbol{\mu} \times \mathbf{B}_0$$

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

We know that torque is also defined as the time-derivative of the angular momentum (in our case: spin angular momentum), i.e.,

$$\mathbf{t} = \frac{d}{dt}\mathbf{s} = \frac{1}{\gamma}\frac{d}{dt}\boldsymbol{\mu}$$

With $\mathbf{t} = \boldsymbol{\mu} \times \mathbf{B}_0$ from above, we have

$$\frac{d\boldsymbol{\mu}}{dt} = \gamma\boldsymbol{\mu} \times \mathbf{B}_0$$

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Physics primer – Nuclear Magnetic Resonance (NMR)

For the net magnetization $\mathbf{M}$ (and omitting indices in $\mathbf{B}_0$), we have the motion equation

$$\begin{aligned} \frac{d}{dt}\mathbf{M} &= \frac{d}{dt}\sum_i \boldsymbol{\mu}_i \\ &= \sum_i \frac{\boldsymbol{\mu}_i}{dt} \\ &= \sum_i \gamma(\boldsymbol{\mu}_i \times \mathbf{B}) \\ &= \gamma(\mathbf{M} \times \mathbf{B}) \end{aligned}$$

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Physics primer – Nuclear Magnetic Resonance (NMR)

In other words, $\mathbf{M}$ precesses around the axis of the external field (in our case around the z-axis, see previous slides).

Net magnetization

In a static magnetic field $\mathbf{B}_0$, we refer to $\mathbf{M}_0$ as the *net magnetization*

We will next consider this in a more formal setting.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

Splitting $\gamma(\mathbf{M} \times \mathbf{B})$ up (by components), we get

$$
\begin{aligned}
\frac{d}{dt} M_x &= \gamma(M_y B_z - M_z B_y) \\
\frac{d}{dt} M_y &= \gamma(M_z B_x - M_x B_z) \\
\frac{d}{dt} M_z &= \gamma(M_x B_y - M_y B_x)
\end{aligned}
$$

This is, however, only true if the spins would be *independent* of each other.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

The Bloch equations describe the motion equations for magnetization in an external magnetic field.

$$\begin{aligned}
\frac{d}{dt}M_x &= \gamma(M_y B_z - M_z B_y) - \frac{1}{T_2}M_x \\
\frac{d}{dt}M_y &= \gamma(M_z B_x - M_x B_z) - \frac{1}{T_2}M_y \\
\frac{d}{dt}M_z &= \gamma(M_x B_y - M_y B_x) - \frac{1}{T_1}(M_z - M_0)
\end{aligned}$$

These equations take into account interdependencies between spins, i.e., *spin-spin relaxation* and *spin-lattice relaxation*.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

Lets consider one concrete example (without relaxation) of $\mathbf{B}_0$ parallel to the z-axis.

$$\text{We have } \mathbf{B}_0 = \begin{pmatrix} 0 \\ 0 \\ B_0 \end{pmatrix} \Rightarrow \frac{d}{dt}\mathbf{M} = \begin{pmatrix} +\gamma B_0 M_y \\ -\gamma B_0 M_x \\ 0 \end{pmatrix}$$

The solution to this motion equation (without derivation) is

$$\begin{pmatrix} M_x(t) \\ M_y(t) \\ M_z(t) \end{pmatrix} = \begin{pmatrix} m_0 \cos(w_0 t) \\ m_0 \sin(w_0 t) \\ C \end{pmatrix}$$

with $w_0 = \nu_L$ being the Lamor frequency and $\mathbf{M}(0) = m_0$.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

The net magnetization $\mathbf{M}_0$ results from *more* nuclear spins in the energetically lower state (out of $2q + 1 = 2$)

The ratio N_+/N_- of energy levels is governed by

$$\frac{N_+}{N_-} = e^{-\frac{E_+ - E_-}{kT}} = e^{-\frac{\Delta E}{kT}} = e^{-\frac{\gamma \hbar B_0}{kT}}$$

where k is the Bolzmann constant and T is temperature (e.g. $\approx$ 310 Kelvin for a human body).

$\Rightarrow$ Larger $\mathbf{B}_0$ lead to greater net magnetization.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

Example for a 3T (Tesla) field $\mathbf{B}_0$:

There are only about 10/million! more protons parallel to the field than anti-parallel.

In practice, we want large magnetic fields (e.g., 7T scanner).

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

Spins in energetically lower states can absorb photons and *switch* to the energetically higher state and vice versa.

If we emit radiation, this *switch* happens if the emitted energy E equals ΔE and, since, $E = hf$ for photons, we have

$$f = \nu_L,$$

i.e., the Lamor frequency.

Example: In a 1.5T B_0 field, ν_L for hydrogen and carbon 13 (the atoms most relevant in medical imaging) are 63.9 and 16.1 MHz.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

Next, we consider the relaxation mechanisms by introducing a rotating coordinate system (x', y', z) which rotates at the Lamor frequency around the z-axis.

The following parts of the Bloch equations remain

$$
\begin{aligned}
\frac{dM_{x'}}{dt} &= -\frac{1}{T_2} M_{x'} \\
\frac{dM_{y'}}{dt} &= -\frac{1}{T_2} M_{y'} \\
\frac{dM_z}{dt} &= -\frac{1}{T_1} (M_z - M_0)
\end{aligned}
$$

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

The solution(s) are (without derivation):

$$
\begin{aligned}
M_{x'}(t) &= M_{x',0}e^{-t/T_2} \\
M_{y'}(t) &= M_{y',0}e^{-t/T_2} \\
M_z(t) &= (M_{z,0} - M_0)e^{-t/T_1} + M_0
\end{aligned}
$$

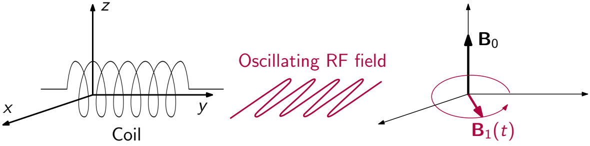
Lets try initial values at the equilibrium state, i.e., $M_{x',0} = M_{y',0} = 0$ and $M_{z,0} = M_0$.

$\Rightarrow$ We get the original precession equations back.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

We are now in the position to consider an additional oscillating magnetic field $\mathbf{B}_1$.



The field is generated by a coil and oriented perpendicular to $\mathbf{B}_0$. With $\mathbf{B}_1(t) = B_1(\cos(w_{ext}t), -\sin(w_{ext}t), 0)^\top$ we get

$$\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_1(t) = \begin{pmatrix} +B_1\cos(w_{ext}t) \\ -B_1\sin(w_{ext}t) \\ B_0 \end{pmatrix}$$

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

We need the nuclei to switch their magnetic moment. This is achieved through the oscillating $\mathbf{B}_1(t)$ field whose photons carry the energy

$$\Delta E = h\nu_L.$$

For *resonance*, i.e., to change energy states, $\mathbf{B}_1(t)$ needs to oscillate at the Lamor frequency $w_{ext} = \nu_L$.

In the following, we will use the Bloch equations to describe what happens to the net magnetization.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

To make our life easier, we switch coordinate systems again. The new axes $\mathbf{x}', \mathbf{y}', \mathbf{z}'$ are:

$$\mathbf{x}' = \begin{pmatrix} +\cos(w_{ext}t) \\ -\sin(w_{ext}t) \\ 0 \end{pmatrix}, \ \mathbf{y}' = \begin{pmatrix} +\sin(w_{ext}t) \\ +\cos(w_{ext}t) \\ 0 \end{pmatrix}, \ \mathbf{z}' = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix}$$

Remark: $\langle \mathbf{x}', \mathbf{y}' \rangle = 0$.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

Lets look at the Bloch equations (without relaxation first). In the rotating new coordinate system we get

$$\left(\frac{d}{dt}\mathbf{M}\right)_{\text{rot}} = \left(\frac{d}{dt}\mathbf{M}\right)_{\text{stat}} + M_x \frac{\partial \mathbf{x}'}{\partial t} + M_y \frac{\partial \mathbf{y}'}{\partial t} + M_z \frac{\partial \mathbf{z}'}{\partial t}$$

The partial derivatives are

$$\frac{\partial \mathbf{x}'}{\partial t} = -w_{ext}\mathbf{y}', \ \frac{\partial \mathbf{y}'}{\partial t} = -w_{ext}\mathbf{x}', \ \frac{\partial \mathbf{z}'}{\partial t} = 0$$

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Physics primer – Nuclear Magnetic Resonance (NMR)

$$\left(\frac{d}{dt}\mathbf{M}\right)_{\text{rot}} = \left(\frac{d}{dt}\mathbf{M}\right)_{\text{stat}} + M_x\frac{\partial \mathbf{x}'}{\partial t} + M_y\frac{\partial \mathbf{y}'}{\partial t} + M_z\frac{\partial \mathbf{z}'}{\partial t}$$

We simply use our expression for **B**, i.e.,

$$\begin{aligned}\left(\frac{d}{dt}\mathbf{M}\right)_{\text{stat}} &= \gamma(\mathbf{M} \times (\mathbf{B}_0 + \mathbf{B}_1(t))) \\ &= \gamma(\mathbf{M} \times (B_0\mathbf{z}' + B_1\mathbf{x}'))\end{aligned}$$

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

Also, we can write the partial derivatives as

$$-w_{ext}(M_x\mathbf{y}' - M_y\mathbf{x}') = -w_{ext}(\mathbf{M} \times \mathbf{z}')$$

Rearranging and collecting terms lead to

$$\begin{aligned}\left(\frac{d}{dt}\mathbf{M}\right)_{\text{rot}} &= \gamma\left(\mathbf{M} \times \left[\left(B_0 - \frac{w_{ext}}{\gamma}\right)\mathbf{z}' + B_1\mathbf{x}'\right]\right) \\ &= \gamma\left(\mathbf{M} \times \mathbf{B}_{eff}\right)\end{aligned}$$

with

$$\mathbf{B}_{eff} = \left(\left(B_0 - \frac{w_{ext}}{\gamma}\right)\mathbf{z}' + B_1\mathbf{x}'\right)$$

We have resonance if the z-component vanishes, i.e., $\gamma B_0 = w_{ext}$ (Lamor frequency).

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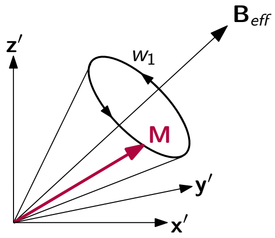
Physics primer – Nuclear Magnetic Resonance (NMR)

Remember that we are in the rotating coordinate system!

The magnetization vector precesses, with frequency w_1, around the effective magnetic field $\mathbf{B}_{eff}$.



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Physics primer – Nuclear Magnetic Resonance (NMR)

At resonance, i.e., $w_{ext} = \gamma B_0$, we have

$$\left(\frac{d}{dt}\mathbf{M}\right)_{\text{rot}} = \gamma(\mathbf{M} \times B_1\mathbf{x}') = \begin{pmatrix} 0 \\ -\gamma B_1 M_z \\ +\gamma B_1 M_y \end{pmatrix}$$

This system can be solved with

$$M_y = m_1 \cos(\gamma B_1 t + \phi)$$
$$M_z = m_1 \sin(\gamma B_1 t + \phi)$$

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Physics primer – Nuclear Magnetic Resonance (NMR)

We notice that ...

1. ... with

$$\phi = {}^{\pi}/_{2}$$

the magnetization is in the direction of $\mathbf{B}_0$ at $t = 0$.

2. ... if $\mathbf{B}_1$ is applied for time $t = T$, $\mathbf{M}$ rotates by angle

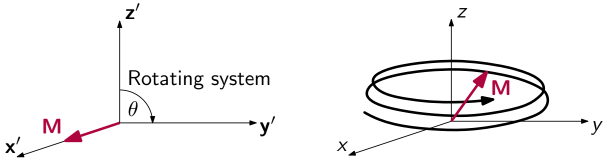
$$\theta = \gamma B_1 T$$

So, choosing the time T and strength B_1 appropriately, allows to tip the magnetization vector into the $\mathbf{x}'\mathbf{y}'$-plane.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

When $\mathbf{B}_1(t)$ is turned off (after time T), we can illustrate what happens to the magnetization as:



In the still coordinate system (right) the precession (at frequency w_1) is mixed with the precession (at frequency w_0) around z.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

With such as 90° pulse, we get maximum magnetization in the xy-plane, referred to as transversal magnetization.

The rotating magnetization induces a current in the RF coil.

Due to relaxation mechanisms, the transversal magnetization decays with time, in particular, exponentially with T_2^*.

This signal is called the *Free Induction Decay*.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

T_1 is called longitudinal relaxation time and measures how long it takes for the z-component of $\mathbf{M}$ to "grow back" along z.

This happens, since magnetic moments switch between states (from high to low) and energy is released to the environment ("spin-lattice" relaxation).

T_2 is called transversal relaxation time and measures the decay of transversal magnetization (i.e., perpendicular to $\mathbf{B}_0$).

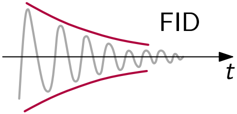
This happens, since spins experience different slightly different magnetic fields and hence precess at different frequencies $\Rightarrow$ "spin-spin" relax.).

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

However, $\mathbf{B}_0$ is not totally homogeneous $\Rightarrow$ different Lamor frequencies $\Rightarrow$ different precession freq. $\Rightarrow$ faster dephasing.

Transversal magnetization decays with $T_2^* < T_2$

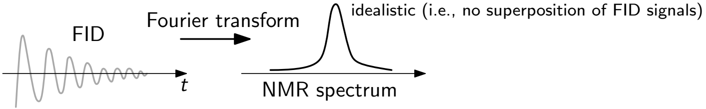


We can only measure T_2^* by observing the FID. To measure T_1 and T_2 we need to work with so called *pulse-sequences*.

Magnetic Resonance Imaging

Physics primer – Nuclear Magnetic Resonance (NMR)

A Fourier transform of the FID signal, gives a *Lorentzian* line shape in the frequency domain.



This can be converted to a measure of *proton density* in the patient.

Typically, the relaxation times T_1, T_2 are also taken into account; we then refer to T_1/T_2**-weighted** images.

Magnetic Resonance Imaging

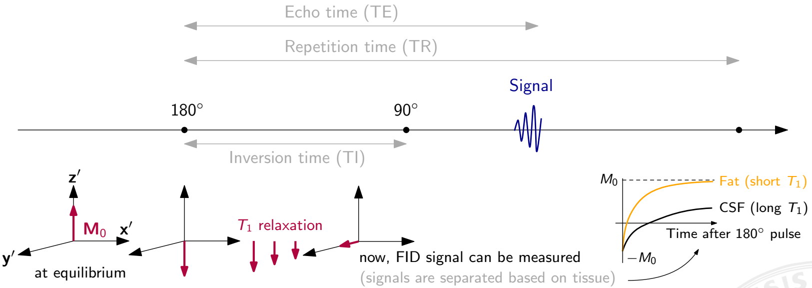
Physics primer – Pulse sequences

Pulse sequences are all about
recovering the relaxation times T_1 and T_2!

Magnetic Resonance Imaging

Physics primer – Pulse sequences

Inversion-Recovery Sequence (to measure T_1)[2]



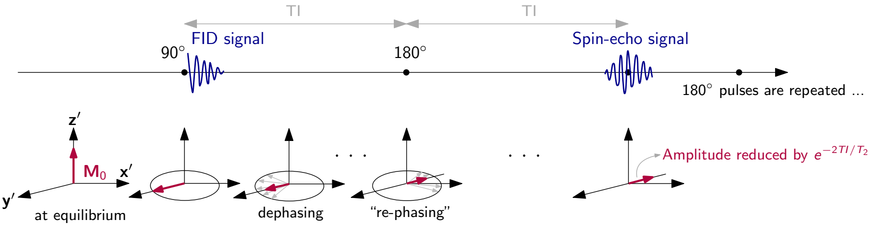
TR,TI and TE control contrast.

[2] For more info on IR sequences, click here

Magnetic Resonance Imaging

Physics primer – Pulse sequences

Spin-Echo Sequence (to measure T_2)

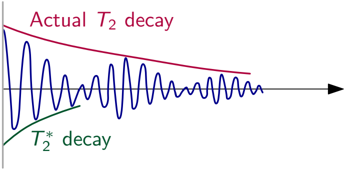


At 2TI, we get a spin-echo signal of a by e^{-2TI/T_2} reduced amplitude.

Magnetic Resonance Imaging

Physics primer – Pulse sequences

Here is a schematic illustration of the whole signal after a couple of 180° re-phasing pulses.

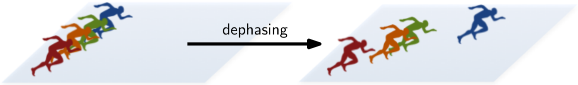


The purpose of multiple re-phasing pulses is to get a better estimate of the T_2 decay.

Magnetic Resonance Imaging

Physics primer – Pulse sequences

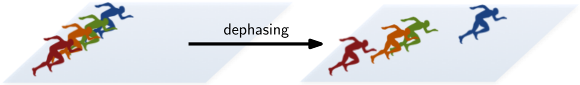
Illustration of re-phasing via a 180° pulse:



Magnetic Resonance Imaging

Physics primer – Pulse sequences

Illustration of re-phasing via a 180° pulse:

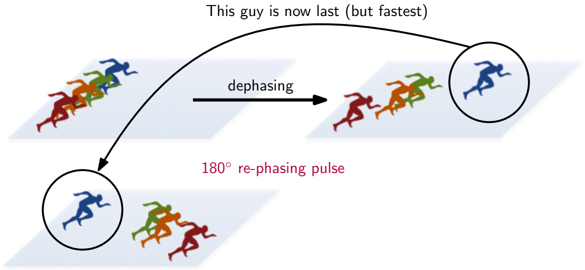


180° re-phasing pulse

Magnetic Resonance Imaging

Physics primer – Pulse sequences

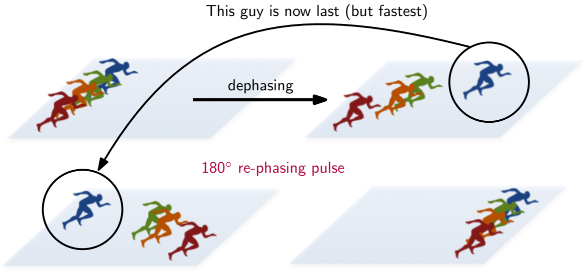
Illustration of re-phasing via a 180° pulse:



Magnetic Resonance Imaging

Physics primer – Pulse sequences

Illustration of re-phasing via a 180° pulse:



Problem

At this point, we *do not* know the location of the signal, i.e., we do not have spatial resolution and can't assign values to voxel!

The solution to this problem are (linear) *gradient fields*.

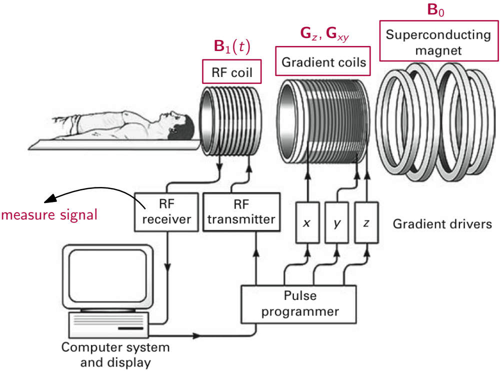
Summary of magnetic fields in MR imaging:

1. Static magnetic field $\mathbf{B}_0$
2. Oscillating RF field $\mathbf{B}_1(t)$
3. Gradient fields $\mathbf{G}_z, \mathbf{G}_{xy}$

Magnetic Resonance Imaging

Physics primer – Pulse sequences

Schematic illustration of the different magnetic fields:



Magnetic Resonance Imaging

Physics primer – Gradient fields (Principle)

We already know almost all the components to understand the principle.

Gradient fields are superimposed on $\mathbf{B}_0$. Remember that Lamor frequencies are proportional to the overall magnetic field.

Through gradients in x, y, z direction, we *could* tessellate the space into cubes.

In practice, this is time-consuming, so this is only done in the z-direction $\Rightarrow$ we get slices of certain thickness!

Magnetic Resonance Imaging

Physics primer – Gradient fields (Principle)

$$\mathbf{B}_{grad} = \mathbf{B}_0 + z\mathbf{G}_z = \begin{pmatrix} 0 \\ 0 \\ B_0 + zG_z \end{pmatrix}$$

Consequently, the Lamor frequency depends on the position of the nuclei on the z-axis, i.e.,

$$w(z) = \gamma(B_0 + zG_z)$$

The 90-degree pulse also has a certain bandwidth Δw. So, we get resonance in only a certain slice of thickness

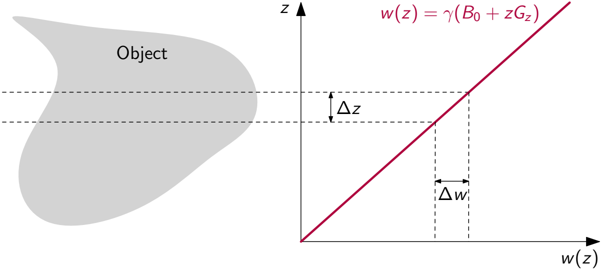
$$\Delta z = \frac{\Delta w - \gamma B_0}{\gamma G_z}$$

This is called slice-selective excitation.

Magnetic Resonance Imaging

Gradient fields (Principle)

Illustration (selective excitation):



The linear gradient constrains the region where resonance occurs to a slice of thickness Δz.

Magnetic Resonance Imaging

Projection-Reconstruction Technique

Next, we turn off the linear z-gradient field and $\mathbf{B}_1$ and turn on a gradient field in xy, i.e.,

$$\mathbf{G}_{xy} = \begin{pmatrix} G_x \\ G_y \\ 0 \end{pmatrix}$$

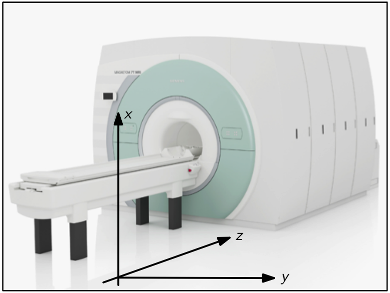
This field remains on during measurement.

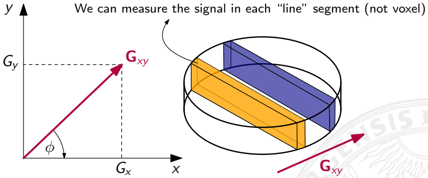
Magnetic Resonance Imaging

Projection-Reconstruction Technique

What happens?

We can set the angle ϕ of the gradient field $\mathbf{G}_{xy}$ by changing G_x and G_y. Say we have the following configuration:





Magnetic Resonance Imaging

Projection-Reconstruction Technique

The spins begin to oscillate at different frequencies once $\mathbf{G}_{xy}$ is turned on (and $\mathbf{B}_1$ and $\mathbf{G}_z$ are off).

Along different "line" segments (perpendicular to $\mathbf{G}_{xy}$), we observe the same frequency (blue and orange on prev. slide).

Obtaining voxel values

Changing ϕ allows us to acquire projections at different angles and then apply *tomographic reconstruction*.

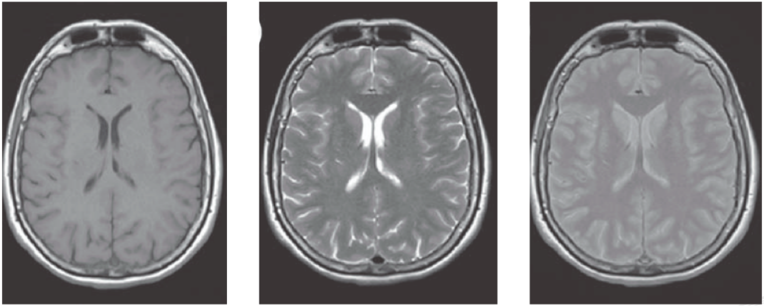
Some relaxation times for 1.5T:

Tissue	T_1 [msec]	T_2 [msec]	Density[3] [%]
Gray matter	950	100	85
White matter	600	80	90
Muscle	900	50	-
Cerebrospinal fluid (CSF)	4500	2200	85
Blood	1400	180-250	85

[3] Proton density

Magnetic Resonance Imaging

Examples



From *left to right*: T_1-weighted, T_2-weighted, Proton density