Administrivia

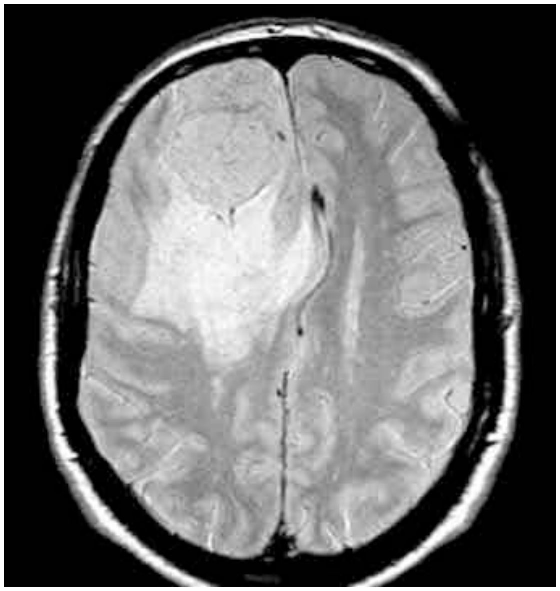
Evaluation

- For the three guest lecturers
- Not the evaluation for the course or me -- there will be a separate evaluation for that later

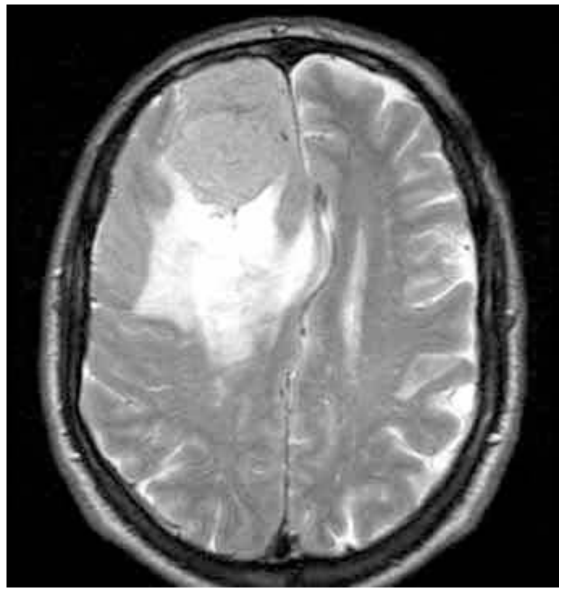
Class Field Trip: Saturday Dec 2nd

- Meet at UWMC Main Entrance at Noon in main hospital lobby
  - if you 'miss the boat', page me at 540-4950
  - should take ~1 to 1.5 hours, depending
- No Class Nov 22nd
- Final report due Nov 29th
- Lecturer on Nov 29th will be Adam Alessio, please read chps 9 and 10
- Exam 2 Nov 29th
- Class Presentation Dec 6th

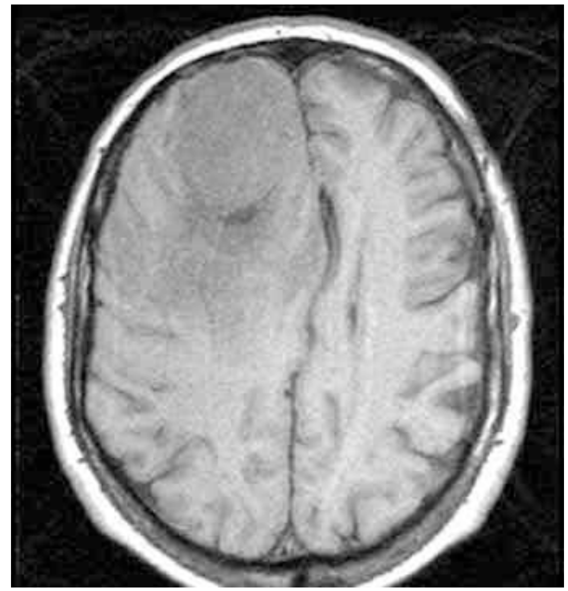
Lecture 7: Magnetic Resonance Imaging (MRI)



Spin density



T2-weighted image



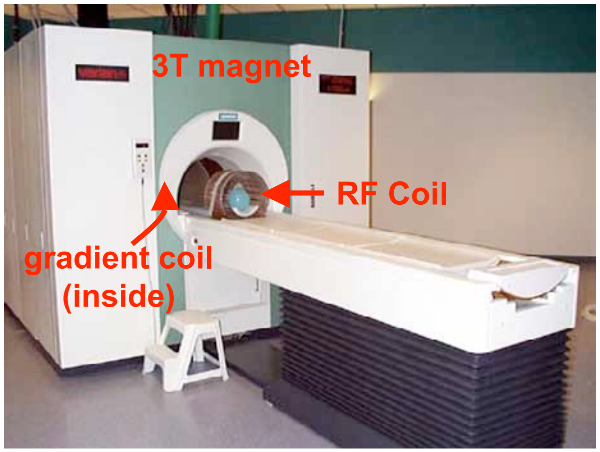
T1-weighted image

- We've spent a lot of time thinking about images, so how are these three MRI images different
  - From each other
  - From images from other modalities (CT, PET/SPECT, US)

What is MRI? The overall picture

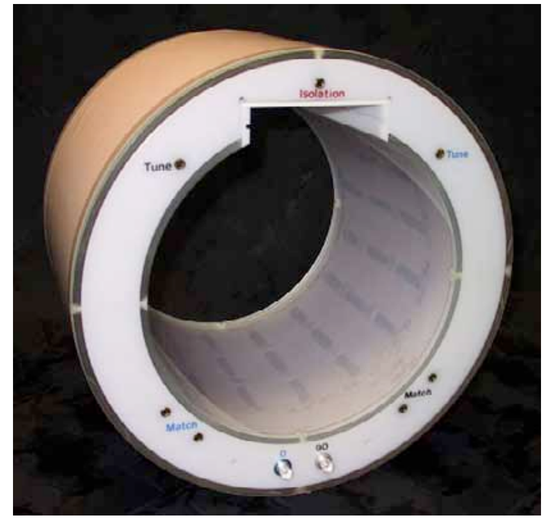
1) Put subject in big steady-state 'main' magnetic field B_0 (hydrogen nuclei 'line up' on average with magnetic field)
2) Adjust magnetic field in a spatially-varying manner using 'gradient' electromagnetic coils
3) Transmit radio waves into subject at the resonance frequency of nuclei using radiofrequency (RF) coils, where resonance frequency depends on magnetic field (thus location)
4) Turn off radio wave transmitter so nuclei re-align with magnetic field and transmit at local frequency, which depends on location
5) Store received radio wave data vs. time
6) Repeat at steps 2-6 many times (BANG, BANG)
7) Process raw data to reconstruct images of hydrogen nuclei density

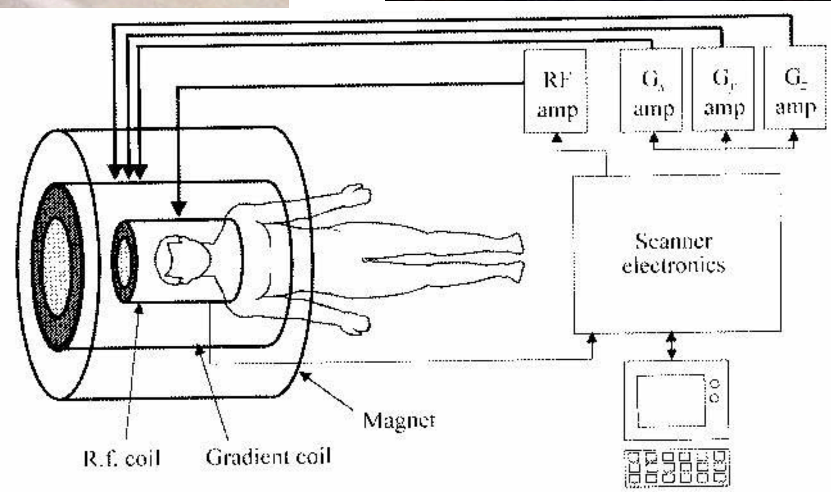
Necessary Equipment for MRI



Gradient Coil

RF Coil





Main Magnet:

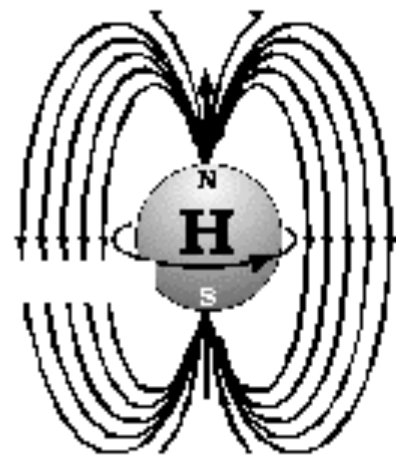
1 Tesla (T) = 10,000 Gauss
Earth's magnetic field = 0.5 Gauss
3 Tesla = 3 x 10,000 ÷ 0.5 = 60,000 X Earth's magnetic field

Angular Momentum - Classical Mechanics

- Angular momentum describes rotational motion of a body
  1. Orbital (Earth orbits the sun)
  2. Spinning (Earth spins on its axis giving us night and day)
- Nuclear Angular Momentum
  1. Protons and neutrons orbit within nucleus (whole nucleus spinning)
  2. Protons and neutrons "spin"

  $\Rightarrow$ Together produce nuclear spin

- Spinning charge produces magnetic dipole (same as electromagnet - sort of)

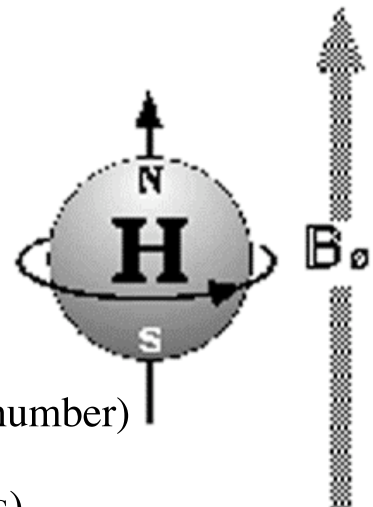


The Reality - Quantum Mechanics

- Quantum Mechanics in sum: "Energy states exist in discrete amounts (quantum)"
  - ⇒Each nucleus in external magnetic field B_0 has energy described by the equation:

eq. 6.10 in book

$$E = -mh^{*}\gamma B_o$$



E is Energy (in Joules)

m = -j,-j+1,…j-1, j = 1/2 or -1/2 for hydrogen (j is spin number)

h^* =h/2π (h is Planck's constant) (6.62×10^{-34}Joules*seconds)

γ is constant - gyromagnetic ratio of atom (in MHz/T)

B_0 is external field (in T, Tesla)

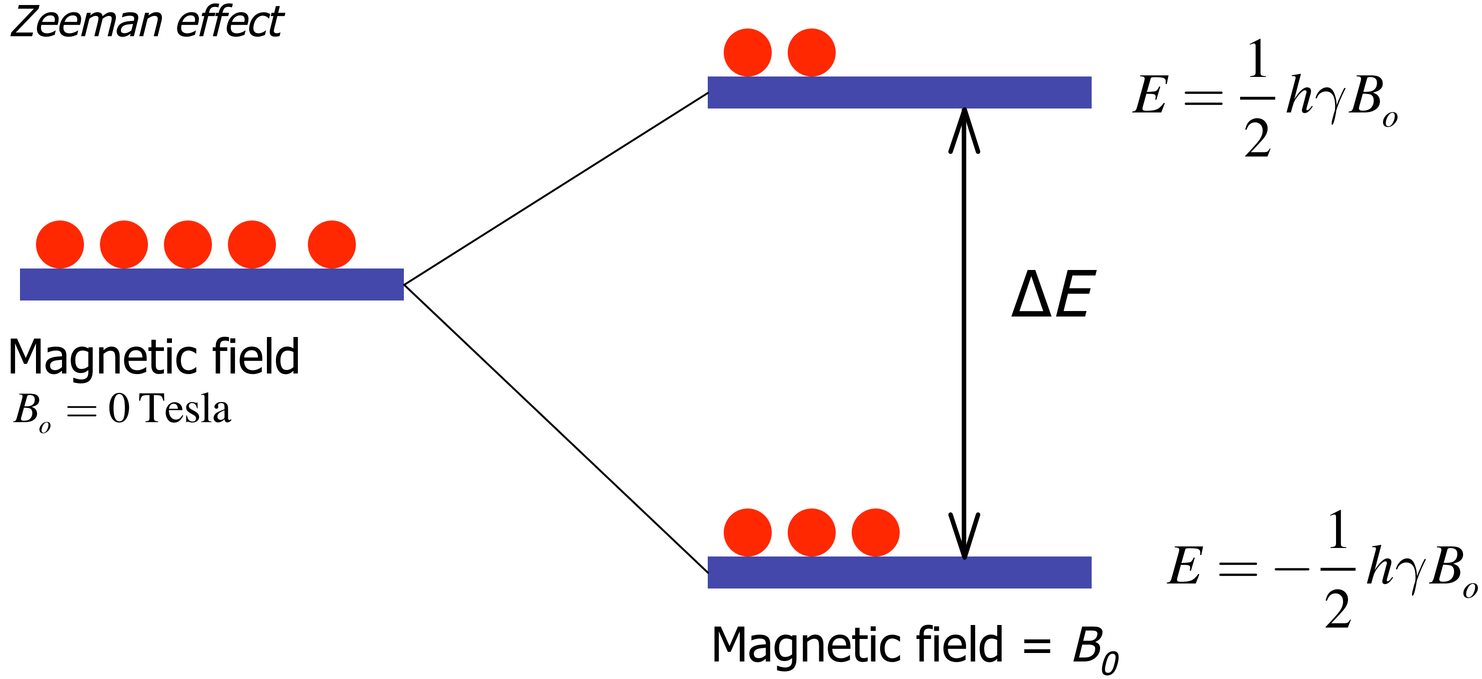
Nucleus can only exist at discrete energy levels for a given external field

Quantum Mechanics Continued

Nuclei	Unpaired protons	Unpaired neutrons	Net Spin #	γ (MHz/T)
$^{1}_{1}H$	1	0	1/2	267.48
$^{2}_{1}H$	1	1	1	41.09
$^{12}_{6}C$	0	0	0	
$^{13}_{6}C$	0	1	1/2	67.29
$^{14}_{7}N$	1	1	1	19.35
$^{16}_{8}O$	0	0	0	

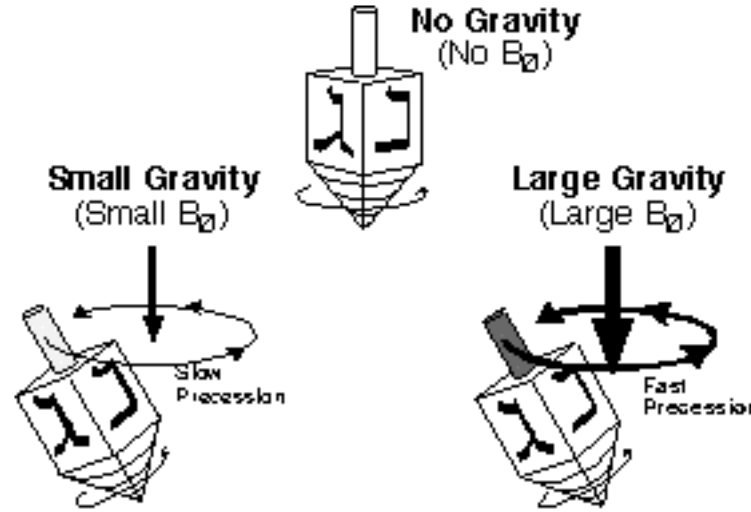
- Hydrogen influenced by external magnetic field (Most common atom in body!)
- Common carbon and oxygen isotopes are not influenced by magnetic field

In presence of magnetic field, two energy levels are established for Hydrogen - Spin up or Spin down - quantized energy states in external magnetic field known as *Zeeman effect*



Precession Effect

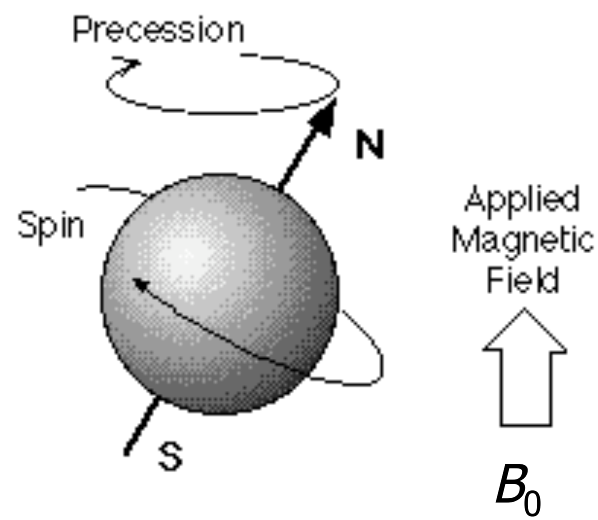
- Atom like a dreidle (top)



Spinning nuclei wobble or precess at a rate:

$$\omega_0 = \gamma B_0 / 2\pi$$

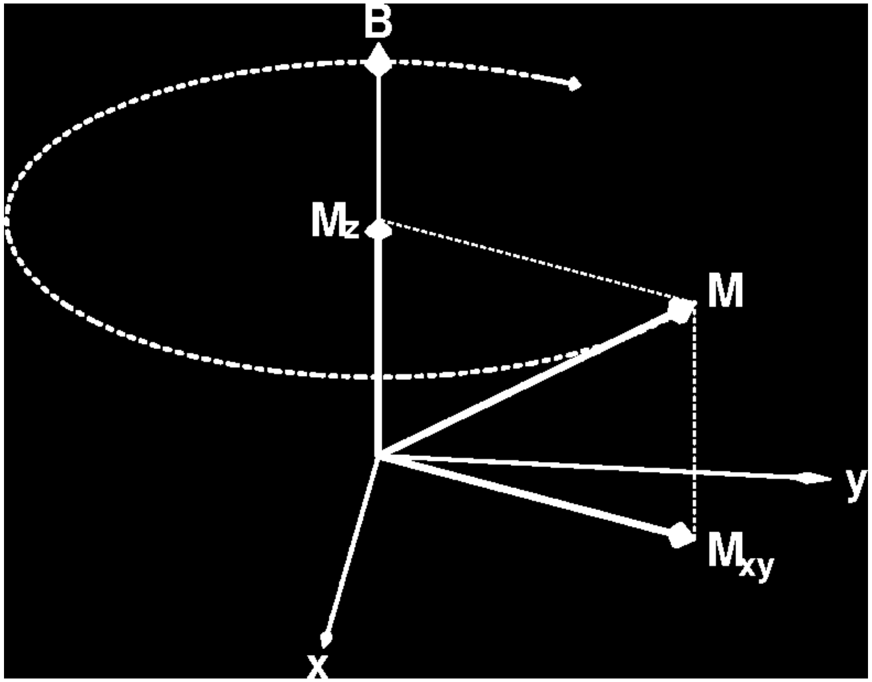
where w_0 is the precessional, Larmor or **resonance** frequency



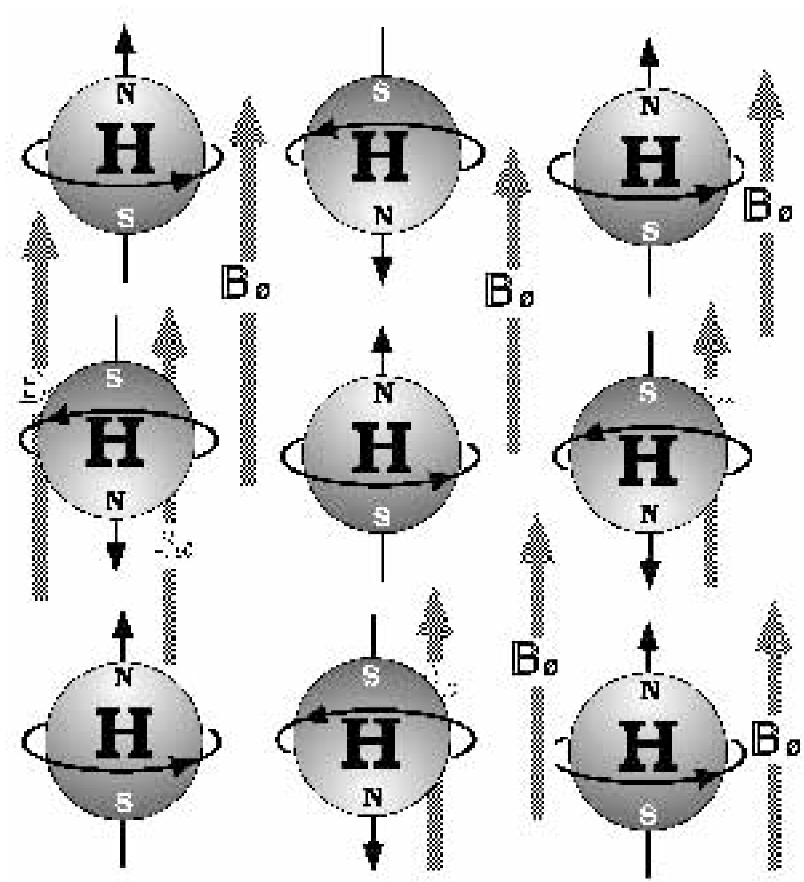
Resonance frequency is proportional to B_0

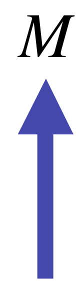
Vector Form

- Magnetic field $\mathbf{B}_0$ causes $\boldsymbol{M}$ to rotate (or *precess*) about the direction of **B** at a frequency proportional to the size of **B** (for hydrogen: 42 million times per second (42 MHz), per Tesla of **B**)
- M_z stays same



Working with a lot of nuclei…





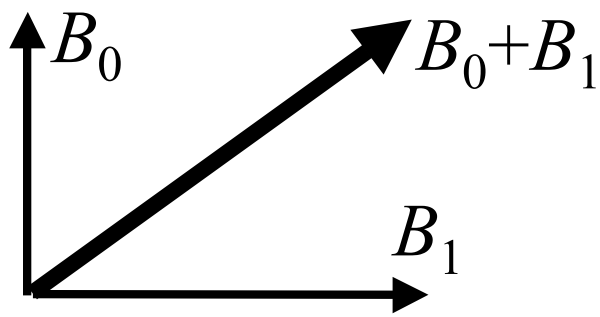
- Small B_0 produces small net magnetization M
- Thermal motions try to randomize alignment of nuclei magnets

- Larger B_0 produces larger net magnetization M, lined up with B_0
- Reality check: 0.0003% of nuclei aligned per Tesla of B_0

Making *M* not parallel to *B*?

- Now have a majority of nuclei in line with large magnetic field, each precessing at its resonance frequency
- Basic Idea: We want to perturb the nuclei and see how long it takes until they "realign"

- A way that does ***not*** work:
  - Turn on a second big magnetic field B_1 perpendicular to main B_0 (for a few seconds)
  - M would drift over to vector sum of B_0 and B_1



  - Then turn B_1 off; *M* is now not parallel to magnetic field B_0
- This **fails** because cannot turn huge (Tesla) magnetic fields on and off quickly
  - But it contains the kernel of the necessary idea:

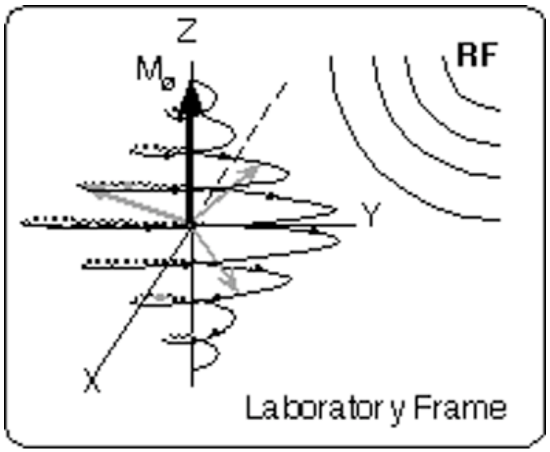
    A magnetic field B_1 perpendicular to B_0

Making M not parallel to B? Mechanical Analogy: Swingset

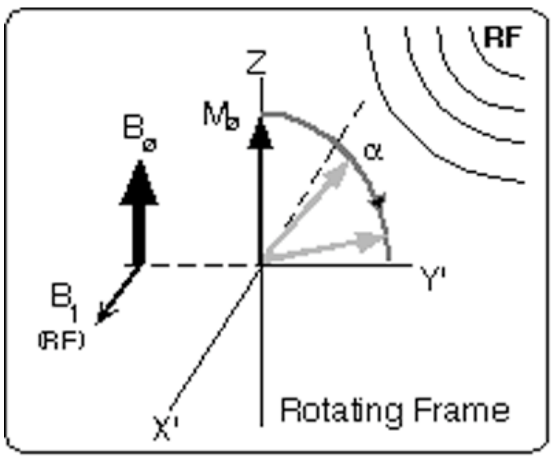
- Person sitting on swing at rest is "aligned" with externally imposed force field (gravity)
- To get the person up high, you could simply supply enough force to overcome gravity and lift him (and the swing) up
  - Analogous to forcing M over by turning on a huge static B_1
- The other way is to push back and forth with a tiny force, synchronously with the natural oscillations of the swing
  - Analogous to using the tiny RF B_1 to slowly flip M over
  - Apply force in Resonance

Making *M* not parallel to *B*?
Excitation with Radiofrequency (RF)

- B_1 is excitation RF field.
- Apply B_1 so fluctuates at the resonance frequency and points perpendicular to B_0



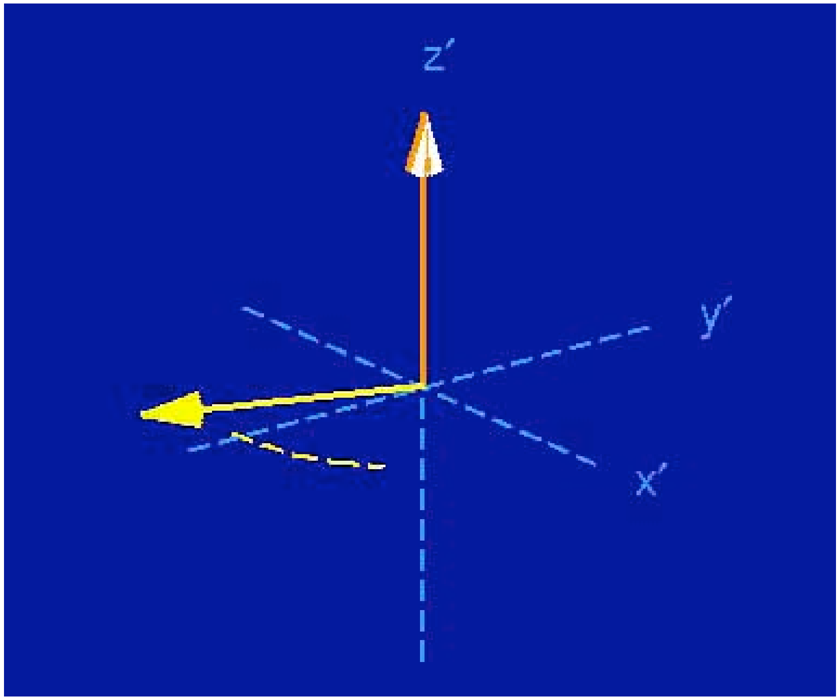
RF energy is absorbed. An observer in the surrounding laboratory will see Mø spiral down to the XY plane (or even to the -Z axis)

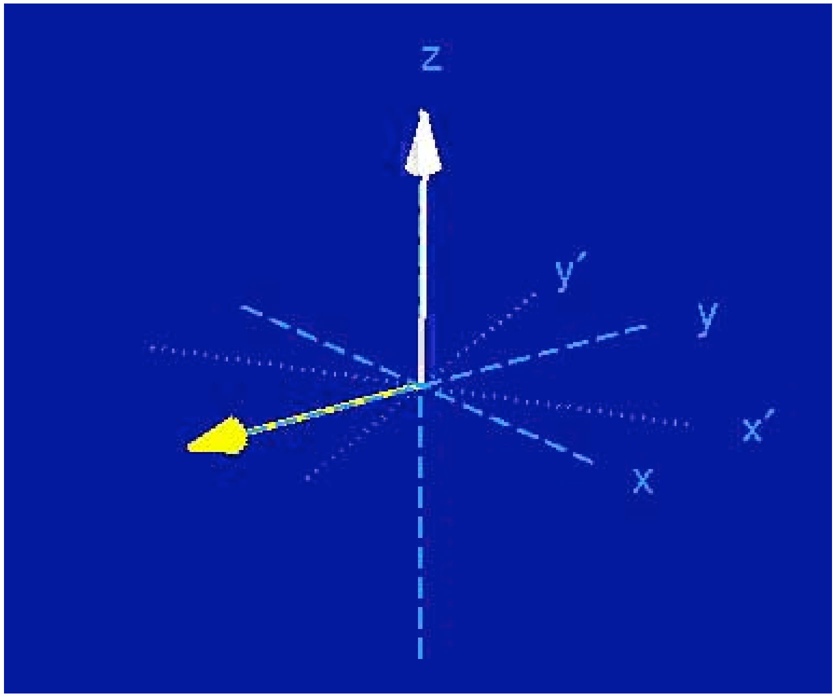


An observer riding on the Mø vector sees the external world rotating about him. Mø then seems to tip α towards the Y' axis.

Making *M* not parallel to *B*?
Excitation with Radiofrequency (RF)

Varying frame of reference



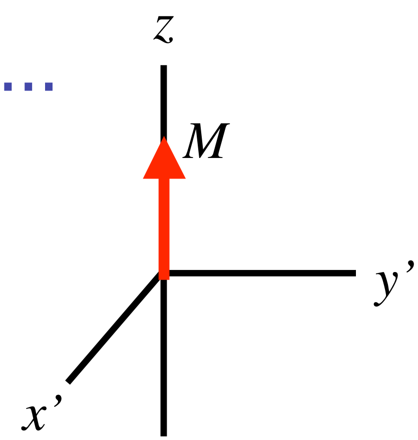


RF energy is absorbed. An observer in the surrounding laboratory will see Mø spiral down to the XY plane (or even to the -Z axis)

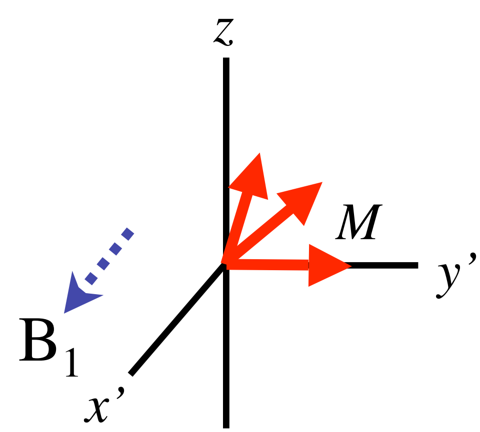
An observer riding on the B1 vector sees the external world rotating about him. Mø then seems to tip α towards the Y' axis.

http://www-mrsrl.stanford.edu/~brian/intromr/

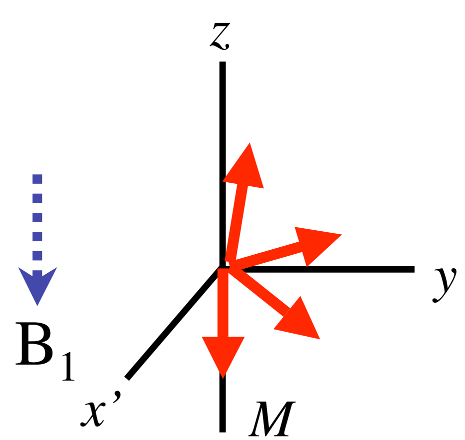
Common RF Pulses…



- *M* begins along *z* axis

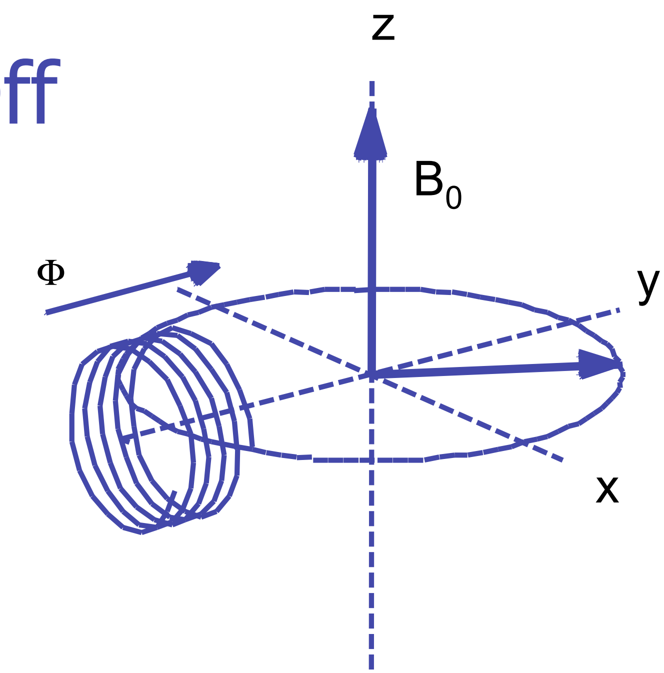


- 90° pulse: *M* lines up with y′ axis
  $M = (0, M_0, 0)$
  - $\alpha = 90°$
  - Quantum Mech: Both energy levels are occupied by same number of spins

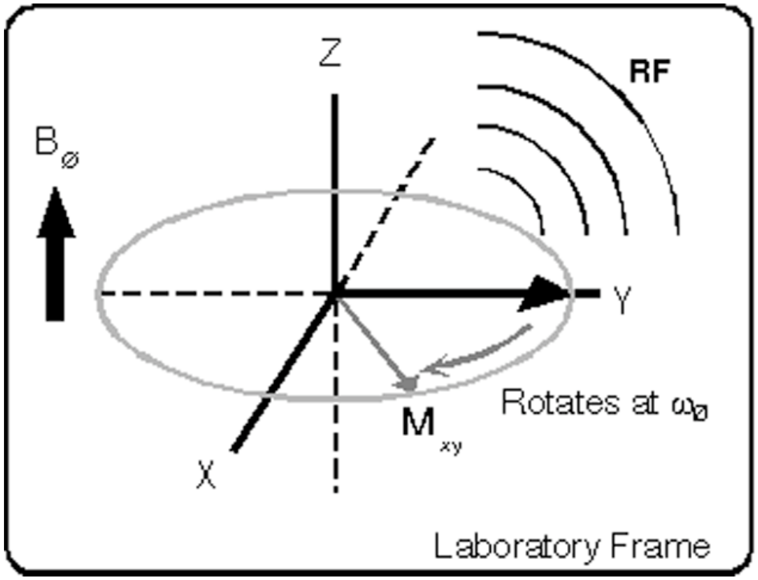


- 180° pulse: *M* lines up with -z axis
  $M = (0,0, M_0)$
  - $\alpha = 180°$
  - Quantum Mech:majority of spins occupy highest energy level

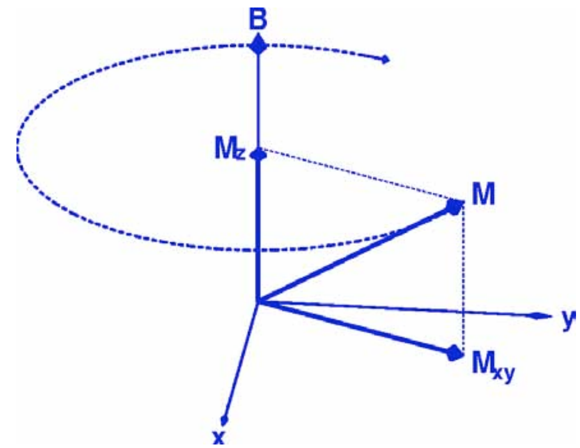
Turn RF Off



- Precessing spins cause a change in flux (Φ) in a transverse receive coil.
- Flux change induces a voltage across the coil.
  - This is the "NMR" signal
  - At the resonance frequency (The frequency of this precession is proportional to the applied magnetic field)
  - Signal proportional to **Proton Density**

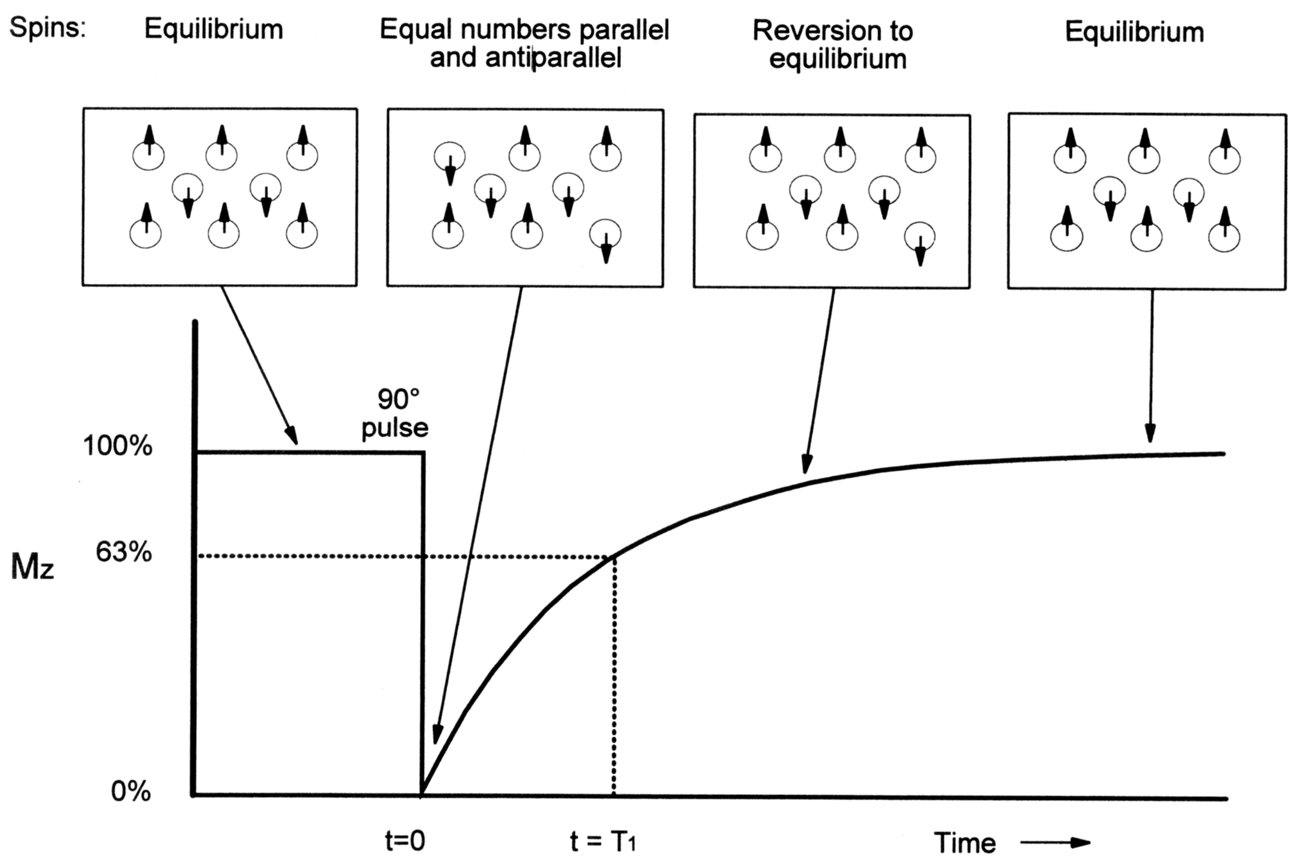


Turn RF Off
Spin-Lattice Relaxation (T1)



Mz begins to recover

- –Exponential recovery of Mz
- –Time constant is called T1
- –Longitudinal or Spin-Lattice Relaxation



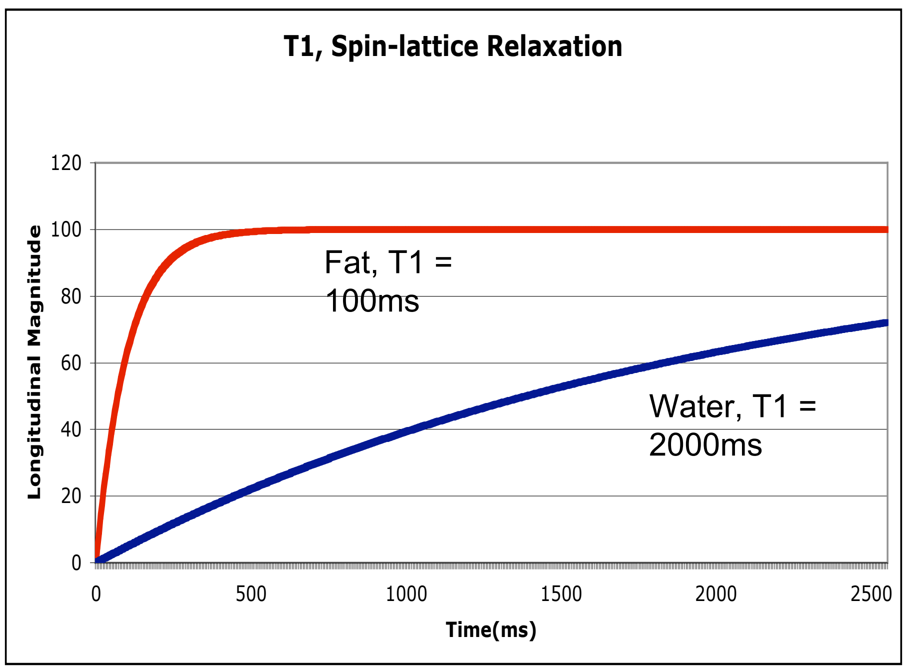
Turn RF Off
Spin-Lattice Relaxation (T1)

Immediately after RF signal: $M_0 \cos(\alpha)$

After long time returns to this: M_0

How?

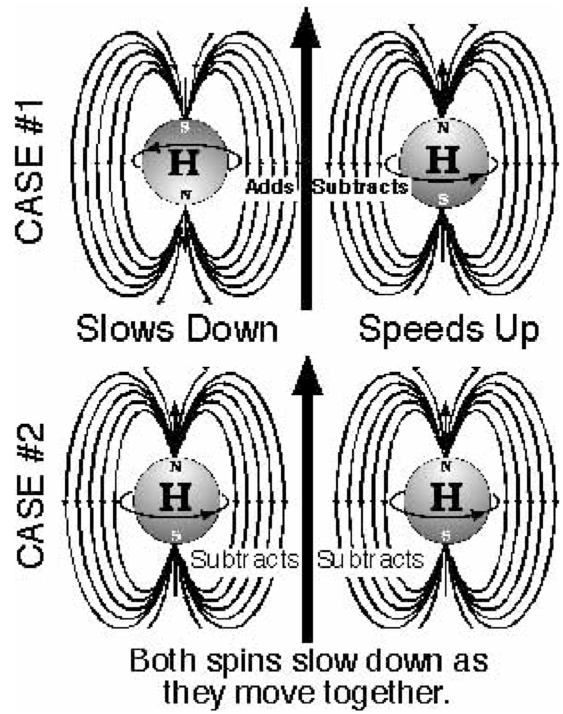
$$M_1(t) = M_0 \cos(\alpha) e^{-\frac{t}{T_1}} + M_0 (1 - e^{-\frac{t}{T_1}})$$

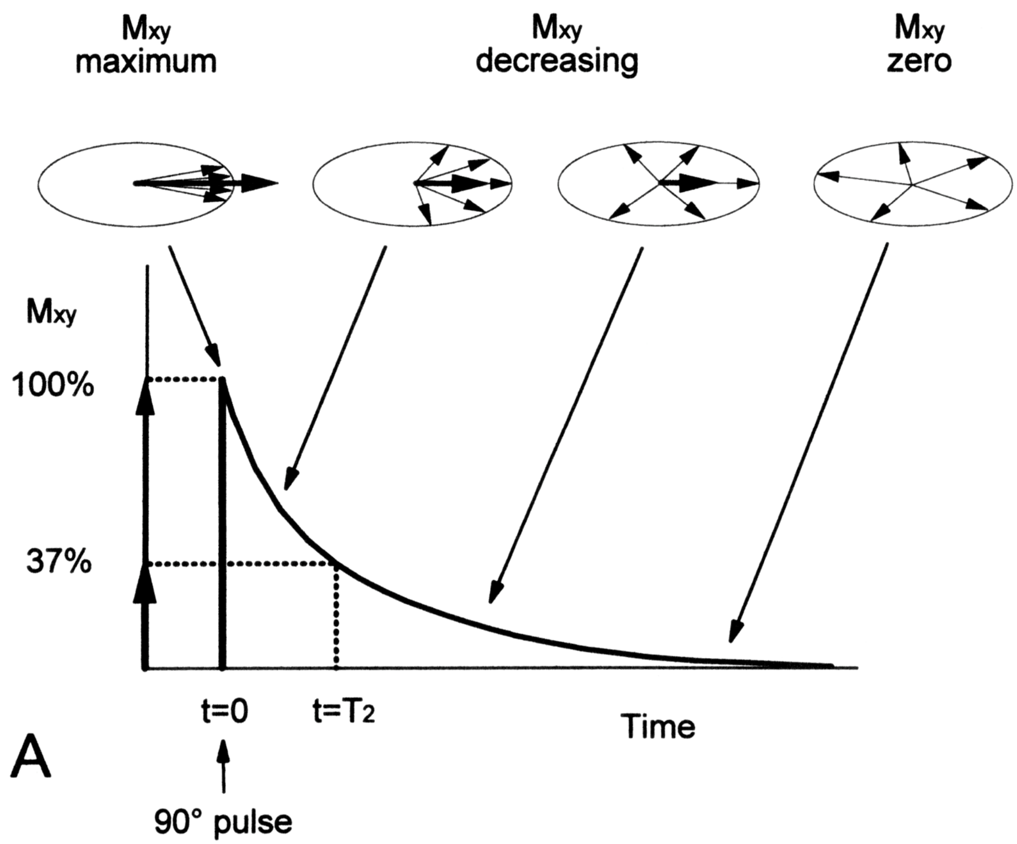


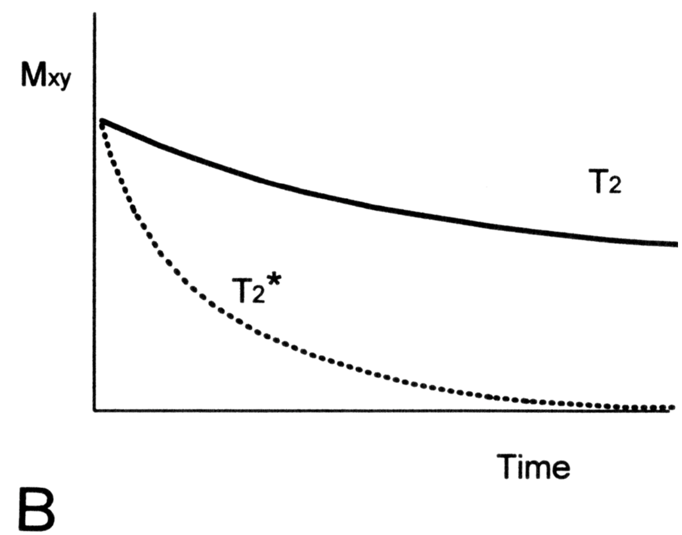
RF Off
Spin-Spin Relaxation (T2)

Spins (Mxy) begin to dephase due

- Exponential decay of signal
- Time constant is called T2 or T2*
- Transverse or Spin-Spin Relaxation



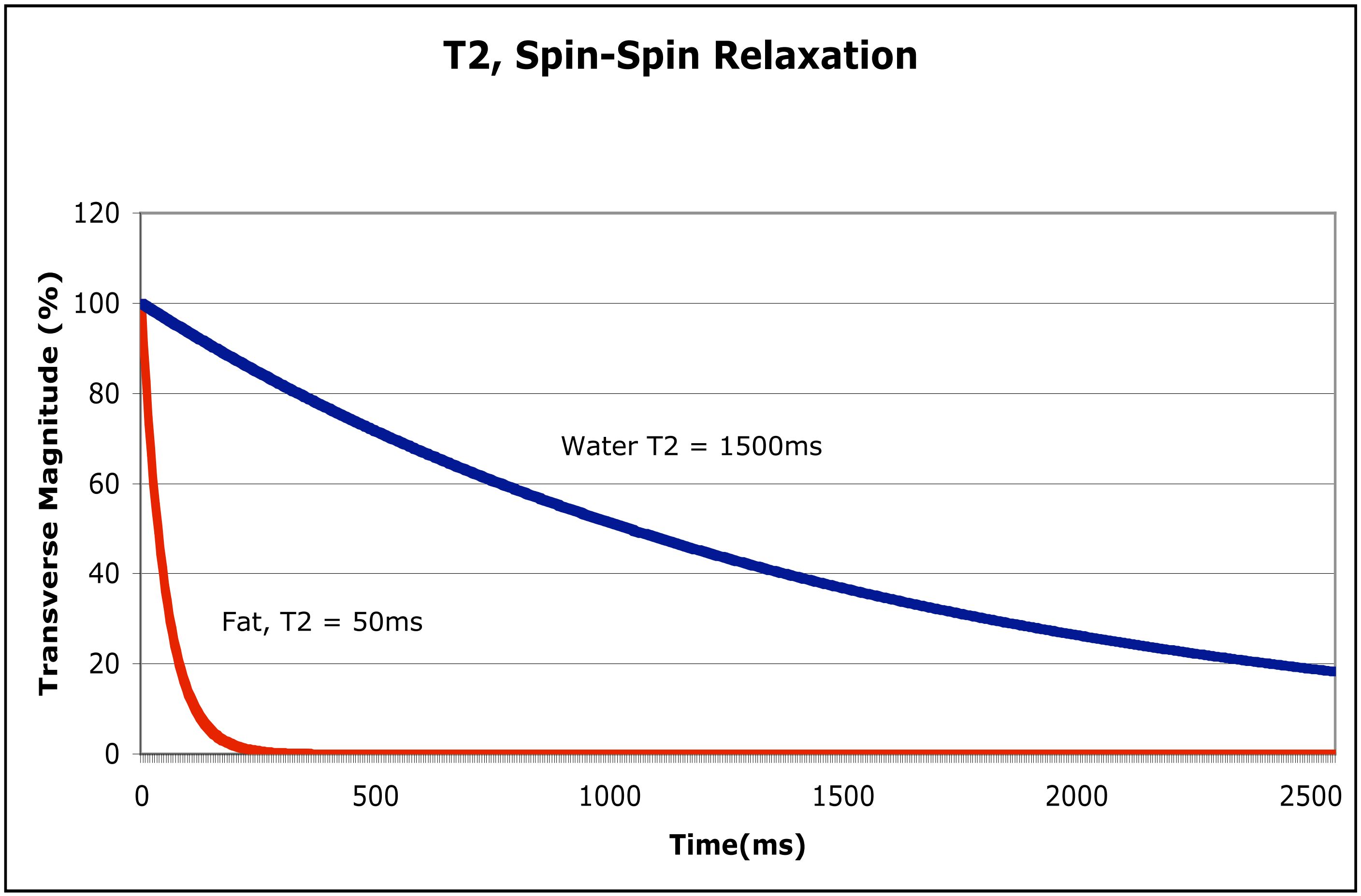




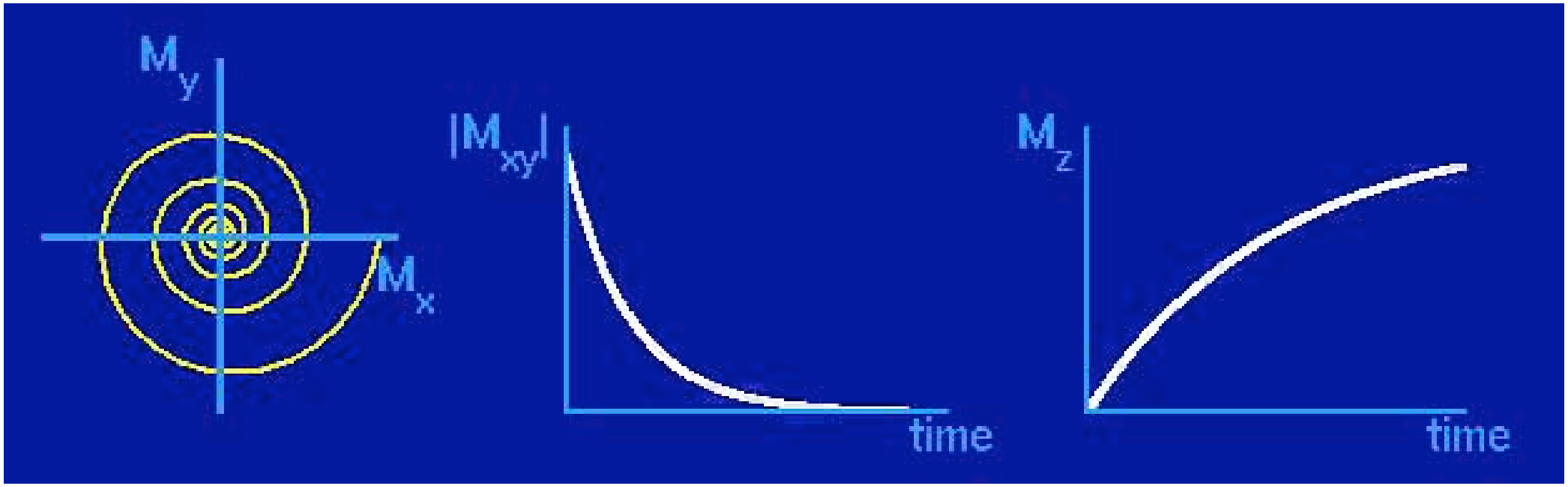
RF Off
Spin-Spin Relaxation

T2 relaxes as $M_{tr}(t) = M_{tr}(0)e^{-\frac{t}{T_2}}$

Eq 6.23 in text



Relaxation Summary



http://www-mrsrl.stanford.edu/~brian/intromr/

Why does M_{xy} decrease?

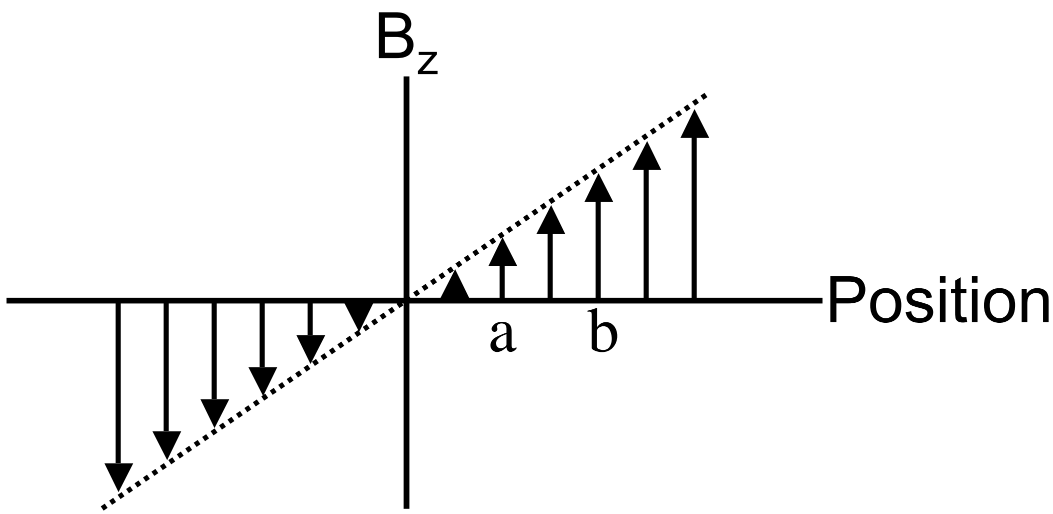
Why does M_z increase?

Current Status:

- Have a big magnet B_0
- Forces all same atoms to precess at same rate (Larmor Frequency)
- Can perturb atoms with RF signal and measure precession and relaxation

Imaging with NMR

- Slice selection:
  - Magnetic Gradient coils provide a linear variation in B_z with position.
    - *1973, Paul Lauterbur, Nobel Prize Laureate in 2003*
  - Result is a resonant frequency variation with position.



$$w(z) = \frac{\gamma}{2\pi}(B_0 + G_z z)$$

Protons at "z=a" will precess at different frequency than those at "z=b"

Exciting a Slice

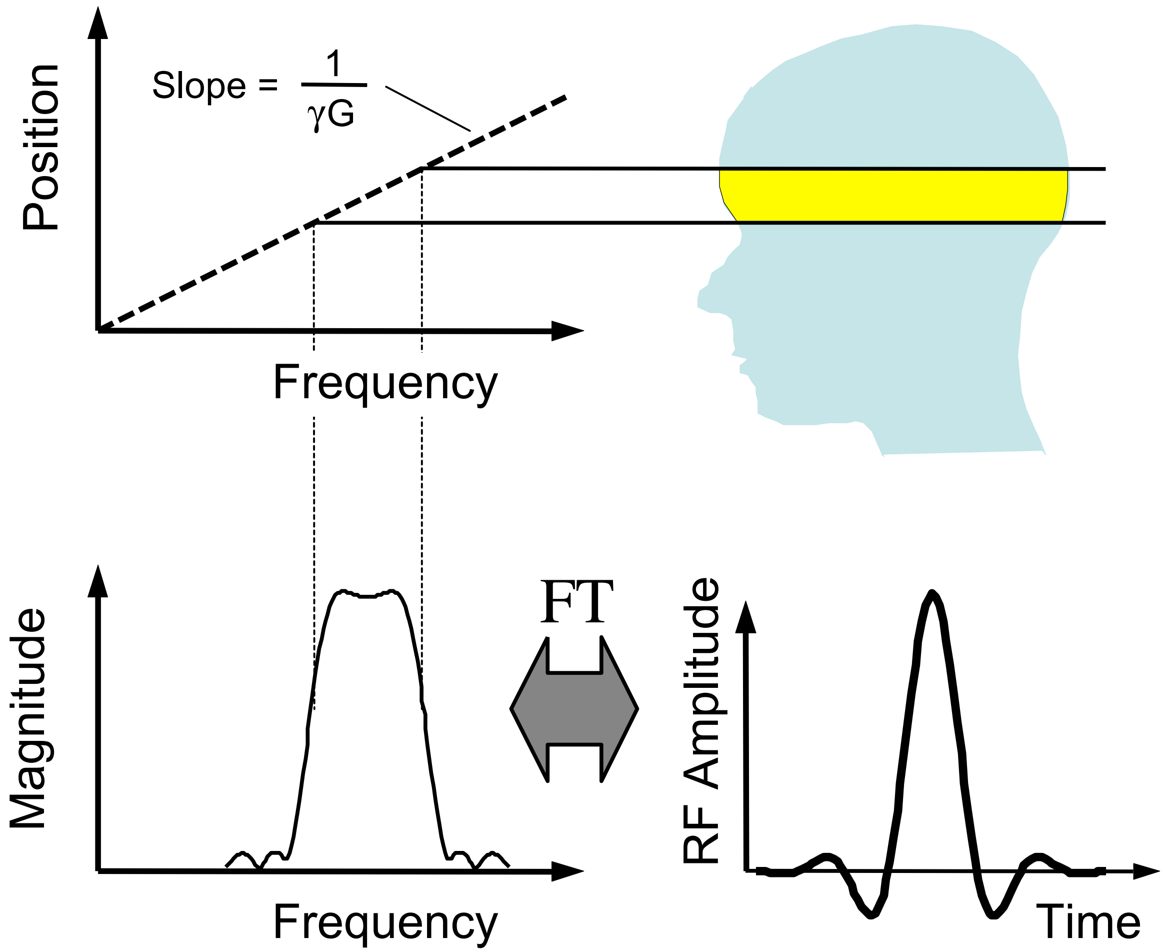


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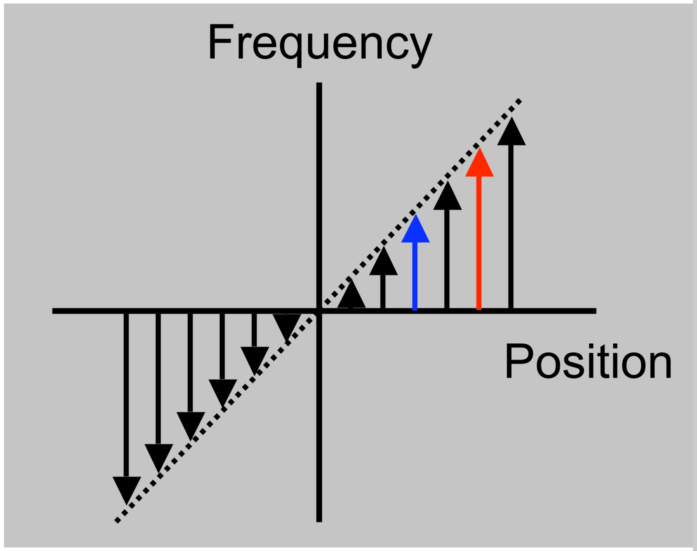
Image Acquisition

- Gradient causes resonant frequency to vary with position.
- Receive sum of signals from each spin.



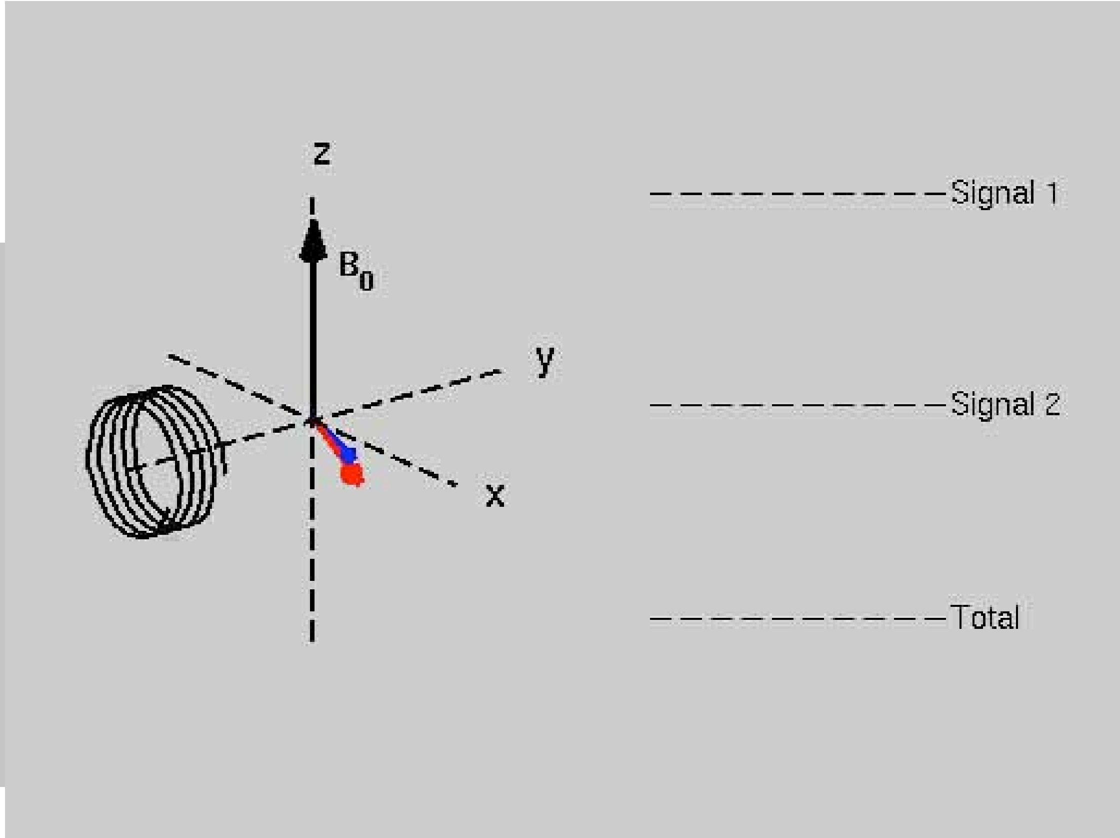
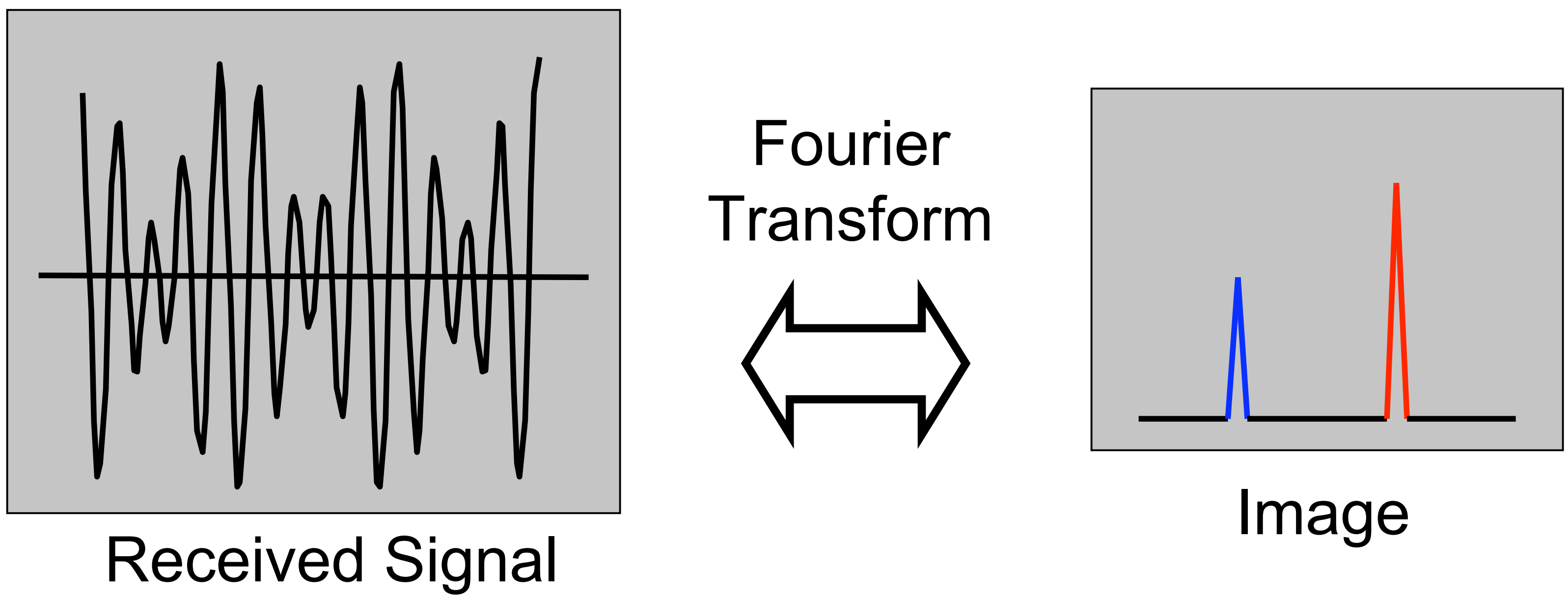


Image Reconstruction

- Received signal is a sum of “tones.”
- The “tones” of the signal are the image.
- This also applies to 2D and 3D images.



MRI: Readout (imaging)

- Next we apply a second gradient field in a perpendicular direction (say the x-direction) to force some change in the signal across the plane (otherwise we can't tell where the signals are coming from in the plane).
- So now the precession frequency of the hydrogen nuclei depend on the x-location $w(x,y) = \gamma(G_x x + B)$
- We can then describe the motion of the transverse component (which generates the RF signal output) using phasor notation as

$$M_{tr}(x,y,t) = M_{tr}(x,y,0)e^{-i\gamma G_x xt}$$

- The RF signal output is the integration of all the signals in the slice

$$s(t) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \rho(x,y)e^{-i\gamma G_x xt}\,dx\,dy$$

proton density (what we want to know)

Fourier transforms in MRI: The k-theorem

- If we define $k_x = \gamma G_x t / 2\pi$ we can write the RF output signal as

$$s(t) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \rho(x,y) e^{-i2\pi k_x x}\, dx\, dy$$

- Now recalling that

$$S(k_x, k_y) = \mathcal{F}\{s(x,y)\} \triangleq \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} s(x,y) e^{-i2\pi(k_x x + k_y y)}\, dx\, dy$$

we see that our signal is part of the Fourier transform of $\rho(x,y)$

$$s(t) = S(k_x, 0) = \mathcal{F}\{\rho(x,y)\}_{(k_x,0)}$$

To sample the other parts of k-space (the Fourier transform of our object of interest), we apply a pre-determined gradient in the perpendicular (y) direction prior to the readout gradient (G_x) this gives us

$$s(t; t_y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \rho(x,y) e^{-i2\pi(k_y y + k_x x)}\, dx\, dy$$

⇦ k-theorem or MRI equation

where $k_y = \gamma G_y t_y / 2\pi$

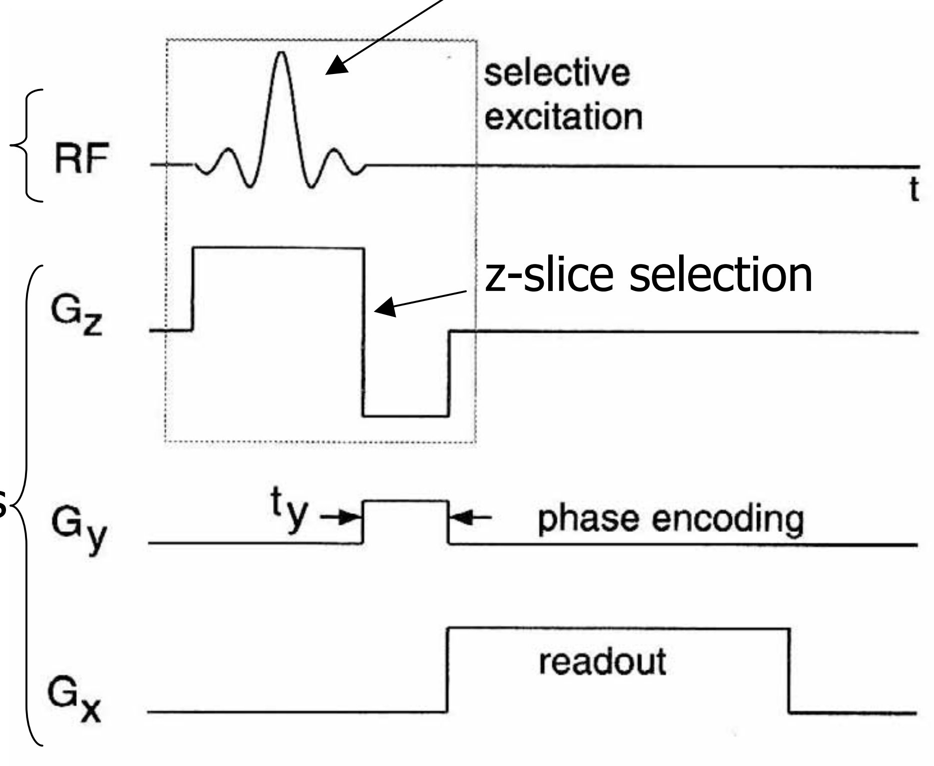
2D Imaging Sequence

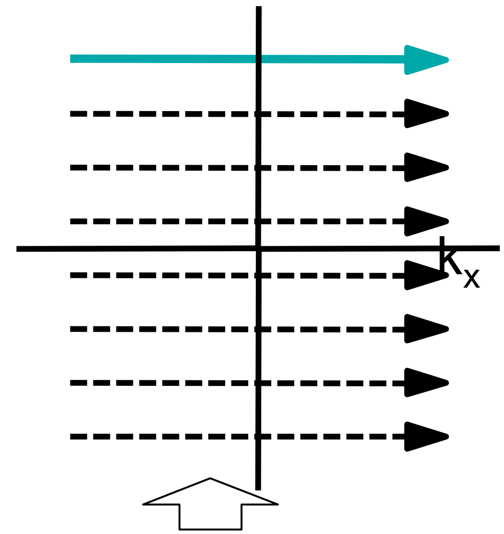
- Bare bones MRI 'pulse sequence'

90 degree flip

RF coil(s)

Gradient coils





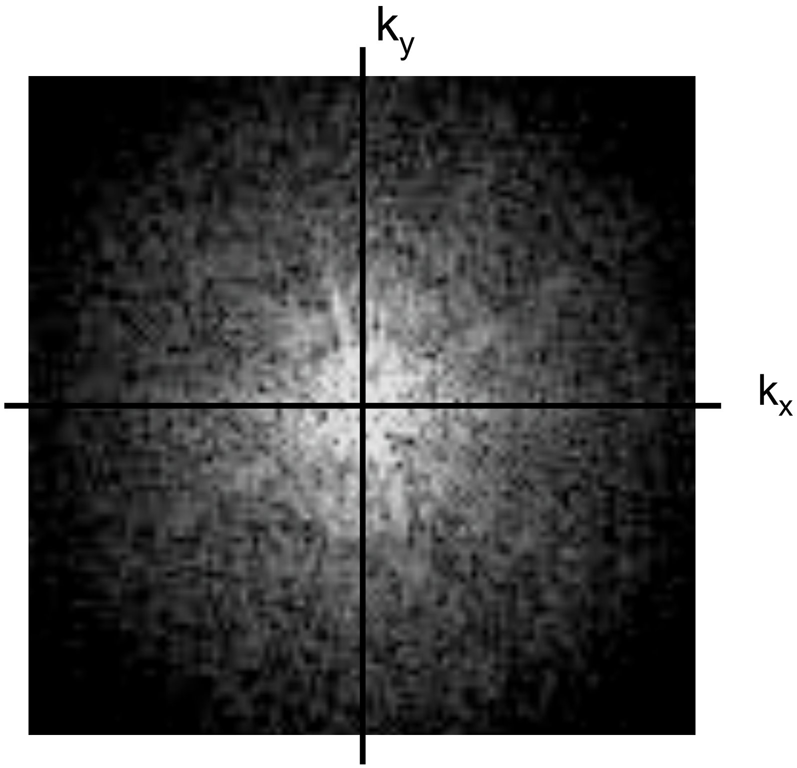
G_y is changed with each repetition (TR) to sample k-space along different k_y values (causes 'banging')

k-theorem or MRI equation: $$s(t;t_y) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \rho(x,y)\exp(-i2\pi(k_y y + k_x x))dx\,dy$$

$$(k_x, k_y) = \frac{\gamma}{2\pi}(G_x t, G_y t_y)$$

2D Image Reconstruction

- So to image the patient slice (remember this is tomographic imaging!) we sample out all of k-space and compute the inverse Fourier transform



Frequency-space (k-space)

Inverse FT

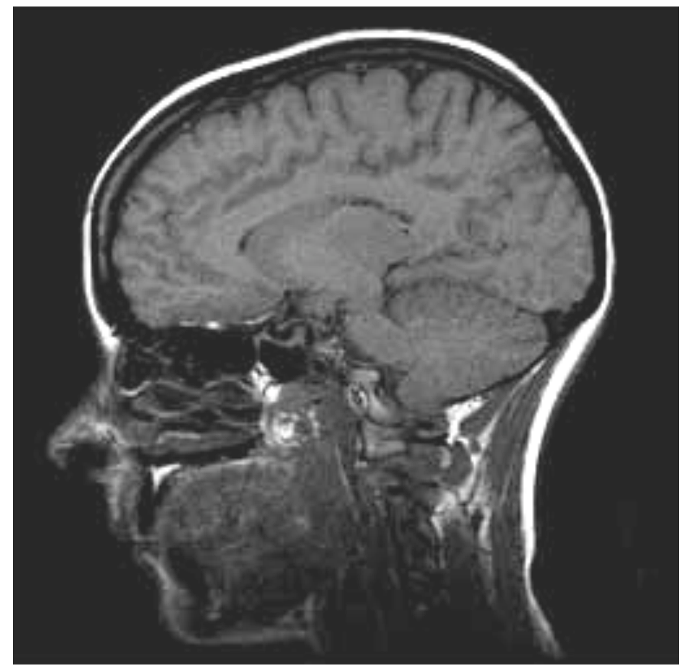
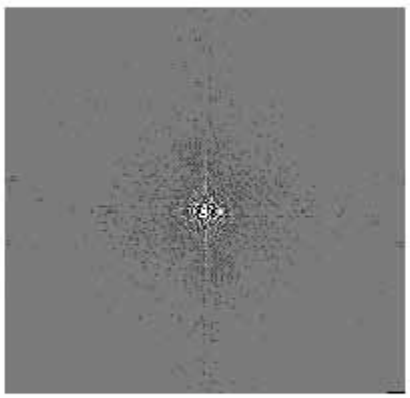
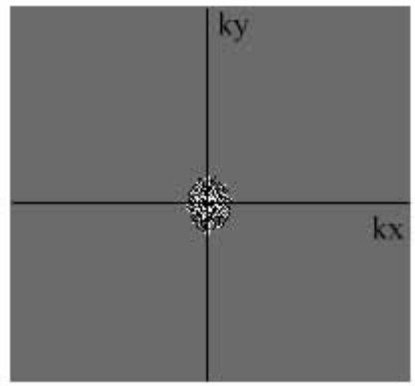


Image space

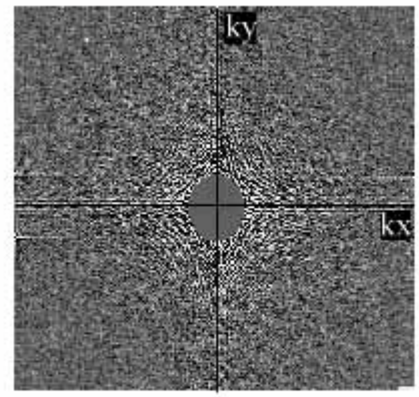
K-Space



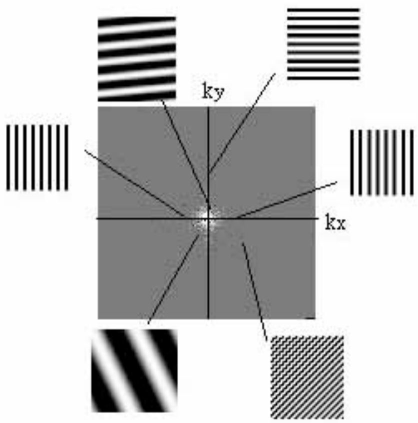
The Mona Lisa in k-Space



k-Space



k-Space



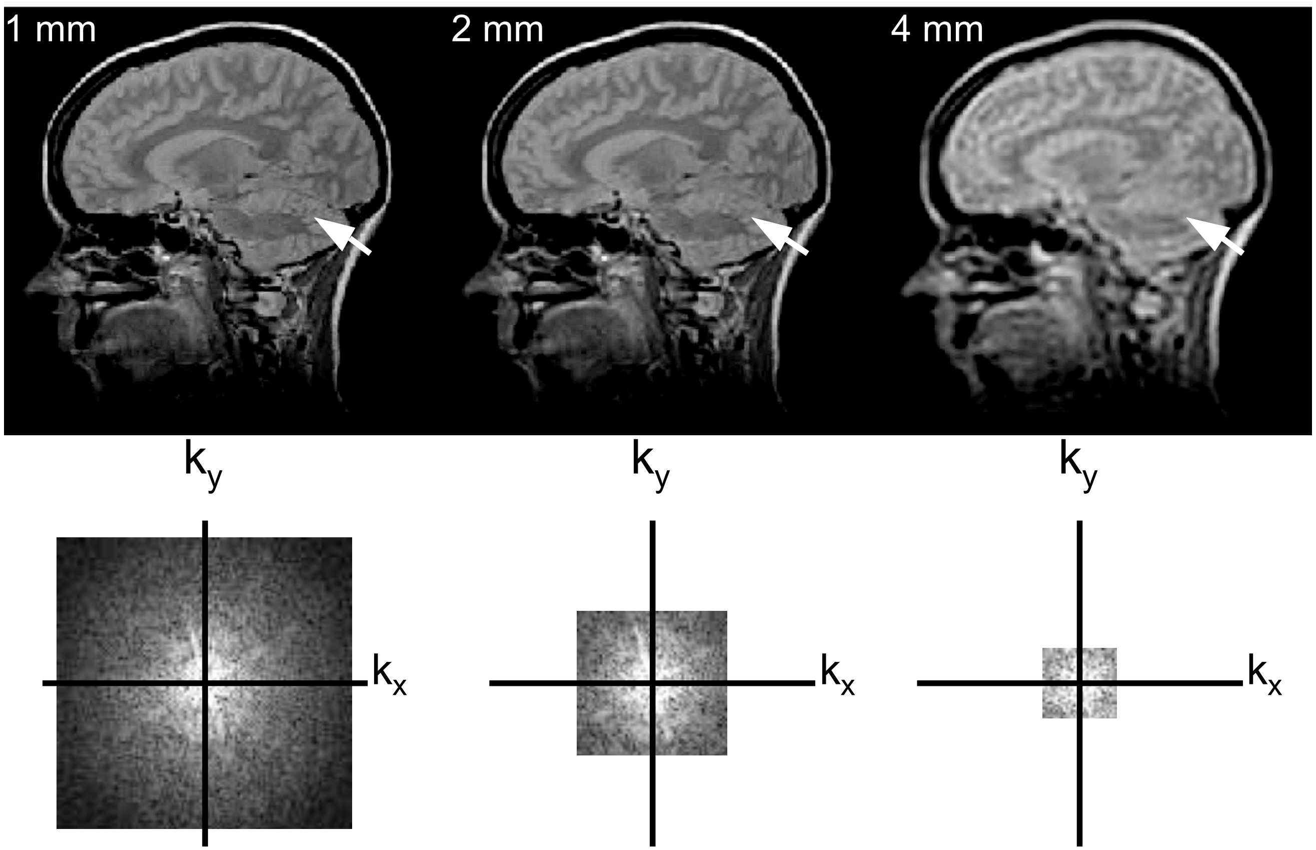
Low Frequency Mona

High Frequency Mona

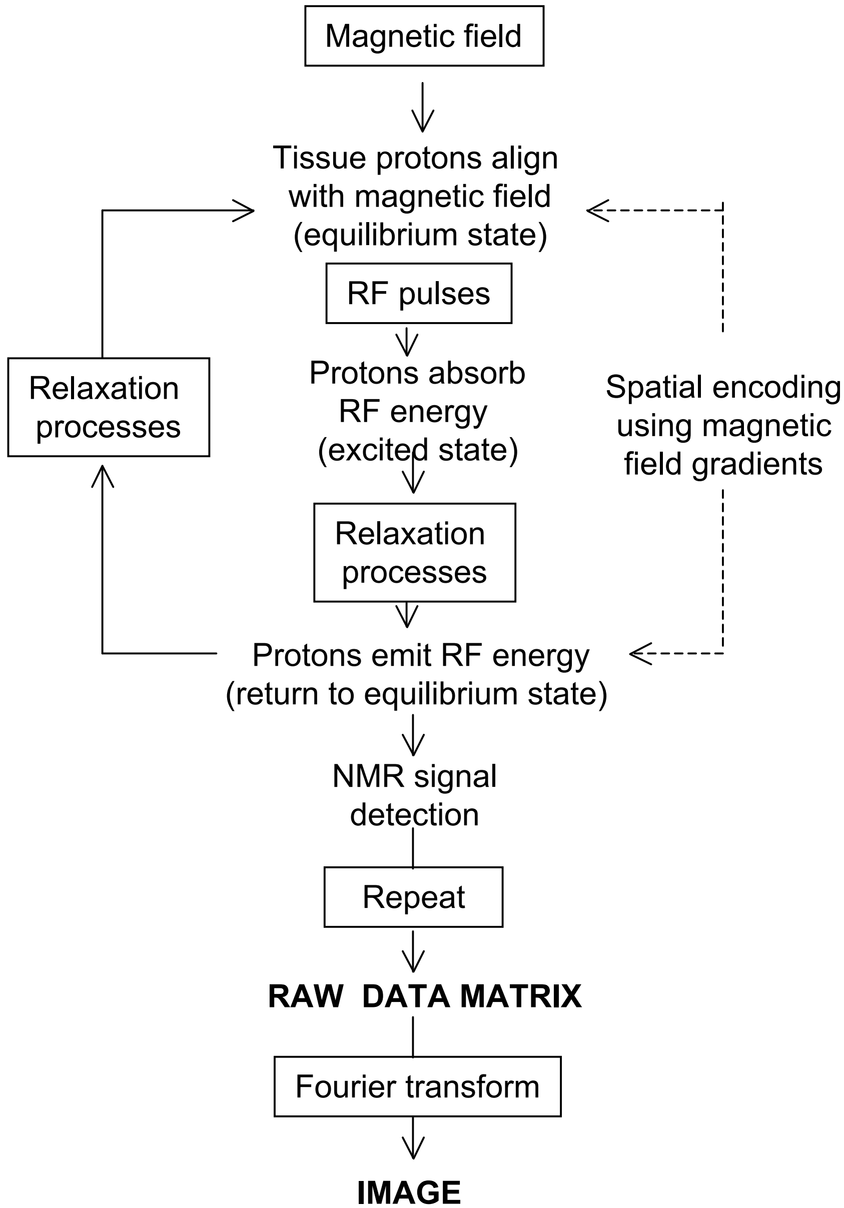
Source: [Traveler's Guide to K-space](#) (C.A. Mistretta)

Resolution

- A lot of MRI development is to figure out how we can more efficiently and/or more accurately sample k-space
- Image resolution increases as higher spatial frequencies are acquired. - Takes time to sample more of k-space



Review


Magnetic field
Tissue protons align with magnetic field (equilibrium state)
RF pulses
Protons absorb RF energy (excited state)
Relaxation processes
Relaxation processes
Spatial encoding using magnetic field gradients
Protons emit RF energy (return to equilibrium state)
NMR signal detection
Repeat
RAW DATA MATRIX
Fourier transform
IMAGE

Dephasing Phenomena

- The bulk magnetization vector M_0 (macroscopic group of spins) has two components longitudinal (M_z) and transverse (M_{tr} or M_{xy}), which actually generates the signal
- Both of these components change separately with time due to physical effects
- In the rotating frame these are given by the *Bloch equations*:

$$\frac{dM_z}{dt} = -\frac{M_z - M_0}{T_1}$$

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

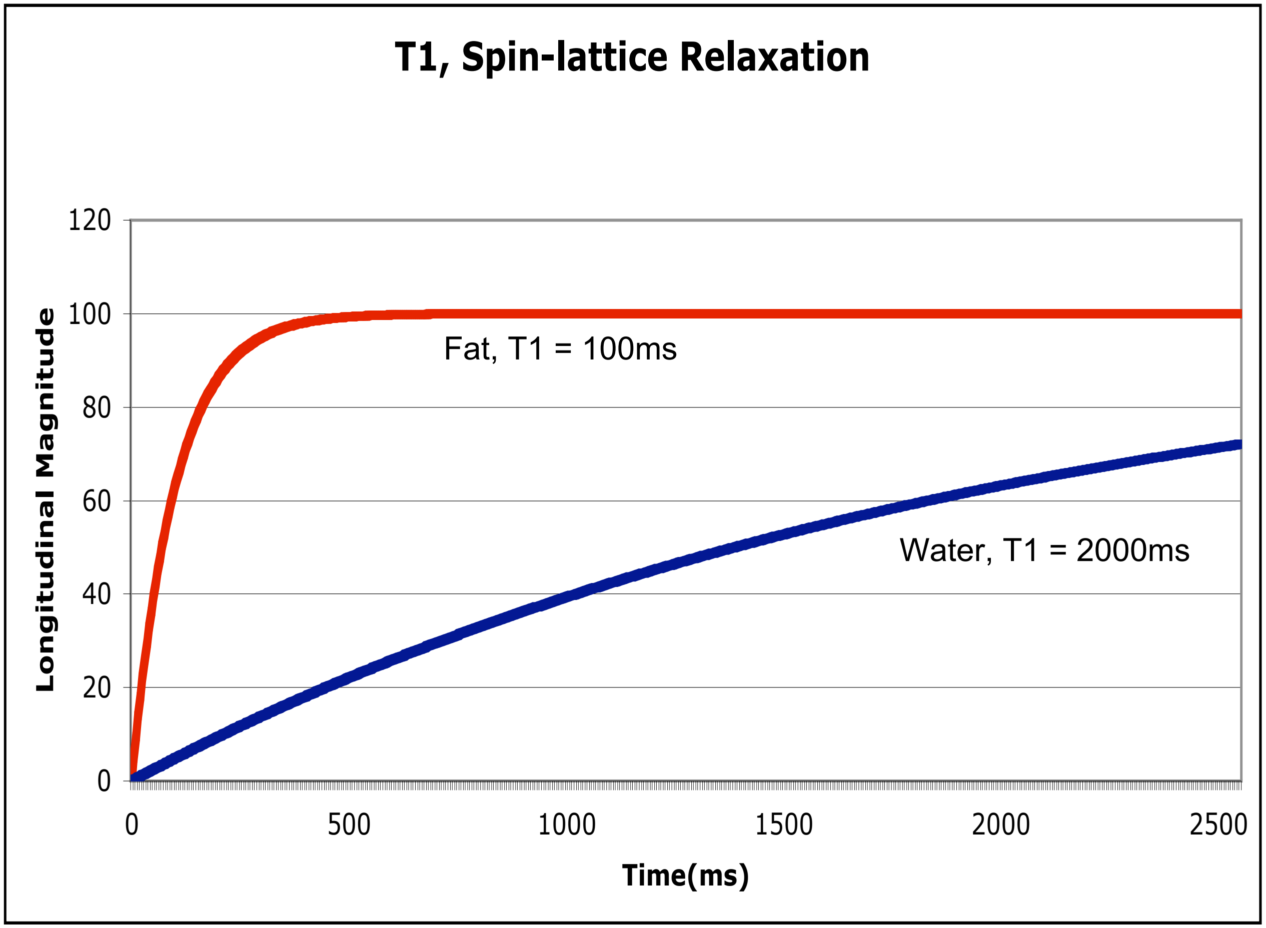
- With a 90 degree flip the resulting time behavior is given by:

$$M_z(t) = M_0(1 - e^{-t/T1})$$

$$M_{tr}(t) = M_0 e^{-t/T2}$$

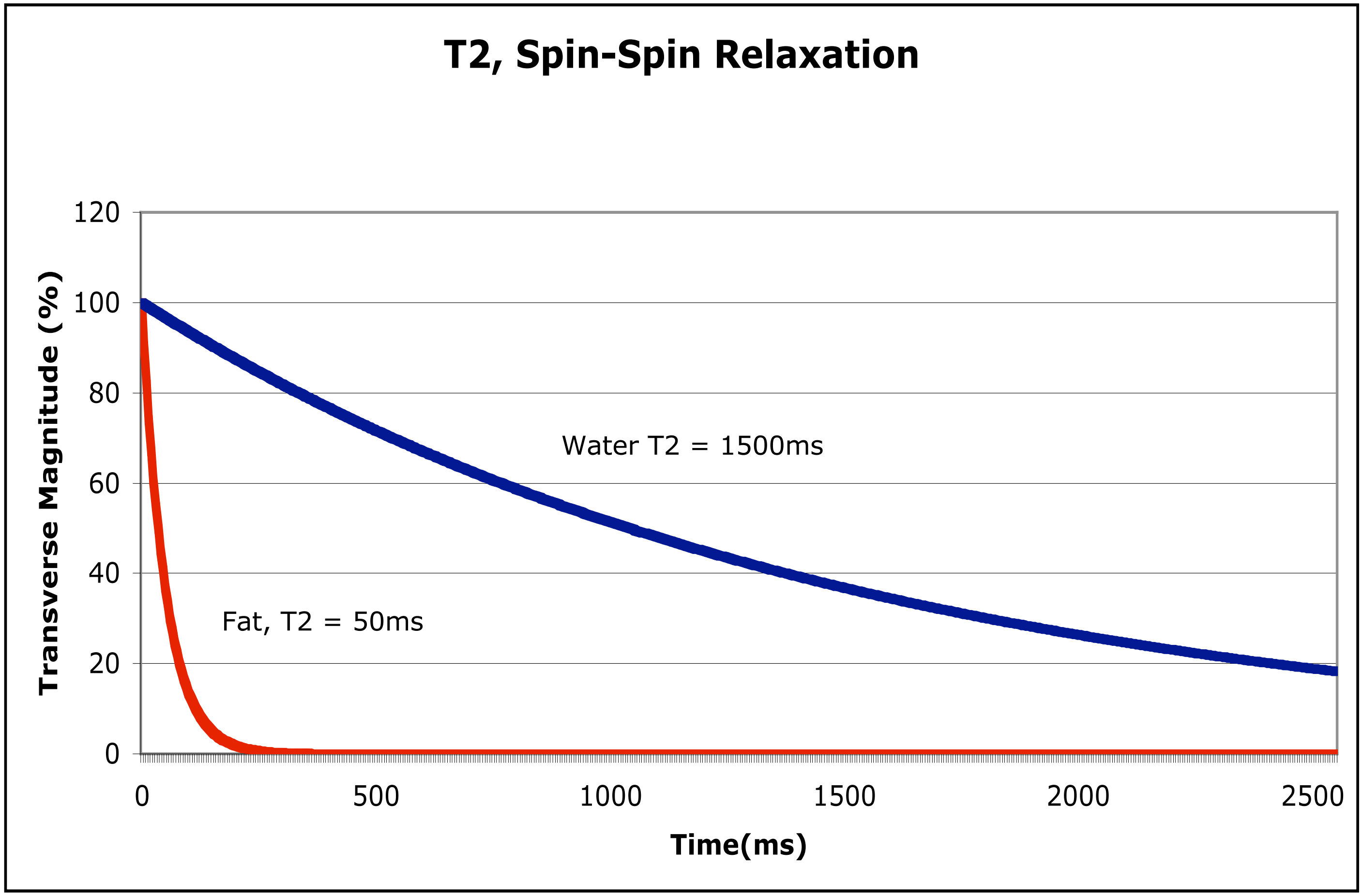
Spin-Lattice Relaxation (T1)

$$M_Z(t) = M_0(1 - e^{-\frac{t}{T_1}})$$



Spin-Spin Relaxation (T2)

$$M_{tr}(t) = M_{tr}(0)e^{-\frac{t}{T_2}}$$ Eq 6.23 in text



Additional T2 effects: T2*

Two factors contribute to the decay of transverse magnetization.

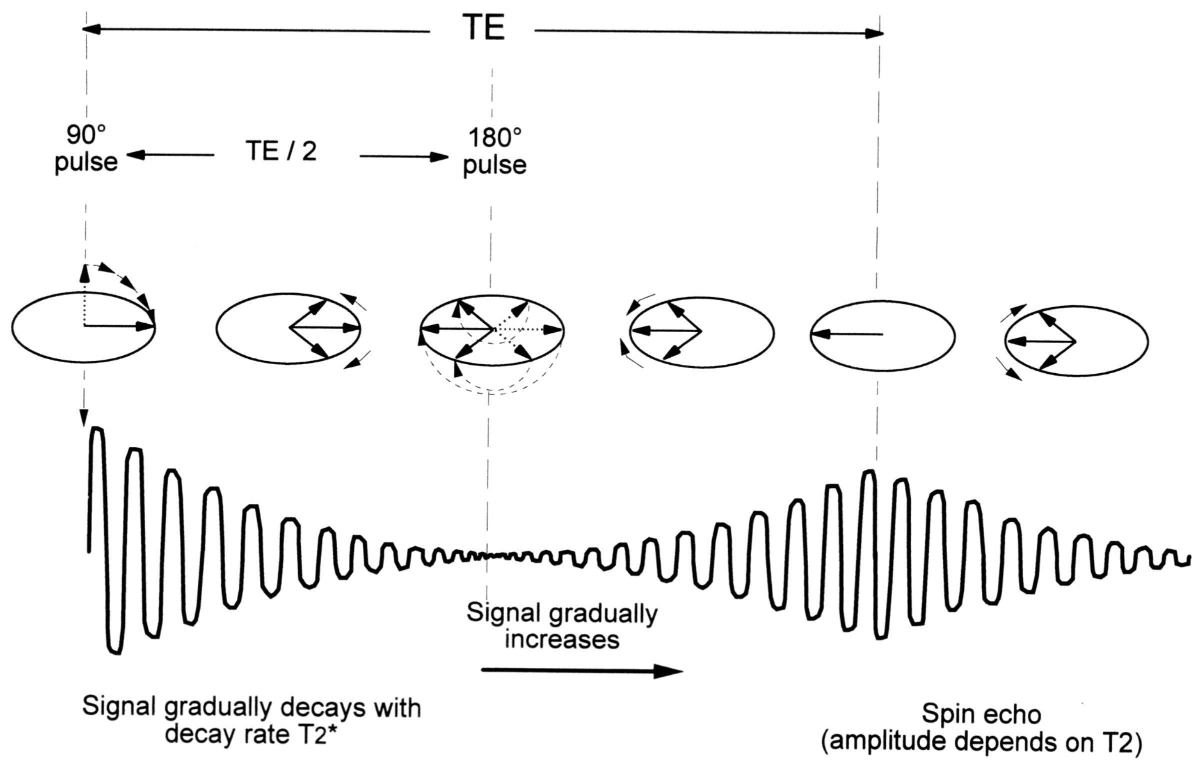
- Molecular interactions (said to lead to a pure T2 molecular effect)
- Variations in Bo (said to lead to an inhomogeneous T2 effect)

The combination of these two factors is what actually results in the decay of transverse magnetization. The combined time constant is called T2 ‘star’ and is given the symbol T2*. The relationship between the T2 from molecular processes and that from inhomogeneities in the magnetic field is $1/T2^* = 1/T2 + 1/T2_{inhomo}$

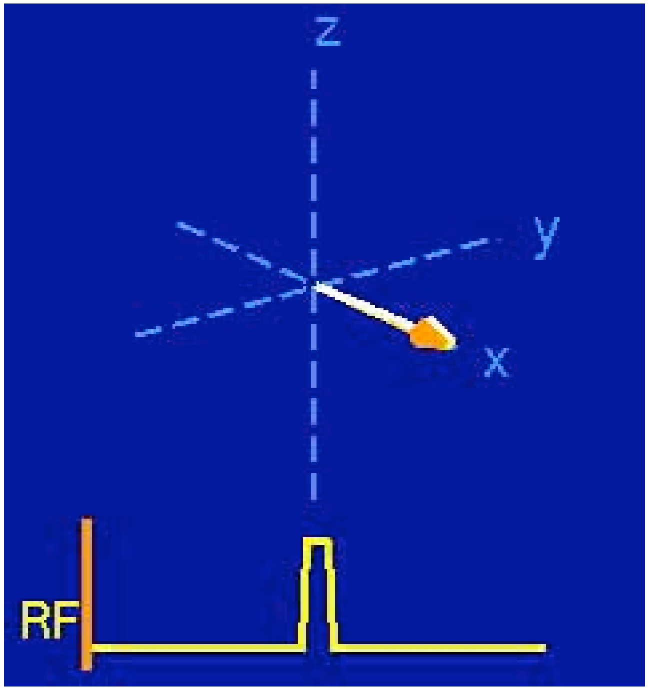
Undo effect of T2* with Spin-Echo Imaging

Spin Echo

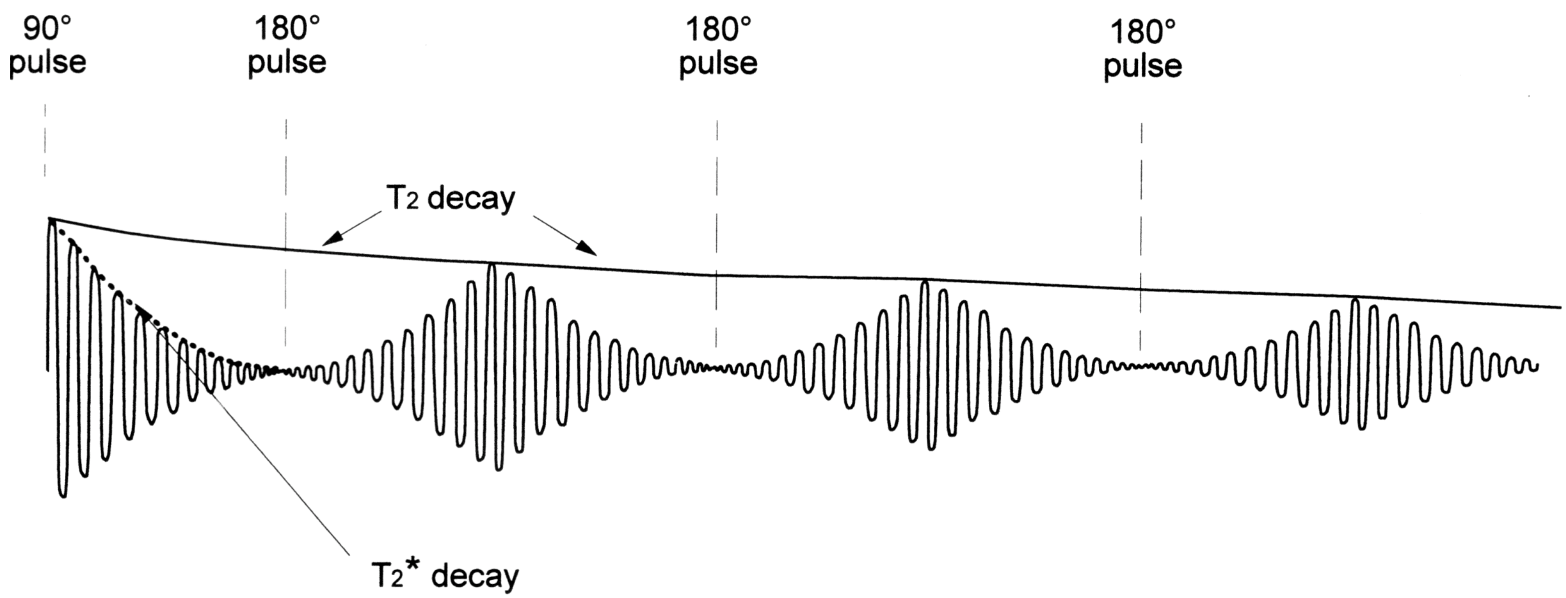
- Apply 90 degree pulse to start signal
- Apply 180 degree pulse to invert direction of dephasing spins ->induces an echo to reform in opposite direction



Spin Echo

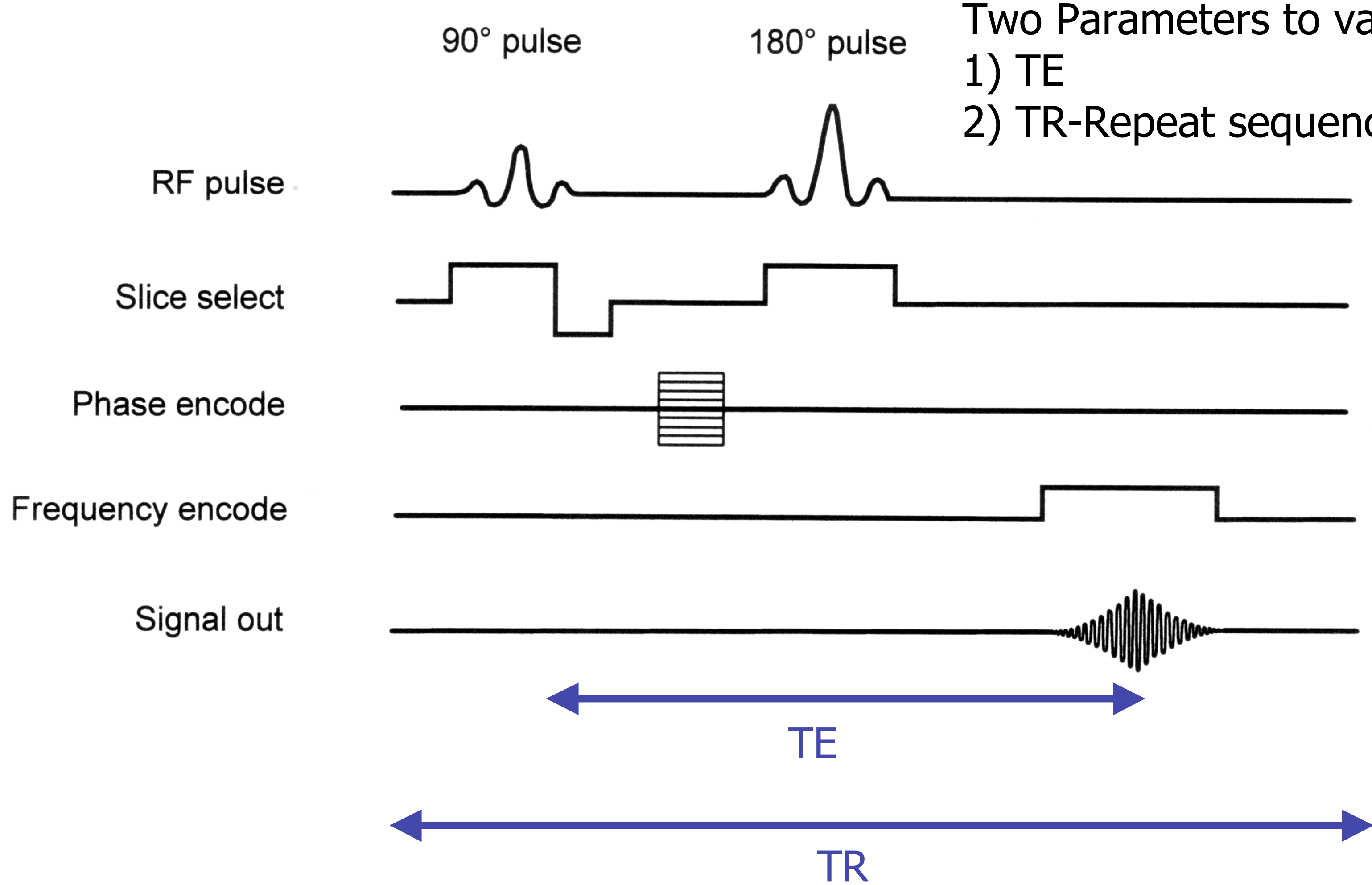


Spin-Echo T2 Decay



Spin-Echo Pulse Sequence

Two Parameters to vary:
1) TE
2) TR-Repeat sequence time



Spin-Echo Pulse Sequence

Basic signal output with a 90 degree spin-echo pulse sequence

$$\rho(x,y)\left(1-\exp\left(-\frac{TR}{T1}\right)\right)\exp\left(-\frac{TE}{T2}\right)$$

Adjust image qualities by changing TR and TE (all values in msec)

	T1 Weighting (short TR and short TE)	T2 Weighting (long TR and long TE)	Spin Density Weighting (long TR and short TE)
TR	400-600	1500-3000	1500-3000
TE	10-30	60-150	10-30

Spin-Echo Pulse Sequence

What Parameters should we set for:

T1 Weighting?

TR ~ T1 - differences in longitudinal magnetization minimized because not enough time for everything to return to equilibrium

Short TE So T2 decay effects minimized

T2 Weighting?

Long TR - reduce T1 effects, has time to return to equilibrium

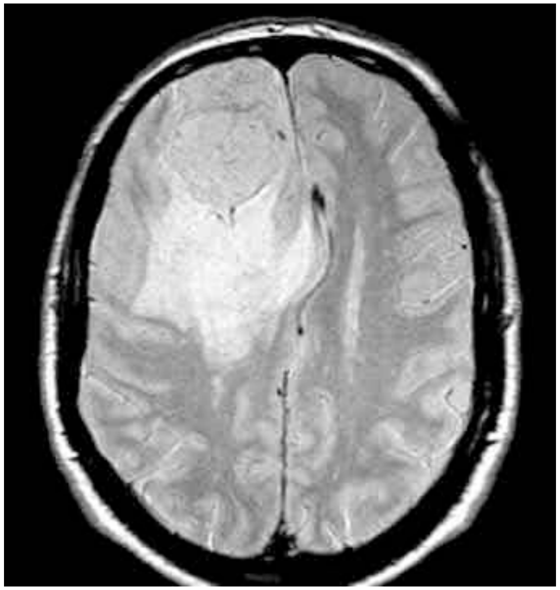
TE ~ T2 - allow for T2 decay to be emphasized between tissue

Spin (Proton) Density Weighting?

Long TR - reduce T1 effects, has time to return to equilibrium

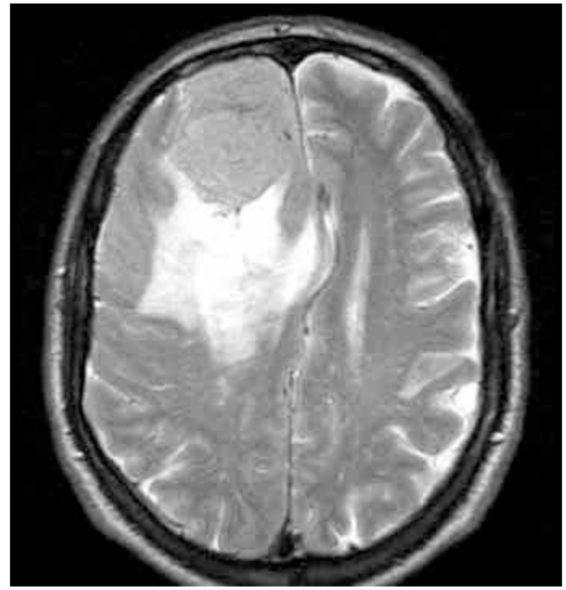
Short TE- keep signal high and reduce effects of T2

Examples of Different Weightings in Spin-Echo 2DFT MRI



Spin (H proton) density:
long TR, short TE

T1-weighted image:
TR~T1, short TE

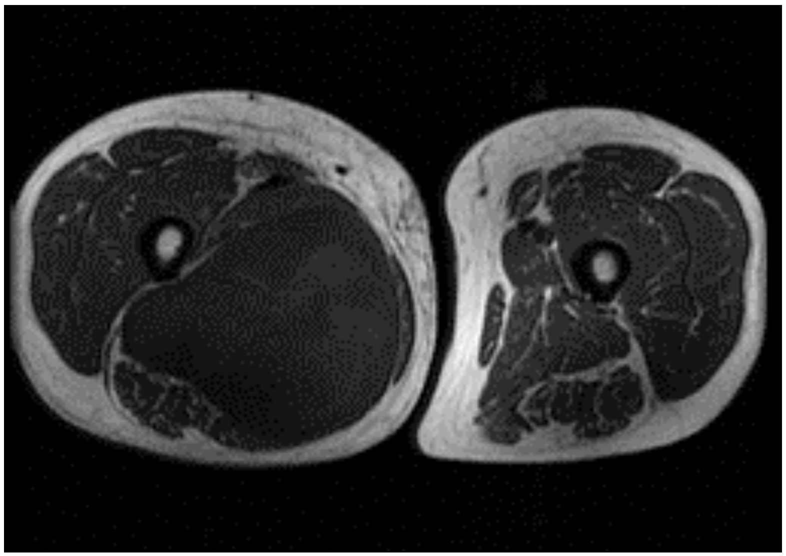


T2-weighted image:
Long TR, TE~T2

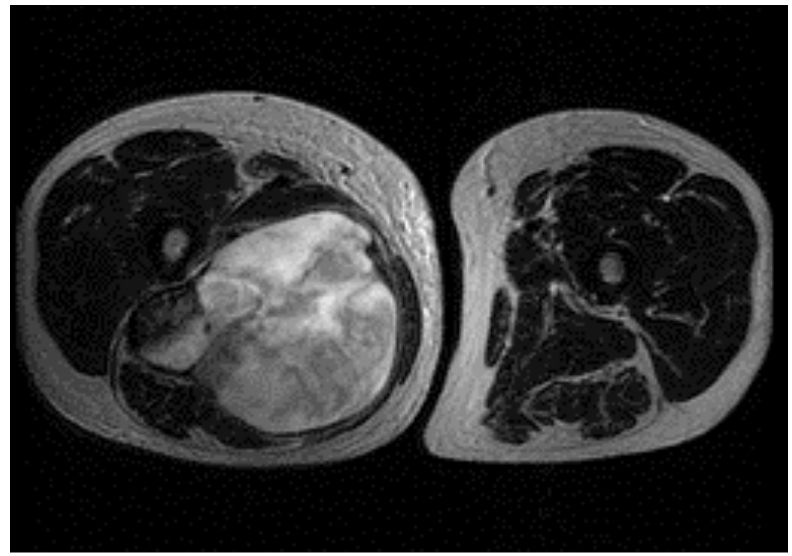
$$\rho(x,y)\left(1-\exp\left(-\frac{TR}{T1}\right)\right)\exp\left(-\frac{TE}{T2}\right)$$

- T1 weighted spin-echo 2DFT MRI is the most common form of MRI
- Again -- this is an example of (1) the differences between the data world and the visual world and (2) that even the data representation does not correspond to a single physical property

Examples of Different Weightings in MRI



T1 weighted



T2 weighted

Examples of Different Weightings in MRI

spin (H proton) density weighted

T2 weighted

Aspects of MRI we won’t have time to discuss

- Flow imaging
- functional brain activation imaging (fMRI)
- Angiography
- The use of dynamic contrast-enhanced MRI