MRI signal in biological tissues

Proton, Spin, T1, T2, T2*

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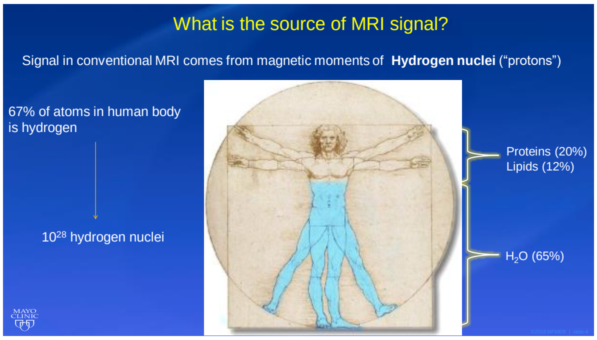
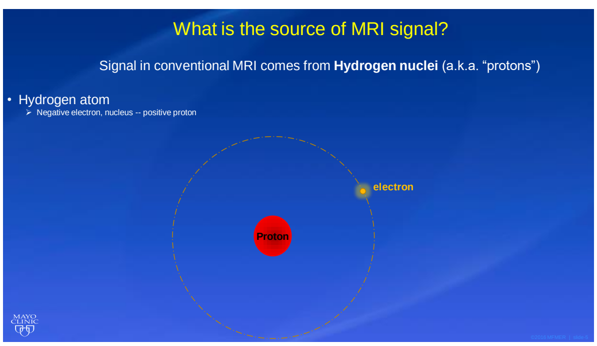
Outline

- Nuclear magnetism
  - nuclear magnetic moment
  - protons - spin ½ system
  - Larmor Equation
  - Resonance
- Magnetic Resonance in tissues
  - Longitudinal magnetization; spin-lattice relaxation time, T1
  - RF pulses
  - Transverse magnetization; T2*, T2 relaxation
  - Spin Echo
  - T1, T2 contrast

MRI scanner

- Very strong (1.5T, 3.0T, 7T), uniform magnetic field – to magnetically polarize the patient
- Radio-frequency coils – to generate and detect MRI signal in tissues (at resonance)
- Gradient coils – to spatially encode signal for reconstruction (loud noise)


What is the source of MRI signal?
Signal in conventional MRI comes from magnetic moments of **Hydrogen nuclei** ("protons")
67% of atoms in human body is hydrogen
10^{28} hydrogen nuclei
Proteins (20%)
Lipids (12%)
H_2O (65%)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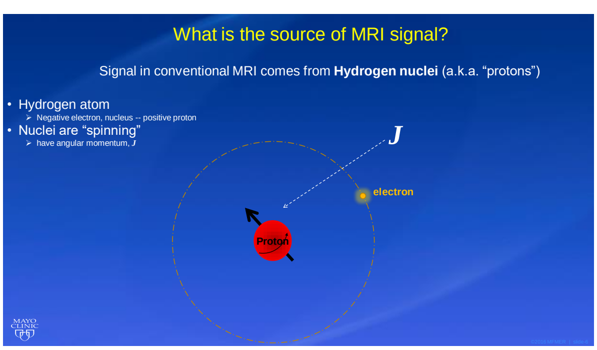
➢ Negative electron, nucleus -- positive proton
electron
Proton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• Nuclei are "spinning"
➢ have angular momentum, J
J
electron
Proton

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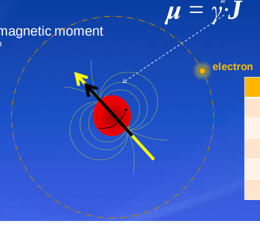
- Hydrogen atom
  - Negative electron, nucleus -- positive proton
- Nuclei are "spinning"
  - have angular momentum, *J*
- Spinning charges have magnetic moment
  - Proportional to angular momentum

$$\mu = \gamma \cdot J$$

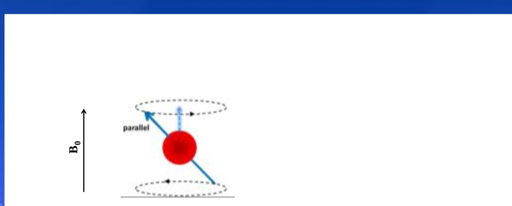
gyromagnetic ratio



Nucleus	γ [MHz/T]
^{1}H	42.6
^{7}Li	16.5
^{23}Na	11.3
^{31}P	17.2
^{129}Xe	-11.8

Hydrogen nuclei ("protons")

- Inside the magnetic field (Quantum Mechanics)
  - moments precess in "**parallel**" (spin up)



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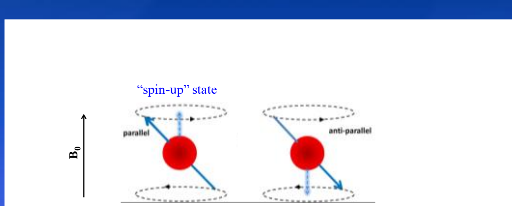

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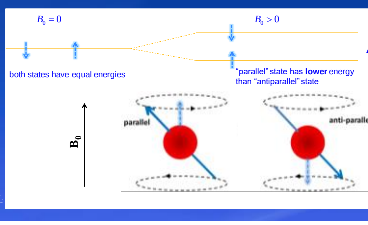


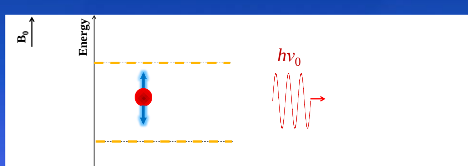
$$\Delta E = h(\gamma B_0) \equiv h\nu_0$$

Larmor frequency

Nucleus	ν_0 [MHz] (1.5T)
^{1}H	64
^{7}Li	25
^{23}Na	17
^{31}P	26
^{129}Xe	18

Spin-lattice relaxation

- Spontaneous transitions between "parallel" and "antiparallel" states are associated with exchange of Larmor photons between protons and the "lattice".



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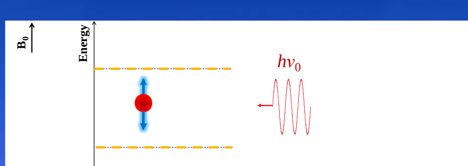
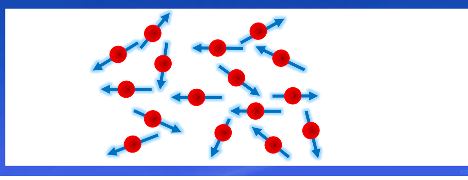


Spin-lattice relaxation

- When B_0 = 0 proton moments are oriented randomly. Tissue magnetization = 0.



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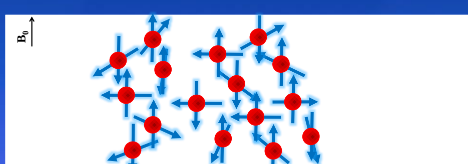
  - Preferential orientation is parallel with the field (lower energy)



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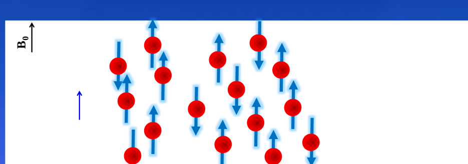

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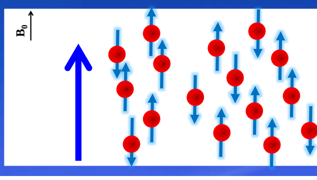

$$\frac{N_{\text{anti-parallel}}}{N_{\text{parallel}}} = \exp\left(-\frac{h\gamma B_0}{k_B T}\right)$$

$$\frac{\Delta N}{N} \propto B_0$$

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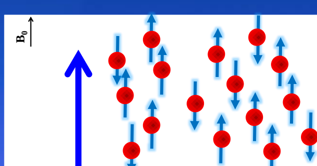
  - Tissue magnetization builds up
  - In thermal equilibrium ratio moment populations are given by **the Boltzman distribution**
  - At **1.5T** for every **1 million** protons there is **excess of 5** "parallel" protons over the "anti-parallel"



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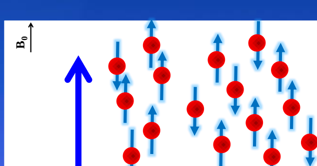
Spin-lattice relaxation

- **T1** -- time scale for reaching equilibrium distribution of proton moments: **spin-lattice relaxation time**



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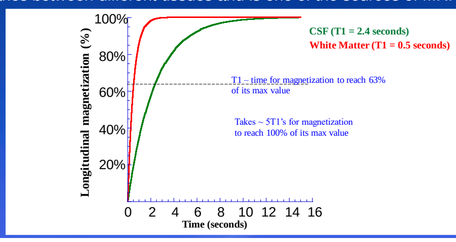
Spin-lattice relaxation

- **T1** -- time scale for reaching equilibrium distribution of proton moments: **spin-lattice relaxation time**
- T1 varies between different tissues and is one of the sources of MRI contrast



Magnetic Resonance

- Transitions between "spin up" and "spin down" states can be driven by RF field applied at **resonance** (@ Larmor frequency)
- **Larmor Equation:** $\nu_{RF} = \nu_0 = \gamma \cdot B_0$ (can select which nuclei we "tune in" to)
  - B_0 = 1.5T, ν_0 = 42.6MHz/T · 1.5T ≈ 64MHz
  - B_0 = 3.0T, ν_0 = 42.6MHz/T · 3.0T ≈ 128MHz

Nucleus	ν_0 [MHz]
^{1}H	64
^{7}Li	25
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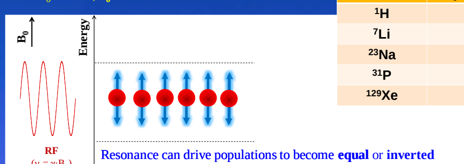
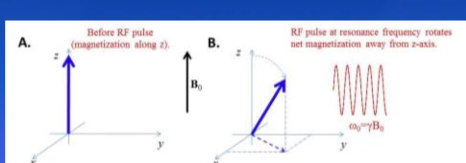


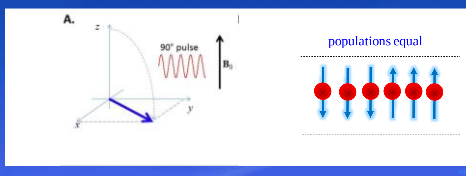
Magnetic Resonance

- The RF pulse applied at resonance **tips** equilibrium magnetization away from B_0



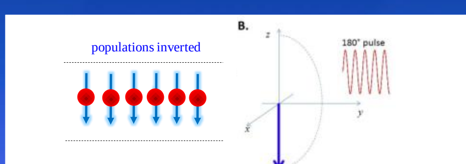
Magnetic Resonance

- The RF pulse applied at resonance **tips** equilibrium magnetization **away** from $\mathbf{B_0}$
- **"90° pulse"** rotates magnetization by 90°



Magnetic Resonance

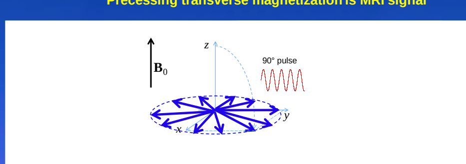
- The RF pulse applied at resonance **tips** equilibrium magnetization **away** from $\mathbf{B_0}$
- **"90° pulse"** rotates magnetization by 90°
- **"180° pulse"** rotates magnetization by 180° (populations of proton moments **inverted**)



Magnetic Resonance

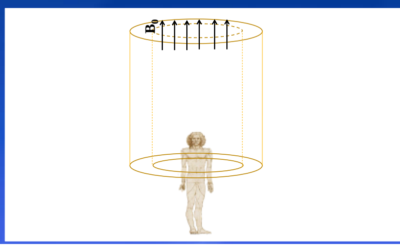
- **Immediately** after the 90° pulse
  - There is **zero** longitudinal magnetization. Entire magnetization is flipped to the transverse plane and becomes **transverse magnetization**
  - The transverse magnetization **precesses** around $\mathbf{B_0}$ with Larmor frequency

Precessing transverse magnetization is MRI signal



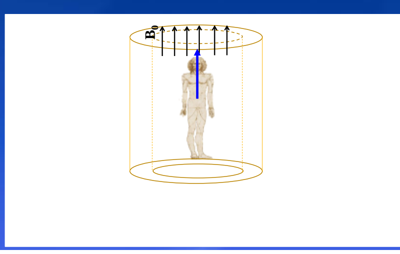
How do we generate and detect MRI signal?

- **Step 1:** Place the patient inside a uniform static magnetic field



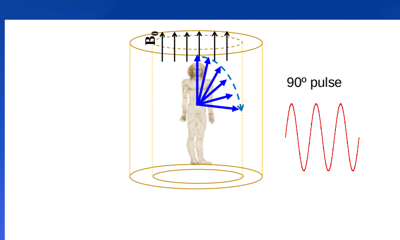
How do we generate and detect MRI signal?

- **Step 1:** Place the patient inside a uniform static magnetic field
  - Tissue magnetization builds up (time-scale T1)



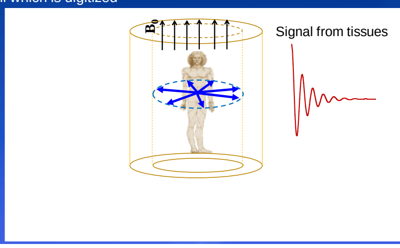
How do we generate and detect MRI signal?

- **Step 2: RF body coil applies 90° RF pulse**
  - Magnetization gets tipped into transverse plane



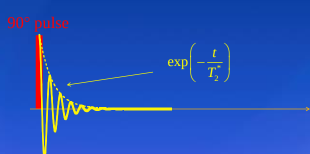
How do we generate and detect MRI signal?

- **Step 2: RF body coil detects the signal**
  - Transverse magnetization **rotates** about B_0 and **induces voltage** in the body coil which is digitized



Transverse magnetization, T2*, T2

- Following 90° pulse the signal induced by rotating transverse magnetization eventually **disappears**
- This relaxation has exponential envelope with a characteristic time-scale, T_2^*



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- There are two major contributions to T2* relaxation (besides T1 process):
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  1. Inhomogeneities of the static magnetic field
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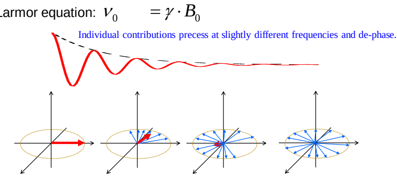
- Magnetization is the **sum** of individual contributions built from proton magnetic moments
  - Immediately after 90° pulse moments precess **coherently** or **in-phase** with one another

Larmor equation: $\nu_0 = \gamma \cdot B_0$



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- Dephasing due to field inhomogeneities can be eliminated using **Spin Echo** sequence.

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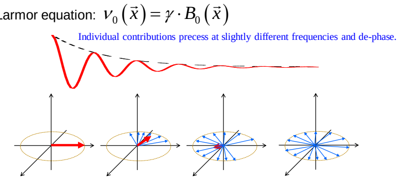

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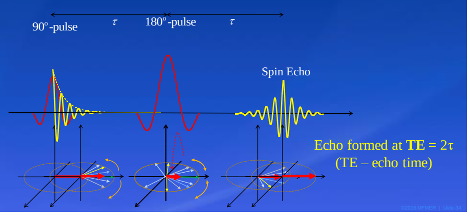
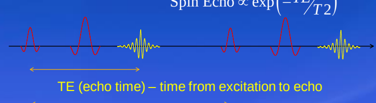


Transverse magnetization, T2*, T2

- There are two major contributions to T2* relaxation (besides T1 process):
  1. Inhomogeneities of the static magnetic field
  2. T2 process
     - Even if $\mathbf{B_0}$ was perfectly homogeneous, transverse magnetization would still diminish
     - Protons interact with **randomly fluctuating** magnetic fields from their neighbors
     - Moments randomly de-phase and **lose their coherence**
     - transverse magnetization decreases and ultimately disappears
  3. T2 process is irreversible

$$\text{Spin Echo} \propto \exp\left(-{TE}/{T2}\right)$$



TE (echo time) – time from excitation to echo

TR (repetition time) – time between 90º pulses (excitations)

T1 and T2 contrast

- T1 and T2 are properties of tissue

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- TR and TE manipulated to enhance one over the other in image
  - T1 weighting: visualization of anatomy
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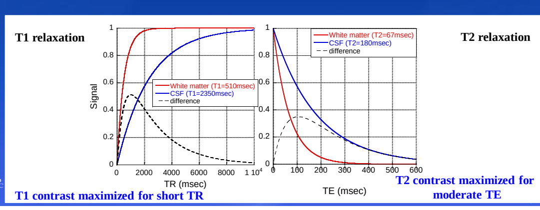

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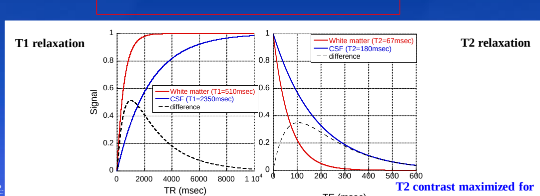
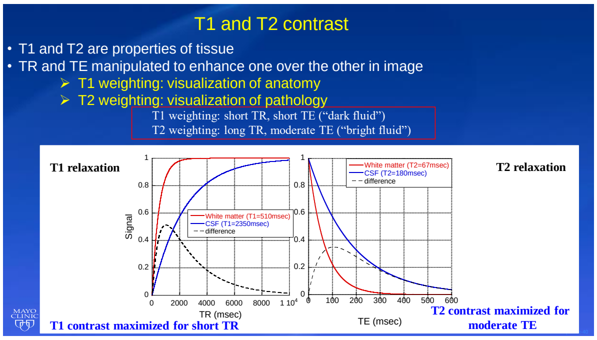
T1 weighting: short TR, short TE (“dark fluid”)




T1 and T2 contrast
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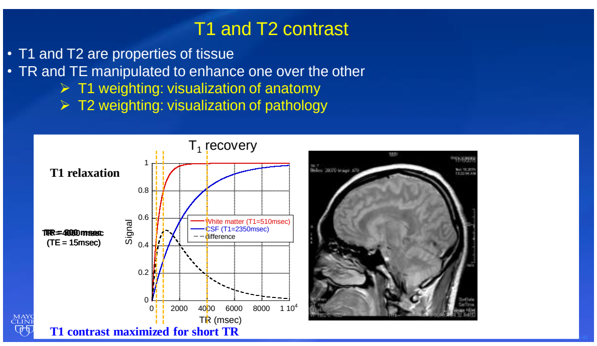
➢ T1 weighting: visualization of anatomy
➢ T2 weighting: visualization of pathology
T1 weighting: short TR, short TE ("dark fluid")
T2 weighting: long TR, moderate TE ("bright fluid")
T1 relaxation
Signal
TR (msec)
White matter (T1=510msec)
CSF (T1=2350msec)
difference
White matter (T2=67msec)
CSF (T2=180msec)
difference
T2 relaxation
TE (msec)
T1 contrast maximized for short TR
T2 contrast maximized for moderate TE


T1 and T2 contrast
• T1 and T2 are properties of tissue
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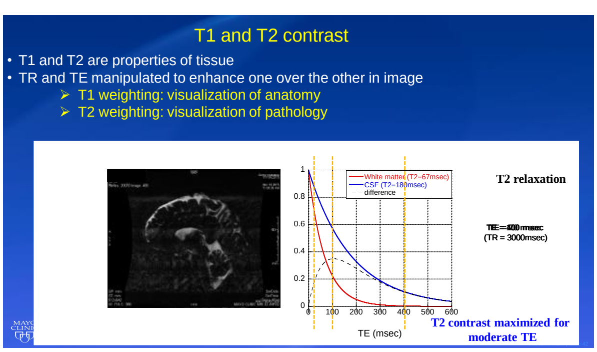
➢ T2 weighting: visualization of pathology
T1 recovery
T1 relaxation
(TE = 15msec)
Signal
TR (msec)
White matter (T1=510msec)
CSF (T1=2350msec)
difference
T1 contrast maximized for short TR


T1 and T2 contrast
• T1 and T2 are properties of tissue
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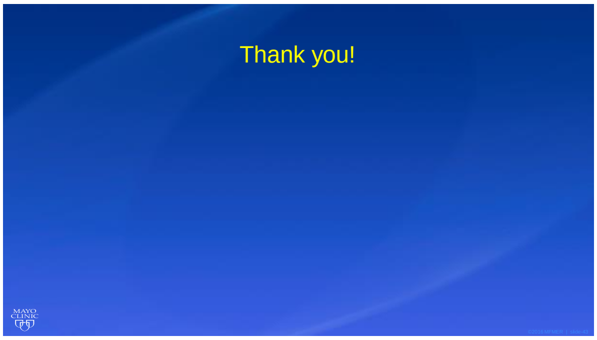
White matter (T2=67msec)
CSF (T2=180msec)
difference
T2 relaxation
(TR = 3000msec)
TE (msec)
T2 contrast maximized for moderate TE


Thank you!