MR Imaging Fundamentals

Shashi B. Mehta

Objectives

✍ The purpose of this short lecture is to introduce you to the basic concepts of Magnetic Resonance Imaging:

After this lecture, you should be able to

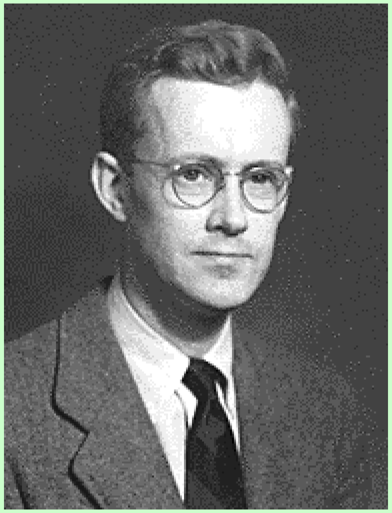
(i) link the physics with the MR Hardware.

(ii) understand the concept of pulse sequence

(iii) how to optimize contrast in MR (covered in a separate presentation.)

(iv) understand the concept of K-space. (covered in a separate presentation.)

A Short History



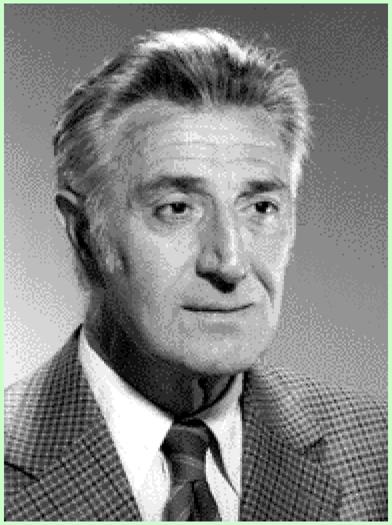
Edward M. Purcell
(1912 -)

Discoverer of NMR Signal in Condensed Matter by Observing Energy Absorption

Felix Bloch (1905 - 1983)

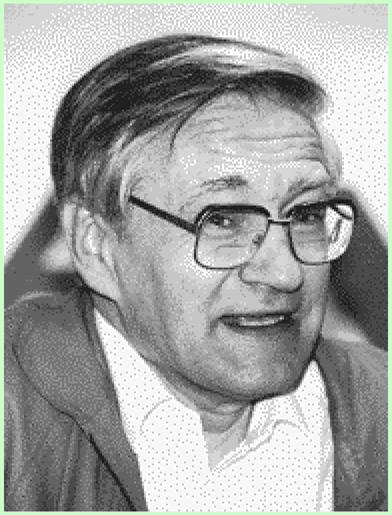
Discoverer of NMR Signal in Condensed Matter Using Nuclear Induction Method

(They shared the Nobel Prize in Physics in 1946)



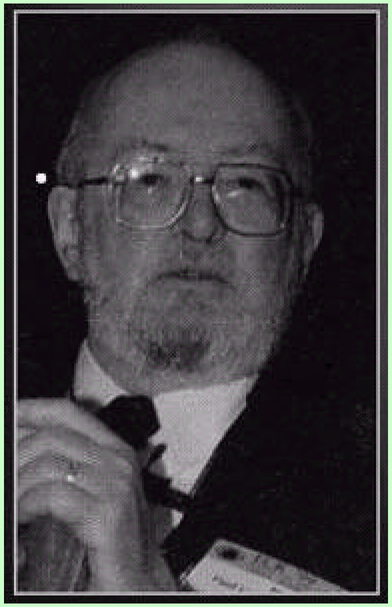
Erwin L. Hahn
(1921 -)

Discoverer of Spin Echoes and Free Induction Decay



Richard R. Ernst
(1933 -)

Pioneer of Fourier-Transform NMR and Two-Dimensional NMR Spectroscopy and Imaging



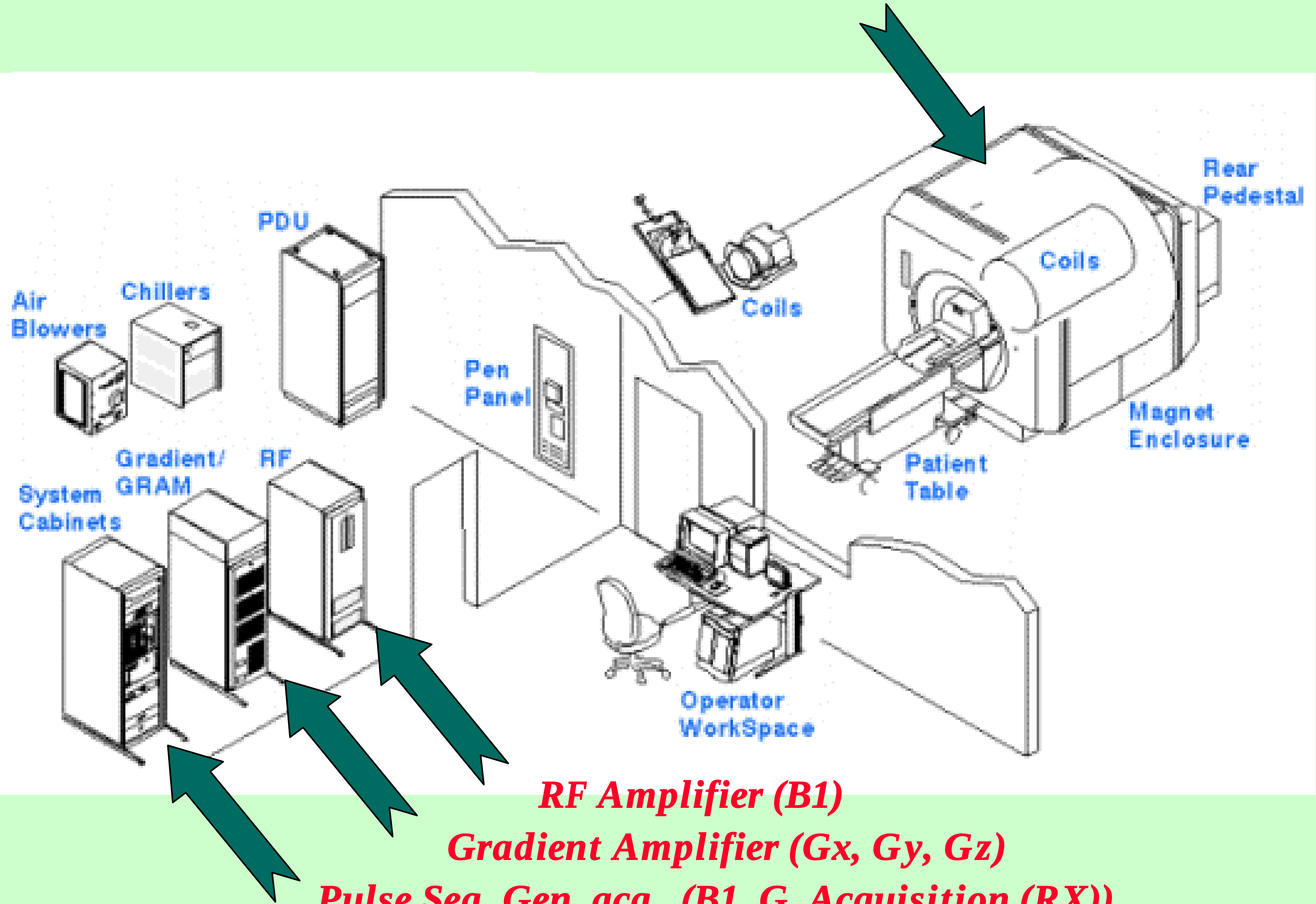
Paul C. Lauterbur
(1929 -)

Originator of a Method for Spatially Localizing NMR Relaxation Information from a Sample and Displaying It as a Pictorial Map

?First described the basic MRI technique in 1972

?Published his first MR image in 1973 (zeugmatography)

B0 (Magnet), B1 (RF Coil)

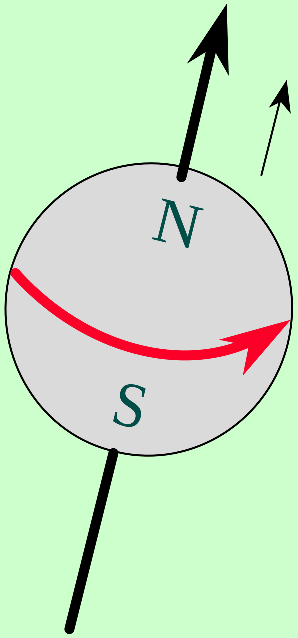


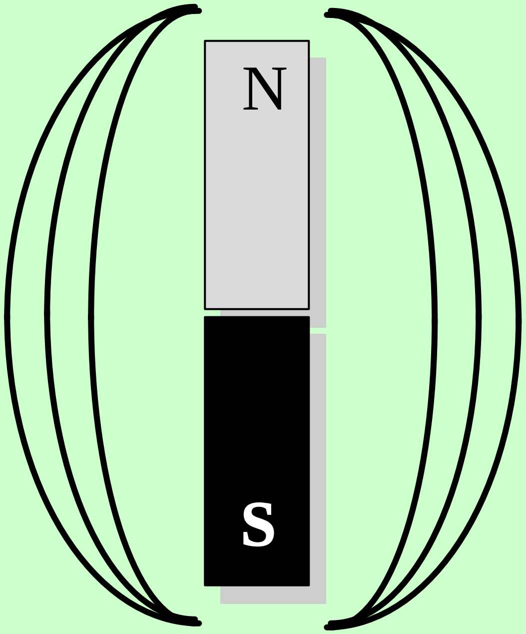
RF Amplifier (B1)
Gradient Amplifier (Gx, Gy, Gz)
Pulse Seq. Gen, acq. (B1, G, Acquisition (RX))

The Origin of the MR Signal

- The Nucleus of a Hydrogen Atom is a Charged Particle.
- The Nucleus of a Hydrogen Atom has a Nuclear Spin.
- A Spinning Charged Particle, e.g., the Hydrogen Atom, will Produce a Magnetic Dipole

Signal :Magnetic Dipole & Bar Magnet

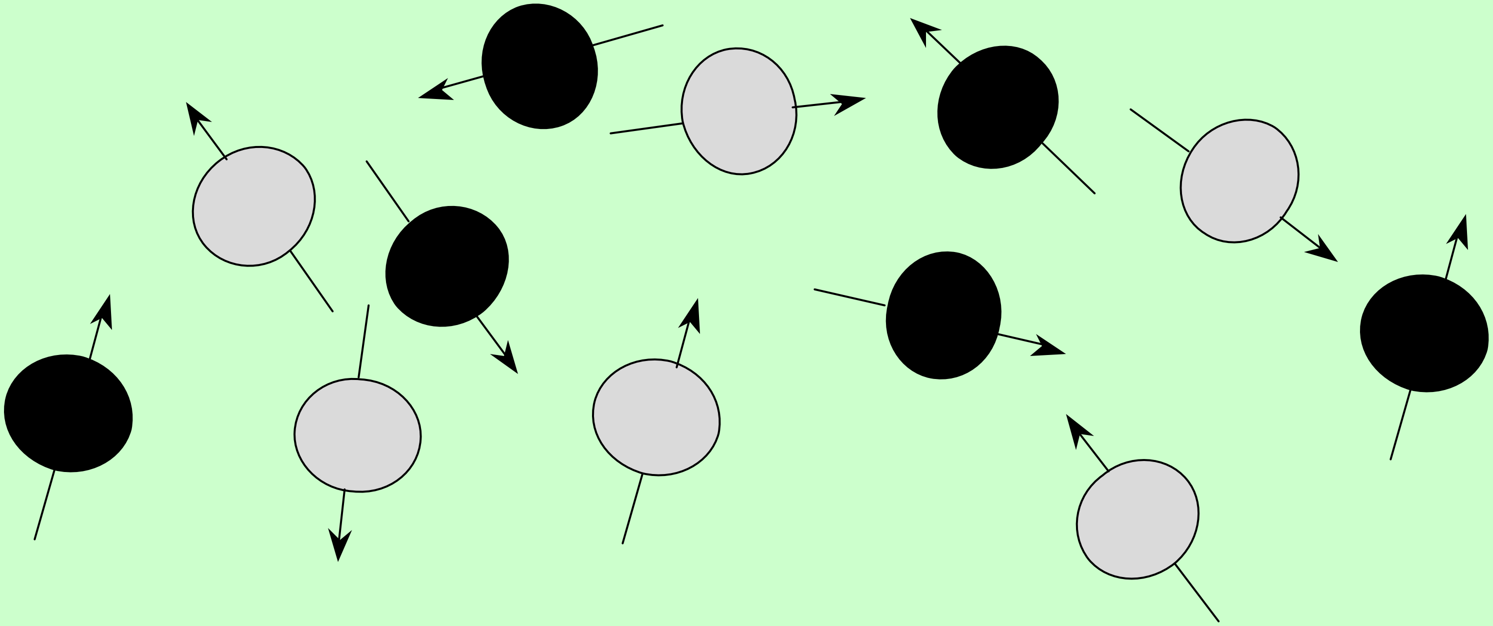




A magnetic dipole will interact with an external magnetic field.

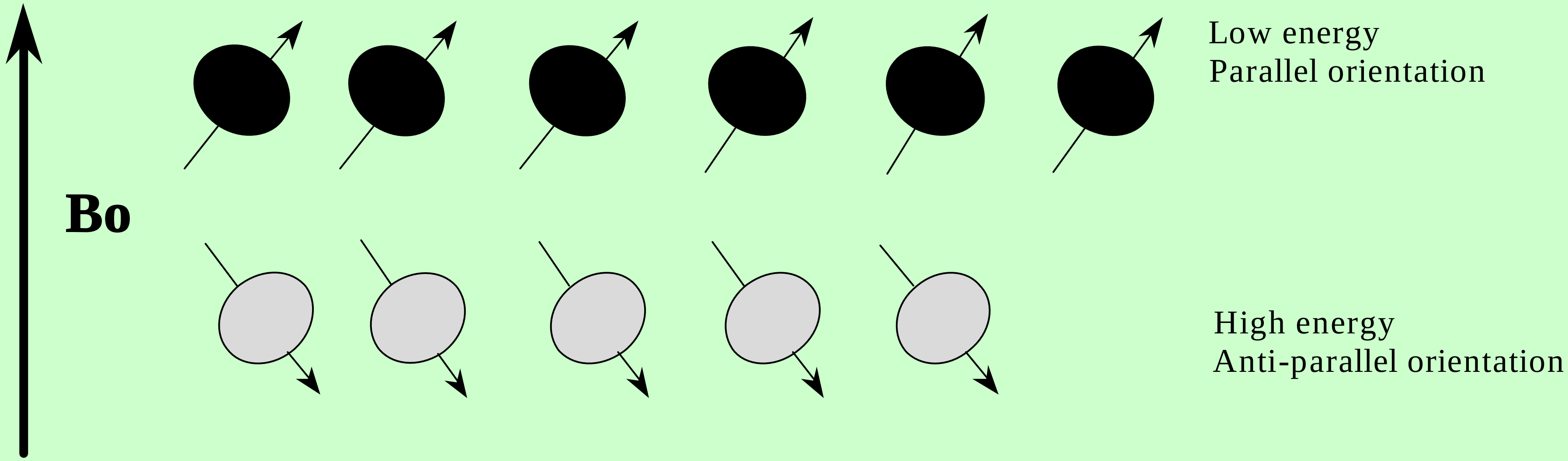
Signal: Alignment

- ✍ Random in absence of applied field.
- ✍ Sum of All Vectors is Zero; no Signal can be Measured.



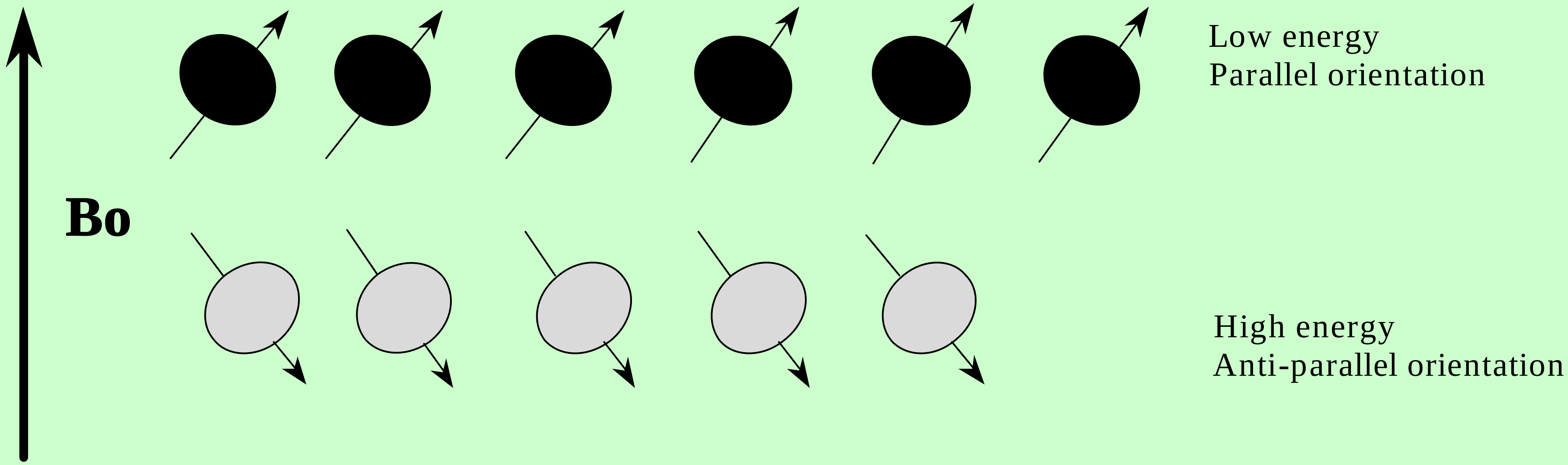
Signal WITH Magnet: Nuclear Orientations in B_0

- With $\mathbf{B_0}$ = Spin-up = Parallel Alignment
- Against $\mathbf{B_0}$ = Spin-down = Anti-parallel Alignment



Signal & Magnet: Alignment Ratio

- Number of nuclei in low energy state is slightly greater (about one per million spins) than the number in the high energy state.
- Only the excess nuclei in the parallel orientation contribute to the MR signal.

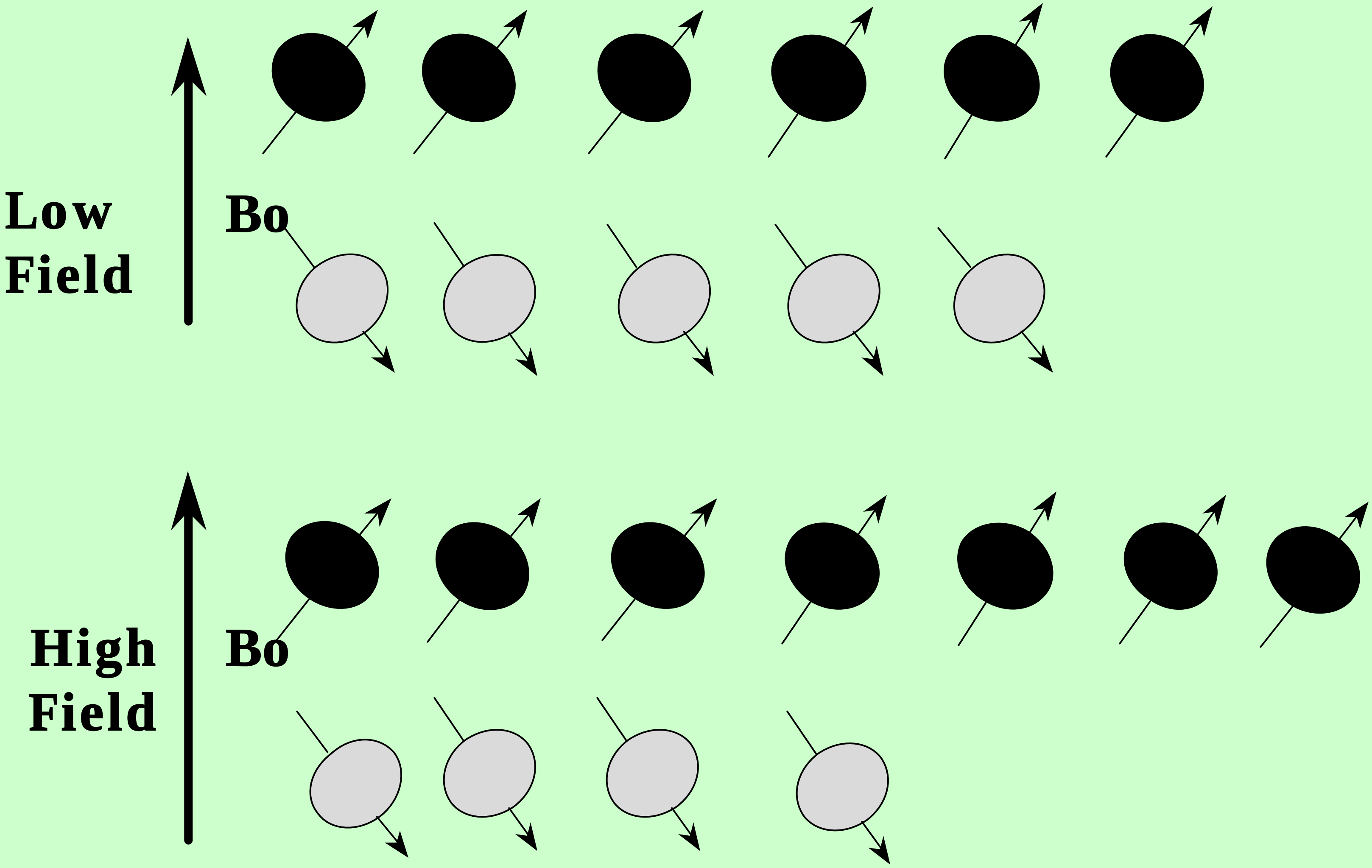


Bo

Low energy
Parallel orientation

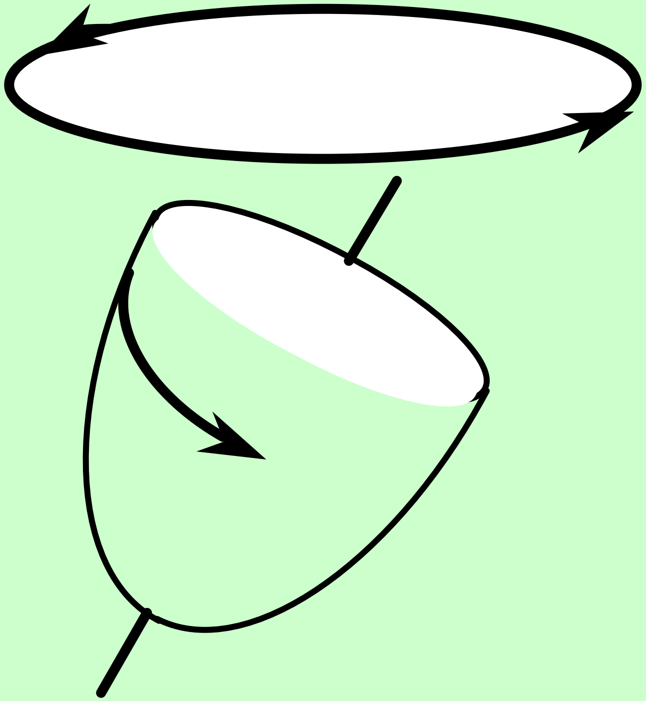
High energy
Anti-parallel orientation

Magnet: The Effect of Field Strength



Two Types of Motion

- Spin
- Precession

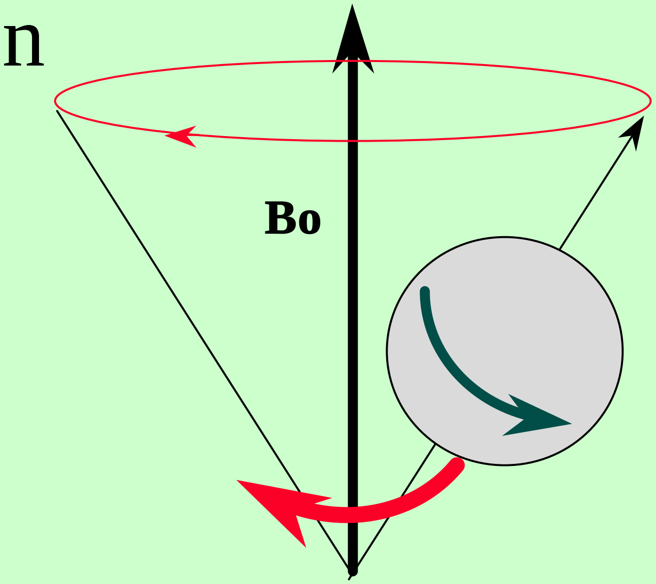


Spinning Top Analogy

Spin + Gravity = Precession

Signal & Magnet: Two Types of Motion

- Nuclear Angular Momentum
- Precession



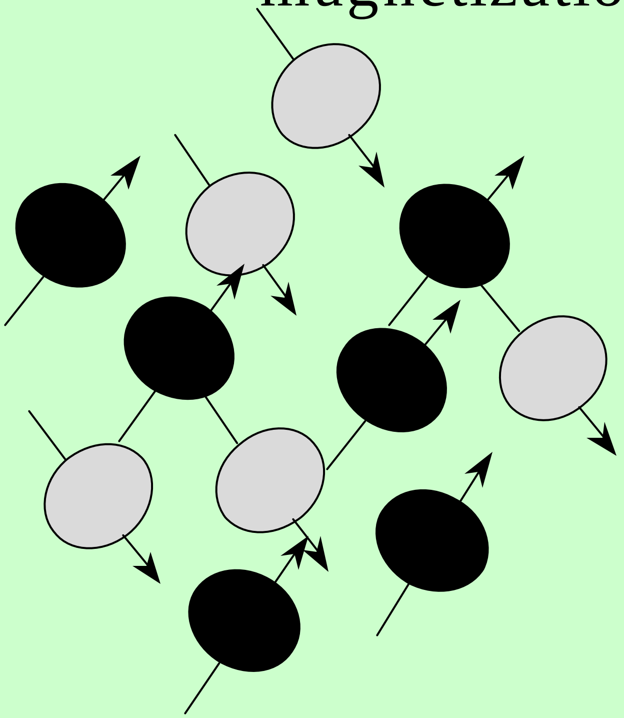
Nuclear Precession

Spin + B_0 Torque = Precession

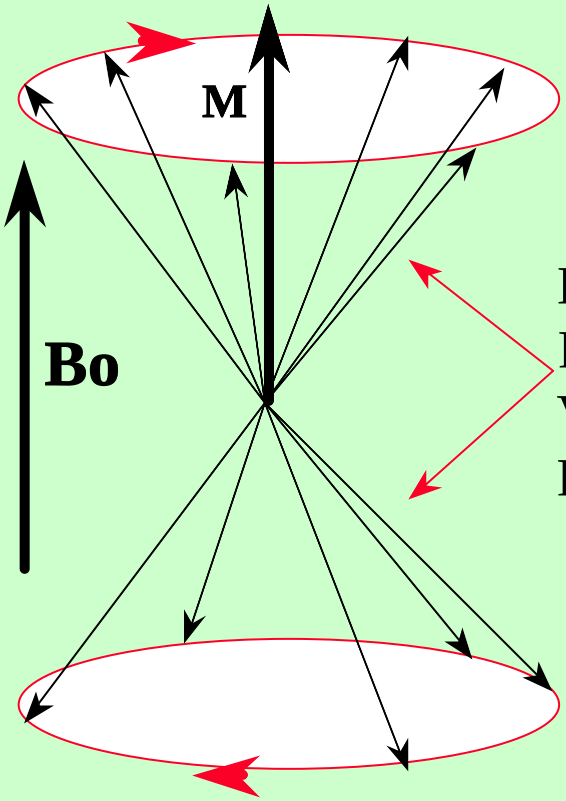
Signal: Net Magnetization Vector

- Vector Sums

Sum of spin-up & spin-down vectors is the net magnetization vector. **M** is the Net Vector Sum.



Real Distribution
of the Nuclei



Individually
Precessing Spin
Vectors: Physics
Representation

Signal & Magnet: Larmor Equation

- Precessional frequency is unique for each type of nucleus and is called the Larmor frequency. It depends on the type of nucleus and the strength of the applied magnetic field.

? ? ? ??

  - ? ??Precession Frequency (specifically $?_{??}$)
  - ??? Gyromagnetic Ratio
  - ? ??Magnetic Field Strength (specifically $?_{?}$)

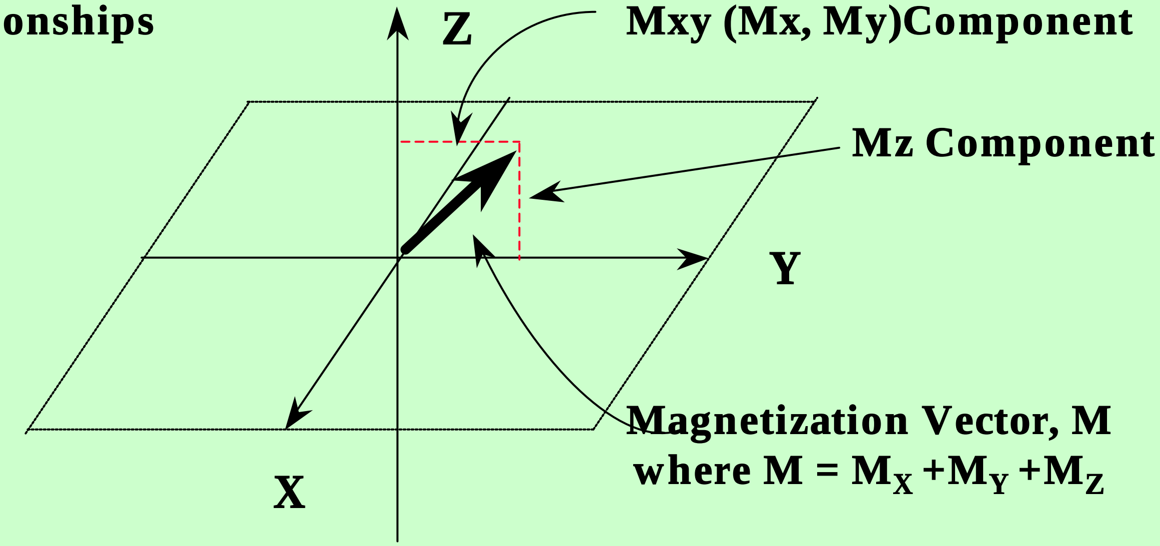
Larmor Equation - Precession Frequencies

- ? $_{??}$? ??? $_{?}$
  - **1.5T:** ? $_{??}$? ??????? **MHz**
  - **1.0T:** ? $_{??}$? ??????? **MHz**
  - **0.5T:** ? $_{??}$? ??????? **MHz**
  - **0.2T:** ? $_{??}$? ??????? **MHz**
- These are Radio Frequencies (RF). The energies of MR are in the RF portion of the electro-magnetic spectrum.

Vector Relationships between B_0, M_Z, M_X, M_Y, and M_{XY}

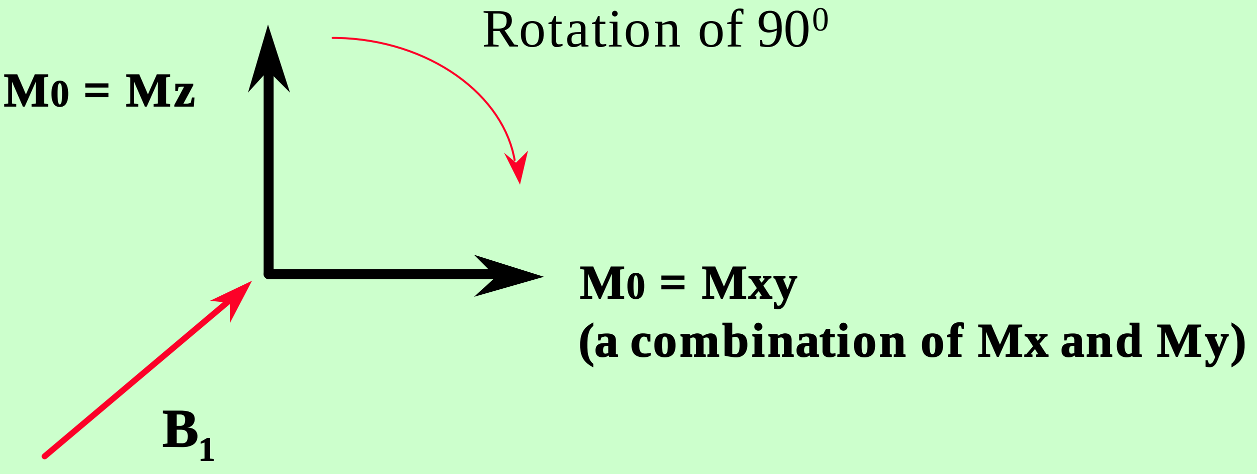
- $\boldsymbol{B_0}$ is Parallel to Z axis.
- **M** projection onto Z axis = $\mathbf{M_Z}$.
- **M** projection onto XY plane = $\mathbf{M_{XY}}$

Vector Relationships



Signal & RF: Rotation of M_0

- **M_0** is aligned with and must rotate with the vector **B_{eff} = B_1+B_0**. The spins also precess around this magnetic field.


Rotation of 90^0

M_0 = Mz

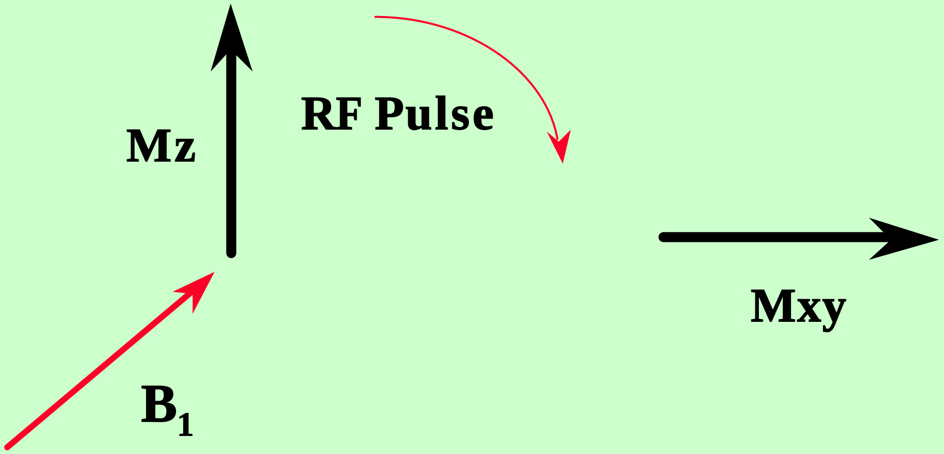
M_0 = Mxy
(a combination of Mx and My)

B_1

- Degree of the Rotation of **M**
  - Depends on amplitude and duration of the RF Pulse.
- RF Pulses are named from the degrees of rotation of **M**.
  - i.e., 90^0 RF pulse produces a 90^0 rotation of **M**.

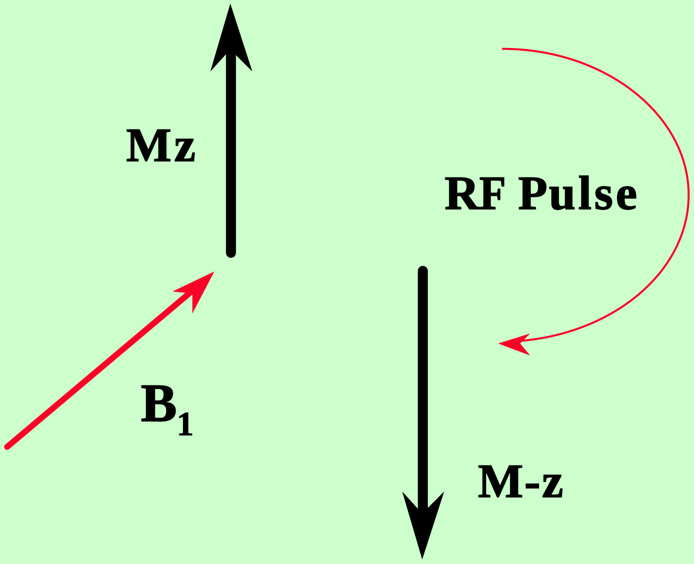
RF: Degree of Rotation - 90^0

- 90^0 Rotation of the Magnetization Vector.



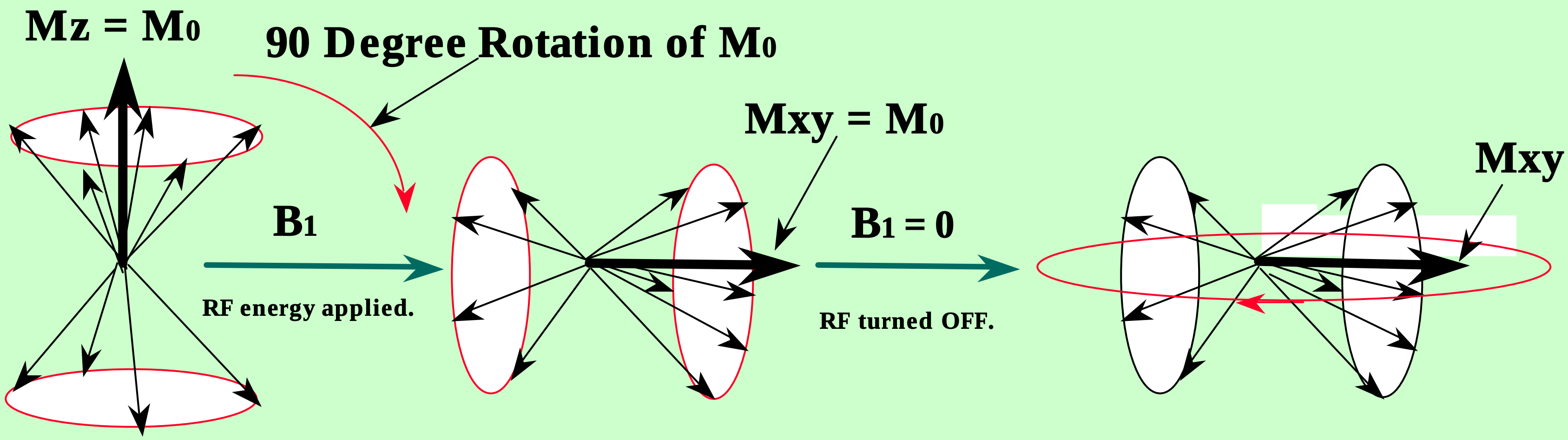
RF: Degree of Rotation - 180^0

- ✍ 180^0 Rotation - The Magnetization Vector is Inverted



RF: Rotation of the Spins

- Measurement of the MR Signal Requires
  - Phase coherence of the individual spins, i.e., **Mxy** > 0. As the phase coherence decreases **Mxy** goes to 0.
  - Precession of **Mxy** in the transverse plane.



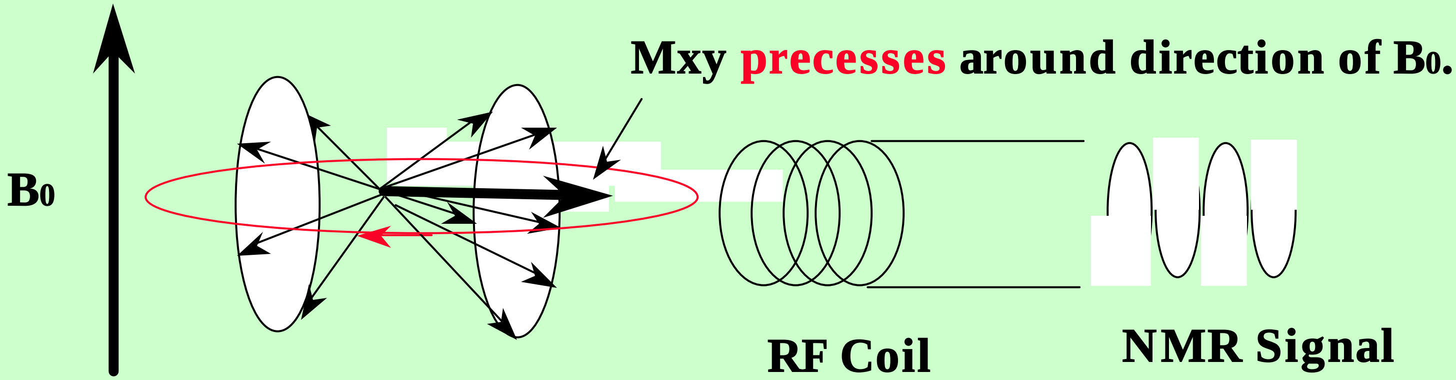
M_0 is stationary, individual spins precesses around direction of B_0.

M_0 Vector precesses around direction of B_1+B_0 which rotates in the zy plane.

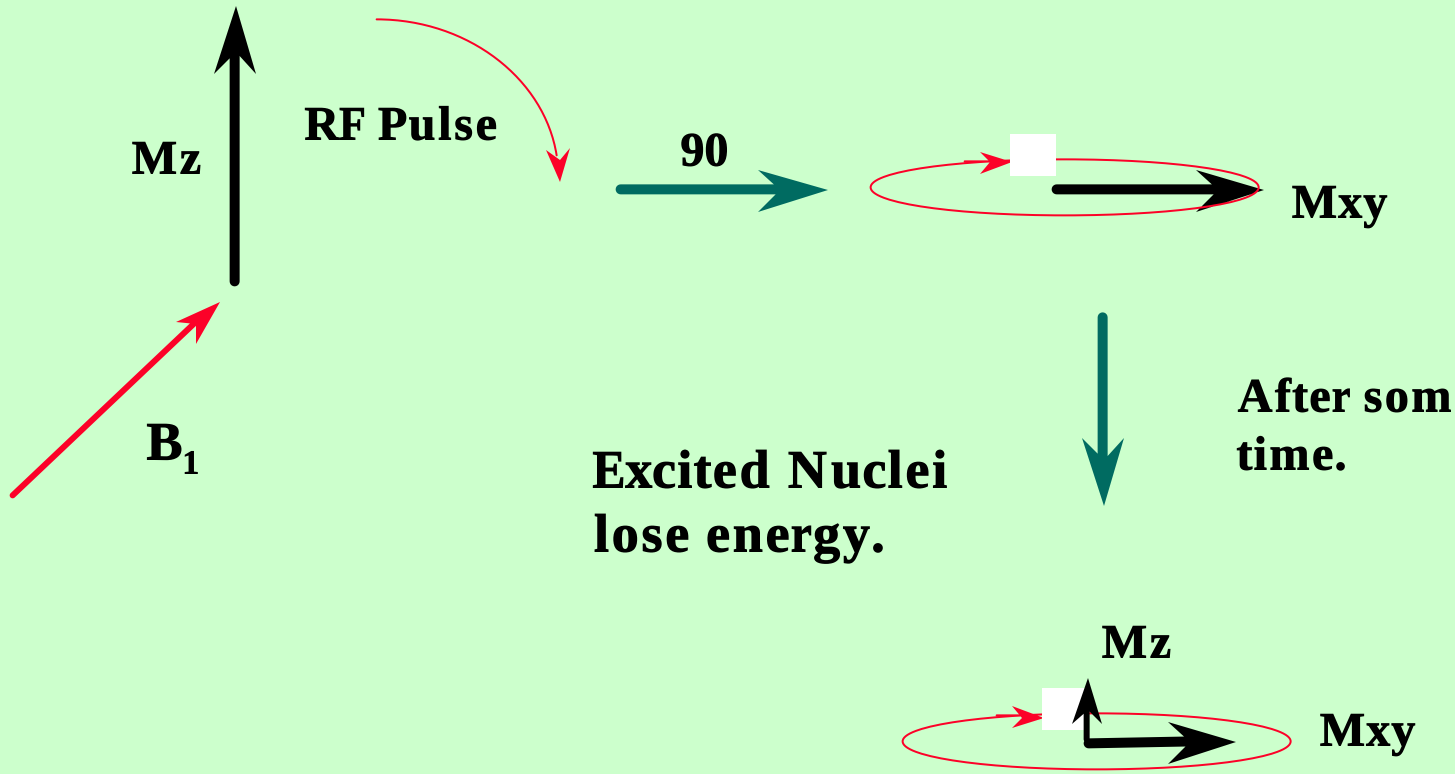
M_{xy} Vector must precess around direction of B_0 in the xy plane.

Signal: from Faraday's Law of Induction

- A magnetic field moving across a conductor will induce an electric current in the conductor.
  - Criteria
    - Conductor = RF Coil
    - Magnetism = Phase coherence of transverse magnetism, **Mxy** > 0.
    - Motion = Precession of **Mxy** vector in xy plane.



T_1 Relaxation: Return of Mz
Longitudinal Relaxation



Mz

RF Pulse

90

Mxy

B_1

Excited Nuclei
lose energy.

After some
time.

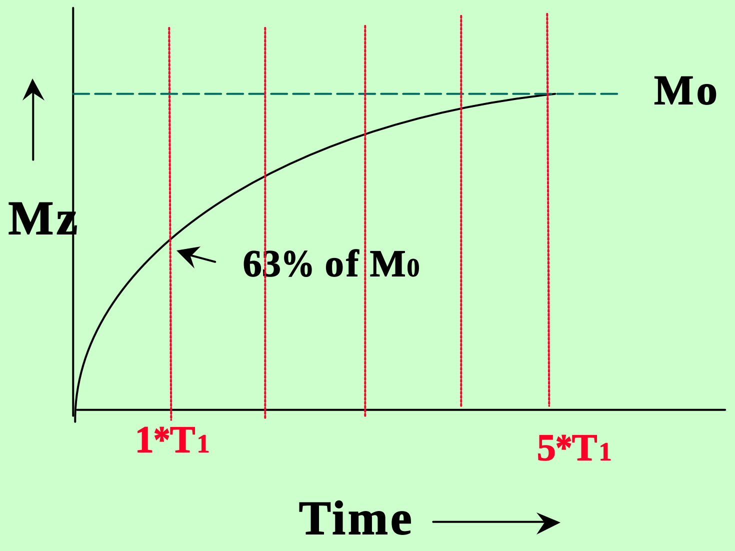
Mz

Mxy

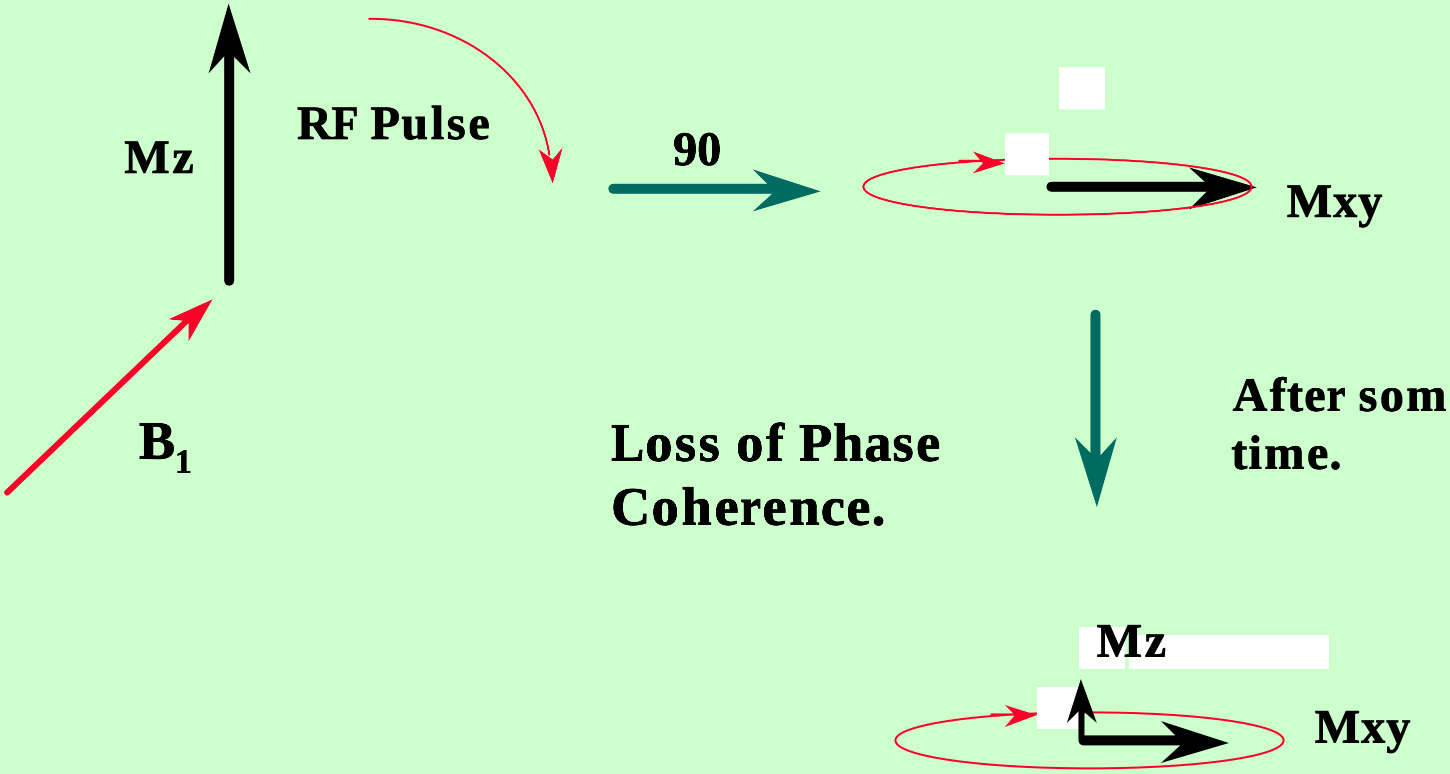
T_1 relaxation results from the transfer of energy from the excited nuclei to the surrounding environment. As a result, the nuclei re-align with B_0 and the Mz vector begins to grow in magnitude while the magnitude of Mxy decreases.

T_1 Relaxation

- T_1 = the time for longitudinal magnetization (**M_z**) to grow to 63% of equilibrium value (**M_0**).
- 5 T_1 times are required for complete recovery of the equilibrium magnetization (**M_z = M_0**).



T_2 Relaxation: Dephasing of M_{xy}, Transverse Relaxation.


Mz

RF Pulse

90

Mxy

B_1

After some time.

Loss of Phase Coherence.

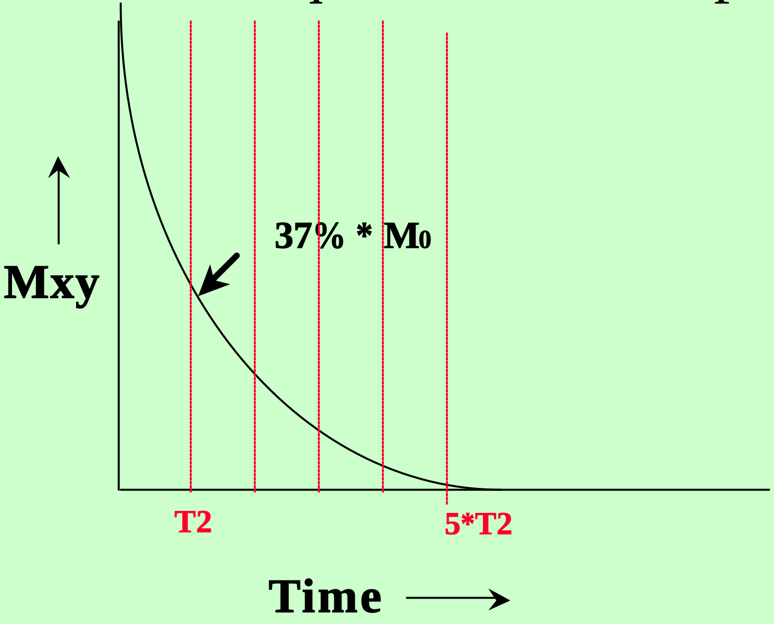
Mz

Mxy

T_2 results from variations in local magnetic fields at each nuclei. The interactions change the precessional frequency of the nuclei therefore causing a loss of phase coherence.

T_2 Relaxation

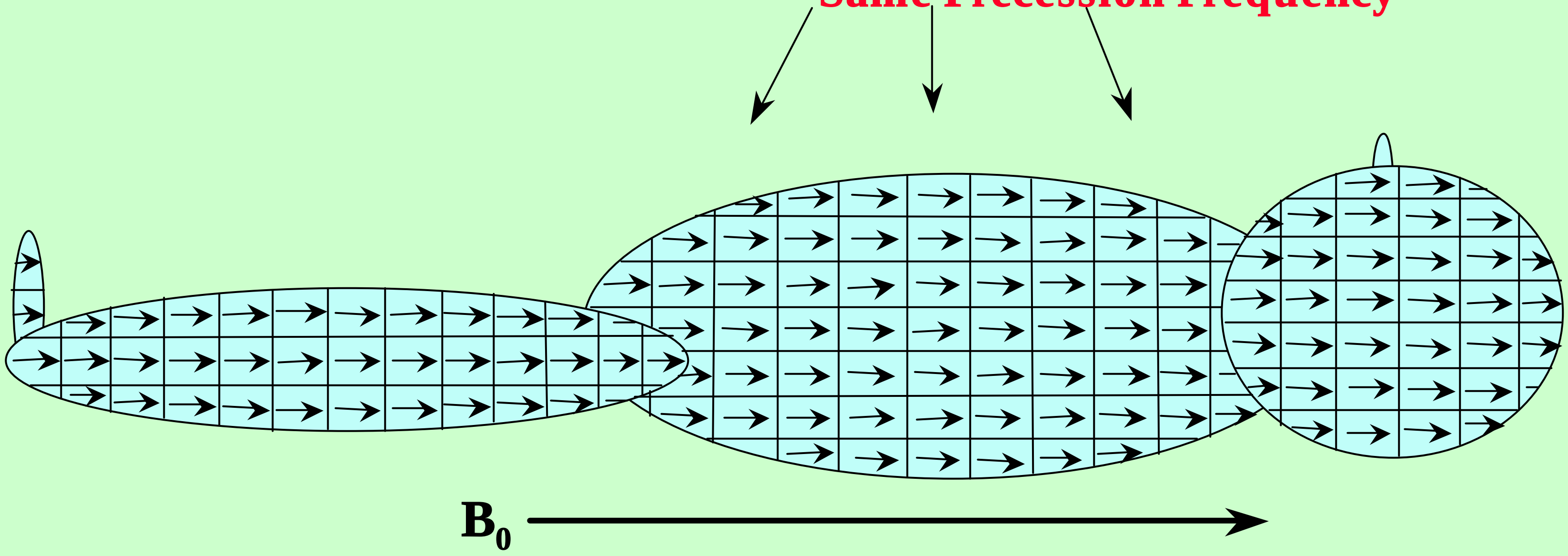
- T_2 - the time required for **Mxy** to decay to 37% of its original value.
- As **Mxy** decreases, the MR Signal decreases.
- 5 T_2 times are required for complete relaxation.



RF: The Patient

- The magnetization vectors (the sum of the individual ^{1}H nuclei) will align along $\mathbf{B}_0$ like small compasses.

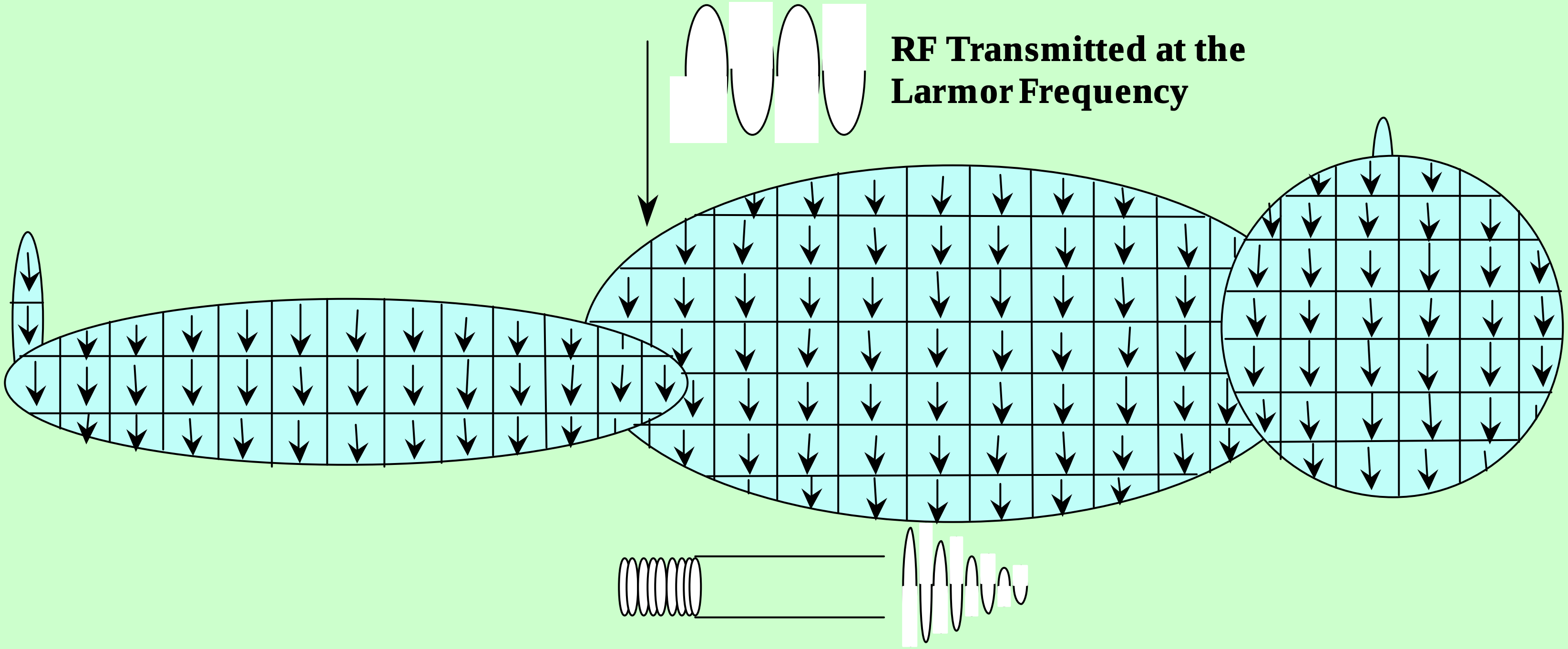
Same Precession Frequency



Homogeneous Field

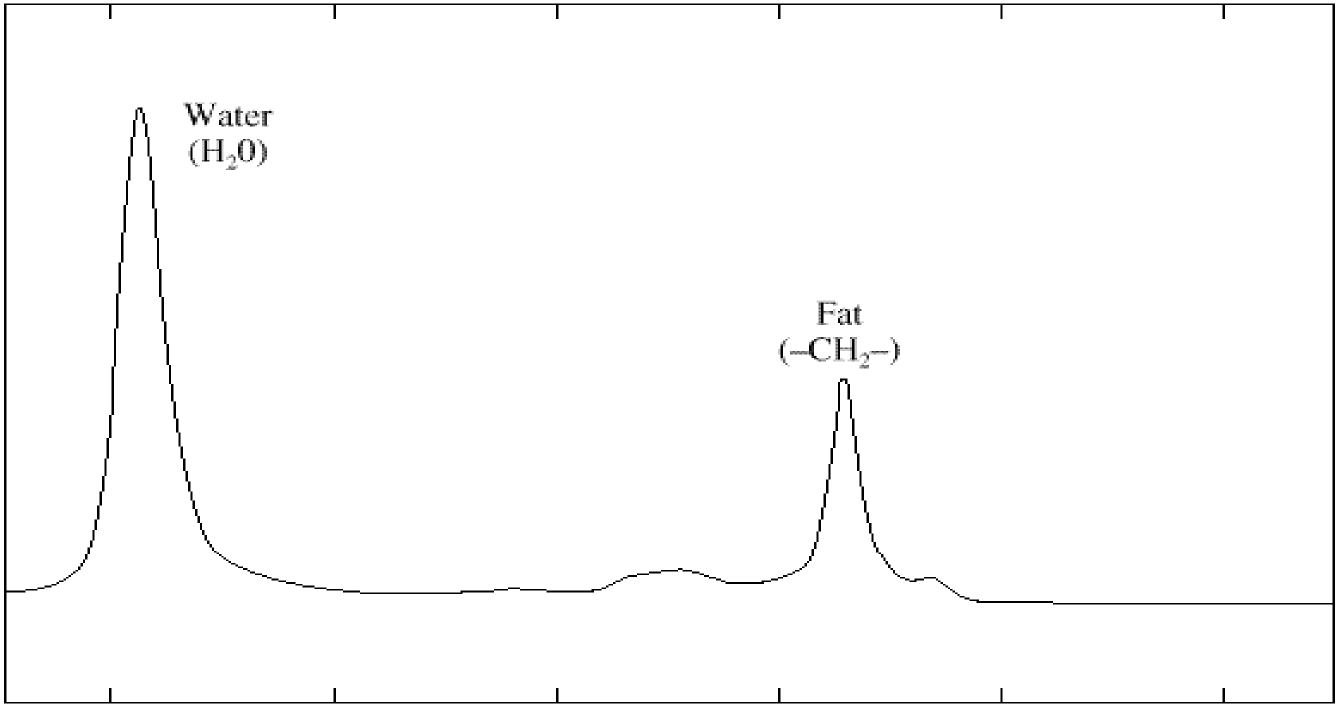
RF: The Patient

- ✍ All the magnetization vectors will interact with the RF field and rotate as long as the RF field is applied. In this case by 90 degrees.



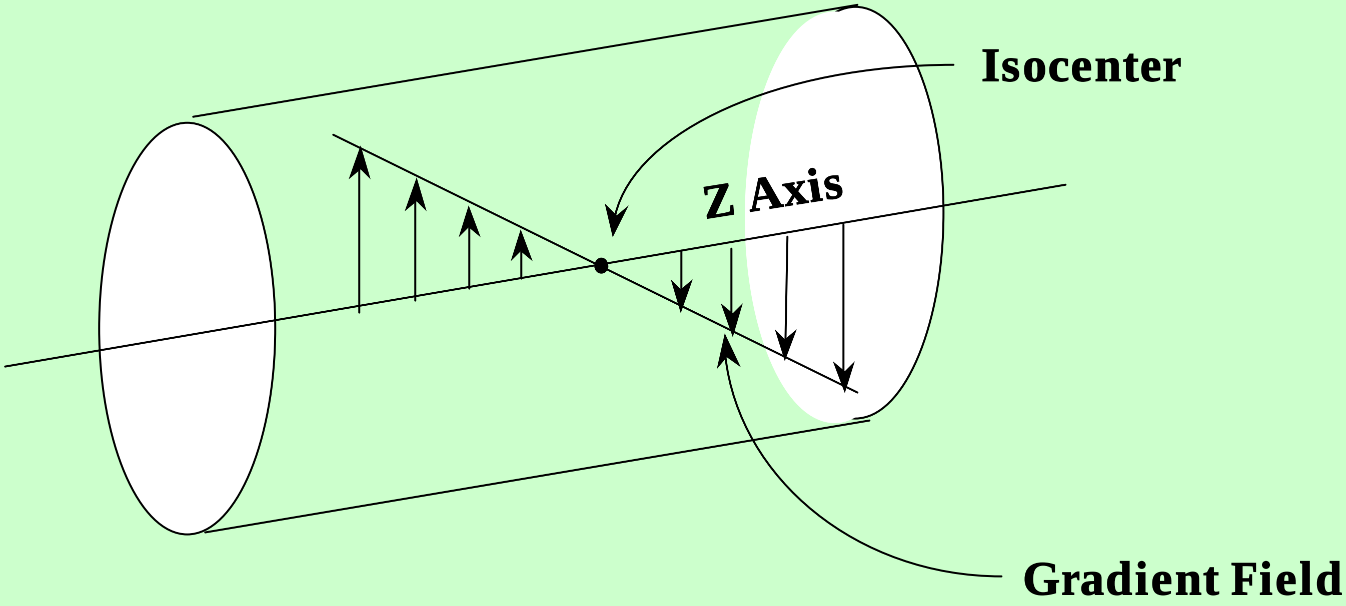
Cannot define where the signal originates... No Spatial Information

A Spectrum: Reality, the Chemical Shift



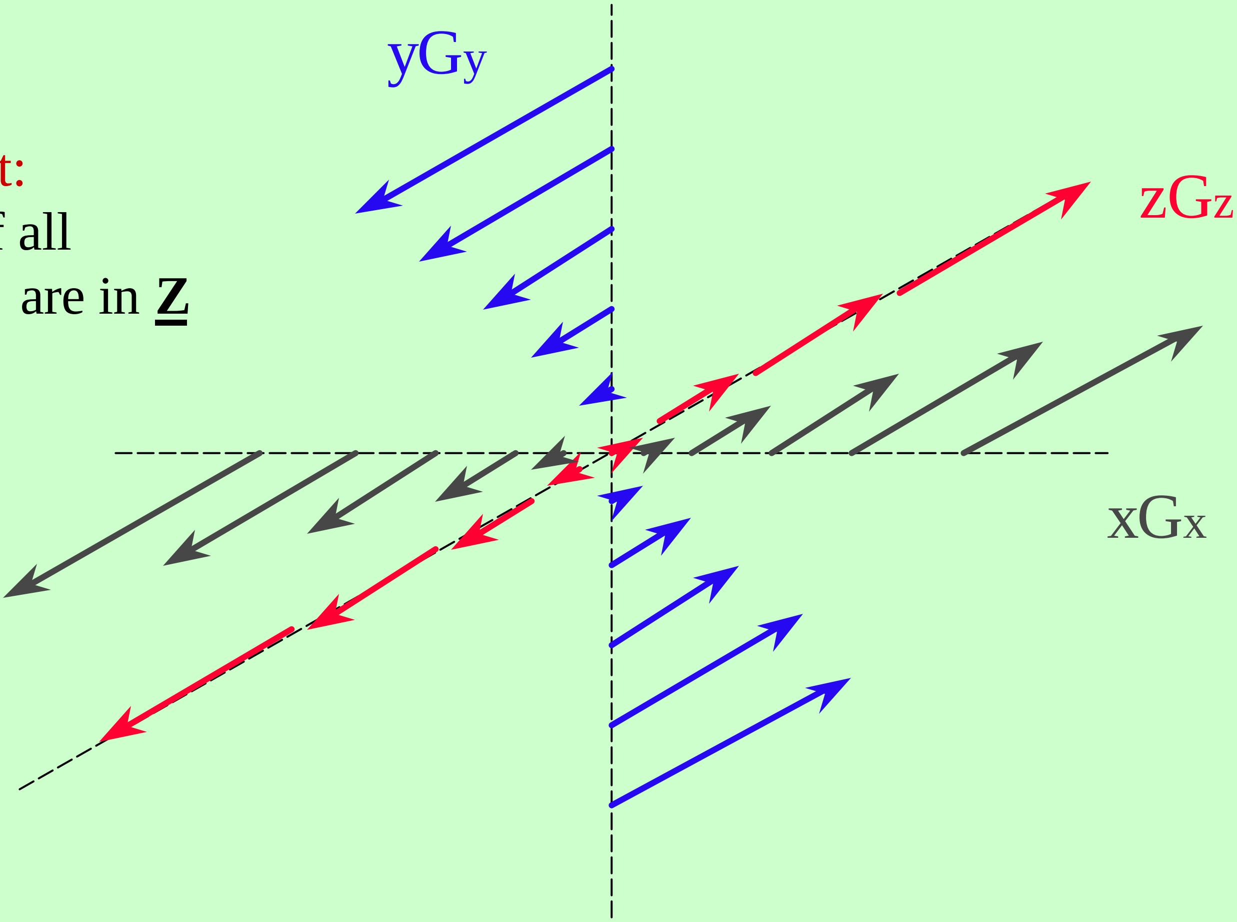
How do we get an image then??? Gradient Fields

- ✍ Gradient magnetic fields change the main magnetic field in a controlled and predictable pattern so the field is no longer homogeneous.



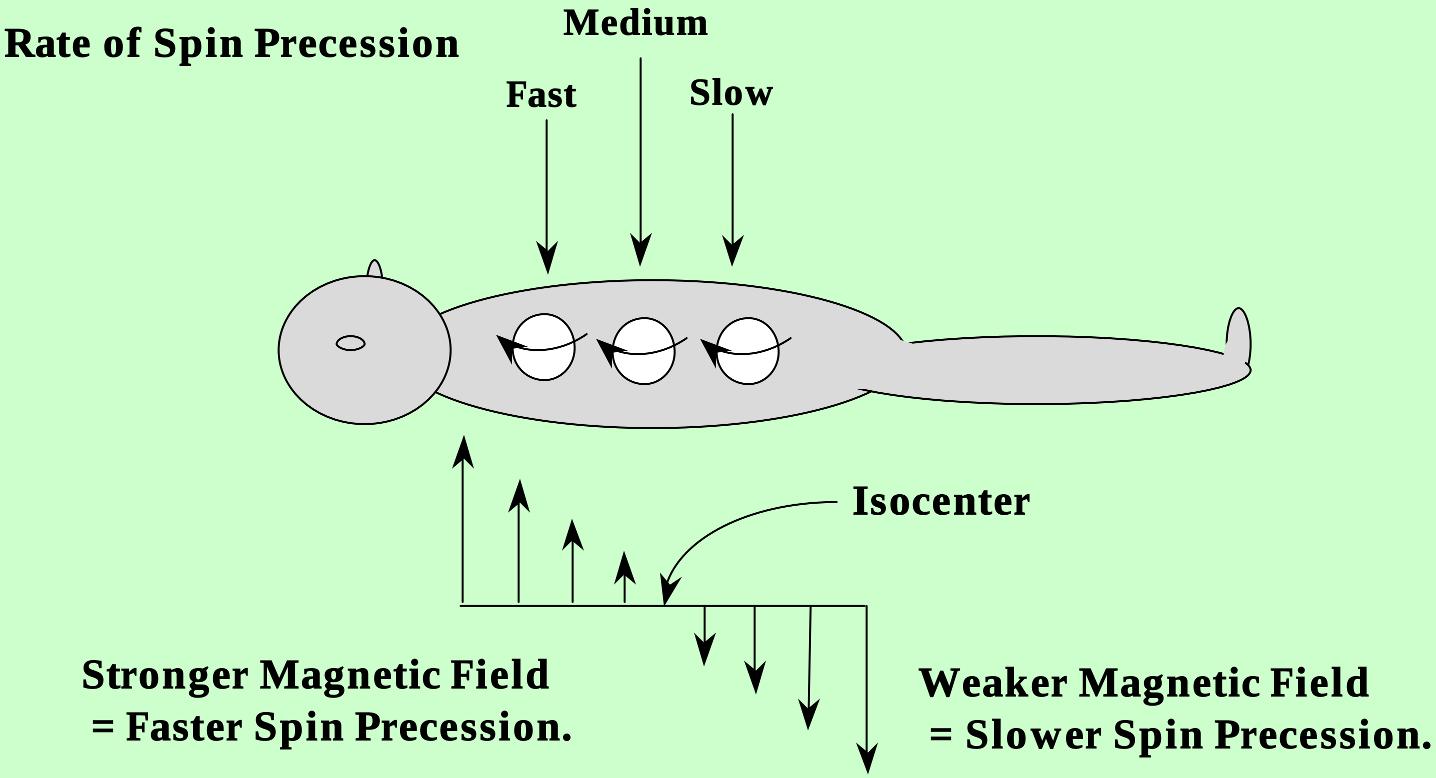
Visualization of the Gradient fields.

Important:
B field of all
gradients are in **Z**
direction.



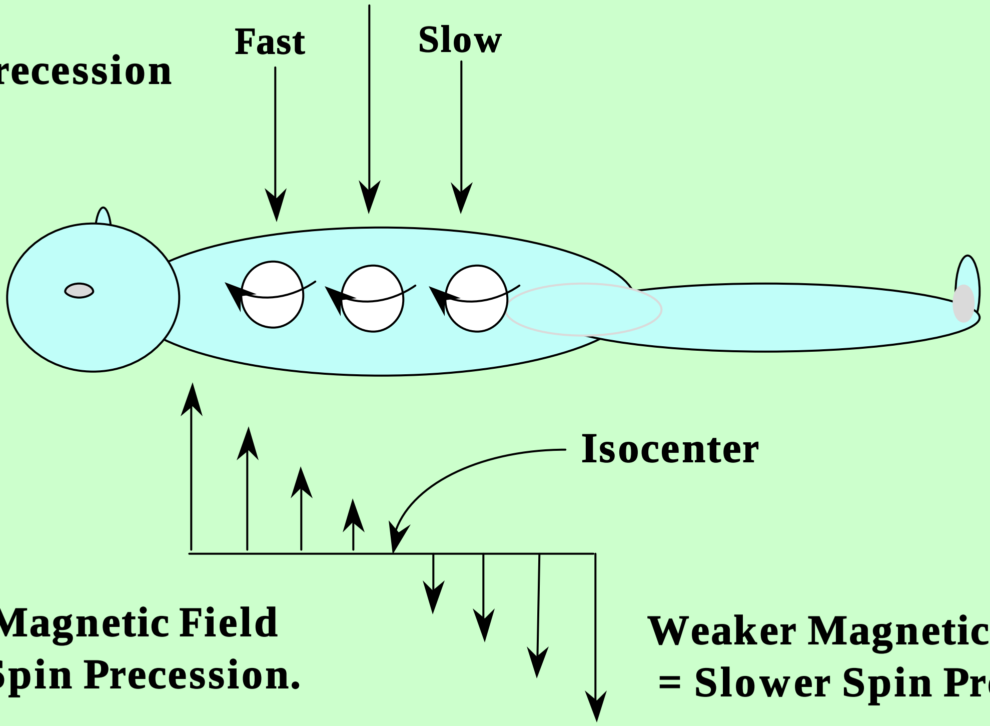
Gradient Fields

- ✍ When a magnetic gradient field is turned on, it adds or subtracts from the main field about a point in space called the isocenter.



Gradient Fields

- If the magnetic field changes, the precessional frequencies of the proton nuclei change. Gradients change the magnetic field in **a known way** in space.



Medium

Fast

Slow

Rate of Spin Precession

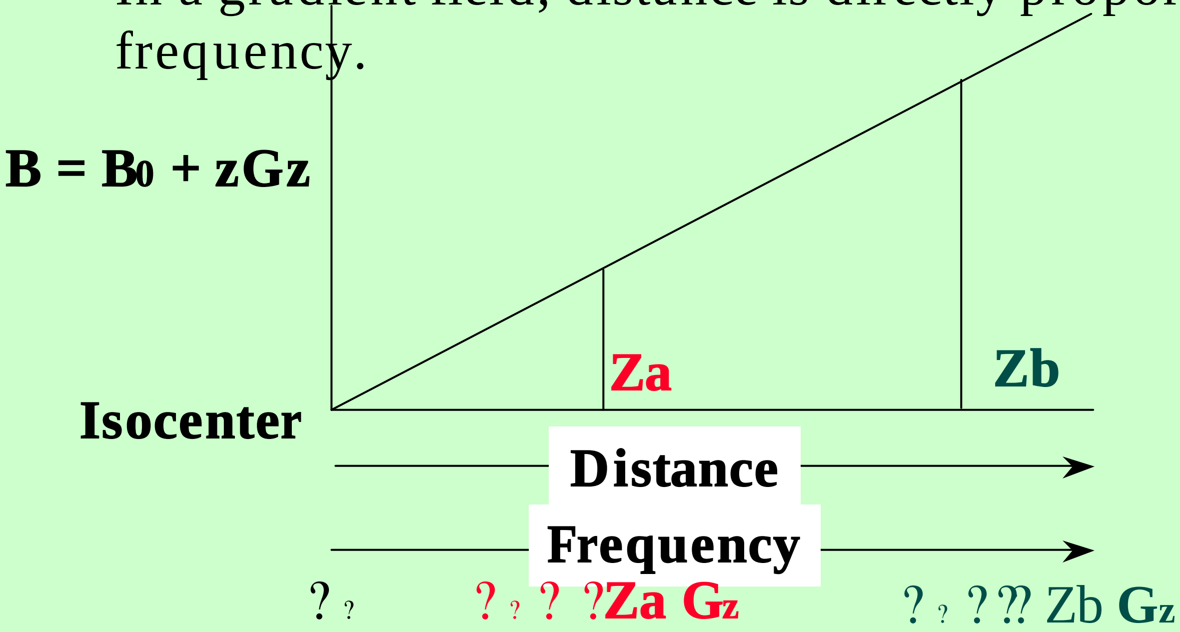
Isocenter

Stronger Magnetic Field
= Faster Spin Precession.

Weaker Magnetic Field
= Slower Spin Precession.

Gradient Magnitude

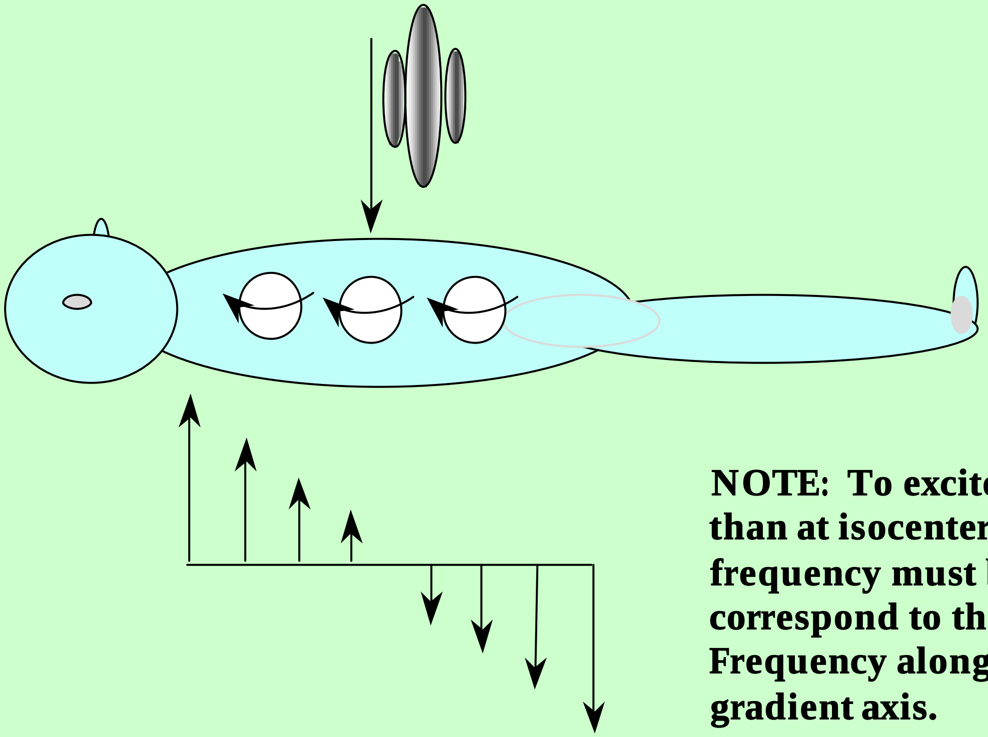
- How does gradient magnitude affect the MR Image?
  - ? ? ? ?? -- From the Larmor equation, as the magnetic field increases or decreases, the resonant, precessional frequency increases or decreases.
  - In a gradient field, distance is directly proportional to frequency.



RF & Gradients: Slice Selection

- While a slice selection gradient is turned on, the RF excitation pulse is turned on.

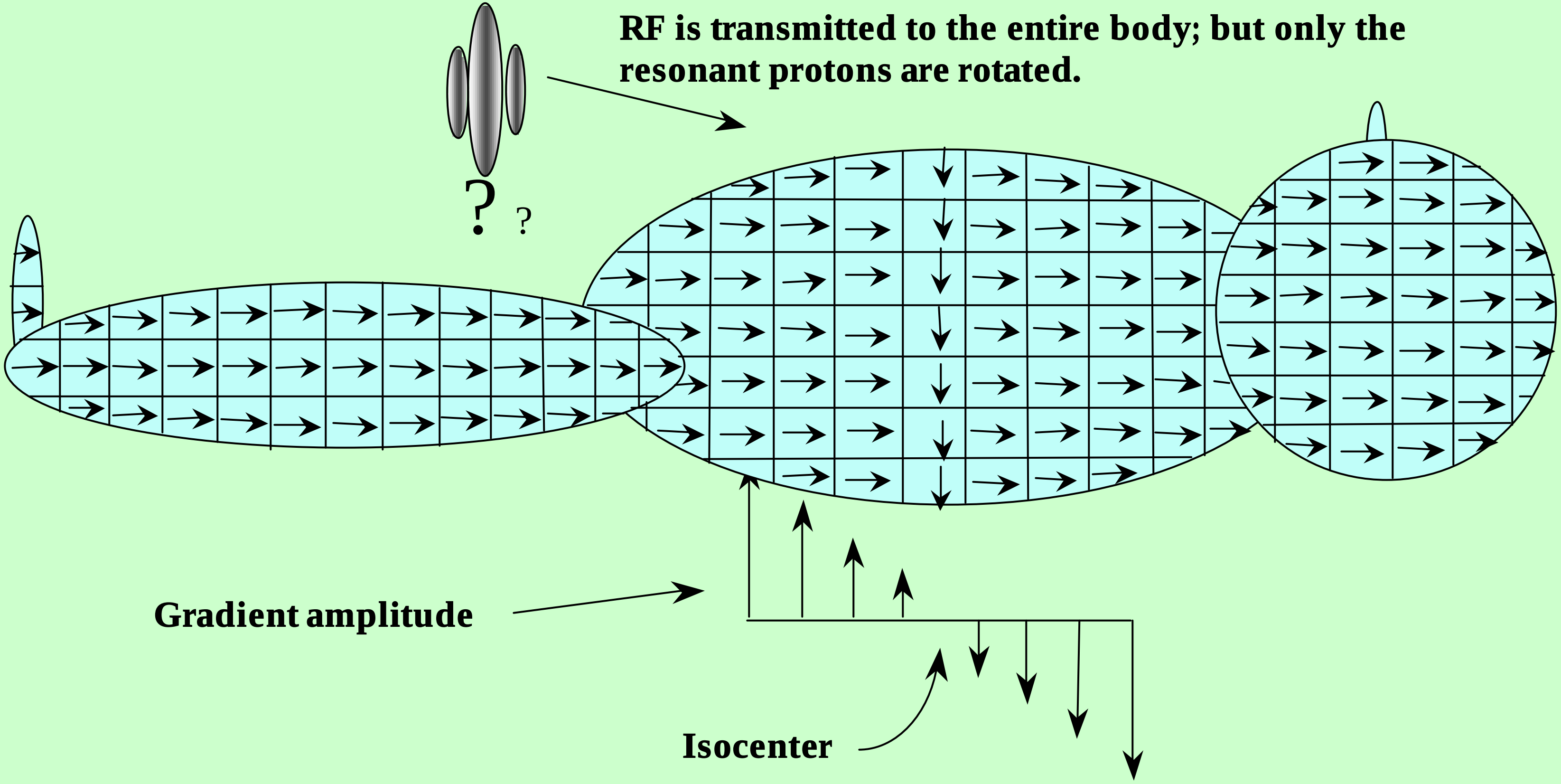
RF is transmitted at the Larmor Frequency. Only those protons precessing at the Larmor Frequency are excited.



NOTE: To excite a slice other than at isocenter the RF excitation frequency must be changed to correspond to the Larmor Frequency along the slice select gradient axis.

RF & Gradients: Slice Selection at Isocenter

- ✍ While a slice selection gradient is turned on, a shaped RF pulse is transmitted at ? ?. Only those protons precessing in a narrow range around ? ? are excited (rotated) by the pulse.



RF is transmitted to the entire body; but only the resonant protons are rotated.

? ?

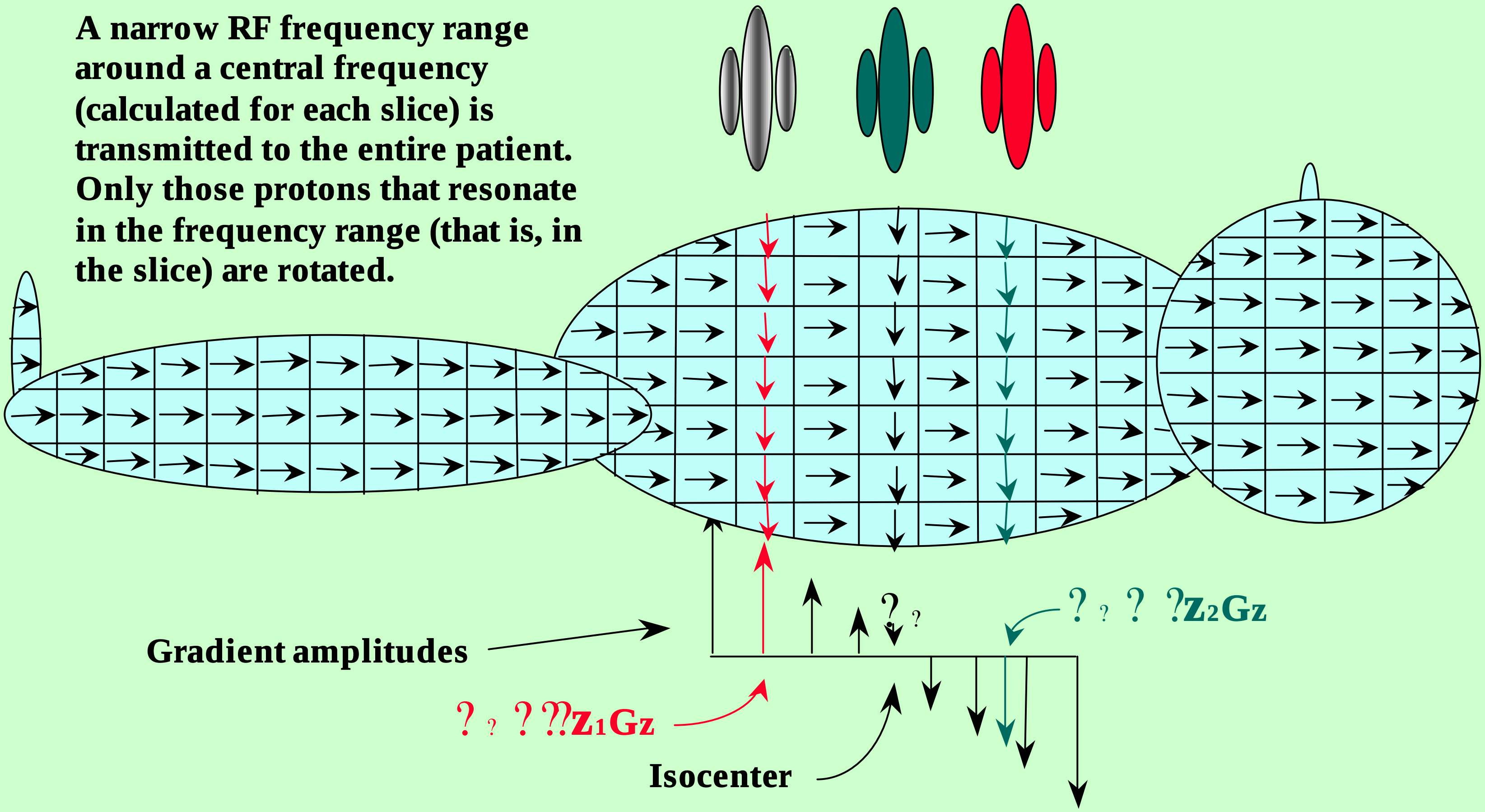
Gradient amplitude

Isocenter

RF & Gradients: Multi-Slice Selection

- Multi-slice Example - RF pulses are transmitted at 3 different times, and frequencies; 3 different slices are selected.

A narrow RF frequency range around a central frequency (calculated for each slice) is transmitted to the entire patient. Only those protons that resonate in the frequency range (that is, in the slice) are rotated.



Gradient amplitudes

? ? ? ??z_1Gz

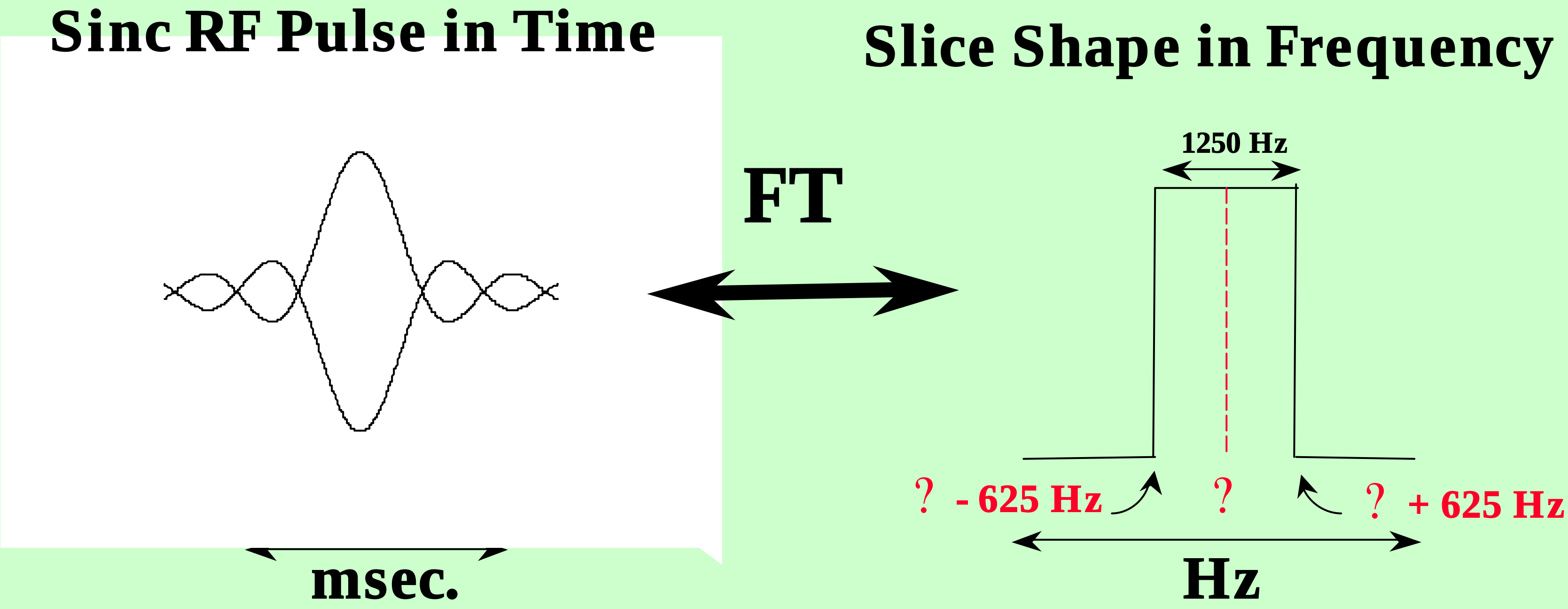
? ?

? ? ? ?z_2Gz

Isocenter

RF Pulse Shape, Slice Selection, and Slice Shape

- Relationship between time and frequency from the Fourier transform.



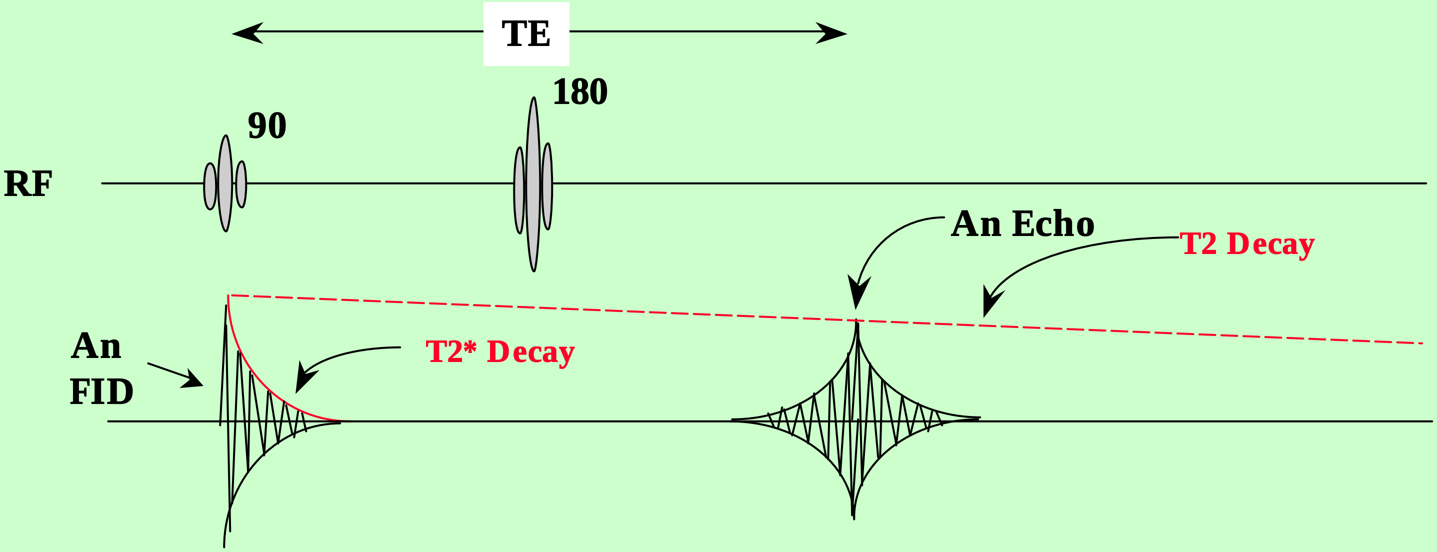
We chose the slice:

Now… How do we scan the slice to get the 2D image??!!!

↓

Gx and Gy gradients assume the responsibility!

A Simple Pulse Sequence

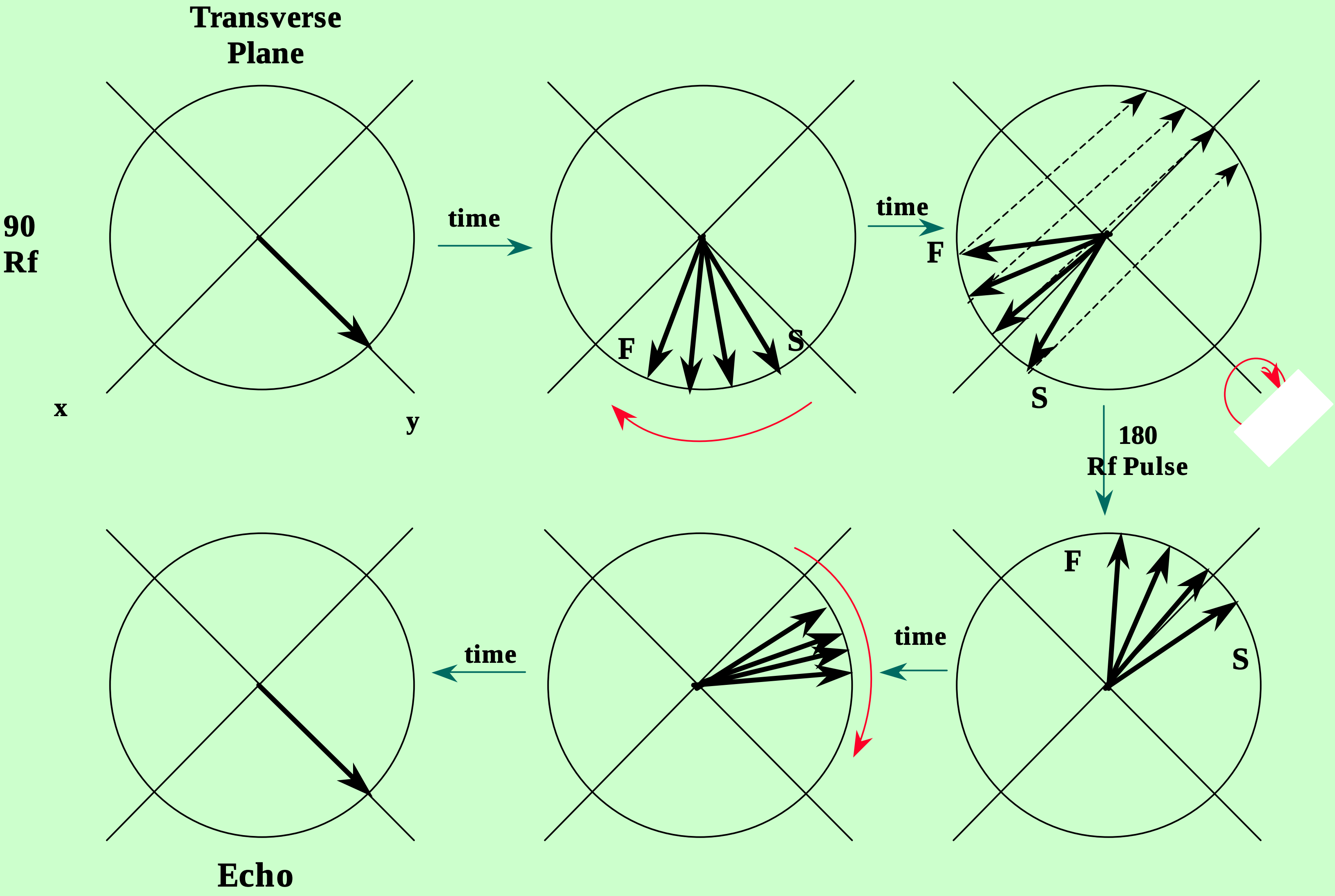


The Spin Echo sequence uses a 180 degree RF pulse to refocus the signal and create an echo; where

$$1/T_2^* = 1/T_2 + 1/T_2'$$

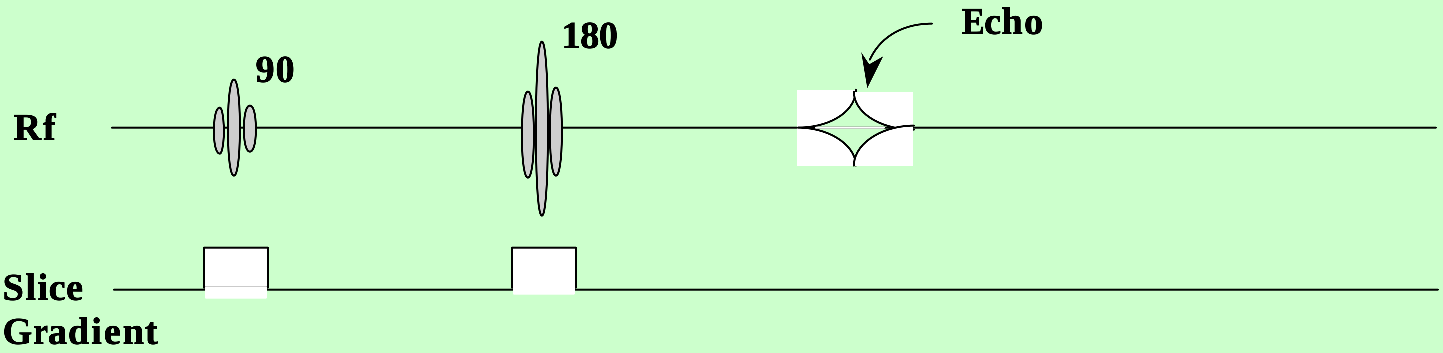
Where T_2' is caused by: Magnet Inhomogeneity, Magnetic Susceptibility Shifts, and Chemical Shifts. Only the T_2' effects are refocused by the 180.

Spin Echo - Signal Refocusing

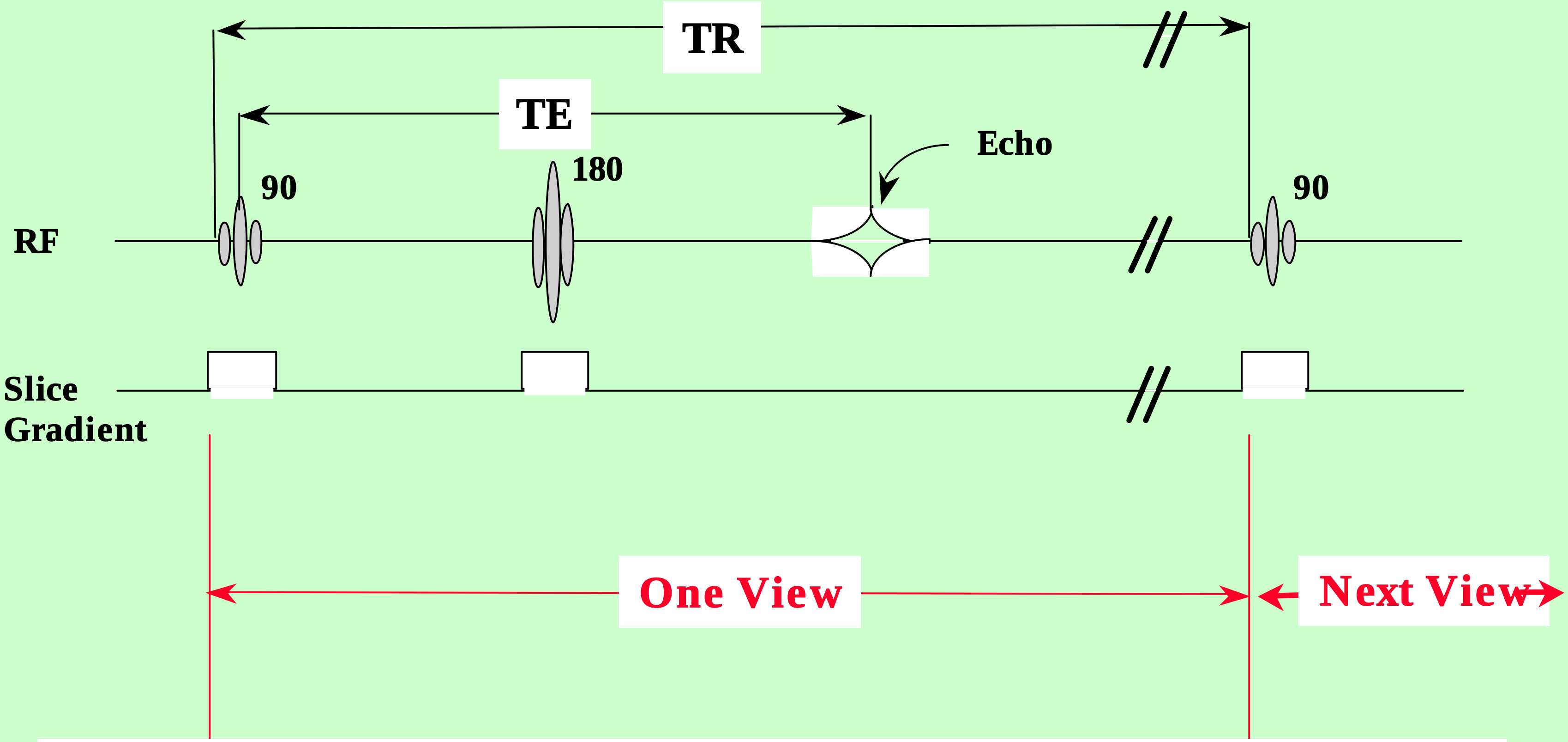


A Simple Imaging Sequence

- The Spin Echo with Slice Selection



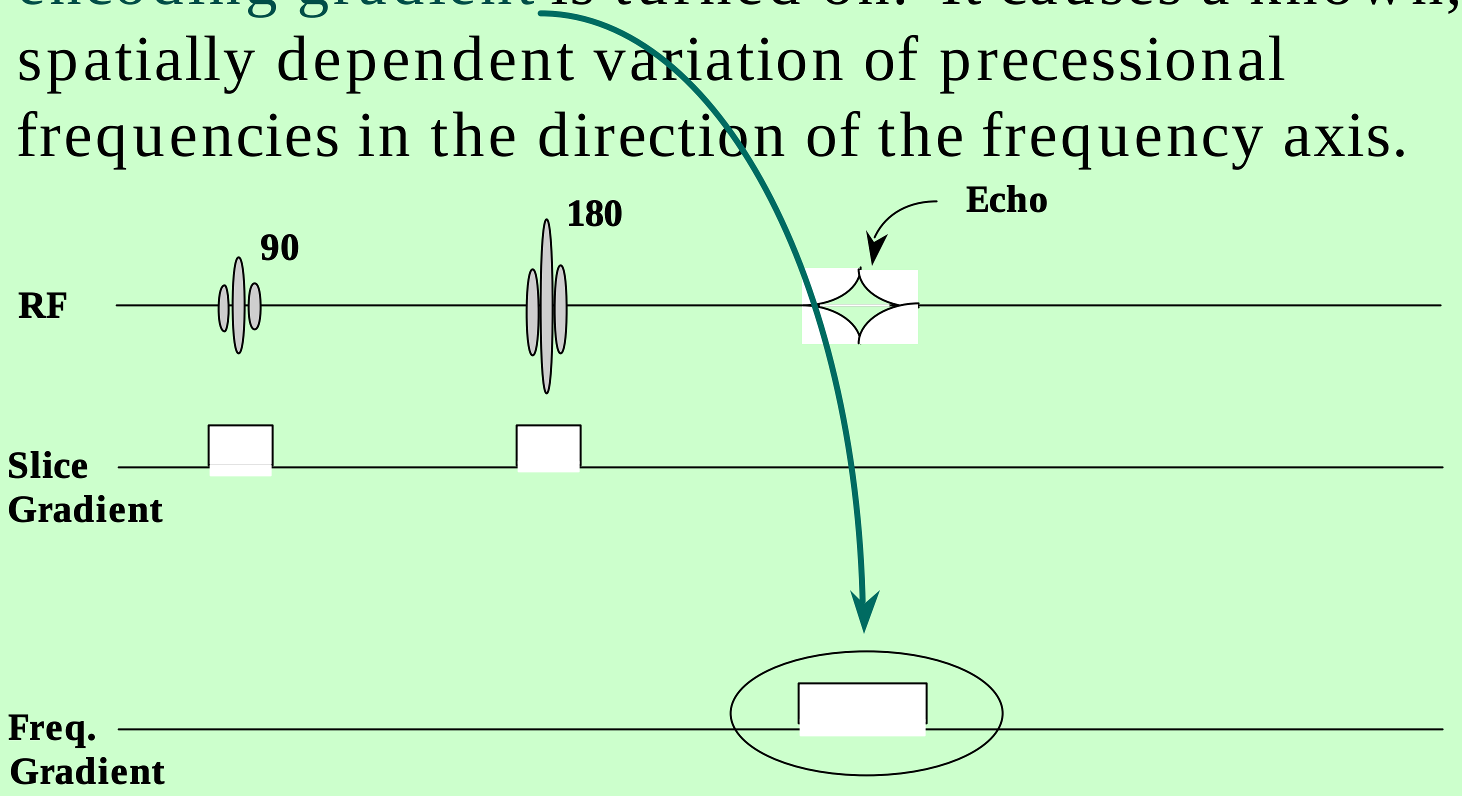
Pulse Sequence Timing Parameters: TE and TR



TE is the Echo Time. The time between the 90 and 180 RF pulse is TE/2.
TR is the Repetition Time; one repetition time is one view in k-space.

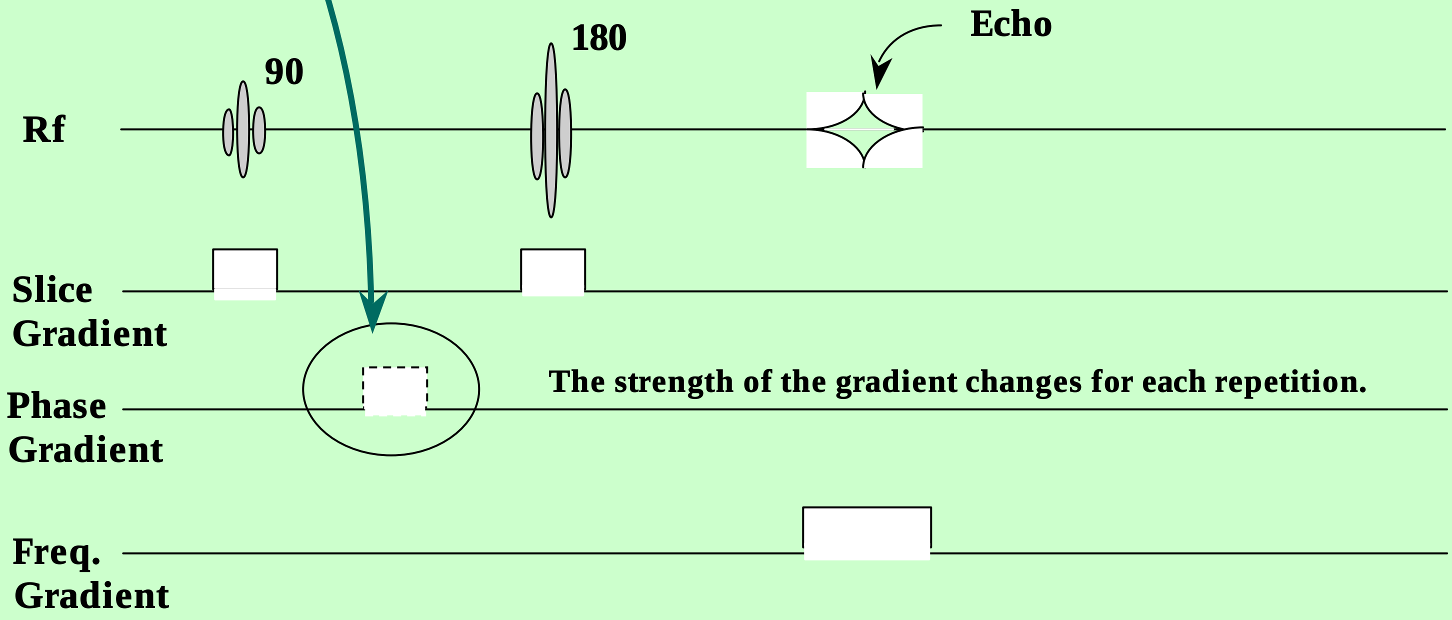
Frequency Encoding

- ✍ During the echo (signal) acquisition, the frequency encoding gradient is turned on. It causes a known, spatially dependent variation of precessional frequencies in the direction of the frequency axis.



Phase Encoding

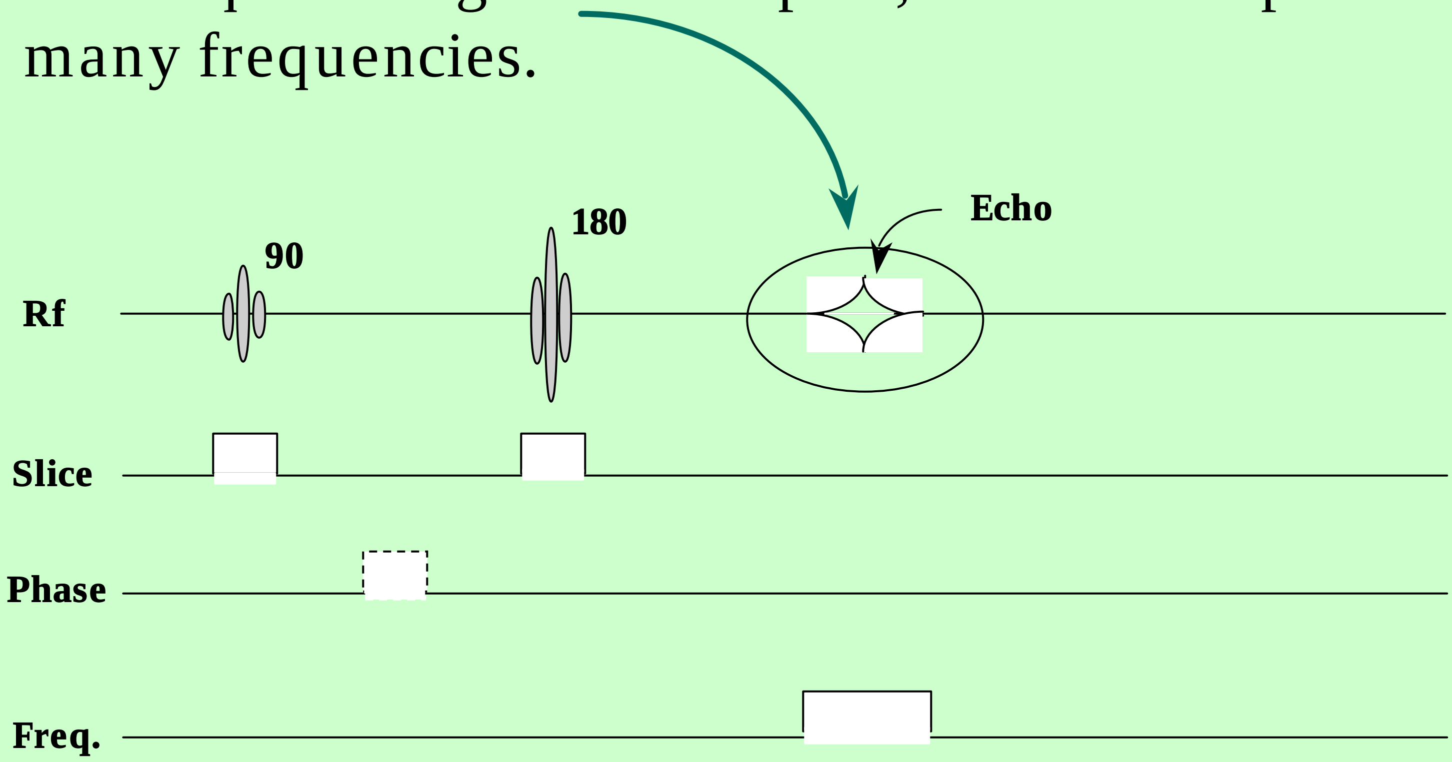
- ✍ Phase encoding occurs after slice selection/excitation. The precessional phase in the direction of the phase axis varies in space according to the magnitude of the phase encoding gradient.



The strength of the gradient changes for each repetition.

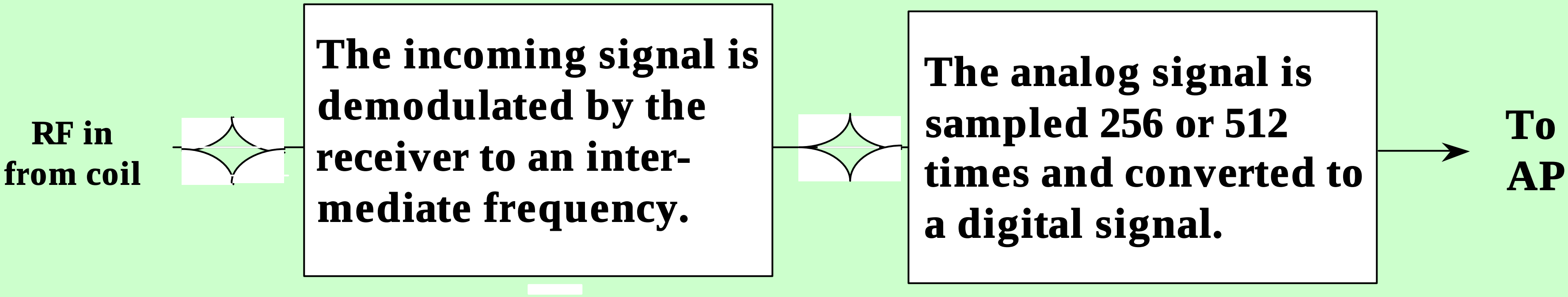
Signal Acquisition

- ✍ The acquired signal is complex, it is made up of many frequencies.



Signal Acquisition

- The analog signal is down converted to a signal with a default bandwidth of +/- 32 kHz and then sampled 256 or 512 times.



RF in from coil

The incoming signal is demodulated by the receiver to an intermediate frequency.

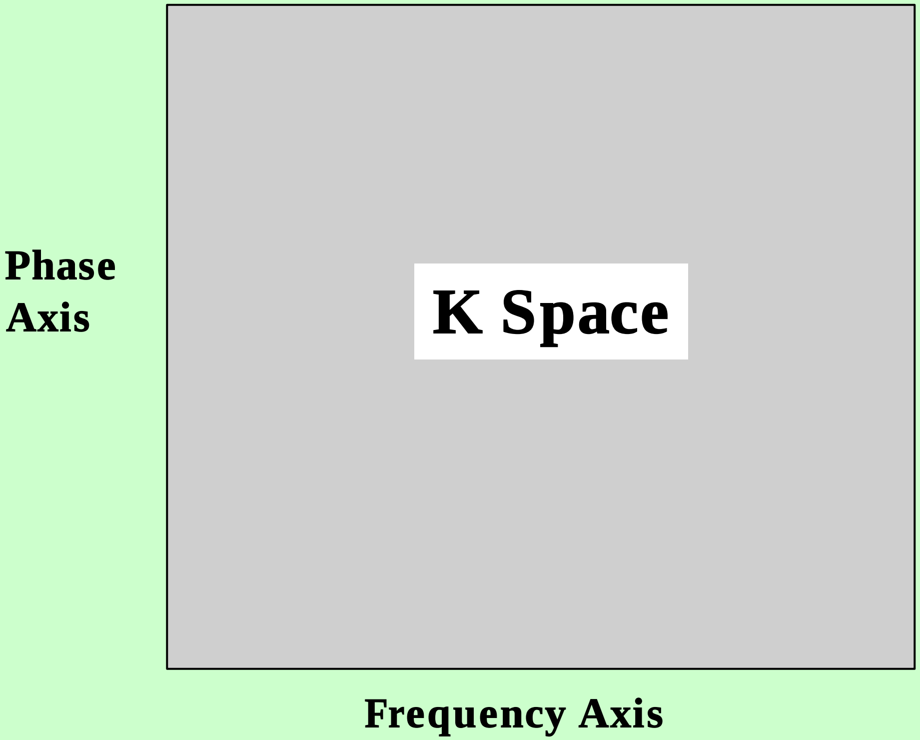
The analog signal is sampled 256 or 512 times and converted to a digital signal.

To AP

Signal Acquisition: Raw Data

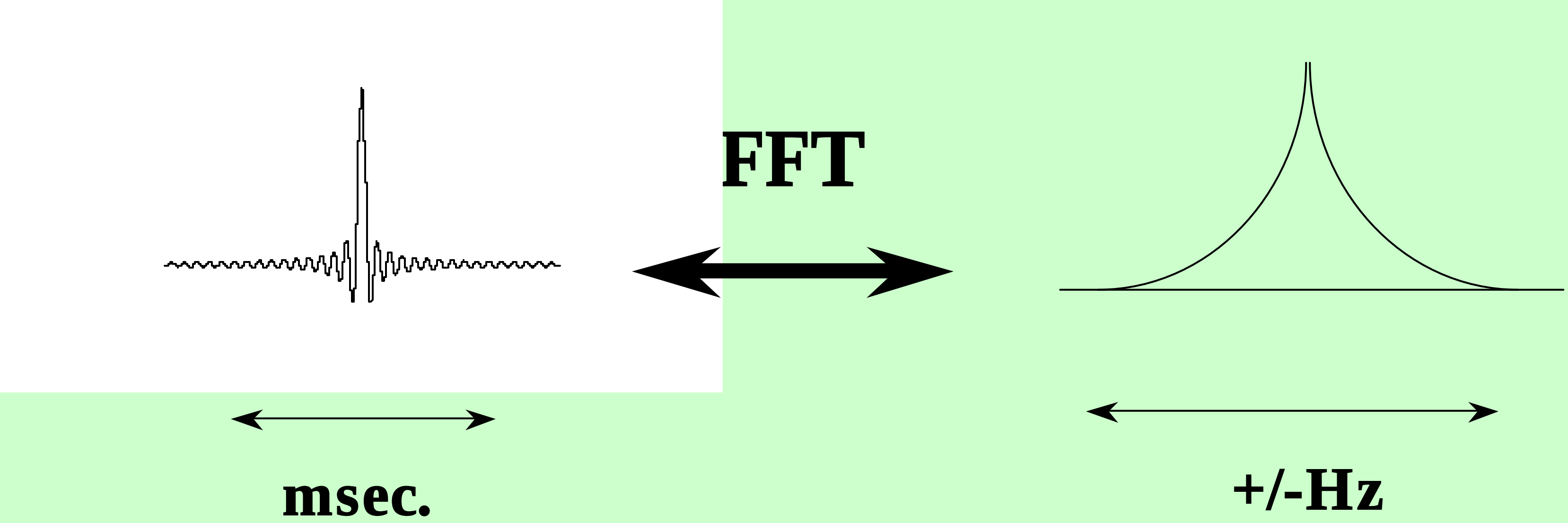
- The digitized data is stored in memory, 256 or 512 data points equal one view.

Each line = 1 view which is 256 or 512 data points of one analog echo.



Reconstruction: Fourier Transform

- ✍ The process of converting time domain data to the frequency domain data is called the Fourier transformation.



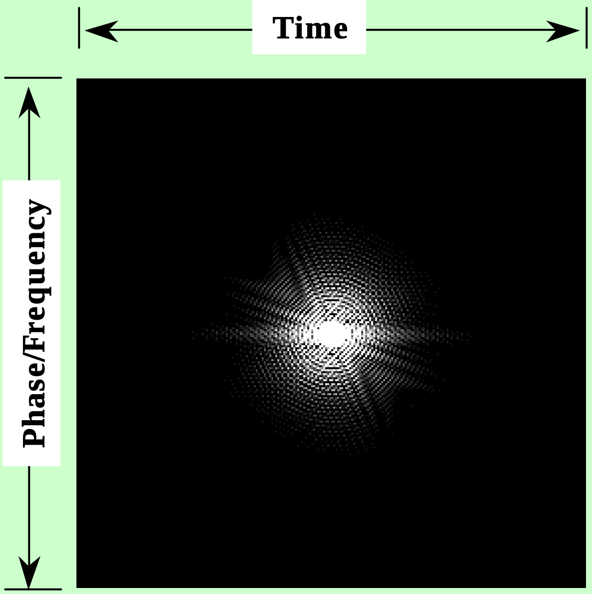
FFT

msec.

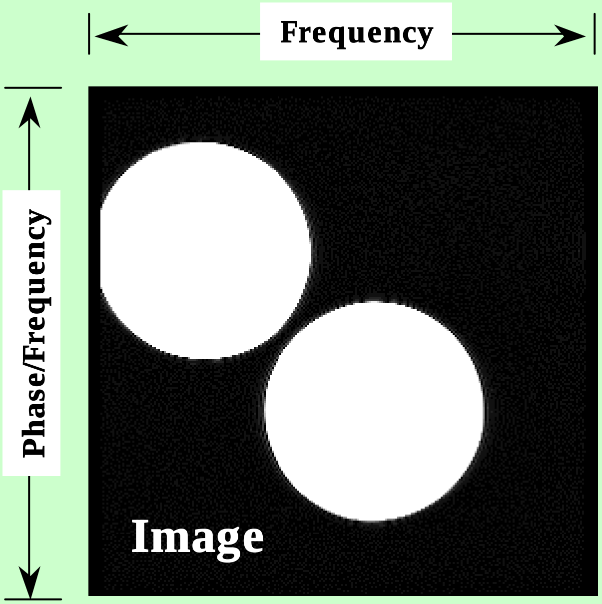
+/-Hz

2 D FFT

✍ The 2D FFT produces the image. The single FFTs performed sequentially will also produce the image.



Raw Data before FFT



An Image: Fully Processed, 2 FFTs

Tissue Contrast in MR Images

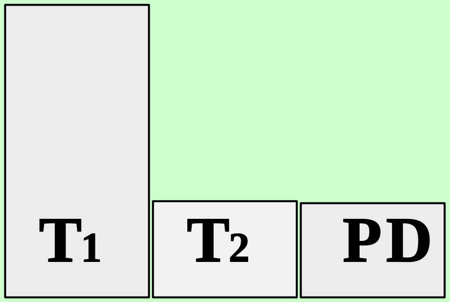
- MR image contrast is a complex combination of T1, T2, and proton density.
- Pulse sequences and pulse timing parameters are used to maximize one tissue characteristic and minimize the others.

T1 **T2** **PD**

Contrast Weighting
Maximize one
Minimize the others

T_1 Weighting

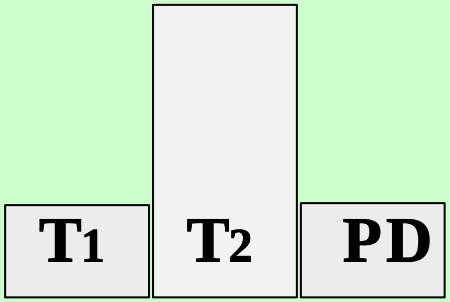
- Maximize T_1 Effects.
- Minimize T_2 and PD Effects.
- Tissue with short T_1 has Brighter Signal.



In a T_1 weighted image, tissues with shorter T_1 are hyperintense or brighter while tissues with longer T_1 are hypointense or dark.

T_2 Weighting

- Maximize T_2 Effects
- Minimize T_1 and PD Effects
- Long T_2 Tissue yields Brighter Signal



In a T_2 weighted image, tissues with longer T_2 are hyperintense because they decay less while tissues with shorter T_2 times are hyointense or dark.

Thank You

Shashi B. Mehta