Biomedical Imaging & Analysis

Lecture 2, Part 2. Fall 2014

Image Formation & Visualization (I): ***MRI & k-Space***

[***Text***: Joseph P. Hornak, *The Basics of MRI*

http://www.cis.rit.edu/htbooks/mri/inside.htm]

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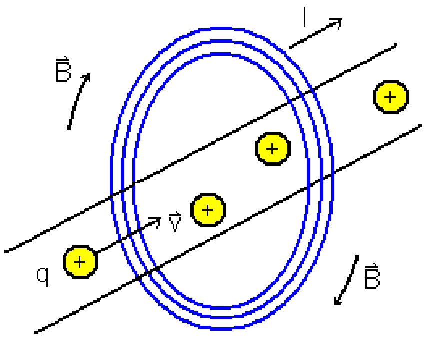
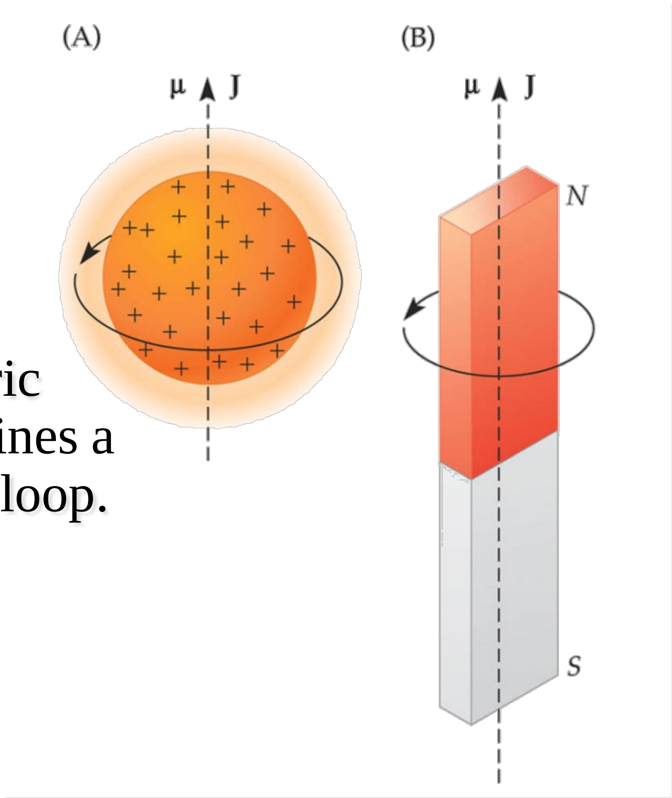
MRI: Physics meets Clinic (Part I)

Origins of Magnetism



$$B = \frac{\mu_0}{2\pi}\frac{I}{r}$$



An Introduction to MRI Physics and Analysis ,Michael Jay Schillaci, PhD

- The proton's motion in the nucleus and its electric charge defines a small current loop and thus defines a magnetic moment, μ = current times area of the loop.
- Moment of an atom:

  - Field is "about" nucleus and depends on :

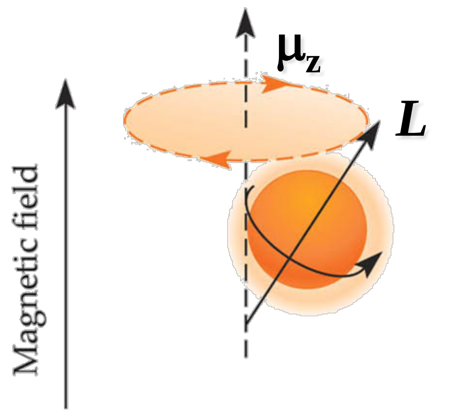
    Material, Current, Radius of loop

But, total angular momentum is the vector sum of the **orbital and spin angular momentum** of the nucleus.

<u>MRI</u>: Physics meets Clinic (Part I)

Magnetic Precession

- The proton "magnet" differs from the magnetic bar as it has mass which generates angular momentum , ***L*** ,while spinning.
- Spin is an intrinsic property of all atomic particles, much like mass.
- Particles can either have their spin vector up (say for example, a counterclockwise rotation) or down (a clockwise rotation).
- In the presence of a static external magnetic field the protons try to align (or anti-align) with the applied field.
- Placing the proton in an external magnetic field causes interactions between the angular momentum and magnetic moment vectors.
  - This leads to precession of the H+ protons.
  - If the spin were aligned exactly with the field then the proton would not precess.



<u>MRI</u>: Physics meets Clinic (Part I)

Contributing factors for MR Imaging

- Quantum properties of nuclear spins – produces a separation of magnetic moments into high and low energy states.

- Radio frequency (RF) excitation properties – produce an emission of radiation at a particular frequency that will ultimately be used to image a particular body feature.

- Tissue relaxation properties and nuclear environment – determines the RF signal that is emitted.

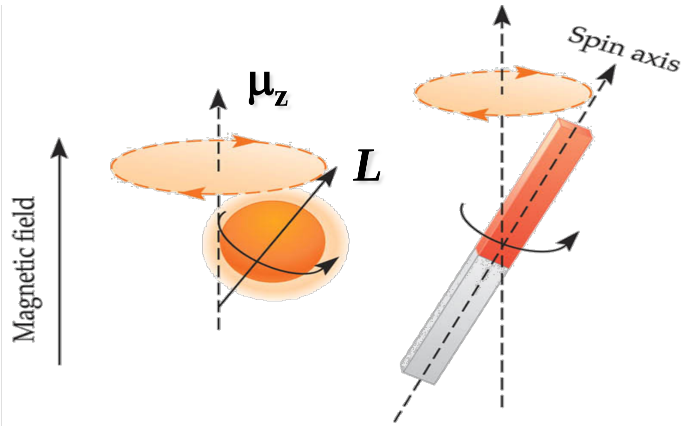
<u>Acquisition parameters – defining a Pulse Sequence:</u>

- Changing <u>magnetic field strength and gradients</u> to probe / scan the body.

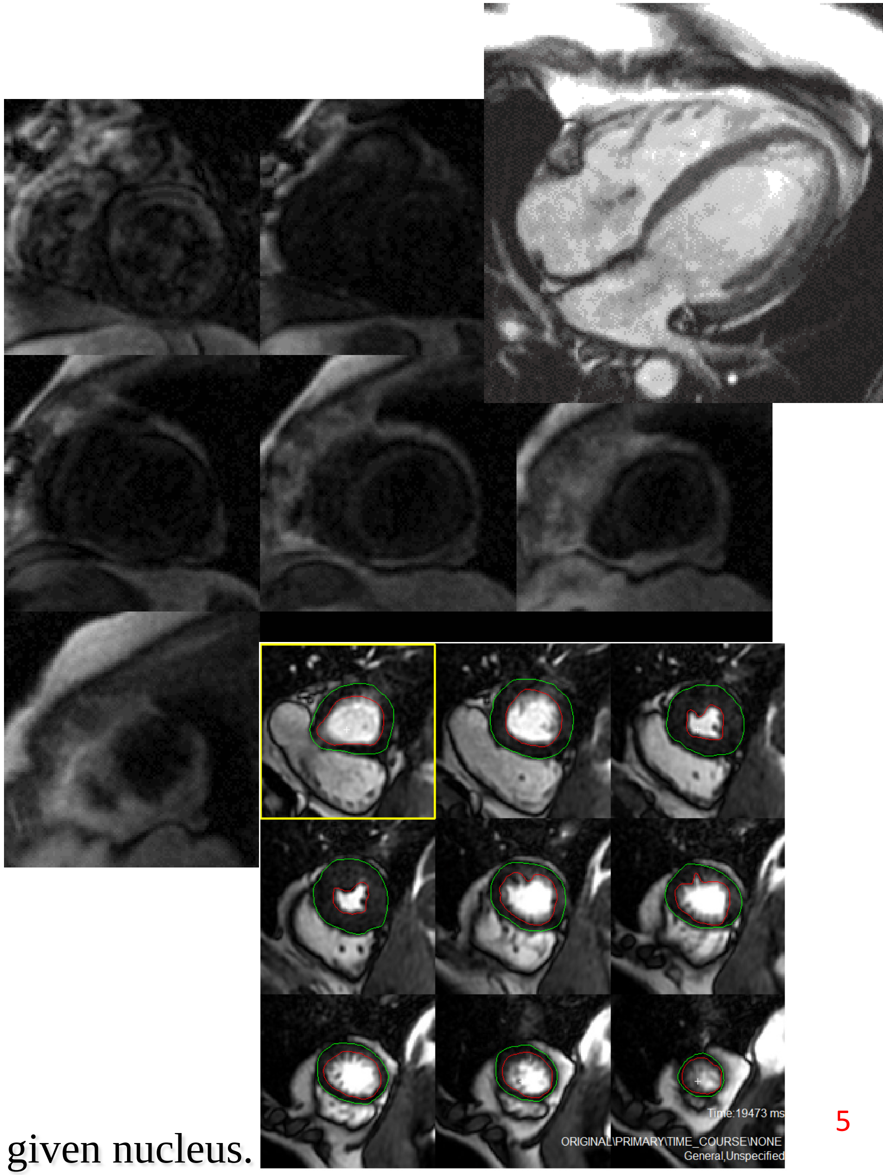
- <u>Timing of gradients, RF pulses, and signal detection</u> to get a complete data set that can be manipulated to view the body.

How are these images formed..?
MRI: Physics meets Clinic (Part I)

So, the proton has magnetic moment, μ, and angular momentum ***L*** when it is spinning, which interacts with external magnetic fields.



An Introduction to MRI Physics and Analysis Michael Jay Schillaci, PhD



- MR measures the net *magnetization* of atomic nuclei which be manipulated by changing the magnetic field environment.
- Magnetic moment, μ and the angular momentum, *L*, are vectors, lying along the spin axis, such that:

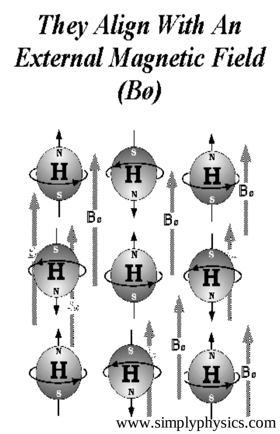
$$\vec{\mu} = \gamma \vec{L}$$

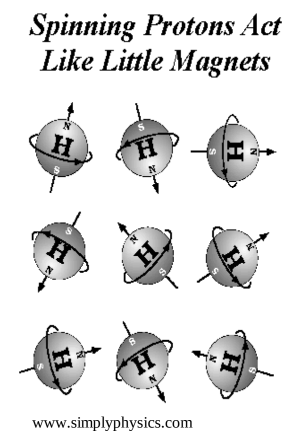
- γ is called the *gyromagnetic ratio* and is a constant for a given nucleus.

MRI: Physics meets Clinic (Part I)

Summarizing the Physics

- A spinning of the charged particle generates its own little magnetic field.
  - Such particles will tend to “line up” with external magnetic field lines (like iron filings around a magnet).
  - This produces magnetic dipoles





- Spinning particles with mass have angular momentum.
  - Angular momentum resists attempts to change the spin orientation (like a gyroscope)

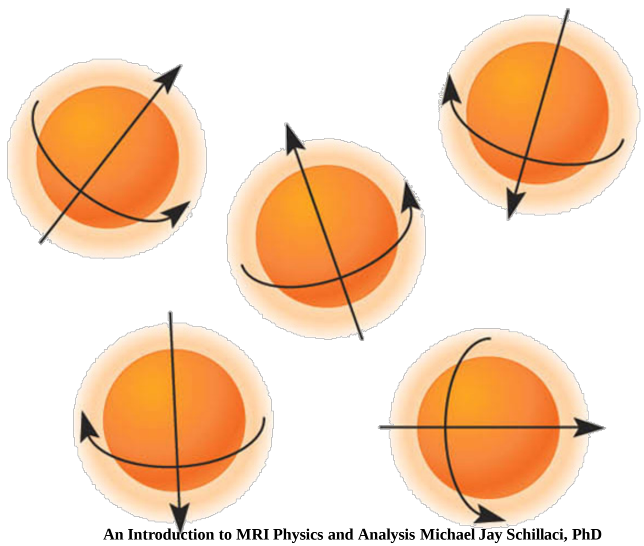
- As there are normally equal numbers of proton spins pointing in every direction the protons spins cancel each other out and the net magnetic effect is zero. This changes under the effect of an external magnetic field.

- **MRI is mainly concerned with the action of hydrogen, in fat and in water, which absorb and re-emit radiofrequency (RF) energy at a specific frequency.**

***MRI**: Physics meets Clinic (Part I)*

Producing an MRI Signal

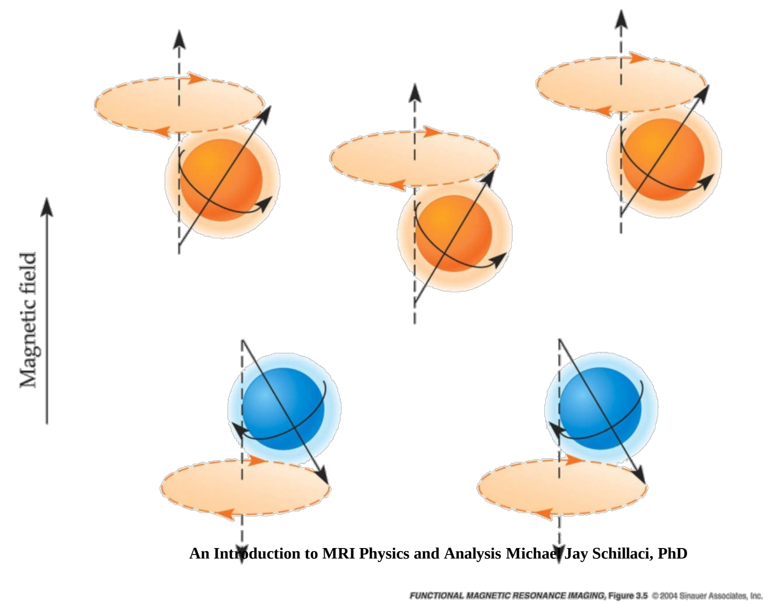
Protons in no magnetic field



In the absence of a strong magnetic field, the spins are oriented randomly.

Thus, there is no net magnetization (M).

In a magnetic field, protons can take either *high*- or low-energy states



There is now a net magnetization (M).

Protons all precessing out of phase.

$\underline{MRI}$: Physics meets Clinic (Part I)

RF Photon Energy, Absorption, Emission and Spin

- M(t) experiences a torque when an external magnetic field B(t) is applied

torque is $\boldsymbol{\tau} = \mathrm{M} \times \mathrm{B}$

- Torque is related to angular momentum

$$\boldsymbol{\tau} = \frac{d\mathbf{J}}{dt}$$

- Eliminate $\mathbf{J}$ to yield

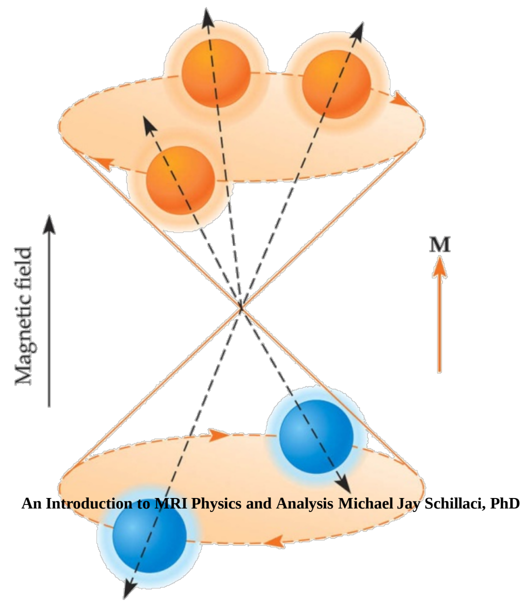
$$\frac{d\mathrm{M}(t)}{dt} = \gamma \mathrm{M}(t) \times \mathbf{B}(t)$$

- Valid for "short" times

Using the right hand rule, M will rotate around z if M is not aligned with z

MRI: Physics meets Clinic (Part I)

Net Magnetization & the Larmor Equation



FUNCTIONAL MAGNETIC RESONANCE IMAGING, Figure 3.7 © 2004 Sinauer Associates, Inc.

$$\Rightarrow \omega_0 = 2\pi f_0 = \gamma B_0$$

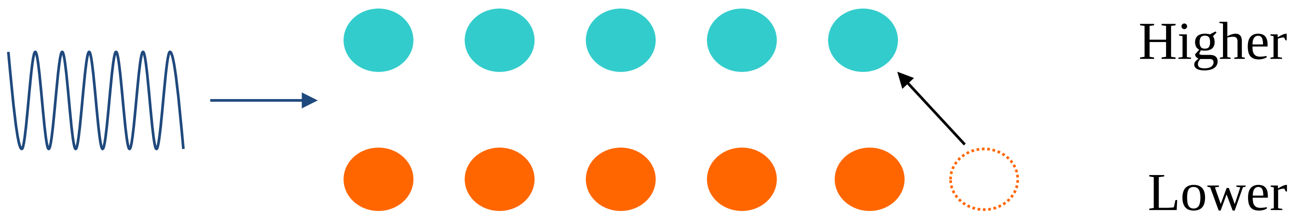
The difference between the numbers of protons in the high-energy and low-energy states results in a net magnetization (M) and gives rise to the Larmor Equation.

The net magnetization points along the static magnetic field.

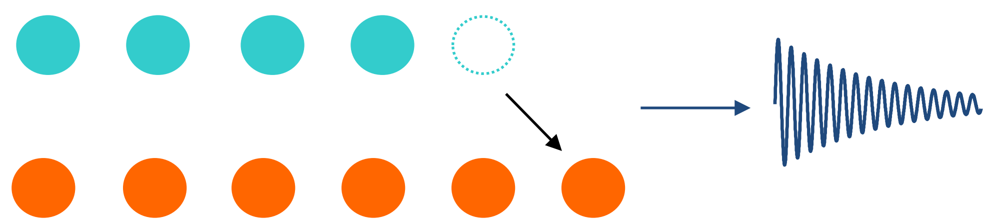
***MRI*: Physics meets Clinic (Part I)**

RF Photon Energy, Absorption, Emission and Spin

- Radiation is absorbed
  - Energy increases



- Radiation is emitted
  - Energy decreases



MRI: Physics meets Clinic (Part I)

RF Photon Energy, Absorption, Emission and Spin

- Quantum Mechanics governs state transitions
  - Energy of transition

$$E = hf_0$$

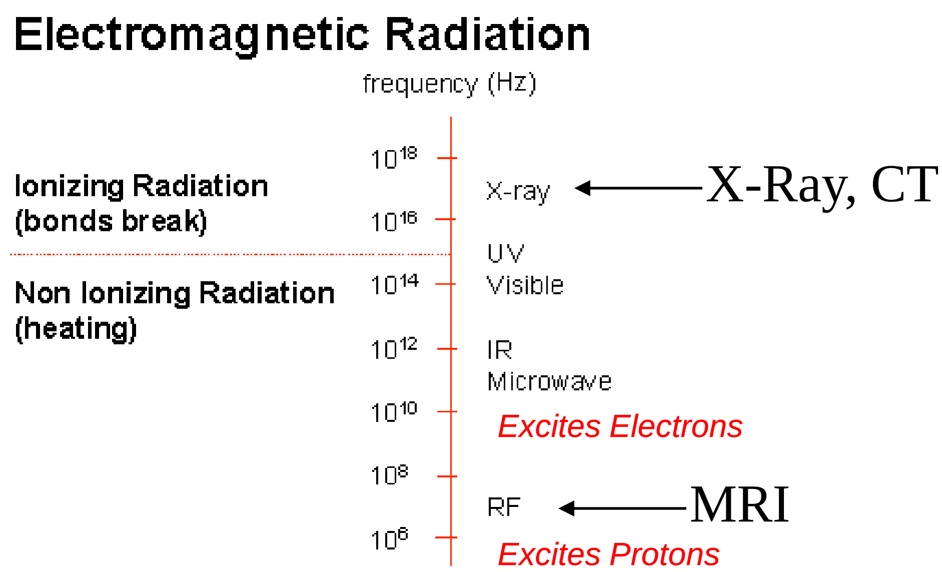
  - Planck's constant

$$h = 4.1357 \times 10^{-15}\, eV \cdot s$$

  - Energy values

$$E_{X-Ray} \cong O\left(10^{2}\right) = 100eV$$

$$E_{MRI} \cong O\left(10^{-9}\right) = \tfrac{1}{1000}\,\mu eV$$

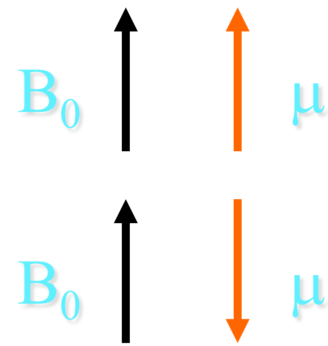


MRI: Physics meets Clinic (Part I)

RF Photon Energy, Absorption, Emission and Spin

- Energy Difference

$$\Delta E = E_{up} - E_{down}$$
$$= \mu_z B_o - (-\mu_z B_o)$$
$$= 2\mu_z B_o$$



Larmor Equation

$$\Rightarrow \omega_0 = 2\pi f_0 = \gamma B_0$$

- Frequency
  - Equate differences

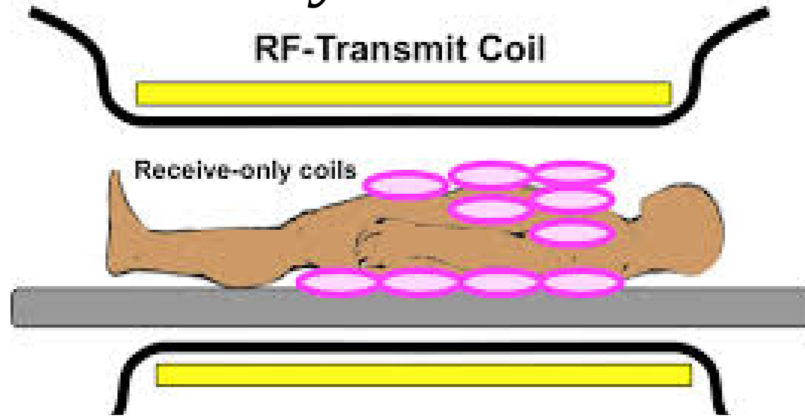
$$\Delta E = hf_0 = 2\mu_z B_o$$

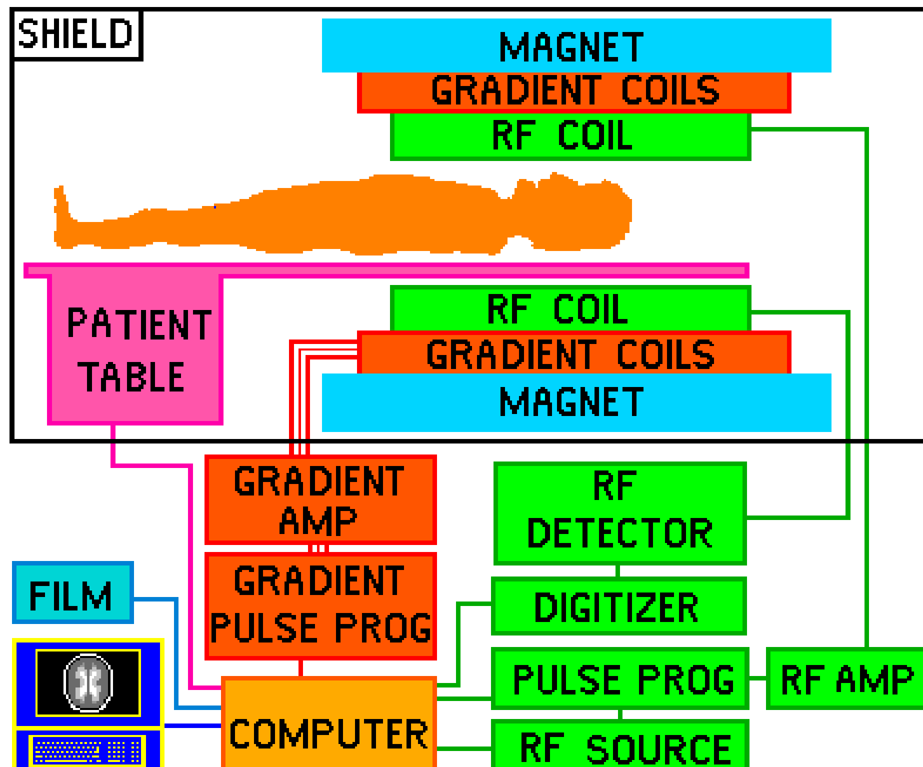
Only certain frequencies are absorbed or emitted by the proton.

These specific frequencies are called resonant frequencies.

MRI: Physics meets Clinic (Part I)

MRI Scanner Anatomy





MRI: Physics meets Clinic (Part I)

Producing an MR Signal – RF excitation

- An oscillating RF signal is applied to the sample and nuclei can absorb energy of the correct frequency. This excites the sample and tips over the high energy states, causing an emission of a photon with a specific frequency that depends on the chemical environment of the proton.
- This RF signal (which is small compared to the static magnetic field) is applied perpendicular to the static magnetic field.
- The net magnetic field creates a force on the magnetization and the magnetization vector begins to precess at the Larmor frequency.
- MRI scanners usually use pulses of RF waves that can flip the dipole by 90^0 or 180^0.
- When the RF field is off the protons relax back to their low energy states with an emission of RF energy and continue to precess at the resonant frequency about the static field.
- The RF photons that can be detected and imaged (not trivial).

***MRI*: Physics meets Clinic (Part I)**

Producing an MR Signal – RF excitation

- **RF Receiver Coils:**

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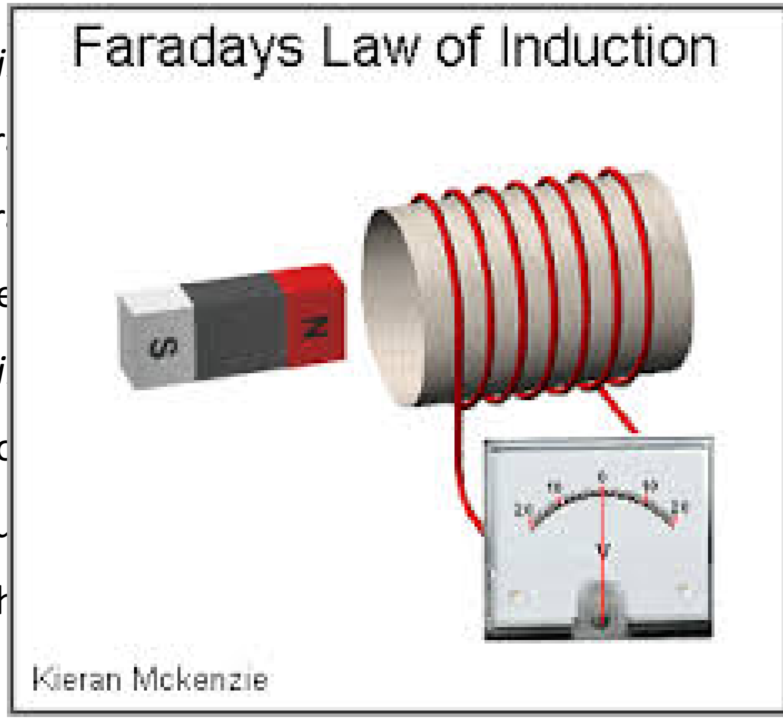
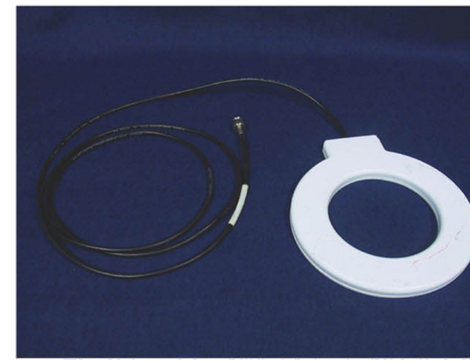


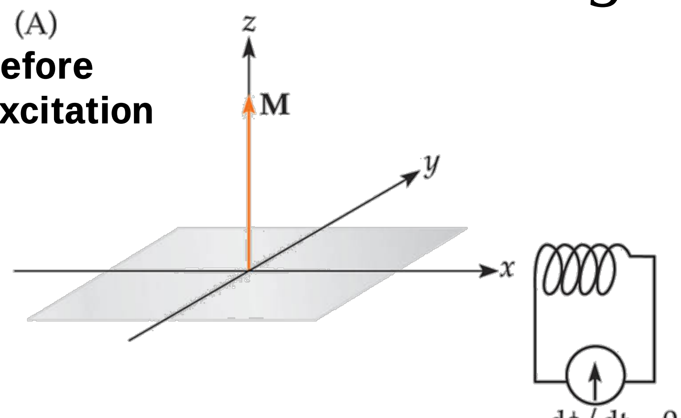


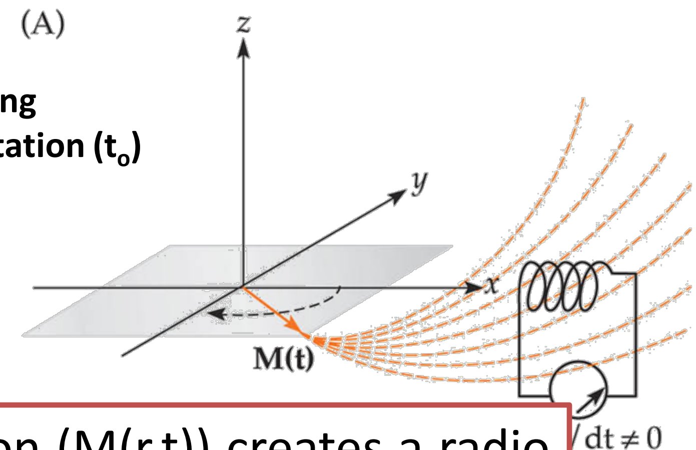
- **Operate based on Faraday's Law of Induction…**

    The strength of the RF signal produced by the protons (or any appropriate nuclei) is proportional to the number of protons (or nuclei) that are excited.

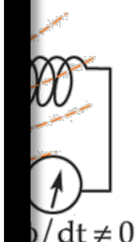
<u>MRI</u>: Physics meets Clinic (Part I)

Detecting an MR Signal – Induction





(B)
After
Excitati



An Introduc

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Rapidly rotating transverse magnetization (M(r,t)) creates a radio frequency excitation within the sample, which is detected via the induced voltage in the receiver / detector coils…

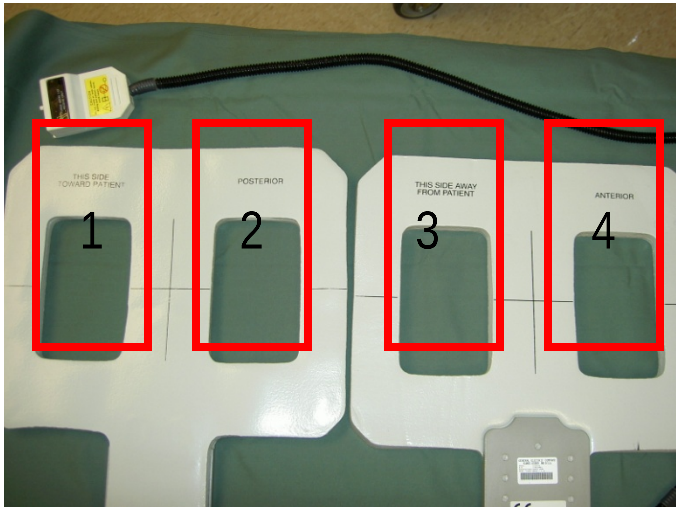
$$V(t) = -\frac{\partial}{\partial t}\int_{\text{object}} \mathbf{M}(\mathbf{r},t)\cdot\mathbf{B}^r(\mathbf{r})\,d\mathbf{r}$$

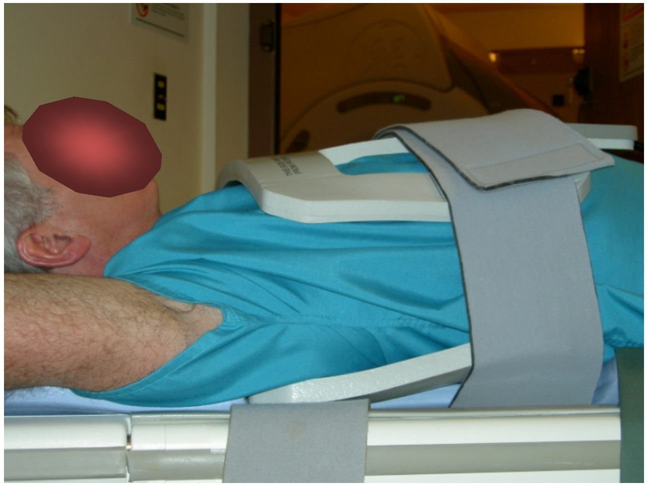
- $\mathbf{B}^r(\mathbf{r})$ is field produced at $\mathbf{r}$ by unit direct current in coil around sample.

MRI: Physics meets Clinic (Part I)

Multiple element coils…

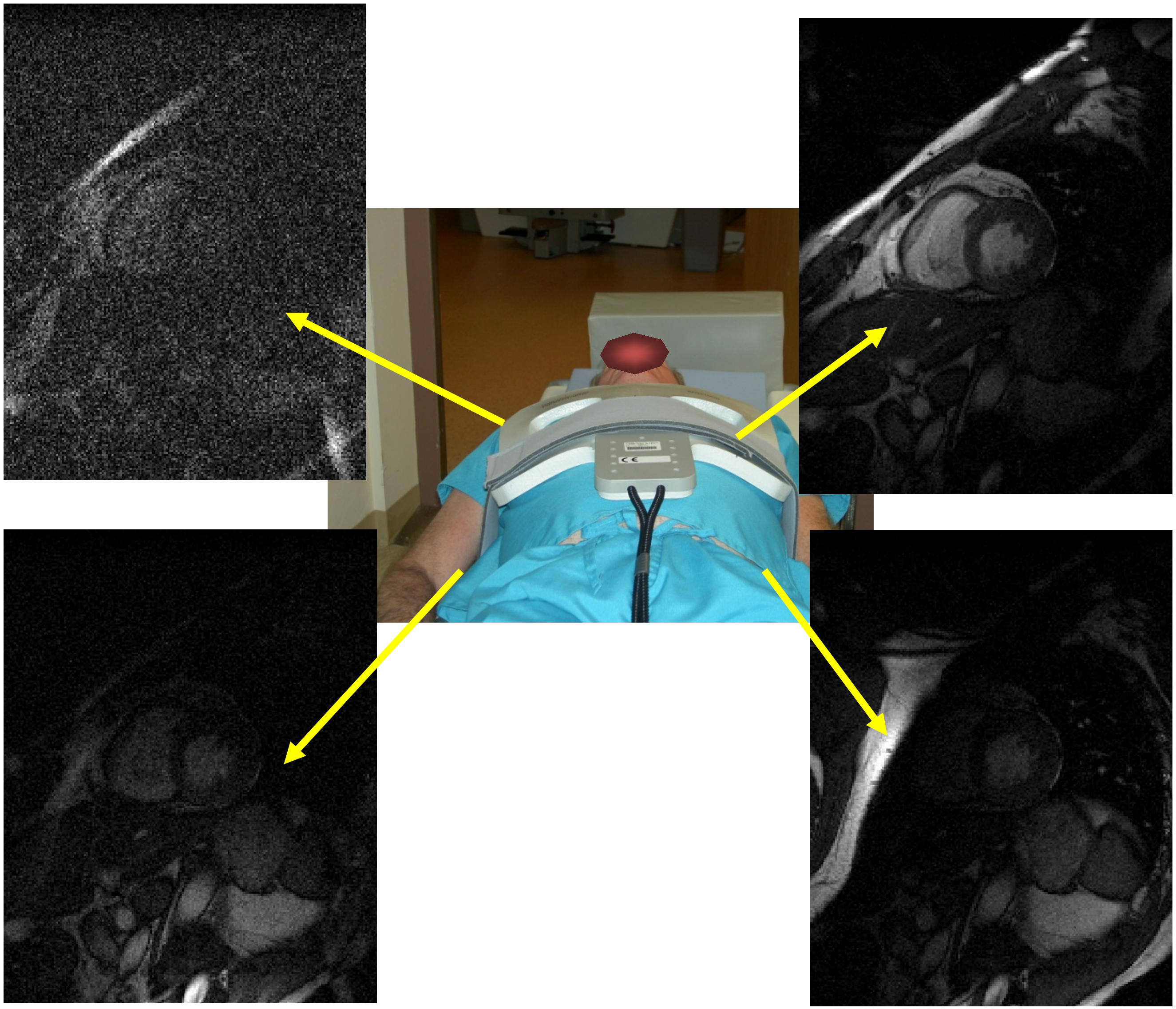
- A conducting wire loop (coil) is required to detect the MRI signal
- Phased array coils are typically configured with 4, 8 or 16 loop elements
- Each coil element primarily receives a signal from a localized region of the body.





***MRI*: Physics meets Clinic (Part I)**

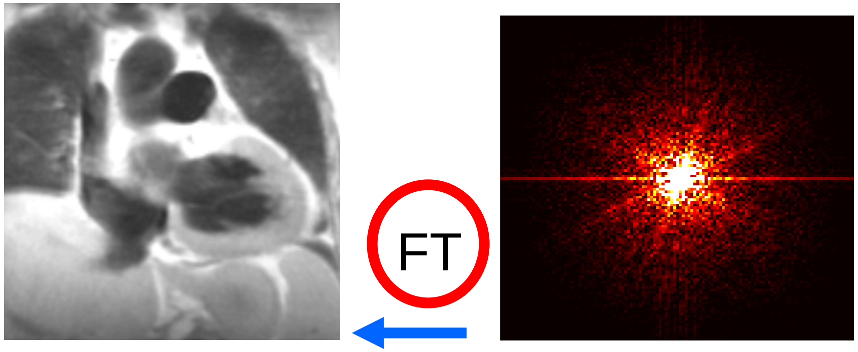
Each coil signal is detected separately…



MRI: Physics meets Clinic (Part I)

Image recovery: k-space. Gradients Encode Space…

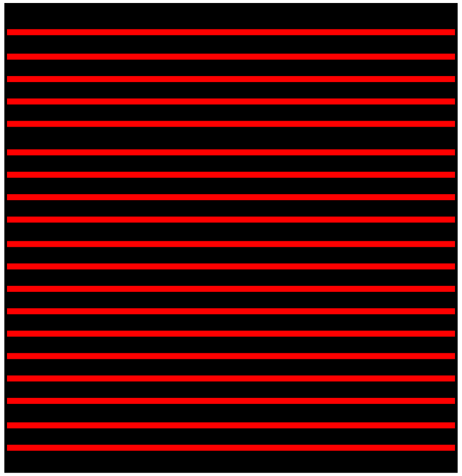
- In MRI, individual lines of frequency or phase space (i.e. k-space) lines are encoded using separately applied magnetic field gradients.
- Typically, a rectangular grid of k-space data are encoded directly, for a 2D slice.
- The image is formed by a performing a Fourier transform

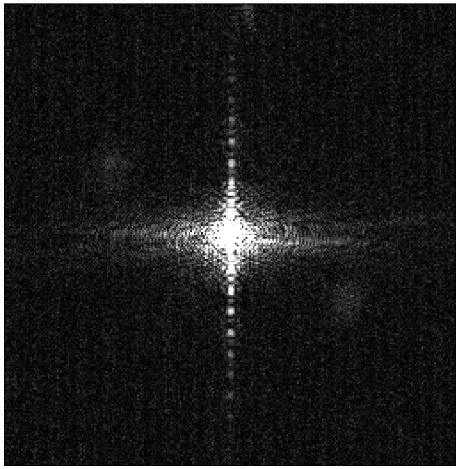


MRI: Physics meets Clinic (Part I)

Image recovery: K-space

- An important aspect of MRI is that k-space is uniformly sampled
- That is, no spatial frequency is weighted more than any other
- Advantage..? Bright pixels do not bleed into adjacent pixels due to the confined nature of the point-spread-function (PSF)
  - We'll learn more about the PSF effect on image acquisition in optical systems.

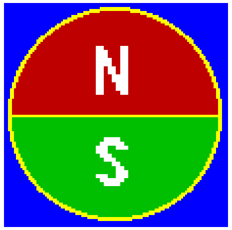




Recap – MRI signal

- Protons (mostly in hydrogen atoms in H_2O) have spin which can be thought of as a small magnetic field.

- *Mathematically*: MRI aims to reconstruct the magnetization (mean <u>magnetic moment</u> of nuclear spin per unit volume) function of each spatial coordinate.



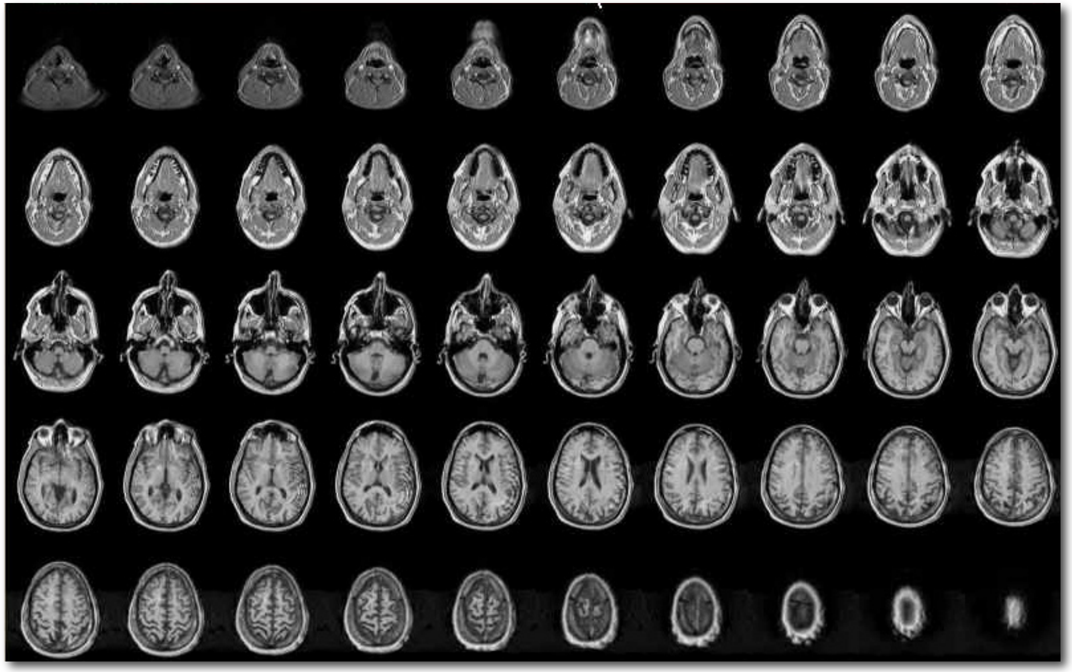
dipole

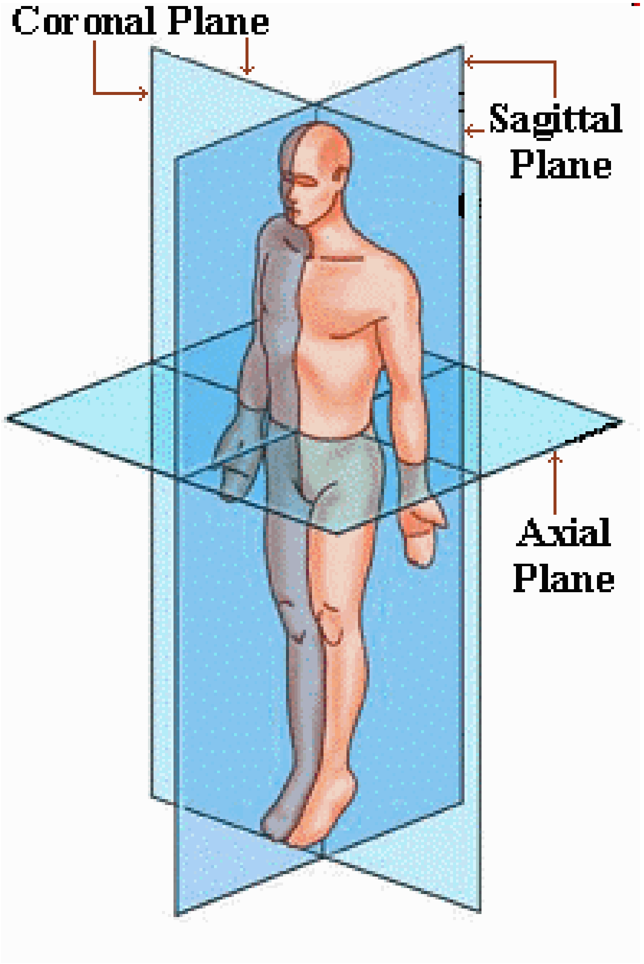
Strength of dipole:

Measured in A m^2

MRI – Image Reconstruction

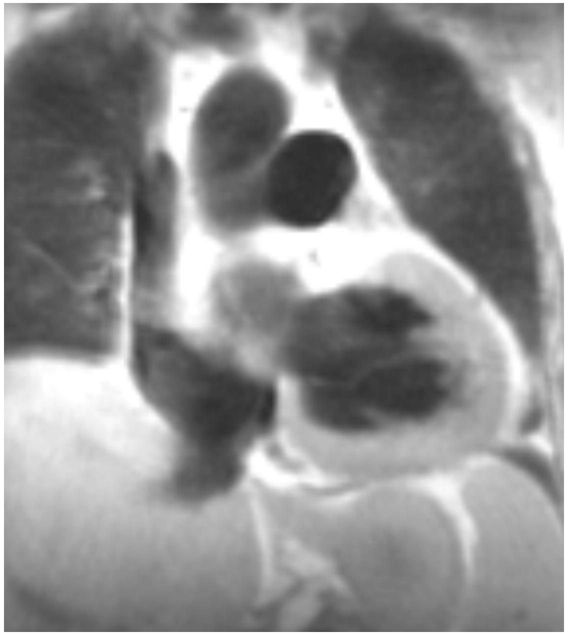
Sample MRI: Sequence of 2D slices





MRI: Physics meets Clinic (Part I)

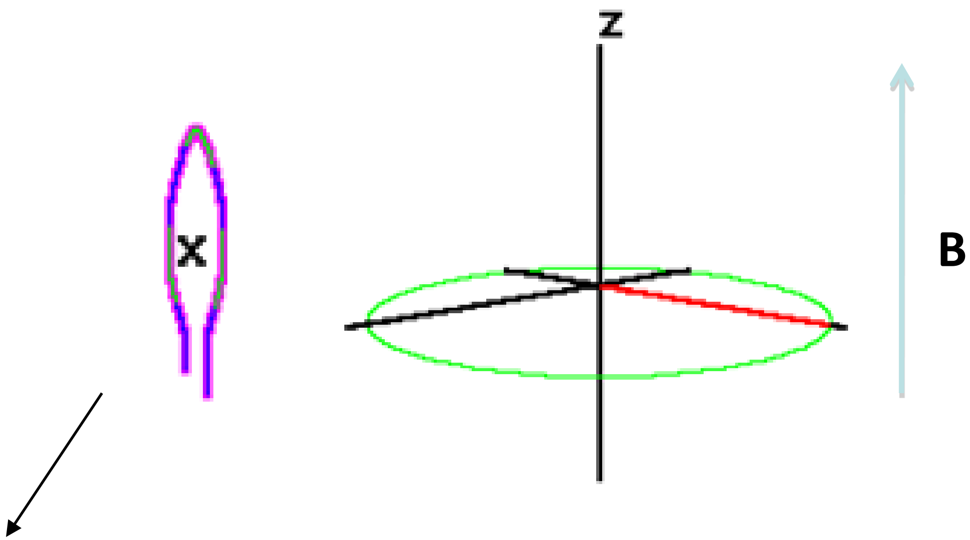
Pulse Sequences: *Spin Echo v/s Gradient Echo*



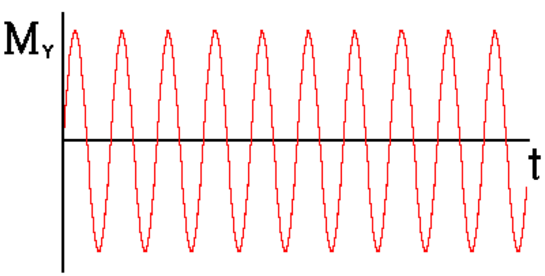
- Spin Echo

Gradient Echo

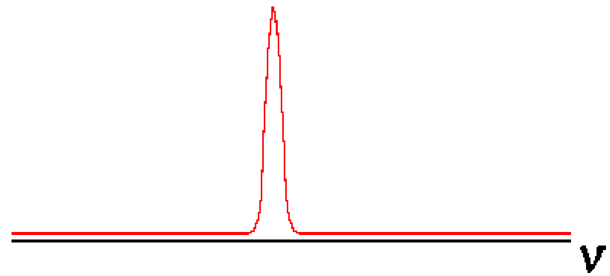
MR signal



Frequency of RF pulse resonates with $B_z(z)$ based on the slice selection gradient so that only the protons in the selected slice precesss…

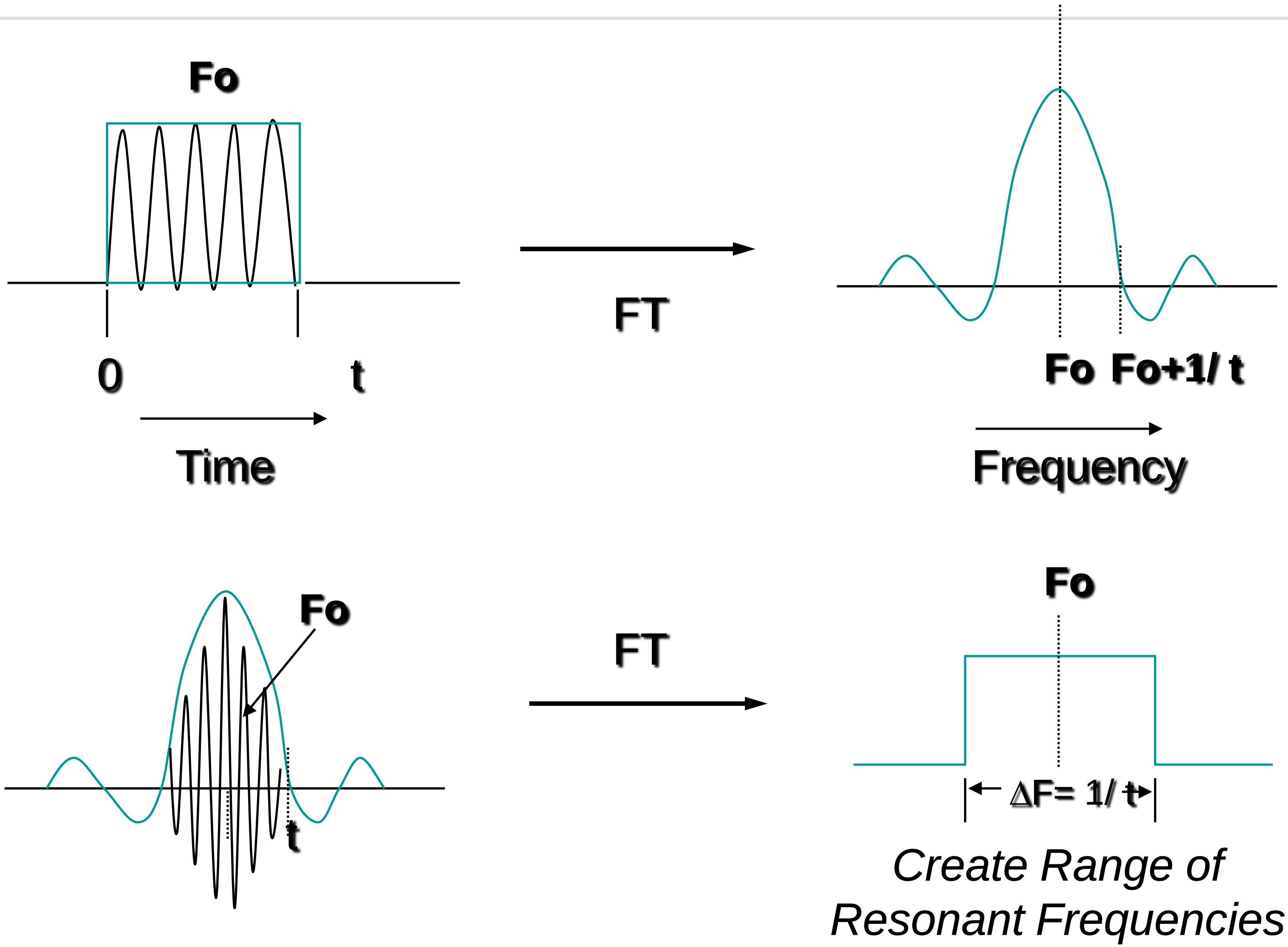


Time-domain signal



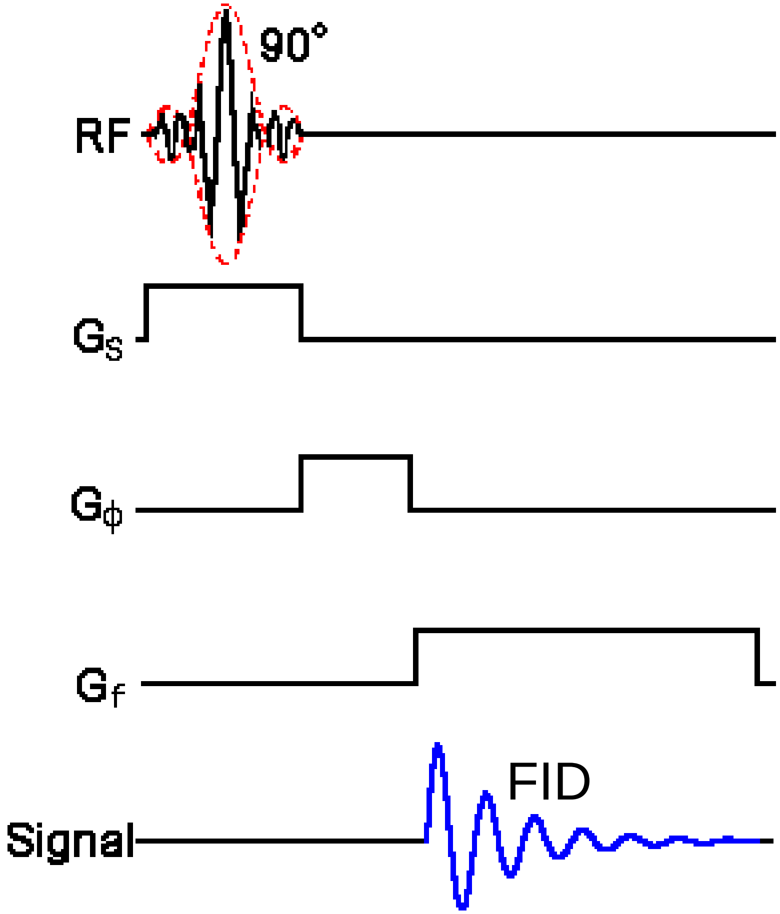
Frequency spectrum

Electromagnetic **Excitation Pulse** (RF Pulse)

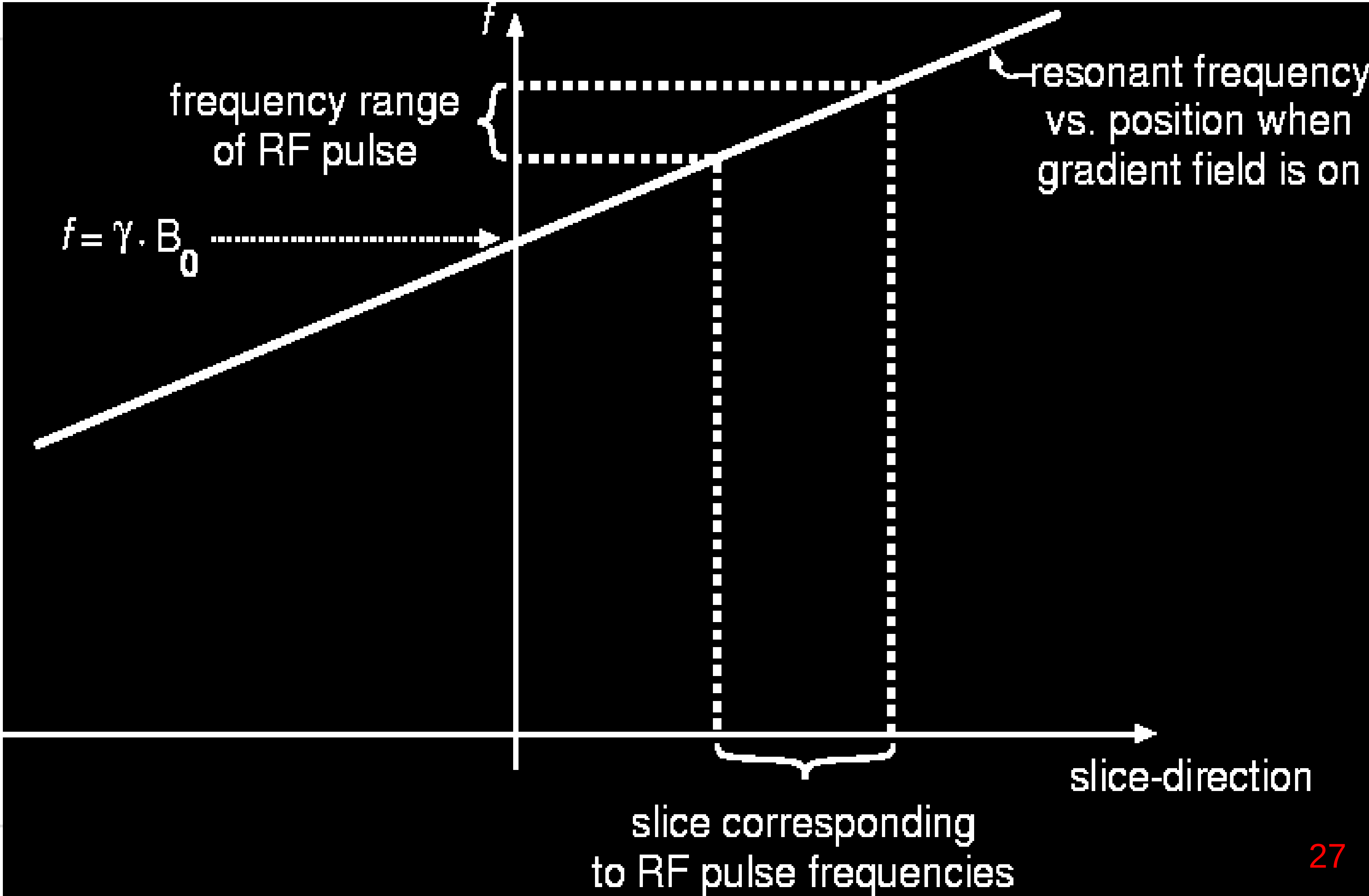


MRI **Pulse Sequence**

*Most basic : free induction decay **(FID)***



Slice **Selection**



Determining **Slice Thickness**

Resonance frequency range as the result of slice-selective gradient:

$$\Delta F = \gamma_H * G_{sl} * d_{sl}$$

The bandwidth of the RF excitation pulse:

$$\Delta\omega/2\pi$$

Thus the slice thickness can be derived as

$$d_{sl} = \Delta\omega \,/\, (\gamma_H * G_{sl} * 2\pi)$$

Steps in **3D Localization**

- Can only detect total RF signal from inside the form factor of the “RF coil” (the detecting antenna)

❶ Excite and receive M_{xy} in a thin (2D) slice of the subject

➔ The RF signal we detect must come from this slice

➔ Reduce dimension from 3D down to 2D

❷ Deliberately make magnetic field strength *B* depend on location within slice

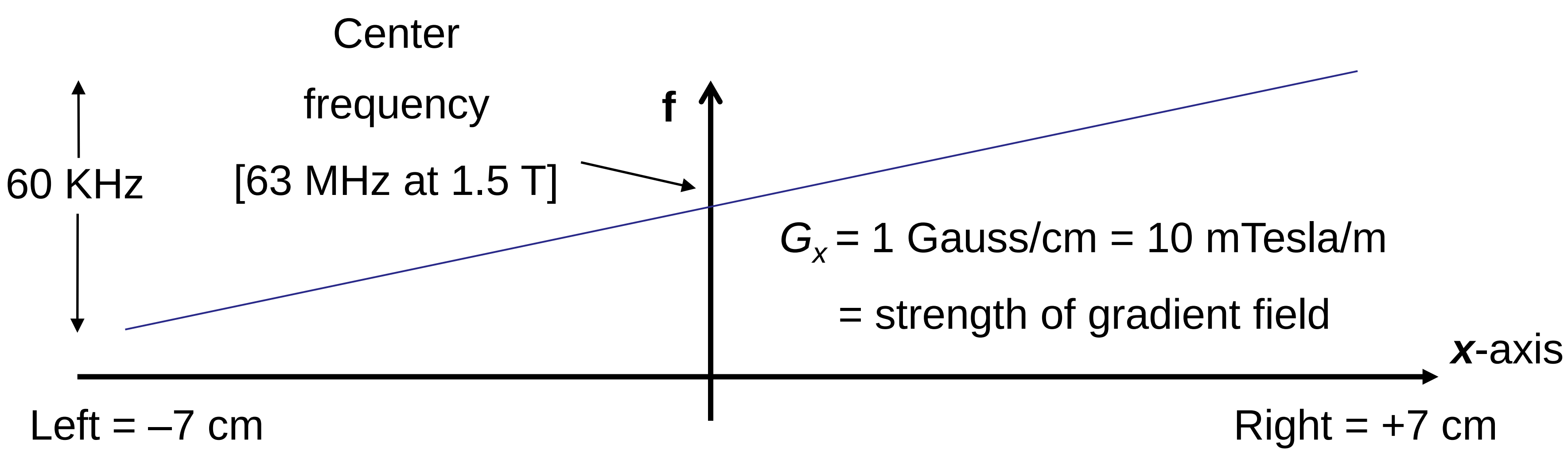
➔ Frequency of RF signal will depend on where it comes from

➔ Breaking total signal into frequency components will provide more localization information

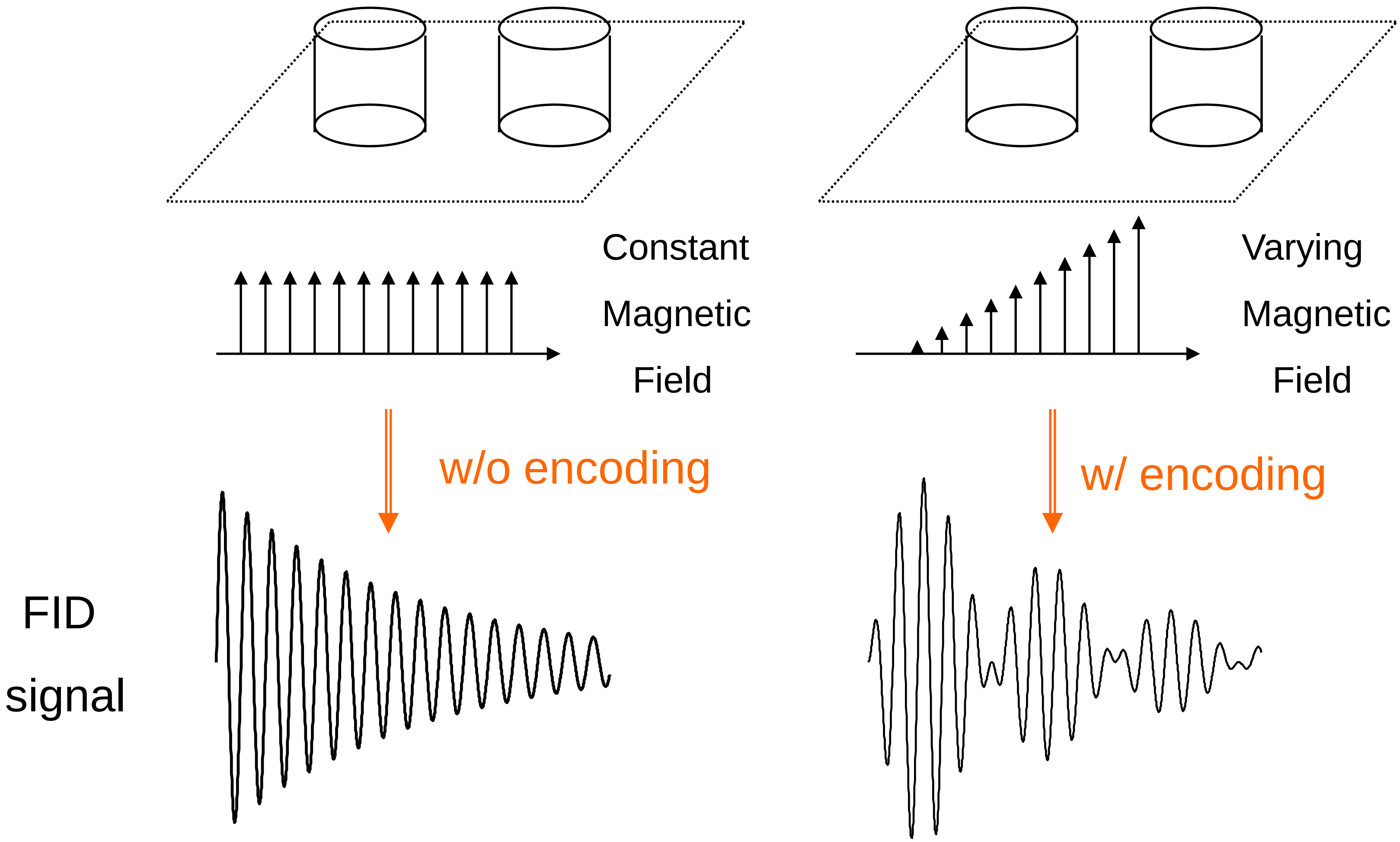
❸ Make RF signal phase depend on location within slice.

Gradient Fields: Spatially Nonuniform *B*:

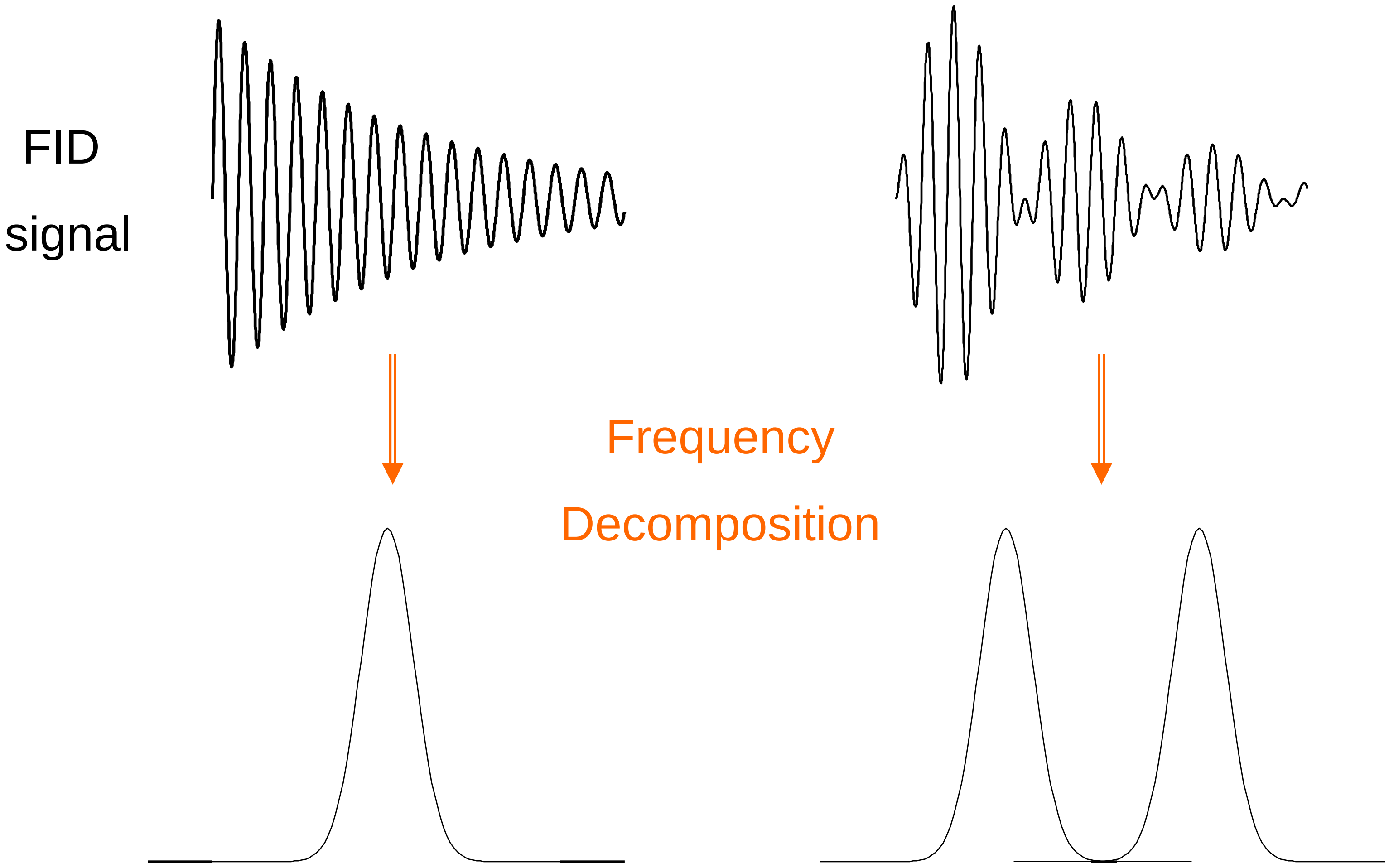
- During readout (image acquisition) period, a *frequency encoding* gradient field is applied --- using a deliberately applied non-uniform field to make the precession frequency depend on location
- Before readout (image acquisition) period, a *phase encoding* gradient field is applied --- during the readout (image acquisition) period. The effect of this gradient field is not time-varying but a fixed phase accumulation is determined by the amplitude and duration of the phase encoding gradient. $\Delta\Phi = \omega T_p$ where T_p is the time of Phase gradient application.



A Simple Example of Spatial Encoding



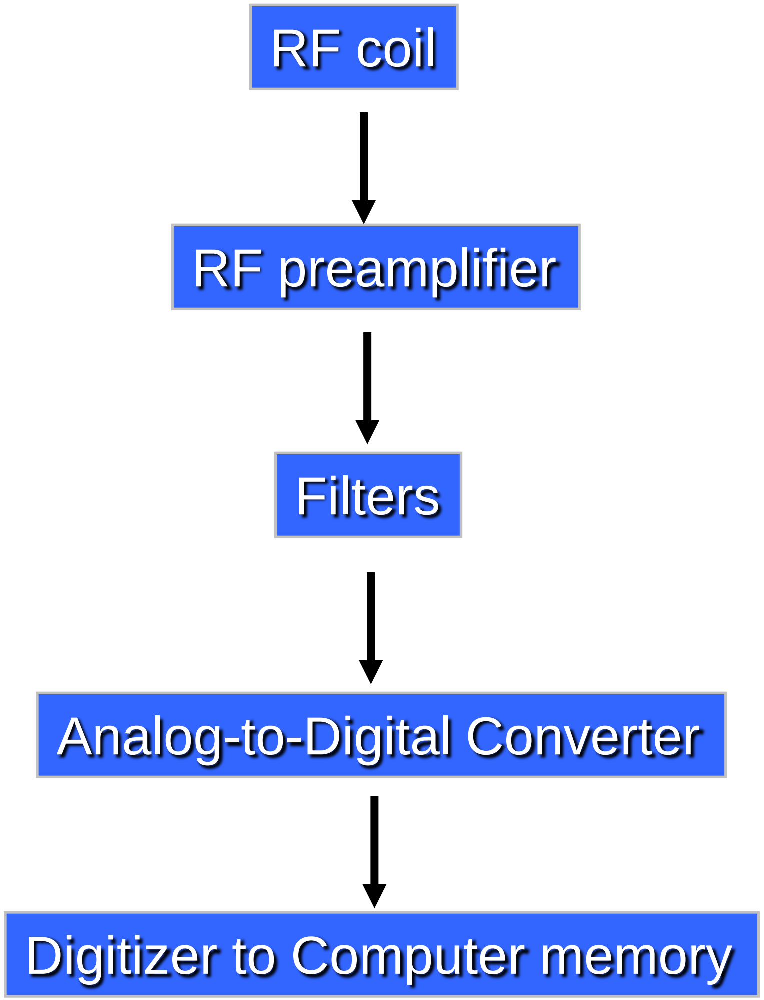
Spatial Decoding of the MR Signal



Receiving M_{xy} in Selected Z-Slice

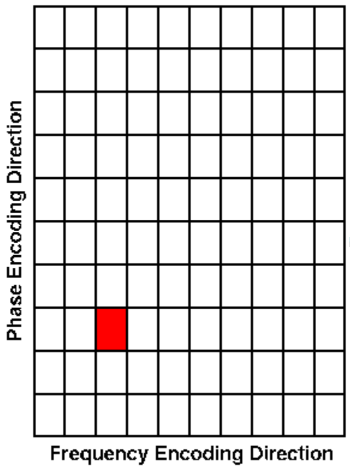
Receive:

- During **readout**, gradient field perpendicular to slice selection gradient is turned on…
- Computer breaks measured signal $V(t)$ into frequency components $v(f)$ — using the Fourier transform
- Since frequency f varies across subject in a known way, we can assign each component $v(f)$ to the place it comes from

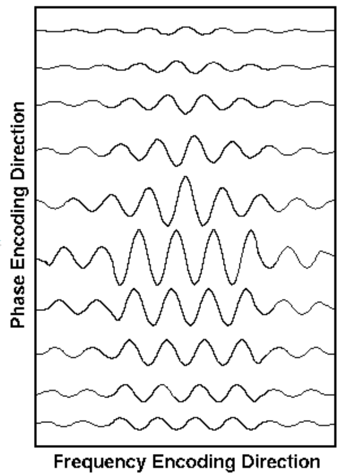


FID – Example 1

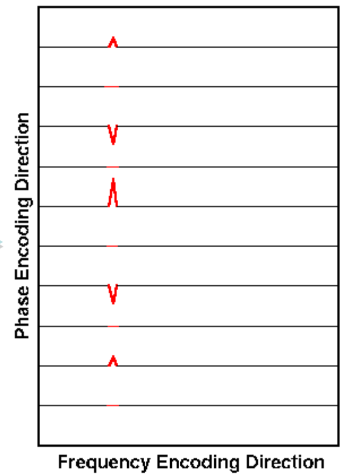
Original image

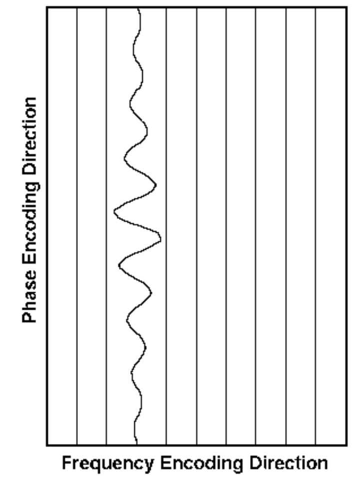


Raw data

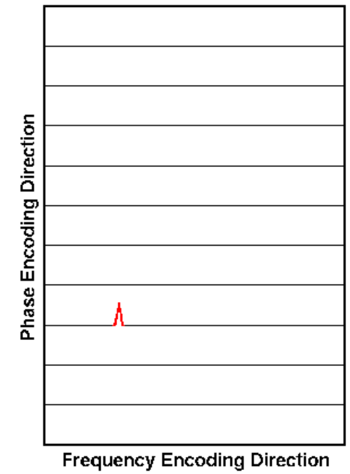


FT in freq. direction





FT in phase direction to get an image

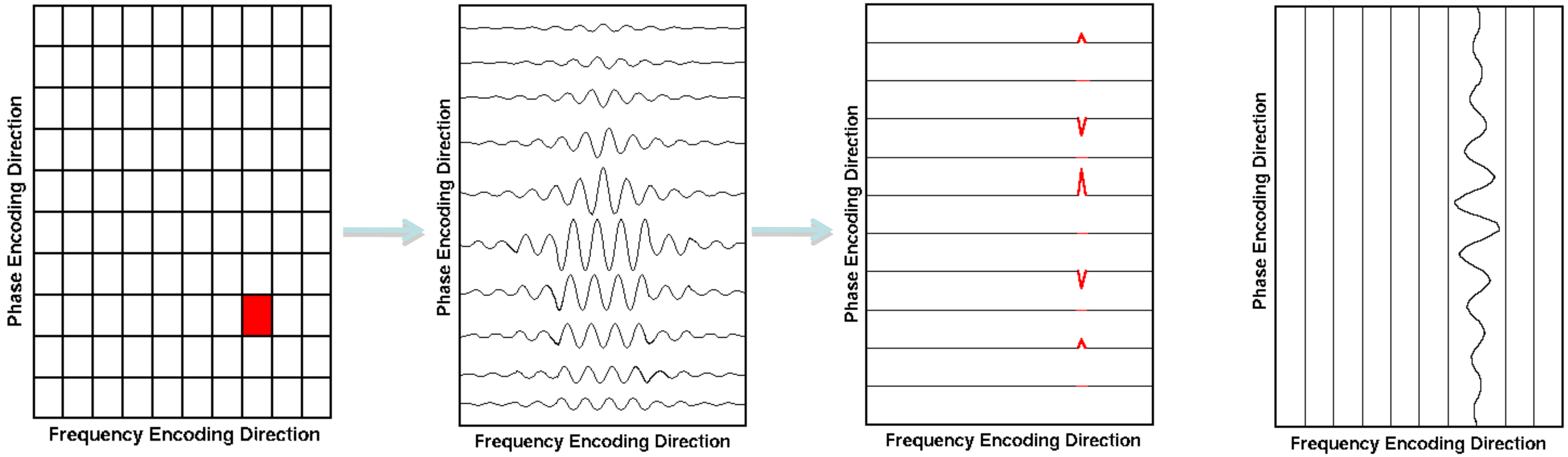


FID – Example 2

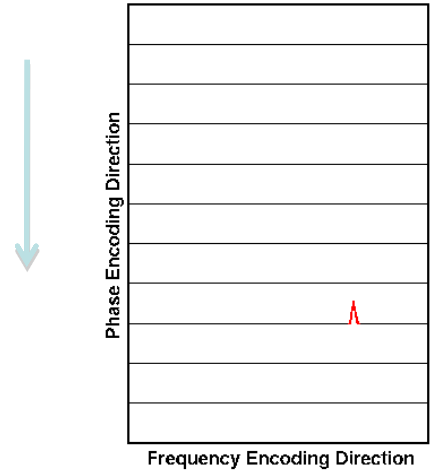
Original image

Raw data

FT in freq. direction

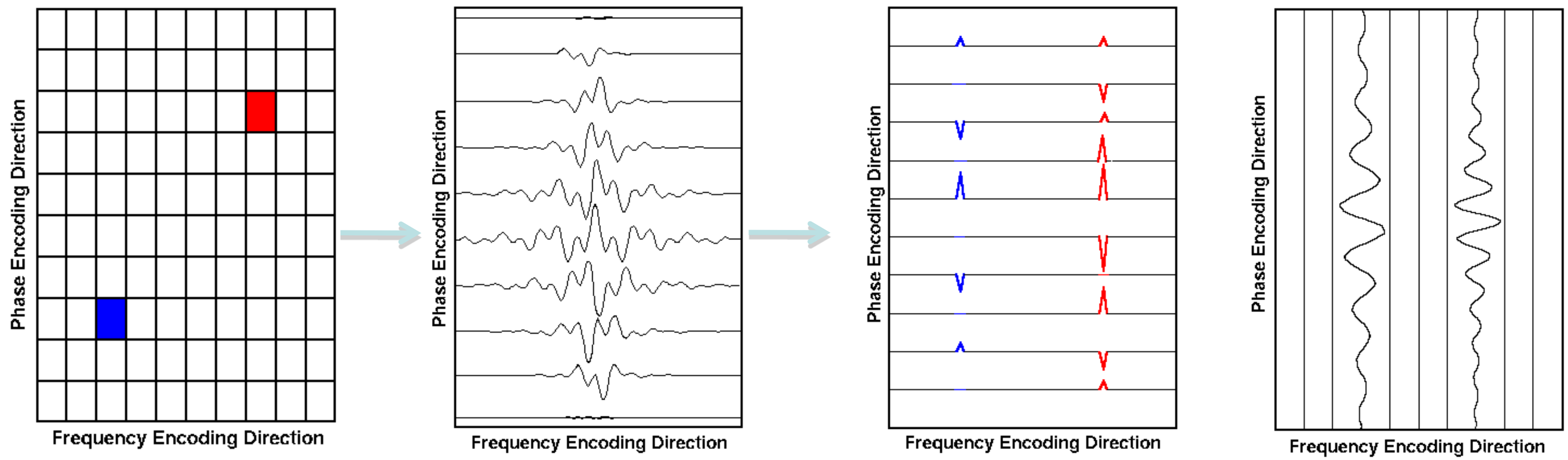


FT in phase direction to get an image

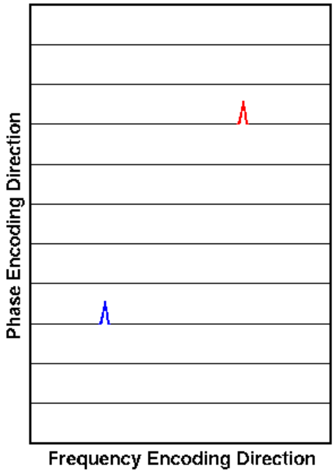


FID – Example 3

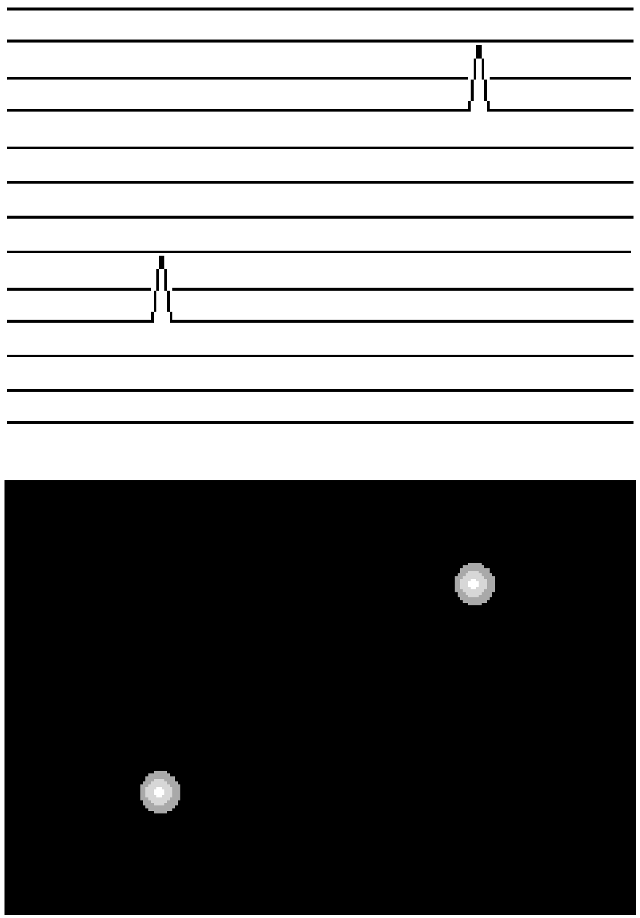
Original image | Raw data | FT in freq. direction



FT in phase direction to get an image



Final Image – FFT in Phase Direction



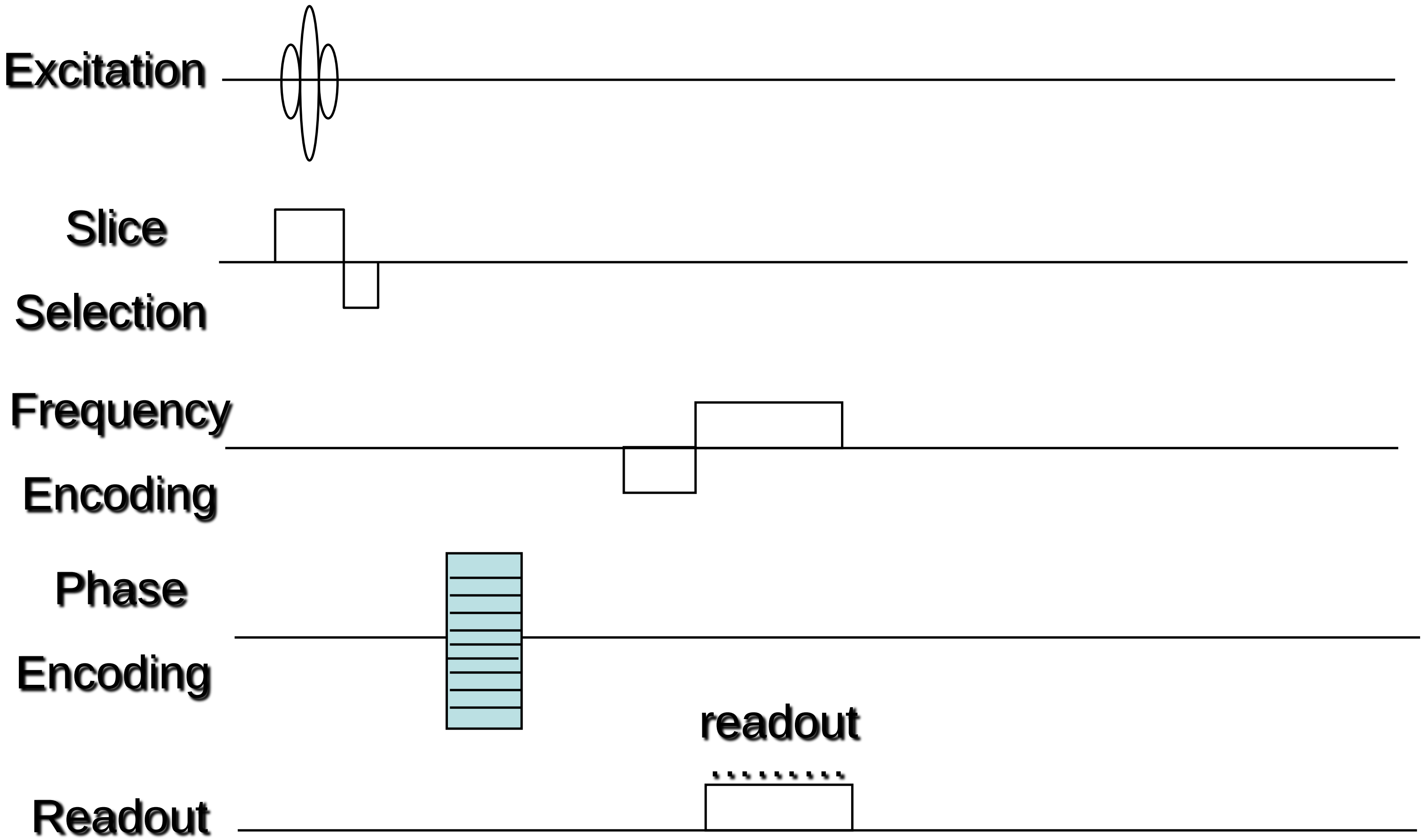
Usually the absolute value of the DFT of the raw data is taken as the pixel intensity value.

=> Raw k-space is richer than the final images we see!

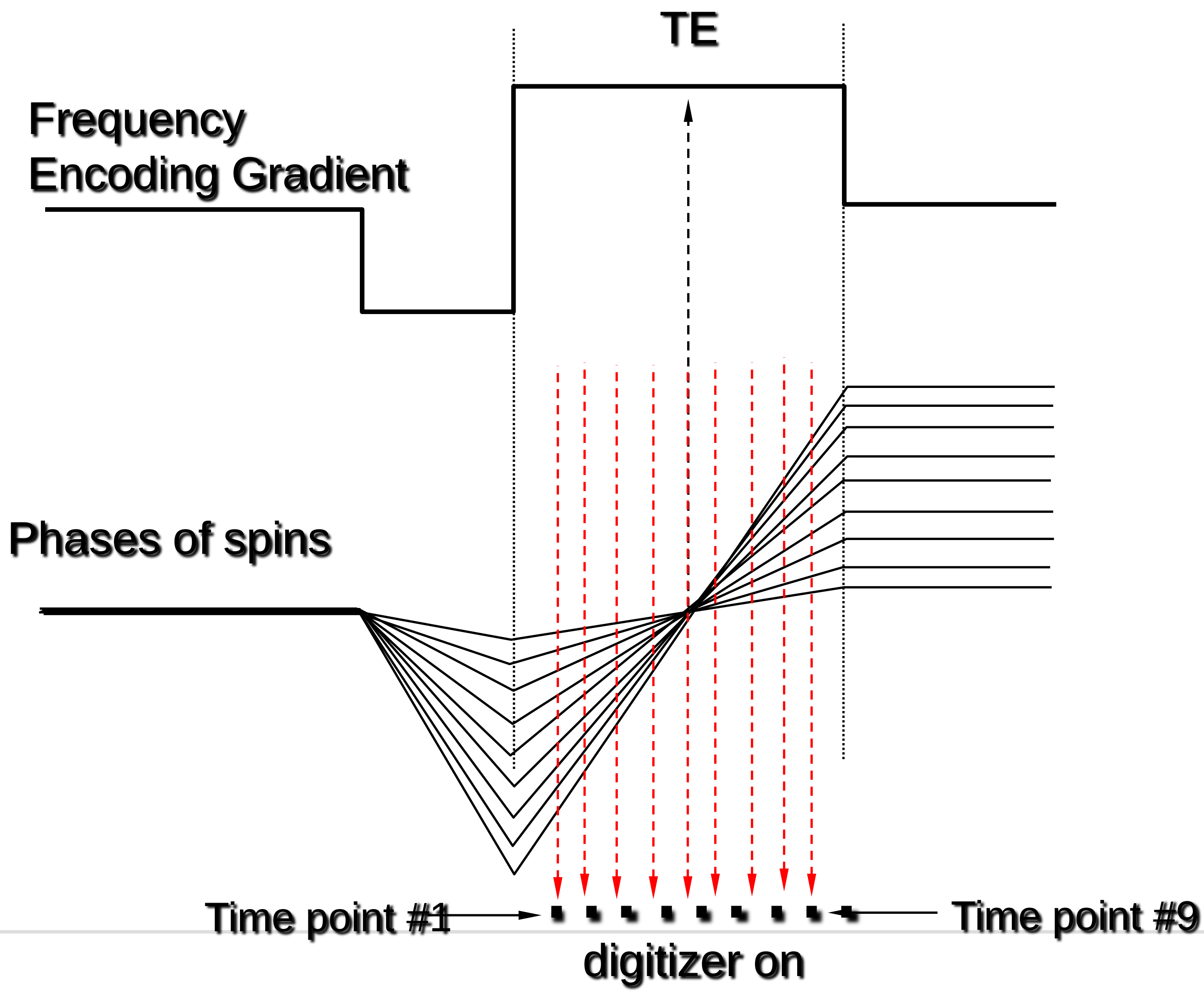
More advanced MRI **Pulse Sequences**

- Gradient Echo
- Spin Echo
- Fast Spin Echo
- Inversion Recovery

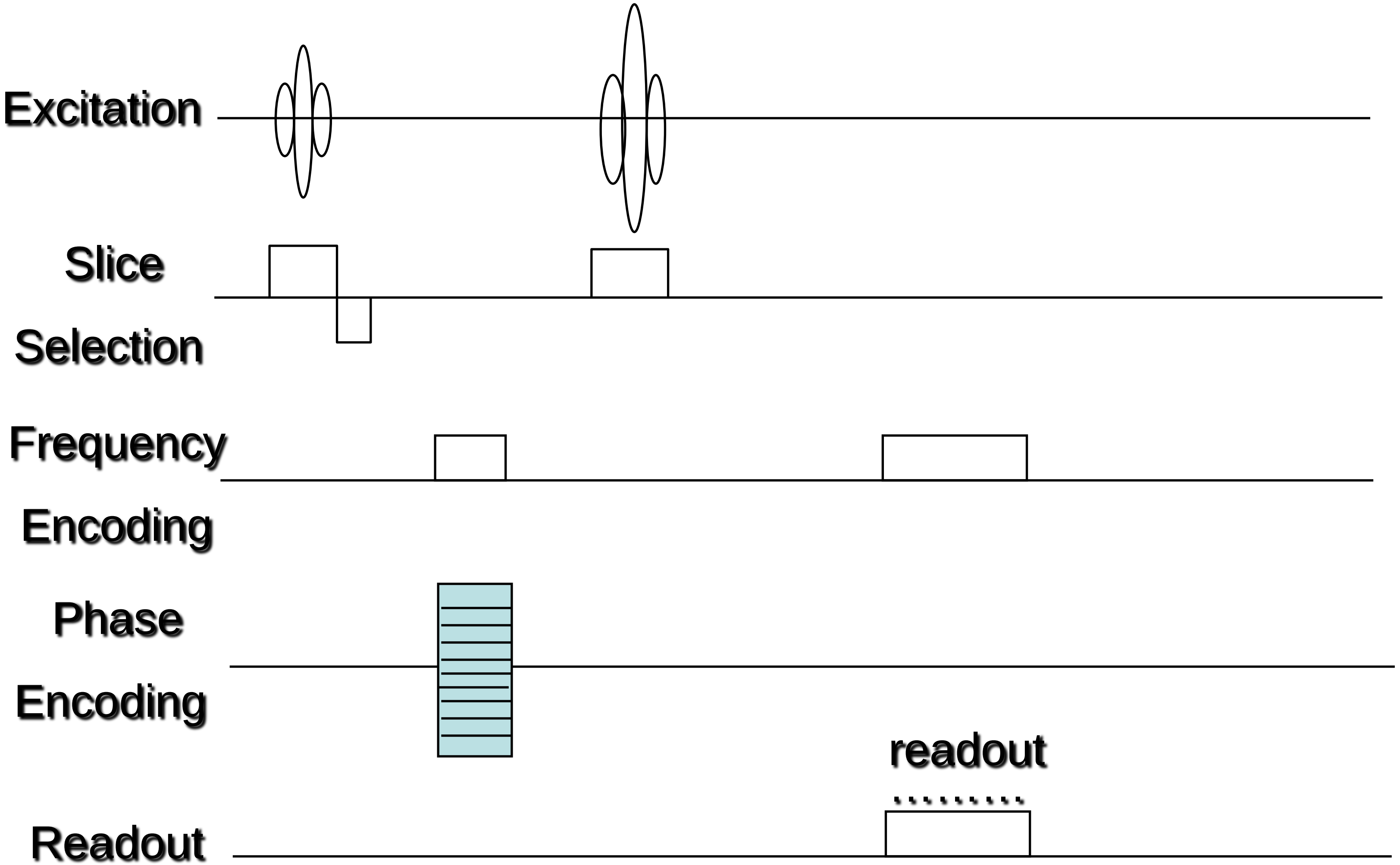
Pulse Sequence: **Gradient-echo** imaging



Phase Evolution of Gradient Echo MR Data with Frequency Encoding (i.e. w/o Phase Encoding)



Pulse Sequence: **Spin-echo** imaging



Phase Evolution of Spin-Echo MR Data with Only Frequency Encoding (i.e. without Phase Encoding)