Basic Principles of Magnetic Resonance

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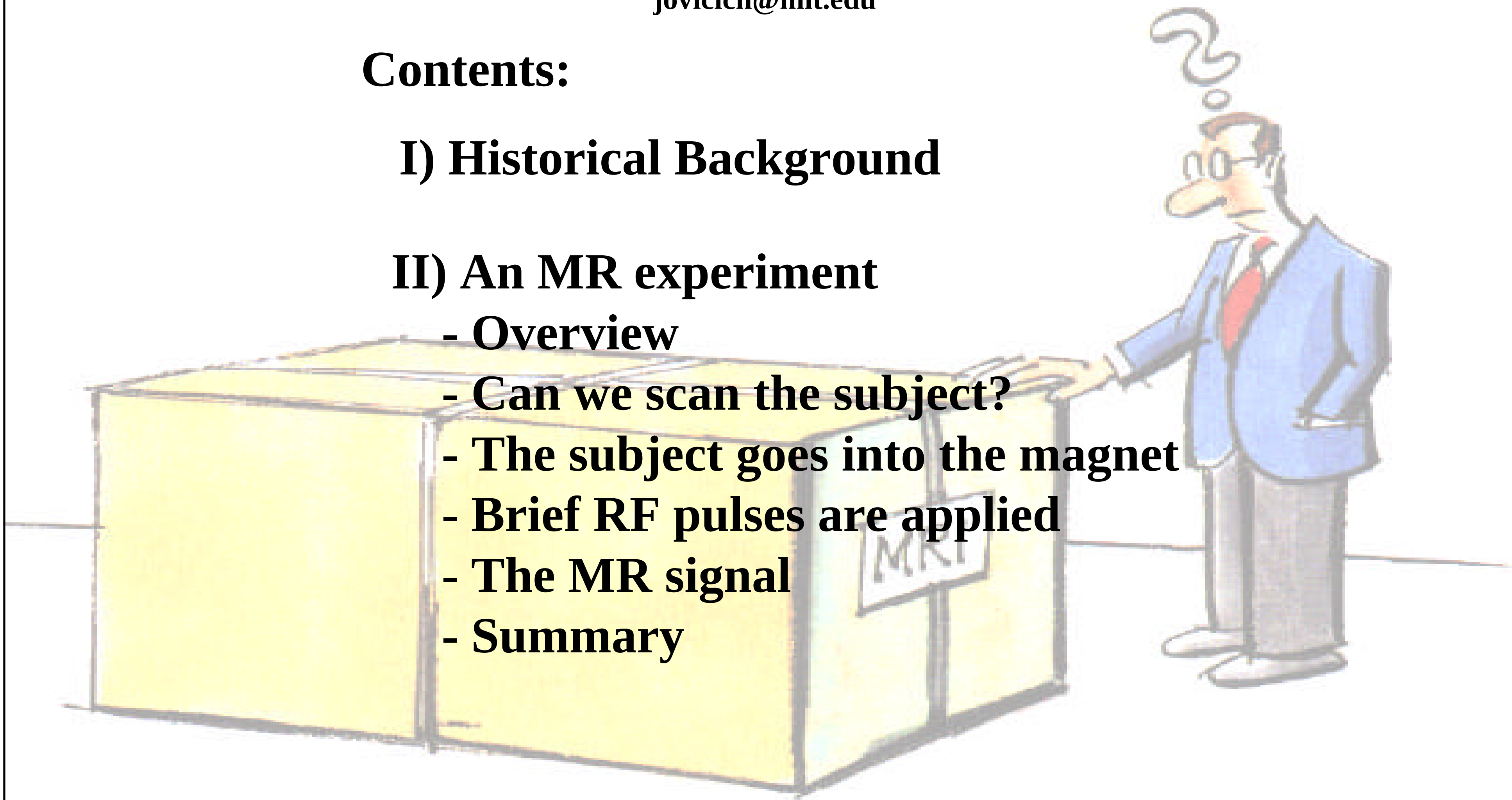
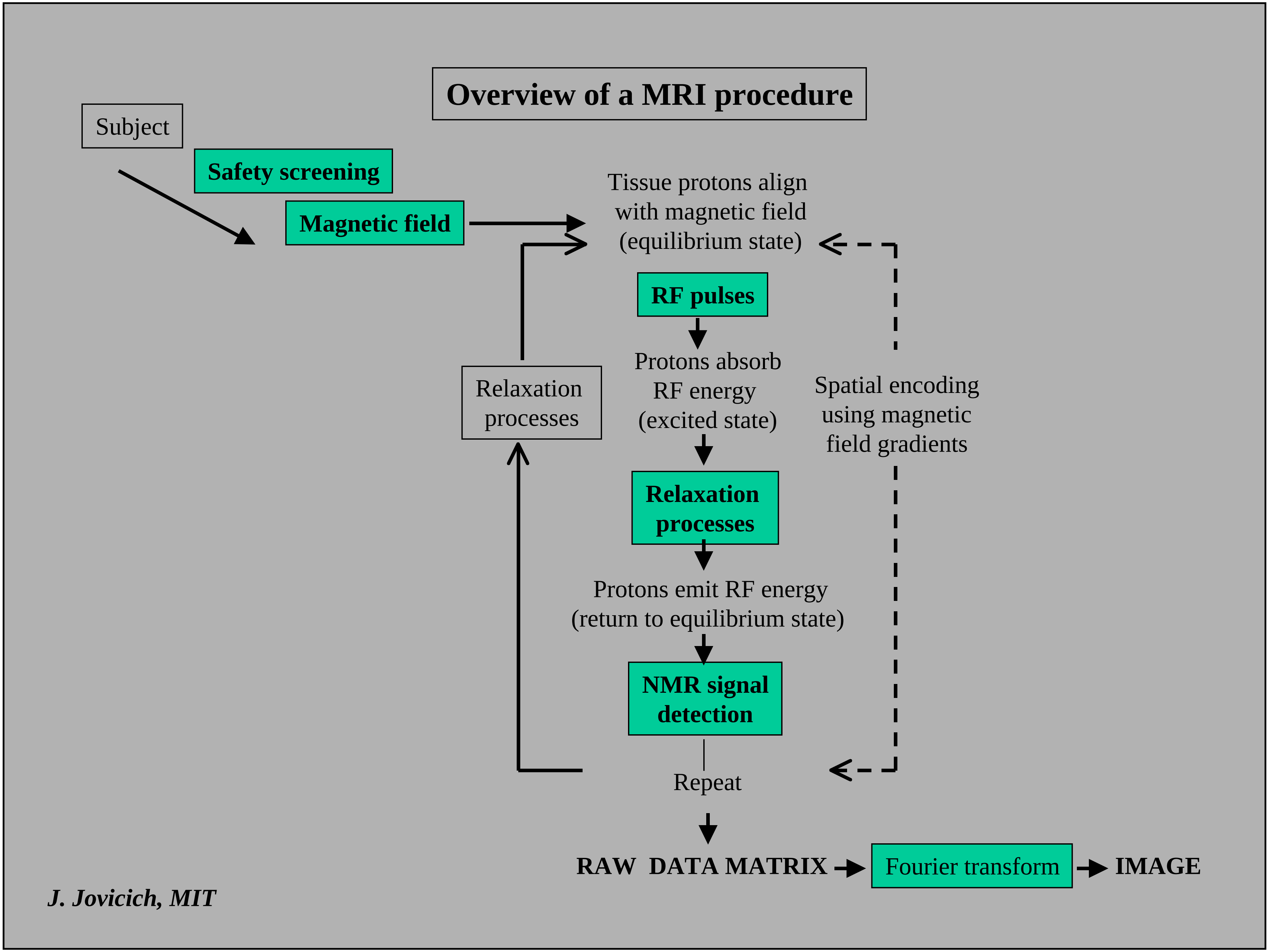
I) Historical Background

II) An MR experiment
- **Overview**
- **Can we scan the subject?**
- **The subject goes into the magnet**
- **Brief RF pulses are applied**
- **The MR signal**
- **Summary**




Overview of a MRI procedure
Subject
Safety screening
Magnetic field
Tissue protons align with magnetic field (equilibrium state)
RF pulses
Protons absorb RF energy (excited state)
Relaxation processes
Relaxation processes
Protons emit RF energy (return to equilibrium state)
NMR signal detection
Spatial encoding using magnetic field gradients
Repeat
RAW DATA MATRIX
Fourier transform
IMAGE
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Can we scan the subject?
Safety Issues

- Not everybody can undergo a MR examination
- Screening is mandatory to ensure safety / quality during the MR examination

A typical MRI scanner

The main magnetic field:

- **is VERY strong** (3T ~ 30,000 times the earth's magnetic field)
- **is** *A L W A Y S O N !!* (superconducting currents)
- **it's strength decays ~ 1 / r^3** (r is the distance from the center)

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Can we scan the subject?
Safety Issues

- Risks:
  - Ferromagnetic materials (unsafe)
    - will be subject to force / torque in the main magnetic field
    - risks associated with motion / displacements
    - active biomedical implants may not function properly

From: www.symplyphysics.com/flying_objects.html

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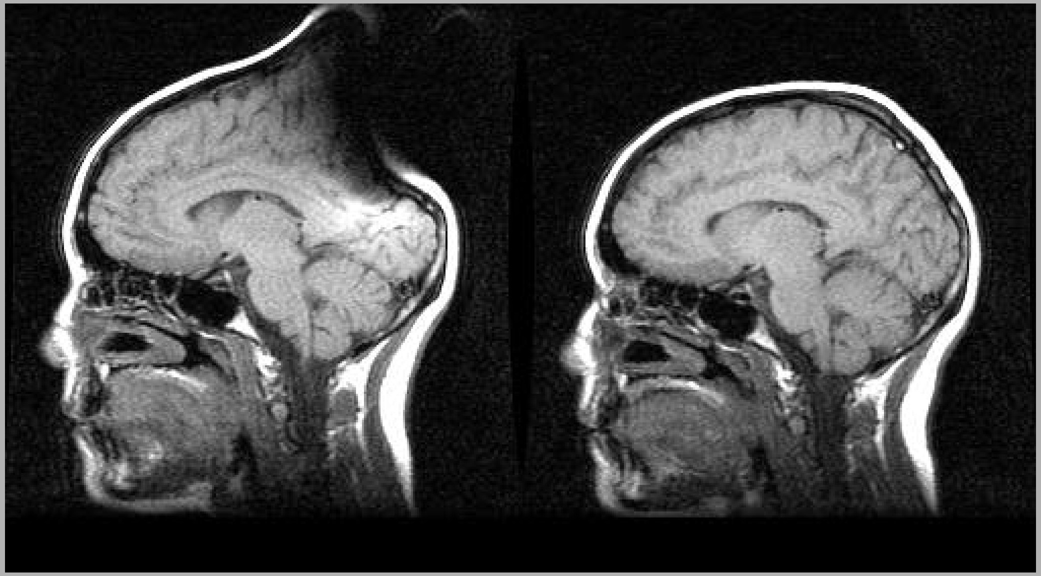
Can we scan the subject?
Safety Issues

- Risks:
  - Ferromagnetic materials (unsafe)
  - Non ferromagnetic materials (safe but give image distortions)

Sagitall MRI of a normal female subject



With hair rubber band*   Without hair rubber band

* The two ends of the rubber band are joined by a ~ 2 mm cooper clamp.

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Can we scan the subject?
Safety Issues

- Risks:
  - Ferromagnetic materials (unsafe)
  - Non ferromagnetic materials (safe but give image distortions)
  - Claustrophobia (subject unhappy → image distortions)

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Can we scan the subject?
Safety Issues

- Risks:
  - Ferromagnetic materials (unsafe)
  - Non ferromagnetic materials (safe but give image distortions)
  - Claustrophobia (subject unhappy → image distortions)
  - Movement during examination (potential problem for dynamic studies)
  - Acoustic protection (mandatory)

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Overview of a MRI procedure

Subject

Safety screening

Magnetic field

We will introduce the following concepts:

- equilibrium magnetization
- dynamics of the magnetization
- rotating coordinate system

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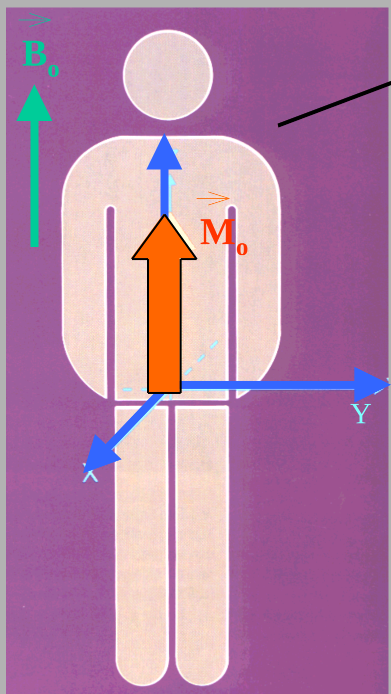
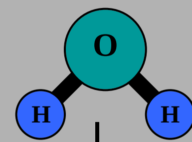
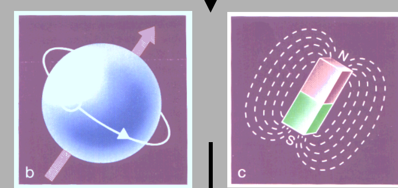
The subject goes into the magnet...

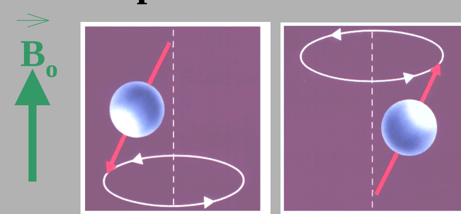


Single nucleus





Anti-parallel **Parallel**



High energy state (E_1)

Low energy state (E_0)

$\vec{B}_0$: uniform static magnetic field

$\vec{M}_0$: static macroscopic magnetization

Water molecules

↓

Hydrogen nucleus: magnetic moment $\vec{\mu}$

↓

Two energy states:

$$\Delta E = E_1 - E_0$$

$$\Delta E = \hbar\omega_0$$

↓

Precession frequency:

$\omega_o = \gamma \mathbf{B_o}$

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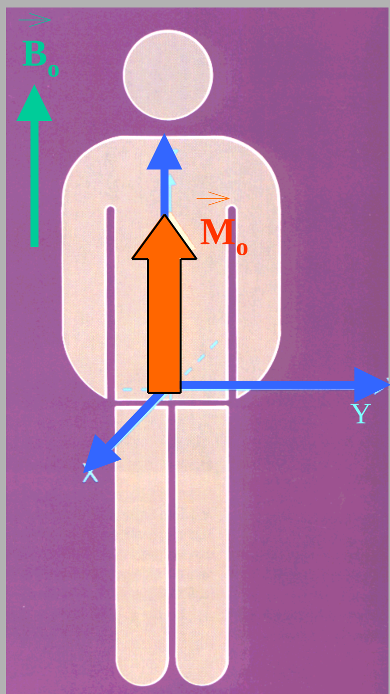
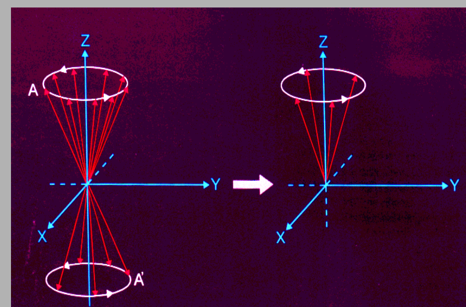
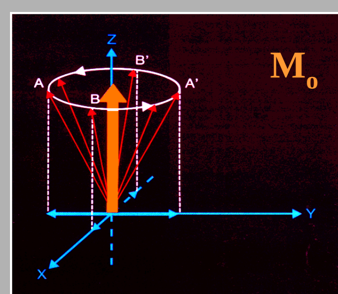
The subject goes into the magnet… (continued)



A group of protons

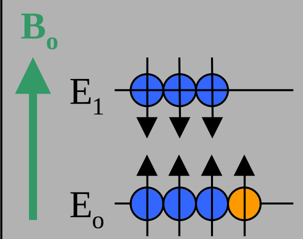


Net magnetization **Mo**



Equilibrium magnetization **Mo**:
- M_z aligned with **Bo**
- $M_{xy} = 0$

Energy states



$$\Delta E = \hbar\omega_0$$

$$\omega_o = \gamma B_o$$

Spin states distribution

$$\frac{N_1}{N_0} = \exp\left(-\frac{\hbar\gamma B_0}{kT}\right)$$

N_1 = # of protons in state E_1
N_0 = # of protons in state E_0
k : Boltzmann's constant
T : temperature

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Reminder of three main steps in MRI

0) Equilibrium (M_o along B_o)

↓

1) RF excitation
(tip M_o away from equil.)

↓

2) Precession of M_{xy} induces signal
(dephasing for a time ***TE***)

↓

3) Return to equilibrium
(recovery time ***TR***)

}

Dynamics of magnetization

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Dynamics of the magnetization

- Equation of motion of $\vec{M}$ in external $\vec{B}_{ext}$
- Classical mechanics formalism
- First, model a single nucleus
- Then, add up for sample
- Finally, consider relaxation (Bloch equations)

Equation of motion for a **single nucleus**:

- Mechanical moment ⇔ angular momentum (spin)

$$\vec{T} = \frac{d\vec{L}}{dt}$$

- Magnetic moment ⇔ spin

$$\vec{\mu} = \gamma \vec{L}$$

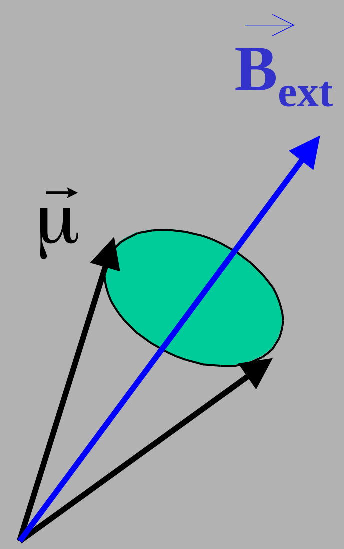
- Magnetic moment and magnetic field interaction

$$\vec{T} = \vec{\mu} \times \vec{B}_{ext}$$

⇒

$$\frac{d\vec{\mu}_{(t)}}{dt} = \vec{\mu}_{(t)} \times \gamma \vec{B}_{ext(t)}$$

Precession of $\vec{\mu}$ about $\vec{B}_{ext}$ with frequency $\omega = \gamma B_{ext}$



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Equation of motion for the **magnetization vector**:

- Assuming no interaction between nuclei

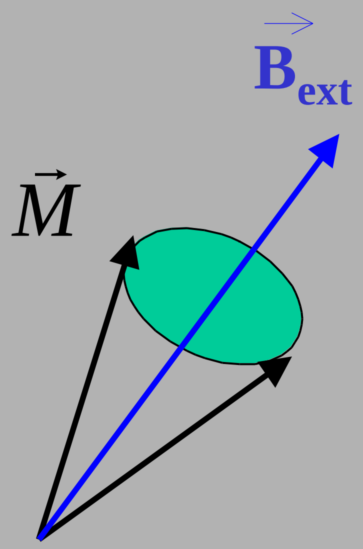
$$\vec{M} = \vec{\mu}_0 + \vec{\mu}_1 + \vec{\mu}_2 + \ldots = \sum \vec{\mu}_i \quad \text{(spin excess)}$$

- And since for each nuclei

$$\frac{d\vec{\mu}_{i(t)}}{dt} = \vec{\mu}_{i(t)} \times \gamma \vec{B}_{ext(t)}$$

$$\Rightarrow \quad \frac{d\vec{M}_{(t)}}{dt} = \vec{M}_{(t)} \times \gamma \vec{B}_{ext(t)}$$

Precession of $\vec{M}$ about $\vec{B}_{ext}$ with frequency $\omega = \gamma B_{ext}$



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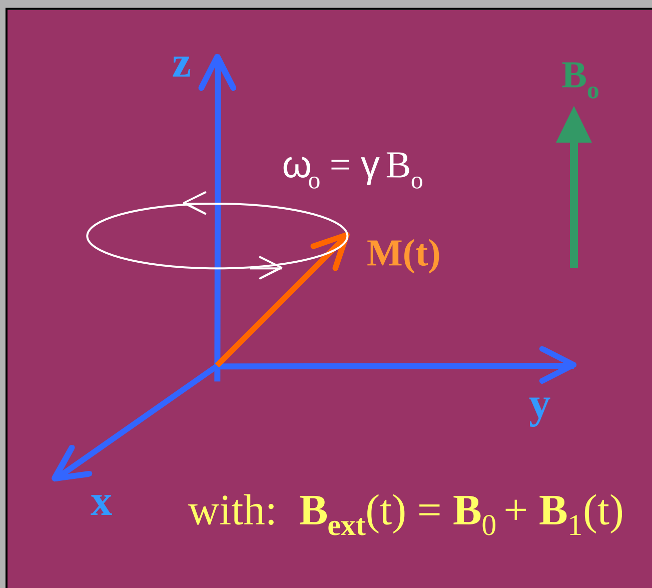
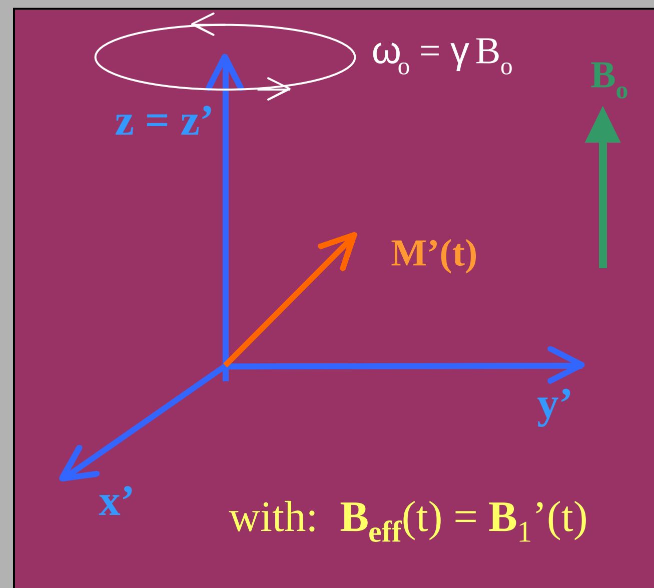
To describe the magnetization we need to choose a coordinate systems

Laboratory coordinate system



$$\frac{d\vec{M}_{(t)}}{dt} = \vec{M}_{(t)} \times \gamma \vec{B}_{ext(t)}$$

Rotating coordinate system



$$\frac{d\vec{M}'_{(t)}}{dt} = \vec{M}'_{(t)} \times \gamma \vec{B}_{eff(t)}$$

Example:

On-resonance spins:	ω_o	static
Off-resonance spins:	$\omega_o + \Delta\omega$	$\Delta\omega$

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The NMR signal

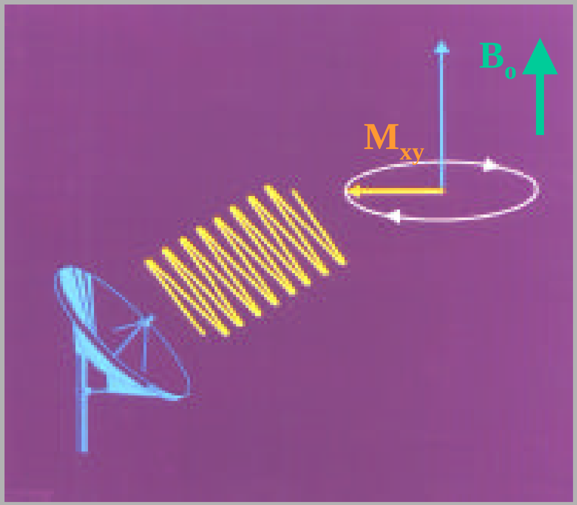
• **At equilibrium no signal**:

- static longitudinal magnetization M_o

↓

• **We need net transverse magnetization**:

- precession of M_{xy} about B_0
- rotating magnetic field
- induces current in a coil: MR signal



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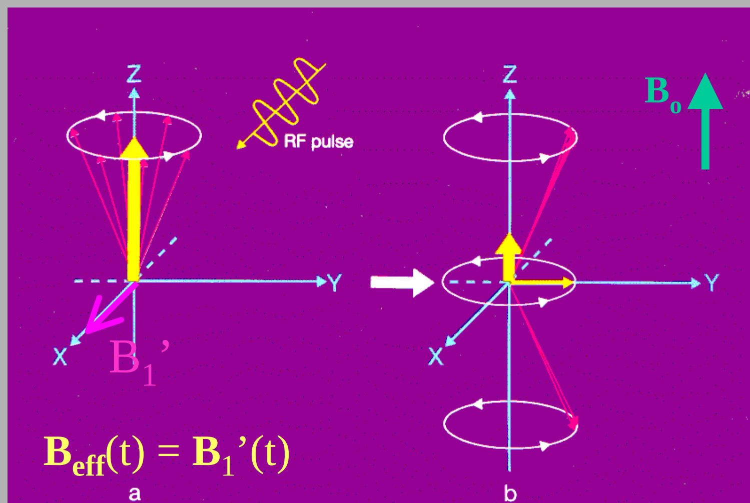
The NMR signal (continuation)

- With an RF pulse on resonance we can rotate M_0



Rotating frame:

- Dynamics: $\frac{d\vec{M}'_{(t)}}{dt} = \vec{M}'_{(t)} \times \gamma \vec{B}_{eff(t)}$
- B_1'(t): B'_1 constant and to B_0
- M' precesses about B_1 with $\omega_1 = \gamma B'_1$
- Flip angle θ: $\frac{\Delta\theta}{\Delta t} = \gamma B'_1$

- Signal relaxation, system goes back to equilibrium

  $M_z \rightarrow M_o$ (T_1 relaxation)

  $M_{xy} \rightarrow 0$ (signal loss, T_2 & T_2* relaxation)

- Relaxation mechanisms give tissue contrast

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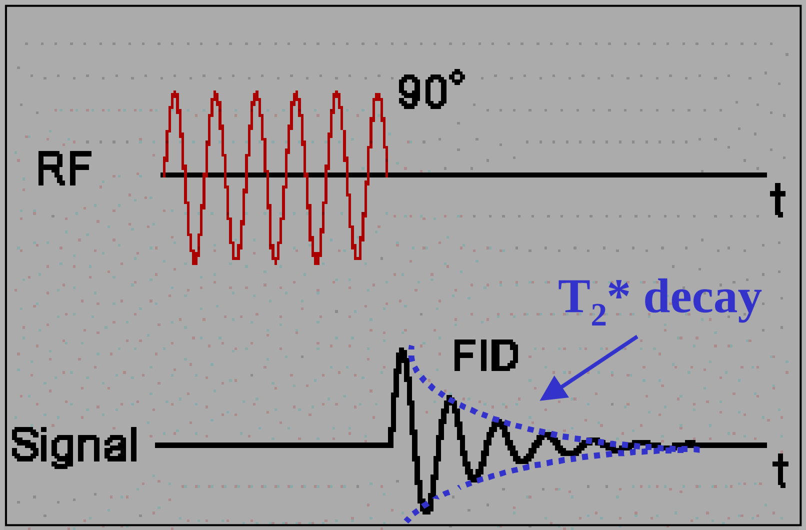
The NMR signal (continuation)

Schematic representation:

Radio-frequency pulse
(oscillating $B_1(t)$ rotating at ω_0)

NMR signal
(transverse magnetization decay)
'Free Induction Decay'



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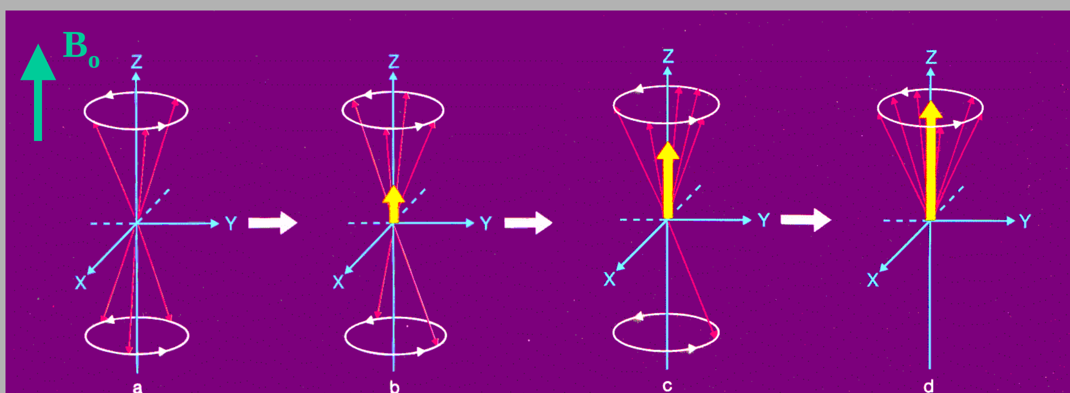
Relaxation mechanisms

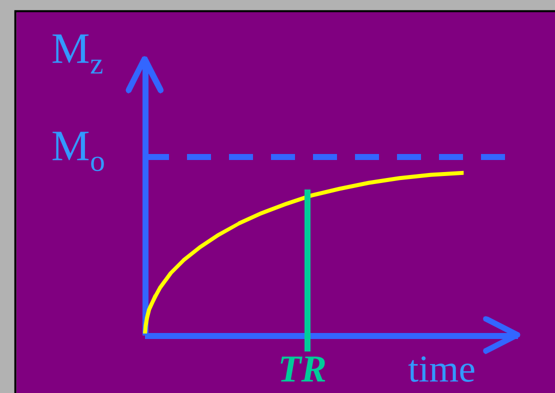
T_1 or spin-lattice relaxation (longitudinal magnetization)

- Mz defined by spin excess population between two energy states
- Mz recovery → transitions between spin states
- transitions → fluctuating transverse field on resonance → molecular motion
- exponential recovery ($T_1 \approx$ 100 - 3000 ms, longer for higher B_o)



Mz=0
after 90°
RF pulse

Mz=Mo
at equilibrium



$$\frac{dM_z}{dt} = \frac{M_o - M_z}{T_1}$$

<u>Repetition time (TR)</u>: time allowed for recovery, defines T_1 contrast

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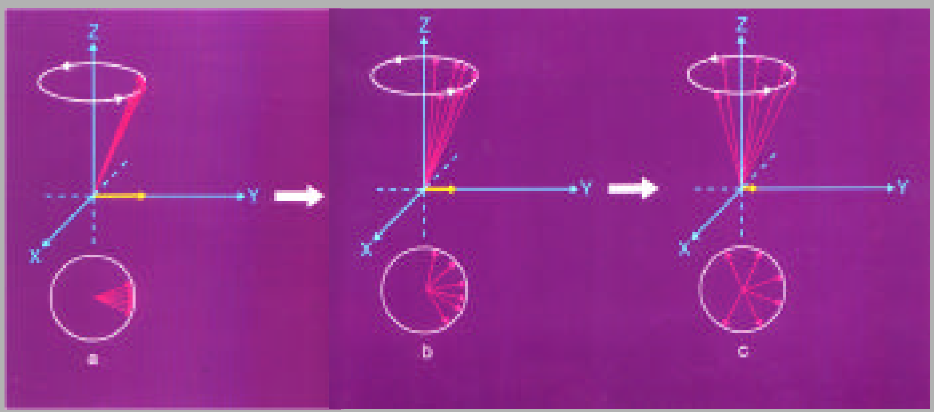
Relaxation mechanisms (continued)

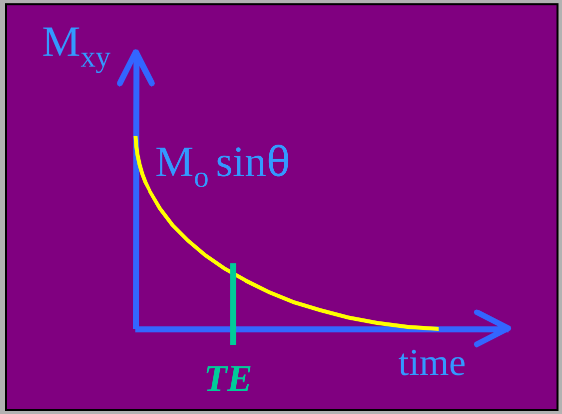
T_2 or spin-spin relaxation (transverse magnetization)

- incoherent exchange of energy between spins
- molecular motion → fluctuations in local B_z → resonance frequency variations
- dephasing of transverse magnetization → signal decay
- exponential decay ($T_2 \approx 70 - 1000$ ms)



M_{xy} max after 90º RF pulse → **spins dephase** → **$M_{xy} = 0$ at equilibrium**

$M_{xy} \leftrightarrow$ NMR signal



$$\frac{dM_{xy}}{dt} = -\frac{M_{xy}}{T_2}$$

<u>Echo time (TE)</u>: time allowed for dephasing, defines T_2 contrast

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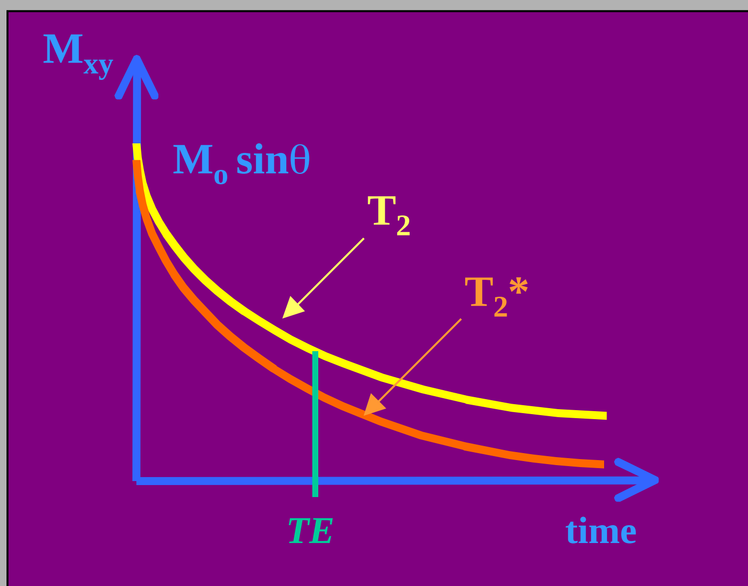
Relaxation mechanisms (continued)

T_2* relaxation

- dephasing of transverse magnetization due to both:
  - microscopic molecular interactions (T_2)
  - spatial variations of the external main field ΔB (tissue/air, tissue/bone interfaces)
- exponential decay ($T_2^* \approx 30 - 100$ ms, shorter for higher B_o)

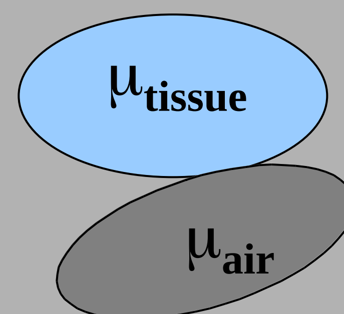


$B = \mu\, \mu_0\, H$

Boundary conditions

} Field distortions (ΔB)

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



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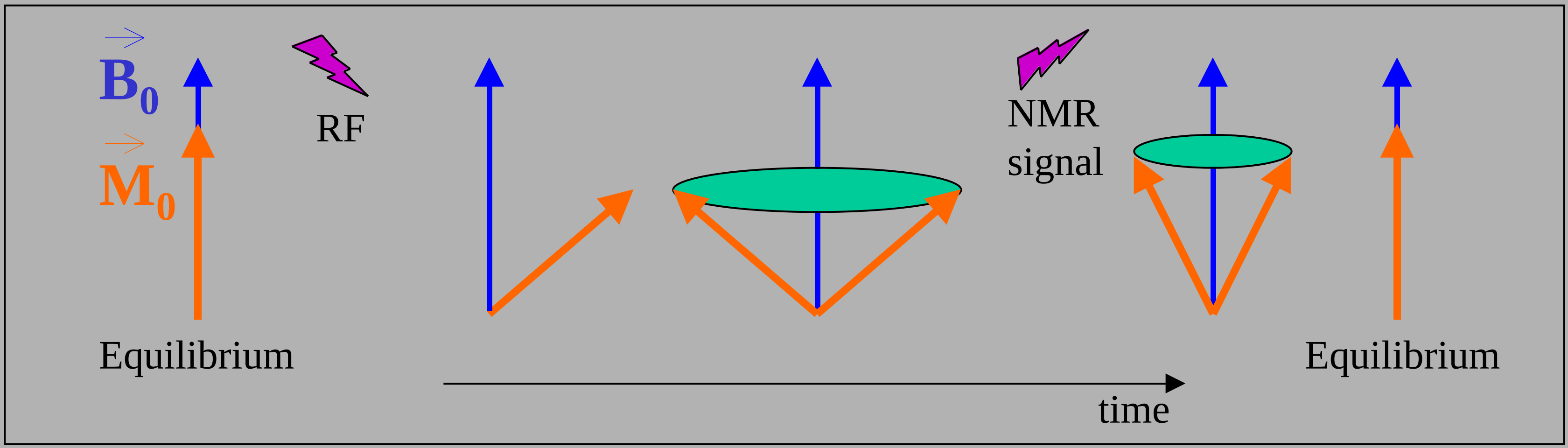
Bloch Equations

• Dynamics of the magnetization + Relaxation effects:

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

• Geometrical description: damped precession (SUMMARY)



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